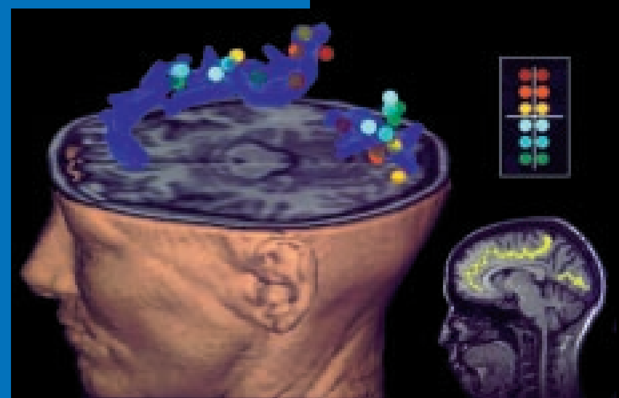

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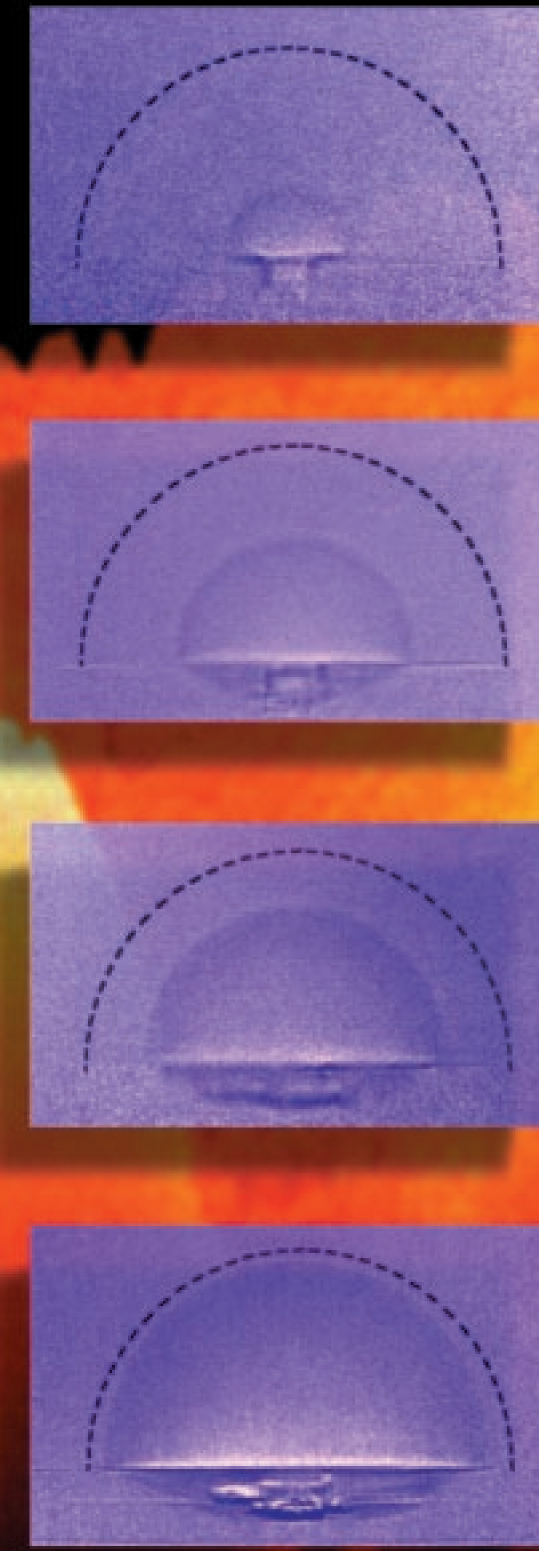
Los Alamos, New Mexico 87545

LA-13355-PR

Physics Division Progress Report

January 1, 1995–December 31, 1996

LA-13355-PR Progress Report



Physics Division Progress Report

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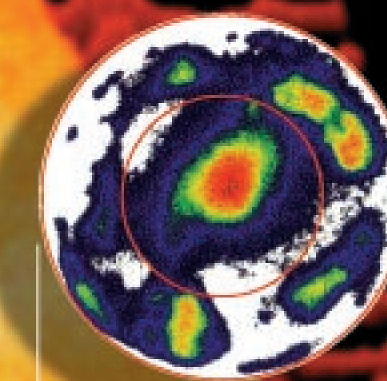

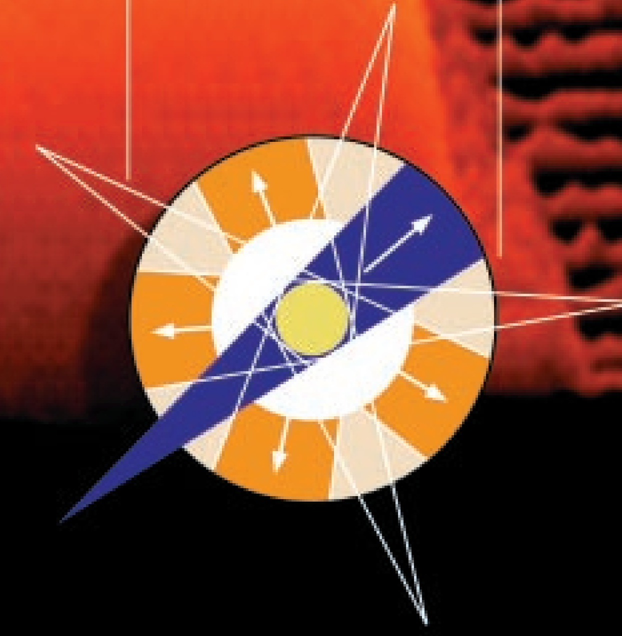

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Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36.

Front Cover:
The background image is a three-dimensional representation of hyper-polarized ^{3}He gas diffusing over time. Shown in the foreground are a series of dynamic proton radiographs of detonating high explosives (left column) as well as a schematic of the illumination geometry of a Nova laser hohlraum below an image of the corresponding plasma instabilities observed in the irradiation chamber (center column).

Back Cover:
Shown in the foreground are a simulation of an imploding target on the Pegasus II Pulsed-Power Facility (lower left) and a magnetoencephalographically generated image of brain activity in the cerebral cortex (upper left).

Art direction and cover design by Donald Montoya, Group CIC-1.

The four most recently published reports in this series, unclassified, are LA-12336-PR, LA-12501-PR, LA-12804-PR, and LA-13048-PR.

LA-13355-PR
Progress Report

UC-910
Issued: October 1997

Physics Division Progress Report

January 1, 1995–December 31, 1996

Compiled and Edited by
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Los Alamos
NATIONAL LABORATORY

Los Alamos, New Mexico 87545

Physics Division Progress Report

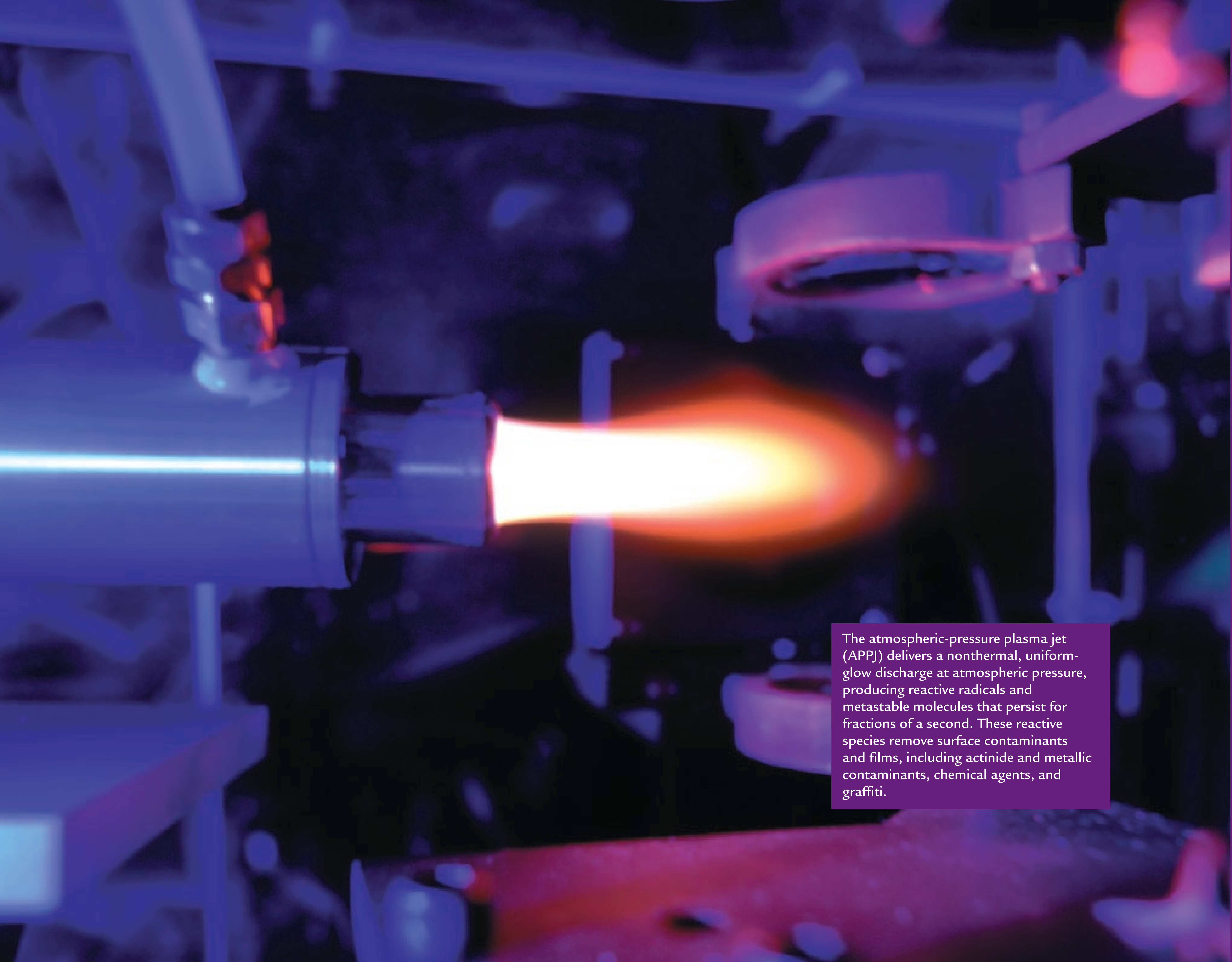
January 1, 1995–December 31, 1996

Abstract

This issue of the Physics Division Progress Report describes progress and achievements in Physics Division research during the period January 1, 1995–December 31, 1996. The report covers the five main areas of experimental research and development in which Physics Division serves the needs of Los Alamos National Laboratory and the nation in applied and basic sciences: (1) biophysics, (2) hydrodynamic physics, (3) neutron science and technology, (4) plasma physics, and (5) subatomic physics. Included in this report are a message from the Division Director, the Physics Division mission statement, an organizational chart, descriptions of the research areas of the five groups in the Division, selected research highlights, project descriptions, the Division staffing and funding levels for FY95–FY97, and a list of publications and presentations.

Contents

Introduction



The atmospheric-pressure plasma jet (APPJ) delivers a nonthermal, uniform-glow discharge at atmospheric pressure, producing reactive radicals and metastable molecules that persist for fractions of a second. These reactive species remove surface contaminants and films, including actinide and metallic contaminants, chemical agents, and graffiti.

Significant progress in research and development has been achieved by Physics Division personnel during the past two years. This Progress Report recounts the work of the Division during this creative and productive period as we supported Laboratory missions and goals in the areas of both basic and applied science.

The mission of the Physics Division is to further our understanding of the physical world, to generate new technology in experimental physics, and to establish a physics foundation for current and future Los Alamos programs. The work described and the publications cited in this report demonstrate the degree to which we have been able to implement this mission. The five main areas of experimental research and development in which Physics Division serves the needs of Los Alamos National Laboratory and the nation are (1) biological physics, (2) hydrodynamic physics, (3) neutron science and technology, (4) basic and applied plasma physics, and (5) subatomic physics.

This report includes Division goals, organizational structure and group summaries, selected research highlight articles, project descriptions, staffing and funding levels for FY95–FY97, and a list of publications and presentations by Physics Division authors. The research capabilities reflected here are based on the very broad array of talents and interests of the more than 300 physicists, engineers, and technicians who contribute to this enterprise. From our senior scientists and technicians, to our experienced support staff, to our newest staff, postdocs, and students, this corps of talented individuals is our most important resource. Their dedication to excellence, their creativity and ingenuity, and their relentless pursuit of scientific understanding are the fundamental drivers of our Division's success.

Additionally, they are empowered with a critical set of facilities that Physics Division operates and/or uses. The latter include the proton and neutron capabilities of the Los Alamos Neutron Science Center (LANSCE) accelerator facility, the Pegasus II and Atlas pulsed-power facilities, the Trident laser complex, and several large plasma-generation devices. We also perform extensive experimental work at off-site facilities, including the underground containment facilities in Nevada, large beamline and detector facilities at the Fermi National Accelerator Laboratory (FNAL) and Brookhaven National Laboratory (BNL), and gamma-ray and x-ray beamlines also at BNL. Our work is not confined to domestic facilities. We are involved with experiments in Russia and states of the Former Soviet Union, at the European Laboratory for Nuclear and Particle Physics (CERN) in Switzerland, at the Atomic Weapons Establishment (AWE) in the U.K., with the Japan Atomic Energy Research Institute (JEARI), and with a host of other foreign collaborations. Finally, new projects are continuously being created in the Division. For example, we are evaluating the research impacts of an improved laser facility and a proton-radiography facility. We are dedicated to accomplishing all of this in a manner that protects the health and safety of our employees, the public, and the environment.

As you browse through this report, I hope that you will gain an understanding of who we are and what we do and that you will share my excitement and enthusiasm for the research it contains. If I can provide assistance or answer questions, please contact me.

Peter D. Barnes, Director
Physics Division

Mission and Goals

The mission of Physics Division is to further our understanding of the physical world, to generate new technology in experimental physics, and to establish a physics foundation for current and future Los Alamos programs.

The goals of Physics Division are to

- provide the fundamental physics understanding supporting Laboratory programs;
- investigate the basic properties of nuclear interactions, high-energy-density systems, and biological systems with a view toward identifying technologies applicable to new Laboratory directions;
- identify and pursue new areas of physics research, especially those to which the unique capabilities of the Laboratory may be applied;
- explore interdisciplinary areas of scientific endeavor to which physical principles and the methods of experimental physics can make an important contribution; and
- maintain strength in those disciplines that support the Laboratory mission.

Physics Division pursues its goals by

- establishing and maintaining a scientific environment that promotes creativity, innovation, and technical excellence;
- undertaking research at the forefront of physics with emphasis on long-term goals, high risks, and multidisciplinary approaches;
- fostering dialogue within the Division and the scientific community to realize the synergistic benefits of our diverse research interests;
- encouraging the professional development of each member within the Division; and
- conducting all of its activities in a manner that maintains a safe and healthful workplace and protects the public and the natural environment.

P. D. Barnes
Division Director

D. J. Rej
Deputy Division Director

K. W. Thomas
Chief of Staff

Program Development
C. Hoffman/L. Veeser/J. Mack/D. Rej*

Atlas Project Office
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Operations Manager
S. Hadden

Facility Manager
L. Rowton

ES&H Officer
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Administrative Specialist
A. L. Hoerr

Business Team Leader
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* Acting

P-21 Biophysics
C. C. Wood
C. J. Aine

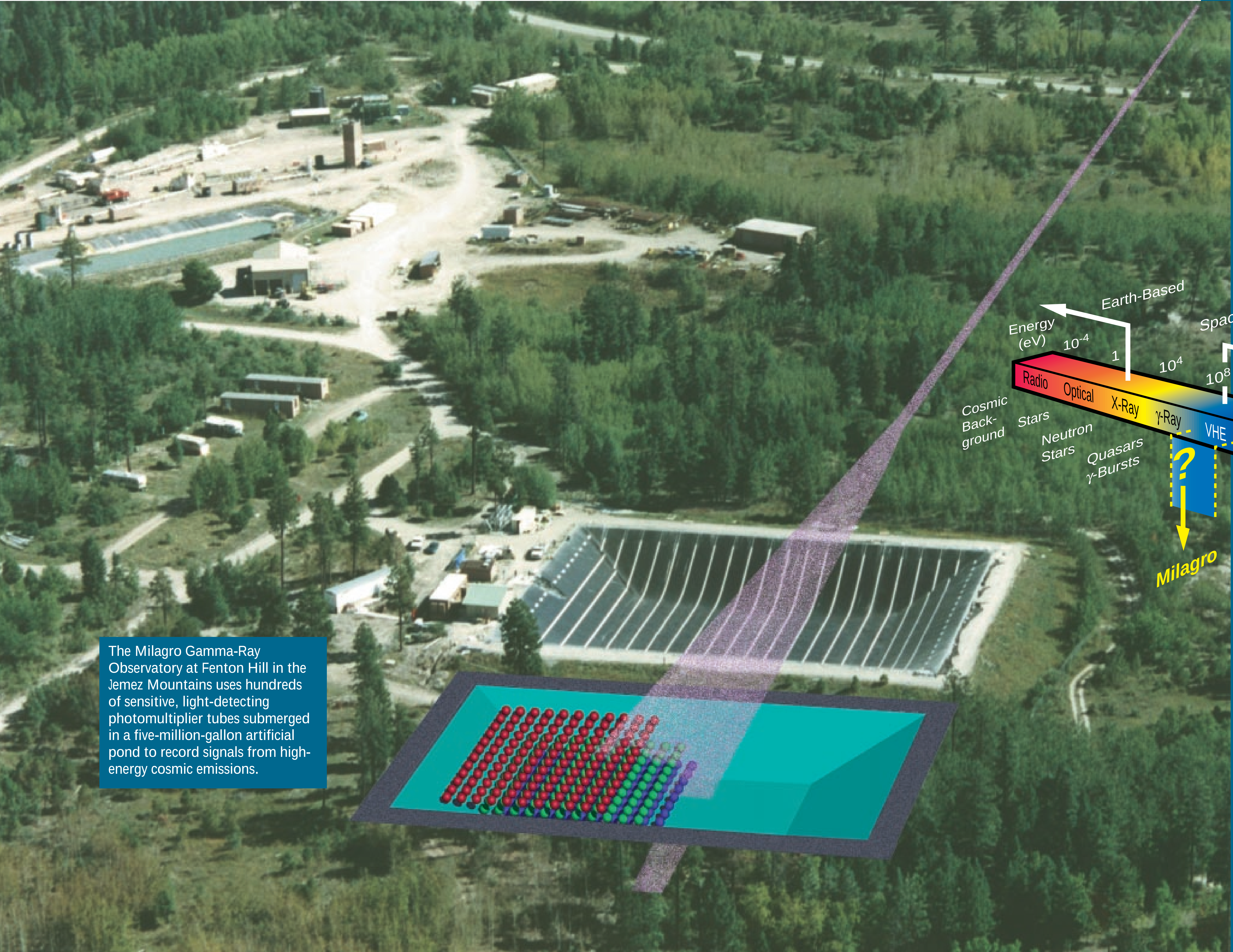
P-22 Hydrodynamic and X-Ray Physics
J. S. Ladish
J. S. Shlachter

P-23 Neutron Science and Technology
M. Y. Hockaday
S. J. Seestrom

P-24 Plasma Physics
K. F. Schoenberg
J. C. Fernández

P-25 Subatomic Physics
J. B. McClelland
A. P. T. Palounek

I. Group Descriptions



The Milagro Gamma-Ray Observatory at Fenton Hill in the Jemez Mountains uses hundreds of sensitive, light-detecting photomultiplier tubes submerged in a five-million-gallon artificial pond to record signals from high-energy cosmic emissions.

P-21: Biophysics

C. C. Wood,
Group Leader
Cheryl J. Aine,
Deputy Group Leader

Introduction

The Biophysics Group (P-21) was founded in 1988 with the goal of applying the scientific and technical resources of Physics Division to the biosciences. The mission of P-21 is to apply physics knowledge and techniques to increase our understanding of important biological phenomena and to use biological systems to elucidate physical principles of complex phenomena. The group has strengthened existing biological projects within the Division and has initiated new bioscience efforts in a number of directions. Group members are engaged in biophysical research over a wide range of physical scales, including characterization of the structure and dynamics of protein molecules and the implications of those qualities for protein function; ultrasensitive detection and characterization of individual molecules using laser fluorescence; design and implementation of biologically inspired robots and adaptive digital hardware; development, validation, and application of noninvasive techniques for the measurement of human brain function; development of nonbiological applications of low-field magnetic sensors; and development of three-dimensional computational models of the human brain.

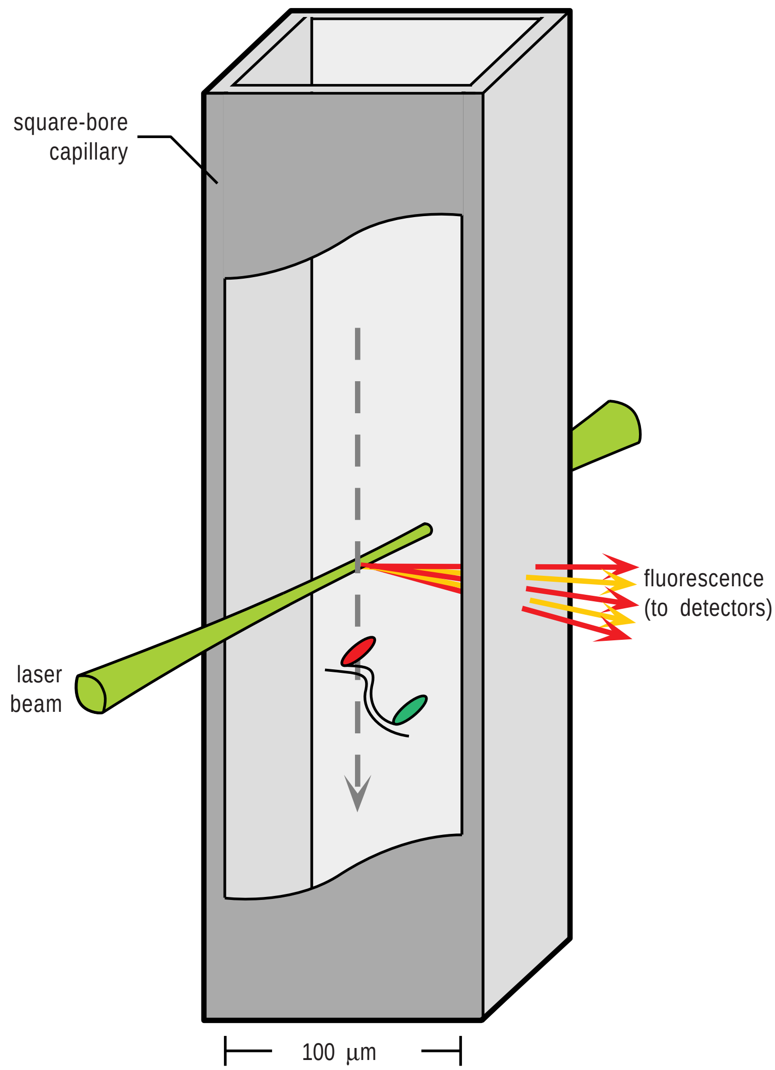


Fig. I-1. Two nucleic-acid probes that complement a targeted sequence are labeled with different fluorescent markers. If the target molecule is present, both probes will bind to the target and reveal it by responding simultaneously when illuminated by the laser-based, ultrasensitive fluorescence system.

Single-Molecule Detection

P-21 and its collaborators have extended their work on the detection and characterization of single molecules in a liquid. The goal of this research is to measure and characterize the spectroscopic properties of individual molecules. Such spectroscopic measurements can be used to identify the presence of a particular molecular species in an extremely dilute solution, or they can be used to probe the local environment that surrounds an individual molecule. The former capability promises a new level of speed and sensitivity for medical diagnostics, whereas the latter capability makes it possible to study properties of biological systems that cannot be measured when a lack of sensitivity confines measurements to the determination of the average properties of a large ensemble of microenvironments. Thus far, the spectroscopic properties measured at the single-molecule level include emission spectra, fluorescence lifetime, and total emission intensity. Recently the single-molecule spectroscopic approach has been extended to include single-molecule electrophoresis and approaches to ultrasensitive detection of viral and bacterial pathogens in soil and water samples. We are exploring additional applications for basic research and for medical diagnostics (Fig. I-1).

Protein Dynamics Studies

The goals of P-21 studies of protein dynamics are to describe protein motion in atomic detail and to understand the consequences of dynamics for protein function. Our approach is to bring crystals of the CO-complex of the protein myoglobin down to liquid-helium temperatures, photolyze the CO with a flash of light, and observe the subsequent rebinding reaction with x-ray crystallography. We have constructed and tested a low-temperature Laue camera, determined the freezing conditions for the CO crystal that maintain the high degree of order required for Laue diffraction, and analyzed diffraction patterns obtained at 5 K. The results of this approach have accomplished the long-sought goal of characterizing the changes in the three-dimensional structure of a protein as it binds to a ligand (I. Schlichting, J. Berendzen, G. N. Phillips, and R. M. Sweet, "Crystal Structure of Photolyzed Carbonmonoxy-myoglobin," *Nature* **371**, 808 [1994]).

Cryo-Crystallography

Cryo-crystallography is being extended to studies of electron transfer in the photosynthetic reaction center and to the understanding of proteins important for bioremediation of trichloroethylene (TCE) and other soil and groundwater pollutants. P-21 is part of a multidisciplinary Los Alamos effort that seeks to enable bioremediation of TCE by genetically engineered microorganisms. The first step in this effort is obtaining a thorough understanding of the enzymatic mechanisms by which TCE can be degraded. We would like, in effect, to watch proteins at work chewing up TCE. In a collaboration with scientists at U.S. universities and at the Max Planck Institute in Germany, members of P-21 have begun to unravel the mystery surrounding the mechanism of one class of enzymes that might be engineered to degrade TCE, the cytochrome P-450s. P-450s bind molecular oxygen, split the dioxygen bond, and insert one oxygen atom into organic substrates. This can be the first step in the biodegradation of TCE. The reaction is also a crucial step in steroid hormone synthesis, and P-450s are important targets for drugs to treat breast cancer and other malignancies.

Noninvasive Imaging Techniques

The P-21 neuroscience effort focuses on the use of magnetoencephalography (MEG) and magnetic resonance imaging (MRI) to develop improved techniques for noninvasive imaging of the human brain. MEG involves the use of superconducting quantum interference devices (SQUIDs) to measure magnetic fields associated with human-brain activity. Measurement of the magnetic fields of the brain (which are approximately a billion times smaller than that of Earth) requires sensitive magnetic sensors, magnetic shielding from the environment (currently implemented through a shielded room), and advanced signal-enhancement and modeling techniques. Because magnetic fields readily penetrate the skull, MEG offers the potential for noninvasive measurement of brain function in much the same way that computed tomography and MRI allow the noninvasive detection of brain structure. MEG has therefore generated considerable interest in its possible use as a tool in basic neuroscience for functional mapping of the human brain (Fig. I-2), as a clinical tool for the assessment of neurological and psychiatric disorders, as a possible source of signals for use in the development of neural prosthetics and human-machine interfaces, and in other applied contexts. Group members are engaged in projects to design improved multichannel magnetic sensors, to develop more accurate mathematical models for localizing the electrical and magnetic signals from the brain, to validate MEG using known current sources in computational and physical models of the brain, and to

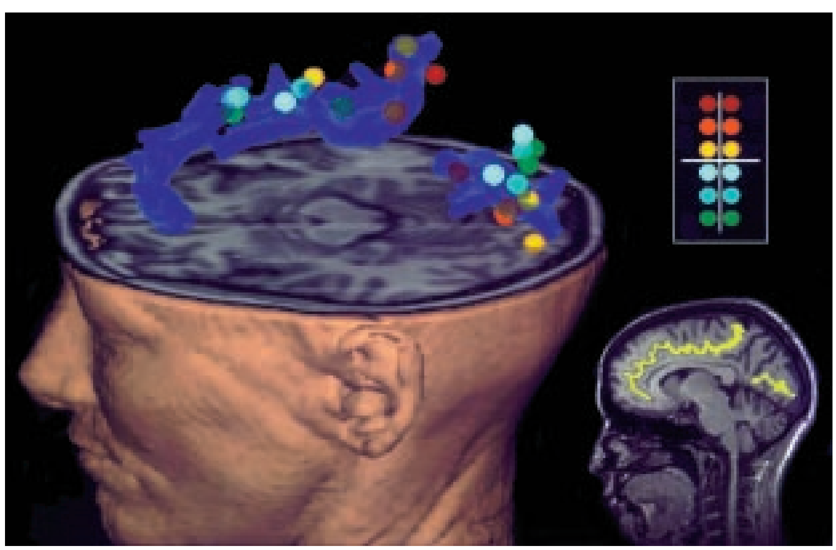


Fig. I-2. The small, colored spheres represent active regions of the cortex along the cingulate sulcus and the calcarine fissure (upper and lower blue structures, respectively) that are responding to small patterns of light from various positions in the visual field (see corresponding spheres in the inset). Systematic mapping is evident: stimuli placed in the upper visual field activated posterior regions of the cingulate sulcus and lower regions of the calcarine fissure; lower-field stimuli activated anterior regions of the cingulate and upper regions of the calcarine.

use MEG to address important questions in basic neuroscience and in research on neurological and psychiatric disorders. Many of P-21's neuroscience projects are conducted in collaboration with the New Mexico Institute of Neuroimaging, a consortium that includes Los Alamos, the University of New Mexico, and the New Mexico Regional Federal Medical Center and is sponsored by the U.S. Department of Veterans Affairs.

Combining MEG and anatomical MRI with other functional imaging techniques such as functional MRI (fMRI) and positron emission tomography (PET) offers the opportunity of increasing the combined spatial and temporal resolution of functional imaging techniques well beyond that of any single method. P-21 is engaged in developing mathematical models for combining these alternative forms of brain imaging. This work is part of a nationwide effort to develop three-dimensional computational models of the brain in which a variety of structural and functional information can be represented for storage, retrieval, and analysis.

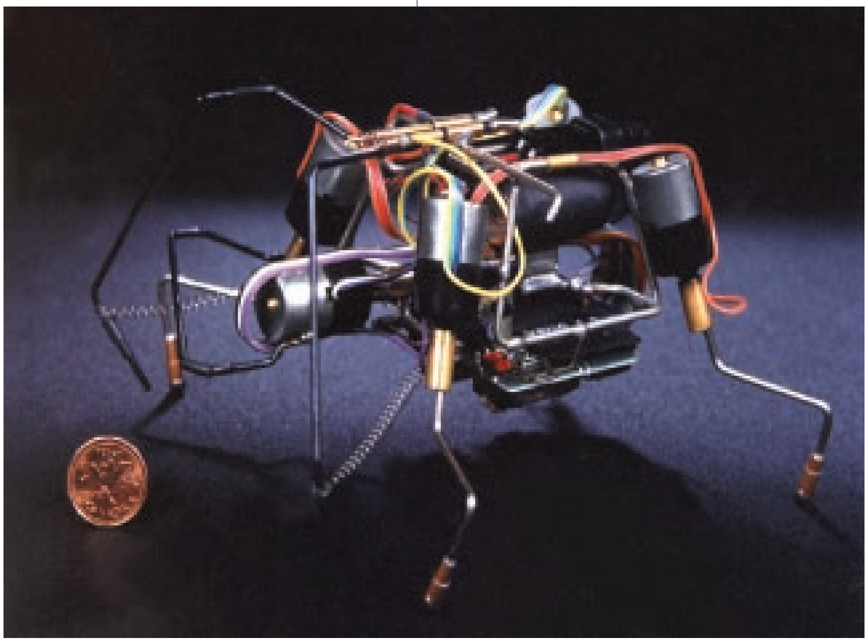
Low-Field Magnetic Sensors

The P-21 low-field magnetic sensor effort has recently been extended to apply low-field sensors to nondestructive evaluation (NDE) of materials, detection of underground objects, and a number of applications in nonproliferation. These applications take advantage of a number of recent Los Alamos developments, including new concepts in superconducting weak-field sensor arrays, the introduction of digital signal processors (DSPs) into the SQUID circuit, and improved high-temperature superconducting (HTS) Josephson junctions for HTS SQUIDs. The resulting sensors will be designed to operate in relatively hostile electromagnetic environments.

Adaptive Control Systems

P-21 has begun investigations into the design, implementation, and application of a variety of adaptive control systems. These include development of biologically inspired, legged robotics with simple, highly robust control circuits (Fig. I-3); applications of wavelets for feature recognition and data compression; and support for advanced multichannel data-acquisition systems. This work promises to contribute both to an improved understanding of robotic control and to a variety of applications in which robust, inexpensive adaptive capabilities are required.

Fig. I-3. Turtle 1.5, a first-generation "biomech" walker, self-optimizes its gait over various terrains, even after considerable damage. Its analog control system adapts to such situations without the need of any programming.

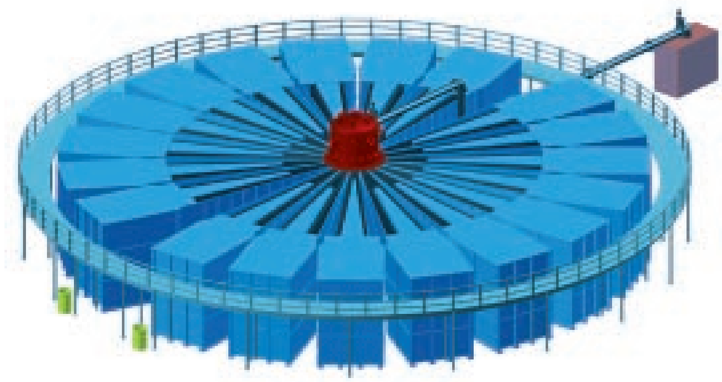


P-22: Hydrodynamic and X-Ray Physics

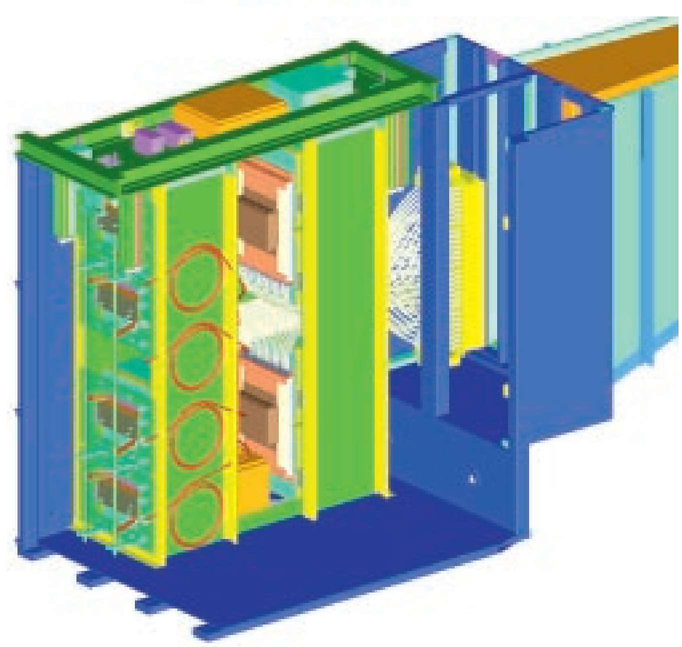
Joseph S. Ladish,
Group Leader
Jack Shlachter,
Deputy Group Leader (1997)
R. Richard Bartsch,
Deputy Group Leader (1996)
Mary Hockaday,
Deputy Group Leader
(1995–1996)

Introduction

The mission of the Hydrodynamics and X-Ray Physics Group (P-22) is to solve challenging experimental physics problems relevant to our national security, particularly when we can reduce the threat of war by helping to ensure the reliability of our nuclear-weapons stockpile and by limiting the proliferation of weapons of mass destruction. We continue to maintain and develop as national assets a creative, multidisciplinary team and state-of-the-art technology. To fulfill its mission, the group maintains a broad physics and engineering capability and pulsed-power facilities. Physics disciplines include hydrodynamics, x-ray spectroscopy and imaging, plasma physics, radiation hydrodynamics, optics and fiber optics, microwaves, electromagnetics, atmospheric physics, and atomic physics. Engineering disciplines include analog and digital electronics; electro-optics instrument design and fabrication; high-voltage, low-inductance, pulsed-power engineering; and fast-transient data recording. P-22 is the home of the Pegasus II Pulsed-Power Facility and of the future Atlas High-Energy Pulsed-Power Facility (Fig. I-4).



(a)



(b)

Fig. I-4. (a) Detail of the heart of the design for Atlas, showing oil tanks (in blue) that will hold the Marx units, the troughs containing the transmission lines (in black), the target chamber (in red at the center), and the vacuum line and evacuation system (the black pipe leading to the brown tank). Each of the oil tanks will contain thirty-two 60-kV capacitors. The two 55-gal. tanks on the left show the size of the designed machine. (b) Cross section of the lower half of one of the maintenance units, showing four large capacitors and the isolation switches for each pair of capacitors.

Nuclear-Weapons Program Research

The mainstay of P-22 has been its support of the nuclear-weapons program. P-22 applies the scientific and engineering expertise that it developed for the nuclear test program to investigate and understand crucial weapons-physics issues in a world without nuclear testing. The foundation of the present Los Alamos nuclear-weapons program is Science-Based Stockpile Stewardship (SBSS), which requires the development of complex experiments on diverse facilities to address the relevant physics issues of the enduring stockpile.

P-22 continues to field experiments underground at the Nevada Test Site (NTS), both to maintain our readiness to support a resumption of nuclear testing, should the need arise, and to study the physics of weapons performance and materials. These experiments increase our understanding of weapons science by allowing improvements in code calculations and in estimates of the severity of problems and changes occurring in the nuclear stockpile as it ages. At present, we are fielding experiments to measure the equation-of-state properties and spall strength of weapons-grade plutonium. We are also designing experiments and developing diagnostics to measure the properties of material ejected when plutonium is shocked by a high-explosive detonation. By performing these experiments underground at NTS, the plutonium is handled and contained in a manner similar to that used for underground nuclear tests.

In the portion of the weapons program involving above-ground experiments (AGEX-1), we are developing diagnostics to study the physics of the release of high-pressure shock waves. Diagnostics under development include the following:

- visible-wavelength and infrared pyrometers to determine the temperature history of a shocked surface;
- a very-short-pulsed laser and an ultrafast streak camera to determine by elastic backscattering the density and size of an ejecta cloud of fine particles, particularly when the particles are too small to be identified by holography;
- low-energy x-ray sources for imaging of low-density material from shocks;
- a reflectivity diagnostic to determine whether the surface of a shocked sample has melted; and
- a measurement of the speed at which moving, high-density material can produce a fiber-optic signal.

These diagnostics will be used to study shocks produced by explosives, gas guns, and the Pegasus capacitor bank.

In other AGEX-1 work, we are supporting the development of the Dual-Axis Radiographic Hydrotest Facility (DARHT) by studying the beam physics of DARHT's technical precursor, the Integrated Test Stand (ITS). We have built and fielded a magnetic spectrometer to measure the beam energy as a function of time in the 70-ns ITS pulse. We are developing a microwave diagnostic to measure nonintrusively the beam electron density, and we are participating in the planning of new advanced radiographic facilities. We built and tested an elastic-backscattering lidar system that can find, track, and map out the shape of the effluent cloud from a small high-explosive detonation miles away, even when the cloud is invisible. The lidar can direct equipment, such as a remotely piloted airplane, to sample the effluent cloud to determine the presence of hazardous materials.

As part of the High-Energy-Density Physics (HEDP, formerly AGEX II) program, the 4.3-MJ Pegasus II Pulsed-Power Facility is used to drive experiments in which the weapons community is interested. Pegasus II can be used as a radiation driver or as a hydrodynamic driver in convergent geometry. Experiments are being performed to investigate nonsymmetric hydrodynamic flow and ejecta formation of shocked surfaces. In addition, pulsed-power research on improved radiation drivers, fast vacuum switching, and power flow channels are being pursued as we look to the future requirements of Atlas and explosive pulsed-power systems. P-22 has provided pulsed-power and diagnostic expertise to Procyon, Ranchito, and Ranchero, the Laboratory's high-explosive pulsed-power systems.

P-22 is the home of Atlas, the next-generation 36-MJ pulsed-power facility. The year 1996 marked the official start of the Atlas construction project, with the first dollars arriving for detailed facility design. Atlas will provide advanced radiation and hydrodynamic capabilities for weapons-physics and basic research. Research and development activities have centered on component development, prototype design and testing, and investigation into how the physics of interest scales to higher energies. The present design would provide operation at 240 kV, 480 kV, and 960 kV, allowing a wider scale of experiments to be performed than in earlier conceptual designs.

P-22 is deeply involved in protecting and archiving the volatile test data it took during more than three decades of underground nuclear testing. Our goal is to bring the group's data to a stable and readily accessible state. These data will be used to benchmark all future calculational tools.

In another part of the HEDP program, P-22's plasma-physics expertise and ability to do large-scale integrated experiments have provided group members with the opportunity to participate in several collaborations with the premier All-Russian Institute of Experimental Physics at Sarov, Russia (VNIIEF), the weapons-design laboratory that is the Russian counterpart of Los Alamos. In addition to giving us the chance to learn about some of the Russians' unique capabilities, the collaborations provide Russian weapons designers with an opportunity to do peaceful basic-scientific research and to integrate themselves into the world's broader scientific community. These collaborations are based on our mutual interests in high-explosive-driven pulsed power, wherein the Russians have clearly demonstrated scalability to large systems that is unmatched to date in the United States. P-22 is participating in experiments on the Russian MAGO system, a possible candidate for magnetized target fusion; in attempts to convert a frozen rare gas to a metal by compressing it in a large magnetic field; in the design and testing of a thin, imploding cylinder for a megajoule x-ray source; and in studies of the properties of materials at cryogenic temperatures in magnetic fields up to 1000 T.

The group has two vacuum ultraviolet beamlines and two x-ray beamlines at the National Synchrotron Light Source (NSLS) at Brookhaven National Laboratory (BNL). These beamlines, which cover the photon energy range from 30 eV to 20 keV, are used to calibrate detectors and to pursue research. Over 100 detectors were calibrated for use in HEDP experiments this year. Presently group members are studying electron-electron interactions in atomic systems by measuring the multiple ionization in rare gases near their respective K-edges. These measurements require the tunability and resolution of the synchrotron x-ray source to further delineate the limitations of the one-electron model.

Technology Transfer

P-22 has increased its involvement in technology transfer with several cooperative research and development agreements (CRADAs). Our knowledge of Faraday fiber-optic sensors is being applied to provide active feedback of the speed of the wheels of large trucks during braking. This work has recently been submitted for a patent. A debris-free, electron-beam-driven lithography source at 130 Å is being developed in conjunction with LANSCE Division and Northrup Grumman Corporation. This effort is an attempt to use the predicted anomalous energy loss of a short-pulse (subpicosecond) electron beam in a preformed plasma to heat and further ionize the ions to a charge state such that efficient 130-Å emission will occur.

Challenging engineering problems must be solved for experiments to succeed. Such challenges include the remote control of instrumentation, specific instrument performance, and package design for both laboratory and field environments. P-22 has an in-house capability to design, prototype, and characterize new components and systems with specialization in microelectronics, high speed, and optoelectronics. Industrial interactions include work with IBM and Motorola through CRADAs and funds-in agreements.

Our integration of broad experimental physics and engineering expertise enables the group to fulfill its mission and opens the door to exciting future opportunities.

P-23: Neutron Science and Technology

Mary Hockaday,
Group Leader (1997)
Geoffrey L. Greene,
Group Leader
(1995–1996)
Susan Seestrom,
Deputy Group Leader (1997)
Frank H. Cverna,
Deputy Group Leader
(1995–1996)

Introduction

Group P-23 (Neutron Science and Technology) applies its extensive experience in both particle detection and the recording of transient events to support the experimental program at the Los Alamos Neutron Science Center (LANSCE), to participate in a variety of Nuclear Weapons Technology (NWT) projects, and to carry out basic research in fundamental and applied physics. The work at LANSCE involves support of Laboratory programs in Science-Based Stockpile Stewardship (SBSS), Accelerator Production of Tritium (APT), and Energy Research (ER). The NWT projects in which P-23 participates include subcritical experiments; nonnuclear hydrodynamic experiments (AGEX-I) at either LANL or the Nevada Test Site (NTS); pulsed-power experiments for the High-Energy-Density Physics (HEDP) program; and archiving and analyzing data from past nuclear-weapons tests. The group's work in fundamental research focuses on nuclear and weak-interaction physics and on astrophysical phenomena involving the detection of solar neutrinos and ultrahigh-energy gamma rays. Applied research conducted by the group includes the development of quantum-information technologies, such as quantum computation and encryption (involving single-photon detection) and the application of imaging and neutron technologies to problems relevant to national defense or industry.

P-23 provides and improves imaging technologies including tomography and holography, wide-dynamic-range data acquisition and recording, and spectral measurements involving the detection of photons across 13 orders of magnitude in energy (infrared to ultrahigh-energy gamma rays) and neutrons across 15 orders of magnitude (ultracold neutrons to 800 MeV). The major experiments in which the group is involved are located at the following facilities: LANSCE, at both the Manuel Lujan Jr. Neutron Scattering Center (MLNSC) and the Weapons Neutron Research (WNR) facility; NTS; the Pegasus pulsed-power facility at Los Alamos; the Milagro site in the Jemez Mountains for detecting ultrahigh-energy photons from outside the solar system (Fig. I-5); off-site accelerators; and the Sudbury Neutrino Observatory (SNO) in Canada.

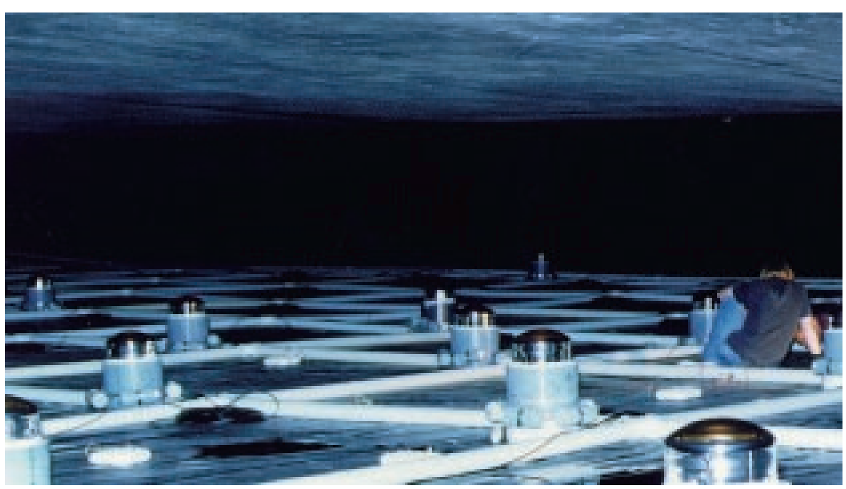


Fig. I-5. Installation of the first set of photomultiplier tubes in the Milagro detector.

LANSCE Support

Data from previous weapons tests do not provide all of the data that we presently believe are required for the weapons laboratories to be able to assure the safety and reliability of the nuclear-weapons stockpile without nuclear testing. NTS experiments answered only a small part of the question of what happens to a weapon as its components age. The SBSS program is intended to put this and other assurance issues on a scientific basis without nuclear testing. Together with our colleagues in other groups, divisions, and laboratories such as Lawrence Livermore National Laboratory (LLNL), we are studying the following:

- the performance of chemical explosives, including changes as they age;
- the fundamental physics of plutonium, e.g., the phonon spectrum;
- the temperature of materials undergoing hydrodynamic instabilities; and
- nuclear cross sections that are required for better analysis of radiochemical data from previous weapons tests.

For these studies we use neutrons from LANSCE, including moderated neutrons from the MLNSC, moderated neutrons with tailored time-structure from the WNR "Blue Room," and unmoderated neutrons from the WNR fast-neutron source. Neutron spectroscopy by time-of-flight techniques is central to all of these projects.

In support of the SBSS program, research in nuclear physics is carried out at the WNR facility with neutrons from below 1 MeV to 800 MeV. A large array of Compton-suppressed germanium detectors (the GEANIE detector) has recently been installed to measure, with very high resolution, gamma rays from neutron-induced reactions. This is a joint project between LLNL and P-23, with additional participation by universities and other LANL groups. Nuclear structure and nuclear reactions can be studied with this new capability, which is described in detail in a Research Highlight of this Progress Report. Our interests at present are in the ^{239}Pu(n,2n)^{238}Pu cross section, where different nuclear-reaction models give markedly different predictions, and in the nuclear structure area of "complete spectroscopy," where models of nuclear-structure symmetries and the transition from order to chaos in nuclear spectroscopy can be tested.

An important element of the SBSS program at LANSCE is hadron radiography. P-23 is supporting this effort with a cold-neutron radiography project at the MLNSC, by participation with P-25 and LLNL in the 800-MeV proton-radiography project at LANSCE, and in the high-energy neutron-radiography project at WNR. P-23 developed a cooled, charge-coupled device (CCD) imaging system with fast gating and image intensification for use in hadron radiography (Fig. I-6). The system was first applied to radiograph a low-density material encapsulated in a high-density casing, using neutrons produced at the WNR in the 5- to 200-MeV energy range. The group has also collaborated with P-25 in the development of a pixelated, gas-amplification wire-chamber detector for hadron radiography.

As part of the SBSS program, P-23 has operated the WNR neutron sources and provided experimental support to experiments on the 6 beamlines at the WNR fast-neutron spallation source, WNR "Blue Room" experiments where the 800-MeV proton beam can be accessed directly, and 5 beamlines at the MLNSC. In the future, the operation of these facilities will be under the control of LANSCE Division, but we anticipate that technical experimental support will continue to be supplied by P-23.

The goal of the APT program is to explore the possibility of using accelerator-driven transmutation of helium to supply the U.S. nuclear-weapons stockpile with tritium. Production of tritium from traditional reactor sources was terminated in the late 1980s. Because tritium decays with a 12-year half-life, a continuing supply of tritium is necessary to maintain the stockpile at any given level. P-23 supplies basic nuclear-physics data, performs integral tests of the calculated neutronic performance of benchmark systems, develops beam diagnostics, and participates in irradiation studies of components for this program. Basic nuclear-physics data include neutron total and reaction cross sections and activation data, mostly measured with the spallation neutron source at WNR. Integral tests employ small-scale mockups of the accelerator target and of the neutron-reflecting blanket. These allow the initial neutron production, the final tritium production, and intermediate steps to be quantified and compared with calculation. Beam diagnostics utilize P-23's imaging capabilities. An important milestone was reached with the demonstration that the superconducting cavity continues to perform well even when irradiated directly with the

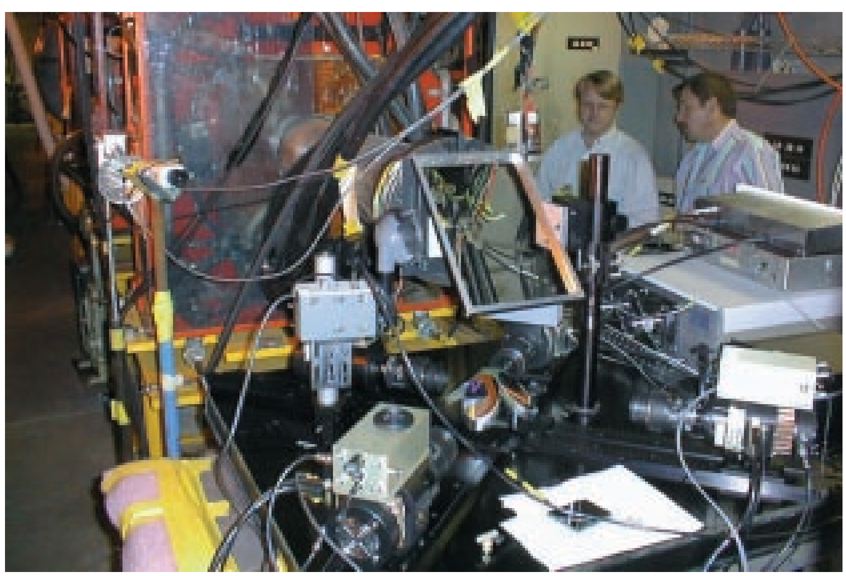


Fig. I-6. Shown in the lower half of this photograph are the four CCD cameras that P-23 operates as part of the dynamic proton-radiography project.

LANSCE proton beam. These data-measurement activities and integral demonstrations are continuing as the APT program progresses.

We work with LLNL and Ohio University at WNR on the measurement of neutron total cross sections. This quantity describes the probability of neutron interactions with materials and is therefore central to all calculations of neutron transport in macroscopic systems, such as targets and shielding in the APT project, nuclear weapons, proton- and neutron-therapy facilities, and basic nuclear-physics accelerator experiments. The WNR facility is ideal for these measurements because of its excellent neutron-source characteristics: a subnanosecond pulse width, low gamma-flash, and high repetition rate. Accuracies on the order of 1% are routine with this approach over a neutron energy range of 5–600 MeV. The data rate is high; the average run time necessary to achieve this accuracy for a given material is about 1 day.

Support of ER programs at LANSCE is described in the later section on Basic Research.

NWT Support

With the end of nuclear testing, our knowledge of the ways in which actual weapons work relies on the data that were obtained from tests at NTS and test locations in the Pacific Ocean. Saving, analysis, and documentation of NTS weapons test data is a major responsibility of P-23 and the other groups responsible for these measurements and is crucial to the success of SBSS. Fortunately, physicists and engineers who performed the original measurements are still available to analyze their data and correlate the data of different events. In addition, new scientists are being trained in the technologies of making such measurements in case the need should arise for future underground tests. P-23 concentrates on the analysis of pinhole neutron experiments (PINEX) imaging data and on neutron emission measurements (NUEX and THREX). These data complement reaction history and radiochemical measurements, which are made by other groups. The process of saving, reanalyzing, and documenting these data has allowed us to obtain a better understanding of the underlying physical processes that generated them. Comparison of the results from different tests is allowing us to study systematically the behavior of nuclear explosives.

If SBSS is to be successful in allowing us to certify the performance of our nuclear weapons in the absence of nuclear testing, we must develop better physics models and incorporate them into computer codes that calculate explosive performance. We must be able to validate these codes against the NTS data that we have. Only then will we be able to address with confidence the issues of aging and remanufacture of our stockpile weapons.

P-23 is participating in a series of experiments to explore weapons-physics issues of a more microscopic nature than those explored in the underground NTS tests of nuclear explosives. We use chemical explosives and pulsed-power machines such as Pegasus as drivers to examine issues such as the equation of state (EOS) of shocked materials, formation and transport of ejecta from shocked surfaces, and growth of hydrodynamic instabilities. Underground experiments (UGEX) that involve plutonium are planned for the U1a facility at NTS. Experimental tools, such as gated visible imaging, gated x-ray imaging, holography, and infrared (IR) temperature measurements, are used to study the physical phenomena. We are developing fast IR imaging. The data that we can thus obtain are used both to understand the physical processes and, as computer models are developed, to benchmark the calculations. These experiments will greatly improve our understanding of nuclear-weapons physics.

A critical—and currently limiting—component to a number of Laboratory weapons-program experiments is an imaging sensor that can be gated (or shuttered) in the few-nanosecond to subnanosecond regime, can achieve a high frame (or data) transfer rate (up to 10^7 frames per second), has a high quantum efficiency (1% to 50%) and sensitivity (<10 photons per pixel detection), and covers the spectrum from visible light into the near IR (380 nm to 5 μm in wavelength). Such advanced-technology imaging capability is not available commercially, and the technology for achieving such imaging is presently state of the art or in development. Prior to the cessation of testing, advanced imaging was required for underground shots at NTS, and the Laboratory (previously in J-12 and P-15, and then in P-23) had developed an in-house capability to meet the needs of the weapons program. After suspension of the underground testing program, the Laboratory's SBSS program is forging above-ground experiments (AGEX) that are again placing ever increasing demands on the imaging and technology development capabilities of the weapons laboratories. Some of the areas in which advanced technology imaging systems are required are the following:

- AGEX;
- subcritical UGEX at NTS;
- hadron radiography;
- shock break-out experiments;
- Advanced Hydrotest Facility diagnostics;
- LANSCE beam diagnostics;
- Trident, Pegasus, HEDP-program, and Atlas diagnostics; and
- plasma physics.

Basic Research

Excitations of complex nuclei are characterized by resolved, well-spaced levels at low excitation. As the excitation energy increases, the number of levels increases until the levels overlap and cannot, in principle, be resolved. The level density in this unresolved region may have underlying structure related to the levels that exist at low excitation. At very high excitation, it is generally believed that the nucleus behaves like a gas of neutrons and protons, a so-called Fermi gas. The transition from the ordered states at low excitation to the disordered Fermi gas is of great interest, both for the basic physics of phase transitions in nuclear matter and for modeling the nuclear reactions of astrophysics and nuclear explosives, where short-lived nuclides can contribute significantly to nucleosynthesis and to the dynamics of a reacting system. At WNR we are studying nuclear level densities through neutron-induced (n,z) reactions that produce charged particles, such as reactions where protons or alpha particles are produced. By studying the evaporation spectra, we can deduce the level density in excited nuclei. Furthermore, we have two other techniques for studying level densities, both of which rely on the intense neutron source at WNR and the fact that the (n,z) reactions can be studied as a function of neutron energy over a wide energy range.

Because of enhancements engendered by the relatively long lifetimes of their states, compound nuclei provide an excellent laboratory for studying violation of basic symmetries. We have observed parity violation in neutron resonance reactions for a large number of resonances in more than a dozen target isotopes. With techniques developed by P-23 and our partners, we are able to identify very weak p-wave resonances in which parity violation can occur and be observed with amplitudes of up to 10% of parity-conserving interactions. Nuclear theory predicted that the sign of the parity-violating effect should be random, and for all but one nucleus, it appears to be. The exception is ^{232}Th, where the violation for the eight resonances with the strongest effects are all of the same sign, which would have a less than 0.25% probability of occurring if the sign were indeed random. We have investigated all of the readily available isotopes at maxima in the p-wave strength function and therefore are bringing this research to a close. The case of ^{232}Th remains an enigma.

We are also active in other tests of fundamental symmetries in the beta decay of trapped atoms and of free neutrons. Sensitive tests of the parity-violating beta-spin asymmetry correlation in the decay of ^{82}Rb constitute one experimental sequence that we anticipate will yield results with a precision one order of magnitude greater than any previous experiment. In studies of the decay of the free neutron, we initiated the EMIT ("time" reversed) collaboration to pursue a search for time-reversal invariance violation (TRIV). For this we have designed an experiment that promises to be seven times more sensitive than previous experiments.

As a follow-on to these measurements, we are planning to study parity violation in the reaction $n + p \rightarrow d + \gamma$. We have demonstrated the feasibility of many aspects of this experiment. We demonstrated that it was possible to achieve the counting statistics limit when taking a current signal from a vacuum photo diode that viewed a CsI gamma detector at the projected rates of a parity-violation experiment. The magnetic-field sensitivity of the current signal was shown to be small—2×10^5 G^{-1}. The spectral densities of position and intensity drifts in the LANSCE beam were also very small.

Finally, we measured the total cross section of the neutrons of ^{3}He with an accuracy of 10^{-3} in the energy range 0.5–500 eV. This cross section is important in understanding the performance of the polarized ^{3}He spin filter that will be required for such an $n + p \rightarrow d + \gamma$ experiment and for studies of the beta decay of polarized neutrons.

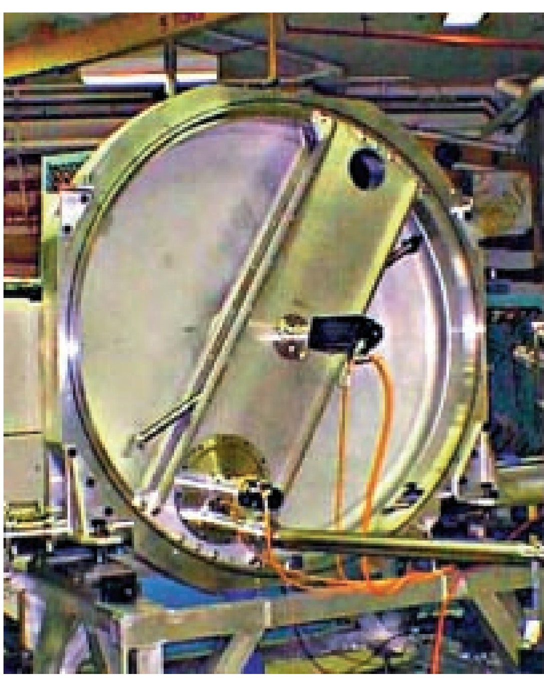
The dispersion relation between parity violation in spin rotation and transmission has been investigated by our study of the parity-violating rotation of the plane of neutron polarization when a transversely polarized neutron beam passes through a sample of ^{139}La. Lanthanum-139 has a resonance at 0.734 eV that exhibits large parity violation in transmission. This experiment also serves as a prototype for future experiments to study time-reversal symmetry violation in neutron transmission.

The basic neutron-proton interaction is studied at WNR in two types of experiments: simple *n-p* scattering and the more complicated situation where a gamma ray is emitted when the two particles interact, called neutron-proton bremsstrahlung (NPB). Simple (elastic) *n-p* scattering at certain angles and energies is sensitive to the interaction mediated by the exchange of a single π-meson, which is the most basic of interactions in meson-exchange theory. Despite decades of work on this interaction, there still is significant disagreement on the fundamental pion-nucleon coupling, and we are working to resolve this disagreement, which has widespread ramifications in the binding of nuclei and in astrophysics. Basic interaction models also give different predictions for NPB, which has not been studied before with differential measurements. The measurements are now being made by a group from the Massachusetts Institute of Technology together with P-23.

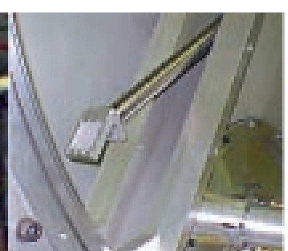
Ultracold neutrons (UCNs) were first produced at LANSCE in 1996 by the use of a rotor reflector. These neutrons travel with speeds of less than 8 m per second. We are continuing to develop this source with improved cold moderators and better rotor reflectors (Fig. I-7). We plan to use this source in the investigation of the radioactive decay of free neutrons and, possibly, in the search for an electric dipole moment (EDM) of the neutron. Both of these projects aim at detecting physics beyond the standard model of strong and electroweak interactions. P-23 is participating with P-25 and others in the design of an EDM experiment at the proposed long-pulse spallation source (LPSS) at LANSCE that will use UCNs produced by the inelastic scattering of cold neutrons in superfluid helium.

Very-high-energy gamma rays from the cosmos have been detected when they enter the atmosphere and produce an air shower of particles. The Milagro project, located in the Jemez Mountains above Los Alamos and inaugurated in 1995, is the construction and operation of a high-efficiency observatory for gamma rays in the energy range around 10^{14} eV. This observatory involves a joint project of Los Alamos and a large number of universities. It will be especially well suited for the study of episodic or transient gamma-ray sources, that is, for recording gamma-ray bursts. It is operational 24 hours a day, 365 days a year, and its field of view is nearly half of the sky. Milagro began providing operational data in 1996 and soon will be fully instrumented.

The number and spectrum of neutrinos from the sun continues to challenge our understanding of solar physics and neutrino properties. For many years we have worked with scientists from the Soviet Union and, now, the Former Soviet Union to detect neutrinos by using large quantities of gallium far underground in the Caucasus Mountains. This is the SAGE (Soviet-American Gallium Experiment) collaboration. The result from this lengthy study was that the number of neutrinos detected is about half of that predicted by the best solar and neutrino models. Now we are



(a)



(b)

Fig. I-7. (a) UCN rotor with (b) a close-up of the mica crystal package.

collaborating in the development of a neutrino observatory more than a mile underground in Sudbury, Ontario. The SNO (Sudbury Neutrino Observatory) detector will soon be operational and consists of an acrylic vessel holding 1,000 tonnes of heavy water surrounded by another vessel with 8,000 tonnes of light (regular) water. All three flavors of neutrinos (electron, muon, and tau) will be detected. Development of this detector includes the design and fabrication of very-low-background ^{3}He detectors and new electronics. As a spin-off, the very sensitive, low-background detectors developed for the observatory will be used to screen high-density microelectronics for trace radioactive contaminants that can cause computer errors by "flipping" bit patterns.

Applications of Basic Research

Quantum computation, a field in its infancy, promises a new approach to solving some problems (regarded as intractable in classical computation) by using the quantum-mechanical superposition of many states (numbers) at once. To realize such a computer, we are developing a system with cold, trapped atoms that represent the quantum-mechanical states. Quantum logical operations are performed with laser manipulations of the states of the trapped atoms. Using conventional lasers, we have recently succeeded in trapping and imaging calcium ions that have the required spectroscopic structure to allow them to serve as basic quantum-mechanical bits. We are developing advanced diode lasers to perform the same operation, but with much reduced power requirements and cost.

Quantum mechanics provides an approach to unbreakable cryptographic codes that not only can transmit the code "key" with security but that can also reveal the presence of eavesdropping. We have demonstrated this quantum cryptography over 48 km of fiber-optic cable and are developing longer transmission demonstrations. In a related effort, we have demonstrated transmission of a "key" through more than 200 m of air and through this technology are aiming at establishing secure communications between ground-based stations and low-earth-orbit satellites.

Using the complementary wave- and particle-like nature of light, it is possible to determine the presence of an object without any photons being absorbed or scattered by it. We are carrying out fundamental studies in such "interaction-free measurements" and have begun investigating the practical implementation of "interaction-free imaging," where these measurement techniques are used to take a (pixelated) image of an object, again with the goal of negligible absorption or scattering; at present, a resolution of better than 10 μm has been achieved, and we hope to improve this even further.

We support Department of Defense (DoD) programs in mine detection and seeker applications. For the detection of land mines, we are investigating the use of neutrons as an interrogating probe, with the detection of the resulting activation gamma rays as the positive signature. High-intensity neutron sources are necessary for the required sensitivity, and we are developing them in collaboration with other groups. Accelerator sources are strongly preferred because their energy can be tuned and specified, and they can be turned off when not in use. We are assessing the required sensitivity of detection, using our extensive experience acquired in developing neutron detectors for the Nuclear Test Program and for accelerator-based experiments. P-23 has also developed a laser-based, range-gated imaging system for the airborne detection of submerged mines. The system has undergone testing in both controlled-tank and open-sea environments. We have supported seeker (target identification) programs with range-gated laser distancing and ranging (LADAR) experiments carried out at the Wright Laboratory's laser range at Eglin Air Force Base. These experiments are part of a joint DOE/DoD technology-development program.

The further development of spallation neutron sources for basic physics research and for applications will depend on the availability of reliable targets that can withstand very high heat loads from accelerator beams. Together with researchers at the Institute for Physics and Power Engineering in Obninsk, Russia, we are developing a molten-metal target that promises to handle much higher heat loads than solid targets. Our Russian coworkers have had extensive experience in using molten-metal cooling in fission reactors. Using the intense, 800-kW LANSCE proton beam, our goal is to test their design of such a target. We are developing a small molten-metal test loop as a first step before the large Russian components are subjected to the full-intensity beam.

We are studying the feasibility of including a cryogenic source of UCNs in the design of the proposed LPSS. Preliminary indications are that if a frozen deuterium source could be operated at 5 K in a flux of neutrons at LPSS densities with a Maxwellian temperature of less than 80 K, it would produce usable UCN densities at least 400 times greater than those presently available anywhere in the world. Such a world-class source of UCNs at LANSCE would open up new opportunities for experiments in fundamental physics and the possibility of novel applications to materials science. P-23 will continue to provide guidance for this project throughout the preliminary and engineering phases of the LPSS design.

P-24: Plasma Physics

Kurt F. Schoenberg,
Group Leader
Juan C. Fernández,
Deputy Group Leader

Introduction

The Plasma Physics Group (P-24) investigates the basic properties of plasmas with a view to applications in important Laboratory and national programs. Plasmas occur in nature when matter exceeds temperatures of roughly 10,000°C. At these temperatures, the constituent atoms and molecules of matter begin to lose their bound electrons to form a substance composed of positive or negative ions and free electrons. All principal phenomena in plasmas can be traced to the fact that ions and electrons interact with each other through long-range electromagnetic forces. The electromagnetic interactions of groups of charged particles are often coherent, leading to collective modes of plasma behavior. This collective interaction of charged particles, a many-body problem, is the essence of the field of plasma physics.

Roughly 99% of the matter in the universe is in a plasma state. Plasmas can exist over a large range of temperatures and densities (Fig. I-8). For example, interstellar space contains plasmas with densities of less than one ion or electron per cubic meter at a temperature exceeding 1,000°C. In contrast, plasmas created by intense laser compression of micropellets achieve densities of 10^{24} ions or electrons per cubic centimeter at temperatures exceeding 10,000,000°C. The understanding and application of such diverse plasmas forms the raison d'être of plasma physics, which is a Los Alamos National Laboratory (LANL) core competency.

P-24 is composed of a diverse technical staff with expertise in plasma physics, plasma chemistry, atomic physics, laser and optical science, and pulsed-high-power engineering. The group uses both on-site and off-site experimental facilities to address problems of national significance in inertial and magnetic fusion, nuclear-weapons stewardship, conventional defense, environmental management, and plasma-based advanced or green manufacturing. Our agenda includes basic research in the properties of energetic matter and applied research that supports the principal Los Alamos mission of reducing the nuclear danger. As shown in Fig. I-8 and discussed below, the pursuit of

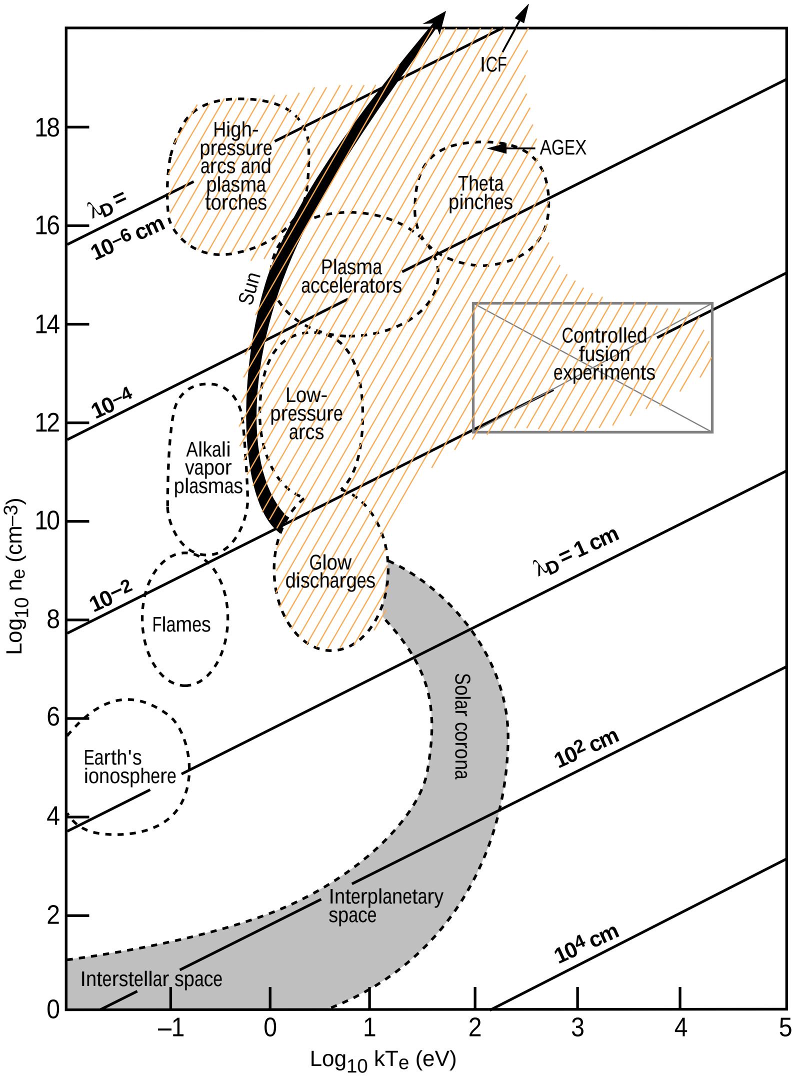


Fig. I-8. Range of plasma temperatures and densities. The orange shaded region shows the regime of P-24 research. λ_D defines the fundamental scale length for plasma interactions.

this agenda entails the physics of plasmas over a wide and diverse range of conditions.

P-24's WWW site (http://fjwsys.lanl.gov/) contains information on our group's organizational structure and research.

Trident Laser Facility

Trident is LANL's multipurpose laboratory for conducting experiments requiring high-energy laser-light pulses. It is operated primarily for Inertial Confinement Fusion (ICF) research, weapons physics, and basic research, and it serves both LANL and external users. Features include flexible driver characteristics and illumination geometries, a broad resident diagnostic capability, and flexible scheduling. A dedicated staff maintains and operates the facility and assists the experimenters.

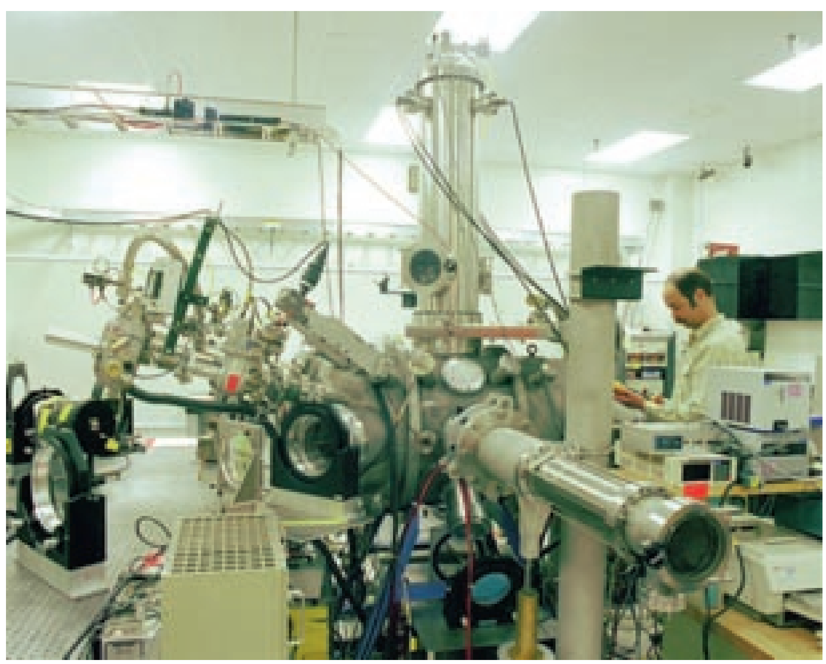
The principal resource at Trident is the laser driver. It employs a neodymium-doped, yttrium-lithium-fluoride (Nd:YLF) master oscillator and a chain of Nd:phosphate glass rod and disk amplifiers in a conventional master-oscillator, power-amplifier (MOPA) architecture. The oscillator output pulse is temporally shaped, amplified, split into two beams, amplified again, frequency-doubled, transported, and focused to the target. A third beamline can be used as an optical probe or to provide an x-ray backlighting capability. Its pulse can be either 100 ps in length or the same length and shape as those of the main drive beams. Although the third beamline is normally operated at 527 nm, fundamental (1054 nm) output of this beamline can also be used directly in the target chamber. The third beam can be timed to become active before or up to 5 ns after the main drive beams. The output of the master oscillator may also be frequency-broadened and "chirped" before amplification to allow compression to subpicosecond pulse lengths. Compressed pulses are presently available at the 1- to 2-J level at a separate target chamber in the front end, and we are anticipating compression of higher-energy pulses in the future.

The main high-vacuum target chamber is a cylinder approximately 150 cm long and 75 cm in diameter (Fig. I-9). Single- or double-sided illumination of targets is possible through several 20-cm-diameter ports on each end of the chamber. More than 40 smaller ports are available for diagnostic instrumentation. Individual targets are inserted through an airlock. The target insertion and positioning mechanism provides *x-y-z* and rotation adjustment under computer control with 1-μm linear and 0.01° angular resolution. The three-axis target-viewing system has 20-μm resolution. The chamber is fitted with a Nova-standard six-inch manipulator (SIM) to accept all SIM-based instruments for checkout, characterization, or use. Although Trident is conveniently located in an "open" area of the Laboratory, the target room can be secured administratively for classified experiments.

Optical diagnostics include illumination and backscattered light calorimeters, backscattered light spectrometers, and high-bandwidth (5-GHz) and streak-camera-based power monitors. Target x-ray emission is monitored by filtered, photoconductive diamond detectors and an x-ray streak camera with <10-ps resolution. A Nova-standard, gated x-ray imager provides 16 gated, filtered x-ray images per nanosecond with a resolution of 80 ps. Various filtered x-ray power and spectral diagnostics can be installed as needed. These cover the energy range of 0–35 keV. Static x-ray pinhole cameras are also available. Most optical and target diagnostics are available for either the main target chamber or the ultrahigh-irradiance chamber.

Trident is available to Laboratory and outside experimenters. The quality of proposed research and its relevance to Laboratory missions are major criteria that the P-Division Trident Steering Committee considers in determining what experiments are fielded. Trident is operated by P-24 as a DOE user facility that principally

Fig. I-9. Target chamber of the Trident laser facility.



supports the ICF and Above-Ground Experiments (AGEX) programs. It is funded through and operated for the Nuclear Weapons Technology (NWT) ICF Program Office. The resources of the Laboratory's Target-Fabrication Facility, operated by the Materials Science and Technology (MST) Division, are also available to assist experimenters in designing, fabricating, and characterizing targets for Trident experiments.

We are actively pursuing a facility upgrade to the Trident laser that should occur in the next few years. As envisioned, the Trident Upgrade will be a flexible, high-shot-rate facility with the required performance for weapons-relevant research in materials properties and in the hydrodynamics of ionized matter. It will enhance the present Trident capabilities in experiments on laser-matter interactions and other fundamental-science topics. It will provide a staging capability to higher-energy-density facilities and will attract high-quality scientific research to stockpile stewardship.

For single-sided, long-pulse illumination, the Trident Upgrade will have similar capabilities to those of the world's two most powerful lasers, Omega and Nova, but with the capability of providing both classified shots and the use of special nuclear materials. In addition, the Trident Upgrade will function as a premier calibration, prototyping, and staging facility for the National Ignition Facility (NIF) and will provide a local, high-shot-rate facility for the LANL weapons-physics/ICF programs to prepare experimental concepts.

Inertial Confinement Fusion

The ICF program at Los Alamos is a principal component of the national ICF program, which is focused on the goal of achieving thermonuclear ignition of an inertially confined plasma in the laboratory. This national goal represents one of the grand scientific challenges of the 20th Century and supports the DOE Stockpile Stewardship Management Plan for nuclear weapons. In pursuit of the ICF mission, P-24 designs, diagnoses, executes, and analyzes the results from experiments in high-energy laser facilities worldwide. We team with theory and modeling efforts in other Laboratory divisions toward the ultimate goal of understanding laser/matter interaction physics.

NIF, a 1.8-MJ laser presently under engineering design, is the principal focus of the national ICF program. NIF is a flexible laser, expected to drive a capsule filled with deuterium-tritium (DT) fuel to thermonuclear ignition by two distinct methods, direct or indirect drive. In direct drive, the laser implodes the capsule by illuminating it directly. With indirect drive, the laser illuminates the interior walls of a cavity (called a hohlraum) that contains the capsule. The hohlraum walls convert the laser energy into x-rays, which illuminate the capsule very symmetrically, analogous to the process of baking an object evenly in an oven. Both direct and indirect drive have different potential failure modes, so the pursuit of both approaches increases the likelihood of achieving ignition at NIF. Considerable challenges will face us in operating NIF and in hastening the achievement of fusion. These include diagnostic development and improving our understanding in three main areas: laser-plasma instabilities, unstable hydrodynamics, and hohlraum dynamics. P-24 has made significant contributions in all three areas with experiments using present ICF lasers. P-24 is also a principal participant in the NIF Joint Central Diagnostic Team.

P-24 has made many important contributions to the national ICF target-physics program in support of NIF. We have devoted considerable effort to studying laser-plasma parametric instability processes. These instabilities pose an important threat to ignition hohlraums because they could potentially scatter most of the laser light, decreasing both the drive efficiency and the capsule-illumination symmetry. Our experiments have verified Los Alamos theoretical models, which predict quantitatively the onset of these instabilities in NIF-relevant conditions. We have also made important advances in establishing the mechanisms by which these processes saturate, the necessary first step before quantitative predictions and control of scattered-light levels are possible.

In support of these experiments, we have recently deployed at the Nova laser at Lawrence Livermore National Laboratory (LLNL) the world's best suite of optical diagnostics for ICF. These diagnostics can image the scattered light within the hohlraum, allowing unprecedented comparisons to theoretical models. P-24 has also done pioneering work in observations of previously unknown instability processes. Several P-24 researchers were part of the team recently recognized with a LANL Distinguished Performance Award for their prediction and direct observation of the deflection of a laser beam by a plasma flowing transverse to the beam-propagation direction.

P-24 research staff have made important contributions to the understanding of unstable hydrodynamics. For example, we have conducted experiments with novel cylindrically imploding targets. These targets allow study of nonlinear, multimode Rayleigh-Taylor (R-T) instability in convergent geometry, without the diagnostic access problems of spherical capsules. Another important successful line of our hydrodynamic research involves the use of gold-coated foams to minimize the imprint of laser nonuniformities in direct-drive targets early in the laser pulse. This imprint is a seed for hydrodynamic instabilities that degrade capsule performance. P-24 also remains in charge of fielding the collaborative LANL-LLNL experiments to benchmark our predictive capability of hohlraum dynamics and capsule illumination symmetry. In addition to fielding the experiments, we have helped develop and have validated the most successful symmetry diagnostic techniques (symmetry capsules and reemission balls).

AGEX: A Research-Based Approach to Science-Based Stockpile Stewardship

The AGEX team investigates the physics of high-energy-density matter in support of the national Stockpile Stewardship and Management Plan. We perform experiments in the areas of radiation-driven hydrodynamics (instability growth, shock propagation, and nonlinear hydrodynamics), radiation transport (opacity, atomic physics, and radiation flow), and material properties (equations of state and constitutive properties of materials). We actively develop and use state-of-the-art diagnostics, including x-ray and visible imaging, spectroscopy, interferometry, and radiography. Experiments on pulsed-power and laser systems are performed both at Los Alamos and at facilities worldwide (Trident, Pegasus II, PBFA-Z, Nova, and Omega) and will be continued on future planned facilities (NIF, Trident Upgrade, Atlas, and X1).

Present experiments include the study of the R-T instability growth in the nonlinear regime using ablative drive, propagation and stability of high-Mach-number perturbed shocks, opacity of open-M-shell atomic systems in local thermodynamic equilibrium (LTE), the study of Marshak waves in the subsonic and supersonic regimes, and equation-of-state measurements of low-Z and high-Z materials. Presently we are constructing a microchannel plate gated intensifier with an optical-gate width of 35 ps to 5 ns for x-ray imaging and spectroscopy and a high-resolution (~1 μm), one-dimensional x-ray imager, as well as other diagnostics. Our collaborators include LLNL, Sandia National Laboratories, the Atomic Weapons Establishment in England (AWE), and the Comissariat à l'Energie Atomique in France (CEA). We work closely with other programs, including the pulsed-power High-Energy-Density Physics and ICF programs.

Magnetic Confinement Fusion

The Magnetic Fusion Team in P-24 focuses on a variety of problems in controlling thermonuclear reactions in a laboratory, generally employing magnetic fields. The team is compact and our research projects are dynamic; these qualities allow us to maintain high visibility in the fusion community with high-quality research work. Our interests in plasma-confinement devices range from exotic alternates (including magnetized target fusion and inertial electrostatic fusion) to more conventional tokamaks, helical devices, and spheromaks. We collaborate experimentally with a number of facilities throughout the world, including JT-60U and LHD in Japan, the Alcator C-Mod tokamak at the Massachusetts Institute of Technology, the Tokamak Fusion Test Reactor (TFTR) and Feedback and Stability Experiment (FSX) tokamaks at Princeton University, the LSX-M Field Reversed Configuration at the University of Washington in Seattle, and the HBT-EP tokamak at Columbia University in New York City.

Our expertise lies in fast plasma diagnostics, neutron detection, high-speed visible and infrared (IR) imaging, plasma control, alternate confinement devices, and disruption studies. The LANL P-24 team has fielded high-power amplifiers to suppress magnetohydrodynamic (MHD) activity in plasmas and is collaborating with the Princeton Plasma Laboratory to scope out a so-called "smart shell" design for the newly proposed FSX tokamak at Princeton. Other off-site collaborations include IR imaging of tokamak diverters, triton burn-up studies in high-temperature deuterium plasmas, a variety of diagnostics on the high-power TFTR DT-plasma experiments, development of a prototype imaging bolometer, and fast imaging using a digital, high-speed, computer-controlled camera system and either periscopes or imaging bundles to view the plasmas. We have also participated in the Tokamak Physics Experimental design effort and are presently participating in the International Thermonuclear Experimental Reactor (ITER) design effort.

At Los Alamos, we have two confinement experiments in which we pursue fundamental fusion research. The first is called the Penning Fusion Experiment (PFX), which forms a spherical well using electrostatic and magnetic fields in a cryogenic trap. This experiment has demonstrated high electron densities and is working at inserting ions into the trap, which ultimately are of interest (and are necessary) for producing neutrons. Magnetized target fusion, or MTF, is our second area of research and involves the adiabatic compression of magnetized plasma to fusion conditions. Ongoing research within the Colt experiment is investigating target-plasma-formation techniques and heat transfer at high energy-density conditions.

Please visit our WWW site at http://wsx.lanl.gov for additional information.

Applied Plasma Technologies

The Applied Plasma Technologies Team in P-24 uses plasma science and technology to solve problems in defense, the environment, and industrial competitiveness. Major technology-development and program elements include the following:

Atmospheric-Pressure Plasma Jet (APPJ)

A nonthermal, uniform-glow discharge at atmospheric pressure in a cylindrical cavity with high gas-flow rates produces reactive radicals and metastable molecules persisting for fractions of a second at atmospheric pressure (Fig. I-10). These reactive species remove surface contaminants and films, providing a new means of cleaning objects and substrates. Current programs include removal of actinide and metallic contaminants, chemical decontamination for the neutralization of chemical agents on surfaces, and graffiti removal.

Intense, pulsed ion beams and accelerated plasmas

Several promising applications of intense ion beams and pulsed, accelerated plasmas that require repetitive beams and plasmas have emerged in the past few years. These include processing of materials, such as surface modification through rapid melt and resolidification, ablative deposition for producing high-quality coatings, and nanophase powder synthesis; production of intense neutral beams for the next generation of tokamaks; and intense, pulsed neutron sources for the detection of nonmetallic mines, neutron radiography, and spent nuclear fuel assay. We are developing a repetitive ion accelerator and an accelerated plasma source to investigate these applications.

Plasma-Source Ion Implantation (PSII) and cathodic arcs

PSII is a non–line-of-sight method for implanting ions from a plasma into a metal for surface modification. Typically, ions from a gaseous plasma are used, but cathodic arc technology allows metal ions to be implanted as well. PSII may be combined with plasma-based surface-coating technologies to form highly adherent, thick coatings of materials such as diamond-like carbon and ceramic metal oxides. Programs include plasma-implanted and plasma-deposited erbia coatings in support of the weapons surety program; molten-plutonium-resistant coatings for near-net-shape casting molds; highly adherent coatings for wear- and corrosion-resistant gun barrels for the Army; and plasma-based surface treatment and coatings for industrial tooling (this is part of a National Institute of Science and Technology [NIST] Advanced Technology Program with more than a dozen industrial partners).

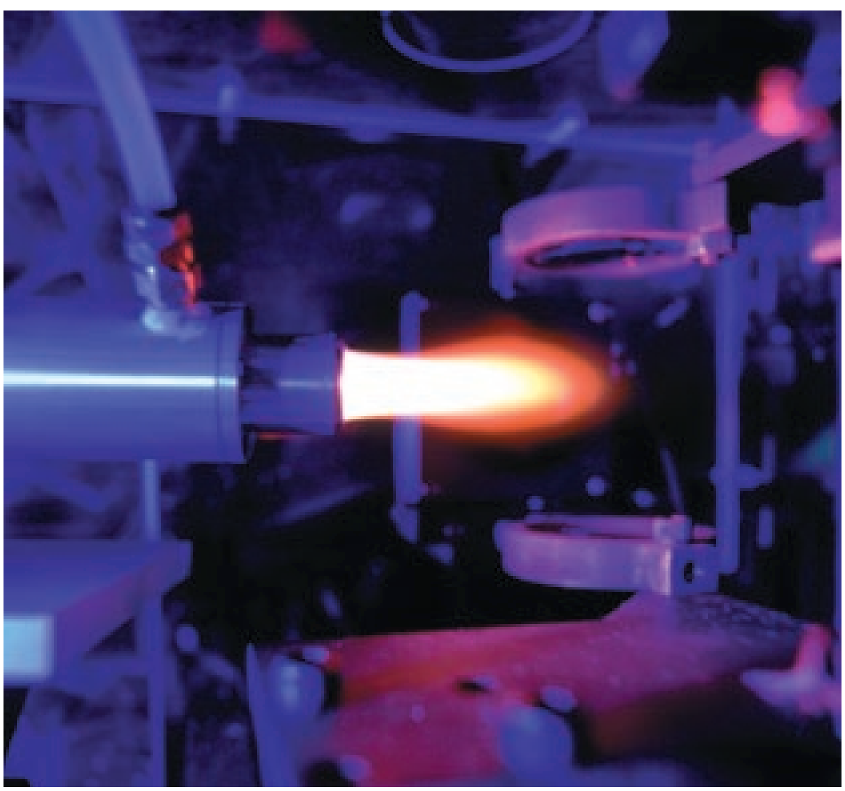


Fig. I-10. The atmospheric-pressure plasma jet has applications that include removal of actinide and metallic contaminants, chemical decontamination, and graffiti removal.

P-25: Subatomic Physics

John B. McClelland,
Group Leader
Andrea P. T. Palounek,
Deputy Group Leader

Introduction

The Subatomic Physics Group (P-25) is primarily engaged in research into nuclear and particle physics. There is also a strong and growing effort to turn the group skills and capabilities to applied programs such as proton radiography. The group currently is conducting research and developing new programs at Los Alamos and at other laboratories, such as Brookhaven National Laboratory (BNL), Fermi National Accelerator Laboratory (FNAL or Fermilab), and the European Center for Nuclear Research (CERN). The people and programs in the Subatomic Physics Group were recently rated highly in a nationwide review of the DOE Nuclear Physics Program. Some highlights of the group's activities and future directions follow.

Pion Physics

The neutral meson spectrometer (NMS) had its final LANSCE (Los Alamos Neutron Science Center) run of 3.5 months before it was shipped to BNL, where it will be used in another experiment. We are now analyzing the new data as well as data from previous runs, with emphasis on the $^{32}S(\pi^-,\pi^0)$ reaction. The report of this work will be available by late 1997. We are rewriting the NMS data analyzer program to improve this and other analyses. That work will be applicable to the BNL experiment.

Hypernuclear Physics: Experiment E907 at the Alternating-Gradient Synchrotron (AGS) at BNL

We led the effort to propose this new hypernuclear experiment at the AGS using the LANSCE NMS to measure the (K^-,π^0) reaction. This experiment will demonstrate the feasibility of using the (K^-,π^0) reaction as a novel tool to produce Λ-hypernuclei with resolution significantly better than the existing (K^-,π^-) and (K^+,π^+) experiments and will measure the Λ-hypernuclear π^0 weak decay modes that have never been studied before. The proposal was approved by the AGS Program Advisory Council in late 1994. The NMS and associated equipment were moved from LANSCE to the AGS in December 1995, and the first test run was completed in May 1996. The LANL group will assume the major responsibilities for the NMS operation and for the physics direction in this experiment.

Quark-Gluon Physics

This has been a highly visible and productive program at Fermilab. Our group was the first to exploit high-energy hadronic processes to explore the quark structure of nuclei. We are investigating the nuclear dependence of lepton-pair production with proton beams to understand how the quark and gluon structure in nuclei differs from that in free nucleons. During 1995–1996 we made substantial progress in the construction and refurbishing of the Fermilab Meson-East spectrometer, where E866 began taking data in July 1996. That experiment will search for deviations in the anti-up and anti-down quark distributions in the proton to provide insight into hadronic and partonic descriptions of the nucleonic sea.

We also continued major analysis efforts on past experiments E772 and E789. We developed Monte Carlo and analysis software that will enable the extraction of cross sections from 1.5 million Drell-Yan and Upsilon production events from the copper beam dump of E772. We completed the analysis (and publication) of the first B-meson cross-section data for 800-GeV proton-nucleus interactions and published the nuclear dependence of J/ψ production in the negative x-Feynman region.

PHENIX Spin Program

The highly successful Los Alamos/RIKEN (Institute for Physical and Chemical Research—Tokyo [Wako], Japan) collaboration was the culmination of two years of work and resulted in the final specification of the RIKEN contribution to the spin-structure function program of the PHENIX detector. RIKEN funding will purchase the PHENIX south-arm magnet plus associated muon tracking and identification systems. This contribution greatly enhances the high-mass dimuon acceptance of the PHENIX detector (Fig. I-11) and permits a large menu of unique spin-structure function experiments to be carried out. Equally important, the muon upgrade will add substantially to the physics reach of the relativistic heavy-ion program.

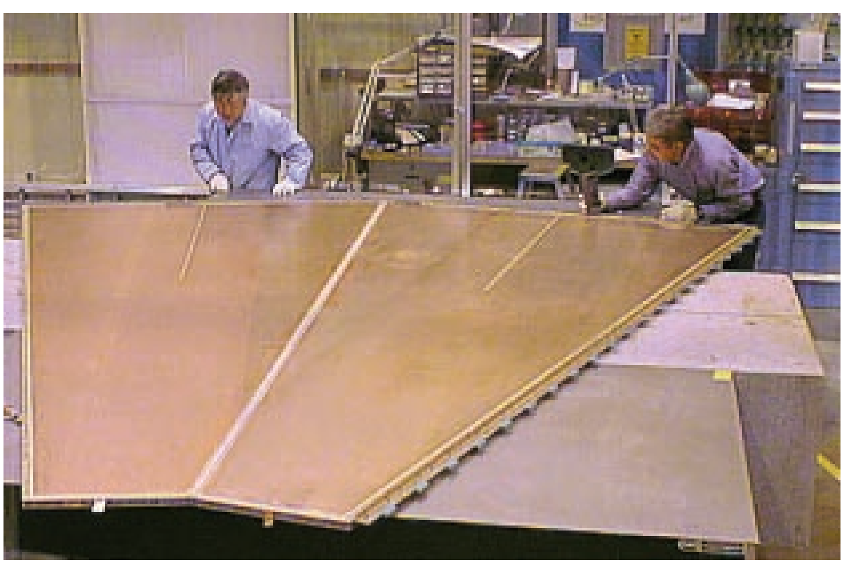


Fig. I-11. P-25 technicians building part of the PHENIX detector.

Electroweak Physics: LSND

The Liquid Scintillator Neutrino Detector (LSND), commissioned at LANSCE in 1993, has led to published papers describing the detector and source systems and the full decay-at-rest analysis of all data taken up to December 1995. The LSND paper "Evidence for Neutrino Oscillations from Muon Decay at Rest" has been published. A first-pass analysis on decay-in-flight data gave encouraging results. That analysis is more difficult than decay at rest since the signal properties are less elaborate. In addition, the magnitude of the excess is likely to have a strong impact on our estimate of Δm^2 and so demands the greatest care. That analysis should be complete during 1997, including papers describing the analysis.

BOONE (Booster Neutrino Experiment)

The definitive experimental establishment of nonzero neutrino mass will have far-ranging impact into other fields such as astrophysics; there is a strong need for experiments to follow up our successes with LSND. We have studied the possible BOONE detector and source systems and explored the level of electron neutrinos that can be expected from the beam and background at Fermilab. The detector seems to be quite adequate for both Δm^2 scenarios suggested by LSND. The detector methodology could follow the LSND method because of performance improvements that the LSND analysis has engendered.

MEGA

The apparent conservation of muon number remains a central problem of weak-interaction physics. Searching for processes that violate muon-number conservation will give insight into the possible extensions of the minimal standard model of weak interactions. MEGA (muon decays into an electron and a gamma ray) was designed to make such a search at the Los Alamos Meson Physics Facility (LAMPF), now known as LANSCE. The final year of taking data for this experiment was 1995–1996. The combined data from the summers of 1993–1995 should yield a statistical precision that improves the current world sensitivity to this process by a factor of 70 to roughly 7×10^{-13}. The MEGA collaboration made substantial strides in the development of algorithms to extract the results. The three major components of the analysis needed are reconstruction of the kinematic properties of the photon, kinematic properties of the positron, and their relative timing. The photon analysis is nearly complete, and the other two have reached an advanced stage.

RHO

The MEGA positron spectrometer was used to measure the Michel parameter ρ. The parameter governs the shape of the polarization-independent part of the energy spectrum for positrons emitted in normal muon decay. The standard model predicts ρ to be 0.75; it is currently known to be within 0.3% agreement with that value. Deviations from 0.75 might indicate the need for right-handed currents in the standard model. Collected data will enable a statistical precision that will allow the value of ρ to be measured to 0.05%, but the systematic errors are being evaluated. Such a precision will allow the checking of the reported deviations from the standard model in neutron decay. The analysis should be complete by the end of 1997.

Measurements of Beta Asymmetry and Atomic Parity Nonconservation

A key step in undertaking the measurements of beta asymmetry and parity nonconservation is the efficient trapping of selected radioactive species. This is done using a magneto-optical trap. Using a high-intensity laser, we have developed one of the world's largest traps, which can trap up to 4×10^{10} atoms of stable cesium. We are further improving the trapping efficiency by coating the inside of the glass trapping cell with a special nonstick coating of octadecyltrichlorosilane (OTS) and by using two lasers operating at slightly different frequencies to reduce light-assisted losses, which become limiting at high beam intensities.

Theory

The Subatomic Physics Group has a small theory component. We are developing a theory for connecting hadron properties in free space. We have also explored phenomenological approaches that can be used to determine (from data) masses and coupling constants for higher-mass resonances in nuclei. We are developing a theory for connecting mean-square matrix elements of the parity-violating interaction, measured by TRIPLE in compound nuclear resonances, to the underlying parity-violating force, exploiting the chaotic properties of the compound nucleus. We have been looking at the reaction theory of pion scattering from nuclei with an eye toward simplifying the description of specific reactions so that these reactions can be more easily used for specific purposes, such as evaluating hadron transport in nuclear collisions and interpreting the results of dibaryon resonance searches.

One group member investigated the phenomenon of neutrino oscillations within a three-state mixing model and found that all reported neutrino-oscillation data are consistent with a mass-mixing-angle analysis in terms of three neutrinos. His "Gravitationally Induced Neutrino-Oscillation Phases" is the First Award Essay for 1996 by the Gravity Research Foundation.

Participants at a relativistic heavy-ion meeting held during the summer of 1995 determined that essentially all relativistic heavy-ion transport event generators are incapable of reproducing the pion production data taken at LANSCE. We are investigating the reasons for this; the answer could have a significant impact on our heavy-ion and PHENIX experimental programs.

Applied Programs: Proton Radiography

The decision to forgo underground nuclear testing and to restrict the nuclear stockpile to an increasingly smaller number of weapons has forced DOE and its laboratories to rethink their role in stockpile stewardship. Much of this reassessment has been embodied in the philosophy of science-based rather than test-based stockpile stewardship.

Proton radiography offers several advantages over conventional x-ray techniques for radiographing thick, dense, dynamic systems. These advantages are (1) high penetrating power, (2) high detection efficiency, (3) very small scattered background, (4) the lack of a need for a conversion target and the consequent phase space broadening of the beam, (5) inherent multipulse capability, and (6) the ability to tolerate large stand-off distances from the test object and containment vessel for both the incoming and outgoing beam. Additionally, proton radiography provides the unique possibility of measuring both the density and the material composition of a test object with a pulsed system.

Protons interact with matter through both the long-range Coulomb force and the short-range strong interaction. Focusing protons using a magnetic lens (Fig. I-12) both allows the magnitude and Z-dependence of the interaction to be changed simply by looking at an object through different angular apertures and leads to the capability of assessing material composition. Multiple images can be made on a single axis by using multiple detectors, lenses, and irises.

P-25 leads this effort, together with a strong cross-divisional team including P, X, DX, ESA, T, and LANSCE Divisions.

Education and Outreach

P-25 continues to be active in education and outreach activities. We are formal members of three education programs run by the Laboratory. Group members visited every teacher and school in the TOPS (Teacher Opportunities to Promote Science) and TOPS Mentor programs at least once in 1995–1996; conducted regional meetings for TOPS teachers, TOPS Mentors, and TOPS alumni; and led several workshops in Los Alamos and Albuquerque. During a recent workshop, TOPS mentors built (from scratch) a simple lightning detector designed by physicists from NIS-1 and P-25. We were also active in the PRISM (Preservice Institute for Science and Math) program, guiding its students through a comparison of the transmission qualities of various brands of sunglasses.

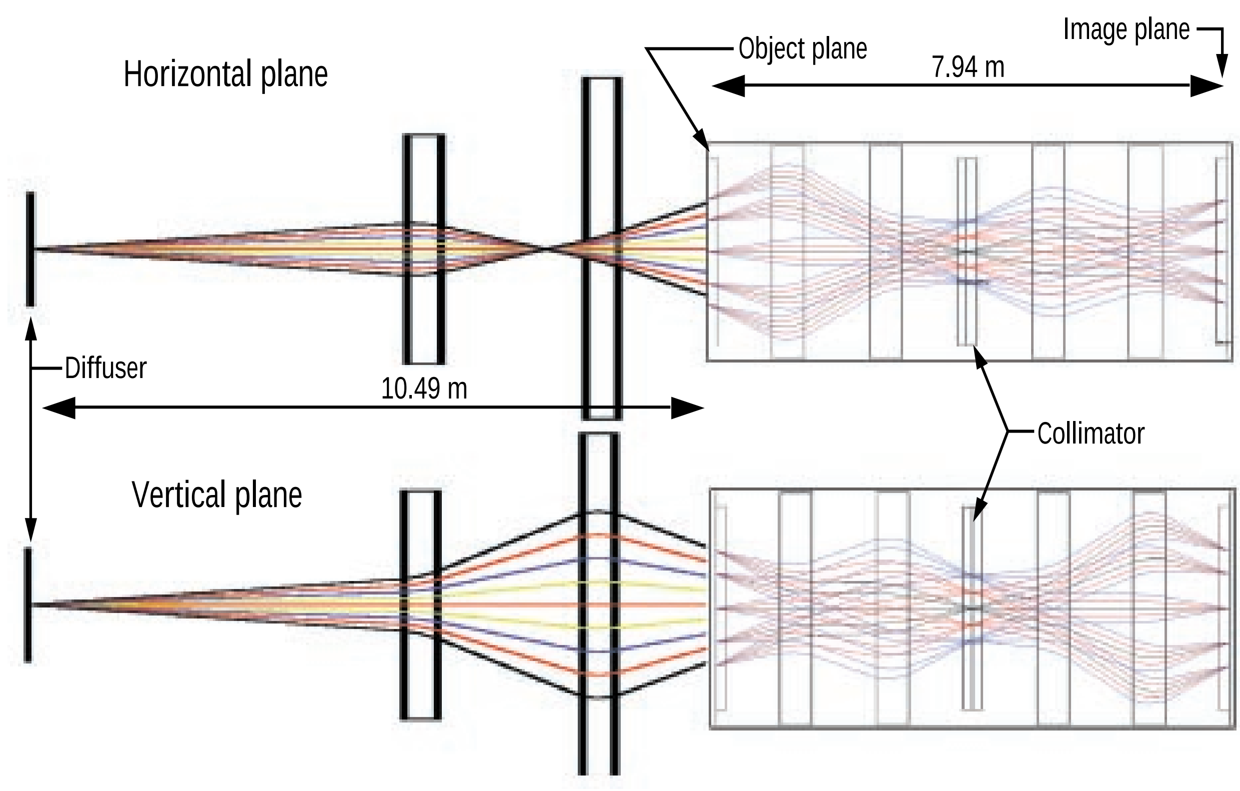
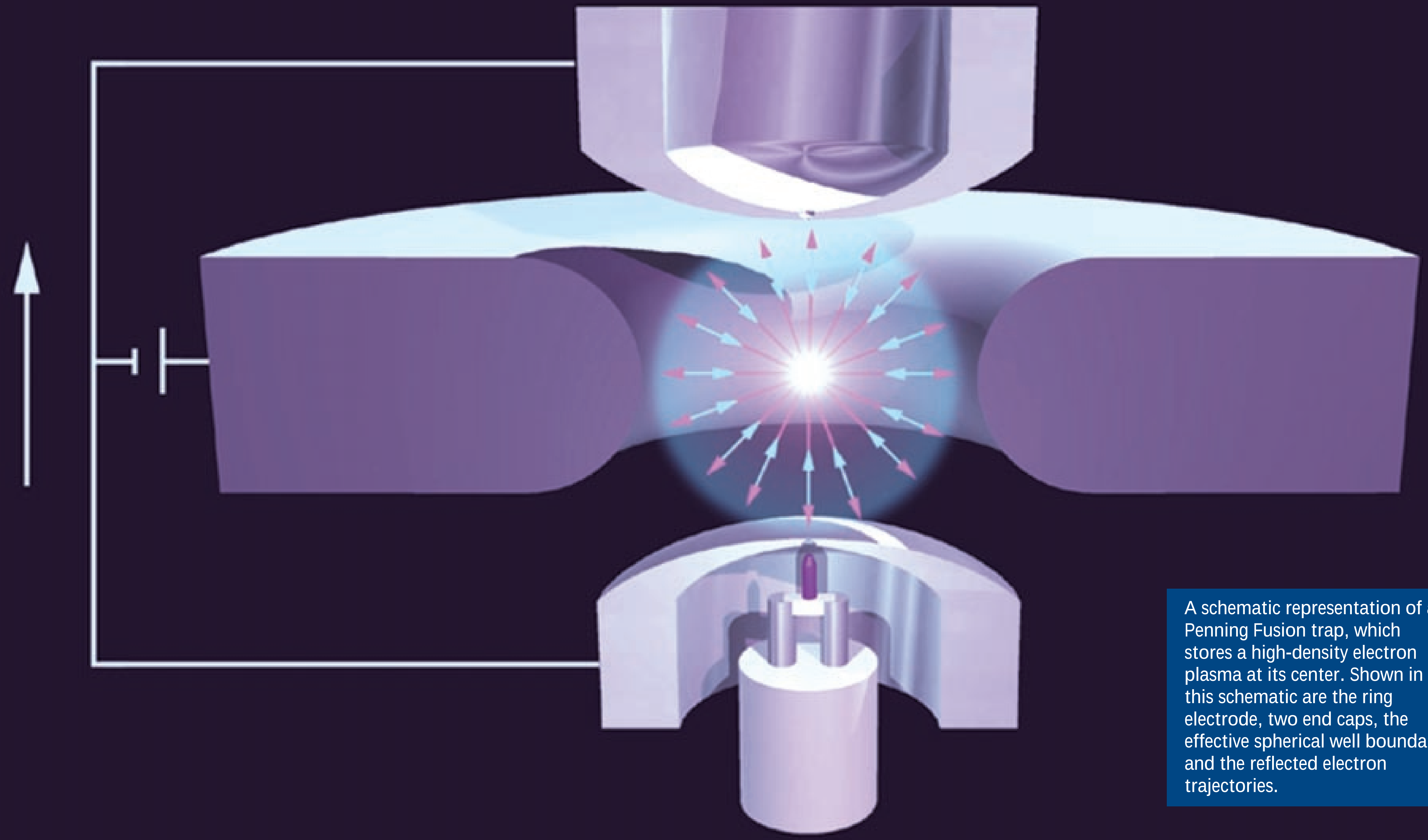


Fig. I-12. Schematic diagram of the lenses and collimator on the dynamic proton-radiography beamline.

II. Research Highlights



A schematic representation of a Penning Fusion trap, which stores a high-density electron plasma at its center. Shown in this schematic are the ring electrode, two end caps, the effective spherical well boundary, and the reflected electron trajectories.

Diffusion Imaging with Hyperpolarized ^{3}He

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Several novel aspects of nuclear magnetic resonance (NMR) or magnetic resonance imaging (MRI) with hyperpolarized noble gases have recently been demonstrated, including the ability to easily image gas-filled spaces[1,2] and to transfer part of the polarization to other nuclei.[3,4] Using these new techniques, we have been investigating diffusion. We obtained one-dimensional images of ^{3}He gas diffusing in a slice that was tagged by inverting its magnetization, a technique previously used for observing the diffusion of thermally polarized ^{129}Xe gas.[5] Also, a one-dimensional diffusion image of the gas was made with and without a temperature gradient present. Our results show that temperature changes can be monitored by diffusion images of ^{3}He gas.

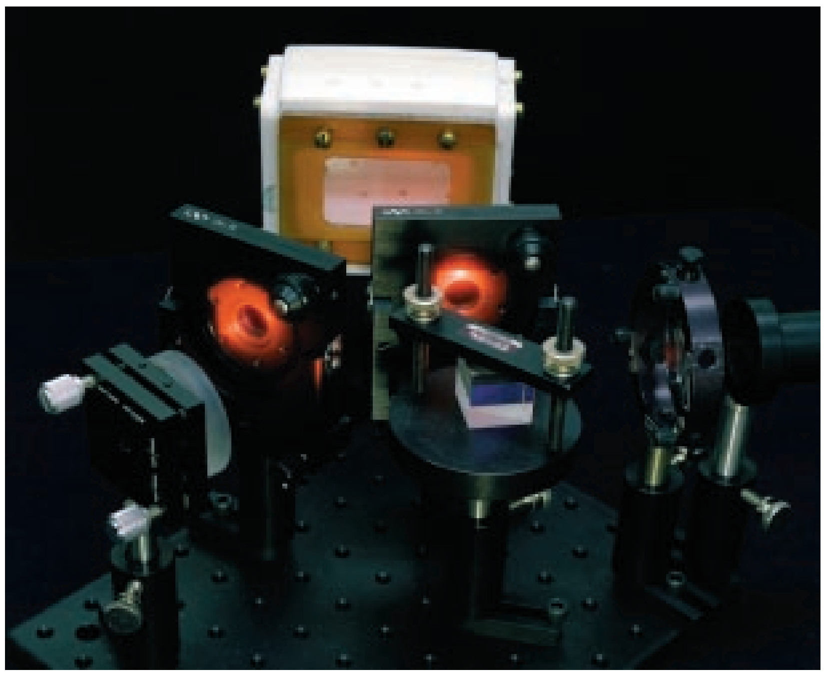

Fig. II-1. A photograph of the portable apparatus used to polarize the ^{3}He gas.

The experiments were performed in an NMR imager/spectrometer at the Lovelace Respiratory Research Institute in Albuquerque, New Mexico. Rather than thermally polarizing the ^{3}He gas in the magnetic field of the imaging magnet, we hyperpolarized the gas externally with a laser. In this technique, rubidium atoms are first polarized with circularly polarized laser light, which then polarizes the ^{3}He gas through spin-exchange collisions.[6,7] The ^{3}He gas was at 7 atm of pressure in a cylindrical glass cell with an inner length of 7.0 cm and an inner diameter of 2.2 cm. Figure II-1 shows the polarizing apparatus. For each set of images, the gas was polarized in the fringe field of the 1.9-T imaging magnet at a distance of 2 m for a few hours using a 15-W diode-laser array.[8] The polarization time constant of the cell (T1) was about 15 h, and with 4 h of optical pumping, a polarization of about 5% was achieved. This polarization is over three orders of magnitude larger than the polarization that would be obtained with conventional thermal polarization, and thus it significantly improves our ability to image the gas. A two-dimensional projection image of the hyperpolarized gas is shown in Fig. II-2.

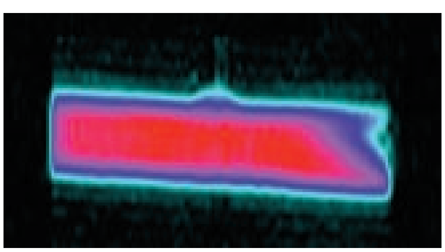

Fig. II-2. A two-dimensional projection image of the hyperpolarized ^{3}He gas in its cylindrical cell. The 1-mm stem that is used for filling the cell is visible in the top-center portion of the image.

A series of one-dimensional images over time were obtained in which the diffusion of two populations of nuclei could be seen in a manner similar to that in Ref. 5. First, the magnetization of the nuclei in a thin, central section of the cylinder was inverted. Then, images were taken every 0.2 s for a total of 5 s, using a constant flip angle of 4.5°. Because the gas had such a long T1, the fraction of the magnetization (sin[4.5°]) that was lost due to dephasing with each image acquisition did not recover over the 5-s duration of the experiment. The series of images, normalized to the same total intensity, are shown in Fig. II-3.

The ^{3}He diffusion coefficient was determined with this data using a simple model. A delta-function spike in density will, through diffusion, form a density profile that is Gaussian, with a variance proportional to the diffusion coefficient and to the time over which diffusion has taken place.[9] We therefore modeled each one-dimensional image by convolving the first image with a Gaussian distribution whose variance V was proportional to a diffusion coefficient D times the time interval t separating the two images: $V = 2Dt$. We then searched for the value of D that minimized the error between the predicted and measured values using a chi-squared statistic. This model does not account for the cell walls, so only the pixels that were sufficiently far away from the walls were used in the fit. In addition, to correct for the decreasing signal, we first normalized each image to the same total signal intensity. A comparison of the experimental data to the model with the best-fitting value of D is shown in Fig. II-4 for a few selected time intervals. A value of $D = (12.3 \pm 0.2)$ mm^2/s was obtained.

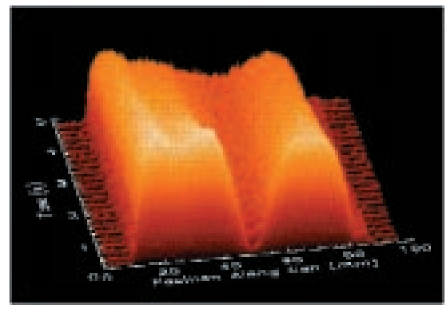

Fig. II-3. A series of one-dimensional images of the gas over time, showing the diffusion of the small central slice of inverted magnetization. Time runs from front to back, with the total duration being 5 s.

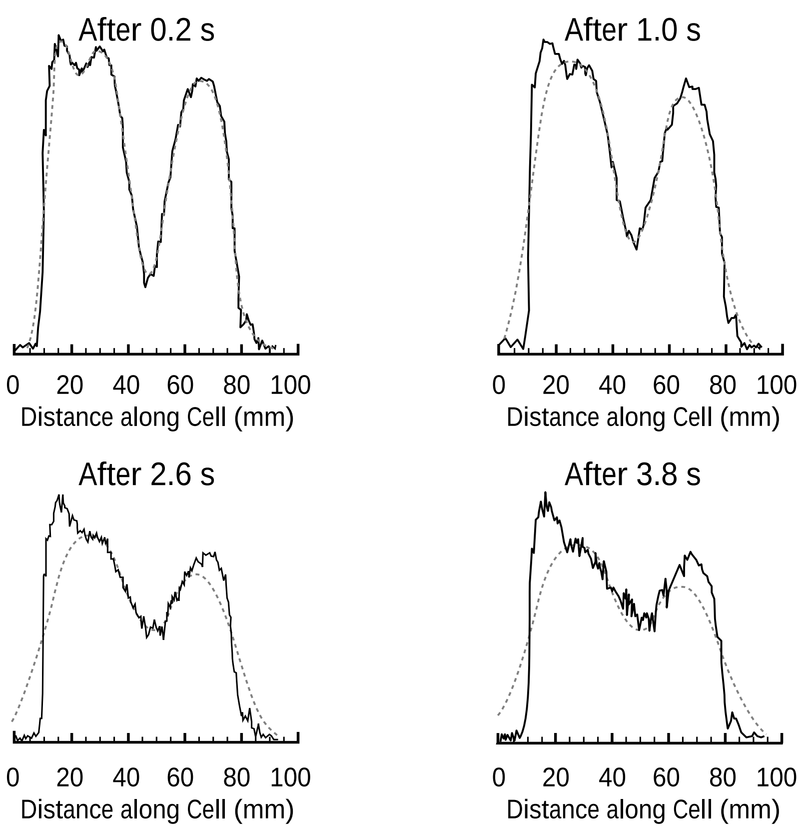

Fig. II-4. A comparison of the data (solid) and model (dashed) for a few selected time intervals using the best-fit value of the diffusion coefficient. The model does not take into account the cell boundaries; the pixels included in the fit are only those that are far enough away from the boundaries to remain unaffected by them.

Next, one-dimensional diffusion images were made using the technique of Stejskal and Tanner.[10] A diffusion coefficient was calculated at each point in the image by taking the ratio of the image intensities with and without a previous magnetic-field gradient in place. With a gradient, the signal will diminish because of diffusion. Knowing the strength and duration of the gradient allows the diffusion coefficient to be determined.

Diffusion can be affected by physical boundaries as well as by temperature or pressure. Images were made both at thermal equilibrium and with a thermal gradient (Fig. II-5). The value of every fifth pixel averaged with its four nearest neighbors is shown in these images. In the upper plot in Fig. II-5, the gas is at thermal equilibrium at room temperature. Error bars in this plot are larger than those in the lower plot because the data for the upper plot were acquired after a shorter polarization time and therefore had smaller signals. The diffusion coefficient away from the ends of the cylinder is consistent with that measured from observing the diffusion of a section of inverted magnetization (described above). The lowering of the diffusion coefficient near the walls of the cylinder is due to the walls restricting the diffusion in this area and is the cause of the edge enhancements discussed in Ref. 11. The lower plot shows a diffusion image when the cylinder had a thermal gradient produced by holding the right end (as viewed in this figure) of the cell in a liquid-nitrogen exhaust plume for a few minutes. The diffusion coefficient decreases with temperature. Again, lowering of the diffusion coefficient at the ends is due to restricted diffusion.

We have demonstrated the use of diffusion imaging with a hyperpolarized noble gas for monitoring temperature and for detecting physical boundaries. Just like relaxation-time images, spatial maps of diffusion can be a useful technique for characterizing the environment of the molecules containing the nuclei being imaged. We believe that diffusion imaging of hyperpolarized noble gases offers unique advantages in characterizing the porosity of materials, studying fractures in rocks, and dynamically imaging the pressure and temperature distributions in biological and acoustical systems.

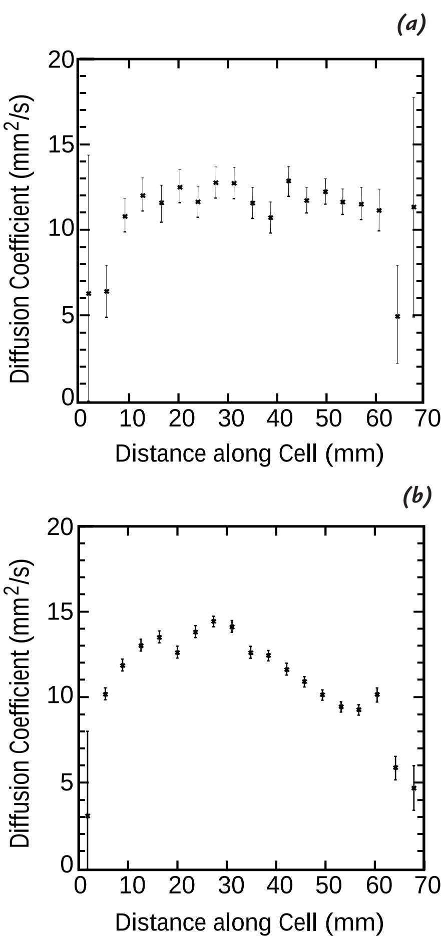

Fig. II-5. Two diffusion images (a) without and (b) with a thermal gradient in place. The reduction in the diffusion coefficient near the cell boundaries in both images is due to restricted diffusion. The decrease in diffusion from left to right in the lower image reflects the decrease in temperature from left to right.

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A Debris-Free Plasma Radiation Source for Extreme Ultraviolet Lithography

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In the quest for increased performance, the microelectronics industry has been reducing the size of individual elements, also known as features, on integrated circuits by a factor of two roughly every six years. Smaller feature sizes result in reduced distance and, therefore, reduced transit time between features, allowing the integrated circuits to be driven at higher clock speeds. Also, greater feature density allows for increased functionality, permitting one chip to perform the tasks that previously required several. This year, commercial devices will become available with 0.18-μm features and with 125 million transistors on a single chip.

In the commercial production of integrated circuits, the patterns for the features are imaged onto a silicon wafer by projection photolithographic methods that use visible and ultraviolet light sources with conventional optics. It is anticipated that this technology will reach its limit at a feature size of 0.15 μm. Achieving features smaller than 0.1 μm using a commercially feasible process will demand advances in future lithography techniques such as using extreme ultraviolet (EUV) radiation in conjunction with molybdenum/silicon multilayer reflective optics. These optics have a maximum theoretical reflectivity of 76% at a wavelength of 13 nm, which is more than an order of magnitude smaller than the shortest wavelength used in today's commercial processes. Using 13-nm radiation will allow for the imprinting of features that may ultimately be smaller than 0.05 μm.

Most of the proposed EUV lithography (EUVL) sources involve the interaction of a high-energy-density source (such as a laser, an electron beam, or an arc discharge) with a solid target. Although all of these methods offer efficient production of EUV radiation, debris generated from solid targets has been demonstrated to deteriorate the very expensive, metal, multilayer system optics. From FY94 to FY96, Los Alamos and Northrop Grumman were developing a debris-free EUVL source under a cooperative research and development agreement (CRADA). This source exploits the predicted anomalous energy deposition of a short-pulse electron beam in a preformed plasma. As a result, the plasma is heated and ionized to a charge state in which efficient radiation with a wavelength of 13 nm or less is generated upon recombination. Because solid targets are avoided, the production of debris is avoided as well. The effort at Los Alamos had three distinct phases: experimental verification of the anomalous energy absorption; construction of a short-pulse, high-brightness accelerator; and the final experiments with the accelerator.

Anomalous energy deposition into a preformed target plasma by a relativistic electron bunch is predicted when the temporal duration (bunch length) is less than or equal to the inverse of the plasma frequency of the target plasma. For a bunch this short, the plasma can no longer respond to the individual electrons but instead responds collectively to the bunch. The energy loss is predicted to scale as the square of the effective charge of the bunch. For a bunch with a few nanocoulombs of charge, $\sim 10^{10}$ electrons, this scaling suggests a considerable enhancement of stopping power over that of individual electrons. The bunch loses energy by driving a large-amplitude electrostatic wave in the target plasma—that is, by generating a plasma wake field. The goal of this work is to drive the wake-field generation process into the nonlinear, wave-breaking regime so that the energy deposited into the plasma wave will efficiently heat and ionize a plasma column that will generate EUV.

Initial experiments to demonstrate anomalous energy absorption are carried out with the accelerator developed for the Los Alamos Free-Electron Laser as the source of the electron bunches. For these experiments, the accelerator is configured to produce 15-ps, 4-nC electron bunches with an energy of 15.5 MeV. The bunches are produced in a manner that accelerates a series of 1–8 bunches with a spacing of 9.2 ns between each bunch (collectively referred to as a macropulse). The macropulse is injected into a 10-cm-long gas cell containing either 0.18 or 0.5 torr of argon. As the first few electron bunches pass through the cell, a weakly ionized (~0.1% ionization) argon plasma column is created by collisional ionization. The plasma frequency, ω_{pe}, increases with increasing plasma electron density, n_e, by the relationship $\omega_{pe} \propto \sqrt{n_e}$. When the inverse of the plasma frequency equals the bunch length, T_b, or, equivalently, when a critical electron-density is reached (that is, when $n_e \cong 3 \times 10^{15}/T_b^2$ cm^{-3}, where T_b is in picoseconds), the plasma responds collectively to the next bunch and slows the bunch, transferring energy to the background plasma electrons. The heated background plasma ionizes the neutral gas. After the macropulse exits the gas cell, the energy of the individual bunches in the macropulse is measured with a time-resolved energy spectrometer. The plasma density along the ionized filament in the cell is measured with a 94-GHz microwave interferometer.

Figure II-6 shows the measured energy for each bunch with and without gas in the cell. The linear drop in energy for each succeeding bunch measured in the vacuum case is an artifact of the acceleration process. The measured bunch energies with gas in the cell show the anticipated results. The collisional losses of the first three bunches are too small to be detectable by our technique. As the ionization increases, the energy loss suddenly increases, peaks at an optimum plasma electron density, and then lessens as the density becomes too high for efficient energy loss for the fixed bunch length. Figure II-7 shows the percentage of energy loss as a function of the plasma electron density. The maximum observed energy loss is 2.2% (for 0.18 torr) and corresponds to an enhancement of 3.4×10^4 over that expected from collisional ionization and radiative losses. Also shown in Fig. II-7 is the result of numerical simulations of the anomalous energy loss. The simulations, which were performed by researchers in XPA with the particle-in-cell plasma simulation code ISIS, show good agreement with the measurements.

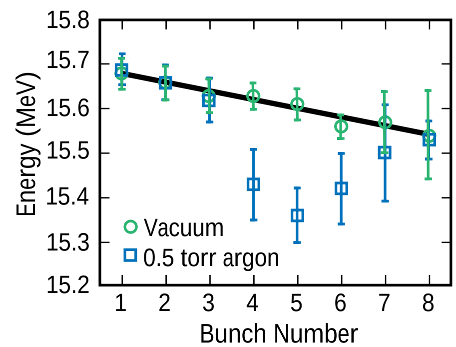


Fig. II-6. Electron energy plotted versus the number of injected electron bunches. The line is a linear fit to the energy of the bunches without a gas fill; the negative slope is an artifact of the acceleration process.

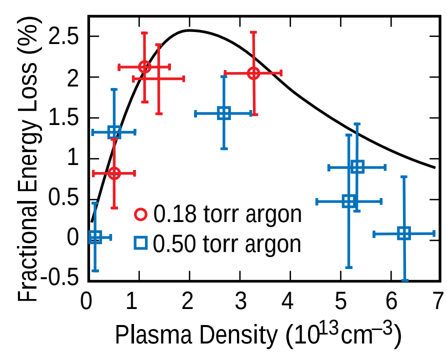


Fig. II-7. Energy loss plotted versus plasma density. The curve is the result from numerical modeling with ISIS.

Although these experiments demonstrate, for the first time, the predicted anomalous energy deposition, the amount of energy deposited is not sufficient to heat and ionize the plasma for EUV production. The fractional energy loss per unit length of a bunch is proportional to the plasma density for a bunch of optimal duration. Numerical calculations show that an 8-MeV, 1.5-nC bunch with a duration of 0.75 ps would suffer an energy loss of 80% for an interaction length of 2.5 mm in a neon plasma with an electron density of ~10^{16} cm^{-3}. Thermalization of the deposited energy results in a 10- to 20-eV plasma filament producing EUV from Ne^{4+} and Ne^{5+} ions. As part of the second phase of the CRADA, a linear accelerator (linac) that can produce bunches with these parameters has been constructed by researchers in AOT-9 (now LANSCE-9). Using photocathode technology, the linac produces 8-MeV-electron bunches with 1.5 nC of charge and an initial length of 20 ps. A time-of-flight compressor, which uses the energy spread created in the acceleration process, reduces the bunch duration to 0.75 ps with no loss of charge. The accelerator can create a macropulse of a series of bunches with a spacing of 9.2 ns. Northrop Grumman developed a pulsed, supersonic gas jet that produces a 0.4-cm × 1-cm jet of neon with a density of neutral atoms of ~10^{19} cm^{-3}. A photograph of the accelerator is shown in Fig. II-8.

As was seen in the initial experiments, it is anticipated that the first few bunches in the macropulse will create a weakly ionized plasma column in which a trailing pulse will strongly couple and deposit a significant amount of its energy. The configuration of the experiment does not permit time-resolved measurements of the individual bunch energies. The primary diagnostics are two filtered silicon photodiodes that view the interaction region. One diode is coated with layers of titanium, zirconium, and carbon that are 5 nm, 200 nm, and 50 nm

Fig. II-8. The EUVL linac located at Los Alamos. The accelerator generates 8-MeV, 1.5-nC electron bunches that are compressed to a bunch length of 0.75 ps.

thick, respectively. This layering results in a filter that has a band-pass between 6 and 16 nm (200 to 77 eV), which blocks any longer wavelengths and passes radiation shorter than 1.3 nm (950 eV). The second diode has a 127-µm beryllium layer that passes wavelengths shorter than 0.9 nm (1265 eV) and blocks all longer wavelengths. This combination of filters permits the detection of radiation between 6 and 16 nm with the Ti/Zr/C-coated diode while rejecting any signals that may be from x-rays and gamma rays because these signals would be seen in the beryllium-filtered diode.

Figure II-9 shows data from the two diodes. Distinct pulses are evident in the Ti/Zr/C-filtered diode that are absent in the beryllium-filtered diode, indicating the generation of radiation within the 6- to 16-nm band. The first pulse seen in the data is coincident with the fourth bunch of a macropulse that contains 10 bunches. The timing is confirmed by measuring the pulses recorded when a metal target is placed in the interaction region. (Using a metal target results in a gamma-ray pulse for each bunch in the macropulse; this pulse is seen in both detectors.) These results show behavior similar to that seen in the initial experiments. The first few bunches of the macropulse show negligible coupling, after which strong EUV generation occurs for the next few pulses. For these experiments, it can only be assumed that the optimum plasma electron density for this bunch length corresponds to the peak in the EUV generation. (The microwave interferometer used in the initial experiments was not used for these experiments because the plasma electron density is beyond its measurement capabilities.) From the energy absorbed by the photodiode, we estimate that on the order of 1% of the bunch's energy is converted to radiation in this band.

These experiments demonstrate debris-free EUV production using anomalous energy deposition of an electron bunch into a plasma. The technique shows promise as a source for EUVL; however, measurements of the conversion efficiency into the 13-nm (±0.15 nm) band are needed. Northrop Grumman estimates the production cost of a commercial EUV source based on this technology to be $1.5 million, an amount that is comparable to cost estimates of laser-based systems.

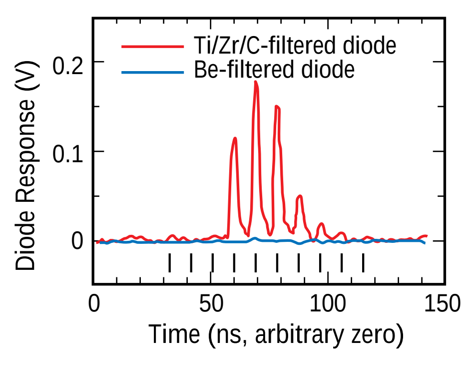


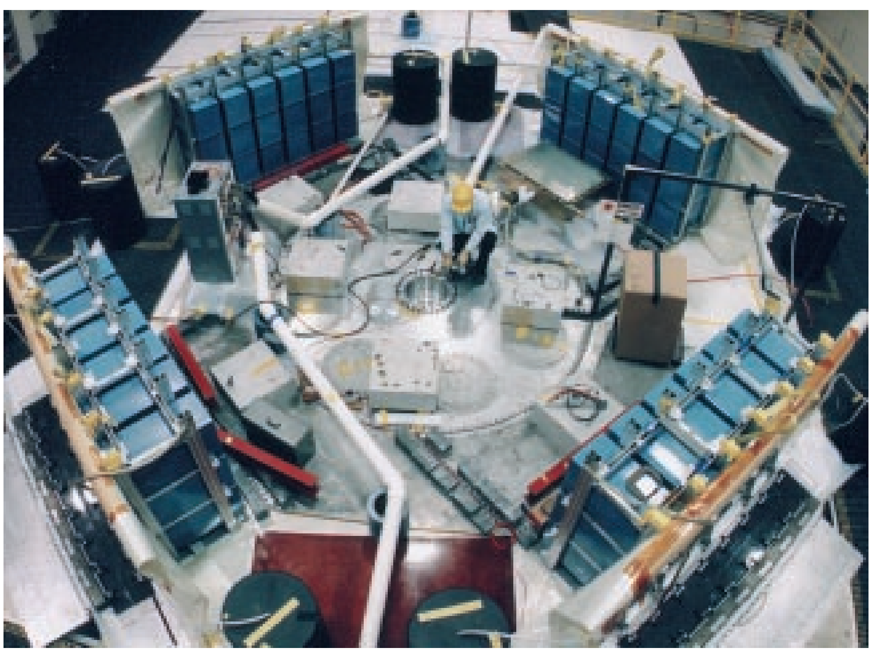
Fig. II-9. Data from the silicon photodiodes that view the interaction region. They indicate the production of EUV in the 6- to 16-nm-wavelength band. The black vertical bars mark the time that each of the 10 electron bunches from a macropulse passes through the interaction region. The data are for a single macropulse.

Pulsed-Power Experiments at the Pegasus II Facility

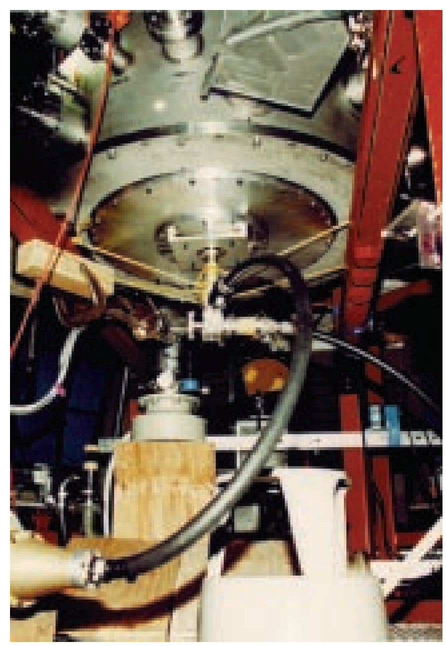
Collaborators from P Division, DX Division, MST Division, X Division, and Bechtel

Overview of the Facility

Pegasus II is a pulsed-power facility at Los Alamos National Laboratory that is used to conduct a variety of experiments in the high-energy-density regime that have applications to the physics of nuclear weapons as well as to basic science. The facility (Fig. II-10) consists of 144 energy-storage capacitors arranged as a two-stage Marx bank with a maximum erect voltage of 100 kV. The 4.3-MJ stored energy for this voltage makes Pegasus II one of the largest capacitor-bank facilities in the world. Pegasus II is used to produce peak currents as high as 12 MA in cylindrical inductive loads and can be operated either with or without a fast opening switch. In addition to conducting plasma- and hydrodynamic-physics experiments, researchers at the Pegasus II facility continue to address technological issues of developing an efficient switch. As a result of the destruction associated with the dissipation of the large stored energy, repair and replacement of components follow each experiment, and shots are fired approximately every two weeks. Several different experimental campaigns in support of the nuclear-weapons program are conducted and involve both heavy, solid liners and thin aluminum foils as the loads for the machine. The foil targets become plasmas during an implosion; in the foil-implosion experiments the imploding plasma stagnates on the axis of the cylindrical system, and the kinetic energy is converted to thermal energy and radiation. The solid-liner experiments are mainly used to address hydrodynamic issues and often involve the impact of the liner on an internal target package. The contact person for Pegasus II projects is Jack Shlachter of P-22.



(a)



(b)

Fig. II-10. View of (a) the upper half and (b) close-up of the target chamber in the lower half of Pegasus II.

Summary of Physics Capabilities

Research during the past two years has been focused mainly on hydrodynamic experiments that use a standardized solid drive liner. The active portion of the liner, made from unalloyed (1100 series) aluminum, is a 3.2-g right hollow cylinder (4.8-cm outer diameter, 2-cm height, and 0.4-mm wall thickness) designed to remain at solid-aluminum density during the course of the experiment. For typical Pegasus II operating conditions, the impact of this liner on an internal target with a diameter of a few centimeters results in shock pressures of 100–500 kbar with liner velocities of ~3 km/s at a peak current of 6 MA and an impact time of ~10 μs.

Ejecta Experiments

When a shock wave interacts at a solid/gas (or liquid/gas) interface, some of the solid or liquid material can be emitted into the gas region. These materials can range in size from submicron to hundreds of microns and are referred to as ejecta. The amount, size, and velocity of ejecta will depend on material properties such as the grain size and surface finish as well as the state of the shock wave in the material. This phenomenon occurs in a nuclear weapon when a shock wave interacts at the interfaces between weapon materials and the gases. At this interface, metallic ejecta can be injected into the gas, contributing to the mix of those materials with the gas, which in turn has an effect on the performance of the nuclear device.

In order to characterize and understand ejecta distributions, P Division has developed an in-line Fraunhofer holography technique to make measurements of the ejecta in dynamic systems. The diagnostic has been developed and implemented on numerous experiments based at Pegasus II. The ejecta experiments use the standard aluminum implosion cylinder with various 3.0-cm target packages inside. When the liner driver impacts a target cylinder, a shock wave is set up in the target. The shock wave then propagates through the 400-μm-thick target, and the ejecta are emitted at the target/vacuum interface. An additional 1.6-cm-diameter cylinder (collimator) with various slit openings is used to control the amount of ejecta that passes through to the axial center. The entire load assembly thus consists of three cylinders with the same axis. To make a holographic measurement of the ejecta, a 60-mJ, 100-ps, 1.5-cm-diameter laser pulse is transported along the collimator axis. The laser beam then interacts with the ejecta that have passed through the collimator slits. This interaction occurs some time after the driver-liner cylinder impacts the target cylinder. The actual hologram is made when the scattered light from the ejecta interferes with the unscattered laser light (reference beam) at the plane of the film. Measuring particles of a few microns in size requires that the holographic film be placed a few centimeters from the ejecta. However, at this distance the film would be destroyed in the experiment. To address this problem, our researchers have developed an optical transfer system that relays the interference pattern 93 cm from the ejecta to the holographic film. The hologram contains information about particles ranging from a few microns to a hundred microns in diameter over a volume of 1 cm^3.

In addition to the holography diagnostic, a visible shadowgraphy, dark-field imaging technique has also been developed. Unlike holography, this diagnostic does not provide three-dimensional information; however, it does provide spatially resolved and time-resolved data about the ejecta front as it moves through space. This diagnostic uses a long-pulsed ruby laser (a 450-µs pulse). The laser passes through the ejecta, and a framing camera makes time-dependent, spatially resolved shadowgrams of the ejecta. This technique has been applied successfully to many experiments. Ejecta data have been obtained for both aluminum and tin targets for which the target surface finish and shock strength have been varied.

Complex Hydrodynamic Experiments

Using the same standard aluminum drive cylinder on Pegasus II, our researchers have conducted a separate series of experiments to look at complex hydrodynamic problems. These experiments offer an approach to studying the vorticity and mixing of materials induced by a shock passing across a nonuniform boundary. Although the details of the target design for an individual experiment vary, one example consists of xenon gas surrounded by three layers; the inner and outer layers are made of lucite and the middle layer of gallium (Fig. II-11). The gallium layer is 2 mm thick all the way around, but one half has a smaller radius than the other half. Thus, a step is formed at the junction where these two half-cylinders meet. As the main shock passes across this nonuniform boundary, vorticity and mixing of materials are calculated to occur. We are mainly using axial x-rays to look for the calculated disruptions. Sufficiently high quality x-ray images will provide us with a code benchmark for this particular hydrodynamic phenomenon.

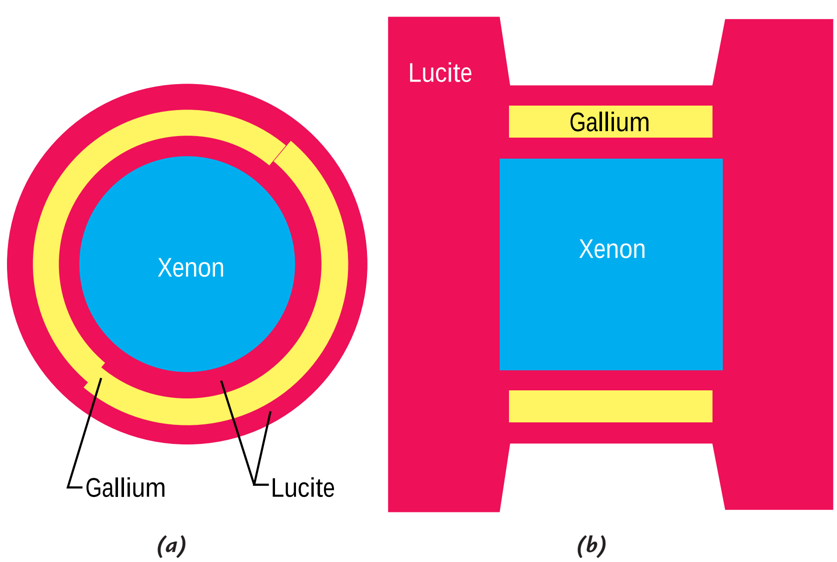


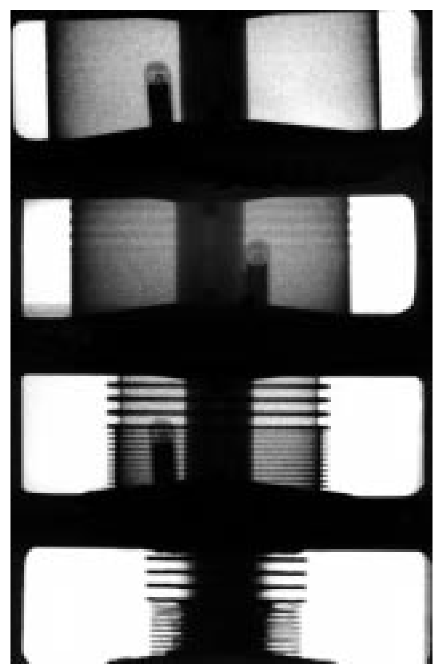
Fig. II-11. Schematic (a) end view and (b) side view of the target package for the complex hydrodynamic experiments.

Liner-Stability Experiments

A series of Pegasus II experiments examining the stability of the imploding liner at near-melt conditions has been conducted. These experiments are motivated by the desire to take full advantage of the Pegasus II facility for performing hydrodynamic studies and to anticipate conditions that will be produced on the Atlas facility that is slated for operation in 1999. Although one-dimensional calculations show that liners can be accelerated to high velocities with a significant fraction of the liner remaining in the solid state, a more detailed analysis using two-dimensional magnetohydrodynamic codes indicates that the liner may break up as a result of instabilities. To provide experimental tests of these calculations, we modify standard liners by coating the inner surface of the aluminum with a thin layer of gold to allow for detailed radial radiographic imaging. For some shots, the liner is fabricated with a precisely machined sinusoidal perturbation in the outer surface. Radiographic images provide experimental data on the observed growth rate of the perturbation as a function of spatial axial wavelength; these data can then be compared with theoretical estimates. Figure II-12 shows radiographic data from a sinusoidally perturbed liner.

Megabar Experiments

The major limitation on imploding-liner conditions is the rise in material temperature associated with the deposition, through the high current, of Ohmic heat. Experiments that require ultrahigh-pressure shock generation, greater than the ~300 kbar achieved with standard aluminum liners on Pegasus II, are of interest for weapons research as well as for basic science. One approach to producing such high pressures on Pegasus II involves the use of composite liners. These systems consist of an outer liner of aluminum with an inner layer of platinum. The aluminum constitutes the bulk of the assembly mass and carries the current. Its low density allows the assembly to achieve maximum velocity. The platinum has a high density and provides for a high shock pressure but remains solid as a result of its high melting point and its relatively low electrical conductivity. With these composite liners, it appears that multimegabar pressures can be achieved on Pegasus II; preliminary results indicate that this approach to high pressures is worth pursuing.



static

6.5-µs exponential-growth regime

8.0-µs nonlinear spike-and-bubble growth

9.5-µs magnetic-field breakthrough

Fig. II-12. Static and sequential x-ray radiographic images of a sinusoidally perturbed liner during implosion.

Near-Term Plans

As the utility of Pegasus II becomes more widely recognized, new experiments and campaigns are being proposed. The present shot schedule includes experiments designed by outside users (from Lawrence Livermore National Laboratory, France, Britain, and Russia) as well as by local researchers. Emphasis for all of these experiments is on issues associated with implosions of heavy metal liners, covering physics topics such as high material strain at high strain rates, Rayleigh-Taylor mix/demix, and laboratory production of ultrahigh magnetic fields. Initial experiments on Pegasus II designed to achieve a peak magnetic field of 6 MG will involve the compression of an axial "seed" magnetic field by the imploding liner. This flux-conservation approach is similar to that used in explosively driven experiments but has the advantages of being fielded in a laboratory environment.

Switch Development

The experiments involving heavy-liner implosions use the Pegasus II facility in a direct-drive mode. Closure of the switches on the capacitor bank couples the current directly to the load through the transmission line. The characteristic waveform for this mode has a peak current at a quarter-cycle time of several microseconds. In the opening-switch mode, the current is allowed to build up to the peak value in a parallel circuit branch and then is rapidly switched to the load. The particular opening switch selected for Pegasus II is a plasma-flow switch; development of this switch is an ongoing activity and involves detailed evaluation of the behavior of a plasma formed between the two conductors in the vacuum coaxial region near the load. Several Pegasus II experiments have been conducted to test the dependence of switch performance on the mass and configuration of the switch material. Additional experiments are being conducted on a smaller pulsed-power facility to analyze possible sources for lost current in the coaxial region. Successful development of opening switches is important for radiation-production experiments on Pegasus II and on its successor, Atlas.

Applications to Basic Science

Pegasus II has applications to a number of important basic-science areas, and the planned Atlas facility will substantially extend these capabilities. The applications extend into the areas of plasma physics, geophysics, planetary physics, astrophysics, and condensed-matter physics. These applications are based upon the capability to produce extreme conditions of pressure, density, magnetic field, and material velocity. As mentioned above, the near-term Pegasus II experiments are designed to reach magnetic fields of 6 MG. When Atlas becomes available in 3 years, axial fields approaching 20 MG should be possible. Field strengths this high can open up new areas of condensed-matter physics. At 2 MG, for example, the Zeeman splitting in materials approaches the thermal energy in a solid and substantially exceeds the magnetic-exchange energy. Thus, magnetic properties of materials should be greatly modified in fields this high. At field strengths above 10 MG, the cyclotron radius of a conduction electron in a crystal becomes less than one lattice constant, meaning that the conventional transport properties of materials are field dominated. Some potential experiments include extending present high-field experimental studies, such as magnetization of high-critical-temperature superconductors and cyclotron resonance in low-mobility materials, and moving into new experimental arenas, such as studying new conductivity mechanisms and quantum-limit phenomena in atoms.

Pegasus II also has the capability to achieve very high pressures, both through shock compression and quasi-adiabatic compressions. With Pegasus II, pressures in the megabar regime are possible. Although such conditions may also be reached using gas guns and diamond anvil cells, the pressures achievable with Atlas will significantly exceed the limits of other conventional techniques. Among problems of great interest in high-pressure research for Pegasus II and Atlas are understanding the thermal properties of the earth's core materials near the center of the earth (i.e., at pressures in the 3-Mbar range) and measuring the equation of state (EOS) of dense, strongly coupled plasmas (which is of importance in testing models of theoretical plasma physics and in benchmarking theories of the interiors of giant planets and brown-dwarf stars). Fundamental studies of material instabilities are also being made at Pegasus II and will be extended on the Atlas facility.

Atlas Capabilities

Atlas is a funded construction project to develop a 36-MJ pulsed-power driver; this energy is approximately 10 times that of Pegasus II. When charged to its full voltage of 240 kV, Atlas will deliver over 40 MA to a load in a pulse rising in about 4 μs. Atlas will provide a rich experimental environment for programmatic experiments in the high-energy-density regime and will be a platform for many basic-physics experiments. Computational studies performed on a 70-g aluminum liner (called the Atlas standard liner) indicate that implosion velocities exceeding 20 km/s will be attained with the inner surface of the liner remaining unmelted. Thus, Atlas will be a premier driver for hydrodynamics and material studies in the very-high-pressure regime. Shock pressures exceeding 30 Mbar will be possible in high-Z materials, and direct, accurate EOS experiments in this range appear feasible. This significantly exceeds the range of any direct EOS experiments conducted by conventional techniques. At these pressures, materials are heated into the multielectronvolt regime and thus will become ionized dense plasmas (e.g., for tungsten at 25 Mbar, the temperature is 8 eV). Atlas will also provide the ability to reach high densities using near-adiabatic compressions. This is important for reaching dense plasma states that cannot be achieved by shock compression. As a hydrodynamic driver, Atlas will be used to extend the high-strain-rate and instability experiments that are now being developed at Pegasus II. Atlas has many uses for basic science. Concepts now being developed for Atlas include dense-plasma properties, materials studies in 20-MG fields, and magnetized target fusion.

Quantum Information Science

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Introduction

The representation of information by classical physical quantities such as the voltage levels in a microprocessor is familiar to everyone. But over the past decade, quantum information science has been developed to describe binary information in the form of two-state quantum systems, such as photon polarization states. (A single bit of information in this form has come to be known as a "qubit.") Remarkable new capabilities in the world of information security have been predicted that make use of quantum-mechanical superpositions of information, a concept that has no counterpart in conventional information science. For example, quantum cryptography allows two parties to communicate securely even in the presence of hostile monitoring by a third party. A quantum computer would make use of logical operations between many qubits and would be able to perform many operations in parallel. Certain classically intractable problems, such as factoring large integers, could be solved efficiently on a quantum computer. We have experimental projects underway in quantum cryptography, quantum computation, and interaction-free measurement, which also takes advantage of quantum properties.

Quantum Cryptography

One of the main goals of cryptography is for two parties ("Alice" and "Bob") to render their (binary) communications unintelligible to a third party ("Eve"). This can be accomplished if Alice and Bob both possess a secret random-bit sequence, known as a cryptographic key. For example, in "one-time pad" encryption Alice adds the key to the original message, known as plaintext, and communicates the sum (ciphertext) to Bob. He is able to recover the plaintext by subtracting his key from the ciphertext, but Eve, who is assumed to have monitored the transmitted ciphertext, is unable to discern the underlying plaintext through the randomization introduced with Alice's key. So, although key material conveys no useful information itself, it is a very valuable commodity, and methods for Alice and Bob to generate key material securely are correspondingly important.

Using quantum cryptography, or, more accurately, quantum key distribution (QKD), Alice and Bob can create shared cryptographic key material whose security is assured by the laws of quantum mechanics. They first independently generate secret random-number sequences, which then undergo a bit-wise comparison that requires the preparation, transmission, and measurement of a single photon for each bit. Alice's photon-state preparations and Bob's measurements are determined by their bit values and are chosen from sets of nonorthogonal possibilities, such as linear and circular polarization. This comparison algorithm, which may be publicly known, ensures that Bob detects a photon (with some quantum-mechanically determined probability) only if he has the same bit value as Alice. They retain only the detected bits from their initial sequences. These subsets are the raw key material from which a pure key is distilled using classical error-detection techniques. Eve can neither "tap" the key transmissions (owing to the indivisibility of a photon) nor copy them (owing to the quantum "no-cloning" theorem). Furthermore, the nonorthogonal nature of the quantum states ensures that if Eve makes her own measurements, she will be detected through the elevated error rate arising from the irreversible "collapse of the wave function" that she introduces.

QKD offers many security and ease-of-use advantages over existing key-distribution methods. Traditional key distribution using trusted couriers requires cumbersome security procedures for preparing, transporting, and handling the key before any communications can take place and may even be impractical (e.g., re-keying a satellite). In contrast, quantum keys do not even exist before the QKD transmissions are made, and a key can be generated at message-transmission time. Public-key cryptography also avoids many of the difficulties of key distribution by courier but provides only the conditional security of intractable mathematical problems, such as integer factorization. Accurate assessment of an adversary's computing power over the useful lifetime of encrypted information, which may be measured in years or even decades, is notoriously difficult: unanticipated advances in fields such as quantum computation could render public-key methods not just insecure in the future but also retroactively vulnerable. QKD could be used for real-time key generation in cryptographic applications where this long-term risk is unacceptable.

The physical systems that can support QKD transmissions determine the potential uses of quantum cryptography. We have demonstrated that QKD is possible over multikilometer optical-fiber paths: the necessary quantum coherence of the QKD transmissions persists even outside the controlled environment of a physics laboratory. At the infrared wavelengths required, germanium or indium-gallium arsenide avalanche photodiodes can be persuaded to detect single photons but at the penalty of a high noise and, hence, a high error rate. Removing these errors reduces the amount of key material and limits transmission distances to 100 km or so. (Optical amplifiers cannot be used to extend this range because they cannot replicate the nonorthogonal quantum states used in QKD.)

In our experiment we demonstrated quantum cryptography over 24 km of optical fiber that had been installed for network applications between two LANL technical areas. We have recently increased the propagation distance to 48 km; Fig. II-13 shows the system that was used in this demonstration. Our system incorporates an encryption/decryption feature that allows us to use the quantum-key material to encrypt short text messages at the sending computer and decrypt them at the receiving computer. This experiment shows that QKD could be used to generate cryptographic keys over “open” optical-fiber links between secure “islands,” such as between different government agencies in the Washington, D.C., area.

In a separate experiment we are developing QKD for “free-space,” line-of-sight communications, such as surface-to-aircraft. This technology could also possibly be used for the re-keying of satellites in low-earth orbits. So far, we have achieved low-error-rate transmissions over 205 m within our laboratory, but we will extend this distance to several kilometers in the near future. These new experiments will take place outdoors and will allow us to assess the daylight background and atmospheric optics issues that will impact the key rate and error rate. Quantum cryptography is likely to be the first practical application of the foundations of quantum mechanics, which illustrates the often unexpected value of basic research.

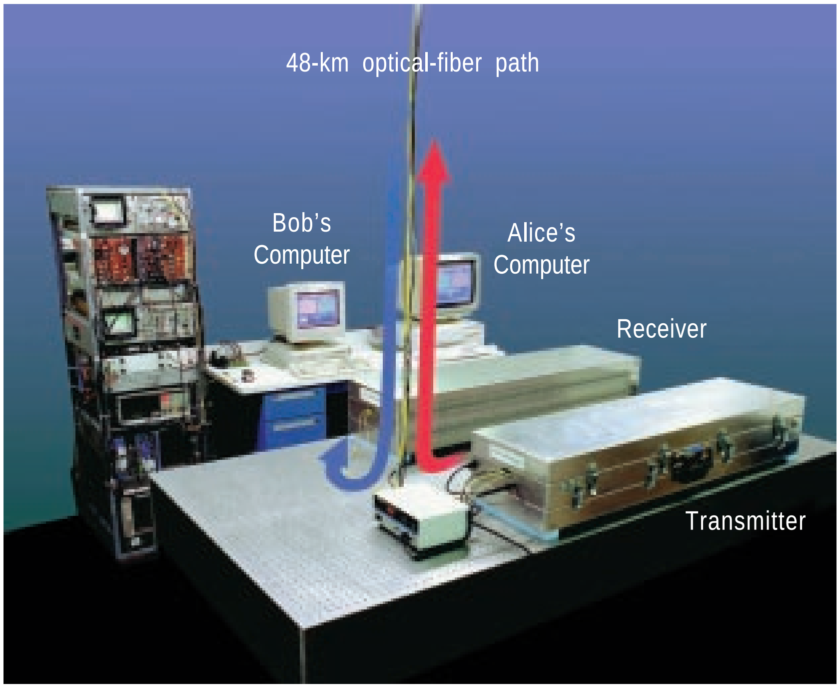

Fig. II-13. The 48-km quantum-cryptography system.

Quantum Computation

With two or more qubits it becomes possible to consider quantum logical-gate operations in which a controlled interaction between qubits produces a coherent change in the state of one qubit that is contingent upon the state of another. These gate operations are the building blocks of a quantum computer (QC), which in principle is a very much more powerful device than any classical computer because the superposition principle allows an extraordinarily large number of computations to be performed simultaneously. In 1994 it was shown that this "quantum parallelism" could be used to efficiently find the prime factors of composite integers. Integer factorization and related problems that are computationally intractable with conventional computers are the basis for the security of modern public-key cryptosystems. However, a quantum computer running at desktop PC speeds could break the keys of these cryptosystems in only seconds (as opposed to the months or years required with conventional computers). This single result has turned quantum computation from a strictly academic exercise into a subject whose practical feasibility must be urgently determined.

The architecture of a quantum computer is conceptually very similar to a conventional computer: multiqubit, or "multibit," registers are used to input data; the contents of the registers undergo logical-gate operations to effect the desired computation under the control of an algorithm; and, finally, a result must be read out as the contents of a register. The principal obstacles to constructing a practical quantum computer are (1) the difficulty of engineering the quantum states required; (2) the phenomenon of "decoherence," which is the propensity for these quantum states to lose their coherence properties through interactions with the environment; and (3) the quantum measurements required to read out the result of a quantum computation. The first proposals for practical quantum-computation hardware, based on various exotic technologies, suffered from one or more of these problems.

In 1994 it was proposed that the basic logical-gate operations of quantum computation could be experimentally implemented with laser manipulations of cold, trapped ions (Fig. II-14): a qubit would comprise the ground (S) state (representing binary 0) and a suitably chosen metastable excited (D) state (to represent binary 1) of an ion isolated from the environment by the electromagnetic fields of a linear radio-frequency quadrupole (RFQ) ion trap.

The principal components of this technology are already well developed for frequency-standard and high-precision spectroscopy work. Existing experimental data suggest that adequate coherence times are achievable, and a read-out method based on so-called "quantum jumps" has already been demonstrated with single trapped ions. We are developing an ion-trap quantum-computer experiment using calcium ions, with the ultimate objective of performing multiple gate operations (and possibly small computations) on a register of several qubits in order to determine the potential and physical limitations of this technology.

The heart of our experiment is a linear RFQ ion trap with cylindrical geometry in which strong radial confinement is provided by radio-frequency potentials applied to four "rod" electrodes and axial confinement is produced by a harmonic electrostatic potential applied by two "end caps." After laser cooling on their 397-nm S-P transition, several calcium ions will become localized along the ion trap's axis because their recoil energy (from photon emission) is less than the spacing of the ions' quantum vibrational energy levels in the axial confining potential. Although localized to distances much smaller than the wavelength of the cooling radiation, the ions nevertheless undergo small amplitude oscillations, and the lowest frequency mode is the axial center of mass (CM) motion in which all the ions oscillate in phase along the trap axis. The frequency of this mode, whose quantum states will provide a computational "bus," is set by the axial potential. The inter-ion spacing is determined by the equilibrium between this axial potential, which tends to push the ions together, and the ions' mutual Coulomb repulsion. For example, with a 200-kHz axial CM frequency, the inter-ion spacing is on the order of 30 μm.

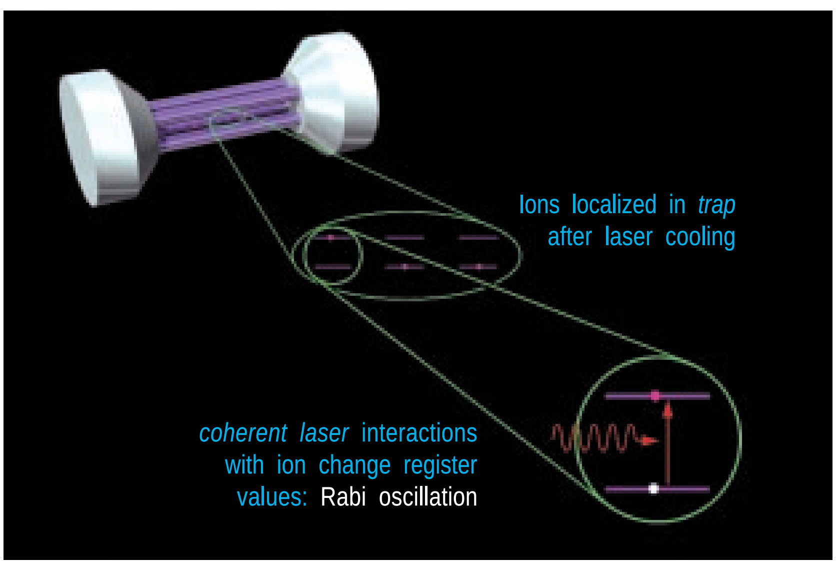

Fig. II-14. A schematic representation of the ion traps and logical gates created by laser-manipulated ions in quantum computation.

Because of its long radiative lifetime (~1 s), the S-D transition has such a narrow width that it develops upper and lower sidebands separated from the central frequency by the CM frequency. With a laser that has a suitably narrow linewidth and is tuned to the lower sideband, an additional stage of laser cooling is used to prepare the "bus" qubit (CM vibrational mode) in its lowest quantum state ("sideband cooling"). On completion of this stage, the QC is prepared with all qubits in the $|0\rangle$ state, ready for quantum computation.

The narrow-linewidth laser tuned to the S-D transition is the essential tool for changing the contents of the quantum register of ions and performing quantum logical-gate operations. By directing this laser at an individual ion for a prescribed time, we will be able to coherently change the value of the qubit that the ion represents through the phenomenon of Rabi oscillations. An arbitrary logical operation can be constructed from a small set of elementary quantum gates, such as the so-called "controlled-NOT" operation, in which the state of one qubit is flipped if a second qubit is in the "1" state but left unchanged if the second qubit is in the "0" state. This gate operation can be effected with three laser operations, using quantum states of the ion's CM motion as a computational bus to convey quantum information from one ion to the other. The result of the quantum computation can be read out by turning on the S-P laser. An ion in the "0" state will fluoresce, whereas an ion in the "1" state will remain dark. So, by observing which ions fluoresce and which are dark, a value can be obtained. We have recently succeeded in trapping calcium ions in our ion trap and imaging them with a charge-coupled device (CCD) camera. This is the first step toward creation of a quantum register.

We have also studied the intrinsic computational potential of ion-trap QCs. By taking into account the relevant decoherence mechanisms, we have found that on the order of one million gate operations could be performed on registers of 50 or so ions. This is a tremendous amount of quantum computation relative to the current state of the art: one logic operation on two qubits. Furthermore, because a QC can create an arbitrary quantum state using quantum logic operations, this computational capacity opens up a wide variety of quantum-mechanics experiments in domains that are today computationally inaccessible. We expect therefore that ion-trap QCs will allow us to explore quantum computation and the foundations of quantum mechanics.

Interaction-Free Measurement

Another area of great interest in the study of the role of quantum mechanics in information is that of "interaction-free measurements," in which the existence of nontransmitting objects (absorbers or scatterers) can be ascertained with arbitrarily small absorption/scattering taking place. In the simplest scheme, an interferometer is tuned for complete destructive interference for one of the output ports. The presence of an object in one of the arms removes the possibility of interference, so that a detector in the "dark" output port now has a chance of detecting an incident photon, which was not possible in the absence of the object. By varying the reflectivity of the inteferometer beam splitters, up to 50% of the measurements can be made interaction-free, as has been demonstrated in our lab.

More amazing, the fraction of interaction-free measurements can actually be made arbitrarily close to 1 by using a repeated interogation scheme—an application of the "Quantum Zeno" effect. In this case, there is an arbitarily small chance that any photons are absorbed by the object, and yet one gains definite information about its presence because the object inhibits an otherwise coherent evolution of the interrogating photon. For example, using simple optical elements, the polarization state of the photon can be made to rotate in small, equal steps from horizontal to vertical. However, the presence of an object that absorbs only the vertical component of the polarization at each stage will inhibit this rotation by collapsing the photon's wave function at each step back into the initial horizontal polarization. The total probability that the photon is ever actually absorbed can be made arbitrarily small by using many steps. Thus, without the object, the final state of polarization is vertical, but with the object present, the polarization becomes "trapped" in the horizontal. Paradoxically, it is the very presence of the absorbing object that alters the quantum state of the interrogating particle, ensuring that it is only rarely absorbed.

At LANL (in collaboration with researchers from the University of Innsbruck), we have achieved measurements that are up to 85% interaction free, which is the first demonstration to break the 50% limit. Efficiencies in excess of 95% are now being sought using a fast switching system. Also, we have begun investigating the practical implementation of interaction-free imaging, in which the techniques would be used to take a pixellated image of an object, again with the goal of negligible absorption or scattering. To date a resolution of less than 10 μm has been achieved in a simple, one-dimensional system looking at objects such as thin wires, optical fibers, and hairs. Finally, one of the most exciting prospects is the ability to couple to a quantum object, such as a single atom or ion, which can be in a superposition state. Using the techniques of interaction-free measurements, the quantum state can be transferred to the interrogating light, allowing the production of macroscopic entangled states of light and Schrödinger-cat states.

Please see the tutorial at http://p23.lanl.gov/Quantum/kwiat/ifm-folder/ifmtext.html for more information.

Stockpile Stewardship and Nuclear Science with GEANIE at LANSCE/WNR

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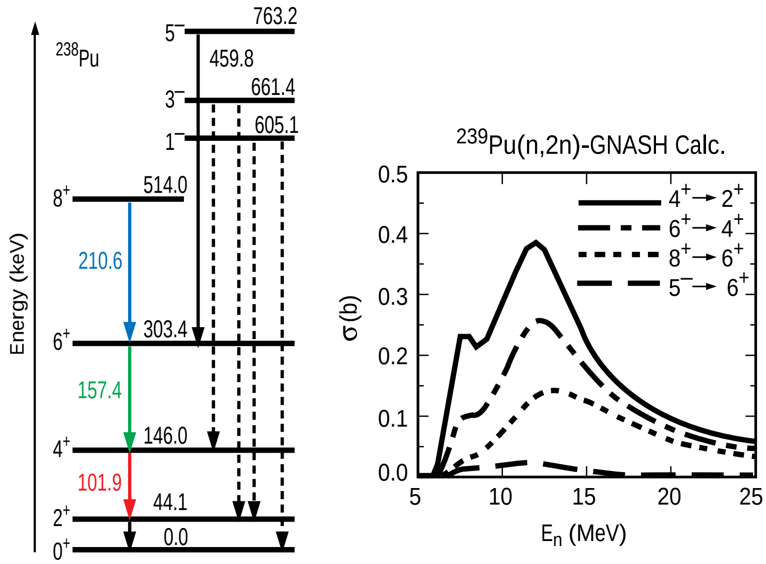
GEANIE (for Germanium Array for Neutron-Induced Excitations) is a large, escape-suppressed germanium detector array in the Weapons Neutron Research (WNR) facility at the Los Alamos Neutron Science Center (LANSCE). The use of GEANIE with the intense, pulsed, white source of neutrons at LANSCE/WNR[1] provides new and powerful capabilities for Science-Based Stockpile Stewardship (SBSS) and nuclear science. The acquisition, installation, operation, and use of the array is a major collaborative effort between researchers from Lawrence Livermore National Laboratory and Los Alamos National Laboratory. The primary goal of the collaboration is to determine the ^{239}Pu(n,2n) cross section to an accuracy of ±10%. Other important nuclear data needs are also being addressed. The unique combination of a high-resolution gamma-ray (γ-ray) spectrometer with a high-energy neutron source provides exciting opportunities in nuclear physics as well.

Advances in the technology of germanium-detector fabrication and in accelerator technology have enabled major advances in nuclear physics. In the past, these improvements have focused on nuclear-structure physics with large arrays of escape-suppressed germanium detectors used at accelerator facilities with heavy-ion beams. The important characteristics of such arrays for nuclear spectroscopy are high energy resolution (1/1000), good efficiency, escape suppression for background reduction, and high granularity. Perhaps the best known physics from these arrays is the discovery of superdeformed bands.[2,3]

The development and use of GEANIE at LANSCE/WNR creates a powerful new tool for SBSS. The use of a spallation neutron source makes it possible to simultaneously measure excitation functions over a wide energy range. At full power, the WNR spallation source is the most intense high-energy neutron source in the world. This is the first time that a large γ-ray detector array has been used at a neutron spallation source. This unique combination opens up new possibilities for research in areas of nuclear excitation that previously have been difficult to access.

Measuring characteristic γ rays that follow neutron-induced reactions usually allows the determination of both the reaction channel—for example, (n,2n) or (n,3n)—and the particular level excited in the product nucleus. In addition, the reaction thresholds and cross-section peaks observed in excitation functions provide valuable information for the identification and study of the various reaction products. Because of the high neutron energies available, many different reactions are possible. A short list includes the following: $(n,n'\gamma)$, $(n,xn\gamma)$ [where $x = 2, 3, 4, \ldots$], $(n,p\gamma)$, $(n,np\gamma)$, $(n,a\gamma)$, and $(n,na\gamma)$.



(a) *(b)*

Fig. II-15. (a) Level scheme showing the ground-state rotational band and negative parity band in ^{238}***Pu. (b) The GNASH-calculated values of the cross sections of these lines as a function of neutron energy.***

An accurate measurement of the ^{239}Pu(n,2n)^{238}Pu reaction cross section is needed to better understand the radiochemical data from past Nevada Test Site experiments. From measured γ-ray production cross sections, we obtain an estimate of total reaction cross sections as a function of incident neutron energy. By combining our results with calculations from the coupled preequilibrium and Hauser-Feshbach computer program GNASH,[4] we can use theory to account for the fraction of the cross section that is not measured with our technique. Figure II-15 shows GNASH values for the excitation functions of some of the γ rays in ^{238}Pu resulting from the ^{239}Pu(n,2n) reaction. In Fig. II-16 we show the GNASH-predicted cross-section ratios of (n,2$n\gamma$) to (n,2n) for some of the stronger transitions. The ability to simultaneously measure excitation functions for many γ-ray transitions provides numerous checks for validation of the data and of the models used in the GNASH code.

Because a large fraction of the γ-ray cascade populates the lowest-lying states in the product nucleus, the cross sections for the decay of the low-lying states provide the best measure of the total reaction cross section. A limitation of this technique occurs for very low energy states, such as the first excited state in ^{238}Pu at 44 keV above the ground state. Very-low-energy γ-rays are highly internally converted (emitting an electron) as well as being highly attenuated in the sample, making these transitions difficult to observe. This technique of determining the reaction cross section from the partial γ-ray cross section can be used for $E_\gamma > 100$ keV. It provides a means to study nuclei via (n,xn) reactions (where x = 1, 2, 3, . . .), probing nuclei that are otherwise difficult to access. Our previous experiments[5] with a single unsuppressed germanium detector, in which we observed reactions on ^{208}Pb up to (n,9n), laid much of the

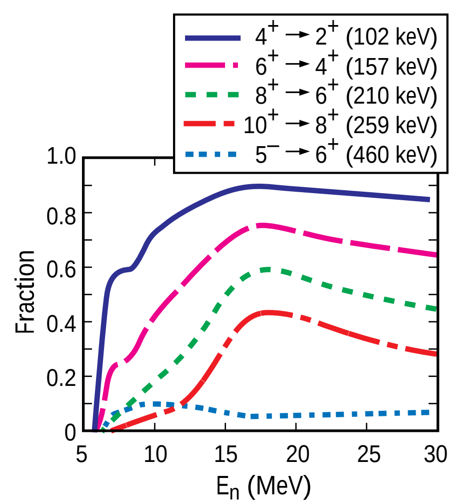


Fig. II-16. Cross-section ratios from GNASH calculated values. The 4^{+}***-to-2***$^{+}$ ***transition has over 70% of the total reaction cross section for*** $E_n > 10$ ***MeV.***

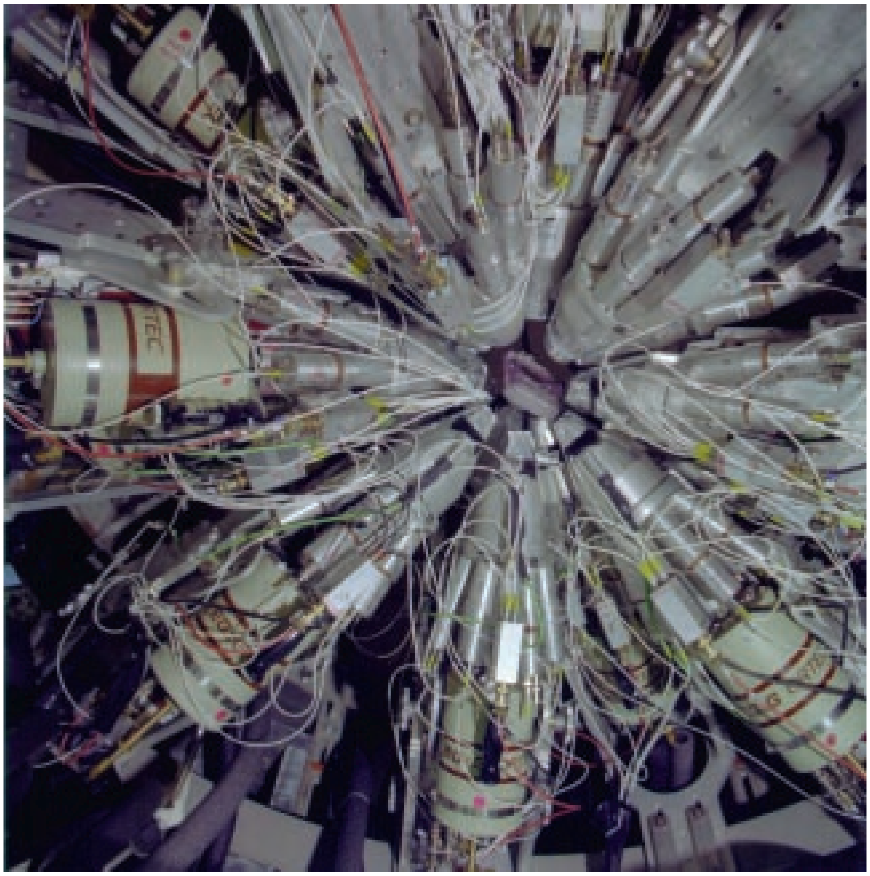


Fig. II-17. Photograph of GEANIE.

groundwork for applying this technique to actinides. The innovation of using planar germanium detectors was important for successful actinide studies, too.

GEANIE presently consists of 20 bismuth germanate (BGO) escape-suppression shields surrounding 20 germanium detectors. Figure II-17 is a photograph of the detector array. GEANIE was built using elements of the High-Energy-Resolution Array (HERA),[6] which was developed by the Nuclear Structure group at Lawrence Berkeley National Laboratory. GEANIE is located 20 m from the production target on a neutron flight path that is 60° to the incident proton beam.

Of the 20 escape-suppressed germanium detectors, 7 have planar geometry and the remaining 13 are coaxial. The coaxial detectors are 25% efficient relative to a 3-in. × 3-in. NaI(Tl) detector. The BGO escape-suppression shields improve the peak-to-total ratio for the coaxial detectors from ~0.15 to ~0.45 for a 1.33-MeV γ ray. All of the germanium detectors are interchangeable within the suppression shields, and the efficiency of the array is on the order of 1% for the full absorption peak of a 1.33-MeV γ ray. Short-term plans call for adding six more unsuppressed germanium detectors to the array. The long-term goal is to operate the array with a total of 30 suppressed germanium detectors, 10 planar and 20 coaxial.

Timing and energy resolution are equally important in our experiments. The timing resolution of the germanium detectors is important because we use it to deduce the incident neutron energy based on the time of flight. Optimal energy resolution is always important in resolving closely spaced γ rays, but this is particularly true for experiments with actinide samples that have closely spaced nuclear levels and numerous γ-decay transitions. The planar germanium detectors produce higher timing and energy resolution than the coaxial detectors, and the planar detectors also have lower background rates from the scattered neutrons because of their thin geometry. The limitation of the planar detectors is their reduced efficiency at higher γ-ray energies. A combination of both coaxial and planar germanium detectors provides a powerful spectrometer for a wide range of experiments. The useful energy range for the coaxial germanium detectors extends from ~50 keV to over 5 MeV. The corresponding range for the planar detectors is from ~30 keV to over 500 keV.

The data that we acquired include single γ-ray events as well as γ-γ coincidences. Both types of data can be used to deduce cross sections, and the coincidence data permit more detailed spectroscopy to be undertaken. The coincidence data enable background reduction that helps in observing less intense γ-ray lines. Our data-acquisition system is based on the 4π array system at Michigan State University.

The use of γ rays is an important tool for (n,xn) measurements on actinide nuclei because the production of neutrons from fission interferes with a direct measurement of the (n,xn) neutrons. The good peak-to-total ratio of the GEANIE detectors allows the resolution of individual γ-ray lines above the background from fission and other γ rays. The planar detectors play an especially important role in these measurements because they have excellent energy resolution and are relatively insensitive to neutrons. This is the first time that multiple planar germanium detectors have been used to study actinide nuclei. Figure II-18 shows a planar detector spectrum from a ^{238}U sample. The uranium x-rays and the first 4^+-to-2^+ excited-state γ-ray transition are clearly visible. The observation of this low-energy transition makes possible an accurate measurement of the $(n,2n)$ cross section.

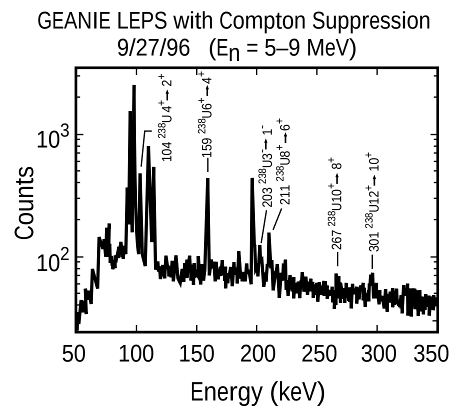
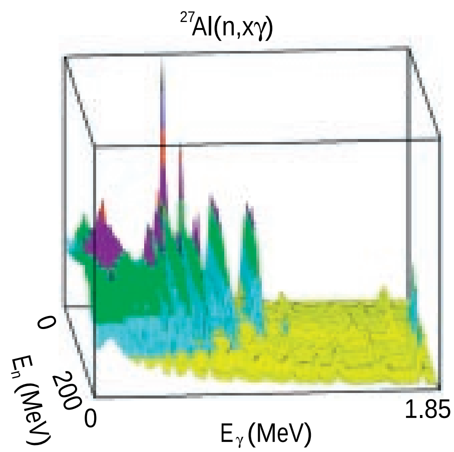
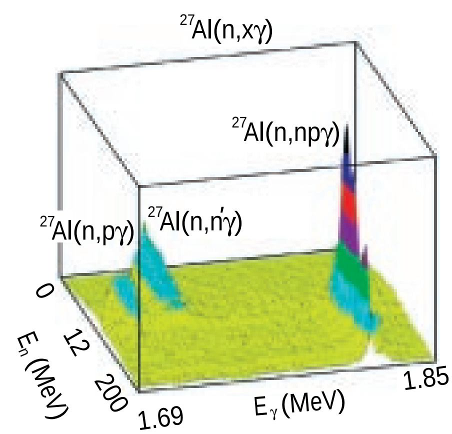


Fig. II-18. Spectrum from planar germanium detectors showing the 4^+-to-2^+ transition located between large x-ray peaks. Gamma rays from higher-lying levels are indicated as well. These data are for neutron energies between 5 and 9 MeV.



(a)



(b)

Fig. II-19. (a) Gamma-ray data from ^{27}Al(n,xγ). The "ridges" are yields from various γ-ray transitions. (b) Detail of part of the data in (a) showing peaks from three different reactions, inelastic scattering, (n,pγ), and (n,npγ).

We designed special ^{239}Pu samples encapsulated in a frame with thin beryllium windows to allow good low-energy γ-ray transmission. The design, fabrication, and use of these samples required a major effort. Using these samples, we have acquired data and observed the 6^+-to-4^+ and other transitions in ^{238}Pu. The radioactive decay of the plutonium makes data acquisition and background reduction challenging. The initial data reduction has been started, and further data will be acquired during the LANSCE accelerator operating period in 1997.

GEANIE at WNR offers an opportunity for complete spectroscopy in regions of angular momentum and excitation that are inaccessible with other neutron sources or with charged-particle beams. Such studies allow detailed tests of nuclear-structure models and level-density parameterizations. Neutron inelastic scattering is expected to be an especially valuable reaction for complete spectroscopy because it tends to populate all levels within the constraints of the angular momentum imparted to the nucleus. Data taken with an ^{27}Al sample that were collected in a brief run in November 1996 show the power of GEANIE/WNR to investigate nuclear excitations. A three-dimensional spectrum from the ^{27}Al($n,x\gamma$) single-event data is shown in Fig. II-19. Gamma rays produced by neutrons with energies from 1 to 200 MeV can be seen as ridges in part (a) of Fig. II-19. This plot shows one-half of the γ-ray energy range measured in the experiment. Part (b) of Fig. II-19 shows a small section of the data from part (a). In this region, γ-rays from ($n,n'\gamma$), ($n,p\gamma$), and ($n,np\gamma$) reactions are visible. The incident neutron energies at which these reactions are energetically allowed are all different, as can be seen by the different points along the E_n axis at which the "ridges" first occur.

From a brief run on a ^{196}Pt target we observed the ^{196}Pt(n,15$n\gamma$) reaction. This is the highest neutron multiplicity we have seen yet and demonstrates the potential for reaching neutron-deficient nuclei.

A sampling of the physics that will be pursued at GEANIE is contained in the objectives of proposals submitted to the December 1996 LANSCE Program Advisory Committee. The proposals included a search for rigid triaxial motion, an investigation of single-particle vibrational interactions in rare-earth nuclei, level-density studies, an exploration of exotic neutron-deficient nuclei, a verification of the double octupole phonon in ^{208}Pb, a search for intermediate states in ^{180}Ta to explain its cosmic abundance, and a study of the level statistics in ^{27}Al. Another proposal is to measure the Lu(n,xn) reaction cross sections for use as a diagnostic in experiments related to Accelerator Production of Tritium (APT). Off-line experiments with GEANIE are planned for times when the accelerator is not in operation. GEANIE is an important asset for stockpile stewardship and is attracting outstanding researchers because of the research opportunities available.

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Measurements of Stimulated-Raman-Scattering Instability Relevant to Ignition Hohlraum Plasmas

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Introduction

Control of laser-plasma instability is important for the success of laser fusion,[1] particularly indirect drive.[2] For indirect drive, laser beams enter a cavity (called a hohlraum) made of a material that has a high atomic number and that reaches a high ionization state (high *Z*). The high-*Z* plasma efficiently converts laser energy into x-rays, which in turn drive the implosion of a fusion capsule. Ignition hohlraums, such as those planned for the National Ignition Facility (NIF),[2] are expected to contain underdense plasmas (a few millimeters in size) with electron temperatures (T_e) in the kiloelectronvolt range. Present NIF hohlraum designs rely on the plasma pressure from a helium-hydrogen gas fill to tamp intrusion into the hohlraum volume by the gold-wall plasma, while allowing laser propagation inside the hohlraum.[3] Thus, the longest scale lengths are expected to be within the low-*Z* helium-hydrogen plasma.

Because scientists lack a fundamental understanding of many aspects of laser-plasma instabilities, it is desirable to study these instabilities in plasma conditions that are as close as possible to those expected in NIF hohlraums. Radiation-hydrodynamic simulations of NIF hohlraums[4] with the LASNEX code[5] (an inertial confinement fusion [ICF] design code) indicate that a variety of plasma conditions will exist within the NIF hohlraum. Not all of these conditions can be studied. Both inspection and postprocessing of LASNEX simulations of NIF hohlraums[6] show that it is clearly worth considering the millimeter-scale plasmas, with low *Z*, $n_e / n_c \approx 0.1$, and $T_e \approx 3$–5 keV expected in NIF-hohlraum plasmas (n_e is the electron density and n_c is the critical density above which the laser's light cannot propagate). Present lasers cannot reproduce all of the required conditions simultaneously, but they can approach the conditions so that useful data can be obtained.

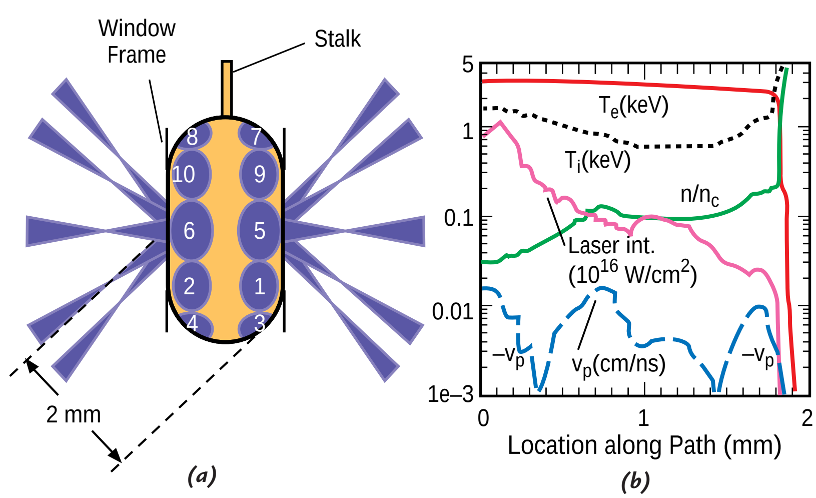

Fig. II-20. (a) An illustration of the gas-filled hohlraum. The footprints of the 10 Nova beams incident on the inner wall are indicated; those on the far wall have a dashed outline. (b) Calculated profiles within the hohlraum along a beam path (starting at the laser entrance hole) are plotted for a time of 1 ns.

Plasma Conditions

In this article we discuss the results obtained with toroidally shaped hohlraums,[7,8] which approach NIF conditions when illuminated with the Nova laser at Lawrence Livermore National Laboratory.[9] These targets were designed by X Division and fabricated by MST Division, and the experiments were fielded by P-Division scientists at Los Alamos. An illustration of the hohlraum is shown in Fig. II-20, reproduced from Fig. 1 of Ref. 7. It is cylindrically symmetric with a length of 1.6 mm and a diameter of 3.2 mm. All 10 laser beams operate at a wavelength of 351 nm. In the toroidal hohlraum we have used various gas fills, contained by thin, 0.3-μm-thick silicon nitride windows covering the laser entrance hole (LEH). Typical fills are low-Z gases such as C_5H_{12}, C_5D_{12}, CF_4, and $CF_4 + C_5H_{12}$ mixtures at 1 atm of pressure, designed to fully ionize to $n_e / n_c = 0.11$. They span the range $Z_{eff} = 2.5$–8. The calculated spatial profiles of n_e, T_e, T_i, and plasma-flow speed (v_p) along the direction of laser propagation ($\hat{k}_0$) for C_5H_{12} are also shown in Fig. II-20. For C_5H_{12}, $T_e = 3$ keV has been measured,[7,8] which is in agreement with LASNEX simulations. From Fig. II-20, the scale lengths for density, $L_n \equiv n_e / (\hat{k}_0 \cdot \nabla n_e)$, and velocity, $L_v \equiv c_s / (\hat{k}_0 \cdot \nabla v_p)$ are similar ($L_n \approx L_v \gtrsim 1$–2 mm). In the latter definition c_s is the ion-acoustic speed.

Laser-Plasma Instability

In the long-scale NIF plasmas, high levels of laser-plasma instability are predicted by linear convective theory.[10] Stimulated Raman scattering (SRS)[11] and stimulated Brillouin scattering (SBS),[12] in particular, could be significant. SRS and SBS involve scattering of laser light by electron-plasma (Langmuir) waves and ion-acoustic waves, respectively. From the initial noise level, these unstable waves would develop a growing amplitude in space. The backscattering direction is expected to have the highest spatial gain. The calculated gains from linear theory, even assuming smooth laser beams, are generally enormous (exp[25]–exp[30]) in plasmas such as ours,[6] and nonlinear saturation mechanisms are expected to occur. The high-energy glass-laser beams used for ICF are not spatially uniform. They have a broad distribution of intensities about the average value. Without any beam modification, these nonuniformities appear mostly as relatively large scale spatial fluctuations, with dimensions nonnegligible relative to the beam diameter.[13] Spatial smoothing can be accomplished with a binary random-phase plate (RPP),[14] which breaks the raw beam into smaller beamlets with a random 0 or π phase delay. RPPs produce a spatially "smooth" focal spot envelope with a superimposed fine-scale speckle (or "hot spot") pattern. The statistics of RPP hot spots are well known,[15] and it is clear that a significant fraction of the beam energy is tied up in hot spots. The known RPP hot-spot statistics allow better theoretical modeling of SBS and SRS in real plasmas, which recently has been successfully done by T-Division scientists.

SRS Onsets

We have verified that laser hot spots change the character of SBS and SRS instability onsets relative to theoretical predictions for smooth beams. With smooth beams, convective amplification of thermal density fluctuations would yield an SRS reflectivity that depends exponentially on laser intensity and L_n (≈ plasma size). But in the fluid model in Ref. 16, which is applicable to SBS and SRS in NIF conditions, instability gain on hot spots is computed including effects such as beam diffraction and pump depletion. Including diffraction is important because it can significantly decrease the spatial gain within a hot spot when the beam *f*-number is moderately small.[16,17] When the results are integrated over the RPP hot-spot distribution, the system becomes nonlinear and exhibits critical behavior. To understand the implications of the model in Ref. 16, one may consider a plasma with a sufficiently long L_n or L_v and a given seed or noise level of electrostatic waves (acoustic for SBS, Langmuir for SRS) that are sufficiently damped. We define the amount of laser light backscattered by such a seed in terms of its reflectivity R_{seed}. As the averaged intensity I of the beam envelope is increased starting from a value below the onset of instability, the laser reflectivity R sharply increases from R_{seed} once a critical intensity I_c is exceeded. The critical intensity is given approximately by the value of I, at which the linear convective gain ($R/R_{seed} = \exp[G]$) is approximately e^1 over the typical length of a hot spot, $l_{hs} \approx 7f^2\lambda$. This stands in contrast to the value $G = 2\pi$ of the gain exponent customarily taken as the threshold for significant convective instability. According to the model, even if we start with the minimum seed given by thermal density fluctuations (typically $R_{seed} \approx 10^{-8}$), once I increases moderately beyond I_c, then most hot spots undergo pump depletion (all the light is scattered) and R levels off.

We have investigated SRS onsets by varying I and measuring the SRS reflectivity from toroidal hohlraums filled with 1 atm of C_5H_{12}.[18] Figure II-21 shows the results. As with SBS, as I increases above a value I_c (about 10^{14} W/cm^2 in this case), the SRS reflectivity rises steeply and saturates at about 20%. Figure II-21 includes a fit to the data using the model in Ref. 16. The observed value of I_c for SRS is consistent with our best theoretical estimate.

The concept of a critical intensity for parametric instability seems to be fairly robust in long-scale plasmas. The critical intensity for SBS also has been measured both in the Nova toroidal hohlraums[7] and in Trident open plasmas.[20] The magnitude of I_c for SBS is predicted by the model in Ref. 16 to a reasonable approximation for a variety of plasma conditions.

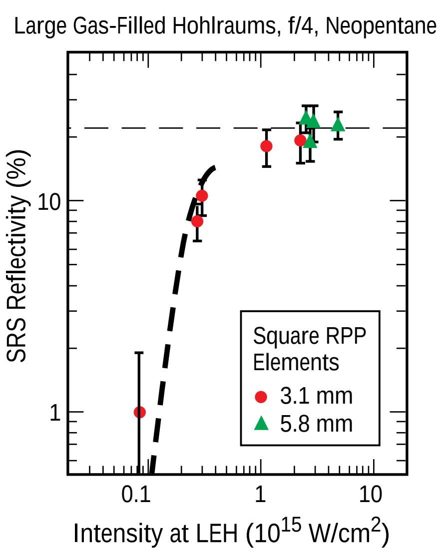

Fig. II-21. A plot of the SRS reflectivity into the interaction-beam cone, integrated over time, versus the interaction-beam intensity at the hohlraum laser entrance hole. The uncertainty in the beam intensity is approximately ±10% of its value.

SRS-Saturation Scaling

We have studied SRS saturation in the toroidal Nova hohlraums. For laser-intensity values similar to those in present NIF designs, it is observed that SRS is in a saturated state so that further increases in laser intensity do not yield a higher beam reflectivity. It is also observed that the SRS reflectivity depends on the damping rate of ion-acoustic waves (IAW), which is normalized to the real ion-acoustic frequency (ν_i/ω_i). Because SRS does not involve IAWs directly, this dependence may seem paradoxical. However, SRS can couple to other processes by further parametric decay of the SRS daughter electron-plasma wave, or SRS Langmuir wave (LW). The leading candidate is the Langmuir Decay Instability (LDI), in which the SRS LW further decays into an IAW and another LW,[22] as seen experimentally.[23] For a sufficiently strong laser drive, LDI daughter LWs themselves undergo LDI decay, creating so-called Langmuir turbulence. Langmuir turbulence is also relevant to ionospheric plasmas.

The dependence of SRS reflectivity on ν_i/ω_i has been studied with various gas fills in toroidal hohlraums, all at 1 atm of pressure and all designed to ionize to $n_e / n_c = 0.11$.[21] Both ν_i and ν_e are dominated by collisionless Landau damping for the plasma conditions of interest. In plasmas with multiple ion species, Landau damping of acoustic waves depends on the relative masses of the ions.[24,25] We have explored this fact, using the hohlraum gas fill, to vary ν_i/ω_i in our experiments. Again, C_5H_{12}, C_5D_{12}, CF_4, and $C_5H_{12} + CF_4$ low-Z gas fills are used.

The time-integrated SRS reflectivity data are shown in Fig. II-22. The data in this figure clearly show that as acoustic damping increases, SRS reflectivity increases. The laser intensity at the LEH is kept in the range of 2×10^{15} to 3.6×10^{15} W/cm^2. The observed scaling versus ν_i is consistent with the linear scaling predicted by a model of SRS saturation by Langmuir turbulence.[26]

SRS Images

It is very likely that SBS and SRS are spatially and temporally localized within the plasmas we study and do not have smooth, convective growth along the whole path of the laser beam within the plasma. In addition, it appears that SBS and SRS can mutually couple.[27–31] In order to resolve these issues, it is very desirable to image the scattered light in space and time and thus localize the SRS and SBS processes within the target. We have deployed two optical imaging instruments, the full-aperture-backscatter station imager (FABSI) and the axial imager at the Nova laser, to accomplish this task.[32,33]

In order to show the potential of SRS imaging as a density diagnostic, we show in Fig. II-23 an image of a conventional methane-filled, cylindrical Nova hohlraum using SRS light from the axial-imager diagnostic. We use the fact that the wavelength of SRS light depends on n_e. This type of hohlraum is used for studies of capsule illumination symmetry,[34] although this particular hohlraum has no capsule. The diagnostic was outfitted with a 550- to 650-nm band-pass filter, corresponding to n_e / n_c of 5%–15%. Out of the 2.2-ns pulse,

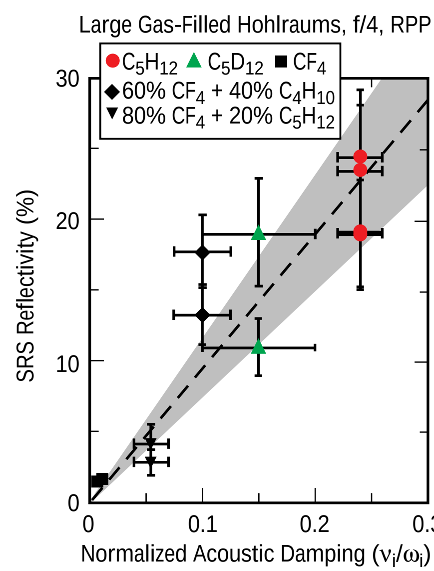

Fig. II-22. Raman backscatter reflectivities of the interaction beam for low-Z hohlraum gas fills. The least-squares linear fit (forced zero intercept) is shown. The shaded area shows the 95% confidence level for the fit.

the frame shown was gated for the 0.2- to 0.7-ns period. The image, when compared with the diagram on the bottom, shows that the LASNEX simulation predicts well the radial location of the 0.05-n_c density contour. However, although LASNEX correctly predicts a slight density buildup at the hohlraum axis, the observed density appears to be higher than the LASNEX prediction.

Summary

In summary, the speckled nature of laser beams used in ICF is an important factor in laser-plasma instability processes. For example, models that account for the laser speckles successfully predict the observed onsets of backscattering due to SBS and SRS. Linear convective theory predicts very large levels of SRS backscattering from the long-scale plasmas expected in ignition hohlraums. Our observations of SRS saturation are inconsistent with linear-theory scaling, but are qualitatively understood in terms of other processes. In particular, we have shown direct evidence for the dependence on acoustic damping of the SRS reflectivity. Since SRS itself is unrelated to acoustic waves, this dependence is evidence of other parametric processes determining the nonlinear saturation of Raman backscatter. We have great expectations from optical imaging diagnostics recently deployed at Nova. They could help elucidate important outstanding questions relating to SBS and SRS nonlinear saturation and could also prove to be a valuable density diagnostic.

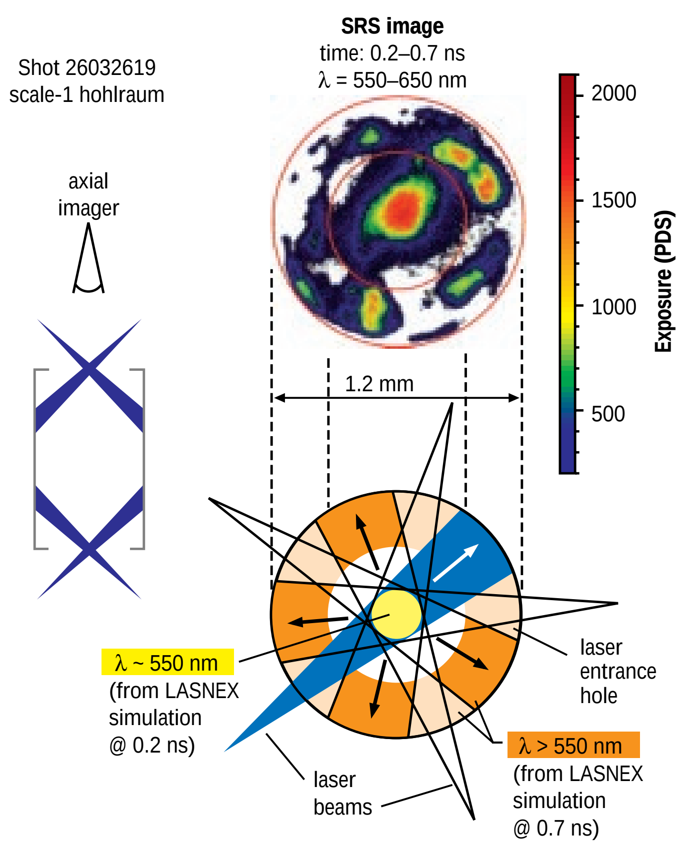

Fig. II-23. An image of the Raman scatter from a methane-filled scale-1 Nova hohlraum. The diagram on the left shows a side view of the hohlraum illumination geometry and the imager line of sight. The diagram on the bottom shows the hohlraum view from the imager location.

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Planar, Ablative Rayleigh-Taylor Instability Growth in Copper Foils Driven by Nova Hohlraum Radiation

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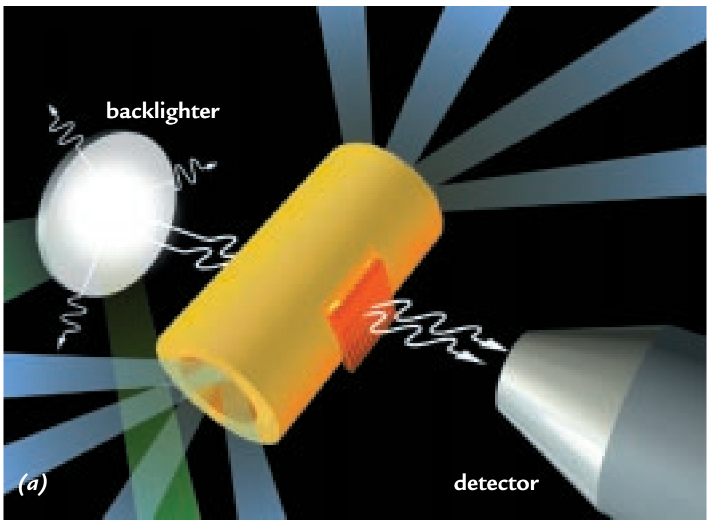
The Rayleigh-Taylor (R-T) instability is an instability of the interface between two materials when a lighter material pushes on and accelerates a heavier material. This situation can occur in implosions of inertial confinement fusion (ICF) capsules as well as in stellar dynamics in astrophysics. Of particular interest is the ablative R-T instability, in which the lower-density ablated material accelerates the bulk material through a rocket effect. The theory for this case was worked out some time ago, leading to an exponential growth rate γ for a perturbation in the ablation surface. This rate depends on the wave number of the perturbation, the scale length of the density gradient across the ablation front, the acceleration of the interface, and the mass-ablation rate. The instability growth rate for the ablatively driven acceleration is less than the classical growth rate (without ablation) under otherwise identical conditions. This reduced rate of instability growth is referred to as ablative stabilization.



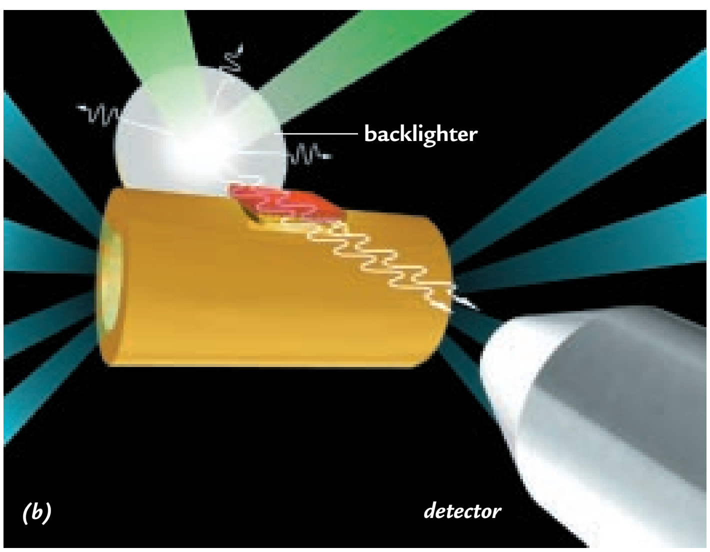


Fig. II-24. The experimental layout for (a) face-on radiography and (b) edge-on shadowgraphy, showing the eight Nova drive beams in blue, the two backlighter beams in green, the hohlraum in gold, the copper foil in red, and the x-rays that are emitted from the backlighter.

The purpose of our research is to experimentally explore the ablative R-T instability in a high-density material and obtain results that can be modeled by various laboratory codes, thus benchmarking these codes with real experiments. The R-T experiments were performed at the Nova laser at Lawrence Livermore National Laboratory. The material that we investigated was copper, and the ablative drive was the ~180-eV radiation density generated in a scale-1 hohlraum. Two distinct experimental configurations were used: one with face-on radiography to measure perturbation growth, the other with edge-on shadowgraphy imaging of the growth. Both configurations used 6.7-keV x-rays. The two layouts are shown in Fig. II-24, and they are described in detail below.

Eight of the ten Nova laser beams (each with a wavelength of 0.351 μm [3ω], a pulse length of 2.2 ns, and an energy of about 3 kJ) were focused into the cylindrical hohlraum to generate the radiation drive of about 180 eV. The other two beams (each with a wavelength of 0.527 μm [2ω], a pulse length of 2–4 ns, and an energy of 3–4 kJ) were passed through random-phase plates to produce fairly smooth focal spots with diameters of about 500 μm on a 2-mm-diameter, 18-μm-thick iron disk. These beams generated 6- to 8-keV helium-like iron lines. This iron backlighter was used for both radiography and shadowgraphy. X-ray imaging devices were filtered with a 0.5-mil, cold-iron foil to remove the higher-energy lines and leave only the $1s^2$-$1s2p$ He$_\alpha$ line at 6.7 keV.

The hohlraums were standard scale-1 gold cylinders that were 2750 µm long and 1600 µm in diameter, with a 25-µm wall thickness and 75%-open end caps for laser-beam entrance holes. The copper targets were mounted over a hole in a slightly flattened region of the cylinder. For face-on radiography, a second hole in the cylinder diametrically across from the target let the backlighter radiation traverse the hohlraum and the target. The target was an 18-µm-thick flat copper foil with 45- or 80-µm-wavelength, 0.5-µm-amplitude sinusoidal corrugations milled on one side. A 600-µm × 600-µm square with the corrugations facing inward was mounted across the opening in the hohlraum.

For face-on radiography (Fig. II-24a), the target was imaged with a gated x-ray imager (GXI) along a line of sight that was normal to the target and that continued through the target and hohlraum to the center of the iron backlighter disk behind the hohlraum. The GXI produced 16 pinhole images in groups of four. Within a group, the images were separated by about 60 ps, and the time separation between groups was adjustable. The temporal resolution of the GXI was about 100 ps; the growth indicated in each image was averaged over that time. Each image then recorded the transmission of the 6.7-keV backlighter x-rays through the foil. The growth of the periodic perturbation caused by the R-T instability in the foil was mapped onto a periodic contrast variation in the GXI image, as shown in Fig. II-25. Also shown in Fig. II-25 is a line-out across the contrast corrugations. The oscillations at the fundamental wavelength and the appearance of a second harmonic are superimposed on the shape of the backlighter image.

The line-out for each image was analyzed, and the temporal development of the foil perturbation growth was reconstructed. The three major steps in this analysis are the subtraction of the backlighter image, Fourier analysis of the periodic perturbations, and correction of the Fourier components for the spatial resolution of the instrument. The amplitudes of the corrected Fourier

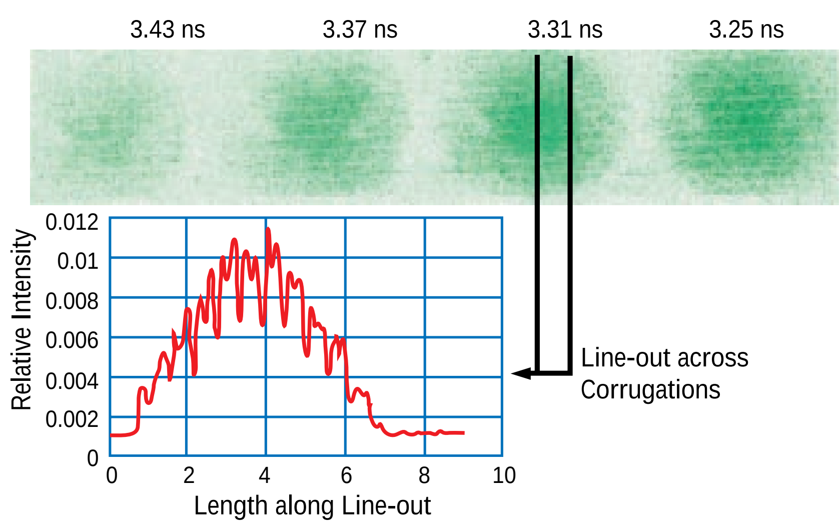
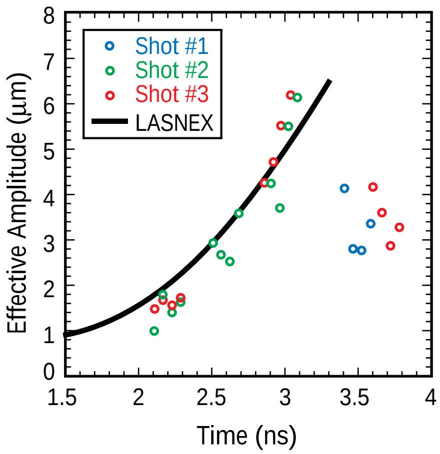
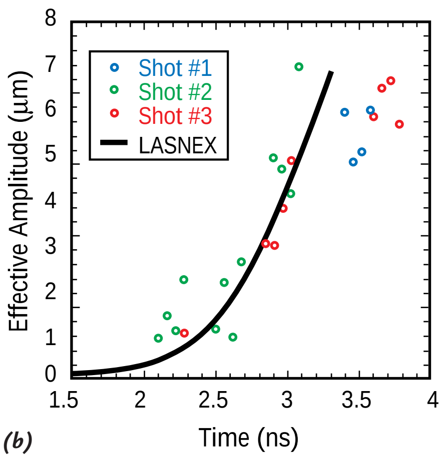


Fig. II-25. A time sequence of radiographs from a gated x-ray imager.



(a)



(b)

Fig. II-26. (a) The growth of the fundamental wavelength for the 45-µm corrugation. (b) The growth of the second harmonic for the 45-µm corrugation. The colors of the data points correspond to three different shots.

components reflect the growth of the contrast, that is, the integral of $\kappa\rho(x)dx$ through the foil, where κ is the absorption coefficient of cold copper at 6.7 keV and ρ is the density. Although the copper was heated, the absorption at 6.7 keV is nearly the same as that for cold copper. Dividing the contrast amplitude by the cold-copper absorption coefficient gives an effective spatial amplitude based on cold, normal-density copper.

Figure II-26 shows this amplitude as a function of time for the 45-µm-wavelength perturbation and its second harmonic at 22.5 µm, respectively. The initial 0.5-µm amplitude of the fundamental wavelength is too small to give an observable contrast, and the second harmonic starts from zero amplitude since it was not initially present in the foil. The data for the fundamental wavelength show an initial exponential growth followed by an abrupt drop. This sharp drop is not fully understood. One would expect a gradual saturation of the amplitude followed by a decrease of all the harmonic amplitudes as the bubble-and-spike plasmas homogenize. Because the scatter in the data indicates fairly large error bars, the data could be consistent with a gradual saturation followed by a gradual drop.

Also shown in Fig. II-26 is a planar, two-dimensional LASNEX calculation (a calculation using an ICF design code) of the R-T growth using the Nova hohlraum drive. Considering the scatter of the data, the agreement is quite good for the earlier times. For later times, the calculation runs into numerical problems, which are being addressed. Results for the 80-µm corrugation foils showed slower growth and poorer agreement with our simulations. A shortcoming of this technique is that the contrast modulation in the GXI image does not directly reflect the spatial development of the perturbation in the foil but only the integral through the material. The bubble-and-spike formation in the later stages of R-T growth is observed indirectly as the appearance and growth of the second harmonic and, presumably, as higher harmonics if the instrument spatial resolution is sufficient. To observe this aspect of the R-T instability, we imaged the R-T growth in an edge-on configuration (Fig. II-24b).

The target was again mounted across an opening in the slightly flattened side of the hohlraum, offset with two 50-µm spacers. The line of sight was edge-on, down the length of the corrugations onto the center of the backlighter disk, which was also visible between the two spacers and the hohlraum and target. Two imaging techniques were used in this configuration. A GXI was used to image the growth of the corrugations directly edge-on. The bubble-and-spike formation at about 3.6 ns in an 80-µm-wavelength corrugated foil is shown in Fig. II-27. The bright region in the lower half of the image is the direct view of the backlighter disk. The shadow of a 25-μm-diameter, gold-wire fiducial is seen in the lower right. The shadow of the lower edge of the copper foil and the spikes toward the top are clearly visible. In this case, the 6.7-keV backlighter x-rays propagated down the 600-μm-long channels of bubbles and spikes, resulting in the dark spikes and lighter bubbles. The light stripe near the top of the image is a view of the backlighter through the 50-μm offset between the foil and the hohlraum. We suspect that the dark region above the bubble-spike region and below the offset is foil plasma from the edges of the foil that were left behind in the drive because the foil was somewhat larger than the opening in the hohlraum. We plan to repeat these shots with foils mounted such that the front and back edges are well inside the opening.

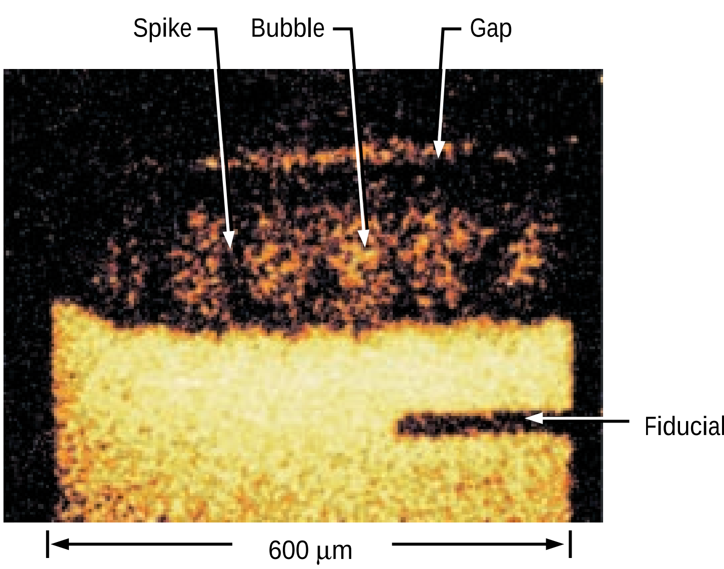


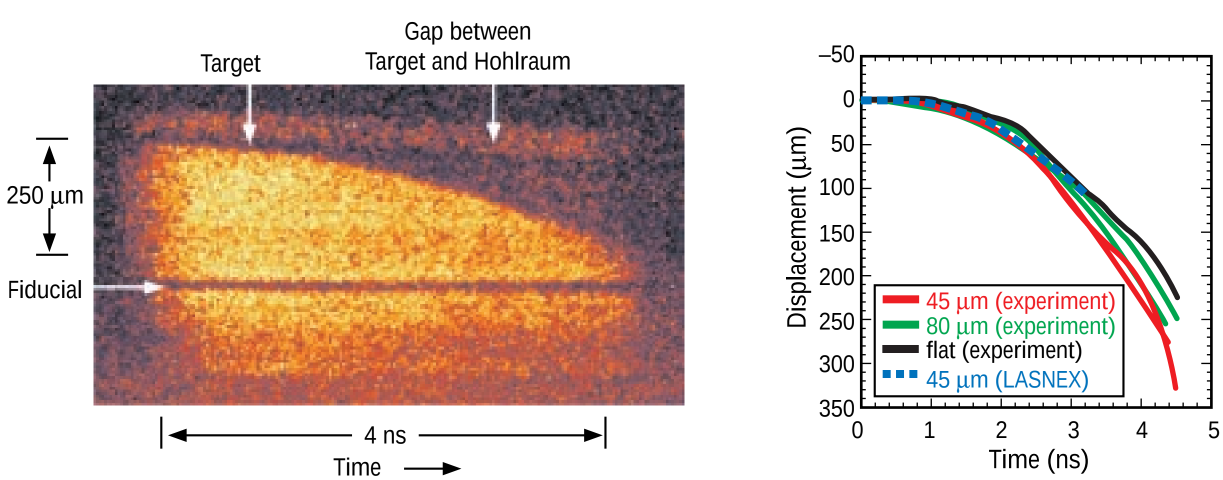
Fig. II-27. A side-on image of the bubbles and spikes.

The GXI images at various time steps can be analyzed to determine the net motion of the foil away from the hohlraum. A more precise measurement of the motion can be made with a streak camera. There is, however, a difference. The GXI image is in two dimensions, whereas the streak camera images only one. Figure II-28a shows a typical streak of the motion of a 45-µm-wavelength corrugation foil. The bright portion of the streak image is the direct view of the backlighter, showing the shadow of a fixed fiducial across the lower half of the image. The upper half shows the near-parabolic path of the back of the foil and the expanding copper plasma with the spikes and bubbles above it. Across the top in the image is the view to the backlighter through the 50-µm offset between the hohlraum and target. Figure II-28b shows the trajectories for a flat foil, for two foils with 45-µm corrugation wavelengths, and for two foils with 80-µm corrugation wavelengths. Also shown is a LASNEX calculation for a foil with a 45-µm corrugation wavelength. The agreement is quite good. There seems to be no dependence of the foil trajectory on the corrugation wavelength within the error of the measurements, considering that the time origin for the five shots is within ±100 ps, consistent with the limitations of the Nova electrical-trigger system.

The experiments discussed above are part of a laser-based, above-ground experiments (AGEX) program to study hydrodynamic instabilities. The preliminary experimental results presented are in reasonable agreement with modeling. However, better diagnostics (better in both spatial and temporal resolution), more accurate techniques for deconvolving the instrument function, and simulations that cover the whole temporal range of the experiment are required to benchmark a calculation in detail. This work is in progress.

The authors would like to thank the P-24 Nova technicians, the MST target-fabrication staff, and the Nova operations staff for their contributions to these experiments.

Fig. II-28. (a) The steaked motion of the back of the 45-µm corrugated target. (b) The streaked motion of the back of a flat foil and the backs of foils with 45- and 80-µm corrugation wavelengths. Also included is the LASNEX simulation for a foil with a 45-µm corrugation wavelength.



(a) ***(b)***

Penning Fusion Experiment

M. M. Schauer, T. B. Mitchell (P-24), D. C. Barnes (XCM)

For over forty years, physicists have pursued the goal of a fusion energy device. Work toward this goal has concentrated on devices that attempt to heat and store neutral plasmas, such as gases consisting of positive ions and electrons in equal or almost equal numbers. These devices have reached impressive temperatures and densities, but the confinement times have left much to be desired because neutral plasmas are prone to instabilities.

At the other end of the spectrum are Penning and Paul traps, which store nonneutral plasmas consisting of pure clouds of electrons, positive ions, or negative ions. These devices have achieved virtually infinite confinement times, but the densities of the stored plasmas have been limited by the Coulomb repulsion between the constituent particles. The limiting value of the density attainable is known as the Brillouin limit. The Penning Fusion Experiment (PFX) seeks to circumvent this limitation in a small electron Penning trap.

In their simplest form, Penning traps are composed of a ring electrode and two end caps (Fig. II-29). If the ring electrode is biased positively with respect to the end caps, the potential inside the trap is a saddle potential that provides confinement for electrons along the trap axis. Obviously, the electrons are not confined radially by the electrostatic potential; they are instead prevented from escaping radially by a magnetic field that is applied parallel to the trap axis. An electron confined by these fields will execute an axial oscillation in the electrostatic well and a cyclotron orbit about the magnetic-field lines. Additionally, the electric and magnetic fields will give rise to an $E \times B$ drift of the center of the cyclotron orbit about the trap axis.

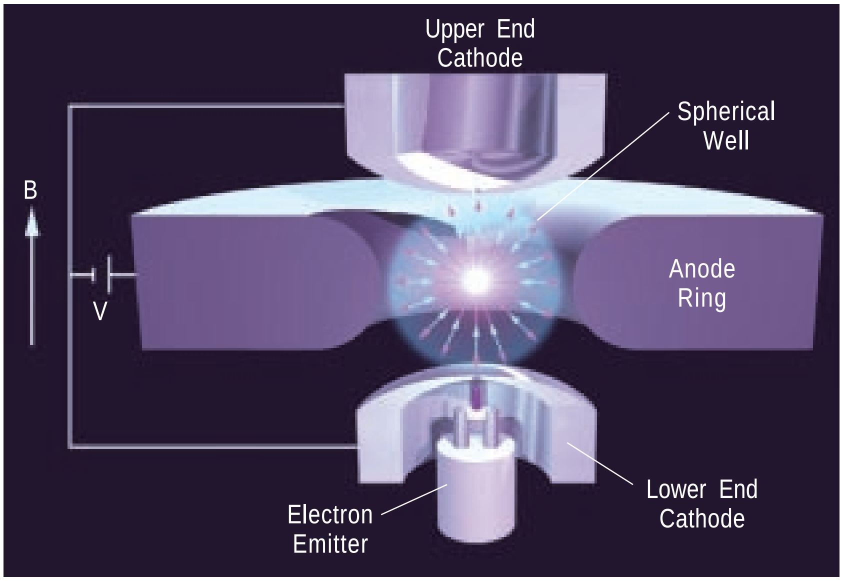


Fig. II-29. Schematic representation of the Penning trap showing the effective spherical well boundary and the reflected electron trajectories.

PFX uses these oscillations to produce a high-density plasma at the center of the trap. This is accomplished by introducing a low-energy, low-divergence electron beam from a LaB_6-crystal electron emitter through a 400-μm-diameter hole in the lower end cap and reflecting it by means of a small, negative voltage applied to the upper end cap. In the absence of scattering, an electron in the beam will simply return to the emitter or to the lower end cap and be lost from the trap. If, however, some of the electron's energy is scattered from its axial motion into its radial degrees of freedom, the electron will remain confined in the axial well and will execute a combination of the oscillations described above.

For a proper choice of trapping potential and applied magnetic field, the period of an electron's axial motion will be twice the period of its radial motion, and any orbit originating at the center of the trap will be constrained to pass through the center again. A collection of electrons that all follow such orbits will produce a dense, "focused" plasma. An alternate picture is that the combined electric and magnetic fields provide an effective well that is spherical for the proper choices of the field strengths. Then, any trajectory originating at the trap center will be reflected back on itself by the spherical wall of the well. This situation is shown schematically in Fig. II-29.

It is important to note that the electrons executing these orbits have zero (or near-zero) angular momentum. To preserve this beam-like state, it is essential that scattering occur mostly at or near the trap center. Excessive numbers of collisions away from the center will result in a more-or-less uniform electron cloud that will effectively wash out the focus. To minimize this thermalizing scatter, we operate PFX at liquid-helium temperature, thereby assuring an extremely low background pressure ($<10^{-10}$ torr). Intrabeam scattering does occur throughout the electron-beam volume but, because of the narrow energy distribution of the beam electrons, proceeds at a sufficiently slow pace to allow focusing effects to dominate the thermal background that is generated. In fact, as we explain later, a small amount of intrabeam scattering is desirable.

In order to maximize the density attained, it is desirable to use high electric-field strengths. Hence, the trap must be designed to hold high ring voltages. The present trap, through judicious choice of materials and the excellent vacuum achieved in the cryogenic environment, is capable of holding up to 30 kV across the 1.5-mm gap between the ring and the end caps. Addition of the magnetic field significantly degrades the voltage standoff so that the actual operation is limited to voltages below 10 kV. Figure II-30 is a picture of the trap assembly, which consists of titanium electrodes and precision ceramic spacers.

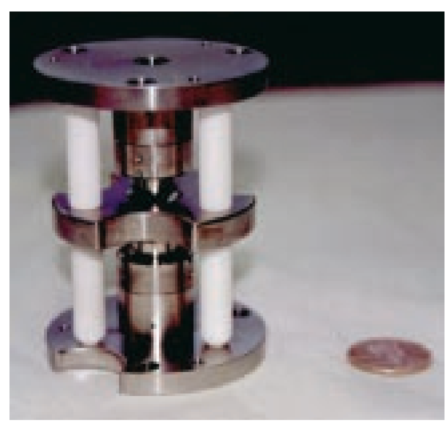


Fig. II-30. The trap used in these experiments. The spacing between the titanium end-cap electrodes is 6 mm and is maintained to within 5 μm by high-precision, polished alumina spacers. The inner diameter of the ring electrode is also 6 mm.

PFX has been operating for almost two years and has conclusively demonstrated the formation of a density focus. The hallmark of this focus is scattering of the injected electron current to the ring electrode. As is evident from Fig. II-29, the electron orbits in the focused, spherical state extend all the way to the ring and thus allow electron current to flow from the beam to the ring. Figure II-31a shows a plot of the current flowing to the ring for a fixed magnetic field as the ring voltage is increased. The sharp peak occurs at the voltage at which a focused state is expected to exist for the given magnetic field.

Current to the anode is shown for two different values of the electron current that is injected through the hole in the lower end cap. For the lower injection current, essentially no current flows to the anode, while at the higher current, a full 20% of the injected current is deflected to the ring. An interesting indication of the mechanism by which the focus establishes itself appears when one examines more closely the relation between the injected current and that current flowing to the anode ring. This data is shown in Fig. II-31b for a fixed magnetic field and anode voltage. The blue curve is for increasing injection current, while the red curve is for decreasing injection current.

The hysteresis is an indication of the role played by thermal electrons. These electrons are scattered out of the injected beam by the intrabeam scattering mentioned earlier and form a uniform (that is, unfocused) thermal population that coalesces to the trap center and remains there for several seconds. An equilibrium is established between scattering into and loss out of the trap, so the density of this population is related to the magnitude of the injected current. At some threshold value, the space charge of the thermal plasma becomes large enough to significantly deflect the injected electrons, thereby forming a density focus as described above. Once established, the focus maintains itself by virtue of its own space charge disintegrating only when the replenishment rate falls below a critical value. This critical value is represented by the lower threshold of the red curve.

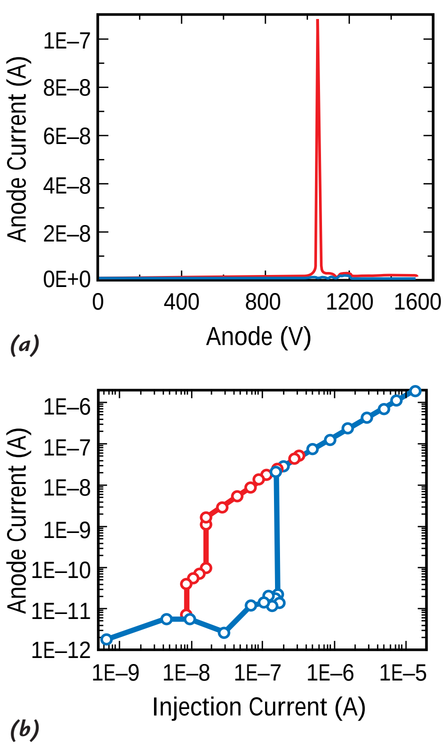


Fig. II-31. (a) The total electron current flowing to the anode ring plotted as a function of the voltage for a fixed magnetic field with two different values of the current injected into the trap. (b) The total electron current flowing to the anode at a fixed "spherical" point as a function of the total current injected into the trap.

Although the attained density has not been directly measured, a numerical calculation of the density has been performed based on PFX data and physical parameters. The results of these calculations are shown in Fig. II-32. The calculation shows a plasma core of peak density approximately 35 times the Brillouin limit with a radius of roughly 20 μm. This calculation is consistent with core sizes inferred from the widths of resonance peaks in various scattering diagnostics. Also shown in Fig. II-32 is the potential in the trap volume, including the space-charge potential of the electron plasma.

Figure II-32 provides the impetus for much of the future work planned for PFX. One can imagine introducing neutral atoms into the trap volume that will be ionized and accelerated by collisions with plasma electrons. The space charge of the electron plasma will confine some of the ions thus produced and will result, it is hoped, in a high-density, thermonuclear plasma. We are presently working on such a gas-introduction capability.

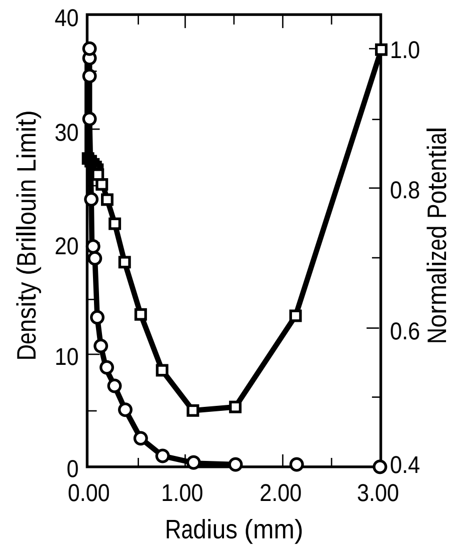


Fig. II-32. The calculated electron density in the trap volume (circles) plotted as a function of the radius, which is normalized to the Brillouin limit. Also shown is the sum of the vacuum potential and the electron plasma space charge (squares), which is normalized to the vacuum potential at the trap wall.

Enhanced Radio-Frequency Field Penetration in an Inductively Coupled Plasma

M. Tuszewski (P-24)

The multibillion-dollar semiconductor industry uses plasma processing to produce various components, including multiple wafers, multichip modules, and flat panel displays. Always searching for methods that will increase yield and throughput and that, at the same time, will allow them to make smaller components, semiconductor manufacturers are focusing much effort on developing uniform, high-density, large-area plasmas that will help them optimize techniques such as sputtering, etching, and ion implantation and deposition. As part of this effort, Los Alamos has worked with Novellus Systems, a leading U.S. manufacturer of semiconductor process equipment, to develop and study a low-frequency, inductively coupled plasma (ICP) source for producing semiconductor devices with 0.25-µm geometries.

ICPs consist of a dielectric chamber surrounded by a conducting coil. Radio-frequency (rf) power is continuously applied to the coil and induces electric fields that partially ionize a gas inside the chamber and sustain a discharge. Most of the rf power is absorbed by the plasma; understanding this absorption is necessary for describing ICP heating and transport properties, which are important factors in predicting whether a plasma is radially uniform. Present models that consider induced rf electric fields (but not magnetic fields) predict that the rf power transfers to plasma electrons within a thin skin layer near the plasma surface. For typical rf frequencies of 0.1–13.56 MHz, the skin depths δ are a few centimeters, whereas the device dimensions are 10–30 cm.

During our work with Novellus, we obtained data that contradicted the current models by indicating deep rf penetration into argon ICP discharges with small skin depths. Because such deep penetrations are needed in semiconductor manufacturing processes,

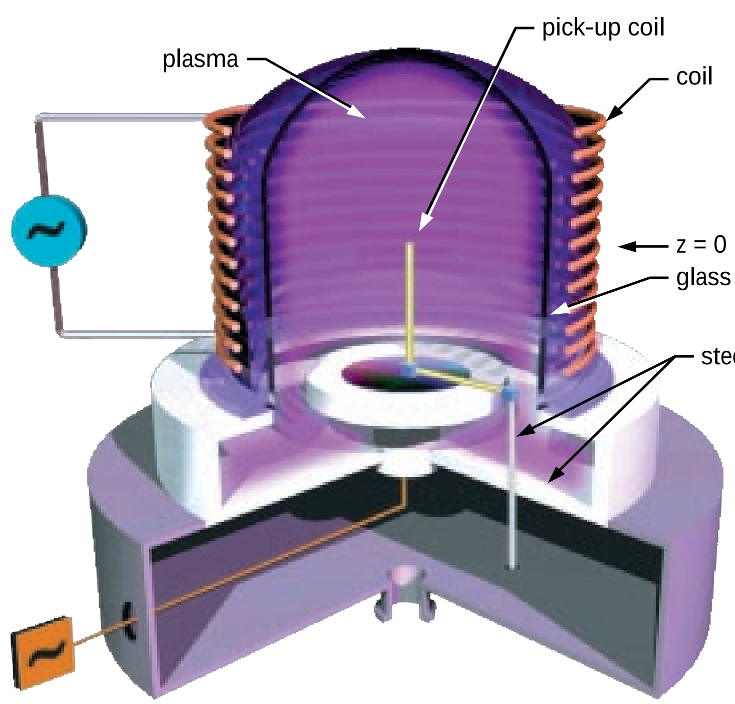


Fig. II-33. Sketch of the inductively coupled plasma.

this enhanced rf field penetration—previously unknown to the semiconductor manufacturers—was an important breakthrough. We realized that we would have to invoke a new mechanism to explain the enhanced penetration. Fluid calculations suggested that this mechanism is a reduction of the plasma conductivity by the induced rf magnetic fields when the electron cyclotron angular frequency ω_c exceeds both the rf angular frequency ω and the electron-neutral collision frequency ν, a condition that is satisfied for many low-pressure ICPs. Hence, the induced rf magnetic fields must be included in ICP models to predict electron heating and the resulting plasma transport.

To test this mechanism experimentally, we measured the induced rf magnetic fields inside a cylindrical ICP, which is sketched in Fig. II-33. A 13-turn copper coil was wound around a glass bell jar with an inner radius of 16.5 cm, and the coil was powered by a 2-kW, 0.46-MHz (ω = 2.9 megacycle) rf generator. A small pick-up coil (with 18 turns, a diameter of 4 mm, and a length of 5 mm) with shielded, twisted leads was inserted near the closed end of a 6-mm-diameter ceramic tubing, which was connected to a stainless-steel shaft via ceramic transition pieces. We oriented the pick-up coil to measure the z (upward) component of the induced rf magnetic field, and we obtained radial scans in the coil midplane (z = 0) by rotating the steel shaft.

Argon discharges were sustained with gas pressures of 5–50 mtorr and with rf powers of 0.5–1.5 kW. We obtained radial profiles of the ion density (Fig. II-34) and estimates of the electron temperatures T_e from a voltage-swept, cylindrical Langmuir probe. For the discharges of Fig. II-34, the T_e profiles are radially uniform, and the electron energy distributions are almost Maxwellian. We also calculated the collision frequency to within 10% of the collision frequencies used in other ICP experiments and models. Our measured magnitudes $|B|$ of the induced rf magnetic field B_z are shown with symbols in Fig. II-35 for 5-mtorr argon discharges. The $|B|$ profiles are quite flat near the wall and change curvature at smaller radii. The magnitudes of B and of the coil azimuthal electric field E_c increase with rf power.

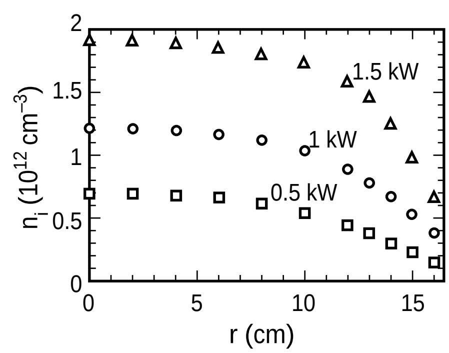


Fig. II-34. Measured radial profiles of the ion density for argon discharges with 5-mtorr gas pressure and with 0.5-, 1-, and 1.5-kW rf power.

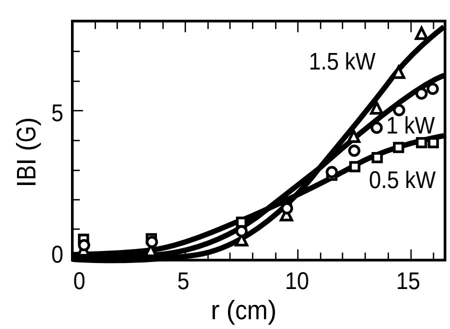


Fig. II-35. Radial profiles of the rf magnetic-field amplitude for 5-mtorr argon discharges. The measured data are indicated with symbols, and the magnetized calculations are shown with solid lines.

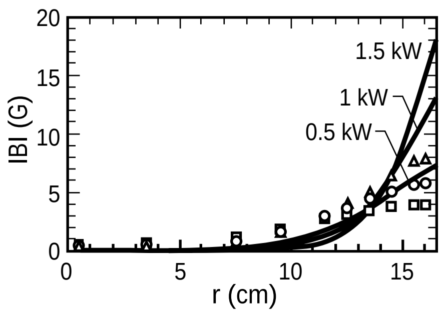


Fig. II-36. Radial profiles of the rf magnetic-field amplitude for 5-mtorr argon discharges. The measured data are indicated with symbols, and the unmagnetized calculations are shown with solid lines.

We first compared our magnetic-field data with the predictions from existing models by using a fluid approach to describe the ICP discharges. For simplicity, we used a one-dimensional model with $B = B_z(r)$, where r is the radius of the ICP. Combining Faraday's, Ohm's, and Ampere's laws, we obtained the following expression:

$$(1/r)(d/dr)(r/\sigma)(dB/dr) = i\omega\mu_0 B \ , \qquad (1)$$

where $\sigma = ne^2/[m(\nu + i\omega)]$ is the plasma conductivity, n is the plasma ion density, m is the electron mass, and μ_0 is the permeability of free space. We solved this equation with the density profiles of Fig. II-34.

The calculated radial $|B|$ profiles are shown in Fig. II-36 with solid curves, and the experimental data are also shown with symbols for comparison. The calculated $|B|$ magnitudes and decays are overestimated by factors of 2–3. In addition, the exponential-like calculated profiles do not reproduce the change of curvature observed near the wall. The uncertainties in the calculated penetration depths δ_c are estimated to be about 40%, but these uncertainties do not explain the above discrepancies. Clearly, a better model is required.

Previously, when we had calculated σ, we had neglected a magnetic term that introduces a nonlinearity into the electron momentum equation from which σ is derived. After including this magnetic term, we were able to define the following effective conductivity $\langle\sigma\rangle$ that is time averaged over an rf period:

$$\langle\sigma\rangle = \sigma_0/(1 + |\omega_c|^2/\nu^2)^{1/2} - i\sigma_0(\omega/\nu)/(1 + |\omega_c|^2/\nu^2)^{3/2} \ , \qquad (2)$$

where $\sigma_0 = ne^2/(m\nu)$ is the zero-frequency collisional conductivity. Replacing σ with the value of $\langle\sigma\rangle$, we solved Eq. 1 again. The calculated $|B|$ profiles are shown in Fig. II-35 with solid curves. The calculated and observed $|B|$ magnitudes agree within 5% near the wall, and the calculations also reproduce the shape of the observed profiles. The edge flattening and the change in the profile curvature are due to low edge plasma conductivities $\langle\sigma\rangle$.

We also measured the $|B|$ profiles for argon discharges with higher gas pressures of 10–50 mtorr. The magnetized calculation agrees with the data for all pressures, and the discrepancy between the unmagnetized calculation and the data gradually diminishes as the gas pressure increases. The experimental data and both calculations coincide within the uncertainties for 40- and 50-mtorr discharges. This agreement is expected since $\langle\sigma\rangle \approx \sigma$ in high-pressure discharges for which ν exceeds $|\omega_c|$ through most of the plasma volume. The agreement between the data and the calculations also implies that the combined experimental uncertainties are less than a factor of 2.

In addition to studying argon discharges, we also measured and calculated the $|B|$ profiles of oxygen discharges, which are more representative of industrial ICPs. These oxygen discharges yield results that are qualitatively similar to those for argon, except that the rf penetration depths are larger by factors of 2–3 because the oxygen discharges have lower plasma densities. The rf magnetic fields of the oxygen discharges are 1–3 G on the axis. Hence, the plasma conductivity is substantially reduced by the rf magnetic field at all radii.

Although we did not experimentally investigate cases with $|\omega_c| > \omega > \nu$, numerical averages of σ over an rf period suggest that Eq. 2 remains a good approximation whenever $|\omega_c|$ is greater than ω and ν, regardless of the relative magnitudes of ω and ν. Hence, the ICP rf-power absorption depends on the largest of ω, ν, $|\omega_c|$, and the effective stochastic frequency ν_s. The regime where $|\omega_c|$ is the largest has been overlooked until now. Because the induced rf magnetic fields are only 3–10 G for typical rf powers (seemingly negligible), they are usually neglected in ICP models. However, the corresponding values of $|\omega_c| \approx (50–180) \times 10^6$ rad/s are often larger than typical values of $\nu \approx (5–20) \times 10^6$ s^{-1} and $\omega \approx (1–85) \times 10^6$ rad/s. As a result, the rf penetration depths δ are often substantially increased by the rf magnetic field, and the ohmic heating-power densities ($\sim 1/\delta^2$) can be reduced by an order of magnitude.

In summary, the induced rf magnetic fields of a low-frequency ICP show substantial penetration, whereas existing models predict absorption in a thin skin layer. Fluid calculations resolve this apparent contradiction: the induced rf magnetic fields appreciably reduce the plasma conductivity, which leads to a larger rf penetration. The rf magnetic fields can significantly modify the electron heating and the resulting plasma transport in many of today's low-pressure ICPs, and they should therefore be included in future ICP models.

MEGA: Search for the Rare Decay $\mu^+ \to e^+\gamma$

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Searching for rare decays like $\mu^+ \to e^+\gamma$ is a sensitive method to discover physics beyond the standard model of electroweak interactions because this model predicts their rates to be zero or immeasurably small. Even though no such transitions have been observed, most physicists believe that the standard model must be imbedded in a larger theory because of the number of unexplained constants it contains. Nearly all of the candidates for the larger theory predict rare decays to proceed at rates close to the current limits.

For a rare decay to be seen at a measurable rate, the process must be mediated by a new particle that is virtually exchanged between leptons and/or quarks. The structure of the electroweak theory is simpler if the mass scale for these new particles is below 1 TeV. The current experiments that are searching for rare decays are sensitive in the mass range between 50 GeV and 1 TeV, spanning the gap between direct production experiments and the 1-TeV scale. The possibilities for a discovery of great importance are nonnegligible. In the past two years, there has been intense speculation over one particular theory, supersymmetry. Supersymmetry postulates matching all of the known particles of spin ½ or 1 with superpartners that have either spin 1 or ½, respectively. These new particles can mediate the process $\mu^+ \to e^+\gamma$ and induce rates within the sensitivity range of the MEGA (muon decays to an electron and a gamma ray) experiment. These models predict that $\mu^+ \to e^+\gamma$ will be the largest rare decay. Supersymmetry can also be a low-energy reduction of a grand-unified theory, in which case the rates are felt to be large because of the high mass of the newly discovered top quark. If one samples supersymmetric models, the MEGA experiment spans about half of the potential parameter space with its branching-ratio sensitivity (90% confidence) down to 10^{-12}; the current limit is 5×10^{-11}.

The MEGA apparatus was described in the 1994 Physics Division progress report (M. D. Cooper et al., "MEGA: Search for the Rare Decay $\mu^+ \to e^+\gamma$," in "Physics Division Progress Report, January 1, 1994–December 31, 1994," G. Y. Hollen and G. T. Schappert, Eds., Los Alamos National Laboratory report LA-13048-PR [November 1995], p. 76). Only a brief recap will be repeated here. MEGA took advantage of the intense beams of the surface muons available at LAMPF (a 20-MHz average stop rate was used). The detector was contained in a large, warm-bore solenoid (1.5 T, 1.85 m$\varphi \times$ 2.9 m long) and consisted of two arms (Fig. II-37). The first, a set of special, cylindrical, proportional chambers, measured the kinematic properties of the decay electrons, and the other, the world's largest pair spectrometers, determined the same quantities for the photon. All of the charged particles arising from muon decay were confined by the magnetic field to the positron elements, leaving the photon counters in a relatively quiet environment. The MEGA collaboration, currently consisting of six university groups and two national laboratories, completed taking its data at the end of 1995. An intense analysis effort was begun to extract viable candidates from the stored events.

There are 4.5×10^8 events stored on tape from the three data runs that occurred during 1993–1995. These events are the remains of roughly 1.5×10^{14} muons that decayed in the detector during its 1.1×10^7 live seconds. Highly improbable events have been discarded in the hardware and software during the acquisition. The signature for $\mu^+ \rightarrow e^+\gamma$ is a 52.8-MeV photon and a 52.8-MeV electron that are back to back, from a common vertex, and in time coincidence, and the excellent resolution of the spectrometers at high rates allows the potential signal to be separated from the background. To establish which events might fit this description, sophisticated software is being used to reconstruct and sort the events.

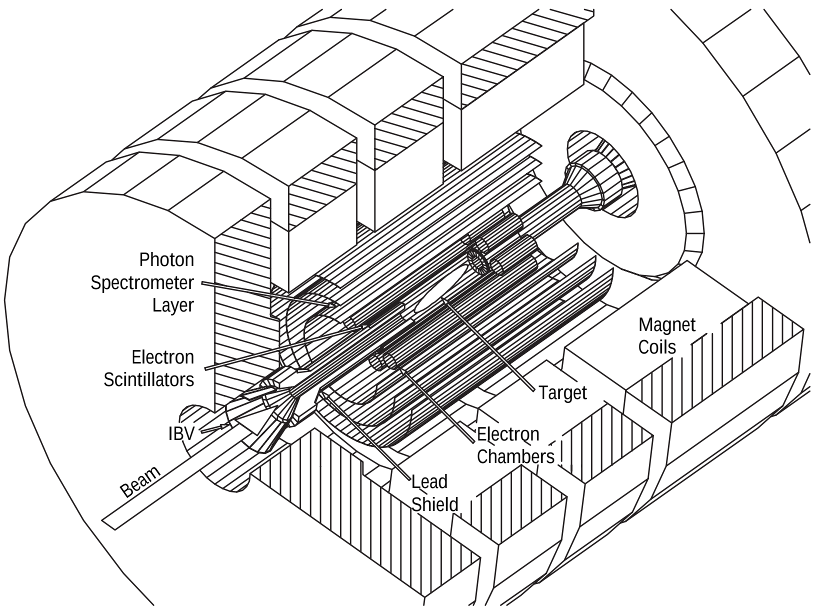

Fig. II-37. A simplified cutaway view of the MEGA apparatus. The detector is mounted inside a superconducting solenoid with a 1.5-T field. The muons enter along the magnetic field and stop in the target. Positrons from muon decays are detected in the eight cylindrical wire chambers and in the cylindrical arrays of scintillators surrounding the beam pipes. The three large cylinders are pair spectrometers for photon detection.

Four pieces of information are needed to measure a branching ratio. First, the energy, time, and geometrical scales of the detector must be calibrated so that the location of the signal is established. Second, the response functions of the detector elements must be determined so that the range of event properties (for example, the energies, times, and angles) for probable events is given by the resolutions. Third, the number of viable candidates, running anywhere from 0 to 100 in our sensitivity range, must be found. Last, the number of muon decays for which the detector was fully efficient $\mu^+ \rightarrow e^+\gamma$ needs to be determined.

The first two necessities of the analysis are given either from the data or from auxiliary measurements. The three simplest kinematic parameters to understand are the positron energy, the photon energy, and the relative time of decay. Figure II-38 displays the energy spectrum for positrons decaying at high rates (250 MHz instantaneously) in black. An idealization of this spectrum would be a roughly flat response up to 52.8 MeV and a precipitous step down to zero counts beyond that point. The experimental result shows that the energy is correctly calibrated to be 52.8 MeV, and the full-width half-maximum of the detector response is 0.7 MeV, as given by the 10%–90% points on the step function. In addition, there are a few percent of unphysical

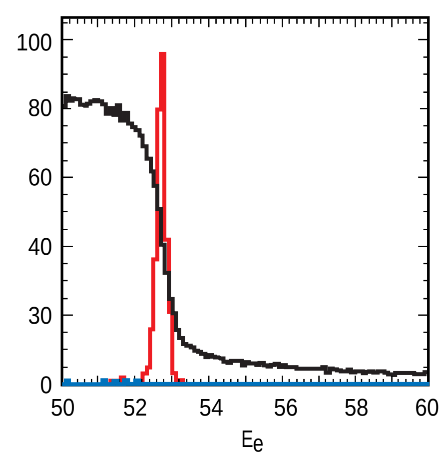

Fig. II-38. The Michel spectrum of normal muon decay at high rates is shown in black. The red curve is the signal expected for $\mu^+ \rightarrow e^+\gamma$ based on Monte Carlo simulations. The blue histogram contains the data with tight cuts on the time difference, the angle between the particles, and the photon energy.

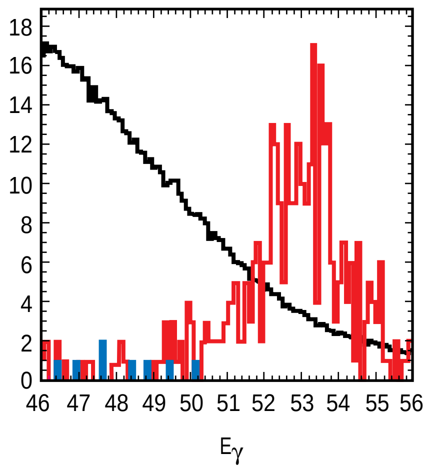

Fig. II-39. The photon spectrum from bremsstrahlung at high rates is shown in black. The red curve is the signal expected for $\mu^+ \rightarrow e^+\gamma$ based on Monte Carlo simulations. The blue histogram contains the data with tight cuts on the time difference, the angle between the particles, and the positron energy.

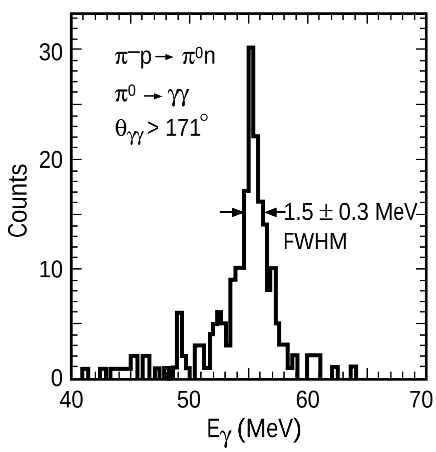

Fig. II-40. A spectrum from $\pi^0 \rightarrow \gamma\gamma$ with the angle between the gamma rays greater than 171°. Each π^0 is produced by stopping a π^- in a CH_2 target.

events at a higher energy that are caused by confusion of the pattern-recognition code by extra hits in this high-rate environment; these unphysical events represent a small inefficiency for finding the signal.

The corresponding energy spectrum for the photons is shown in black in Fig. II-39. This spectrum, whose origin is bremsstrahlung ($\mu^+ \rightarrow e^+\gamma\nu\nu$), is expected to fall rapidly as the energy approaches the 52.8-MeV endpoint. Again, there are some unphysical high-energy events that represent extra background. This spectrum contains no distinct features to use as a calibration. To overcome this deficiency, photons are measured from the decay $\pi^0 \rightarrow \gamma\gamma$. If the π^0 is made from stopping pions via the process $\pi^- p \rightarrow \pi^0 n$, the energies of the two gamma rays range from 54.92 to 82.96 MeV. By selecting only decays with an angle of at least 171° between the photons, nearly monoenergetic gamma rays of 55 MeV are isolated, as seen in Fig. II-40. Again, the energy calibration is seen to agree with its predicted value, and the resolution is 1.5 ± 0.3 MeV.

The primary background to the $\mu^+ \rightarrow e^+\gamma$ process is random coincidences between a positron from one muon decay and a photon from a second muon decay via the $\mu^+ \rightarrow e^+\gamma\nu\nu$ process. At the full beam intensity, the prompt coincidences from $\mu^+ \rightarrow e^+\gamma\nu\nu$ are completely swamped by the accidentals. However, if the beam intensity is greatly lowered and the magnetic field is somewhat reduced, a clear peak is observed at a time difference of zero (Fig. II-41). This feature demonstrates that the timing is correctly prepared. The observation of the peak demonstrates that the apparatus can observe a real coincidence process.

At this time, the collaboration has analyzed the 1993 data, which represent one-sixth of the total sample. Each event must be reconstructed by a very-time-consuming program that converts the detector signals into particles whose kinematic properties are known. For this subset of the data, the equivalent of 30 Hewlett-Packard 100-MHz workstations have computed continuously for one month at Indiana University, Los Alamos, and Texas A&M University.

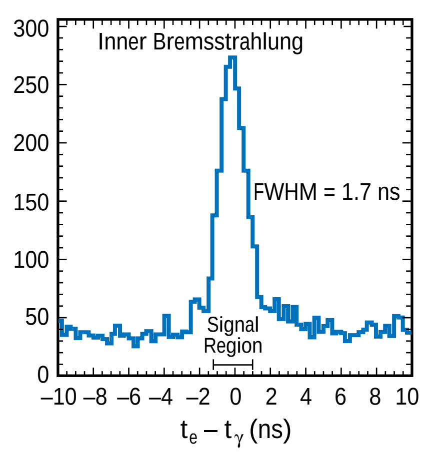

Fig. II-41. The timing spectrum that indicates the presence of coincidences of positrons and photons from the expected process $\mu^+ \rightarrow e^+\gamma\nu\nu$.

Figures II-38, II-39, II-42, and II-43 are a set. For the four primary variables that characterize the kinematics, these figures show the raw data (black), the expected signal based on Monte Carlo simulations (red), and the data cut tightly on the three other variables not displayed in the particular figure (blue). The structure in the uncut, relative-time spectrum is an artifact of the on-line filter; otherwise it would be flat. These figures allow the observation of several points. First, the evolution of the full spectrum to a few events is seen as the severe cuts are imposed to isolate the signal. Second, the number of events in the signal region is seen to be zero. Third, the distinct character of the signal is easily identified. Last, the proximity of candidates to the signal region can be evaluated.

The energies of photons and positrons for events that are within ±1.0 ns of being in coincidence and that have an angle between them of at least 178.1° are plotted in Fig. II-44. There are no events inside the box that indicates the signal region. The number of muon decays in the sample is 2.3×10^{13}. Taking Poisson statistics and the detector acceptance into account, a new limit for the branching ratio (90% confidence) for $\mu^+ \rightarrow e^+\gamma$ is established to be 4×10^{-11}. This value represents a slight improvement over the previous best limit of 5×10^{-11}, a result that was based on subtracting 50 events of background. These results are preliminary and may be improved by the imposition of cuts on kinematic properties not considered here; this work is in progress. It is hoped that when the remaining techniques for background reduction have been employed, the result for the remaining five-sixths of the data will be background-free and will get close to the desired sensitivity. Of course, the exciting possibility of actually observing a $\mu^+ \rightarrow e^+\gamma$ signal remains.

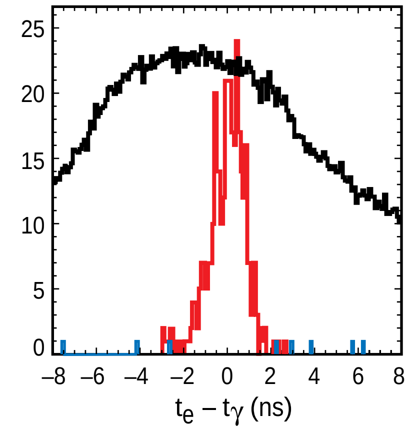

Fig. II-42. The relative timing spectrum at high rates is shown in black. The red curve is the signal expected for $\mu^+ \rightarrow e^+\gamma$ based on Monte Carlo simulations. The blue histogram contains the data with tight cuts on the angle between the particles, the positron energy, and the photon energy.

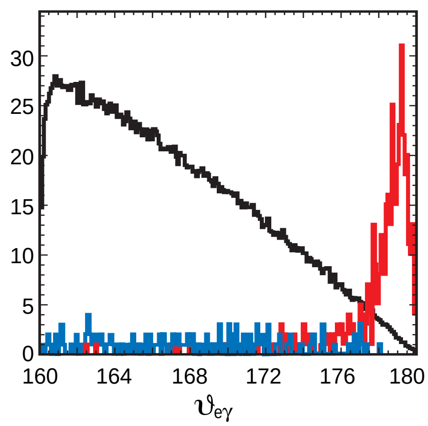

Fig. II-43. The spectrum of angles between the positron and photon at high rates is shown in black. The red curve is the signal expected for $\mu^+ \rightarrow e^+\gamma$ based on Monte Carlo simulations. The blue histogram contains the data with tight cuts on the time difference, the positron energy, and the photon energy.

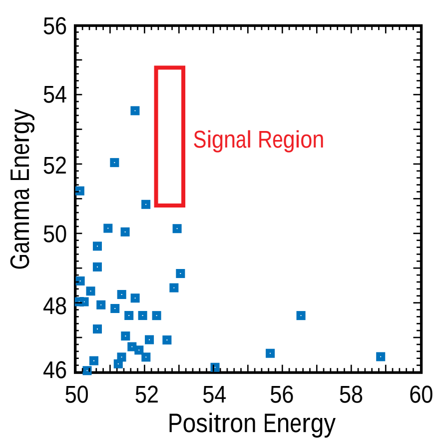

Fig. II-44. The photon energy plotted versus the electron energy for a set of events that are nearly back to back and in time coincidence. The empty box is where a potential $\mu^+ \rightarrow e^+\gamma$ signal should be.

NUSEA—Measurement of the Asymmetry in the Light-Antiquark Nucleonic Sea

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Recent measurements of deep inelastic muon scattering by the New Muon Collaboration (NMC)[1] have suggested that the up sea antiquark ($\bar{u}_p$) and down sea antiquark ($\bar{d}_p$) distributions of the proton are not equal. The Gottfried sum rule,[2]

$$S_G = \int_0^1 (F_2^p(x) - F_2^n(x))dx / x$$
$$= \frac{1}{3} + \frac{2}{3}\int_0^1 (\bar{u}_p(x) - \bar{d}_p(x))dx,$$

says that the integral over the nucleon momentum fraction (x) of the difference of the structure functions for the proton (F_2^p) and the neutron (F_2^n) divided by x should be equal to one-third plus a term that is zero if the $\bar{u}_p$ and $\bar{d}_p$ distributions are equal. The NMC result for the Gottfried sum rule is $S_G = 0.235 \pm 0.026$. This result implies that $\bar{u}_p < \bar{d}_p$ in the proton.

One possible cause for an enhancement of $\bar{d}_p$ over $\bar{u}_p$ is Pauli blocking.[3] Here the idea is that because the proton is composed of two up quarks and a down quark (uud), it is less likely that a $u\bar{u}$ pair can be formed since the u would be blocked by the two up quarks in the proton more strongly than a d from a $d\bar{d}$ would be blocked by the single down quark in the proton. Another possible cause is from the pion-cloud model[4] of the proton. In this model the proton can produce pions in the cloud through mechanisms such as the following:

$$p \to p\pi^0 \Rightarrow p + \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})$$
$$p \to n\pi^+ \Rightarrow n + (u\bar{d}).$$

Together, these mechanisms give more down antiquarks than up antiquarks.

A direct measurement of $\bar{u}_p$ and $\bar{d}_p$ can be made using the Drell-Yan (DY) process (Fig. II-45), in which a quark from an incident proton annihilates with a sea antiquark in a target nucleus and forms a virtual photon that then decays into a $\mu^+\mu^-$ pair. If this measurement is done on hydrogen and deuterium targets, then the following is true:

$$\left.\frac{\sigma_{p+d}(x)}{2\sigma_{p+p}(x)}\right|_{x_F>0} \cong \frac{1}{2}\left(1 + \frac{\bar{d}_p(x)}{\bar{u}_p(x)}\right),$$

where $\sigma_{p+p}(x)$ is the DY cross section for protons incident on hydrogen, and $\sigma_{p+d}(x)$ is the DY cross section for protons incident on deuterium. Using this process, the NA51 Collaboration[5] at the European Center for Nuclear Research obtained the result $\bar{u}/\bar{d} = 0.51 \pm 0.04 \pm 0.05$ at $x = 0.18$. The NUSEA experiment E866 at Fermilab, which we report on here, has measured the deuterium to hydrogen ratio in the DY process over values of x ranging from 0 to 0.3. This range is much wider than that of the NA51 experiment, and

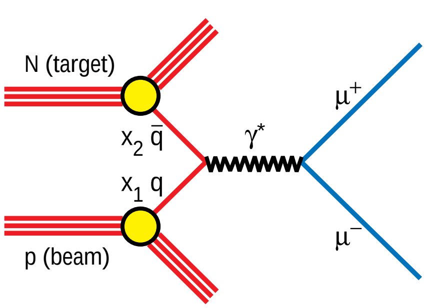

Fig. II-45. Diagram of the Drell-Yan process.

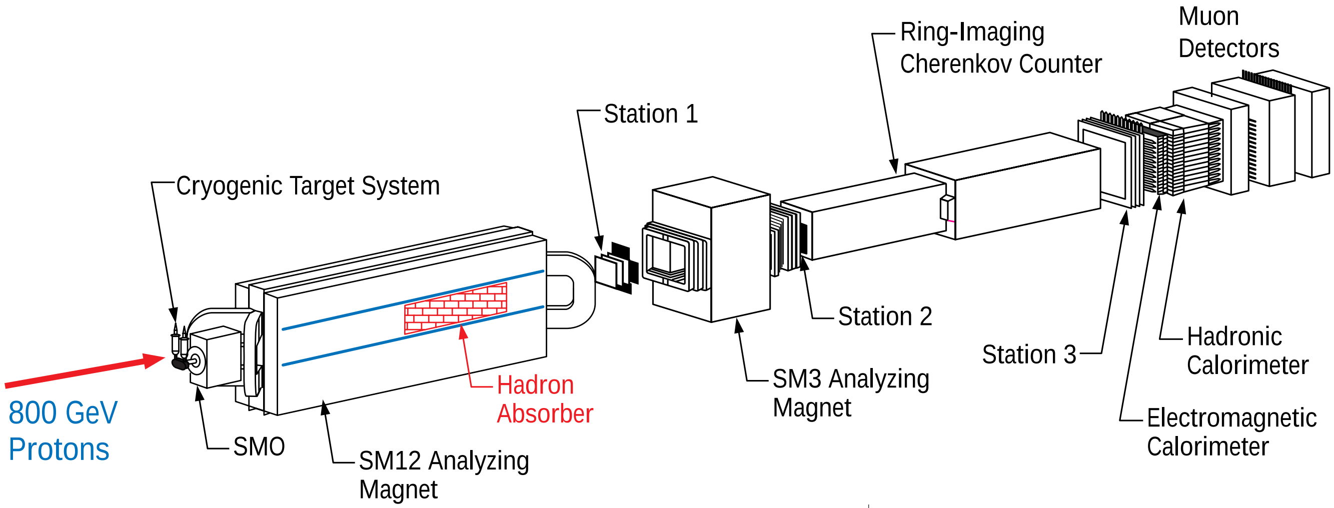

Fig. II-46 Schematic view of the NUSEA pair spectrometer.

the NUSEA experiment has over 350,000 events recorded, compared with NA51's 6,000 events. Los Alamos personnel are leaders in the NUSEA experiment and in two previous experiments, E772 and E789; all three experiments used the same spectrometer. The earlier experiments studied nuclear effects on dimuon production and the production of *D* and *B* mesons. Pat McGaughey, from Los Alamos, is the spokesperson for the NUSEA Collaboration.

The NUSEA pair spectrometer (Fig. II-46), which is on one of the 800 GeV/*c* proton beam lines at Fermilab, detects $\mu^+\mu^-$ pairs for very high incident-proton intensities ($\approx 10^{11}$ protons/s). Two 20-in.-long cryogenic targets, one filled with liquid hydrogen and the other with liquid deuterium, and an empty cryogenic vessel are located just upstream of the first magnet. On alternate 20-second beam spills, the target intercepting the beam is changed from deuterium to hydrogen to empty. The portion of the beam that does not interact with the targets is stopped in a 168-in.-long copper beam dump. Opposite-sign muon pairs are bent vertically above and below the beam dump by the first two magnets (SM0 and SM12) and are tracked through a series of scintillator hodoscopes and drift chambers before and after the last bending magnet (SM3). Using the hits in the drift chambers, we measure the bend angle in SM3 and, from this angle, determine the momentum of each muon. Then the muon tracks are traced backwards through the known magnetic field of SM12 and SM0, and the muons' momenta and direction at the target are reconstructed. Thick absorber walls both in SM12 and in front of a set of hodoscopes and proportional tube detectors assure that all of the tracked particles are muons because hadrons or electrons would not penetrate the absorbers. Finally, the pair mass is reconstructed from the tracks at the target.

A 6-month-long measurement of $\bar{u}/\bar{d}$ has just been completed, and analysis of the data is well under way. We present our preliminary results here. Data were taken at three magnetic-field settings that emphasized high, intermediate, and low masses. Figure II-47 shows the combined mass spectra for the three mass settings as well as that for the high-mass setting alone. In addition to the continuum DY

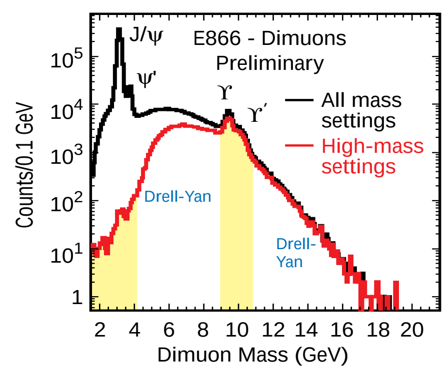

Fig. II-47. Dimuon mass spectra obtained in the NUSEA experiment. The black curve shows the composite spectra for the three mass settings, while the red curve shows the spectrum for the high-mass setting alone. Only the unshaded regions for the high-mass setting are used in the preliminary analysis presented here. The shaded regions were not used so that only DY would be included and all contributions from the resonance mass peaks excluded.

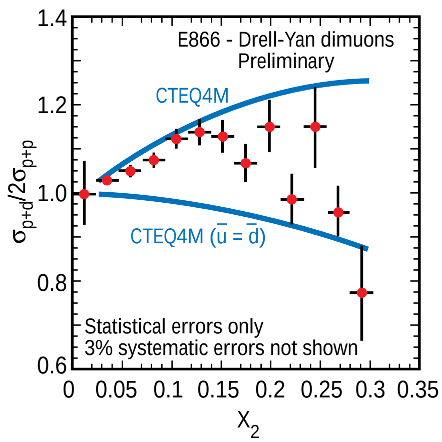

Fig. II-48. Preliminary results from the NUSEA experiment for the ratio of the deuterium cross section divided by two times the hydrogen cross section ($\sigma_{p+d}/2\sigma_{p+p}$) plotted versus the target momentum fraction (x_2) of the sea antiquark.

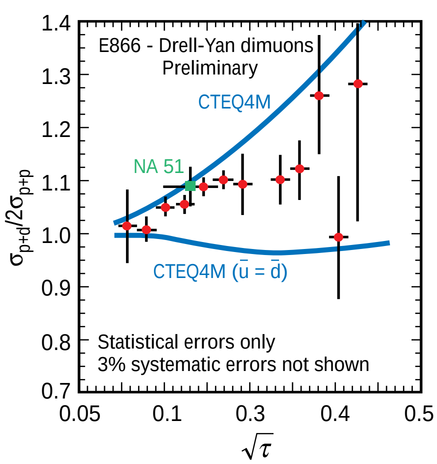

Fig. II-49. The same ratio seen in Fig. 4 plotted versus $\sqrt{\tau}$, where $\tau = x_1x_2$. The single data point from the NA51 experiment is shown along with the NUSEA data.

muon pairs, one also sees peaks corresponding to production and decay of the J/Ψ, Ψ', and Υ, and Υ' resonances. For the $\bar{u}/\bar{d}$ analysis that follows, we excluded the mass regions corresponding to these resonances. Preliminary results for the ratio of deuterium to hydrogen versus x, obtained from an analysis of most of the data for our high-mass setting, are shown in Fig. II-48. Results are not yet available for the other mass settings because of the need to correct for rate-dependence effects that are not present in the high-mass data. Also shown are theoretical calculations with phenomenological CTEQ4M[6,7] structure functions and a calculation based on CTEQ4M but with $\bar{u} = \bar{d}$. The former fixes its $\bar{u}/\bar{d}$ asymmetry from the NMC and NA51 data. In Fig. II-49 we plot the ratio versus $\sqrt{\tau}$, where $\tau = x_1x_2$, and x_1 and x_2 are the beam and target momentum fractions, respectively. Here the NA51 data point is seen to be consistent with our data.

As the analysis of our NUSEA data progresses and data from the other two magnetic-field settings are incorporated into our results, we will have a direct and accurate measurement of the $\bar{u}/\bar{d}$ asymmetry over a wide range of x. At the present our preliminary analysis confirms that $\bar{d}$ is enhanced over $\bar{u}$ when x is in the range of 0–0.2. Below about $x = 0.2$ our results agree well with the CTEQ4M theoretical result, but at higher x they fall substantially below it.

In addition to the $\bar{u}/\bar{d}$ asymmetry measurement, NUSEA has been approved for an extension during which we will address a number of issues, including many that relate to our future studies at the Relativistic Heavy-Ion Collider. We will measure the polarization of DY pairs and of J/Ψ resonances to try to better understand their production mechanisms, notably whether the J/Ψ resonances are initially produced in a color-octet state.[8] We will also measure the nuclear dependence of J/Ψ production near zero and at very large x_F (where $x_F = x_1 - x_2$) in order to better determine the most important nuclear effects in p-A reactions. Finally, we will study DY pairs at masses below the J/Ψ resonances and try to understand the different contributions to the continuum at these low masses.

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Neutrino Oscillation Results from the Liquid Scintillator Neutrino Detector

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In the past few years, a number of experiments have searched for neutrino oscillations, in which a neutrino of one type (such as $\bar{\nu}_\mu$) spontaneously transforms into a neutrino of another type (such as $\bar{\nu}_e$). In the standard model of particle physics, neutrinos are considered to be massless, but the existence of neutrino oscillations would imply that neutrinos actually do have mass. Neutrino mass of even a few electronvolts would profoundly affect theories related to cosmology and to the development of structure in the universe.

In 1995 the LSND (Liquid Scintillator Neutrino Detector) collaboration published data showing candidate events that are consistent with $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations.[1] Since then, the collaboration has reported additional data that provide stronger evidence for neutrino oscillations.[2,3] The LSND results complement hints from solar and atmospheric neutrino experiments that neutrino oscillations occur. In the solar experiments the sun emits fewer neutrinos than the standard solar model predicts, and in the atmospheric experiments the ratio of muon neutrinos to electron neutrinos that are generated by cosmic-ray interactions in the upper atmosphere is unexpectedly low. This current neutrino data combined with data from future experiments may eventually allow physicists to determine the masses and mixings of all three flavors of neutrinos.

The LSND experiment at the Los Alamos Neutron Scattering Center (LANSCE)[4] is a high-sensitivity search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations from μ^+ decay at rest. With its 1-mA proton intensity and 800-MeV energy, LANSCE is an intense source of low-energy neutrinos. The LANSCE neutrino source is well understood[5,6] because almost all neutrinos arise from π^+ or μ^+ decay; π^- and μ^- are readily captured in the iron of the shielding and the copper of the beam stop. The

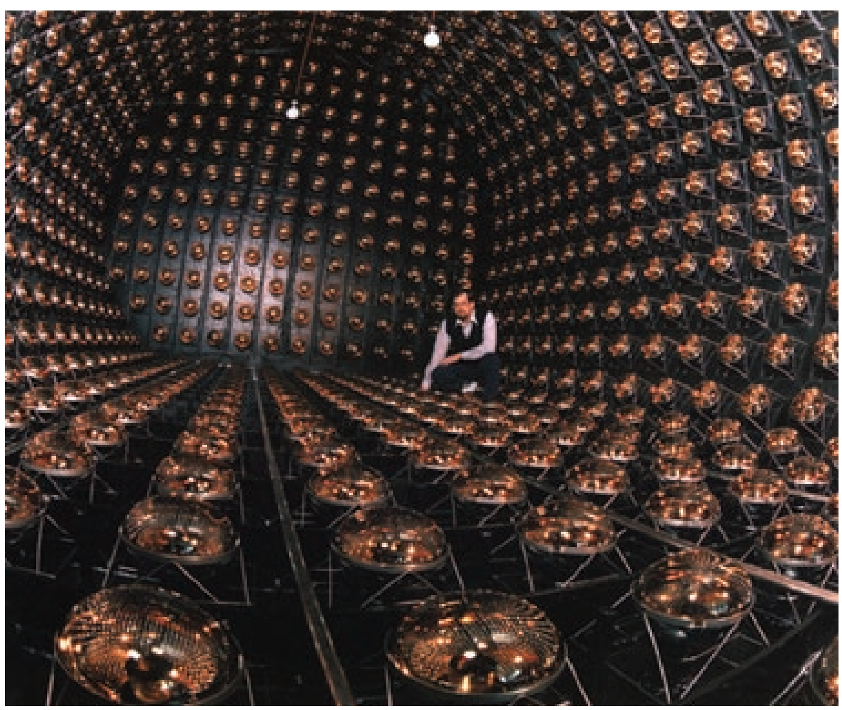

Fig. II-50. An interior view of the LSND detector, showing a portion of the 1,220 phototubes that cover the inside surface.

production of kaons and heavier mesons is negligible at the 800-MeV LANSCE energy. In the 36- to 52.8-MeV energy range, the ratio of $\bar{\nu}_e$ to $\bar{\nu}_\mu$ is calculated to be only 4×10^{-4}, so the observation of a significant $\bar{\nu}_e$ rate would be evidence for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations.

The LSND detector consists of a cylindrical tank, 8.3 m long by 5.7 m in diameter, surrounded by a veto shield[7] that detects cosmic-ray muons going through the detector. The center of the detector is 30 m from the neutrino source. Mounted on the inside surface of the tank are 1,220 Hammamatsu phototubes (8 in. each), which cover 25% of the surface. These phototubes can be seen in Fig. II-50, a photograph of the inside of the LSND detector. The tank is filled with 167 metric tons of liquid scintillator, which consists of a small concentration of the organic compound butyl PBD in mineral oil. Because of the low scintillator concentration, both Cerenkov light and scintillation light can be detected, and a relatively large attenuation length of more than 20 m occurs for wavelengths greater than 400 nm.[8] A typical 45-MeV electron created in the detector produces approximately 1500 photoelectrons, of which around 280 are in the Cerenkov cone. The phototube time and pulse-height signals are used to reconstruct the electron and positron tracks with an average rms position resolution of ~30 cm, an angular resolution of ~12°, and an energy resolution of ~7%. The Cerenkov cone for relativistic particles and the time distribution of the light (broader for nonrelativistic than for relativistic particles) provide excellent particle identification.

The signature for a $\bar{\nu}_e$ interaction in the detector is the reaction $\bar{\nu}_e p \rightarrow e^+ n$. The recoil neutron, n, then undergoes the reaction $np \rightarrow d\gamma$, in which γ is a correlated 2.2-MeV photon. To distinguish between a correlated photon and a photon that is accidentally coincidental, we use a likelihood ratio, R, which is the probability that the photon is correlated divided by the probability that it is accidental. The ratio depends on the number of phototubes that the photons have hit, the reconstructed distance between the photon and the positron, and the relative time between the photon and the positron. Figure II-51 shows the R distribution for events with positrons in the energy range of 20–60 MeV, where an event is defined as the primary positron and any associated photons. The R distribution yields a range of 26.9–78.5 excess events after beam-off background is subtracted from beam-on readings; this range includes statistical and systematic errors. If these excess events are due to neutrino oscillations, then the oscillation probability, including statistical and systematic errors, is in the range of 0.14%–0.43%. With such a small probability, it is not surprising that neutrino oscillations are difficult to detect.

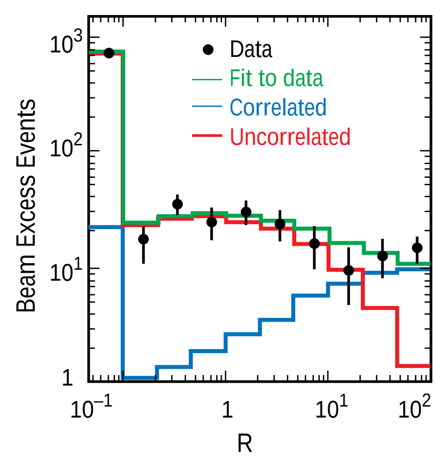

Fig. II-51. The R distribution for events with positron energies in the range of 20–60 MeV. Shown are the total fit to the data (green), the component of the fit with uncorrelated photons (red), and the component with correlated photons (blue). High values of R indicate a high probability that a photon is correlated.

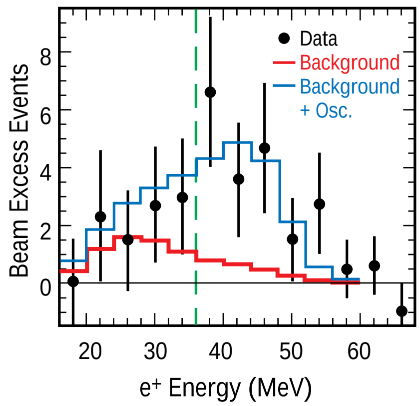

Fig. II-52. The positron energy distribution for events with R>30. Shown are the beam-excess data, estimated background from all neutrino reactions (red), and neutrino background plus the expected distribution for neutrino oscillations at asymptotically large Δm^2 (blue).

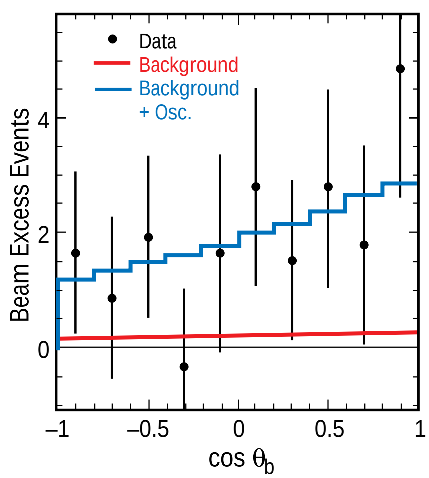

Fig. II-53. The angular distribution for events with R>30, where θ_b is the angle between the positron direction and incident neutrino direction.

Figures II-52 and II-53 show the positron energy and angular distributions (with beam-off background subtracted) for events that have an associated photon with R>30. If R is greater than 30, the total efficiency of detecting 2.2-MeV photons is 23%, and the probability that an event has an accidental photon in coincidence is 0.6%. In the 36- to 60-MeV energy range, a range chosen because it has little background from known neutrino interactions, there are 22 beam-on events and a total estimated background range of 4.0–5.2 events; the total estimated background includes beam-off background and known neutrino-induced interactions. The probability that this excess of beam-on events is a statistical fluctuation is less than 10^{-7}.

If neutrino oscillations cause the observed excess, then Fig. II-54 shows the allowed region (90% and 99% likelihood regions) of $\sin^2 2\theta$ plotted against Δm^2. This plot is a maximum likelihood fit to the excess events, where θ is the mixing angle and Δm^2 is the difference between the squared masses of the two neutrino mass eigenstates. For this plot to have meaning, neutrinos must have mass, and furthermore, different flavors of neutrinos must have different masses. Also shown in Fig. II-54 are the 90% confidence limits from the ongoing KARMEN neutrino experiment at the spallation neutron source ISIS,[9–11] the E776 experiment at Brookhaven National Laboratory,[12] and the Bugey reactor experiment.[13] To the left of these limits are the 90% likelihood regions. If we consider the regions from all four experiments, the most favored region has a Δm^2 of approximately 0.2–2 eV^2/c^4.

By acquiring additional data from the experiment and studying the performance of the LSND detector, we expect to improve our understanding of the phenomena described in this article, and we hope eventually to settle the issue of whether neutrino oscillations exist.

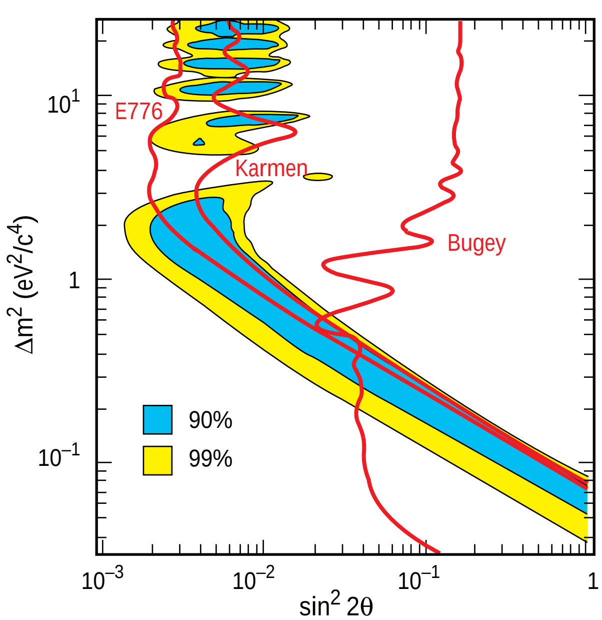

Fig. II-54. The 90% and 99% likelihood regions of Δm^2 vs $\sin^2\theta$ for the LSND experiment, including systematic errors. Also shown are the 90% confidence level limits from KARMEN at ISIS, E776 at BNL, and Bugey reactor experiments; their 90% likelihood regions lie to the left of the limits.

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Proton Radiography

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Introduction

Protons can be used to probe with high spatial and temporal resolution the interior structure of systems that are static, imploding, or exploding. Protons have already been used to image thin systems, but the technique was limited by the image blurring caused in the object by the multiple scattering of the protons. The new development coming out of Physics Division is the introduction of a magnetic-lens system to remove much of this blur. Also, we are extending this technique further to gain information on the material composition of the object being probed by allowing a second detection of the transmitted protons through a reduced aperture. Experiments have been performed at the Los Alamos Neutron Scattering Center (LANSCE) and the Alternating Gradient Synchrotron (AGS) at Brookhaven National Laboratory (BNL) to confirm many of the concepts of proton radiography. A three-year program has begun to demonstrate the capabilities of proton radiography as a tool for advanced hydrotesting of nuclear-weapons primaries using high-energy (50-GeV) protons. A program at LANSCE is starting, using 800-MeV protons as a research tool for Science-Based Stockpile Stewardship (SBSS), looking at shock-wave propagation in high-explosive (HE) systems.

The SBSS Program and the Stockpile Stewardship and Management Program were developed to assure the reliability and safety of the weapons in the enduring stockpile without the use of nuclear testing. Effects that will need to be addressed will arise due to aging of components, remanufacture of weapons and weapon components, or possible packaging changes. In the past, such effects often were assessed with nuclear testing. As part of this comprehensive program to understand the fundamental physics of a nuclear device through modeling and nonnuclear experiments, the integral performance of a nuclear assembly must be measured with substantially improved fidelity. An advanced radiographic capability is an essential component of this program, providing the ability to measure the integral performance of stockpiled primaries using inert materials and thereby derive nuclear performance information that previously could only be obtained from nuclear testing. Detailed data from these hydrodynamic experiments are the necessary starting points for modeling the explosion phase of the primary and thus for assessing the performance and safety of stockpiled primaries.

The primary is the most difficult component of a nuclear weapon to assess for reliability because changes, though small, have the potential to affect the boost process. Three of the most important parameters affecting primary boost and thus yield performance are the level of supercriticality produced by HE compression, the shape of the boost cavity, and mix within the cavity. For assessing nuclear safety in an accident, the integral of the level of supercriticality over of time must be determined. Hydrodynamic testing is the only available tool for measuring the integral performance of a primary up to the beginning of criticality. Currently, pin measurements (wherein electrical pins of varying lengths are arrayed inside of a primary or primary surrogate and are progressively shorted out as the primary implodes) and radiography of an imploded pit and cavity are used to constrain computational simulations from which nuclear performance and safety are calculated. In the absence of nuclear testing, it is essential that hydrotest capabilities be expanded to include experimental validation of calculated nuclear performance. A multiaxis (>2 axes), multipulse, radiographic system does not currently exist, and none is anticipated for the near future. The Advanced Hydrotest Facility (AHF) is being proposed to meet this challenge.

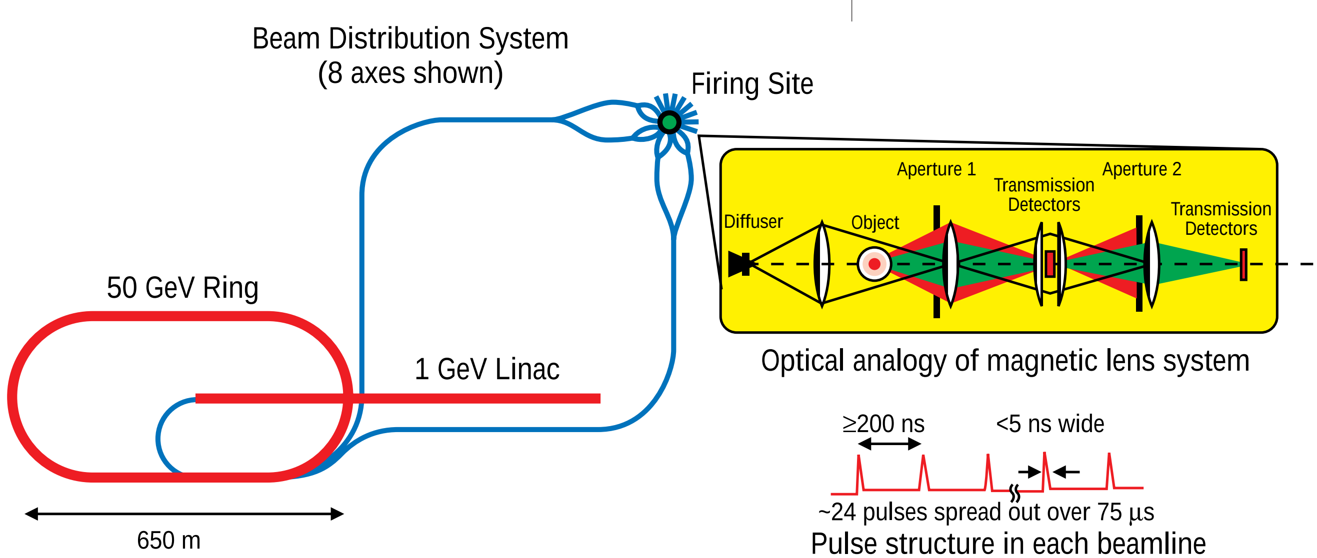
Hydrodynamic radiography refers to that technology used to view inside thick material objects (specifically the primaries of nuclear weapon assemblies) as they are undergoing implosion and compression because of the detonation of surrounding HE. The principal tool of hydrotesting is thick-object-penetrating radiography. The images obtained must be formed very quickly (in ~50 ns or less) to freeze the motion of the moving components and features and to avoid motion blur. The images are negatives, in that the information depicting the primary assembly's internal structure is obtained from the attenuation of the penetrating radiation. Current state-of-the-art facilities are PHERMEX at LANL and FXR at Lawrence Livermore National Laboratory (LLNL). Both are important elements of current stockpile maintenance, and efforts are continuing to upgrade their capabilities through double pulsing and enhanced detector capability. These two facilities will remain the prime radiographic facilities until the completion of the Dual Axis Radiographic Hydrotest (DARHT) facility in FY 1999 (for the first axis) and FY 2002 (for the second axis). DARHT will improve radiographic resolution and x-ray intensity (dose) and provide dual-axis tomographic data to evaluate asymmetries in primary assemblies. It will also provide improved data for the development of the analysis tools that will be needed for the proposed AHF. The AHF is proposed to provide improved understanding of three-dimensional effects associated with aging and weaponization features of weapons and to provide time-dependent, high-resolution measurements of pit density and gas-cavity configurations. It would expand multipulsed, multiaxis capabilities well beyond those being planned for DARHT.

An advanced radiographic capability will have to provide accurate information about densities and material positions, from which we can infer the degree of supercriticality, the shape of the boost cavity, and the mix that would be present in an actual imploding primary. Allowed manufacturing tolerances can cause an implosion to be three dimensional even in normal operation, and accidental detonations are almost always three dimensional. As a result, radiographs are needed from a number of directions (at least 4 and preferably 12) so that material densities can be reconstructed with accuracies sufficient to derive nuclear parameters. Also, since the implosion progresses with time, a temporal series of radiographs (5–10) is needed over a time period relevant to the processes being recorded. This time window may need to cover a period as long as the full implosion. Two radiation species are under consideration as possible advanced technologies for an AHF: multi-MeV x-rays and multi-GeV protons. The overall utility and performance of both types of radiation will be studied to select an optimal technology mix.

In x-ray radiography, a beam of energetic electrons is accelerated and then focused onto a dense, high-atomic-number material target, producing bremsstrahlung x-rays. The necessary penetrating dose requires many kiloamperes of electron beam current with >10 MeV of kinetic energy impinging on a converter target located about a meter from the hydrodynamic object. To resolve small feature-sizes within a weapon-primary assembly, the x-ray source must be a very small spot size (approaching a point source) thus requiring a very-small-diameter electron beam. There are two technology paths under consideration for x-ray hydrodynamic radiography: linear induction accelerators (LIAs) and inductive voltage adders (IVAs). The LIA approach uses a single high-voltage, high-transport-current (20- to 40-MeV, 1- to 6-kA), large accelerator producing a long-duration electron beam that is distributed via a kicker into many axes, each of which transports a shorter-duration beam to a bremsstrahlung converter. The IVA approach uses smaller medium-voltage, higher-current (12-MeV, 40-kA), individual accelerators to directly generate the short-duration pulses that are delivered to the bremsstrahlung converters.

In proton radiography, a high-energy beam of protons impinges directly on the object to be radiographed. There is no need for an equivalent bremsstrahlung converter since the proton beam directly illuminates the primary assembly. Unlike x-rays, protons undergo a large number of very forward-angle scatterings as they pass through the object and the exit window of the containment vessel. This introduces a blur to the image that is then removed, for the most part, by a magnetic lens system between the object and the detectors. The residual blurring can be further reduced by increasing the energy of the proton beam. For typical weapon-primary assemblies and containment-window thicknesses, this corresponds to proton beam energies near 50 GeV. The proton beam is produced in conventional accelerator architectures, including an injection linac and synchrotron ring. The inherent time structure of the acceleration process lends itself naturally to the variable pulse formats needed for advanced radiography. Each pulse in the ring is of short duration (less than 50 ns), with many pulses present in the ring. A kicker system is used to deliver the required pulse format, both the pulse spacing and the total duration of the pulse train. Each pulse can then be split into multiple pulses and delivered simultaneously to the object through multiple beamlines. The number of protons in a single pulse must be adequate to meet the density and field-of-view requirements. At the present time, it is estimated that 5×10^9 protons per pulse per axis are needed. With 10 axes, this would imply 5×10^{10} protons per pulse. Considerably more intensity is available with current technologies (over 10^{13} at the AGS at BNL and the proton storage ring [PSR] at LANSCE), so that higher fluxes are available if warranted by refinements in the radiographic requirements. Figure II-55 is a schematic of a proton-based AHF, showing the injection linac, 50-GeV ring, beam distribution system, firing point, and lens system.

Fig. II-55. Schematic of a proton-based Advanced Hydrotest Facility.



Proton Radiography

Proton radiography marks a sharp departure from flash x-ray technology, which has been the exclusive radiographic tool for stockpile support for more than thirty years. Here, the primary proton beam of a suitably high energy (near 50 GeV) is used to image the imploding object directly. Both the nuclear attenuation and the multiple scattering of the protons contain information on the distribution and composition of materials in the object. The principle virtues of protons are (1) the relatively long mean-free-paths of protons, well matched for the imaging of dense objects, (2) the maturity of proton-accelerator technology, which can accommodate the multiaxis, multipulse format required for an AHF, (3) lack of significant scattered background in the final image, (4) sensitivity to both material density and composition, (5) direct utilization of the proton beam as the radiographic probe, (6) high detection efficiency, (7) high reliability because the beam is coasting in the storage ring before the time of firing, and (8) the ability to easily deliver a test beam in advance of firing. The capabilities of proton radiography will likely exceed the current AHF requirements in several categories, providing a great deal of flexibility for enhancing future AHF capabilities. What is mostly wanting for protons at this time is radiographic experience with weapons-relevant dynamic systems. Common to both protons and x-rays is the need for fast, large-format, pixelated detectors; simulation capabilities to better understand the performance of the full radiographic system; and the facility issues related to practical problems of actually making the required measurements.

800-MeV SBSS Research Tool

We can use 800-MeV protons to radiograph dynamic systems with areal densities up to 20 g/cm[2] for low-Z materials using intensities available from the LANSCE linac, typically 2×10^9 protons per 40-ns pulse. This capability is well suited for studies of HE shock propagation. A dynamic radiographic system has been installed in Line B at LANSCE, including a beam transport system, imaging lens, multiframe detection system, and containment system. LLNL is collaborating on this project and has been involved in simulations and detector development. The first experiments have looked at shock propagation in HE hemispheres and have also explored cylindrical geometries. The major issues to be addressed are how the shock from the detonator propagates through the HE and which parts of the HE react as a function of HE properties and temperature.

Figure II-56 shows the measured spatial resolution of the LANSCE apparatus. A metal "comb" with 1- and 2-mm-spaced slots was radiographed. The fitted position resolution was found to be better than 0.5 mm full width at half maximum (FWHM).

Fig. II-56. Measured resolution of the LANSCE proton-radiography apparatus.

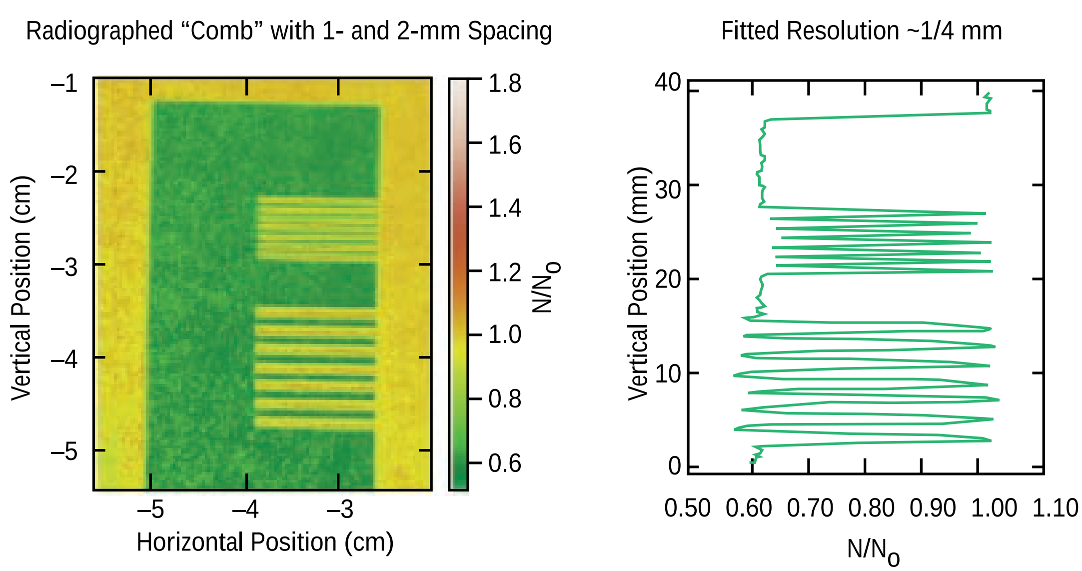


Figure II-57 shows a detonation wave at four different times in an HE assembly. The assembly consists of two embedded hemispheres of high explosives with a detonator. The inner shell is normal HE and the outer shell is insensitive high explosive (IHE). The diameter of the outer shell is approximately 5.7 cm, with a total HE mass of 92 g. The dotted line represents the edge of the unreacted HE. The propagation of the detonation wave is clearly evident in the radiographs as it propagates from the detonator to the outer surface of the IHE. What is shown is actually the ratio of the dynamic radiograph to a radiograph of the object taken before detonation. This enhances the changes visible in the dynamic radiograph. The images were recorded on a phosphor image plate that allows for one image per shot. An active camera system has now been installed, which is capable of taking up to six frames during the time of a single HE explosion.

The limitations to thin, low-Z systems at 800 MeV come primarily from multiple scattering within the object and aberrations in the lens system. Both of these effects become less important as the beam energy goes up, so these are not basic limitations for weapons-geometry hydrotests. A beam energy of approximately 50 GeV would be adequate to achieve 1% density measurements on a 1-mm^2 pixel size, with submillimeter resolutions for thick, dense systems (several hundred g/cm^2).

It is possible to overcome some of the limitations at 800 MeV by reducing the aperture in the lens through which the transmission is measured. This reduces the effects of chromatic aberrations in the lens. However, this also reduces the transmitted intensity, and hence, the sensitivity of the measurement. By using the beam from the PSR at LANSCE, the initial intensity of the pulse can be increased by four orders of magnitude, since 2×10^{13} protons are stored in a PSR pulse. A

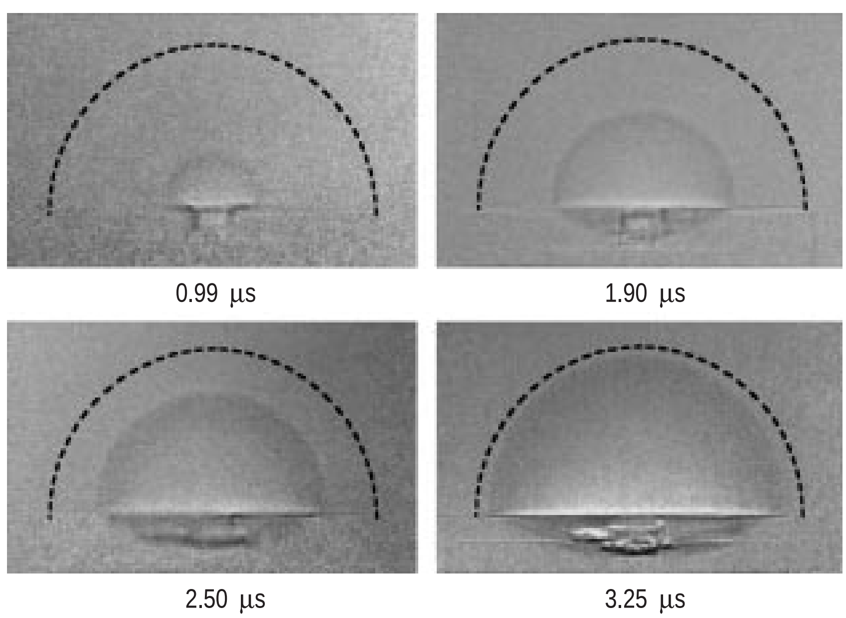


Fig. II-57. Proton radiographs of shock propagation at four different times in an HE assembly.

development has been recently completed where the PSR pulse was split into two pulses separated by 360 ns, each pulse being less than 50 ns wide. The PSR is being upgraded to store three pulses at full intensity. By using this splitting technique, 6 pulses could be extracted from the PSR and delivered to a firing site to radiograph thicker (100 g/cm^2) higher-Z dynamic systems. A study was recently completed that showed how to marry the higher-intensity 800-MeV proton radiography capability with neutron resonance spectroscopy, which can measure temperature and velocity in materials, in one facility at LANSCE.

Advanced Hydrotest Capability

Protons are one of three technology options being considered for an AHF. Recently, the three weapons program directors from LANL, LLNL, and Sandia National Laboratories (SNL) requested a technology development plan that would demonstrate over a three-year period the viability of the three technologies. LANL was designated the coordinating laboratory for protons, LLNL for LIAs, and SNL for IVAs. Technical Contracts, modeled after the Nova Technical Contracts for NIF, have been drafted that define the critical issues to be addressed, together with the tasks and goals, and Implementation Plans with cost and schedule information for accomplishing the Technical Contracts have been completed, as well as an additional contract covering physics requirements. Work began in FY97 toward these objectives. LLNL is now collaborating with LANL on proton radiography, and all planning is being done jointly with them.

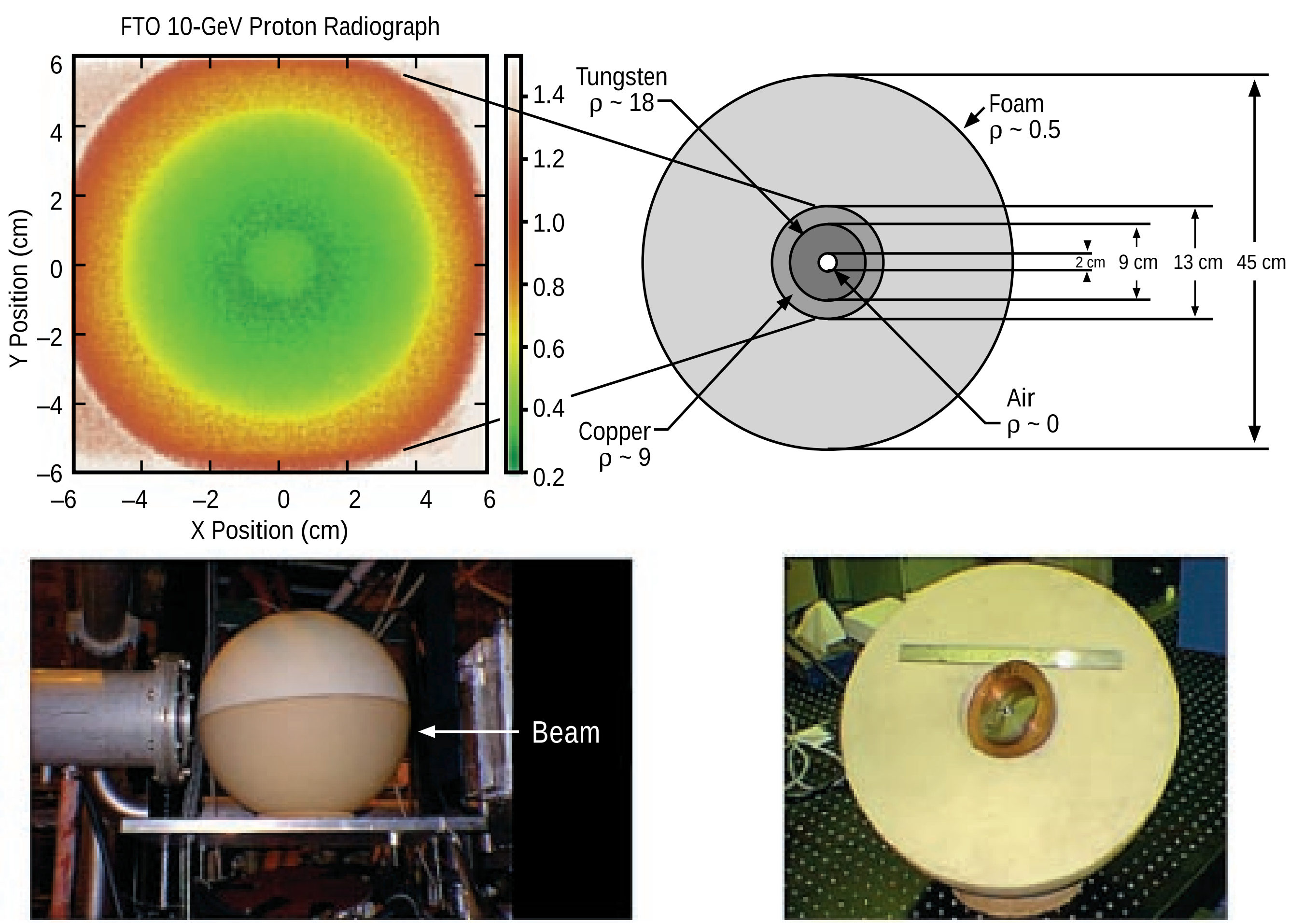
The 3-year plan addresses the following critical issues for proton radiography:

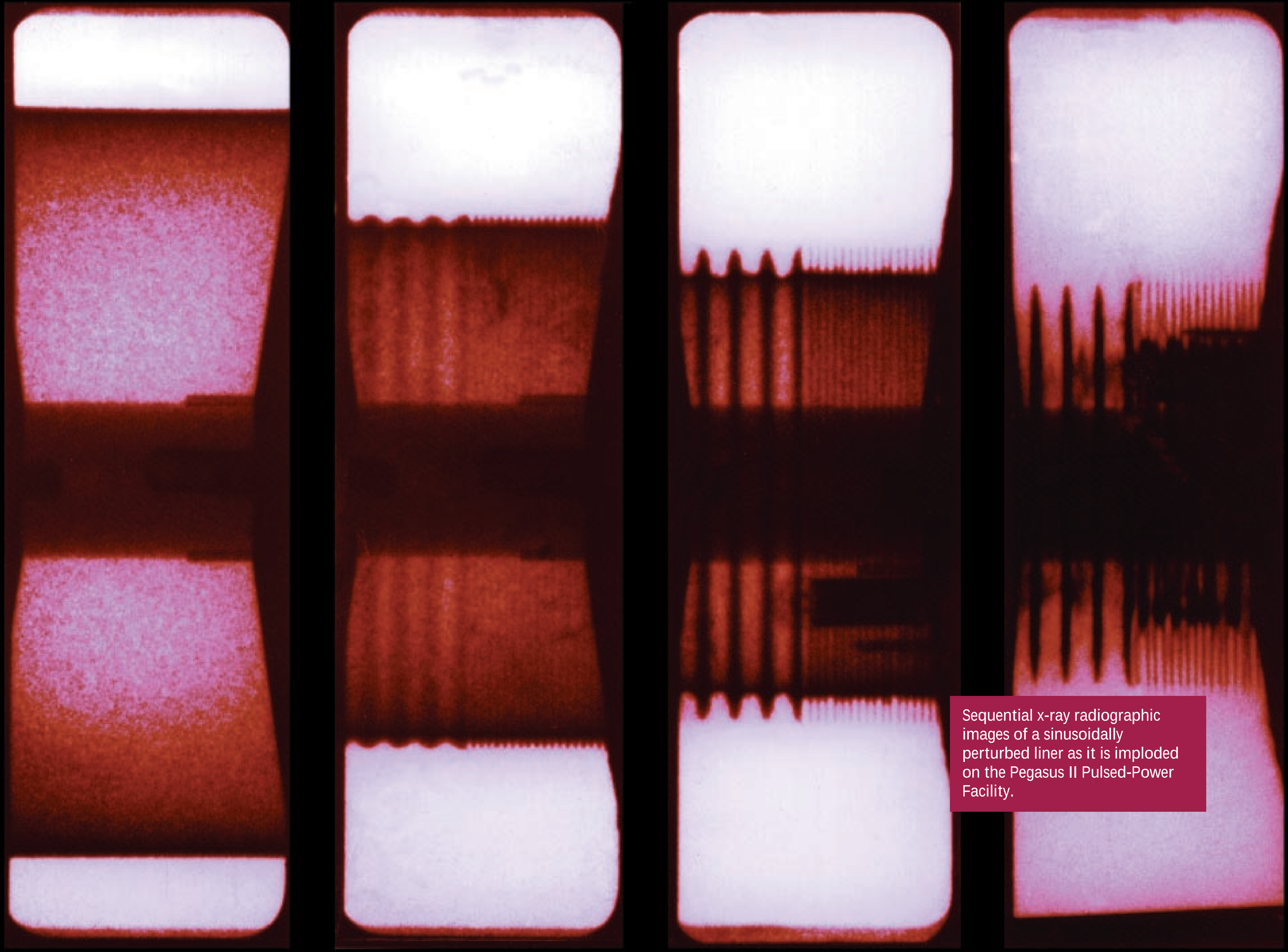
- demonstration of proton radiography performance on a suitable array of test objects under conditions as near as possible to the anticipated design parameters of an AHF;
- development of instrumentation capable of meeting the AHF requirements for spatial and temporal resolutions and required pulse format;
- demonstration of a proton-accelerator concept capable of meeting AHF requirements;
- examination of the effects of the confinement system on resolution and of its interfacing to the lens system; and
- demonstration, in conjunction with the physics requirements modeling effort, that uncertainties in the radiographic image, after correction for known experimental effects, are consistent with criticality, cavity shape, and mix physics-data requirements.

One of the major experimental efforts of this plan is to construct a new beamline at the AGS at BNL to accept up to eight pulses of 25-GeV protons directly from the AGS at intensities typical of an AHF. This will allow tests of thick, weapons-geometry objects at near-AHF conditions. Previous experiments at the AGS used secondary beams of lower energy and intensity. These provided some of the early concept validation of proton radiography and have set the stage for this next step. Figure II-58 shows a proton radiograph of the French Test Object using 10-GeV protons at the AGS. The reconstructed densities and material boundaries are in good agreement with the known values. We plan to move the present proton-radiography experiments from Line B to the adjacent Line C, providing more space for multiple-lens configurations and larger containment vessels for larger HE charges. It is expected that this new area will be available for experiments in the FY98 run period at LANSCE.

Another major element of the program is development of high-resolution detection systems that are capable of multiple-frame recording. Since protons are charged, direct detection is possible. A prototype pixelated silicon array has been constructed, capable of buffering 1024 frames with 200-ns interfame separation. Electro-optic systems are also being developed. We anticipate that the testing of these systems will use the LANSCE beam and Line B apparatus over the next three years. This same setup can be used to evaluate and test new containment designs that would be applicable to the AHF requirements. Data from the Line B/C experiments will be used to benchmark and validate many aspects of the simulation and analysis effort for AHF development. At the end of this research and development program, proton radiography will be in a position to be evaluated, together with the other two technologies, as a viable tool for advanced radiography.

Fig. II-58. Proton radiograph of the French Test Object using 10-GeV protons from the AGS at BNL.





Sequential x-ray radiographic images of a sinusoidally perturbed liner as it is imploded on the Pegasus II Pulsed-Power Facility.

III. Project Descriptions

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P-DO: Physics Division Office

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Neuromagnetic Mapping of Multiple Visual Areas in Humans

C. J. Aine [(505) 665-2551], H.-W. Chen, J. S. George, M. Huang, J. C. Mosher (P-21), D. Ranken, E. Best (CIC-12)

This NIH (National Institutes of Health) project includes a series of experiments aimed at identifying and characterizing multiple visual areas in the human brain. These studies employ stimulus manipulations that have been shown in nonhuman primates to differentially activate specific cortical regions (e.g., regions with color or motion processing). Magnetoencephalography (MEG), in conjunction with magnetic resonance imaging (MRI), is used to determine the locations and arrangement of multiple visual areas in the human cortex and to probe their functional significance. In addition to suggesting human parallels to the nonhuman primate results, the proposed experiments provide an opportunity to discover new properties of the human visual system that may not exactly parallel those in nonhuman primates or expectations from other data in humans. For example, results obtained during the preceding project period on the retinotopic organization (point-to-point projection of the visual field onto areas of the brain) of the human visual cortex suggest that although the functional anatomy of the human occipital cortex corresponds in general terms to the "cruciform model" derived from lesion and human event-related potential (ERP) data, there are important differences revealed by the combination of magnetic measurements and anatomical MRI (Aine et al., "Unexpected Features of Retinotopic Organization in Human Visual Cortex Revealed by Neuromagnetic Mapping," in "Physics Division Progress Report, January 1, 1994–December 31, 1994," G. Y. Hollen and G. T. Schappert, Eds., Los Alamos National Laboratory report LA-13048-PR [November 1995], p. 36). We have also made a new and unexpected finding: the cingulate cortex in the central/frontal regions is not only responsive to visual stimulation but also appears to have some crude retinotopy. Because this region shows evidence of retinotopy, it should be classified as a visual area. This result has not been shown in invasive monkey studies because this region is too difficult to access in monkeys.

Identification of Two Streams of Visual Processing Using Magnetoencephalography, Functional Magnetic Resonance Imaging, and Positron Emission Tomography

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Recent studies in nonhuman primates and noninvasive functional imaging studies in humans suggest the existence of two streams of processing visual information, labeled the “dorsal” and “ventral” streams, that represent two different paths of activation along the cortex. The dorsal stream progresses from the occipital to the superior parietal cortex and is associated with processing spatial location and motion. The ventral stream (arrayed along the inferior occipital and temporal cortex) is associated with the processing of color and form. Anatomical and physiological studies indicate that these two streams differ in terms of their sensitivities to stimulus parameters such as luminance, spatial frequency, temporal frequency, and chromatic cues. In collaboration with the German National Laboratory in Juelich, we acquired positron emission tomography (PET), functional magnetic resonance imaging (fMRI), and magnetoencephalographic (MEG) data in the same six subjects in order to separate the streams of processing in the visual cortex. Responses to a stimulus containing a combination of features that preferentially excite the dorsal stream are being compared with responses to a stimulus containing features that should preferentially excite the ventral stream. Two different stimuli (circular with radially symmetric sinusoidal variation in either color contrast or luminance, using a black background and the highest possible contrast) were presented in the lower right visual field. The stimulus designed to activate the ventral stream was 3.5-deg in diameter, isoluminant, placed foveally, with a spatial frequency of 4.5 cycles/deg, and alternated at 2 Hz. The luminance of the red and green bands was adjusted to be equal for each subject. The larger (7.3-deg-diameter) isochromatic stimulus with luminance cues was placed as peripherally as possible, within the limitations of the hardware. The spatial frequency of the yellow bands was 3.5 cycles/deg, and alternated at 4 Hz. In all subjects, the activation evident in the primary visual cortex, for both fMRI and MEG measures, was found to be more anterior when the stimulus was presented more peripherally. Activations evoked when the stimulus was located more foveally were more posterior. This result reveals retinotopic organization. As predicted, more regions of activation were evident in the ventral slices for the foveal stimulus (of isoluminant color) than for the more peripheral stimulus containing luminance cues. Activity associated with the more peripheral stimulus was more medial and dorsal, in general.

Ultrasensitive Genetic Analysis

Alonso Castro [(505) 665-8044] (P-21)

Our research group focuses on the development of laser-based techniques for the ultrasensitive detection and analysis of biological molecules and the application of these techniques to molecular biology and medical diagnosis. We have recently developed a procedure for the rapid, direct detection of specific nucleic-acid sequences in biological samples. This method is based on a two-color, single-fluorescent-molecule detection technique. The basis of our approach is to monitor for the presence of a specific nucleic-acid sequence of bacterial, human, plant, or other origin. The nucleic-acid sequence may be a DNA or RNA sequence and may be characteristic of a specific taxonomic group, a specific physiological function, or a specific genetic trait. The detection scheme involves the use of two nucleic-acid probes that have sequences that are complementary to the nucleic-acid target. The two probes are labeled with two different fluorescent dyes. If the target is present when the probes are mixed in the sample under investigation, both probes bind to the target. The sample is then analyzed by a laser-based ultrasensitive fluorescence system capable of simultaneously detecting single fluorescent molecules at two different wavelengths. Since the probes bind to the same nucleic-acid target fragment, their signals will appear at the same time. Thus, the simultaneous detection of the two probes signifies the presence of a target molecule. When there is no target present, the probes will emit signals after illumination that are not coincident in time.

Studies of the Human Visual System Using m-Sequences and Sparse-Stimulation Techniques

H.-W. Chen [(505) 667-0825], C. J. Aine, E. Flynn, C. C. Wood (P-21), E. Best, D. Ranken (CIC-12)

The m-sequence pseudorandom signal has shown itself to be a more effective probing signal for studying nonlinear biological systems using cross-correlation techniques than the traditional Gaussian white noise. However, anomalies occurring in the measurements of second- and higher-order cross-correlations become obstacles to the m-sequence being more widely used in studying nonlinear systems. In these studies, a new approach using a short m-sequence as a probing signal together with the “padded sparse-stimulation” method is proposed. Simulation results showed that when using the sparse-stimulation method the estimation errors caused by anomalies will be greatly alleviated even for a short m-sequence. Another advantage of the padded sparse-stimulation method is that it can obtain all the information of the second- and higher-order kernels, whereas the traditional “inserted sparse-stimulation” method could not obtain all of the information of a nonlinear system. The new approach has been applied to neuromagnetic studies of the human brain. The weak neuromagnetic responses were stimulated by light modulated by short m-sequences

(1023 in length for binary and 728 in length for ternary) and measured by highly sensitive SQUID (superconducting quantum interference device) sensors located on the scalp of the human head. Cross-correlations with high signal-to-noise ratios were obtained, which show that the proposed methods in these studies are well applicable to the study of practical systems. These methods will be useful for both basic research and clinical applications.

Automatic Source Localization Procedures for MEG

M. Huang [(505) 665-6133], C. J. Aine, J. C. Mosher (P-21), E. Best (CIC-12), S. Supek (Department of Physics, Faculty of Science, Bijenická c. 32, 10 000 Zagreb, Croatia)

Cortical brain activity encountered in magnetoencephalography (MEG) studies can usually be modeled as electric current dipoles, if the regions of activation are relatively focused. The dipole location, orientation, and moment parameters are determined by fitting the measured data with a nonlinear minimization procedure. Due to the existence of many local minima and the properties of various minimization techniques, such minimization in a high-dimensional search space is usually very sensitive to the initial guesses when the number of modeled dipoles is greater than one. Manually selecting initial guesses is a time-consuming procedure, and if the initial guesses are not close enough to the global minimum, the calculation may fail to find the global minimum and become trapped in the local minima. Therefore, it is necessary to find an automated procedure to effectively handle the multiplicity of local minima. In this project, the performance of a number of global-minimization techniques applied to MEG is studied. These techniques include: (1) Multi-Start Downhill Simplex, (2) Genetic Algorithm, and (3) Simulated Annealing. These algorithms are tested for different simulated noise conditions (different noise levels and white noise versus color noise) and head models (a spherical head model and a real-shape head model). In addition to the simulated conditions, we will examine the algorithms using empirical MEG data collected with 122 channels from the whole-head Neuromag system.

Spatio-Temporal Magnetoencephalography and Electroencephalography Source Estimation

J. C. Mosher [(505) 665-2175], M. Huang, C. C. Wood (P-21), R. Leahy, J. Phillips, M. Spencer (University of Southern California Signal and Image Processing Institute, Los Angeles, California)

MEG and electroencephalography (EEG) provide unique views of the dynamic behavior of the human brain because they are able to follow changes in neural activity on a millisecond time scale. There is a clear need both for the development of new algorithms that exploit the most recent advances in sensor design, signal processing theory, and other functional and anatomical imaging modalities, and for a detailed study of the limitations of these and existing inverse procedures. LANL is a subcontractor to the University of Southern California on a three-year National Institute of Mental Health grant to develop such algorithms and to distribute the software and phantom data generated by this research. In addition to providing a suite of thoroughly tested inverse procedures, we anticipate that this work will provide insight into the fundamental limitations of EEG- and MEG-based source estimation.

Nuclear Magnetic Resonance Imaging with Hyperpolarized Noble Gases

D. M. Schmidt [(505) 665-3584], J. George (P-21), S. I. Penttila (P-23), A. Caprihan, E. Fukushima (The Lovelace Institutes, Albuquerque, New Mexico)

Several novel aspects of nuclear magnetic resonance (NMR) or MRI with hyperpolarized noble gases have recently been demonstrated, including the ability to easily image gas-filled spaces and to transfer part of the polarization to other nuclei. Using these new techniques, we have been investigating diffusion. We hyperpolarized ^{3}He by applying laser-optical pumping in the presence of rubidium molecules. We obtained one-dimensional images of ^{3}He gas diffusing in a slice that was tagged by inverting its magnetization, a technique previously used for observing the diffusion of thermally polarized ^{129}Xe gas. Also, a one-dimensional diffusion image of the gas was made with and without a temperature gradient present. Our results show that temperature changes can be monitored by diffusion images of ^{3}He gas.

Biomorphic Walking Machines for Unattended UXO (Unexploded Ordinance) Detection

M. W. Tilden [(505) 667-2902] (P-21)

The purpose of this project was to demonstrate the feasibility of building an automatic system for locating and, eventually, destroying UXO on military test ranges. The system would consist of three parts: sensors, legged robot platforms to carry the sensors, and an interface to connect the sensors and robots to implement a search strategy. In this first year, it was decided to concentrate on the development of robots capable of surviving harsh (Yuma desert) environments while carrying minimal sensor payloads. The robots are distinguished by the nervous-net (Nv) analog design, which is very inexpensive and is based on biological organism control. This design avoids the complexity and cost of computer-based systems and allows the use of inexpensive, off-the-shelf components. In September 1996 the most successful of the legged-walker prototypes was tested on a Yuma range, and, using a prototype Nv magnetic gradiometer sensor, found its footing, True North, and a mock magnetic mine during repeated trials. It was the first such device in the history of the range to perform these actions with complete autonomy and under full desert conditions (ground temperature ≅ 140°F). Work is proceeding now on a solar-powered version with a weeks-long survival potential and on more sophisticated magnetic sensors for true UXO detection.

Biomorphic Control of Autonomous Spacecraft

M. W. Tilden [(505) 667-2902] (P-21), J. R. Frigo, K. R. Moore (NIS-1)

The objective of this project is to define a mission to continuously monitor the characteristics of a major portion of the terrestrial magnetopause. This would be accomplished using one hundred or more biomorphically controlled, autonomous microsatellites with simple sensors. The mission would capitalize on highly innovative and radically smaller and cheaper satellite and sensor technologies that are currently under development by NASA, the Department of Defense (DoD), and DOE. This is a first step toward defining a useful, minimal microsatellite design for the future and is relevant to all areas that use spacecraft platforms. Toward this, we presented an application of a technology that seems, in experiment, to overcome most of the problems normally present in space missions: complexity, reliability, redundancy, and cost. Although the nervous-net (Nv) control method could be adapted to most types of machine control, we have applied it to autonomous satellite control because of the difficulty that conventional control systems have in solving the seemingly simple task of negotiating complex magnetic gradients. Over a dozen “nanosat” magnetic gradiometer prototypes were built and studied in a range of magnetic fields; analyses were performed, papers published, and a prototype presented at NASA and JPL workshops. The conclusions are that Nv systems could trivialize the cost of small-scale (20-g) satellite systems, and work is progressing toward a larger (200-g) prototype to assess payload control and handling requirements for commercial platforms.

Nonlinear Analysis of Nervous-Net (Nv) Designs

M. W. Tilden [(505) 667-2902] (P-21), B. Hasslacher (T-13)

Three years of studying experimental Nv control devices has resulted in various successes and several amusing failures that have implied some general principles on the nature of capable control systems for autonomous machines and, perhaps, biological organisms. These systems are minimal, elegant, and, depending upon their implementation in a "creature" structure, astonishingly robust. Their only problem seems to be that since they are collections of nonlinear asynchronous elements, only a very complex analysis can adequately extract and explain the emergent competency of their operation. The implications are that so long as Nv nonlinear topologies can retain some measure of subcritically coupled planar stability, the Piexito theorem will guarantee a form of plastic mode-locking necessary for broad-behavior competency. Further experimental evidence also suggests that if Nv topologies are kept in subchaotically stable regimes, they can be implemented at any scale and still automatically fall into effective survival strategies in unstructured environments. The conclusion is that Nv controllers have the power to scale, both physically and dimensionally, into any range of tasks that would otherwise require sophisticated programming. Research continues into understanding how such devices can converge their skills to evolve retentive abilities similar to neural-net structures, resulting in capable learning machines that have a trivial setup cost.

Autonomous Self-Assembling Robotic Mechanisms

M. W. Tilden [(505) 667-2902], M. S. Moses (P-21)

This research is aimed at the study, development, and integration of minimal nervous-net (Nv) artificial agents and the principles that allow for their elegant design, operation, organization, and self-assembly. Previous work along these lines (by Hasslacher and Tilden) has hinted that the field of nonlinear dynamics may provide important, broad principles with which we can promote the survival of active, robust devices in unstructured environments. Advances in this area will allow for the design of devices that are "smart enough" for a task without the usual cost-intense complexity that accompanies traditional robotic construction. Since the start of the project, 18 self-contained "assembler bots" have been built and studied in our robot "Jurassic Park." New control systems have been devised to allow these devices to power-mine their environment—exploiting the available light-energy sources—without having to resort to internal batteries. Future work will examine and promote the development of these mobile machine components so that they may act as coordinating organs in sophisticated robots for application-specific tasks, creating a form of "living Lego" with inherent self-repair and self-optimization characteristics.

P-22: Hydrodynamic and X-Ray Physics

Subcritical Experiments: Data Recording

G. Allred [(505) 667-2497], D. Bartram, T. Petersen (P-22)

The JTO-1 trailer at the Nevada Test Site (NTS) provides much of the high-speed data-recording capability for the P-22 activities in the U1a underground complex. Amplitude calibration and absolute timing of approximately 200 data-recording channels have been performed, using simulated signals generated in the downhole "zero" room that are transmitted in some cases over fiber-optic links. While preparation continued on the first subcritical event (Rebound), dry runs were performed on a routine basis to confirm system reliability.

Radiation Science

R. Bartlett [(505) 667-5923], J. Benage, G. Idzorek (P-22)

P-22 is collaborating with other Los Alamos groups and with Sandia National Laboratories (SNL) personnel on several pulsed-power radiation-driven campaigns on PBFA-Z (the Z-pinch radiation driver at SNL). The two most active efforts at this time are the Integrated Compression Experiment and the Dynamic Hohlraum Experiment. In the former experiment, several aspects relevant to weapons physics are addressed simultaneously, with the result that designs and codes can be tested in an integrated manner. In the Dynamic Hohlraum Experiment, the goal is to create high-temperature hohlraums and to drive inertial confinement fusion (ICF) capsules by using the pinch itself to form the hohlraum. By using the pinch or the end-on radiation to drive the experiment, more energy will be available than would be possible through the more conventional approach of radially coupling the radiation from the pinch to a secondary hohlraum.

P-22 is involved in the definition of the experiments and in fielding diagnostics on the shots. We also analyze and interpret the results. In the past we have fielded filtered silicon diode arrays, pinhole cameras, and a transmission-grating spectrometer. We have also been involved in the calibration of these instruments at the National Synchrotron Light Source (NSLS) at Brookhaven National Laboratory (BNL), where Los Alamos owns and maintains three synchrotron beamlines. Calibration of these instruments is very important to the interpretation of the results.

High-Explosive Pulsed Power

D. Bartram [(505) 667-2501], G. Allred, O. Garcia, T. Petersen, J. Stokes, L. Tabaka (P-22)

P-22 is working with DX Division, preparing for a series of upcoming tests at the Lawrence Livermore National Laboratory (LLNL) facility in Area 4 at NTS known as BEEF (Big Experimental Explosive Facility). These tests, Ranchito, Ranchero, and Caballero are part of the High-Explosive Pulsed-Power (HEPP) program.

P-22 is performing the diagnostic recording for all of these experiments. These will include Faraday rotation, Rogowski loops, B-dots, and voltage probes. The first shot, Ranchito III, will be recorded by the LLNL bunker personnel under the guidance of P-22 and DX-3. Subsequent experiments are planned to be recorded in a P-22 trailer that will be moved into a recently completed protective enclosure. Current plans and support funding (from Bechtel Nevada) suggest that there will be two experiments in FY97 and some preliminary work for a third.

The facility is currently completing two years of development and certification. The first official experiment to be performed will be the LANL Ranchito III shot, which is currently scheduled for the first week in March 1997.

Radiation Source/Switch Development

J. Benage [(505) 667-8900], R. Newton (P-22), F. Wysocki, T. Ortiz (P-24)

The radiation-source project has been focused on the development of a plasma flow switch for use on the Atlas pulsed-power facility when it becomes operational in FY 2000. This switch consists of two components: an aluminum wire array and a plastic barrier film. The switch works by carrying an electric current for a few microseconds, during which the switch moves down a coaxial transmission line driven by the magnetic force from the current. It then transfers the current to another area, called the load region, as it passes by. This allows the machine to provide electric current to the load region on a time scale much shorter than the natural time scale of the machine, which is necessary if the Atlas facility is to be used to produce a radiation source for weapons-physics experiments.

The effort in this past year has been focused on the initial conditions produced in the switch plasma and on how to manipulate these conditions. We have done a series of experiments on the P-24 Colt facility and the P-22 Pegasus II facility. These experiments indicate that our past designs have not produced the right conditions in the switch. The plasma does not assemble as a single switch but seems to come together in two pieces, creating a thick plasma sheath and not producing in the coaxial conductor the current rise times that are needed. We believe the reason for this is that the machine parameters are not well matched to the requirements for this initial formation. We are planning another set of experiments on Colt in the near future to investigate this discrepancy between parameters and requirements in more detail and to attempt to design a slightly different switch to compensate for the machine parameters available to us. The overall goal is to understand this initial formation process and to determine what is required to get the best performance. Once we have reached this goal, we are planning more experiments to investigate the interaction of the switch with whatever is in the load region. This effort will move us a long way toward a working switch for Atlas.

Dense-Plasma Equation-of-State Project

J. Benage [(505) 667-8900], J. Workman (P-22), G. Kyrala, S. Evans, P. J. Walsh (P-24)

The purpose of the dense-plasma equation-of-state (EOS) project is to measure the EOS of aluminum under dense-plasma conditions. By "dense plasma" we mean material that is 0.1–1.0 times the solid density of aluminum and has a temperature of tens of electronvolts. These conditions are such that the material is ionized and in the plasma state, but interactions between particles in the plasma are very strong and the linear theories used to describe the properties of the plasma are no longer valid. It is under just such conditions that the thermodynamic properties of materials are least well known and where there are no data available to compare to theory.

We have designed a novel way of producing a dense plasma and will use a standard technique for determining the EOS of this plasma. The standard technique, which has been mainly used on solids, is to produce a shock and then measure the velocity of the shock and the density of the material in front of and behind the shock. Using these measurements and the conservation equations across the shock front, one can determine the density, pressure, and internal energy of the material and thus the EOS of the material under those conditions. We produce our plasma by using a small capacitor bank to electrically heat an aluminum wire to a temperature of ~2 eV. This aluminum plasma is allowed to expand into a vacuum through a rectangular slit, producing a uniform plasma that is used as a target for a powerful laser. The laser is focused onto this plasma, producing a shock that propagates through it. We then use an x-ray backlighter to image this plasma and measure its density and the velocity of the shock.

We have begun preliminary measurements of the x-ray backlighter source and have nearly completed construction of the new capacitor bank that will be used to produce these plasmas. We will soon be testing this bank and using the backlighter to make preliminary measurements of the target plasma we produce. We have also begun construction of the laser needed for producing the shocks in the plasma, and we expect this laser to be completed by August 1997, at which time we expect to begin measurements of the EOS of the plasma. We are also in the process of designing and constructing an x-ray microscope for imaging the shock propagation through the plasma. This diagnostic should also be ready for operation in August.

Optical Constants Research on LANL Synchrotron Beamlines

R. L. Blake [(505) 667-7369] (P-22)

A program of measuring atomic constants has been active on LANL beamlines for seven years. Our experience and precision x-ray spectrometer/reflectometer, combined with existing LANL beamlines at NSLS at BNL, place us in a unique position to contribute high-accuracy (~0.1%–1% 3σ-error) measurements of both the real and imaginary parts of the complex dielectric constants of elements and materials. We are able to make these measurements over a wide energy range, from 50 eV to 15 keV, including all of the edge structure that is largely nonexistent in literature compilations for most of the energy range. The hardware and computer software is transportable between LANL beamlines.

From combined reflectivity and transmission measurements, we have provided new or improved optical constants of gold, iridium, molybdenum, palladium, and platinum over the energy range 2–15 keV. Iridium and the polymer polyimide ($C_{22}H_{10}O_4N_2$) have also been measured from 50 to 1000 eV. Measurement precision has varied from 0.1 to 1.0 percent, depending on the beamline and the circumstances. Present accuracy of a few percent will soon be improved to better than one percent by using multiple techniques to refine the sample thicknesses and smoothness. Detailed measurements through the M-edges of gold, platinum, and iridium have provided new values of the x-ray absorption edge energies that differ by 30 to 40 eV from photoelectron spectroscopy binding energies. These differences have been explained with atomic modeling for gold; they are due to the slow onset of the $3d * f$ transition. Further band structure modeling confirms this explanation and confirms the observed x-ray absorption fine structure as well.

Self-Directing Elastic-Backscatter Lidar

D. A. Clark [(505) 667-5054] (P-22), collaborators from NIS and Bechtel Nevada

Lidar (light detection and ranging) has many applications in the fields of atmospheric research and environmental monitoring. Elastic-backscatter lidar, also called Mie lidar, can "see" aerosols in the air, even if the concentration is very slight and the aerosol cloud is not visible to the eye. Elastic-backscatter lidar systems have been used to detect aerosol emissions from industrial stacks and debris clouds from transient events such as above-ground explosions. However, they have not been used to track the path of debris clouds or to map cloud evolution.

A new adaptive, scanning, self-directing, elastic-backscatter lidar that automatically tracks and maps isolated clouds has been developed at Los Alamos. It has been used to gather cloud data from two above-ground explosive tests. Accurate cloud volume, density distribution, and track information was obtained from small, fast-moving, low-density, invisible debris clouds. The new lidar control system utilizes the backscatter signal itself to direct the lidar toward the cloud and minimize the scan dimensions. As the cloud evolves, both spatially and temporally, the system dynamically readjusts the scan to cover the entire volume of the cloud. Confinement of the scan region to the immediate vicinity of the cloud allows more scans in a given time, producing high-resolution information during the cloud evolution.

Cloud-tracking lidar can be used as part of an environmental monitoring program to assess the migration of emissions from transient events. It can also direct other remote-sensing devices for species identification.

High-Energy Liner Experiment

D. A. Clark [(505) 667-5054], T. Petersen, L. Tabaka, B. Anderson (P-22), collaborators from the NWT Program office, DX, and X Divisions

Magnetically driven, imploding liner systems can be used as a source of shock energy for materials EOS studies; implosion-driven, magnetized-plasma fusion experiments; and similar applications. Such systems can play an important role in support of nuclear-weapons stockpile stewardship by allowing us to verify our abilities to perform accurate calculations. The imploding liner is a cylinder of conducting material through which a very high current is passed in the longitudinal direction. Interaction of the current with its own magnetic field causes the liner to implode at high velocity. Experiments requiring high-velocity impact or volume reduction are placed at the center of the liner. In order to be effective, the liner must remain in a condensed state (not vaporized), retain its cylindrical shape (liner stability), and attain a high velocity during the implosion. In order to meet these requirements, liners must be thick and of large diameter, be manufactured to precise tolerances, and have high convergence ratios. High energy is required to move these heavy liners. Robust and accurate diagnostics are needed to measure the liner performance and target responses.

In August 1996, a collaboration of scientists from LANL and the All-Russian Scientific Institute of Experimental Physics (VNIIEF) of Sarov, Russia, conducted a high-energy liner experiment in Sarov. It was the highest-energy and largest liner experiment ever performed. The purpose of the experiment was to measure performance of the explosive pulsed-power generator and the heavy imploding liner, to test the capabilities of various diagnostics under extreme conditions, and to obtain data for comparison with performance calculations. A 5-tier, 1-m-diameter explosive disk generator provided electrical energy to drive a 48-cm-outside-diameter, 4-mm-thick aluminum-alloy liner having a mass of about 1 kg onto an 11-cm-diameter diagnostic package.

The experiment was a great success. Peak current was greater than 100 million amperes and the liner kinetic energy was more than 20 megajoules. Results of this American-Russian collaborative effort will provide needed information for improved performance in future high-energy liner systems.

Nuclear Weapons Archiving Project (NWAP) in P-22

K. Croasdell [(505) 667-2483], D. Bartram, G. Idzorek, J. Lamkin, D. Mills, J. Pelzer, D. Thayer, B. Wright, C. Young, L. Zongker (P-22)

Several objectives and priorities for Science-Based Stockpile Stewardship (SBSS) have been established by LANL and the nation as a whole. Weapon-design competence is presently viewed as the cornerstone of this stewardship. In the absence of any new nuclear testing, designing nonnuclear physics experiments and applying new computational skills to past NTS data will be important steps in the development of our predictive capability and in the improvement of our ability to solve unanticipated nuclear-weapons problems.

P Division is the steward of much of the data recorded in past NTS tests. Collecting the data, putting it into a usable format, and maintaining the expertise required for interpretation of the data are crucial tasks for the present group of weapons-physics scientists in P Division.

In P-22, NWAP has grown from a funding base of $100 K in FY94 to $1.21 M in FY97. We are addressing four major tasks in this project.

Collection/analysis of reaction-history experiments. We completed our review and reanalysis of the reaction-history data from the W76 weapon system in FY95. The actual data files and metadata were placed on the Common Event Data System (COEDS) and have been transferred to LLNL to satisfy requirements of the Dual Revalidation Program. COEDS is a weapons-information database that resides in XCM for the use of the LANL weapons community. In FY96, we concentrated on the W87 and B61 systems. In FY97, we continued to work on the B61 data. New analysis requirements for FY97 include reanalyzing events related to the W80 system and events related to tests that are unusual and not related to a specific weapon system.

Experimental procedure documentation and training. We are using weapons-test data and our staff expertise to document experimental procedures and build a foundation for training future scientists. In FY97 one of our primary tasks is to describe how to perform a reaction-history measurement. We are also updating and expanding a glossary on COEDS of terms that relate to weapons testing. We are writing a general electromagnetic-pulse (EMP) report, addressing the technical basis for EMP experiments and writing physics reports for several NTS events dating back to the early 1980s. We are working with Bechtel to develop 1990s hardware and software platforms for converting and working with the historical data; this task will occupy us well into FY98.

Collection and analysis of advanced diagnostic experiments. P-22 is learning what advanced diagnostic experiments were fielded and is planning to suggest appropriate reprioritizations of the list of tasks that we are pursuing. Many of these advanced diagnostic experiments were unclassified, resulting in inconsistent organization of the initial archiving of the event. In several instances this deficiency makes it very difficult to locate pertinent data for reanalysis. We are interpreting and documenting shot-physicist notebook quotations to obtain more details of these NTS experiments.

Completion of physics reports on the most recent NTS events. Only two of the six experimentalists involved in the original NTS events still work as full-time staff members for P-22, so completion of this task becomes ever more important. Divider, Whiteface A, Whiteface B, Sundown A, Sundown B, and Junction are the first shots we are examining. Victoria, Lubbock, and Houston will need extensive work. The archiving-project members have contributed information for the P-Division Internal Weapons-Physics Report and to the Nuclear Weapon Technology “Green Book,” which describes the procedures for stockpile stewardship.

P-22 will continue to address requests as needed to support the weapons program. Reaction-history data about the W76 were given to LLNL to use in the Dual Revalidation Program, and W87 reaction-history data were collected from LLNL for the X-Division weapons designers to use in the Life Cycle Program. Data archived for the B61 were instrumental in the certification process for the B61 mod 11. We have participated in the interlaboratory information group (NWIG) to establish data-transfer standards between the three nuclear laboratories, the production plants, and the U.K. Atomic Weapons Establishment (AWE). We may perform analyses of U.K. shots if funding becomes available.

High-Speed Multiwavelength Infrared Pyrometer

D. Holtkamp [(505) 667-8082], P. Rodriguez, J. Studebaker (P-22), G. Schmitt (DX-1)

P-22 has assembled a high-speed, multiwavelength infrared (IR) pyrometer for use in Pegasus II and high-explosive (HE) experiments. We expect to be able to measure temperatures between 500 and 1300 K. The unit uses four liquid-nitrogen-cooled detectors (HgMgTe) operating over various wavelength bands between 1 and 5 μm. These detectors are coupled via four 1-mm-diameter IR fibers to a position that views the surface of interest. The instrument has been repackaged by Bechtel Nevada into an electromagnetic-interference- (EMI-) and debris-shielded box for use in pulsed-power and HE environments. The bandwidth of the system is approximately 10 MHz. Improvements are planned that will extend the measurements to colder temperatures and higher bandwidths. Calibrations are currently in progress, and we expect to field the instrument at Pegasus and in HE shots in early 1997.

Radial Radiography at Pegasus II

D. V. Morgan [(505) 665-6679], D. Platts, D. Martinez (P-22), B. Carpenter (P-24)

At Pegasus II, electromagnetically driven implosions in a cylindrical geometry are observed using three radially oriented, flash x-ray sources. Our three x-ray sources backlight the target with tungsten line and bremsstrahlung x-rays with an endpoint energy of approximately 270 keV. The x-ray pulse duration for each source is approximately 20 ns, which is quite short compared to the time scale of the implosion. The radiographs are recorded on film and deliver quantitative information about the position and density of the imploding material. Recent improvements to the three radial x-ray imaging systems include reduced x-ray scattering, improved source collimation, blur reduction, and an improved signal-to-noise ratio. We have developed a computer code that can generate a simulated radial radiograph of both static and dynamic Pegasus targets. Radial radiography was an important diagnostic for Liner Stability, Megabar, Ejecta, and Liner Gap experiments at Pegasus in 1995 and 1996. We expect that radial radiography will continue to provide quality data for future Pegasus and Atlas experiments.

Fiber-Optic Data-Link System

T. Petersen [(505) 665-2786], D. Bartram, G. Allred (P-22), collaborators from Bechtel Nevada

A new fiber-optic link system has been produced in association with Bechtel Nevada to deliver experimental data from hazardous areas to data-recording areas. The hazards that were thus circumvented include both severe electrical and high-explosive hazards. The transmitters are enclosed in an EMI-shielded enclosure that is battery powered for electrical isolation and has fiber-optic-coupled calibration and monitor functions. The optical receivers also have monitor functions. Two different fiber-link modules are interchangeable in this system, a 200-Hz to 75-MHz light-emitting-diode (LED) link and a 2-kHz to 450-MHz laser link. They have a linear signal level of 0.5 V and a signal-to-noise ratio of better than 40 dB. There are about 100 channels available of each fiber link. At present this system is in use on Pegasus II, the Atlas Test Bay, BEEF (at NTS), Ancho Canyon, and the Integrated Test Stand.

Ejecta Experiments at the Pegasus II Pulsed-Power Facility

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When a shock wave reaches a solid/gas (or liquid/gas) interface, pieces of the solid or liquid can be emitted into the gas region. This material can range in size from submicron to hundreds of microns and is referred to as ejecta. The amount, size, and velocity of ejecta will depend on material properties such as grain size, surface finish, and the state of the shock wave in the material. Ejecta occur in a nuclear weapon when a shock wave interacts at interfaces between weapon materials and gases. At these interfaces, materials can be injected into the gas, contributing to the mix of weapon materials and gas, which in turn has an effect on the performance of the nuclear device. In order to characterize the ejecta, P Division has developed an in-line Fraunhofer holography technique to make measurements of ejecta in a dynamic system. This diagnostic has been developed and implemented on numerous experiments based at the Pegasus II Pulsed-Power Facility. This facility has the capability of driving many megaamperes of current through an aluminum cylinder (liner) that is 400 μm thick, 10 cm in diameter, and 2 cm high. Physics experiments are performed inside the cylinder, making use of its cylindrical geometry. For the ejecta experiments, a 3.0-cm-diameter target cylinder is placed inside the liner cylinder. When the liner impacts the target cylinder, a shock wave is set up in the target. The shock wave then propagates through the 400-μm-thick target, and at the target/vacuum interface, ejecta are emitted. An additional 1.6-cm-diameter cylindrical collimator with various slit openings is used to control the amount of ejecta that passes through to the axial center. This target assembly consists of three cylinders with the same axis. To make the ejecta holographic measurement, a 60-mJ, 100-ps, 1.5-cm-diameter laser pulse is transported along the collimator axis. The laser beam then interacts with the ejecta, which passed through the collimator slits some time after the liner cylinder impacted the target cylinder. The actual hologram is made when the scattered light from the ejecta interferes with the unscattered laser light (reference beam) at the plane of the film. In order to measure particles a few microns in size, the holographic film should be placed a few centimeters from the ejecta. However, at this distance the film would be destroyed in the experiment. To address this problem, an optical transfer system was developed, which relays the interference pattern 93 cm from the ejecta to the holographic film. The hologram contains information about particles ranging in size from a few microns to a hundred microns in diameter, over a volume of 1 cm^3. In addition to the holography diagnostic, a visible shadowgraphy and dark-field imaging technique has also been developed. This diagnostic does not provide three-dimensional information like holography, but it provides time- and spatially resolved data about the ejecta front as it moves through space. This diagnostic makes use of a long-pulsed ruby laser (with a 450-μs pulse), in which the laser beam passes through the ejecta and a framing camera is used to make time-dependent, spatially resolved shadowgrams of the ejecta. This technique has been applied to many experiments successfully. Ejecta data have been obtained for both aluminum and tin targets for which the target surface finish and shock strength have been varied.

Liner Gap 7

J. L. Stokes [(505) 667-4900] (P-22), P. Brown, M. Fell, P. Jones (Atomic Weapons Establishment, Aldermaston, England), R. D. Fulton, D. Platts, D. L. Martinez, D. M. Oró (P-22), A. W. Obst, N. S. P. King (P-23), B. Carpenter (P-24), P. J. Adams, J. A. Guzik, (XTA), H. Oona (DX-3)

Liner Gap 7 was successfully fired on April 11, 1996, at 2:35 p.m. This was the first test fielded in collaboration with the Atomic Weapons Establishment (AWE) in the U.K. The classified target was designed by Peter Brown and Michael Fell (AWE) and was built by LANL in MST-7 by Wally Anderson and his crew. The process from concept to actualization was completed in a very short period of time: the definition occurred March 9, and the shot was fired April 11.

The normal gap diagnostics were fielded by LANL. These included axial x-ray images at two different times, radial x-ray images at three different times, framing cameras looking at a backlighter for shock position, radial visible imaging at three different times, as well as the normal machine diagnostics. All systems returned good data, and the axial imaging data were the best to date. They showed shock structure that we did not expect to see, but having seen it, we reexamined the calculations and found that it had been calculated before the shot.

We were extremely pleased with the results, as was AWE. As a result of the good-quality data from Gap 7, AWE expects to continue our collaboration on future tests. The next joint test will be in the second quarter of FY97.

In June 1996 we reviewed the Gap 7 data with B-Division members at Livermore, and they were very interested. They have proposed to do tests with us on Pegasus, and we are looking forward to this collaboration as well.

Peter Adams and Joyce Guzik (XTA) are designing Gap targets for the Gap tests in FY97.

Liner Gap Experiments

J. L. Stokes [(505) 667-4900], R. D. Fulton, D. Platts, D. L. Martinez, D. M. Oró (P-22), A. W. Obst, N. S. P. King (P-23), B. Carpenter (P-24), P. J. Adams, J. A. Guzik (XTA), H. Oona (DX-3), E. Chandler, P. Egan (LLNL), collaborators from Bechtel Nevada

We are planning three Gap shots for FY97. The first two shots are planned as a campaign. We have chosen designs for the first two shots from a list of ideas for future shots. Some calculations were done on several of the ideas and one of the more interesting was chosen to be the first shot, in February 1997. The second shot is already designed and will follow a week later.

We are improving the axial x-ray imaging system for the first campaign of Gap shots. The new system will be a single optical path that will be split in the screen room. This will solve the vignetting problem. We also hope to have new cameras for this new system. One small disadvantage will be that there will be only two cameras on this system, which means no redundancy for either image capture. One advantage is that this is a simpler system and should be fielded more easily. This updated system is expected to be in place by the second campaign, which is scheduled for the summer of 1997.

The Dirac Series of Experiments at Multimegagauss Magnetic Fields

L. R. Veeser [(505) 667-7741], P. J. Rodriguez, D. E. Bartram, D. A. Clark (P-22), collaborators from DX, T, and X Divisions, All-Russian Scientific Institute of Experimental Physics, Bechtel Special Technologies Laboratory, and Bechtel Nevada

In May 1996 we began a series of experiments using explosive-driven flux compression generators that produce microsecond-time-scale, megagauss magnetic fields at Firing Point 88 in Ancho Canyon. The series was named for P. A. M. Dirac, whose contributions to quantum theory are basic to all of the physics in the series. The experiments attracted scientists from Japan, Australia, Russia, and several U.S. laboratories, including Louisiana State and Florida State Universities and the National High Magnetic Field Laboratory. We used two types of generators, inexpensive Los Alamos–designed strip generators, capable of 130-T fields, and more elaborate Russian MC1 generators, which can produce over 1000 T (10 MG). In addition to recording the data for all of the experiments, P Division participated in several of the research efforts, including improved-geometry glass crystals to optically monitor high magnetic fields, a technique of particular interest to us because we will be producing very high fields on the Atlas Pulsed-Power Facility when it comes on line in 1999. We measured the Faraday rotation of polarized laser light in the diluted magnetic semiconductor CdMnTe, in which the spin exchange between magnetic ions (Mn^{2+} in this case) and the band electrons produces a large splitting of the band and consequently a giant Faraday effect. We took some interesting data, which we are now trying to interpret, and we will make further measurements. We also fielded a first attempt to determine a measurement standard for ultrahigh magnetic fields using samarium or europium. The ions Eu^{3+} and Sm^{3+} encounter jumps in Faraday rotation when the Zeeman-split excited states cross the ground states in energy. The critical fields at which these jumps occur are determined only by atomic constants and are unaffected by the environment in which the ions find themselves. This last experiment was unsuccessful because of a lack of light in our sample, so we will repeat it. All of the experiments, and perhaps some new ones, will be continued when the series resumes in the summer of 1997.

Equation of State (EOS) of Plutonium

L. R. Veeser [(505) 667-7741], P. J. Rodriguez, D. A. Clark, D. M. Oró, G. D. Allred, R. D. Fulton, O. F. Garcia (P-22), F. H. Cverna, N. S. P. King (P-23), collaborators from DX, X, and ESA Divisions, Sandia and Lawrence Livermore National Laboratories, and Bechtel Nevada

Following the decision by DOE to use NTS for experiments involving plutonium and uranium isotopes that are hazards to the environment, we are preparing a measurement of the EOS of delta-phase plutonium to increase our understanding of the physics of nuclear weapons. The first of these experiments, Rebound, is being fielded jointly by P Division, DX Division, and the rest of the support groups formerly responsible for experiments on underground nuclear tests (UGTs). We will have three experimental assemblies contained underground in a way similar to UGTs. In each assembly we will accelerate a steel flyer plate with high explosives, and the plate will impact several flat plutonium samples. By measuring the plate velocity and the velocity of the shock waves induced in the plutonium for each explosive configuration, we will obtain three EOS data points for plutonium at pressures between 80 and 230 GPa. Each impact will produce a shock that travels back through the flyer plate, unloads into the vacuum, and returns toward the plutonium as a rarefaction. For each assembly we will determine the sound speed in the shock-heated plutonium from the position where the rarefaction overtakes the shock in a heavy glass sample on the back of the plutonium. The sound speed results will be used to determine the shock pressures at which phase changes occur in plutonium. Jointly with experimenters from Livermore, we will measure a point on the plutonium release adiabat by placing a low-density foam on one of the samples and measuring the shock velocity in the foam that is induced by the unloading of the plutonium shock. Finally, DX and Sandia will measure the spall strength of shocked plutonium using a VISAR interferometer to follow the velocity of the back surface of one of the samples. The role of P Division is similar to its UGT role: participating in the experiment design, fielding the diagnostics and recording equipment, and working on the data interpretation. We have carried out seven local experiments substituting copper for the plutonium to test out the diagnostics and procedures, and we will execute Rebound in 1997.

Isentropic Compression of Argon

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Los Alamos National Laboratory and the All-Russian Scientific Institute of Experimental Physics are performing a set of experiments to explore the conductivity and possible metalization of argon when it is compressed to more than five times its normal density. The experiments use a magnetic field of several megagauss generated by a Russian MC1 explosive-driven flux-compression generator. The field compresses a small metallic tube (~14 mm in diameter by 180 mm long) containing solidified argon. A probe in the center of the tube measures the electrical conductivity to the walls, and a 60-MeV betatron serves as a source for a radiographic measurement of the compression at a point near its maximum. For a compression of ~4.9 times (at a calculated pressure of about 7 Mbar and temperature of 2000 K), we measured a conductivity of 8 $\Omega^{-1}\bullet cm^{-1}$, more characteristic of electron hopping than incipient metalization. Upon increasing the compression to about 5.1 and improving the probe design, we saw a conductivity of 75 $\Omega^{-1}\bullet cm^{-1}$, still far from a metal. The radiographically measured compression of 5.1 is theoretically above metalization for body-centered cubic (bcc) lattice structure, but below metalization for face-centered cubic (fcc) and hexagonal close pack. A transition from fcc to bcc is predicted to occur at a compression of 3.91. Because of the temperature, substantial fractions of each lattice structure are expected. Calculations of the lattice indicate that we are in a region where the highest point in the valence band is above the lowest point in the conduction band, but the two points occur at different places in the crystal structure. As a result, indirect transitions are needed for an electron to move from one atom to another. In view of the surprisingly small conductivity and its variation with compression, we are planning substantial improvements in the experiment, including a repeat of the low-compression measurement with the new conductivity probe and a measurement with a Teflon insulator inside the tube wall to verify that the observed conductivity was due to the argon and that the insulators in the experiment remained nonconducting at the high pressures obtained. The compression remains at its maximum for a very short time, at most a few hundred nanoseconds, so we intend to measure the compression curve with time to confirm the timing of the radiograph relative to peak compression. For this, the betatron has been modified to produce a series of three pulses per event. We will use a thin scintillator—to convert to visible light the x-rays transmitted through the tube—and an electronic camera that will record the images. We will also begin to measure the conductivity of krypton, which has a similar lattice structure but is expected to metalize more easily than argon, to determine the compression at which full metalization of krypton occurs.

Beam Diagnostics for the Dual-Axis Radiographic Hydrodynamic Test (DARHT) Accelerator

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Microwave diagnostics are being developed by P-22 to monitor the diameter of the electron beam of the DARHT linear accelerator. Nonintrusive diameter measurements are needed in the DARHT beam-transport sections to ensure proper focusing of the beam on the x-ray-generating target. A two-pass microwave interferometer at 24 GHz has been assembled for this purpose. It is currently undergoing trials on the Integrated Test Stand (~4 MeV, ~4 kA). Looking ahead to the more stringent requirements of DARHT itself (~20 MeV), a microwave resonator concept has been examined in detail. The latter approach, at 8 GHz, offers increased sensitivity and better control of geometrical factors.

P-23: Neutron Science and Technology

Sudbury Neutrino Observatory Experiment

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In order to make a model-independent test of the origin of the solar-neutrino problem, we have joined the Sudbury Neutrino Observatory (SNO) experiment. The SNO detector (which will soon to be operational) is a water Cerenkov detector with 1,000 tonnes of heavy water contained in an acrylic vessel. The acrylic vessel is surrounded by another vessel with 8,000 tonnes of light (regular) water in which 9500 8-in. photomultipliers view the Cerenkov events in the heavy water. Solar neutrinos produced from the decay of ^{8}B in the sun may interact with the deuterium in the heavy water either to produce an electron (which is observed from its Cherenkov radiation) or to break up the deuteron into a proton and a neutron. The first (charged current) reaction can be initiated only by electron-type neutrinos, whereas the latter (neutral current) reaction can be produced by any of the three flavors of neutrinos (electron, muon, or tau). Our group at Los Alamos National Laboratory (LANL) originated and developed the use of extremely low background ^{3}He counters to be installed in the SNO detector as a means of detecting the neutrons produced by solar neutrinos. (As a spin-off, the semiconductor industry is very interested in using the very sensitive, low-background detectors to screen high-density microelectronics for trace radioactive contaminants that can cause computer errors by "flipping" bit patterns.) The SNO detector will carry out two model-independent tests of the origin of the solar-neutrino problem. In the first method, we will accurately measure the shape of the ^{8}B neutrino spectrum and see if the distortion characteristic of neutrino oscillations is occurring. In the second, we will observe if the rates of the charged and neutral current interactions are equal. If they differ, this would also indicate that neutrino oscillations are occurring.

GaAs Detector Development

T.J.Bowles [(505) 667-3937], S.Brice, A.Goldschmidt, A. Hime (P-23), M.Fowler, J.Wilhelmy (CST-11), collaborators from the Institute for Nuclear Research (Moscow, Russia), and Ioffe Institute of Physical Sciences

A GaAs detector can offer substantial advantages over other technologies in searches for weakly interacting massive-particle (WIMP) dark matter and high-resolution measurements of the solar-neutrino spectrum. GaAs offers the prospect of providing lower backgrounds than possible in other detectors along with a low energy threshold and very good energy resolution at room temperature. The physics that can be addressed is at the forefront of modern physics. In the short term, our efforts will be directed at searching for the cold dark matter that apparently makes up 90% of the mass in the universe. In the long term, it may prove feasible to address the question of neutrino mass using a large GaAs solar-neutrino detector. This could provide the possibility of making a very precise determination of the neutrino-oscillation parameters (if neutrino oscillations are shown to be the source of the solar-neutrino problem), a model-independent test for the existence of sterile neutrinos, and a model-independent measurement of the central temperature of the sun.

We have formed a collaboration with the Institute for Nuclear Research in Moscow to develop small GaAs detectors and to construct a prototype dark-matter detector. If successful, we then plan to propose a full-scale dark-matter detector that would be capable of covering most of the predicted range for the existence of WIMPs. This research would also allow us to determine the technical feasibility of pursuing a large-scale GaAs solar-neutrino detector.

EMIT

T. J. Bowles [(505) 667-3937] (P-23), G. L. Greene (LANSCE-DO), collaborators from the University of Michigan, National Institute of Standards and Technology (NIST), University of California at Berkeley, University of Washington, and Notre Dame University

The discovery of charge-parity violation by Cronin and Fitch, coupled with the CPT theorem (one of the basic tenets of modern physics), necessarily implies the existence of time violation. However, unlike parity violation, time-reversal invariance violation (TRIV) has been observed only in the kaon system, and presently several alternative theoretical explanations are possible. Untangling this interesting puzzle requires a variety of experiments that have unique sensitivities to the many models that predict possible TRIV effects.

Los Alamos initiated the EMIT ("TIME" reversed) collaboration to pursue a search for TRIV in the beta decay of the free neutron. A nonzero triple correlation between neutron spin, electron momentum, and proton recoil violates T symmetry. The experimental technique is to record the betas and proton recoils from the in-flight decay of polarized, cold neutrons. The TRIV signal consists of a nonvanishing difference when the neutron spin is flipped. A Monte Carlo study to model experimental sensitivity, verified by a test measurement, has revealed an optimized detector geometry seven times more sensitive than geometries employed in previous experiments. An octagonal detector geometry (4 proton- and 4 electron-detector assemblies) has been constructed, and we are now beginning to exploit this sensitivity and take data using the cold-neutron beam at the NIST reactor. We expect to improve the sensitivity of the previous measurements (which were at the 3×10^{-3} level) by an order of magnitude.

SAGE

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The number and spectrum of neutrinos from the sun continues to challenge our understanding of solar physics and neutrino properties. Los Alamos has been the lead U.S. laboratory in the SAGE (Soviet-American gallium solar-neutrino experiment) collaboration since it began in 1985. SAGE is a radiochemical experiment located at the Baksan Neutrino Observatory in southern Russia.

Solar neutrinos produce ^{71}Ge atoms by inverse beta decay on ^{71}Ga. The ^{71}Ge atoms are chemically extracted from the 60 tons of metallic liquid gallium, and their decay is measured in miniature ultralow-background proportional counters. SAGE is sensitive to all of the fusion reactions occurring in the sun. Beginning in 1990, we have carried out measurements of the flux of solar neutrinos and have found that the flux of neutrinos detected is about half of that predicted by the Standard Solar Model. We have also confirmed the correct overall operation of the experiment using an intense (0.5 MCi) ^{51}Cr artificial neutrino source. Combined with results from other solar-neutrino experiments that measure only the higher-energy solar neutrinos produced from ^{7}Be and ^{8}B reactions in the sun, it appears that the most plausible explanation of the observed deficit is neutrino oscillations. If this proves to be true, it will be the first evidence for physics beyond the Standard Electroweak Model, as predicted by the Grand Unified Field Theories.

Ultracold Neutrons

T.J.Bowles [(505) 667-3937], S.J.Seestrom, R.Hill (P-23), C.Morris, G. Hogan (P-25), T.Brun (LANSCE), collaborators from the University of Rhode Island, University of California at Berkeley, and Petersburg Nuclear Physics Institute

Ultracold neutrons (UCNs) are neutrons whose wavelengths are sufficiently long that they can undergo total internal reflection from a variety of materials. This makes it possible to confine UCNs in a bottle for more than 100 seconds, providing a compact source for use in fundamental physics research.

At LANSCE, ultracold neutrons were first produced in 1996 by Bragg-scattering cold neutrons (having a velocity of 400 m/s) from a moving mica-crystal package so that the cold neutrons were Doppler shifted into the ultracold regime (<7 m/s). We are continuing to develop this source with improved diagnostics, a mica-crystal package with higher reflectivity, and better control of the matching of the source to the MLNSC cold moderator. We are also developing the use of cryogenic moderators for UCN production at the proposed Long-Pulse Spallation Source. This source promises densities 100–1000 times higher than presently available. Such an intense source of UCNs may make it possible to pursue materials-science applications with UCNs.

A fundamental-physics research program with UCNs is now being started with plans for measurement of angular correlations in polarized UCN beta decay and the electric dipole moment of the neutron. These experiments aim at detecting physics beyond the Standard Model of strong and electroweak interactions.

Neutron Total Cross Sections

F.S.Dietrich (Lawrence Livermore National Laboratory), W.P.Abfalterer [(505) 667-3632], R.C.Haight (P-23), R.W.Finlay (Ohio University)

This joint project of Lawrence Livermore National Laboratory (LLNL), Ohio University, and LANL is making precise measurements of the neutron total cross sections over a wide neutron energy range for a comprehensive set of materials for the Accelerator Production of Tritium (APT) program. These data are necessary in the calculations of neutron transport in APT systems, and they are essential input to model calculations of neutron scattering and reactions. In 1996, we investigated over 30 samples in the energy range 4–550 MeV and obtained data accurate to approximately 1%. The WNR fast-neutron spallation source at LANSCE is ideal for this work. We are continuing this work in 1997 with additional materials, including isotopes of tungsten and iron.

Nuclear Level Densities

R.C.Haight [(505) 667-2829], F.B.Bateman (P-23), S.M.Grimes (Ohio University), H.Vonach (University of Vienna)

At low excitation energies, a given nucleus has a sequence of energy levels that can be described by their quantum numbers and spectroscopic properties. At higher excitation, the number of levels rises very quickly, so that the properties of the individual levels cannot be determined individually but must be understood as statistical averages such as the "nuclear level density." It is generally believed that there is a transition from the ordered set of states at low energy to a Fermi gas (a gas-like collection of protons and neutrons) at much higher energies. The characterization of the transition between the two regimes is the subject of many theories. We test these models by measuring, with the WNR/LANSCE spallation neutron source, neutron-induced, charged-particle-producing reactions over the range from threshold to 50 MeV. Three independent approaches are possible with these reactions: the shape of the emission (evaporation) spectra gives information on the nuclear level density in the residual nucleus; the cross section as a function of energy indicates level densities for excited states in the target nucleus; and very-high-resolution measurements with respect to incident neutron energy reflect overlapping states in the compound nucleus. The quantification of nuclear level densities is essential for nuclear-reaction models of reactions that cannot be measured, such as reactions on unstable species that are formed in stellar nucleosynthesis and in the explosion of nuclear weapons.

Milagro Gamma-Ray Observatory at Fenton Hill

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The Milagro Gamma-Ray Observatory at Fenton Hill in the Jemez Mountains uses hundreds of sensitive, light-detecting photomultiplier tubes submerged in a five-million-gallon artificial pond to record signals from high-energy cosmic emissions. Milagro—the Spanish word for "miracle"—is a collaboration involving researchers from LANL; University of California (UC) campuses at Irvine, Riverside, and Santa Cruz; the University of Maryland; George Mason University; the University of New Hampshire; and New York University. The $2.5-million project is funded by the National Science Foundation, DOE, and UC. The 25-ft-deep pond was emptied and covered with durable, waterproof plastic. The water in the pond is circulated, filtered, and treated to maintain its clarity in a support building next to the pond, which also holds the computers and electronics that process the signals recorded by Milagro. The pond was refilled with water after the first 225 light detectors in the bottom array were installed. In the summer of 1998, project members will drain the pond and expand the array to its full size.

Milagro is sensitive to a range of gamma rays, high-energy photons with energies above 500 GeV. These gamma rays, generated by black holes, active galaxies, supernovae, or “gamma-ray bursters,” strike air molecules in the upper atmosphere before they reach Earth. These initial collisions produce showers of subatomic particles and lower-energy photons that avalanche groundward in a cone. Each air shower either dissipates in the atmosphere or, at high elevations, intercepts the ground. Milagro’s pool acts as a camera larger than a football field and stares at the sky around the clock. A light-tight cover on the pool keeps the inside of the observatory absolutely dark but is easily penetrated by the energetic particles in the air shower. When a gamma-ray-generated air shower strikes the pool, electrons and positrons in the shower create Cerenkov radiation as they move through the water. Milagro’s light detectors sense this light and record information for reconstructing the point on the sky from which the original gamma ray came. Milagro observes hundreds of events each second. Computers automatically sift the arriving data, discarding the many background events generated by cosmic rays and recording the gamma-ray signals.

Gamma-ray bursters, which flash briefly into view and then disappear, have puzzled astronomers since they were discovered by Los Alamos scientists in the 1960s. Currently, astronomers are debating whether gamma-ray bursters originate in our own galaxy or reach us from the most remote reaches of the universe. The latter explanation would require exotic new physics to explain such powerful bursts of energy. Milagro can help to answer the question of whether or not the gamma-ray bursters are located at cosmological distances; researchers are eager to combine its data with those from the Gamma Ray Observer satellite, which observes less-energetic gamma rays from its vantage point in space. Milagro builds on the success of the CYGNUS experiment, which ran at Los Alamos for 10 years. CYGNUS, begun by Darragh Nagle of Los Alamos and collaborators at the University of Maryland, used only scintillation detectors and was sensitive only to gamma rays at the upper end of Milagro’s range of detection. Data from the CYGNUS experiment have to date produced 10 doctoral dissertations. Milagro’s flood of data will support many more graduate students studying high-energy physics and astrophysics; the project currently employs 7 graduate students, including 4 doctoral candidates.

Fundamental Symmetry Measurements with Trapped Atoms

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With the advent of optical and magnetic traps for neutral atoms, a new generation of fundamental symmetry experiments has arisen that would exploit point-like, massless samples of essentially fully polarized nuclei. At Los Alamos we are pursuing a measurement of the beta-spin correlation function in the beta decay of ^{82}Rb confined to a time orbiting potential (TOP) magnetic trap as a means to probe the origin of parity violation in the weak interaction. A new generation of atomic-parity nonconservation experiments that test the neutral current part of the weak interaction is also envisioned, wherein measurements with a series of radioactive isotopes of cesium and/or francium could eliminate atomic structure uncertainties that presently limit the ultimate precision of such experiments.

Our near-term goals are to demonstrate the high-efficiency optical trapping of rubidium and cesium radioisotopes, to polarize and transfer these cold atoms to a pure magnetic trap that confines only one polarized state, and then to measure the beta-asymmetry using a symmetric array of beta-telescopes surrounding the trap. Initial trapping and cooling of rubidium and cesium isotopes have been carried out, and we are now working to complete the design of the transfer and the second magnetic trap, where ^{82}Rb atoms will be polarized and placed in a magnetic TOP trap for high-precision beta-asymmetry measurements. Our initial studies will concentrate on the pure Gamow-Teller transition in ^{82}Rb; our goal is to measure the parity-violating beta-spin asymmetry correlation with a precision one order of magnitude greater than any previous experiment.

Quantum Cryptography for Secure Communications to Low-Earth-Orbit Satellites

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Cryptanalysis techniques and algorithms are advancing rapidly and by the start of the twenty-first century will necessitate the development and use of new encryption technologies to ensure secure communications to satellites. The aim of our project is to develop quantum cryptography so that it may provide absolutely secure encryption of communications to low-earth-orbiting satellites. We will develop and demonstrate the cryptographic technology to a stage where it can be feasibly incorporated into new satellites. During the past year, we have designed, constructed, and tested a quantum-cryptography system that creates and transmits—using single-photon transmissions—cryptographic random numbers between sending and receiving instruments separated by more than 200 m within our laboratory. The system is based on the propagation and detection of nonorthogonal polarization states of single photons in free space at a wavelength (771 nm) for which the atmosphere has a very low attenuation.

Quantum Computation Using Cold, Trapped Ions

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Quantum computation is a new computational paradigm that is much more powerful than classical computation because it allows computing with quantum-mechanical superpositions of many numbers at once. In a quantum computer, binary numbers will be represented by quantum-mechanical states (“qubits”). We are developing a quantum-computational device in which the qubits will be two electronic states of calcium ions that have been cooled with a laser to rest in an ion trap. We will then perform quantum logical operations with a laser beam that is resonant with the qubit transition frequency and is directed at individual ions. We have recently succeeded in trapping and imaging a cloud of calcium ions using two titanium-sapphire lasers: one, frequency doubled to 397 nm; the other at 866 nm.

Quantum Cryptographic Key Distribution over Optical Fibers

R.J.Hughes [(505) 667-3876], G.G.Luther, G.L.Morgan, C.G.Peterson, C.Simmons (P-23)

The secure distribution of secret random-bit sequences, known as “key” material, is an essential precursor to the use of that key material for the encryption and decryption of confidential communications. Quantum cryptography is an emerging technology for secure key distribution with single-photon transmissions. Heisenberg’s uncertainty principle ensures that an adversary can neither successfully tap the key transmissions nor evade detection, because eavesdropping raises the key error rate above a threshold value. We are performing quantum cryptography over 48 km of underground optical fiber using nonorthogonal single-photon interference states to generate shared key material. Key material is built up by transmitting a single photon per bit of an initial secret random sequence. A quantum-mechanically random subset of this sequence is identified and becomes the key material after a data-reconciliation stage with the sender. The nonorthogonal nature of the quantum states ensures that an eavesdropper cannot identify the bit values in the key sequence. Our experiment demonstrates that secure, real-time key generation over “open,” multikilometer node-to-node, optical-fiber communications links is possible.

Diode Laser Development for Quantum Computation

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Titanium-sapphire lasers are a proven technology for our quantum-computation application, but they are expensive, require a laser expert, use over 40 kW of power, and fill an entire laser table. The objective of this project is to develop diode lasers for this application because diode lasers are easy to use, low in cost, and compact. This year, we have developed diode lasers at the 866-nm and 794-nm wavelengths that are required for cooling calcium ions, and in the next few months, we will double the frequency of the 794-nm light to obtain 397-nm light. We have assembled external-cavity diode-laser systems and, with a prototype, demonstrated locking to an existing frequency standard. We have developed frequency-offset techniques using modulators and/or ultrastable cavities to reference the 866- and 397-nm wavelengths to stable atomic lines. Typically, the wavelength of the light emitted by the laser must be controlled with respect to a reference wavelength, which is near the desired wavelength. For our diode lasers, we can reference light wavelengths to an absolute atomic standard or to a very stable optical cavity that resonates at a very well defined frequency.

"Interaction-Free" Measurements

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Using the complementary wave- and particle-like nature of light, it is possible to determine the presence of an object without any photons being absorbed or scattered by it. The maximum efficiency of the simplest schemes (wherein the object, if placed in one arm of an interferometer, prevents interference) is only 50%. However, by incorporating a repeated interrogation scheme—an application of the Quantum Zeno effect—one can, in principle, achieve efficiencies arbitrarily close to 100%, with an arbitrarily small chance that any photons are absorbed. So far, an 85%-interaction-free measurement has been achieved (in collaboration with researchers at the University of Innsbruck), and this is the current world record. A fast switching system that should allow efficiencies in excess of 95% is currently under development. Also, we have begun investigating the practical implementation of interaction-free imaging, in which these techniques are used to obtain a pixelated image of an object, again with the goal of negligible absorption or scattering. To date, a resolution of less than 10 μm has been achieved, and we hope to improve this even further. Finally, we are beginning research on coupling our measurement system to a quantum object in a superposition state. This would allow the production of macroscopic entangled states of light and Schrödinger-cat states.

Development of a Cold-Neutron Radiography Capability at the Manuel Lujan Neutron Scattering Center (MLNSC)

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Neutron radiography is an attractive technique for nondestructive testing and evaluation due to the strong variation of neutron cross sections from element to element. Cold-neutron radiography (CNR), which uses neutron energies in the millielectronvolt (meV) regime, has been employed for the most part with reactors in which a steady-state source of cold neutrons can be obtained. Spatial resolutions of a few tens of microns can be obtained in radiographs from such sources. An important behavior of the cross sections of crystalline materials for cold neutrons is that below an energy of a few meV (the exact energy depends on the material), there is an abrupt drop in the cross section when the wavelength reaches twice the largest d-spacing of the material. The energy at which this abrupt drop occurs is referred to as the Bragg cutoff. This behavior is generally not exploited in a reactor environment because the steady-state nature of the neutron source does not facilitate the separation of neutrons of different energies. However, a pulsed neutron source using a time-of-flight capability can easily differentiate neutron energies and thus has the capability to obtain radiography at various neutron energies. By recording image data at different times during a neutron pulse, it is possible to obtain neutron images below and above the abrupt drop (or threshold) in the cross section for a given component of the sample.

We recently demonstrated this phenomenon at the MLNSC on Flight Path 11a. A beam guide was installed to achieve a flight path of approximately 19 m. A lithium zinc sulfide scintillator was used as a neutron-to-light converter, and a set of mirrors and lenses relayed the image from the scintillator to a gated image intensifier, the output of which was recorded by a cooled charge-coupled device (CCD) camera. We have demonstrated the Bragg cutoff at 6 meV on a block of beryllium that is approximately 73 mm thick. Imaging at energies above about 7 meV shows the beryllium to be dark, and items being shadowed by the beryllium cannot be seen. However, imaging at energies below approximately 5 meV shows the beryllium to be almost clear, and items previously shadowed by the beryllium can be clearly seen. These images are our first proof-of-concept experiment, and we expect to achieve increased resolution and image quality in subsequent work.

Neutron-Based Land-Mine Detection System Development

T.E.McDonald, Jr.[(505) 667-7294] (P-23), H.A.Davis (P-24), R.A.Nebel (T-15), M.M.Pickrell (NIS-5)

Determining the location of land mines is important both militarily and in peace time. Even in today's absence of large conflicts, more than 26,000 people are killed or wounded yearly by land mines that were deployed previously. The goal of this project is to examine the feasibility of developing a buried-land-mine detection system using the detection and analysis of prompt gamma rays that are induced by neutron interrogation. This technique is a mature concept and has been used in a variety of explosives-detection applications. However, it has not successfully been applied to the buried-mine detection problem because of lack of both a suitable neutron source (that is, one having sufficient intensity) and a detection system having a sufficiently high signal-to-noise ratio. The basic concept is to interrogate a suspected area with neutrons. The explosives in any mines that may be present would have an elevated presence of nitrogen, whereas the surrounding earth generally would have little or no nitrogen. Some of the neutrons would react with the nitrogen in the explosive, and gamma rays that have specific and unique energies would be emitted as a result of the reaction. Most previous attempts to use this neutron-based (NB) technology for mine detection have relied on spontaneous fission sources, which can be used only at low intensity, in the range of 10^6–10^7 neutrons per second (n/s), together with heavy shielding, because of personnel safety considerations. A system using such low-intensity sources is slow (requiring several minutes) and requires close proximity (within a few centimeters) to the explosive being detected. Most studies indicate that a source strength in the range of 10^9–10^{11} n/s would be necessary to achieve a relatively high signal-to-noise ratio in an interrogation time of a few seconds. In this project, we consider two alternative neutron sources that have the potential of producing neutron fluxes in the neighborhood of 10^{11} n/s: the Intense Ion-Beam Source and the Inertial Electrostatic-Confinement Source. The advantage of these sources is that they can be turned off when not in use and can be operated over a wide range, from steady state to pulsed. We also review alternative detection techniques and have carried out preliminary measurements using mock high-explosive (HE) material.

Advanced Technology Imaging Sensor Development (Fast CCD Sensors)

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The goal of the Advanced Technology Imaging Sensor Development (Fast CCD Sensors) project is to develop an advanced, gated, intensified imaging system for use over a broad range of applications in the Department of Defense (DoD) and Department of Energy (DOE). Our focus is on increased frame rate, extended spectral range sensitivity into the near infrared (including the "eye-safe" spectrum in the neighborhood of 1.54 μm), reduced gate width, increased resolution, and increased quantum efficiency. Such an advanced imager would be used in the DoD in lidar; range gating; imaging through scattering media such as fog, clouds, and turbid water; long-distance target acquisition and ranging; underwater imaging; and laser detection and ranging (LADAR) imaging, including eye-safe LADAR. Applications in the DOE include shock-wave-breakout characterization, neutron and proton radiography of dynamic systems, imaging of high-speed assembly and associated reactions, and diagnostics of accelerator beam pulses. The high-speed imaging technology developed by Los Alamos and the other DOE national laboratories for use in the underground testing program at the Nevada Test Site (NTS) serves as the technology foundation for this project. Starting with this base, we are advancing the technology along several fronts. We are designing a high-speed camera around a new 512 × 512 pixel, 16-port CCD. The camera is designed to operate continuously at up to 4000 frames per second. We are working on the design of microchannel plate intensifier configurations that will gate in the few-hundred-picosecond regime, and we are working with manufacturers on the fabrication of such intensifiers. We are also working with intensifier manufacturers on extending the sensitivity of the photocathode to cover the near infrared up to the eye-safe spectrum range. In addition, we are pursuing a quantum improvement in intensifier technology by using a back-thinned, electron-bombarded CCD (EBCCD) that will be placed directly in the intensifier envelope and replace the microchannel plate, phosphor, and intensifier-camera coupling. If the EBCCD development is successful, we expect close to an order-of-magnitude improvement in sensitivity and resolution.

Basic Physics with Spallation-Neutron Sources

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Progress in basic physics with neutrons strongly depends on the availability of intense neutron sources. High-flux reactors are at the limit of their technical possibilities, with no substantial progress in performance in the last twenty years. Spallation-neutron sources (SNSs) that use intense proton beams (of about 1 GeV) already have demonstrated both interesting capabilities that complement those of reactors and great potential for future development. Although neutron sources are mainly used for condensed-matter studies, they also present attractive possibilities for studies in other fields, including nuclear physics, fundamental physics, and particle physics.

The interest and future potential of SNSs, which can produce neutrons with an energy range spanning 16 orders of magnitude, and their possible use in scientific disciplines outside that of condensed matter have been reviewed in detail in a major 3-volume report[1] written by more than 30 scientists from inside and outside LANL. This report forms a comprehensive base in support of the launching of LANSCE as a truly multidisciplinary national user facility.

1. "Basic Physics with Spallation-Neutron Sources," A. Michaudon, Ed., Los Alamos National Laboratory document LA-UR-94-1320 (1994).

Use of Ultracold Neutrons for Condensed-Matter Studies

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Ultracold neutrons (UCNs) have played a very important role in fundamental-physics research but can also be used in condensed-matter studies. Because of their small penetration depth into matter, UCNs are well suited for surface studies. High-resolution UCN spectrometers can also be built, using gravity as a strongly dispersive medium for low-energy neutrons. With such excellent resolution, UCN quasielastic scattering can give insight into slow dynamics over long distances in macromolecules such as polymers or biopolymers. All these studies were recently reconsidered with the possible advent of new, more-intense UCN sources, which are now envisaged. This reassessment, now available as a Los Alamos report, includes a broad review of UCN properties (including their reflectivity by different types of samples), UCN spectrometers and their comparison with other high-resolution instruments, experimental results obtained with all these instruments, and neutron microscopes.

Infrared Pyrometry for Temperature Measurements of Shocked Surfaces

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Measurements of the time-dependent absolute temperature of surfaces shocked by high explosives (HE) provide valuable constraints on the equation of state of materials and on the state of ejecta from those shocked surfaces. A pyrometer system has been designed and built for studying these temperatures, which typically lie in the range 0.04–0.2 eV, corresponding to shock heating of surfaces to temperatures from about 400 K to about 2000 K. These temperatures are equivalent to infrared (IR) wavelengths in the range of 1 to 10 μm. Blackbody IR spot pyrometry, utilizing the color ratio technique, permits a measurement of these surface temperatures. An a priori knowledge of the behavior of the surface emissivity with wavelength is required, but the absolute values of the emissivity are not. This detector system will be applied to experiments in the above-ground experiments (AGEX) program.

The detector system uses IR lenses to image a spot (whose diameter is determined by the optics) onto a mixing rod. The mixing rod allows spatially homogenized samples of the IR emission to be transferred to three 3-m-long IR fibers. The other ends of the fibers go to a detector box, which can be protected from the HE shock. The IR radiation from each of the three fibers is focused through a doublet lens system onto quad metal (HgCdZnTe) IR detectors. Filters are placed between the doublets to transmit IR radiation only from moderately narrow bands. The three bands are centered about 3, 6, and 8 μm to optimize the color ratios for the temperature range of interest. The system is being characterized and will be tested on flyer plate configurations driving polished copper plates, for which the temperature has been well characterized.

Ejecta Measurements Using In-Line Fraunhofer Holography

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When a shock wave interacts at the interface between a solid (or liquid) and a gas, pieces of the material can be emitted into the gas region. This material can range in size from submicron to hundreds of microns and is referred to as ejecta. Ejecta can occur in a nuclear weapon when a shock wave interacts at such an interface. The amount, size, and velocity of ejecta will depend on material properties such as grain size, surface finish, and the state of the shock wave in the material. In order to characterize ejecta, P-23 has played a major role in developing an in-line Fraunhofer holography technique to make measurements of ejecta in a dynamic system. This diagnostic has been developed and implemented on numerous experiments based at the Pegasus II Pulsed-Power Facility and is currently being developed for HE experiments. At Pegasus, an aluminum cylinder is imploded and then impacts a smaller-diameter target cylinder, which sets up a shock wave in the target. When the shock wave interacts at the target/vacuum interface, ejecta are emitted. To make the ejecta holographic measurement, a laser pulse is transported through the ejecta, where part of the laser light scatters and part is unscattered. These two beams interfere at the film plane where the hologram is formed. The hologram contains information about particles ranging in size from a few microns to a hundred microns in diameter over a volume of 1 cm^3. Ejecta data have been obtained for both aluminum and tin targets over a range of surface finishes and shock strengths.

X-Ray Imaging Experiments Using Pulsed-Power and High-Explosive Facilities

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Many weapons-physics issues deal with instabilities and shock waves interacting in materials and gases. In order to investigate these issues associated with dynamic systems, groups P-23 and P-22 are developing a spatially resolved, time-dependent x-ray imaging system. Providing time-dependent information is critical in understanding the physics involved and in comparing experimental data with predictions given by the hydrodynamic weapon codes. The system makes use of 600-keV x-ray sources developed in P-22, which provide roughly 100 mrad at a distance of one foot in a 10-ns full-width-at-half-maximum (FWHM) pulse. P-23 has developed scintillator packages for forming the image, an optical transfer system for relaying the image, and gated-intensifier camera systems for recording the image. Depending on the type of experiment, the scintillator type and thickness are optimized to maximize image contrast. The optical-transfer system is designed to relay the image far enough from the experiment that the camera systems are protected, while still providing high resolution and good light collection. Many experiments have been successfully completed at the Pegasus II Pulsed-Power Facility, where images at two different times were obtained. For the Icebound and local HE experiments, a time-dependent x-ray imaging system is being developed. With this system we are making images over an 18-mm-diameter area that allow us to measure ejecta mass with an accuracy of 10%.

P-23 Weapons-Physics Experimental Team

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This team performs experiments that expand our understanding of the physical processes that take place in the detonation of nuclear devices. Some issues that are being studied include the development of instabilities that form in imploding systems, the formation of ejecta from shocked surfaces, interaction of shock waves with materials, and equation-of-state (EOS) measurements in materials and pressure regimes of interest to weapons physics. The experiments are performed using liners imploded with pulsed power at the Pegasus II facility and on explosively driven systems both at LANL and in the U1a facility at the Nevada Test Site (NTS).

We apply a variety of diagnostics to measure the physical phenomena that occur in these experiments. Holograms, taken with a pulsed laser, measure the distribution of particle size in ejecta. We have developed a system to take a sequence of gated x-ray images to provide information on the evolution of instabilities and the mass distributions in surface ejecta. Visible imaging experiments, which either use framing cameras to capture the emitted light from shocks or use lasers or argon candles to backlight the experiments, provide information on the evolution of the phenomena being investigated. We are developing pyrometers to measure time-dependent temperatures and IR imaging techniques to study spatial distributions of temperatures for shocked systems. Various techniques, including the use of streak cameras, are employed to measure shock arrival times in EOS experiments.

P-23 NTS Prompt Diagnostic Archival Team

M.L.Stelts [(505) 667-1507], P.Liu, K.B.Morley (P-23), collaborators from Sumner Associates and Bechtel Nevada

The laboratory is now required to certify our nuclear-weapons stockpile without being able to test the weapons. This will require the development of better physics models and better computer codes that, ultimately, should be able to compute the performance of the weapons, including effects of aging, defects, and remanufacture. To have confidence in the ability of these codes to provide realistic predictions, we must be able to use them to successfully model the performance of devices tested at NTS. Thus, the NTS data will be a crucial link in attaining this goal.

P-23 and its predecessor groups have been responsible for experiments that involve precision neutron output measurements from these devices (NUEX and THREX) and for the imaging of sources of radiation in the devices (PINEX), as well as many other experiments that have been performed to investigate weapons-physics issues. The responsibility of P-23 is two-fold. We are documenting the experimental techniques that were used in the NTS shots so that future users of the NTS data will understand how an experiment is designed, what information can be derived on the weapons-physics issues, and how to field the experiment if we are required to return to testing. We are also systematically saving the data, frequently having to reanalyze experiments, and providing the necessary additional information that will allow comparison of the experimental results with the calculations of device performance. These data are being electronically archived on the P-23 classified computer system in a form that facilitates access and use by other experimentalists, weapon designers, and code developers. To aid in this process, we have installed a World Wide Web–type page on our classified network (behind a firewall computer that limits access to those with a "need to know") to allow easier access to the data through a web browser.

The task of saving and documenting the data taken over decades of testing is formidable. It is necessary to recover data not only on stockpile systems, but on events designed to investigate weapons-physics issues and on those interesting failures, where the results were not what were anticipated.

Neutron Measurements to Support the Optimization of Treatment of Cancer Patients with Fast Neutrons

J. L. Ullmann [(505) 667-2517], R. C. Haight (P-23)

Over 15,000 people with cancer have received radiation treatment with fast neutrons. This clinical experience has shown that 10%–15% of all cancer patients would benefit from this neutron therapy. Accurate dosimetry depends on the knowledge of neutron interactions with elements of tissue such as carbon, nitrogen, and oxygen. In particular, neutron reactions that produce charged particles are of interest because these reactions deposit energy, and hence radiation dose, locally at the point of the interaction. Although there have been measurements in the energy range of importance, from 20 to above 70 MeV, the data base is sparse (we have measurements at only a few selected energies), and there are significant discrepancies among literature values. We are beginning a program to supply accurate data on neutron reactions that produce protons, deuterons, tritons, ^{3}He, and ^{4}He from 0–150 MeV, thereby covering the full range used in neutron therapy. The WNR/LANSCE neutron source covers this range continuously, and the specific neutron energy for a particular reaction can be determined by time-of-flight techniques. Applications of these data extend also to radiation protection at high-energy and medium-energy accelerators and to radiation effects from neutrons produced by cosmic rays.

Molten-Metal-Target Test Loop

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The development of molten heavy-metal-target technology for spallation neutron sources has recently become recognized as an important objective for several programs at Los Alamos. It is generally believed that the only way to take advantage of the accelerator-beam power levels now possible for compact neutron-spallation targets is to use molten metal as the target material. Molten-metal targets are called for in the National Spallation Neutron Source (NSNS) being designed by Oak Ridge National Laboratory, the European Spallation Source (ESS), and the SINQ project at the Paul Scherrer Institute (PSI). The accelerator-driven transmutation technology (ADTT) program at Los Alamos is proposing systems that depend heavily on molten lead or lead-bismuth eutectic (LBE) fluids for neutron production and for cooling. In addition, molten lead or LBE targets have been suggested as advanced concepts for use in the accelerator production of tritium (APT).

As a first step toward developing this technology at Los Alamos, we are constructing a simple LBE test loop. This test loop will allow us to address many issues, such as material compatibility and corrosion, and to gain experience with LBE. We will be working in close collaboration with scientists from the Institute of Physics and Power Engineering at Obninsk, Russia, who have considerable experience with LBE from their naval propulsion program. We expect the loop to be operational in late 1997.

P-24: Plasma Physics

Development of Methods for Obtaining On- and Off-Hugoniot Equation-of-State Data Using Laser-Driven Shocks

G.R.Bennett [(505) 667-9318], R.E.Chrien (P-24), J.M.Wallace (XPA)

This project investigates advanced equation-of-state (EOS) experimental techniques relevant to measurements such as those suggested for the proposed Trident-Upgrade laser facility at Los Alamos. Experiments, which recently began at the Nova laser facility of Lawrence Livermore National Laboratory (LLNL), are focused toward simultaneous measurements of the direct-laser-drive principal Hugoniot (PH) and zero-pressure-release isentropes of beryllium. Beryllium was chosen as the EOS sample because it is an important inertial confinement fusion (ICF) material with particular relevance to National Ignition Facility (NIF) capsule designs. Furthermore, its low x-ray opacity and high shock and particle speed—in comparison with denser metals—make beryllium an ideal material with which to develop these advanced techniques. Direct drive with side-on x-ray radiography is believed to be the optimum approach toward obtaining a high-accuracy, laser-based EOS. To this end, a novel, one-dimensional, state-of-the-art x-ray microscope, designed by P-24 researchers, has been conceived and is currently under fabrication. Upon completion of this x-ray device, experimental work will be transferred to the Omega laser facility at the University of Rochester. The completion of an active shock-breakout diagnostic in the future will extend this project to include the novel addition of "sound speed" to the PH and isentrope measurements.

Design of Weapons-Physics Experiments Driven by X-Rays from the PBFA-Z Pulsed-Power Facility at Sandia and the Nova Laser at Livermore

R.E.Chrien [(505) 667-1674] (P-24), G.R.Magelssen, F.J.Swenson, B.H.Wilde, D.C.Wilson (XTA)

We are evaluating the PBFA-Z pulsed-power facility at Sandia National Laboratories in Albuquerque (SNL) as an x-ray source for weapons-physics experiments. PBFA-II, originally constructed as a set of 36 light-ion-beam accelerators for ICF experiments, has been reconfigured as PBFA-Z to drive z-pinch implosions using wire-array loads. The implosion efficiently converts the electrical energy in the pulsed-power system into x-rays when the imploding wire plasma stagnates on the cylindrical axis. The initial operation of this reconfigured facility has been very encouraging. X-ray yields of ~2 MJ and peak powers of ~200 TW in 25-cm^3 hohlraums have been produced in early experiments, corresponding to peak black-body temperatures of 100 eV. We are planning to reduce the hohlraum volume to ~5 cm^3 in an effort to raise the peak temperature to 120 eV or more. These hohlraums will be used for studies of foam-filled tubes with diameters in the range of 2.4–5 mm. Similar x-ray drive conditions can also be produced in laser-driven hohlraums on the Nova laser at LLNL but are limited to smaller-diameter tubes. The smaller size of the laser-driven targets is partially offset by the superior imaging diagnostics at the Nova facility. In both the pulsed-power and laser facilities, development of improved x-radiographic capabilities will be important for our above-ground studies.

Fusion Neutrons from the Gas/Pusher Interface in Deuterated-Shell ICF Implosions

R.E.Chrien [(505) 667-1674] (P-24), N.M.Hoffman, J.D.Colvin (XTA), collaborators from Lawrence Livermore National Laboratory

In this project we have performed the first measurements and numerical simulations of fusion neutrons from the gas/pusher interface of indirectly driven ICF implosions using hydrogen-filled capsules made with a deuterated inner layer. Contrary to the case of conventional capsules with D-T (deuterium-tritium) or D-D (deuterium-deuterium) gas fills, neutron yields in these capsules are due mostly to undesirable mix at the pusher/gas interface. We varied the nonlinear saturation of the growth of hydrodynamic perturbations in implosions with high linear growth factors (~325) by adjusting the initial surface roughness of the capsule. The neutron yields are in quantitative agreement with the direct simulations of perturbation growth, and they also agree with a linear-mode superposition and saturation model, including enhanced thermal loss in the mixed region. Neutron spectra from these capsules are broader than expected for the calculated ion temperatures, suggesting the presence of nonthermal broadening from mass motion during the fusion burn.

Instability-Coupling Experiments on the Nova Laser

R.E.Chrien [(505) 667-1674] (P-24), N.M.Hoffman, G.R.Magelssen, D.P.Smitherman (XTA)

Our research team is studying the coupling of Richtmyer-Meshkov (RM) and ablative Rayleigh-Taylor (ART) instabilities with indirectly driven, planar foil experiments on the Nova laser at Livermore. The foil is attached to a 1.6-mm-diameter, 2.75-mm-long gold hohlraum driven by a shaped laser pulse that is 2.2 ns long with a contrast ratio of 1:5. A shock is generated in 35-μm- or 86-μm-thick aluminum foils with a sinusoidal perturbation (with a wavelength of 50 μm and an amplitude of 4 μm) on its rear surface. In some experiments the perturbation is applied to a 10-μm beryllium layer on the aluminum. An RM instability develops when the shock encounters the perturbed surface. The flow field of the RM instability can "feed out" to the ablation surface of the foil and provide the seed for ART perturbation growth. This is an important problem for ICF, in which the nonuniformity in the D-T ice surface inside the capsule can feed ART growth in the capsule exterior. We use face-on and side-on x-radiography to observe areal density perturbations in the foil. For the 86-μm foil, the perturbation arrives at the ablation surface while the hohlraum drive is dropping, and the data are consistent with RM instability alone. For the 35-μm foil, the perturbation feeds out while the hohlraum drive is close to its peak, and the data appear to show strong ART perturbation growth. The data are in generally good agreement with LASNEX simulations (simulations performed with the Los Alamos version of the ICF design code first developed at Livermore) except that the simulations do not reproduce the strong development of a second harmonic in the thin aluminum samples.

High-Intensity Illumination of an Exploding Foil

J.A.Cobble [(505) 667-8290], R.P.Johnson (P-24), R.J.Mason (XPA)

Successful ICF involves the compression of a D-T fuel to sufficiently high density, ignition in a hohlraum hot spot within the fuel, and a propagating fusion burn within the fuel. Conventional ICF relies on carefully timed, converging shocks driven by the compression beams. A promising alternate concept, the "fast-ignitor," relies on a high-intensity laser to light the hot spot on the preassembled fuel. In order to achieve that, the beam must propagate through the underdense plasma surrounding the capsule, where laser-plasma instability could break up the beam.

During the first year of research, we employed the short-pulse capability of the Trident laser at Los Alamos to measure the penetration of a high-intensity beam through a 1-mm-scale-length, underdense, C-H plasma. The highest laser irradiance was 7×10^{18} W/cm^2. The plasma density is controlled via the delay between the low-intensity plasma-formation beam and the high-intensity probe beam. Our experiment used plasmas of several percent of the critical electron density (above this critical density the laser cannot propagate). The probe beam was focused with an f/2.5 parabola. We found that the beam f number was increased after the beam had passed through the plasma; i.e., it was more collimated on account of its interaction with the plasma. In order to measure this effect, we allowed the transmitted beam to strike a diffuser plate behind the target. The scattered light from the plate was imaged by a camera to produce the data shown in Fig. III-1. We also measured the reflected and transmitted light for different delays (different plasma densities). Even at the low plasma densities used, the transmission was less than we had expected. Theoretical studies that attempt to model the behavior of the beam in the plasma are under way. Work from our first year of research will be published in *Physics of Plasmas*. More experiments, in which the plasma density and laser wavelength will be varied, are planned for 1997.

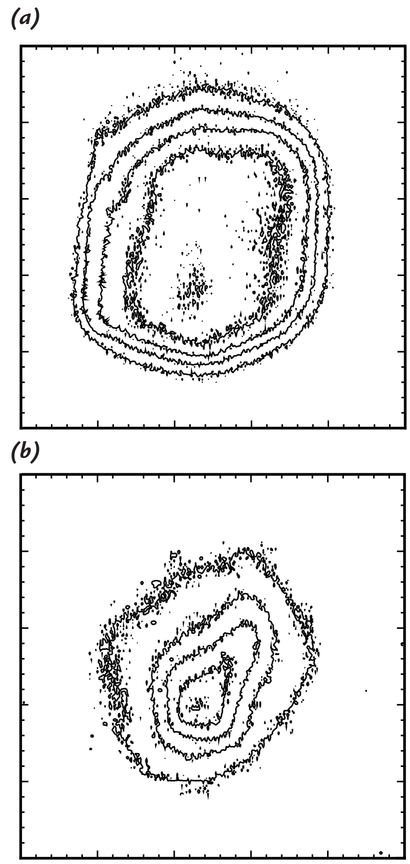

Fig. III-1. The f number of the probe beam is approximately doubled on passage through a 3% critical-density plasma. The case with no plasma is shown in (a); the case with a plasma is shown in (b). Each frame is an array of 250 × 250 pixels.

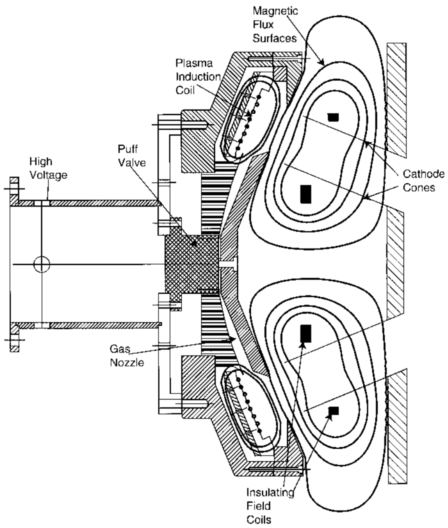

Fig. III-2. Design of the intense-ion-beam source.

Microsecond-Duration, Repetitive, Intense-Ion-Beam Accelerator

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A number of intense-ion-beam applications are emerging that require repetitive, high-average-power beams. These applications include ablative deposition of thin films, rapid melt and resolidification for surface-property enhancement, advanced diagnostic neutral beams for the next generation of tokamaks, and intense pulsed-neutron sources. We are developing an intense-ion-beam accelerator called CHAMP (continuous high-average-power microsecond pulser) with a beam energy of 250 keV, a beam current of 15 kA, a pulse length of 1 ms, and a pulse frequency of 1–30 Hz. The accelerator will use a magnetically insulated extraction diode in a ballistically focused geometry (see Fig. III-2). The 450-cm^2 active plasma anode (MAP diode) can utilize any gaseous species. Gas is supplied from a puff valve located on the system axis and is ducted through a radial flow channel. The anode plasma is formed by currents induced in the gas by a fast-rising, two-turn, flat, spiral-wound coil with four parallel sets of windings. The insulating transverse magnetic field will be generated by two magnetic-field coils on the grounded cathode focusing cones. We will use a set of parallel, lumped-element, Blumlein circuits and a step-up pulse transformer to supply the diode acceleration voltage. Our current work is centered on testing and optimizing the plasma-generation system.

Laser-Plasma Instability Research in Fusion-Ignition-Relevant Plasmas

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Laser-plasma instability could pose a threat to success in ICF either by scattering light outside of the target or spoiling the symmetric illumination of the fusion capsule. The speckled nature of laser beams used in ICF is an important factor in laser-plasma instability processes. Models that account for the laser speckles successfully predict the observed onsets of backscattering due to stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS). Linear convective theory predicts very large levels of SRS backscattering from the long-scale plasmas expected in ignition hohlraums. Our observations of SRS saturation are inconsistent with linear theory scaling, but are qualitatively understood in terms of other processes. In particular, we have shown direct evidence for the dependence on acoustic damping of the SRS reflectivity of a 351-nm, random-phase-plate laser beam from a long-scale hohlraum plasma. Because SRS itself is unrelated to acoustic waves, this is evidence of other parametric processes determining the nonlinear saturation of Raman backscatter. We have great expectations from optical imaging diagnostics recently deployed at Nova. They could help elucidate important outstanding questions relating to SBS and SRS nonlinear saturation, and they could also prove to be valuable electron-density diagnostics.

Effort in Support of the Core Science and Technology Plan for Indirect-Drive ICF Ignition

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In conjunction with other researchers in MST and T Divisions, we have carried out a number of theoretical and experimental studies of nonlinear optical phenomena important to the design of the National Ignition Facility (NIF) laser. These studies include measurements of nonlinear refractive index coefficients (n_2), Raman scattering in atmospheric oxygen, and theoretical studies primarily of harmonic conversion. Our motivations for measuring n_2 were the relatively large scatter in the data that had been obtained for fused silica by different techniques at 355 nm and the importance of this effect in setting the size of optics at NIF in order to avoid damage due to self-focusing. Our results were consistent with the lower range of previously reported measurements and indicated that the chosen size for the NIF final optics assembly would not have to be increased; a larger optics assembly would have cost significantly more. We made our measurements by a modified Z-scan technique in which the intensity distribution of an initially flat top beam that is relay-imaged onto a charge-coupled device (CCD) camera is recorded when a sample is scanned through the focus. These measurements were also confirmed by MST-Division researchers using the recently developed ultrashort-pulse characterization technique of frequency-resolved optical gating, with which they determine phase shifts induced by propagation through a sample. The Raman-scattering studies were prompted by some earlier calculations, which indicated that the method that had been suggested to avoid rotational Raman scattering by nitrogen in long air paths at NIF would not be adequate. This suggested method—to place part of the propagation path in a breathable oxygen/argon atmosphere—would be inadequate because the Raman gain in the atmospheric concentration of oxygen is approximately 77% of the nitrogen gain. Experiments to measure the relative gains validated this calculation to within a few percent. The NIF design has since been altered to incorporate inert-gas beam tubes. Work in T Division on efficient, multiple-crystal, harmonic-conversion geometries for NIF has been extended to look at the effect of such geometries as a means of possibly mitigating phase perturbations that result from the baseline design, which are a major contributor to damage in downstream optics. We have observed some improvements with such designs, but we are still seeking an ideal case that maintains high conversion efficiencies. Ongoing work also includes the examination of multiphoton absorption effects in potassium dihydrogen phosphate (KDP) harmonic-conversion crystals and the pursuit of designs for spatial-filter pinholes that do not close because of rapid plasma production.

Plasma-Based Removal of Transuranic Contaminants from Surfaces

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The primary goal of this project is to develop and demonstrate the utility of plasma-based processes for the removal of transuranic (TRU) contamination from targets of interest to the DOE complex. The first stage of the process has been to design, fabricate, and perform initial tests of a small prototype plasma-decontamination system, using both uranium and nonradioactive surrogate contaminant materials. We have designed, fabricated, and integrated a small system (~0.5 m^3) with a two-stage cryogenic trapping and recovery system. Examination of the etching characteristics of various gases (including CF_4, NF_3, and SF_6) led to the selection of NF_3 as the plasma precursor gas because of its reduced potential for particulate formation and for nonvolatile material deposition. We have conducted experiments to examine the removal of various contaminant materials in a number of different target geometries. These geometries have included the removal of uranium contamination from the shielding material used in explosives tests as well as from the inside of relatively small diameter pipes (with an inside diameter of 1.25 cm and a length of 20 cm). We have also conducted a very large scale test (~3-m^2 target area) in another available facility. This test examined the removal of a very hard, chemically resistant, amorphous carbon material from the surface of an extremely complex aluminum target. We used an oxygen plasma in this case as an analogue for the fluorine-based plasma that would be used to volitalize and remove plutonium or uranium from contaminated surfaces. Experiments with NF_3 and tungsten (as the TRU surrogate) have demonstrated material-removal rates in a mild, reactive-ion-etching (RIE) mode. These rates are nearly an order of magnitude faster than the material-removal rates we observed in the plasma-immersion mode. Tests using uranium have demonstrated >99% removal of the original contaminant, based on surface alpha-count techniques. Experimental work is now moving in the direction of direct demonstrations using plutonium-contaminated surfaces.

Plasma-Source Ion Implantation and Plasma-Immersion Ion Processing

C.Munson [(505) 667-7509], J.T.Scheuer, B.P.Wood (P-24)

Plasma-source ion implantation (PSII) and plasma-immersion ion processing (PIIP) can be used to provide economical surface modification in order to satisfy industrial and DOE needs. These technologies promise low-cost methods with widespread application for the manufacture and utilization of high-strength, low-friction, corrosion-resistant, or biocompatible materials. R&D is focused on recipe development and materials characterization, pulsed-power equipment development, advanced inductive plasma sources and plasma diagnostics, and manufacturing process controls. Important applications include the following:

Advanced manufacturing. Work in this project includes demonstration implants on industrial components and high-temperature implantation experiments. In addition, we have developed a process to deposit adherent diamond-like carbon films on steels, and we have designed and fabricated a solid-state, insulated-gate, bipolar transistor modulator.

Automotive and other industries. This program, supported by DOE and NIST, involves a vertically integrated consortium of approximately more than a dozen industrial partners directed toward the commercialization of PSII techniques for these industries.

Gun barrels on tanks. In this project we are developing highly adherent coatings for wear- and corrosion-resistant gun barrels. This project supports Army work and involves ion implantation and deposition with plasmas inside 120-mm gun barrels on tanks.

Liquid-metal containment. This area includes containment associated with metal-casting of actinides (for Advanced Design and Production Technology) and of aluminum and magnesium (for industry).

Machine tools. The goal of this project is to commercialize PSII in order to extend the life of machine tools. Los Alamos, the site of the world's largest PSII facility, has teamed with Empire Hard Chrome (EHC) of Chicago, Illinois, to construct the world's first commercial PSII facility. To make this venture a success, Los Alamos will provide hands-on training of EHC equipment operators as well as the plasma and materials expertise that EHC requires to develop recipes, optimize conditions, and qualify applications.

Pistons and automotive tooling. We have successfully completed our major technical goals in this CRADA between Los Alamos and General Motors.

Pits. We are supporting the Nuclear Weapons Technology weapons-surety program by using PSII to develop fire-resistant erbia coatings for pits. In addition, we are developing molten-plutonium-resistant coatings for near-net-shape casting molds, a project that supports the pit-rebuild program.

Penning Fusion Experiment

M.M.Schauer [(505) 665-6014], T.B.Mitchell (P-24), D.C.Barnes (XCM)

The Los Alamos Penning Fusion Experiment seeks to confine high-density, nonneutral plasmas in a Penning trap. These traps combine static electric and magnetic fields to confine charged particles for up to several hours. However, because the traps can hold only a single charge, we are restricted to nonneutral plasmas, and the resulting space charge limits the ultimate density we can attain. The limiting value is known as the Brillouin density. In these experiments we have demonstrated the feasibility of forming a high-density core plasma in a volume-averaged, sub-Brillouin-density electron plasma through spherical focusing of the plasma. This is achieved by tuning the electric and magnetic fields of the trap so that the effective well seen by the electrons is spherical. Hence, the electrons are reflected by the well toward the center of the trap and form a high-density focus. We have seen conclusive evidence of the existence of such a focus in the form of scattering resonances in the trap parameter space. Electron-density distributions inferred from collected data indicate a peak density 35 times the limiting Brillouin value. In addition, we have documented an interesting hysteresis in the onset of the focus as a function of pumping current. Our future plans include an experiment that will confine ions in the virtual cathode provided by the confined-electron space charge.

Particle Removal in a High-Pressure Plasma

G.S.Selwyn [(505) 665-7359] (P-24), collaborators from Beta-Squared, Inc.

Plasma processes are used in 35% of the process steps needed to fabricate a semiconductor device. Particle contamination is a serious problem encountered during fabrication of devices and is a problem exacerbated by the formation of particulate contamination during plasma processing. Also, cleaning steps required to prepare semiconductor surfaces for processing consume several million gallons of water each day for a large foundry, and the use of solvents also required for surface cleaning produces chemical waste and ground-water pollution. Plasma processes may be used to clean wafer surfaces and materials of interest to DOE. The development of this technology offers an approach that is pollution-free because it uses harmless, inert gases; that may be done *in situ* prior to processing steps inside a plasma tool; that rapidly cleans the entire wafer while it is under vacuum; and that avoids redeposition of removed particulate matter back onto the wafer.

The first phase of this technology development was the demonstration of particle removal from wafer surfaces by plasma processes. In this collaboration, LANL applied its knowledge and skills in the development of technology for particle detection and removal from surfaces; Beta Squared, Inc., applied its capabilities in the design of a plasma tool suitable for use with this technology. This program proved highly successful: the Laboratory and Beta Squared, Inc., collaborated to build a prototype tool and successfully demonstrated that particulate contamination could be removed from wafers using plasma processes. The technology is suitable for immediate use on processing tools; a patent is currently in preparation. The same technology can now be applied for the development of a nonpolluting and nonhazardous method for removal of radioactive dust from surfaces. This can offer substantial benefits in cost-effectiveness and safety for decontamination and cleanup of contaminated areas.

Pollution-Free Plasma Cleaning of Materials

G.S.Selwyn [(505) 665-7359], I. Henins, J. Velarde, J. Park, (P-24), R.F.Hicks (University of California at Los Angeles), K. Wilson (Atmoplaz)

A new plasma process is being developed at LANL and at the University of California at Los Angeles (UCLA) for the pollution-free cleaning of materials. In addition to the R&D 100 Award–winning PLASMAX cleaning process, which uses a novel plasma/mechanical process for removal of particulate contamination, we have recently invented an Atmospheric-Pressure Plasma Jet (APPJ) that is capable of removing organic, metallic, and oxide contaminants from materials at rates between 1 and 15 μm/h. These rates are up to ten times faster than can be achieved with conventional, low-pressure plasmas. The APPJ does not require a process chamber; thus, it can decontaminate materials of any size and shape, and it can be used out in the field if necessary. The jet is not like a plasma torch, which ionizes gas through excessive heating. Instead, the APPJ produces a stream of electronically excited metastable and radical species at about 450 K. This makes it safe for use on a wide variety of materials.

We are pursuing several applications for the plasma jet, including the decontamination of nuclear wastes and the cleaning of silicon wafers during integrated-circuit manufacturing. In the former case, the APPJ will etch away plutonium deposits on objects so that they may be reclassified from transuranic to low-level radioactive waste. We have won a $1.2-million DOE Environmental Management Science Program award to develop the science and technology of plasma-jet decontamination of nuclear wastes. The APPJ may also be used to clean semiconductor substrates. Currently, silicon wafers are cleaned with large quantities of deionized water, acid, and organic solvents. The industry wants to replace these wet-chemical methods because they are expensive, are hazardous to workers' health, and can pollute the environment. The APPJ is a promising alternative for wafer cleaning that uses no toxic chemicals and will not pollute the environment. In FY98 we will investigate the physics and chemistry of APPJ etching of tungsten and tantalum films (surrogate metals for plutonium) and of photoresists from silicon wafers. The plasma-source physics and gas chemistry will be investigated at LANL, and the surface chemistry of etching materials will be studied at UCLA. We are hopeful that this research will lead to a new, pollution-free technology for the cleaning and decontamination of materials.

Ion Sources for Etching and Deposition

M.Tuszewski [(505) 667-3566], J.T.Scheuer, J.A.Tobin (P-24)

Inductively coupled plasmas (ICPs) are used increasingly by the semiconductor and other industries as an important class of relatively high density (10^{11}–10^{12} ions/cm^3), low-pressure (1–10 mtorr) plasma sources for etching and deposition processes. Such high-density plasma sources can meet the industrial requirements of submicron feature size, low contamination, and high throughput. We have developed several novel ICP plasma sources for new applications: (1) ICPs powered by continuous radio frequency (0.4–13.56 MHz) in hemispherical, planar, and cylindrical geometries; (2) high-power, pulsed ICPs for plasma-based ion implantation; and (3) inverted ICPs (with a coil inside a dielectric tube) for vacuum chambers with difficult access. We have also studied inductive heating physics with various plasma diagnostics and with theoretical analysis. In particular, the large influence of the induced radio-frequency magnetic fields on low-frequency ICPs has been uncovered for the first time. Finally, we have developed a comprehensive set of plasma and gas diagnostics to gain understanding of how ICPs work and of how to achieve uniform plasmas of the desired composition over increasingly large areas. The above research is performed in part as a collaboration with industries such as Novellus Systems, Inc., Dow Chemical, and North Star Research Corporation.

Alcator C-Mod Tokamak Imaging Diagnostics

G.A.Wurden [(505) 667-5633] (P-24), collaborators from Massachusetts Institute of Technology

A collaboration between Los Alamos and the Massachusetts Institute of Technology (MIT), this project is designed to provide specialized imaging diagnostics to the Alcator C-Mod tokamak. A new digital infrared (IR) camera system and IR periscope, intended to view the heat loads on the inner wall and divertor structures, has been designed, and construction will begin in FY97. Los Alamos delivered a full set of engineering drawings, optical design, and parts lists to MIT. Los Alamos systems at MIT include two fast visible cameras and a neutral-particle, time-of-flight diagnostic.

Columbia HBT-EP Magnetohydrodynamic Feedback Stabilization

G.A.Wurden [(505) 667-5633] (P-24), collaborators from Columbia University

This project is a collaboration between Los Alamos and Columbia University that will provide a high-power, fast-feedback module to the HBT-EP (High-Beta Tokamak—Extended Performance) at Columbia University for the purpose of controlling plasma instabilities in real time. The unit will be used to study the effects of mode locking by using external coils to study driven plasma rotation and disruption prevention. It is the second of a set of two 10-MW, 0- to 30-kHz, 1000-A amplifiers. Although this collaboration was primarily an engineering effort in FY96, in future years we intend to study the underlying physical processes of these instabilities.

Diagnostic Development Relevant to the International Thermonuclear Experimental Reactor

G.A.Wurden [(505) 667-5633], C.W.Barnes, H.A.Davis, R.J.Maqueda, J.C.Olson, W.A.Reass (P-24), R.R.Bartsch (P-22), P.Staples (P-25), S.Han, R.S.Wagner (MST-11), collaborators from Cornell University, DuPont, and University of California at San Diego

Los Alamos is participating in a number of diagnostic-development activities that support the International Thermonuclear Experimental Reactor (ITER). We are supporting ongoing US/Japan collaborations with two advanced diagnostic systems under development and testing; this effort was also used to enhance our collaboration with the Tokamak Fusion Test Reactor (TFTR) at Princeton. First, our studies of diamond neutron detectors were concluded at the LAMPF neutron source at Los Alamos. Ongoing efforts with scintillating-fiber, 14-MeV-neutron detectors at the large JT-60U tokamak at the Japanese Atomic Energy Research Institute in Naka, Japan, continued with demonstration of remote diagnostic control over the Internet and of virtual presence at off-site experiments using integrated services digital network (ISDN) video conferencing. We are also designing a new diagnostic that could be applied directly to ITER for eventual prototyping on the new Large Helical Device in Nagoya, Japan. This diagnostic is a state-of-the-art imaging bolometer that will be able to measure the entire spectrum of energies emitted by a hot steady-state plasma. Los Alamos is also conducting scoping studies and doing diagnostic design to support the ITER Engineering Design Activity (EDA). This includes work on some physics R&D issues deemed important by the U.S. home team. In FY96 we worked on Phase I and II designs for several neutron-detector diagnostics (including neutron-activation and source-strength monitors). We also studied the prospects for an intense diagnostic neutral beam to be used for a variety of plasma measurements, especially for active spectroscopy.

Tokamak Fusion Test Reactor Experiment

G.A.Wurden [(505) 667-5633] (P-24), collaborators from Princeton University

This project is an on-going collaboration between Los Alamos and Princeton University on the TFTR experiment at Princeton. Los Alamos fielded a new digital imaging system on an existing periscope to view plasma disruptions, plasma instabilities, and lithium-pellet injection during deuterium-tritium experiments. Los Alamos personnel are studying the sudden and violent demise of the plasma current and the formation of runaway electron tails, circumstances in which several megajoules of energy can be suddenly deposited on the vessel structures. Irradiation studies of Hall-probe magnetic-field sensors also continued in the realistic neutron environment of the TFTR.

A Target Plasma Experiment for Magnetized Target Fusion

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Achieving controlled fusion is a scientific “grand challenge” that has been pursued for over 40 years. Fusion energy would help satisfy the long-term energy needs of the growing population on Earth. Magnetized target fusion (MTF) is an approach to controlled fusion in which a premagnetized, preheated target plasma is near-adiabatically compressed to fusion conditions. The objective of this project is to develop the ability to generate suitable target plasmas for MTF, the first critical milestone in the development path for achieving fusion with the MTF concept. Our approach involves driving a fast-rising electrical current reaching 1–2 MA through a fiber of cryogenically frozen deuterium on the order of 200 mm in diameter. The fiber rapidly turns to plasma, heats, and expands to fill a plasma-containment chamber, thus becoming confined by the walls of the chamber.

This project relies heavily on existing facilities and equipment at the Laboratory that are adapted to our needs. This year, we designed and constructed a power-flow-channel and plasma-chamber system, and we incorporated this system into the Laboratory’s Colt capacitor-bank facility. The capacitor bank has a maximum stored energy of 0.25 MJ, and it delivers a maximum of 3 MA of current with a rise time of 2–3 ms. We have performed initial plasma-formation experiments using a static fill of hydrogen gas. The diagnostics that we have fielded include an array of 12 B-dot probes used to determine plasma current; a 1.3-mm laser interferometer to determine plasma density; an optical framing camera; a gated, optical, multichannel analyzer for visible spectroscopy; a visible/near-ultraviolet monochromator with time resolution for spectral time history; photodiodes to measure light emission; and the usual capacitor-bank monitors. The data show that we are generating a plasma that lasts 10–20 ms with no obvious signs of impurities. Further analysis of the data is ongoing. The results from the 1.3-mm interferometer show that we need to go to a shorter-wavelength laser interferometer to reduce beam deflection caused by density gradients in the plasma and to reduce the overall sensitivity of the system. In accordance, we have borrowed a HeCd laser, purchased the supporting optics, and assembled and bench-tested the new interferometer. We will install the new interferometer on the actual plasma chamber in the near future. We are also refurbishing the cryostat used for making the cryogenically frozen deuterium fibers and will be installing it on the plasma chamber.

P-25: Subatomic Physics

Measurement of the Electric Dipole Moment of the Neutron

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The Electric Dipole Moment (EDM) project is a new project in which we will develop an experiment to measure the EDM of the neutron. A nonzero value of the neutron's EDM would imply that a fundamental symmetry of space-time reversal has been violated. The only example of such a violation is in the neutral kaon system, although the violation is expected to be a general, but small, phenomenon. A measurement of the neutron's EDM is important for understanding the baryon-antibaryon asymmetry of the universe and for searching for physics beyond the standard model of electroweak interactions, especially grand-unified supersymmetry. We propose to take advantage of the construction of the Long Pulse Spallation Source at LANSCE to build a special superthermal source of ultracold neutrons that will allow us to measure the EDM to a level of 10^{-28} e•cm, an improvement of three orders of magnitude over past measurements. The international collaboration for this complicated experiment is just beginning to form, and development work is commencing in preparation for submitting a funding proposal to DOE at the end of 1998.

MEGA

M. D. Cooper [(505) 667-2929], M. Brooks, A. V. Chernyshev, G. W. Hart, G. E. Hogan, M. A. Kroupa, V. D. Laptev, D. M. Lee, G. B. Mills, R. E. Mischke (P-25), F. J. Naivar, C. Pillai, J. C. Sturrock (LANSCE-6), collaborators from Fermi National Accelerator Laboratory, University of Houston, Indiana University, Texas A&M University, Valparaiso University, University of Virginia, and Virginia Polytechnic Institute and State University

The apparent conservation of muon number remains a central problem of weak-interaction physics. Searching for processes that violate muon-number conservation will give insight into the possible extensions of the minimal standard model of weak interactions. MEGA (muon decays into an electron and a gamma ray) is designed to make such a search at LAMPF, now known as LANSCE. This past year was the final year of acquiring production data. The combined data from the summers of 1993–1995 should yield a sensitivity of roughly 7×10^{-13}, an improvement by a factor of 70 in the current world sensitivity to this process. The MEGA collaboration made substantial strides in developing algorithms to extract the results. The three major components of the analysis include reconstructing the kinematic properties of the photon and of the positron and determining their relative timing. The photon analysis is nearly complete, and the other two components have reached an advanced stage.

Theory

M. B. Johnson [(505) 667-6942], D. Ahluwalia (P-25), J. D. Bowman (P-23), collaborators from institutions in the United States, Canada, France, Israel, Kazakhstan, Russia, and Taiwan

The Subatomic Physics group has a small theory component. We are currently developing a theory for connecting hadron properties in free space, and we have also explored phenomenological approaches that use data to determine masses and coupling constants for higher-mass resonances in nuclei. In addition, we are developing a theory for connecting mean-square matrix elements of the parity-violating interaction (measured by TRIPLE in compound-nuclear resonances) to the underlying parity-violating force. This theory exploits the chaotic properties of the compound nucleus. Another project involves the reaction theory of pion scattering from nuclei. In this project we are simplifying the description of specific reactions so that these reactions can more easily be used for specific purposes, such as evaluating hadron transport in nuclear collisions and interpreting results of dibaryon resonance searches. One group member investigated the phenomenon of neutrino oscillations within a three-state mixing model and found that all reported neutrino-oscillation data are consistent with a mass mixing-angle analysis in terms of three neutrinos. His "Gravitationally Induced Neutrino-Oscillation Phases" is the Gravity Research Foundation's First Award Essay for 1996. Participants at a relativistic heavy-ion meeting held during the summer of 1995 determined that essentially all relativistic heavy-ion transport event generators are incapable of reproducing pion production data taken at LANSCE. We are investigating why the data are irreproducible; the answer could have a significant impact on our heavy-ion and PHENIX experimental programs.

Experiments E866, E789, and E772: Quark-Gluon Physics at FNAL

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This program at the Fermi National Accelerator Laboratory (FNAL) has been highly visible and productive. Our group was the first to exploit high-energy hadronic processes for exploring the quark structure of nuclei. We are investigating the nuclear dependence of lepton-pair production with proton beams to understand how the quark and gluon structure in nuclei differs from that in free nucleons. During the past year we made substantial progress in the construction and refurbishing of the

FNAL Meson-East spectrometer, where E866 began taking data in July 1996. In that experiment we are searching for deviations in the distributions of anti-up and anti-down quarks in the proton to provide insight into hadronic and partonic descriptions of the nucleonic sea. We also continued major analysis efforts on past experiments E772 and E789. We developed Monte Carlo and analysis software that will enable us to extract cross sections from 1.5 million Drell-Yan and Upsilon production events from the copper beam dump of E772. In addition, we finished analyzing and published the first B-meson cross-section data for 800-GeV proton-nucleus interactions and published the nuclear dependence of J/Ψ production in the negative x-Feynman region.

Electroweak Physics at the Liquid Scintillator Neutrino Detector

W. C. Louis [(505) 667-6723], R. L. Burman, F. J. Federspiel, G. T. Garvey, G. B. Mills, V. Sandberg, R. Tayloe, D. H. White (P-25), J. B. Donahue (LANSCE-7), collaborators from the University of California at Riverside, University of California at San Diego, University of California at Santa Barbara, Embry-Riddle Aeronautical University, University of California Intercampus Institute for Research at Particle Accelerators, Linfield College, Louisiana State University, Louisiana Tech University, University of New Mexico, Southern University, and Temple University

With the Liquid Scintillator Neutrino Detector (LSND) at LANSCE, we are searching for evidence of neutrino oscillations, in which neutrinos transform from one flavor into another. These oscillations would imply that neutrinos have mass, an implication that contradicts the standard model of particle physics. If neutrinos have mass, they may profoundly affect cosmology and the evolution of the universe. The LSND collaboration has published papers describing the detector and the analysis of the full decay-at-rest data sample through December 1995. The LSND paper "Evidence for Neutrino Oscillations from Muon Decay at Rest" was published in the November 1996 issue of *Physical Review C*. We have also analyzed our decay-in-flight data and have observed an excess of events that is consistent with neutrino oscillations and with our decay-at-rest data. Because the decay-at-rest and decay-in-flight searches have completely different backgrounds and systematics, this decay-in-flight analysis provides strong additional evidence that we are indeed observing neutrino oscillations.

Applied Programs: The Role of Proton Radiography in Stockpile Stewardship

J. B. McClelland [(505) 667-7291], J. F. Amann, J. G. Boissevain, C. J. Espinoza, J. Gomez, G. W. Hart, G. E. Hogan, C. Morris, H. A. Thiessen, H.-J. Ziock, J. D. Zumbro (P-25), collaborators from P-23, DX Division, LANSCE Division, T Division, X Division, ESA Division, Lawrence Livermore National Laboratory, Lawrence Berkeley National Laboratory, Brookhaven National Laboratory, Indiana University Cyclotron Facility, and Bechtel

The decisions to forgo underground nuclear testing and to restrict the nuclear stockpile to an increasingly smaller number of weapons have forced DOE and its laboratories to rethink their role in stockpile stewardship. Much of this reassessment has been embodied in the philosophy of science-based rather than test-based stockpile stewardship. Proton radiography offers several advantages over conventional x-ray techniques for radiographing thick, dense, dynamic systems. These advantages include (1) high penetrating power, (2) high detection efficiency, (3) very small scattered background, (4) no need for a conversion target and the consequent phase space broadening of the beam, (5) inherent multipulse capability, and (6) the ability to tolerate large stand-off distances from the test object and containment vessel for both the incoming and outgoing beams. Additionally, proton radiography provides the unique possibility of measuring both the density and the material composition of a test object with a pulsed system. Protons interact with matter through both the long-range Coulomb force and the short-range strong interaction. Focusing protons using a magnetic lens allows the magnitude and Z-dependence of the interaction to be changed simply by looking at an object through different angular apertures and, thus, leads to the capability for assessing material composition. Multiple images can be made on a single axis by using multiple detectors, lenses, and irises. P-25 leads this effort together with a strong cross-divisional team that includes P, DX, LANSCE, T, and X Divisions.

Booster Neutrino Experiment at FNAL

G. B. Mills [(505) 667-7330], W. C. Louis, V. D. Sandberg, R. L. Tayloe (P-25), collaborators from Columbia University, Louisiana State University, and University of California at Riverside

Los Alamos has long been a world leader in subatomic-particle physics, especially in the field of the elusive neutrino particle. The recent success of the LSND at LANSCE has excited the physics community around the world. The LSND experiment has been in operation since 1993, and plans are to continue its operation until roughly the year 2000. The startling discovery of neutrino oscillations at LSND has given Los Alamos physicists the motivation to take the next step in this line of research: to make precise measurements of the oscillation phenomena. The ideal setting for these measurements takes us away from Los Alamos to FNAL in Batavia, Illinois. Proton beams from a rapid cycling booster synchrotron at 10 times the energy of the LANSCE beams are available to produce neutrinos at FNAL. The Booster Neutrino Experiment (BOONE) will capitalize on the technology developed for the LSND experiment. It will reuse much of the equipment that is currently being used in the LSND experiment. The neutrino beams to be developed at FNAL will give a 40-fold increase in the rate of neutrino-oscillation events over the current LSND experiment. The ultimate goal will be to measure the oscillation parameters with a precision of a few percent. A more challenging goal will be to study the fundamental symmetries of the neutrino mixing matrix, especially the charge-conjugation and parity-reversal properties of neutrinos. These studies require the use of neutrino and antineutrino beams, which can be made available at FNAL.

RHO Experiment: Measurement of the Michel Parameter

R. E. Mischke [(505) 667-6814], J. F. Amann, M. D. Cooper, G. W. Hart, G. E. Hogan, T. Kozlowski (P-25), R. D. Bolton (NIS-6), W. Foreman (NIS-8), R. Harrison (DX-5), C. Pillai (LANSCE-6), S. A. Schilling (ESA-DE), collaborators from the University of Chicago, Fermi National Accelerator Laboratory, University of Houston, Indiana University, Texas A&M University, Valparaiso University, University of Virginia, and Virginia Polytechnic Institute and State University

The energy spectrum for positrons emitted in normal muon decay contains a portion that is independent of polarization, and the shape of this portion is governed by the Michel parameter, ρ. In this project we measured ρ with the MEGA positron spectrometer. The standard model predicts ρ to be 0.75; it is currently known to within 0.3% of that value. Deviations from 0.75 might indicate the need for right-handed currents in the standard model. Collected data will enable us to measure ρ with a precision of 0.05%, but we are still evaluating the systematic errors. Such a precision would allow us to check the reported deviations from the standard model in neutron decay. Our analysis should be complete by early 1997.

PHENIX Experiment at the Relativistic Heavy-Ion Collider at Brookhaven National Laboratory

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The quark-gluon plasma (QGP) is a postulated phase of matter in which quarks and gluons are deconfined. Proof of its existence has, to date, eluded experimentalists, although theoretical speculations about its nature abound. If the QGP phase transition does occur, then the characterization of that transition is of intense interest and importance to nuclear and particle physics.

The PHENIX detector is a large, multipurpose detector designed to detect the QGP and characterize its properties at the Relativistic Heavy Ion Collider (RHIC) being built at Brookhaven National Laboratory. PHENIX is being constructed by a large collaboration of physicists and engineers from universities and laboratories around the world. The detector design as a whole focuses on leptons (that is, electrons and muons), photons, and hadrons. Los Alamos collaboration members continue to have a significant impact on this major thrust of the nationwide nuclear-physics effort. P-25 members are responsible for the construction of the muon arms and the silicon multiplicity/vertex detector (MVD). The Los Alamos PHENIX muon-tracker team leads the conception, design, construction, and commissioning of the two large muon spectrometers that are crucial to the search for signatures of the quark-gluon plasma. The Los Alamos PHENIX MVD team leads the conception, design, construction, and commissioning of the MVD. Both construction efforts continue to meet major milestones. The Muon Station 2 has been fully prototyped and tested; it met or exceeded all requirements, including those for resolution and efficiency. The Station-3 full-size prototype was constructed and tested to demonstrate the feasibility of the design. The silicon-MVD preliminary design and safety plan have been reviewed with high marks, and there has been a successful beam test to demonstrate the design.

PHENIX Spin Program

J. M. Moss [(505) 667-1029], J. G. Boissevain, M. Brooks, T. A. Carey, D. Clark, J. Kapustinsky, W. W. Kinnison, T. Kozlowski, D. Lee, M. Leitch, J. McClelland, P. L. McGaughey, M. Murray, J. Simon-Gillo, J. P. Sullivan, H. W. van Hecke (P-25), PHENIX Collaboration

The scattering of high-energy, polarized muons from polarized protons at the European Center for Nuclear Research (CERN) revealed a big surprise about ten years ago. The spin of the proton receives only a small contribution from its valence quarks, those elusive building blocks of matter that determine most of the proton's other attributes. More recent experiments have refined and confirmed the CERN results, but they have added little hard evidence about the location of the missing spin. We hope that a new generation of polarized proton experiments, to be carried out at the Relativistic Heavy-Ion Collider at Brookhaven National Laboratory (BNL), will allow us to determine directly the contribution of specific degrees of freedom (such as quarks and antiquarks) to the proton's spin. The highly successful Los Alamos/RIKEN (Institute for Physical and Chemical Research, Tokyo [Wako], Japan) collaboration culminated two years of work, resulting in the final specification of the RIKEN contribution to the spin-structure function program of the PHENIX detector. RIKEN funding will purchase the PHENIX south-arm magnet plus the associated muon tracking and identification systems. This contribution greatly enhances the high-mass dimuon acceptance of the PHENIX detector and permits us to carry out a large menu of experiments on unique spin-structure function. Equally important, the muon upgrade will substantially increase the physics reach of the relativistic heavy-ion program.

Education and Outreach

A. P. T. Palounek [(505) 665-2574], J. F. Amann (P-25)

As members of three education programs run by the Laboratory, P-25 group members continue to be active in education and outreach activities. Group members visited every teacher and school in the TOPS (Teacher Opportunities to Promote Science) and TOPS Mentor programs at least once; conducted regional meetings for TOPS teachers, TOPS mentors, and TOPS alumni; and led several workshops in Los Alamos and Albuquerque. During the most recent workshop, TOPS mentors built (from scratch) a simple lightning detector designed by physicists from NIS-1 and P-25. Group members were also active in the PRISM (Preservice Institute for Science and Math) program. As a part of this program, we guided students through a comparison of the transmission qualities of various brands of sunglasses.

Experiment E907 at the Brookhaven National Laboratory Alternating-Gradient Synchrotron: Hypernuclear Physics

J.-C. Peng [(505) 667-9431], C. Edwards, C. Morris (P-25), collaborators from institutions in the United States, Croatia, and Japan

Los Alamos led the effort to propose a new hypernuclear experiment at the BNL Alternating-Gradient Synchrotron (AGS) using the LANSCE Neutral Meson Spectrometer (NMS) to measure the (K^-,π^0) reaction. Our proposal for this experiment was approved by the AGS Program Advisory Committee in late 1994. The experiment will demonstrate the feasibility of using the (K^-,π^0) reaction as a novel tool to produce Λ-hypernuclei with resolution significantly better than the existing (K^-,π^-) and (π^+,K^+) experiments, and it will measure the Λ-hypernuclear π^0 weak decay modes never before studied. The NMS and associated equipment were moved from LANSCE to the AGS in December 1995, and the first test run was completed in May 1996. The LANL team will assume responsibility for the NMS operation and physics direction in this experiment.

Pion Research

C. M. Riedel [(505) 665-4516], J. F. Amann, C. L. Morris, D. Tupa, J. D. Zumbro (P-25), M. A. Espy (P-21), S. I. Penttila, S. J. Seestrom (P-23), R. L. Boudrie (DX-6), J. N. Knudson (LANSCE-7), B. K. Park, M. W. Rawool-Sullivan (NIS-6), collaborators from institutions in the United States, Canada, Croatia, Germany, Japan, Russia, Switzerland, and the United Kingdom

We are currently analyzing pion data from the final 1995 LANSCE run and from previous runs. Of particular interest are the recent data taken with the NMS from the $p(\pi^-,\pi^0)$ reaction. The pi-nucleon charge-exchange database has historically been weak, and these recent measurements are expected to contribute to topics such as chiral symmetry breaking in the nucleon and isospin symmetry breaking in the pi-nucleon system. We expect to finish analyzing data collected at LANSCE, including pion charge-exchange data taken with the NMS as well as other elastic and inelastic pion-scattering experiments, and we will soon publish the final measurements of the low-energy cross sections and intermediate-energy analyzing powers for the pi-nucleon charge-exchange reaction. This work is being done in collaboration with colleagues from a number of institutions.

The NA44 Experiment: Relativistic Heavy-Ion Collisions at the European Center for Particle Physics

J. P. Sullivan [(505) 665-5963], J. G. Boissevain, D. E. Fields, B. V. Jacak, J. E. Simon-Gillo, W. E. Sondheim, H. van Hecke (P-25), collaborators from institutions in Denmark, France, Japan, Sweden, Switzerland, and the United States

Heavy-ion collisions at very high energies provide an opportunity to recreate the conditions that existed very early in the universe, just after the big bang. Experiment NA44 at the European Center for Particle Physics (CERN) is a second-generation relativistic heavy-ion experiment that searches for evidence that quarks and gluons are deconfined in matter at very high energy densities. The experiment focuses on correlations among identical particles as a function of transverse momentum in order to provide a closer look at the space-time extent of the central-region heavy-ion collisions. A long lifetime of matter in the central region is an indication of the formation of deconfined quarks and gluons.

In 1995 and 1996 the experiment took data with 160-GeV/nucleon lead-ion beams. Among the heavy-ion experiments at CERN, NA44 is unique in its ability to compare correlations of identified pions, kaons, and protons. Comparison of pion and kaon results clarifies the effects of resonance decays versus the time evolution of the emitting source. The high statistics from NA44 allow a careful study of the behavior of the chaoticity parameter (which is usually not well understood) and the exact shape of the correlation function. NA44 also measures single-particle distributions. Measurements of the distributions of protons emitted in Pb + Pb collisions and measurements of the ratio of negative- to positive-pion production both suggest significant stopping in these collisions, meaning that the protons and neutrons in the incident nuclei do not pass through one another in the collision (that is, they do not have transparency) but are slowed down significantly.

Members of the collaboration also interact with theoretical colleagues to study correlation functions predicted by the Relativistic Quantum Molecular Dynamics (RQMD) event generator and to compare those predictions with NA44 data. This work has provided the first detailed explanation of the information contained in the shape of the correlation function.

Measurements of Beta Asymmetry and Atomic Parity Nonconservation: Fundamental Symmetry Studies with Trapped Radioactive Atoms

D. Tupa [(505) 665-1820] (P-25), S. G. Crane, R. Guckert, M. J. Smith, D. J. Vieira, X. Zhao (CST-11), S. J. Brice, A. Goldschmidt, A. Hime, S. K. Lamoreaux (P-23)

With the advent of optical and magnetic traps for neutral atoms, a new generation of fundamental symmetry experiments can exploit point-like, massless samples of essentially fully polarized nuclei. At Los Alamos we are probing the origin of parity violation in the electroweak interaction by attempting to measure the beta-spin correlation function in the beta decay of ^{82}Rb confined to an atomic trap. By exploiting the geometry and the intrinsic features of such traps, we plan to measure the beta-spin correlation as a continuous function in both energy and angle of the emitted beta particles relative to the nuclear polarization. This continuous measurement would allow us to simultaneously extract new physics, such as the existence of right-handed currents, and recoil order effects, such as weak magnetism. With these traps we may also extract further information, such as the recoil ion momentum, that would allow a study of a much wider range of correlation parameters. Finally, we envision a new generation of atomic parity nonconservation experiments that test the neutral current portion of the weak interaction.

In these experiments, measurements with a series of radioactive isotopes of cesium and/or francium could eliminate uncertainties about atomic structure that presently limit the precision. A fundamental ingredient for performing these symmetry measurements is the efficient trapping of selected radioactive species. To this end we are using a magneto-optical trap (MOT) that is coupled to a mass separator. To date we have developed one of the world's largest MOT traps; it can trap up to 4×10^{10} atoms. By coating the inside of the glass trapping cell with a special nonstick coating of Dryfilm, we have measured a trapping efficiency of 20%. If we couple the MOT to a mass separator, we can introduce the species of interest into the trap without the deleterious effects of gas loading. In recent work using the mass separator–MOT system, we have successfully trapped stable ^{85}Rb, and we are currently attempting to trap a million ^{82}Rb atoms using a 2-mCi mother source of ^{82}Sr. We have also made good progress in modeling and designing the beta-asymmetry detection system and polarization trap.

P-DO: Physics Division Office

High-Current, Cold-Cathode Discharge Sources for Ion Implantation

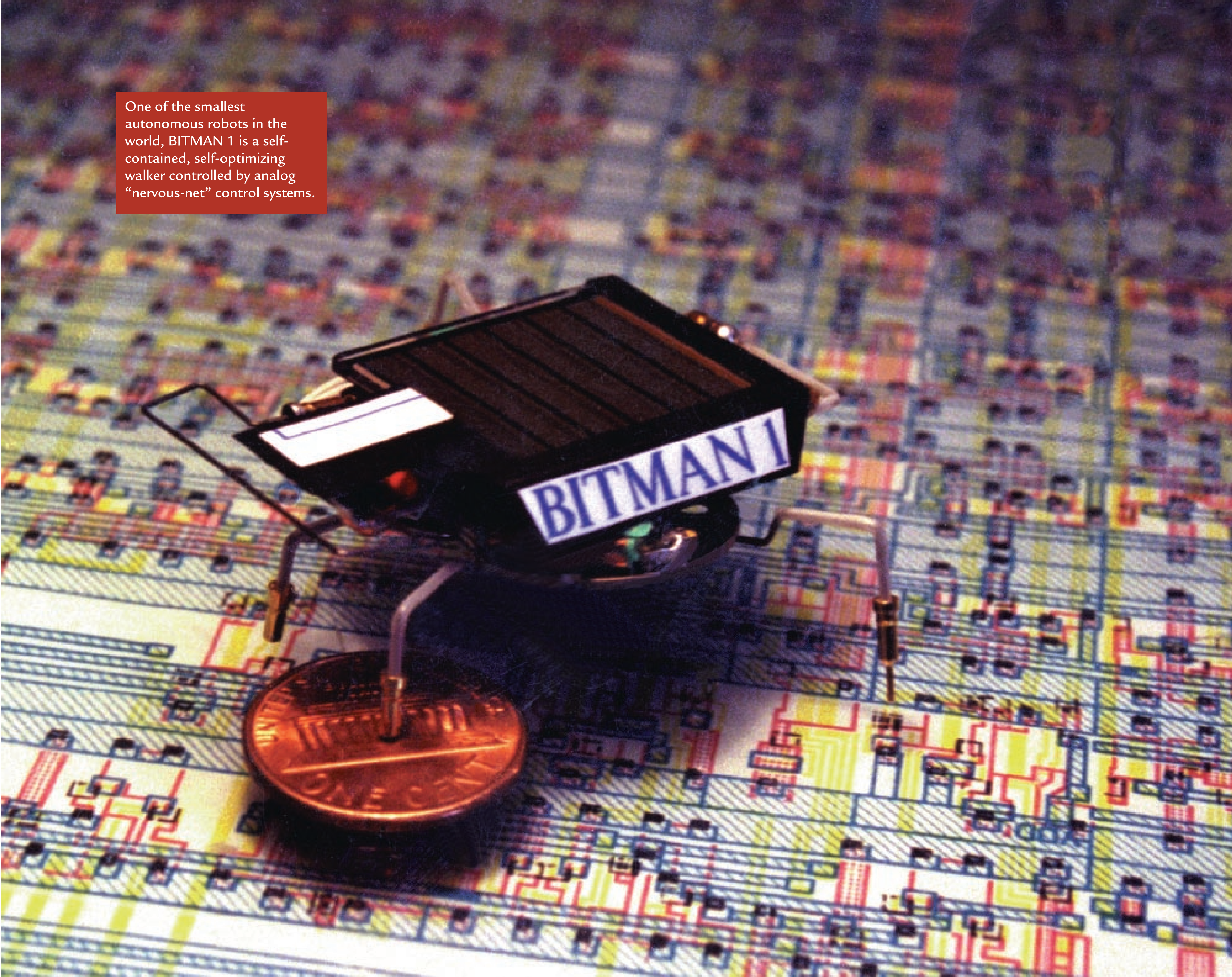
D. J. Rej [(505) 665-1883] (P-DO), M. Nastasi (MST-4), N. V. Gavrilov, G. A. Mesyats (Institute of Electrophysics, Yekaterinburg, Russia)

We are developing reliable, high-efficiency, high-power ion sources that are applicable to a broad class of material-surface modification processes (e.g., the production of wear- and corrosion-resistant metals and polymers). The reverse magnetron, a plasma configuration invented at the Institute of Electrophysics in Yekaterinburg, Russia, is a high-current glow discharge with a cold cathode in crossed electric and magnetic fields. Prototype ion sources of ~150 cm^2 have been constructed that have operated successfully and reliably at 50 mA and 40 keV in reactive gases. Our program is directed toward developing a 1000-cm^2 source, with emphasis on (1) studying ignition and stable-discharge operation under low gas pressures with high currents; (2) optimizing conditions for formation of the ion-plasma emitter that produces a high ion current density with uniformity over a large area; and (3) decreasing contaminants generated by cathode erosion. Ion-implantation experiments were performed with carbon, nitrogen, and oxygen ions implanted into stainless steel over a wide range of temperatures and current densities. Significant increases in the surface hardness were observed in carbon and nitrogen implants, with the best results at intermediate temperatures of 400–500°C, resulting in case depths of 5–10 times the ballistic ion ranges. Improvements in wear of up to 100 times were observed.

Materials Processing with Intense, Pulsed Ion Beams

D. J. Rej [(505) 665-1883] (P-DO), H. A. Davis, J. C. Olson (P-24), M. Nastasi (MST-4), G. E. Remnev (Nuclear Physics Institute, Tomsk, Russia), V. A. Shulov (Moscow Aviation Institute, Moscow Russia)

Intense, pulsed ion beams (IPIBs) are an emerging technology that has been developed throughout the world over the last two decades, primarily for nuclear-fusion and high-energy-density physics research. IPIBs are created in magnetically insulated vacuum diodes from which 10- to 1000-kA beams of low-Z ions are accelerated to energies typically between 10 keV and 10 MeV in 10- to 1000-ns pulses. Physics Division is collaborating with two Russian institutes to develop IPIBs for the surface treatment of materials. The short range (0.1–10 μm) and high energy density (1–50 J/cm^2) of these short-pulsed beams make them ideal for flash-heating a target surface in a way that is similar to the more familiar pulsed laser processes. IPIB surface treatment induces rapid melt and solidification at up to 10^{10} K/s, which causes amorphous layer formation and the production of nonequilibrium microstructures. On the Anaconda accelerator at LANL, a 300-keV, 30-kA, 1-μs intense beam of carbon, oxygen, and hydrogen ions is used for the surface treatment of AISI-4620 steel, a common material used in automotive gear applications. Treated surfaces are up to 1.8 times harder than untreated surfaces and have no discernible change in modulus over depths of 1 μm or more. Qualitative improvements in the wear morphology of treated surfaces are observed.



One of the smallest autonomous robots in the world, BITMAN 1 is a self-contained, self-optimizing walker controlled by analog "nervous-net" control systems.

Appendices

Appendix A
Physics Division Data
FY95–FY97

Group		FY95	FY96	FY97
P-21: Biophysics	Operating Costs[a]	4.3	4.2	4.4
	Staff Members[b]	16.5	14.0	13.7
	Graded Employees[c]	7.5	7.0	9.2
P-22: Hydrodynamic and X-Ray Physics	Operating Costs	12.3	11.8	12.4
	Staff Members	28.1	29.0	28.8
	Graded Employees	53.4	36.0	36.8
P-23: Neutron Science and Technology	Operating Costs	13.8	11.2	13.6
	Staff Members	34.4	34.0	40.0
	Graded Employees	27.5	23.0	20.0
P-24: Plasma Physics	Operating Costs	12.9	14.3	15.4
	Staff Members	34.6	39.0	40.3
	Graded Employees	21.0	36.0	41.2
P-25: Subatomic Physics	Operating Costs	12.6	10.8	10.6
	Staff Members	40.0	39.0	38.8
	Graded Employees	16.7	16.0	15.7
P-DO: Division Office	Operating Costs[d]	0.2	2.2	3.3
	Staff Members[e]	10.5	11.0	9.6
	Graded Employees[e]	6.1	9.0	8.6
	Total Operating Costs	56.1	54.5	59.7
	Capital Equipment Costs	3.3	4.8	4.9
	Total Costs	59.4	59.3	64.6
	Total Income	56.0	60.5	64.6
	Total Underrun/(Overrun)	(3.4)	1.2	0.0

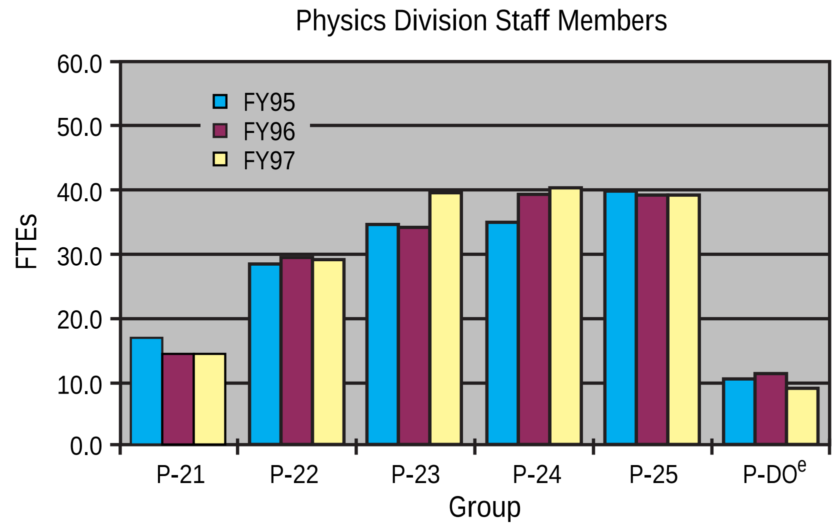
[a]*Costs, income, and underrun/overrun are reported in $M.*

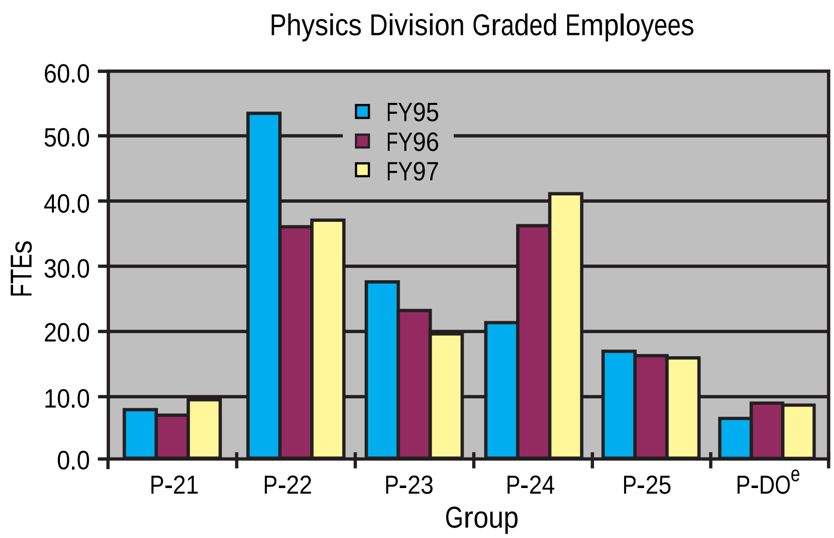
[b]*Staff Members are reported in FTEs and include technical staff members (TSMs), TSM contractors, postdocs, and management.*

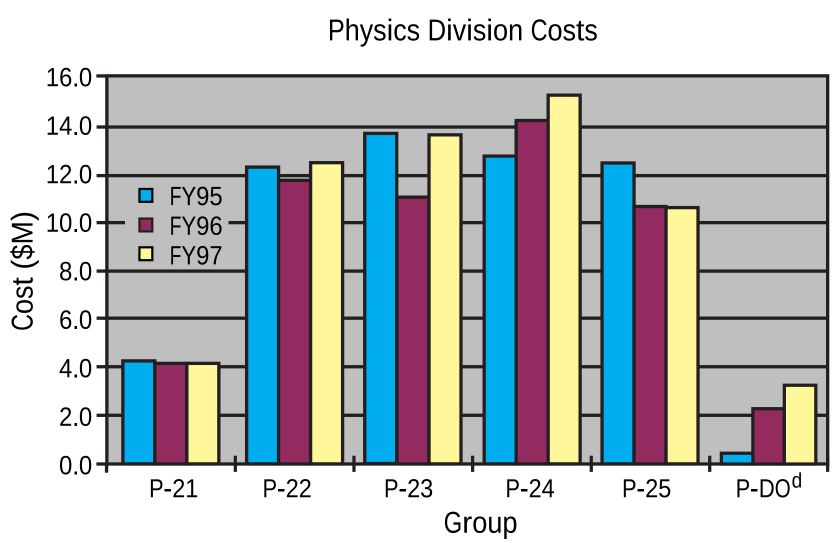
[c]*Graded Employees are reported in FTEs and include office support, technicians, graduate research assistants (GRAs), undergraduate students (UGSs), and contractors.*

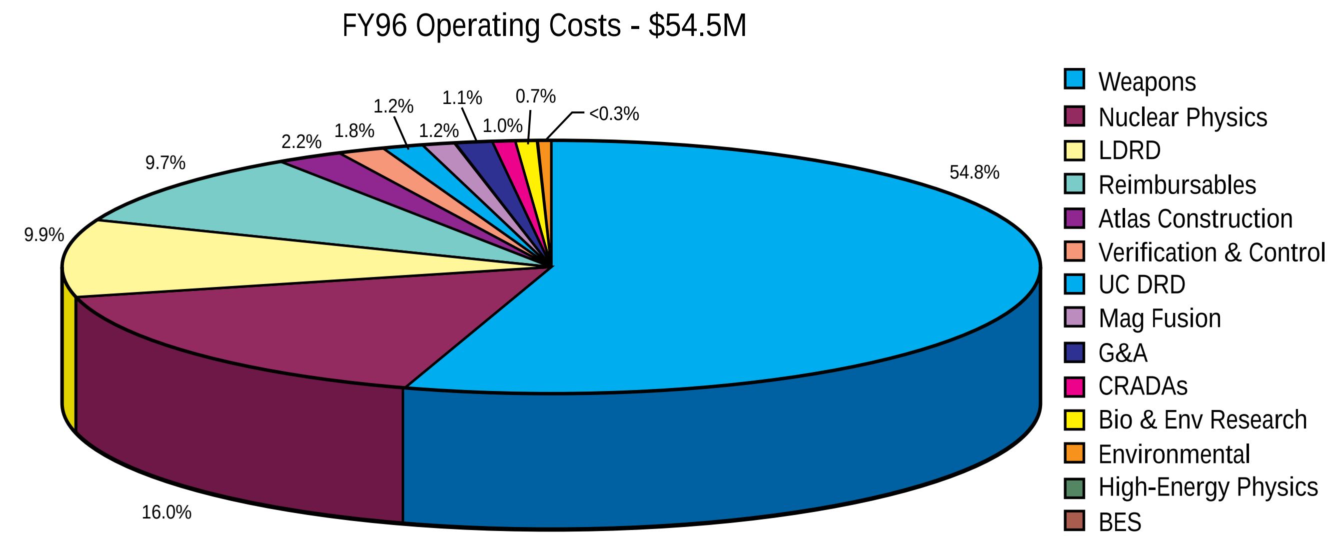
[d]*This value is the direct costs.*

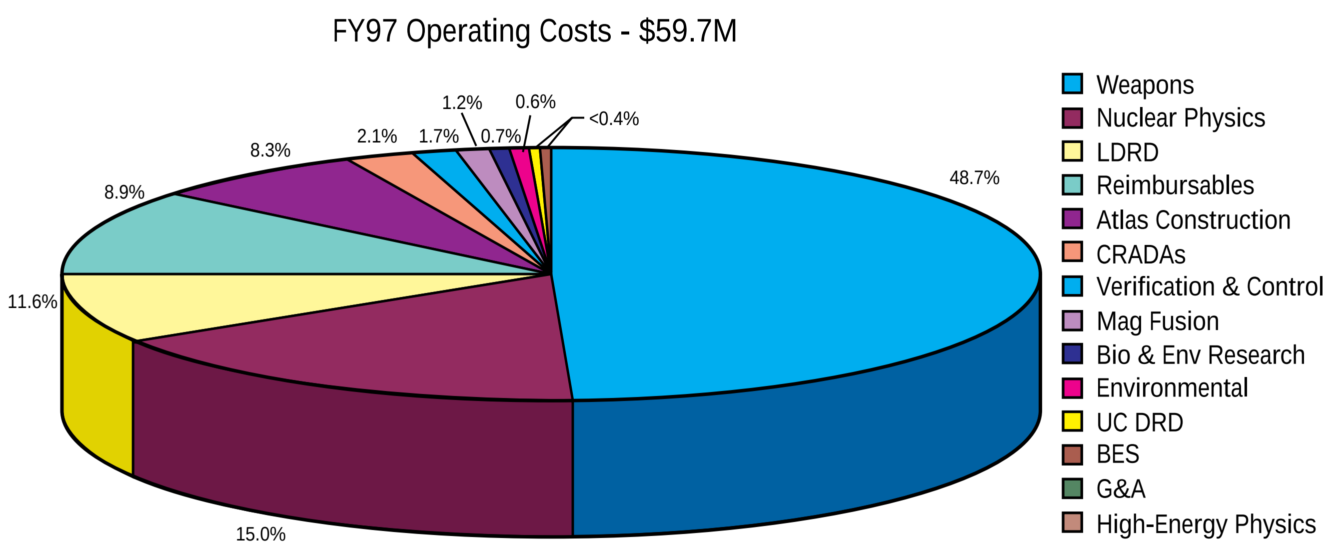
[e]*This value includes indirect and direct FTEs.*


Physics Division Staff Members
FTEs
60.0
50.0
40.0
30.0
20.0
10.0
0.0
FY95
FY96
FY97
P-21
P-22
P-23
P-24
P-25
P-DOe
Group


Physics Division Graded Employees
FTEs
60.0
50.0
40.0
30.0
20.0
10.0
0.0
FY95
FY96
FY97
P-21
P-22
P-23
P-24
P-25
P-DOe
Group


Physics Division Costs
Cost ($M)
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
FY95
FY96
FY97
P-21
P-22
P-23
P-24
P-25
P-DOd
Group


FY96 Operating Costs - $54.5M
54.8%
16.0%
9.9%
9.7%
2.2%
1.8%
1.2%
1.2%
1.1%
1.0%
0.7%
<0.3%
Weapons
Nuclear Physics
LDRD
Reimbursables
Atlas Construction
Verification & Control
UC DRD
Mag Fusion
G&A
CRADAs
Bio & Env Research
Environmental
High-Energy Physics
BES


FY97 Operating Costs - $59.7M
48.7%
15.0%
11.6%
8.9%
8.3%
2.1%
1.7%
1.2%
0.7%
0.6%
<0.4%
Weapons
Nuclear Physics
LDRD
Reimbursables
Atlas Construction
CRADAs
Verification & Control
Mag Fusion
Bio & Env Research
Environmental
UC DRD
BES
G&A
High-Energy Physics

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