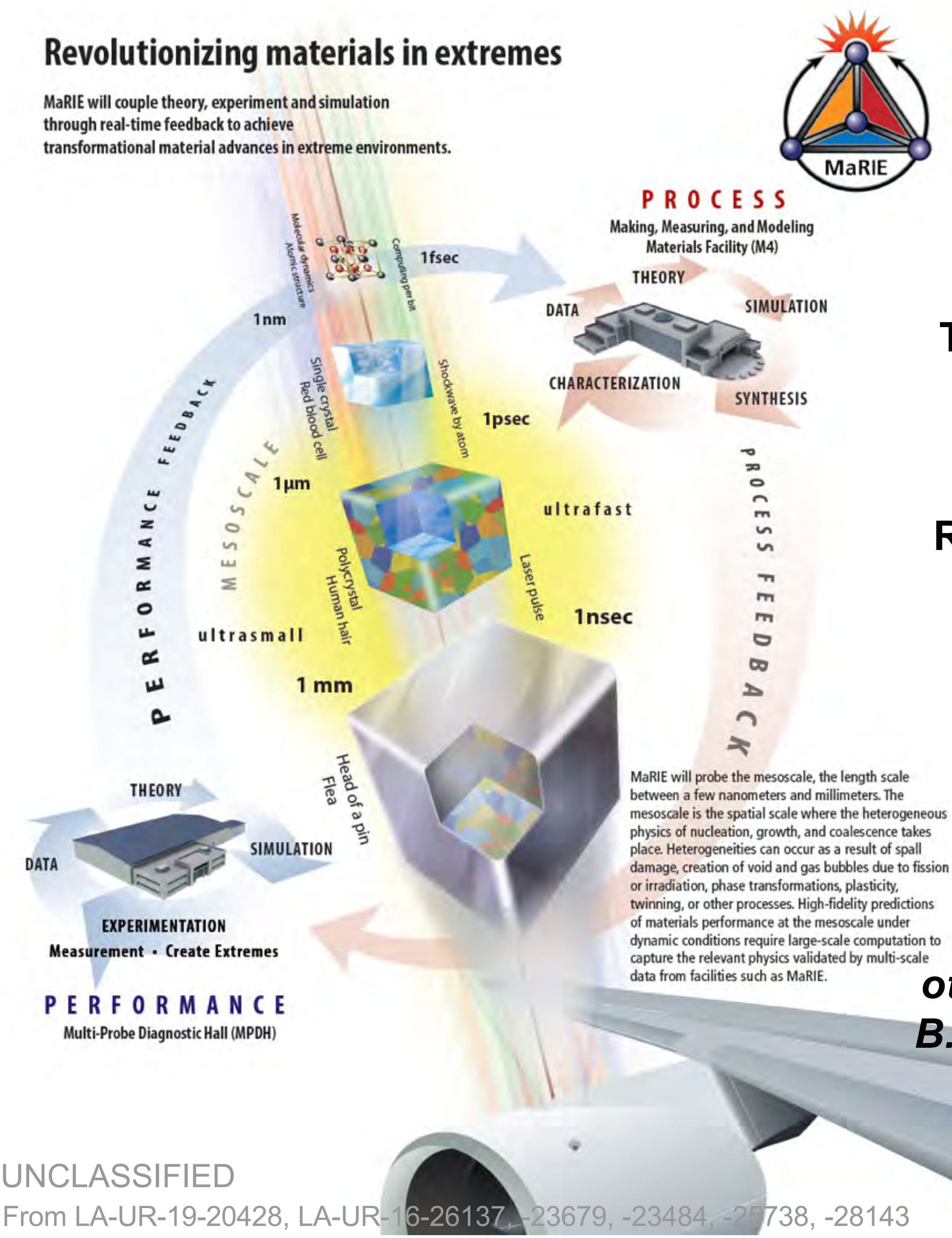

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DMMSC

The Dynamic Mesoscale Materials Science Capability (DMMSC is the problem) Formerly known as the Matter-Radiation Interactions in Extremes Project (MaRIE could be the solution)

P/T Colloquium,
Cris W. Barnes
February 14, 2019

(stealing profusely from many others such as A. Bishop, J. Sarrao, B. Carlsten, R. Sheffield, and more!!)

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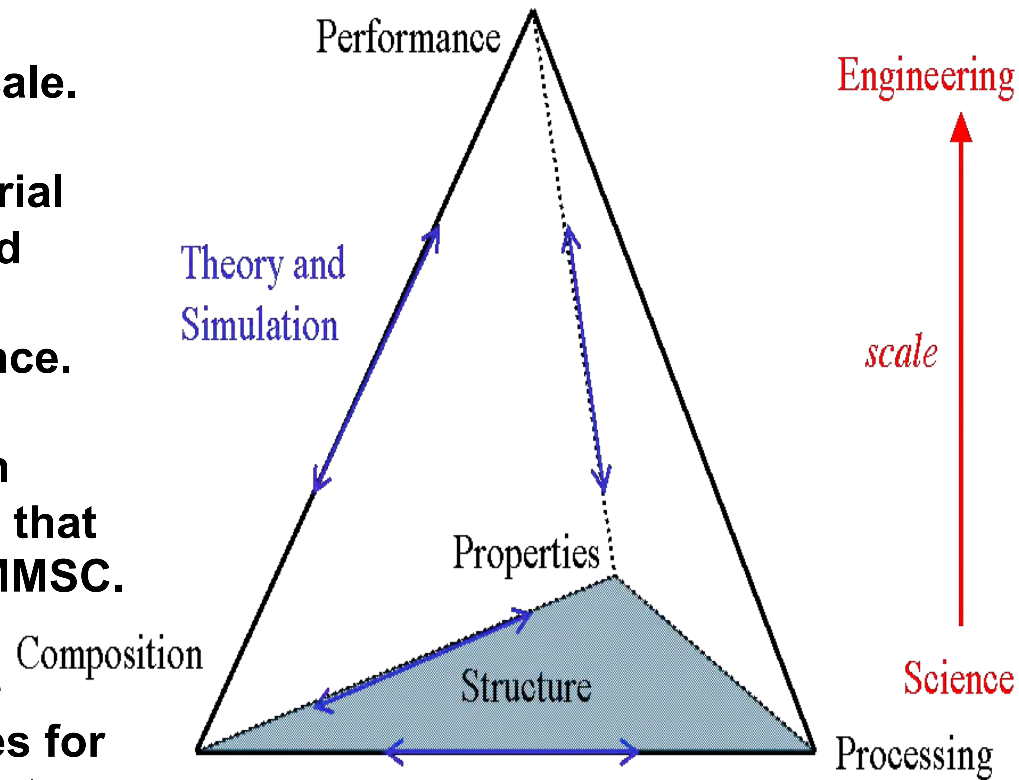
Bottom Line Up Front

- The Dynamic Mesoscale Materials Science Capability (DMMSC) addresses a national unmet scientific need for understanding material performance and production at the mesoscale.
- The ultimate goal is the integration of material structure and processing to achieve desired material properties and ultimately desired performance – supporting production science.
- The MaRIE (Matter-Radiation Interactions in Extremes) Facility is one plausible solution that meets all the validated requirements for DMMSC.
- The mission need for the capability and the facility project are important timely priorities for DOE/NNSA and Los Alamos National Laboratory.



Understanding process-structure-property-performance relationships requires a research capability to explore mesoscale dynamics

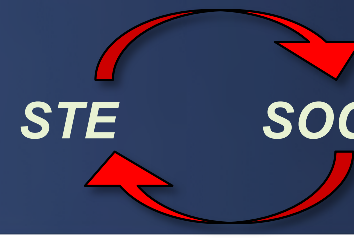
A Theme for this Presentation: my four primary personal characteristics

To be a "Capture Manager" for a major, revolutionary, scientific capability, I try to be:

- » **Ludicrously Optimistic**
- » **Patient**
- » **Crazy**
- » **Honest**

Ludicrous Optimism!

As scientists, we are all engaged in the grand journey of Making History



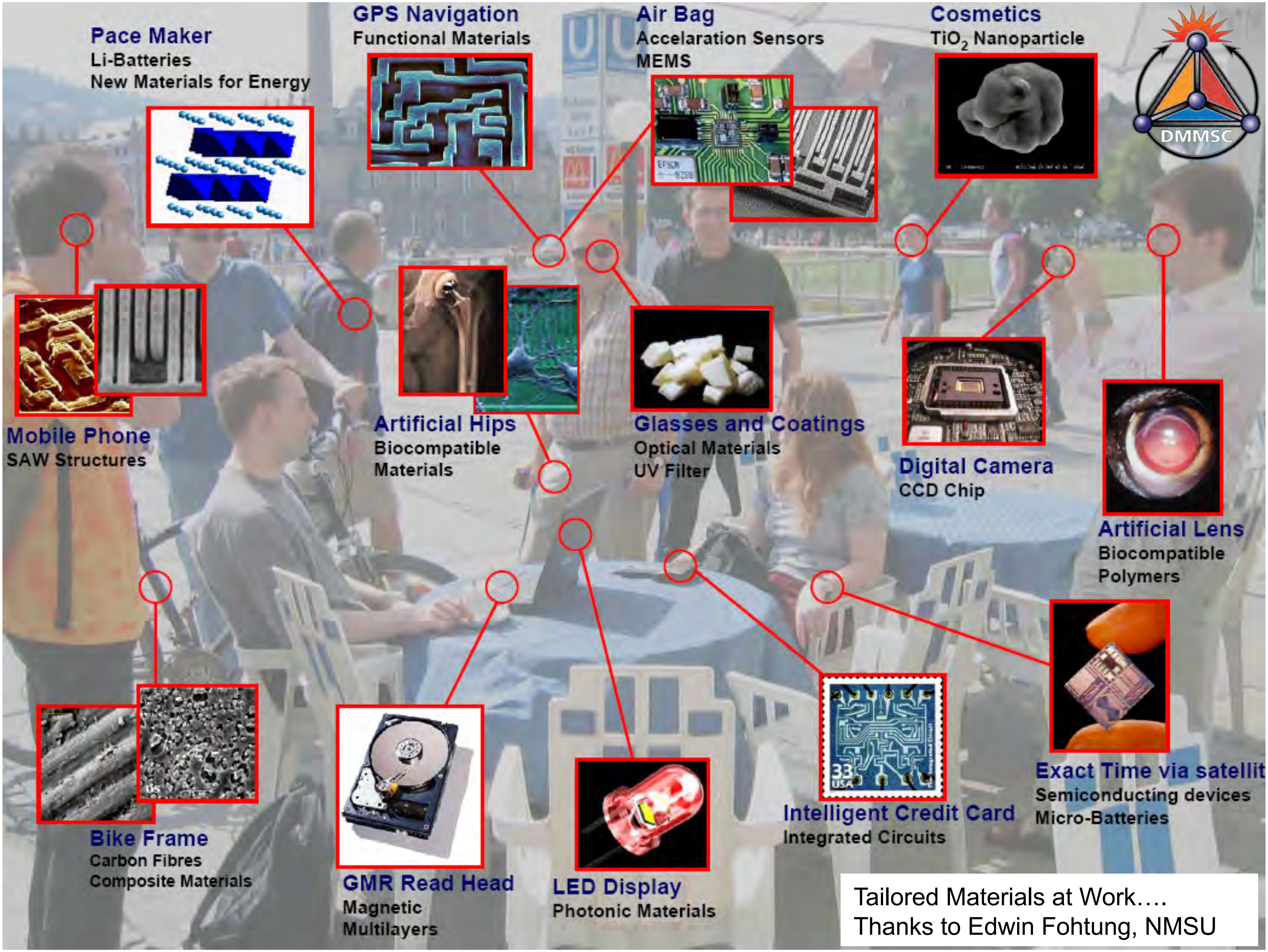
Wheel Steel Internet Digital/Cyber/AI/Ubiquitous Sensing…“Data Fusion”

Materials

> “**Invention** is the product of a creative or curious mind. **Innovation** is something that changes the life of our customers or their world.”
>
> *–Arno Penzias,*
> *Former VP, Bell Labs,*
> *Nobel Laureate*

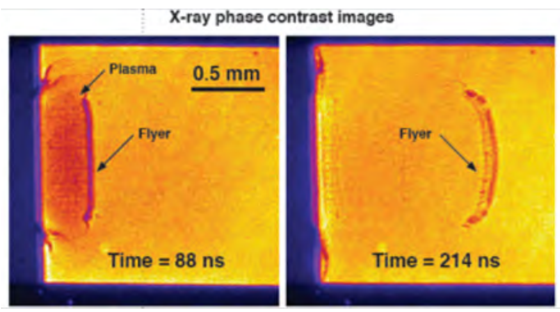
Matter

Designing Materials to Achieve Desired Performance is a Revolutionary Advance for Humanity

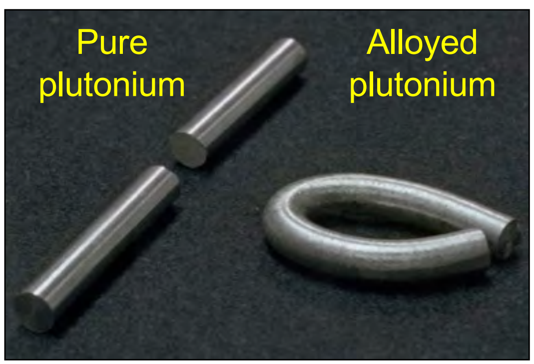

Pace Maker
Li-Batteries
New Materials for Energy
GPS Navigation
Functional Materials
Air Bag
Accelaration Sensors
MEMS
Cosmetics
TiO_2 Nanoparticle
Mobile Phone
SAW Structures
Artificial Hips
Biocompatible
Materials
Glasses and Coatings
Optical Materials
UV Filter
Digital Camera
CCD Chip
Artificial Lens
Biocompatible
Polymers
Exact Time via satellit
Semiconducting devices
Micro-Batteries
Intelligent Credit Card
Integrated Circuits
Bike Frame
Carbon Fibres
Composite Materials
GMR Read Head
Magnetic
Multilayers
LED Display
Photonic Materials
Tailored Materials at Work….
Thanks to Edwin Fohtung, NMSU

As a Laboratory, Los Alamos stewards broad and deep capabilities for multi-program leverage and benefit

Stockpile Stewardship

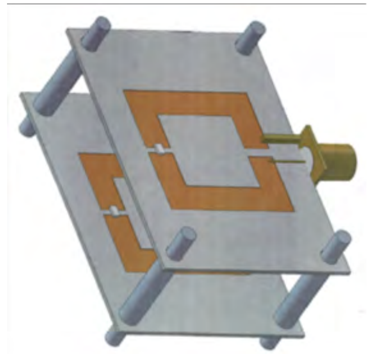


Detonator Safety, Performance in LEPs
Movies of functioning detonators



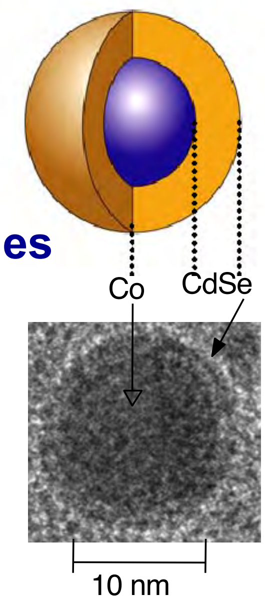
Plutonium Science
Metallurgy

Global Security

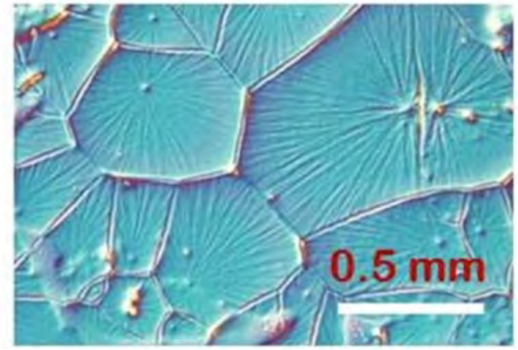


Microwave Technology
Electrically small antennae based on metamaterials concepts

Center for Integrated Nanotechnologies (CINT)
Functional nanomaterials



Energy Security

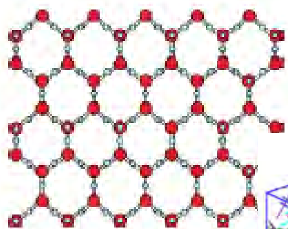


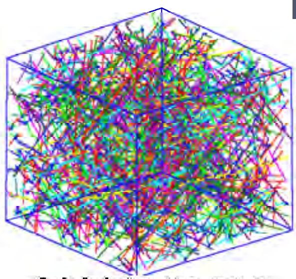
Perovskite Materials
Tailored material for sensors and collectors

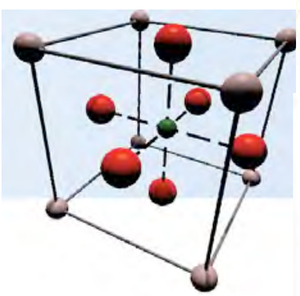
Flow Battery
New materials for energy generation, storage & transmission

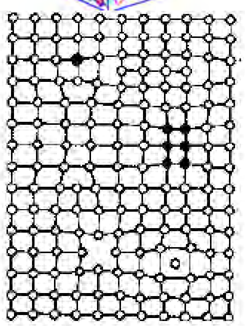
Revolutionizing Materials in Extremes requires understanding material behavior at the Mesoscale

Atomic





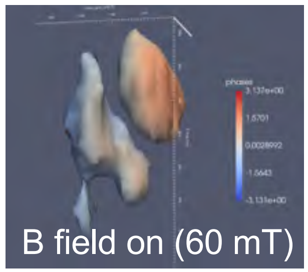




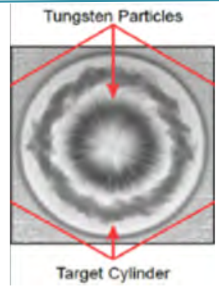
Simple Perfect Homogeneous

10^{-10} 10^{-8}

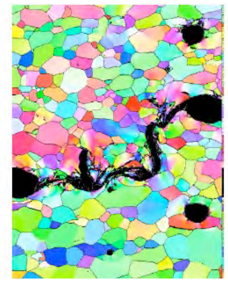
Mesoscale



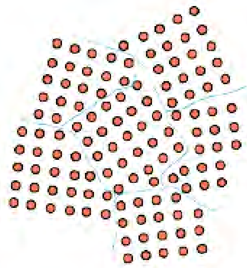
Emergent Phenomena

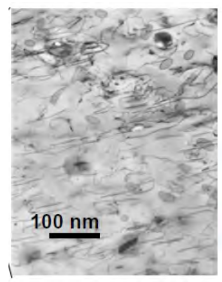


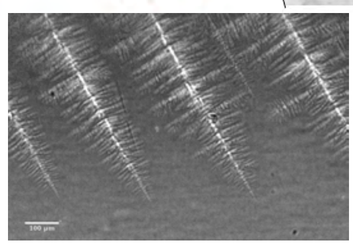
Extreme Environments



Defects and Interfaces

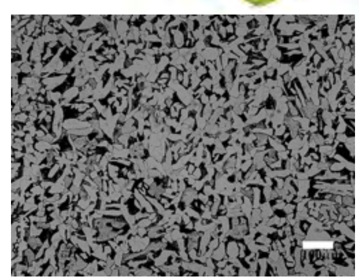






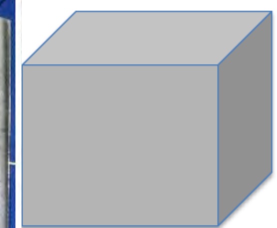
Internal features Interacting

10^{-7} 10^{-6}



phase separation

Macroscale



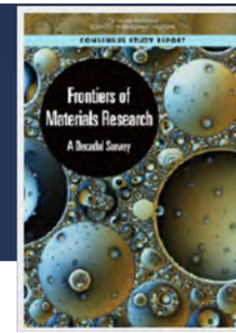
bulk

Wrought Cast

Continuum Bulk Behavior

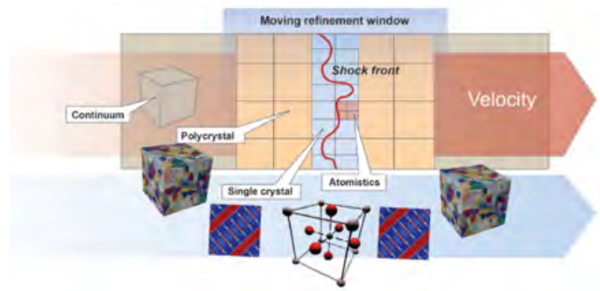
10^{-2} 10^{-1}

Understanding material structure-property-process relationships requires understanding the mesoscale



Many applications demand process-aware performance.

- Aging
- Manufacturing
- Material replacement
- Safety and surety

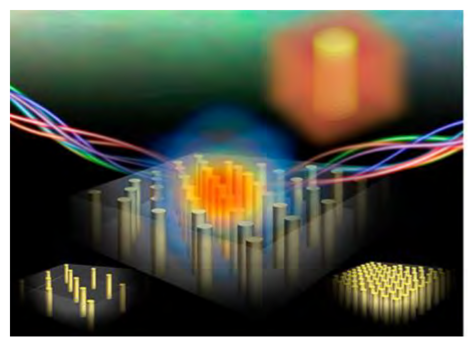


integral testing (macro)

microstructure-aware

Nano-scale manufacturing and nanoscience integration.

- Pulsed laser deposition yields epitaxial metallic nanopillars integrated in oxide matrices
- Tunable densities on selected substrates yields controllable anisotropic optical properties

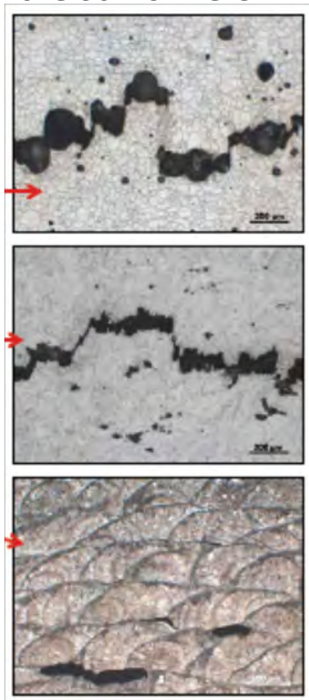


mesoscale

nanoscale

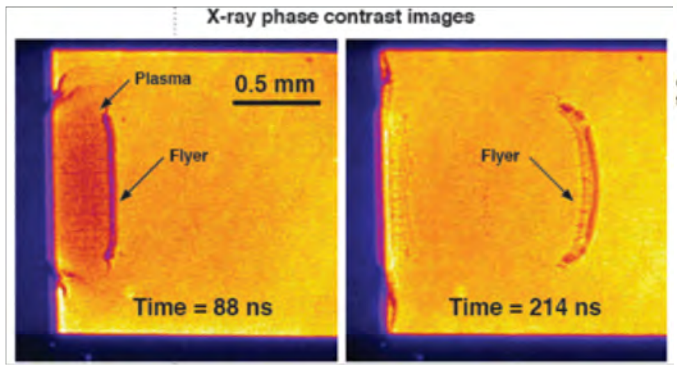
DMMSC will address the control of performance and production of materials for national security science at the mesoscale

Performance of additively-manufactured (AM) structural components



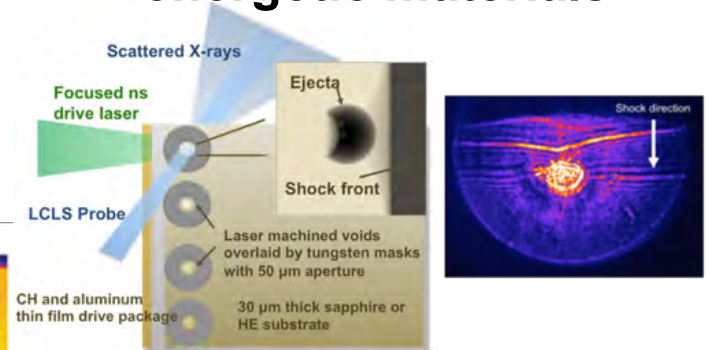
Damage in wrought vs additively-manufactured steel

High Explosive performance and safety



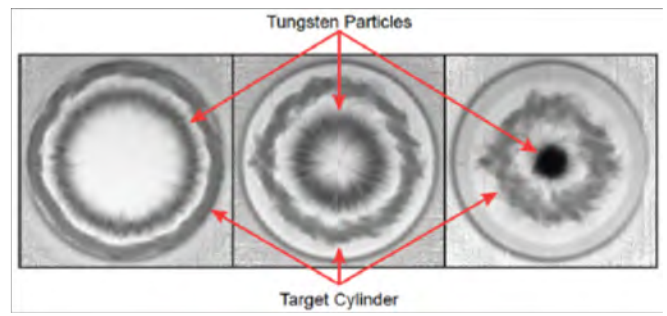
Movies of functioning slapper detonators

Void Collapse in energetic materials



Identify mechanisms of initiation

Ejecta and Mix



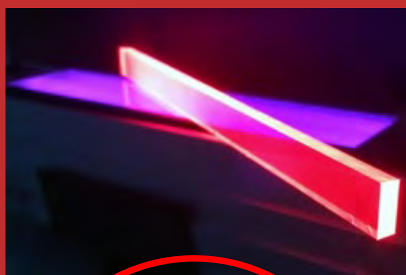
Movies of ejecta in convergent geometry

Requirements for MaRIE are set from analysis of such experiments. -- *"(U) MaRIE First Campaigns," LA-CP-15-00501, June, 2015*

DMMSC fills a critical gap in length scale between the integral scale addressed by DARHT and U1a and facilities such as NIF and Z.

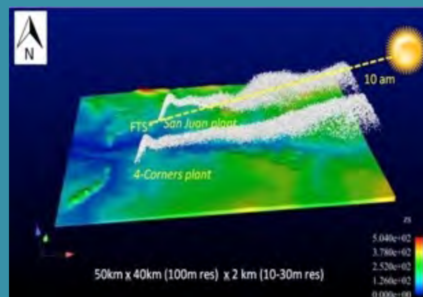
Our Science Pillars define strategic capability investment areas at Los Alamos for present and future missions

DMMSC



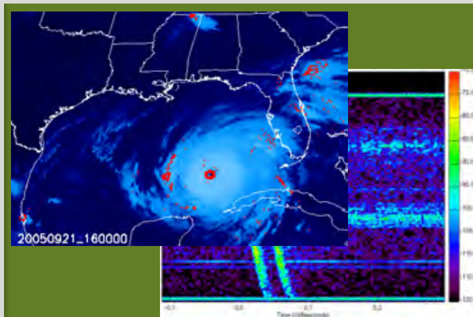
Materials for the Future

- Defects and Interfaces
- Extreme Environments
- Emergent Phenomena



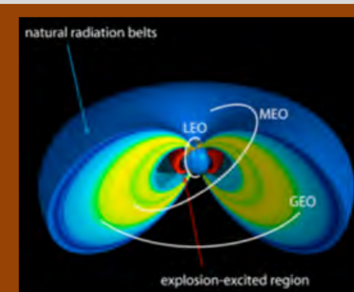
Science of Signatures

- Discover Signatures
- Revolutionize Measurements
- Forward Deployment



Information, Science, and Technology for Prediction

- Complex Networks
- Computational Co-Design
- *Data Science at Scale*



Nuclear and Particle Futures

- High Energy Density Physics & Fluid Dynamics
- Nuclear & Particle Physics, Astrophysics & Cosmology
- Applied Nuclear Science & Engineering
- Accelerators & Electrodynamics

MaRIE

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The Matter-Radiation Interactions in Extremes (MaRIE) now DMMSC project has followed a rigorous pre-conceptual approach to meet mission and science challenges

DMMSC

» Benefit from the scientific community Workshops and studies surveying the decadal challenges for materials science.

» Motivate the science need for the mission through development of "First Campaigns"*

» Develop and Justify the scientific functional requirements by analysis of detailed "First Experiments" in each mission-relevant campaign

  » Assert that a coherent, brilliant x-ray source that has energy and repetition rate characteristics matched to address materials performance challenges is required

» Develop a pre-conceptual reference design, that can meet the requirements, with credible scope, cost and schedule estimates, and that can determine technical risks and define technology maturation plans.

Dynamic Materials Performance
First Campaigns
- Multiphase High Explosive Evolution
- Dynamic Performance of Plutonium and Surrogate Metal Alloys
- Turbulent Material Mixing in Variable Density Flows

Process-Aware Manufacturing
First Campaigns
- Old Materials: Aging
- New Materials: Controlled Functionality
- New Processes: Advanced and Additive Manufacturing

*"(U) MaRIE First Campaigns," LA-CP-15-00501

There is an envelope of common technical requirements on the probes to be able the make required measurements

DMMSC

Mission Need → Scientific Functional Requirements

	Metals and Age Aware performance	HE certification and qualification	Turbulent Materials Mixing	Pu Casting	TBD
Spatial resolution	<100 nm - 20 μm	< 100 nm - 20 μm	100 nm	< 1 μm – 100 μm	?
Field of View					
# of frames	~ 30	~ 30	~ 30	1000 per second	?
min pulse sep	< 300 psec	< 500 psec	1 nsec	10 nsec	?
macropulse length	5 μsec	7 μsec	15 μsec	1 msec	?
sample thickness	> 250 μm	> 10 μm – 6 cm	1 – 10 cm	0.1 to 10 mm	?
repetition rate	< 1 Hz	< 1 Hz	10 Hz	10 Hz	?
max pulse length	< 1 ps	< 1ps	< 1 ns	< 100 ps	?
lattice measurement	0.1%	0.2%	-	0.01%	?
species	Be - Pu	Typically C, H, O, N	Noble gases, Ga, Be	Pu	?
density	1%	3%	2%	1%	?

I apologize for not taking the time in this talk to walk through the justification for these functional requirements.

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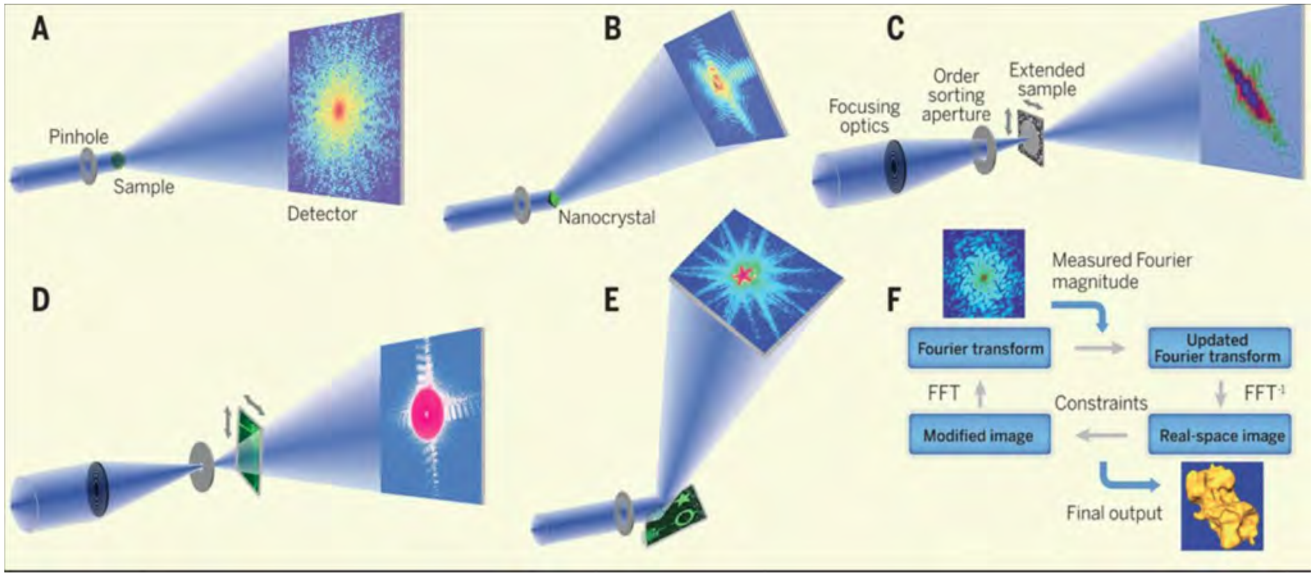
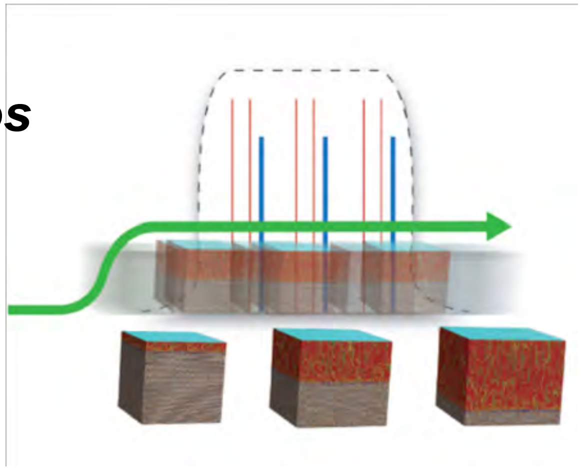
To see with time-dependence into and through the mesoscale requires: x-rays; coherent; brilliant and high repetition-rate; of sufficient high energy; and multiple probes at multiple scales

DMMSC builds on the major technical revolutions in: **x-ray lasers** and their brilliance (for time-dependence); and **coherent imaging** (allowing high-resolution observation of non-periodic microstructure).

"Ordered Light for Disordered Systems" – Paul Alivisatos



From "Beyond crystallography: Diffractive imaging using coherent x-ray light sources," by J. Miao, T. Ishikawa, I. K. Robinson, and M. M. Murnane, *Science* **348** (1 May 2015), pg 530.

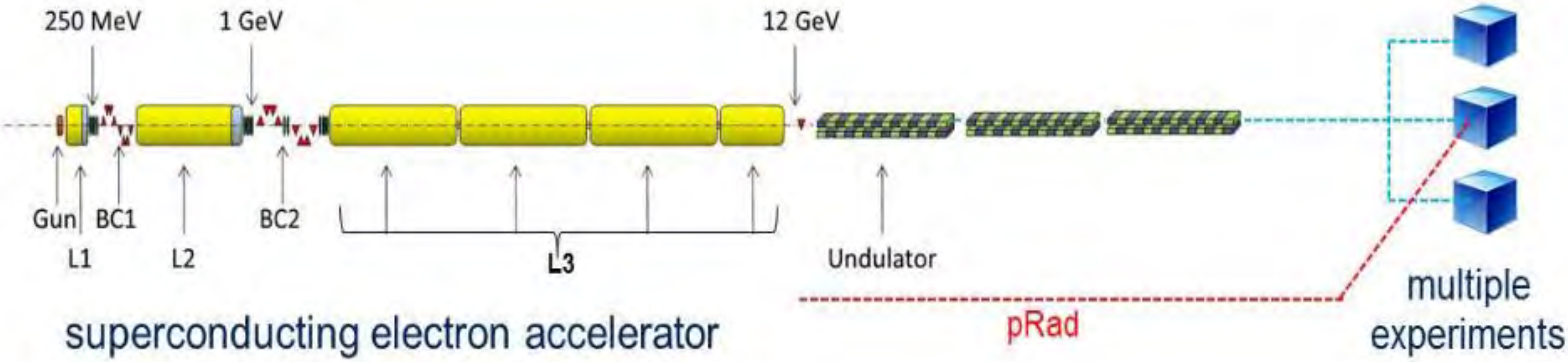


The concept features multiple probes (x rays, protons, electrons, optical photons) to maximize the science.

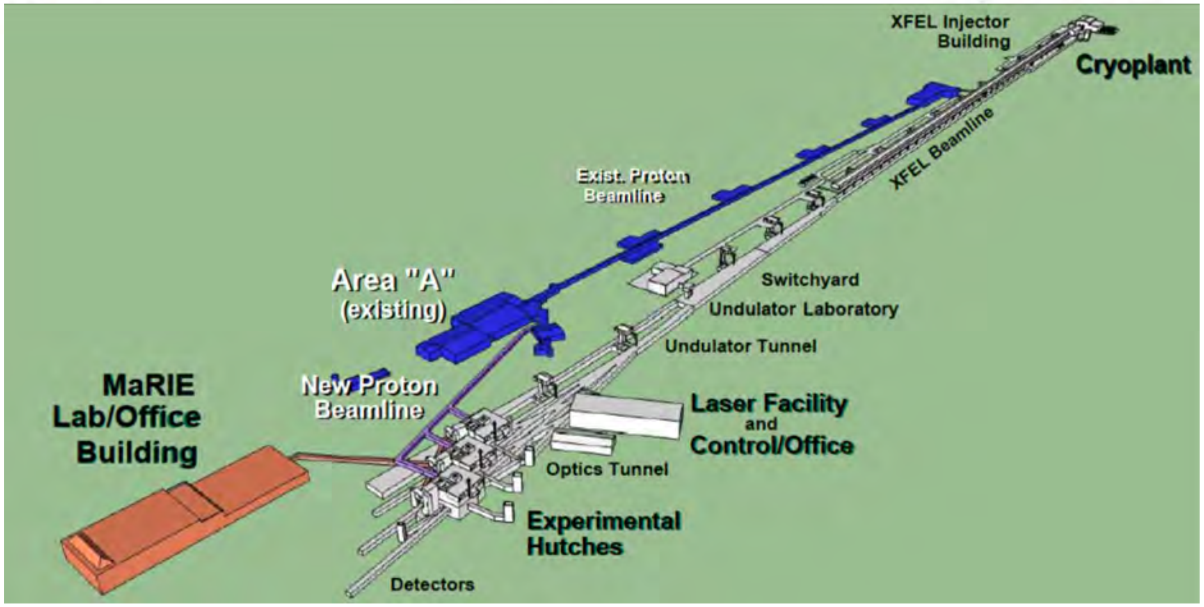
DMMSC Unique Complementary Characteristics:

- ***Harder in energy for mesoscale, high-Z materials***
- ***Higher in repetition rate to make movies of microstructure evolution***
- ***Multiple probes to support maximum science return***

DMMSC (the Project) could provide the capability by building a 12-GeV electron linac feeding a 42-keV XFEL with experimental facilities



Our pre-conceptual reference design would be located on the north side of the LANSCE mesa, leveraging the capabilities of that proton/neutron facility.



DOE is formally progressing through approvals in DOE Order 413.3B on the path towards a conceptual design.

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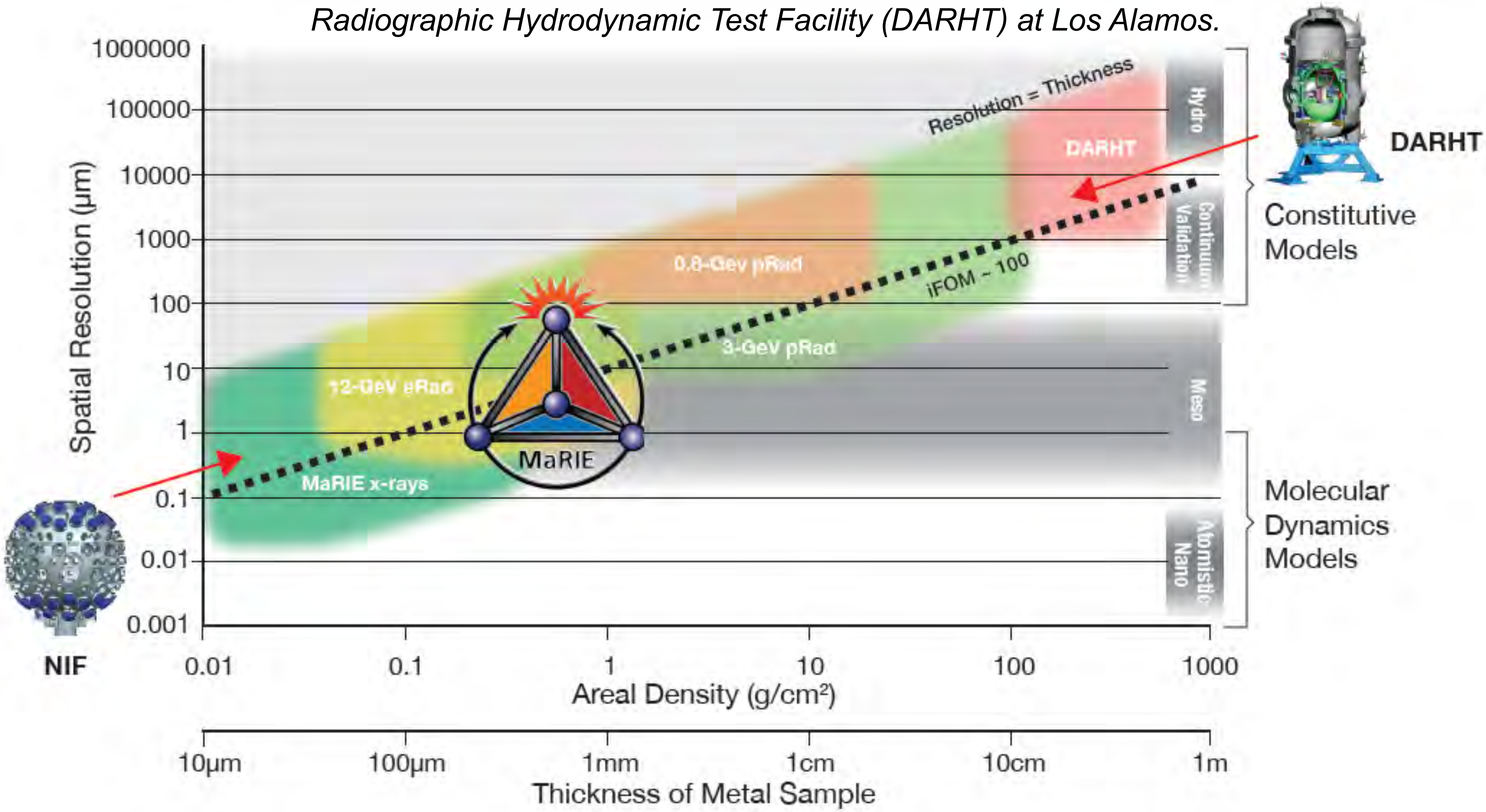
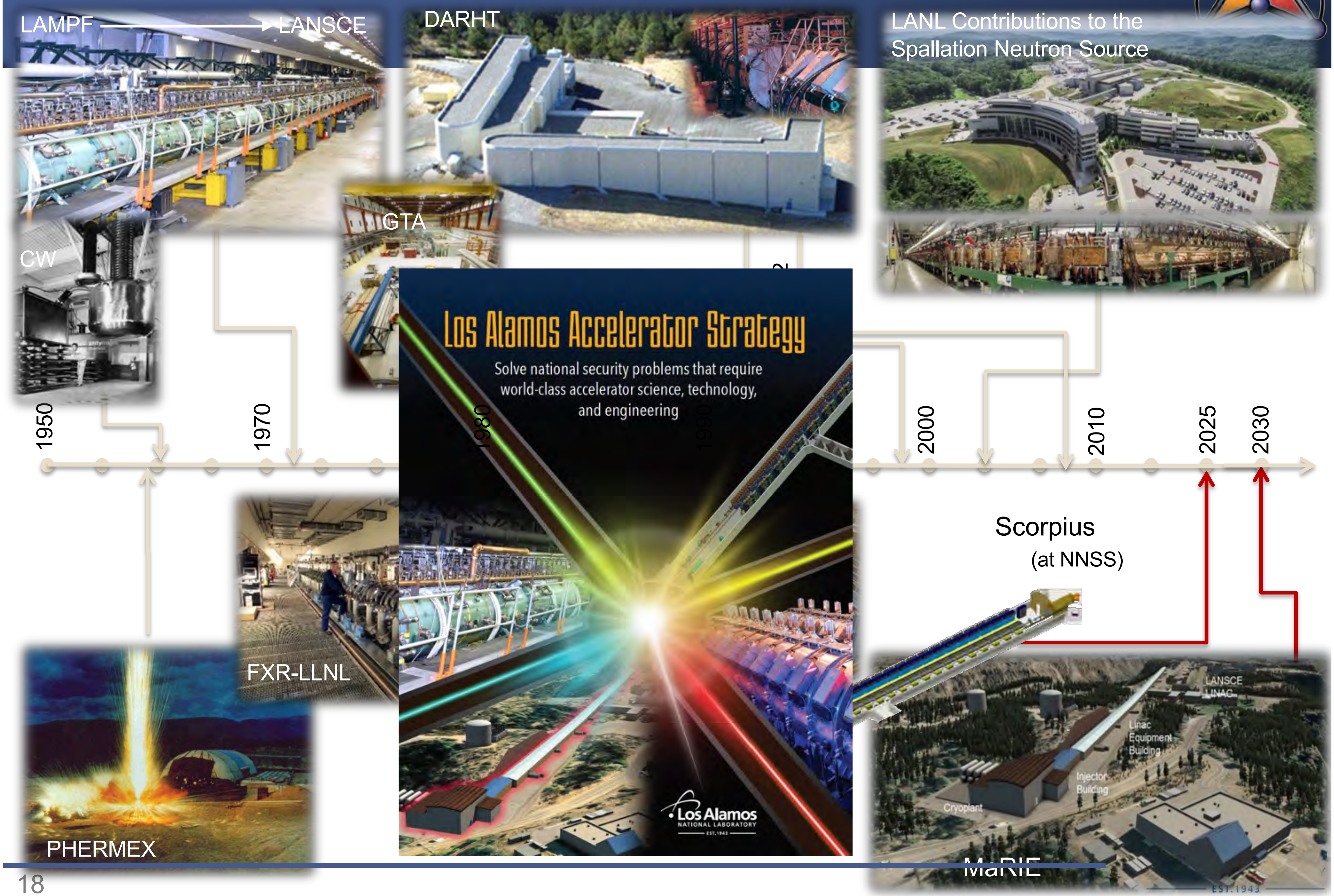
DMMSC would fill a critical capability gap for dynamic (time-dependent) mesoscale materials science

DMMSC uses material samples that allow resolution of mesoscale science. DMMSC is positioned to deliver critical stockpile science data, filling a "knowledge gap" between existing facilities such as the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory and the Dual-Axis Radiographic Hydrodynamic Test Facility (DARHT) at Los Alamos.

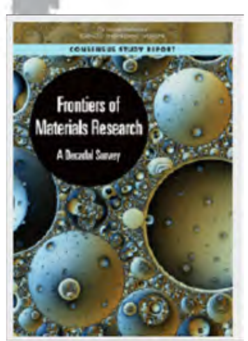


Accelerator Capability has long been central to Los Alamos execution of mission



DMMSC will complement the growing number of world-wide 4th generation light source capabilities

DMMSC



"The United States had a significant fraction of all the world-leading capabilities 20 years ago, but that lead has eroded and today's landscape is one of intense competition from both Europe and Asia."

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Slide modified from Bob Cauble LLNL/HiBEF

Patience

My first P/T colloquium on “MaRIE” was nearly 10 years ago in June, 2009

Los Alamos has been working toward our vision of MaRIE since 2006 – a clear path is now defined!

DMMSC

LANS Contract Transition
Concept Definition/Internal Competition
MaRIE selection

(2006-2008)

Pre-MaRIE

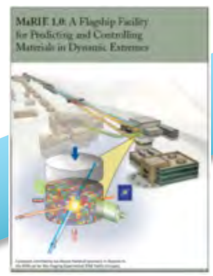
Developing the Science Case

(2009)

Facility Definition

(2010)

Pre-conceptual Proposal



(2012)

"Move to CD-0"

(2013)

Setting the Stage for Mission

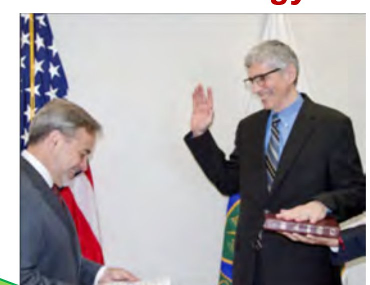
(3/2014)

Submittal of CD-0 Package

(5/2015)

(3/2016)

Formal Approval of the Mission Need for a Project by the Deputy Secretary of Energy



CD-0 (2016)

Validate Requirements (2018)

Analysis of Alternatives (2019)

Begin Conceptual Design (2020)

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The acquisition of major capital projects by the DOE is governed by Order 413.3B and follows a series of "Critical Decisions"

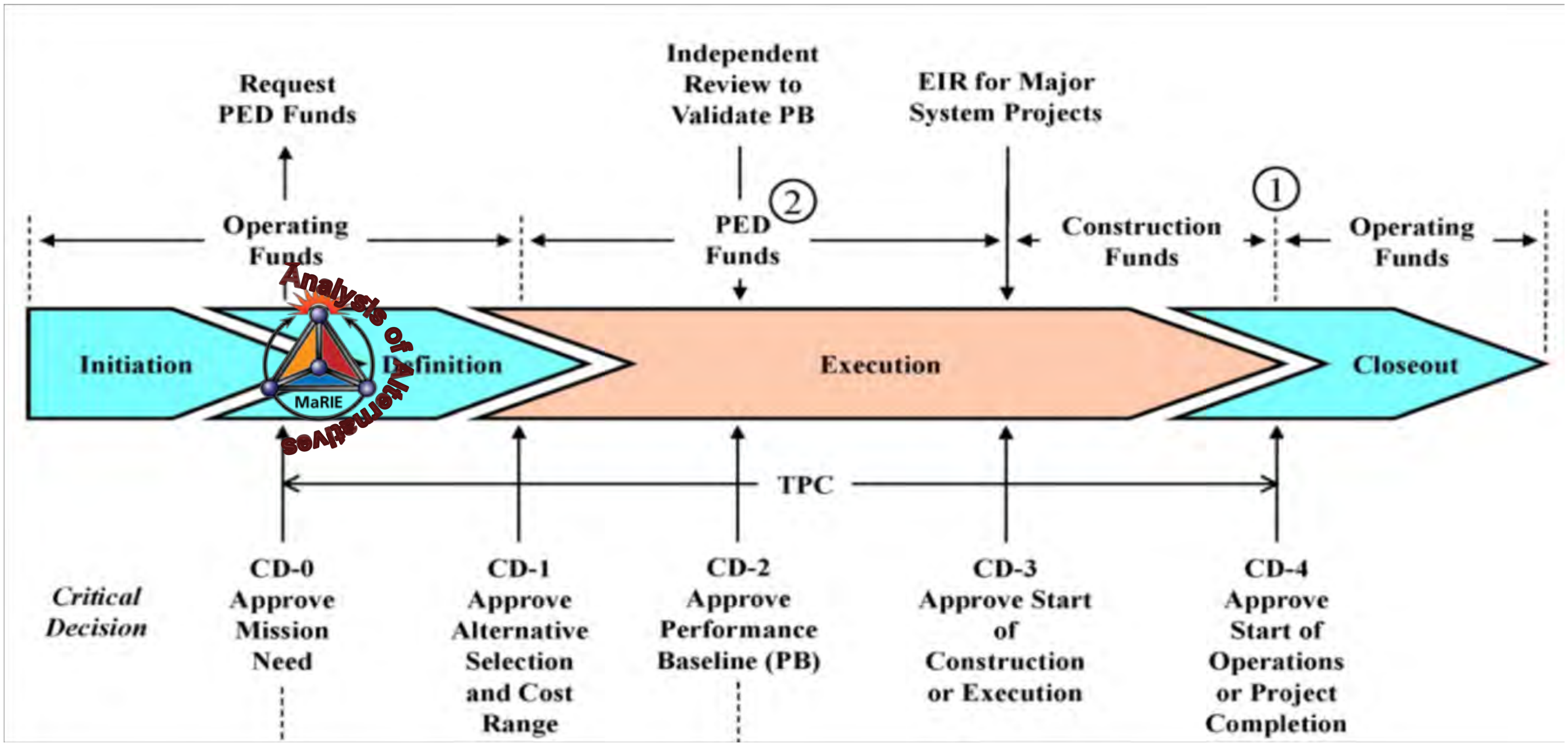


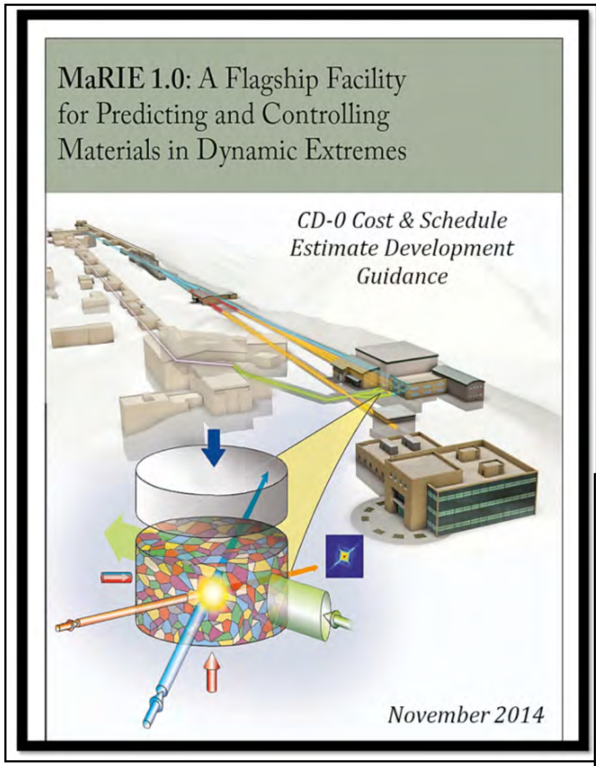
Figure 1. Typical DOE Acquisition Management System for Line Item Capital Asset Projects

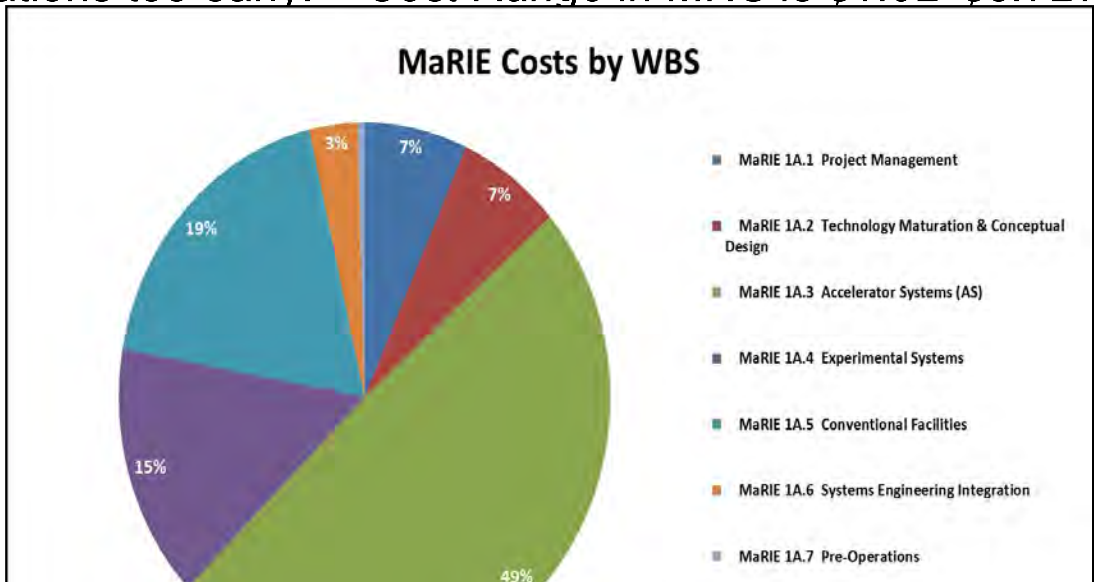
MaRIE has received CD-0 and is now on the Path to CD-1

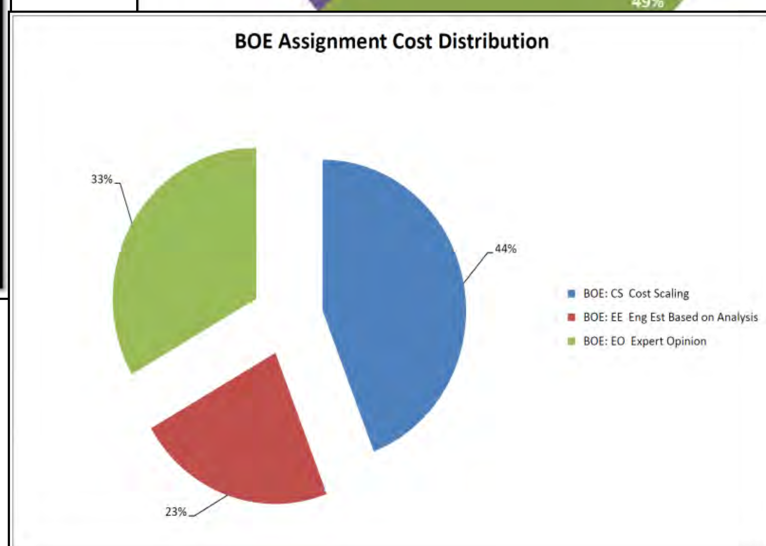
We developed a reasonably detailed design and cost estimate for the CD-0 Package

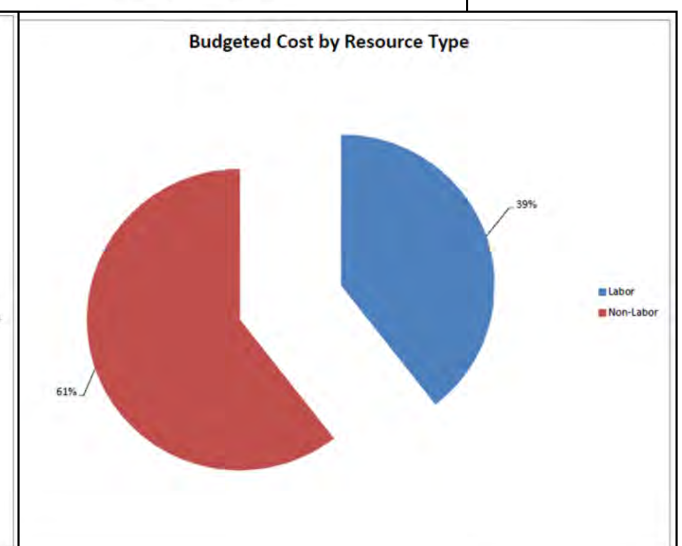
DMMSC

The TPC for MaRIE was independently reviewed. Key lesson is we must avoid setting cost/schedule performance expectations too early! *Cost Range in MNS is $1.9B-$3.7B.*









Cost estimate is fully burdened with 38% average contingency

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EST. 1943

LANL sees the future Weapon Science program supporting three major objectives; we envision a need for specific next-generation capabilities

DMMSC

1. Complete PCF out-year pegposts

- Primary performance, Secondary Performance, **Hostile Survivability**, Delivery Environments

2. Sustain an aging stockpile

How long will a weapon be viable? What is its lifetime?

- Aging
- Features

3. Enable stockpile responsiveness

What warhead options can be developed and certified?

- Advanced Manufacturing
- Features

Next-generation capabilities:

- MaRIE
- ECSE/NDSE
- Next-gen NIF/ Z
- Hostile Recapitalization
- Exascale

From Michael Bernardin, ALDWP, May 2018

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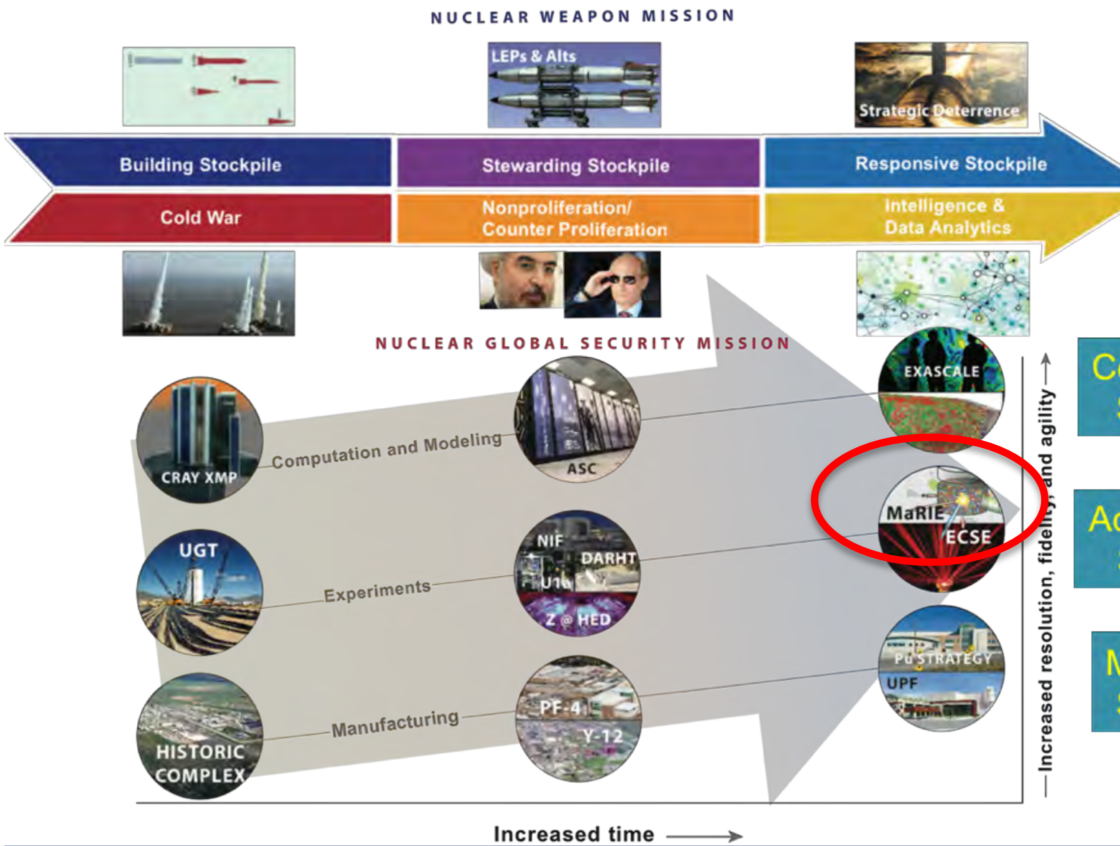
The Dynamic Mesoscale Materials Science Capability has been and continues to be central to the strategy for the future nuclear enterprise.

We will deliver on commitments today while ensuring capabilities for an uncertain future. And integration of those capabilities is vital.

The new LANL Agenda (November 2018)

Strategic Objectives	Excellence in Nuclear Security	Excellence in Mission-Focused STE	Excellence in Mission Operations	Excellence in Community Relations
Critical Outcomes	Design, produce, and certify current and future nuclear weapons and reduce global nuclear threats	Deliver scientific discovery and technical breakthroughs that support DOE/NNSA missions	Execute sustained operations that are reliable and responsive to mission needs	Sustain and enhance LANL's partnership with the community across the Northern New Mexico region
Major Initiatives	• Execute LANL's manufacturing mission to deliver 30+ plutonium pits per year • Transform nuclear weapons warhead design and production • Develop and deploy revolutionary tools to detect, deter, and respond to threats to global security • Achieve First Production Unit (FPU) and Last Production Unit (LPU) for the W88 ALT 370, B61-12 LEP, and ALT 940	• Refresh and refine the LANL capability pillar framework – Materials for the future – Science of signatures – Integrating information, science, and technology (IST) for prediction – Nuclear and particle futures – Complex natural and engineered systems • Advance accelerator science, engineering, and technology to enable ECSE → MaRIE and related capabilities • Advance the frontiers of computing to exascale and beyond • Assert leadership in the national quantum initiative • Develop and implement an integrated nuclear energy and materials initiative	• Achieve culture change with an emphasis on organizational learning • Improve integrated planning across priority mission activities and infrastructure • Address critical issues related to NMC&A, nuclear safety, criticality safety, and waste operations • Implement systematic process improvement to drive increased rigor and efficiency in work execution • Enhance quality of work life, workforce planning, and training and development	• Institute a personal commitment to community service by LANL leadership • Engage in mission-centered workforce and pipeline development • Enhance small business participation in executing LANL scope across all directorates • Implement a Community Commitment Plan to provide educational, economic development, and philanthropic support to the surrounding community

Los Alamos National Laboratory 11/7/2018



Computing Strategy

Accelerator Strategy

Materials Strategy

We are planning to meet acceptable conceptual design pegpost by September 2020 and start of line-item funding in FY 2022.

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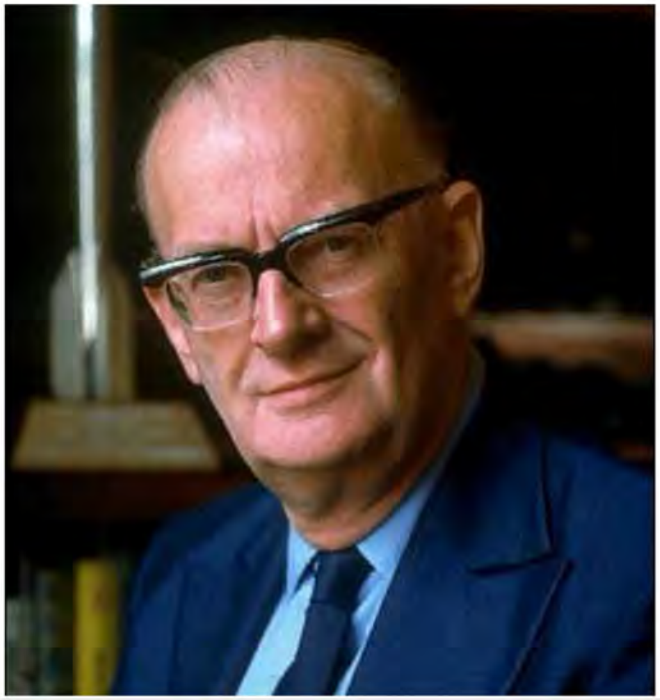
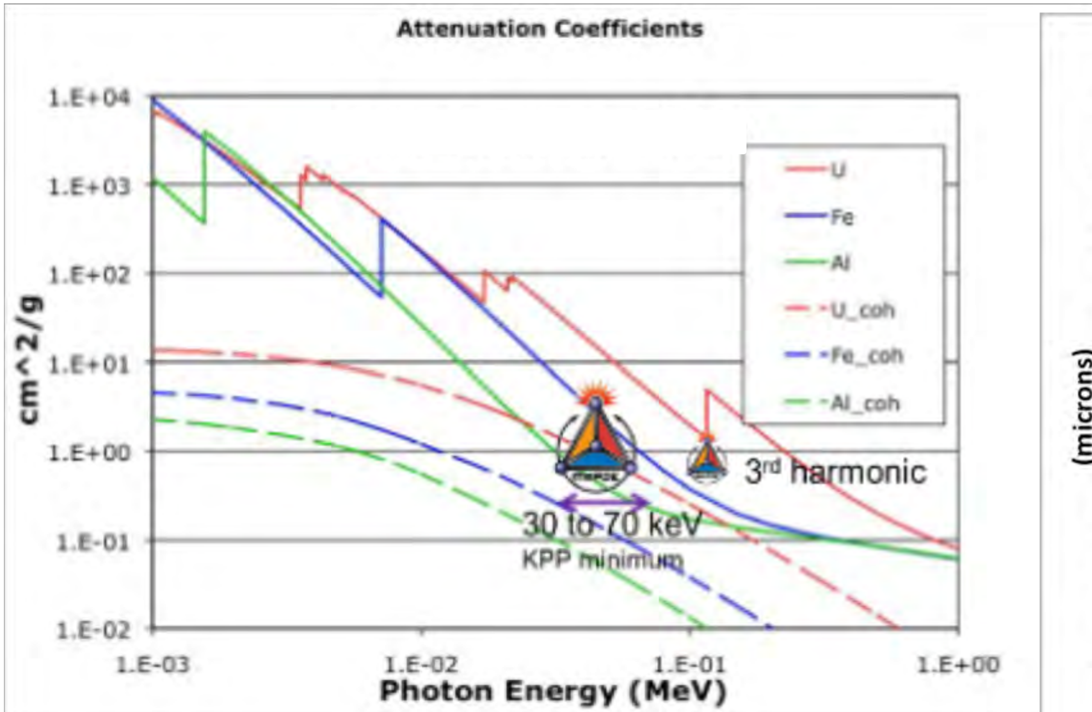
Craziness!

Arthur Clarke's First Law:

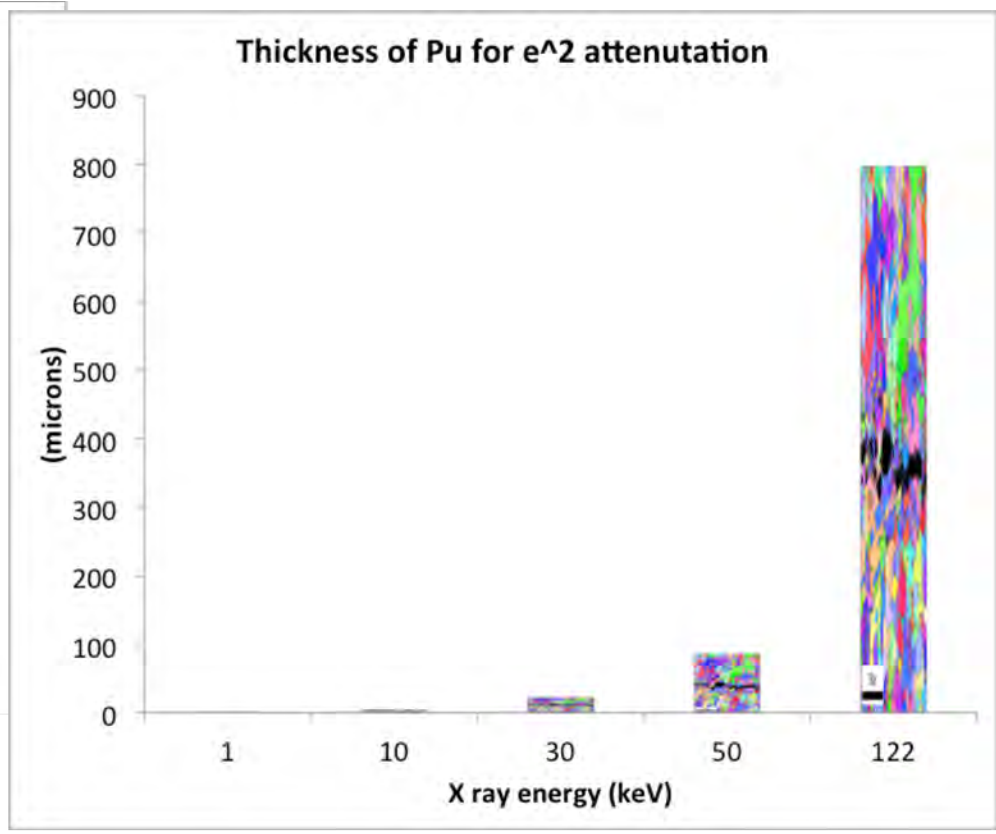
When a distinguished but elderly scientist states that something is possible, he is almost certainly right. When he states that something is impossible, he is very probably wrong.



Unique Characteristic 1: High energy photons allow measuring bulk properties by maximizing elastic scattering for diffraction and minimizing absorptive heating.



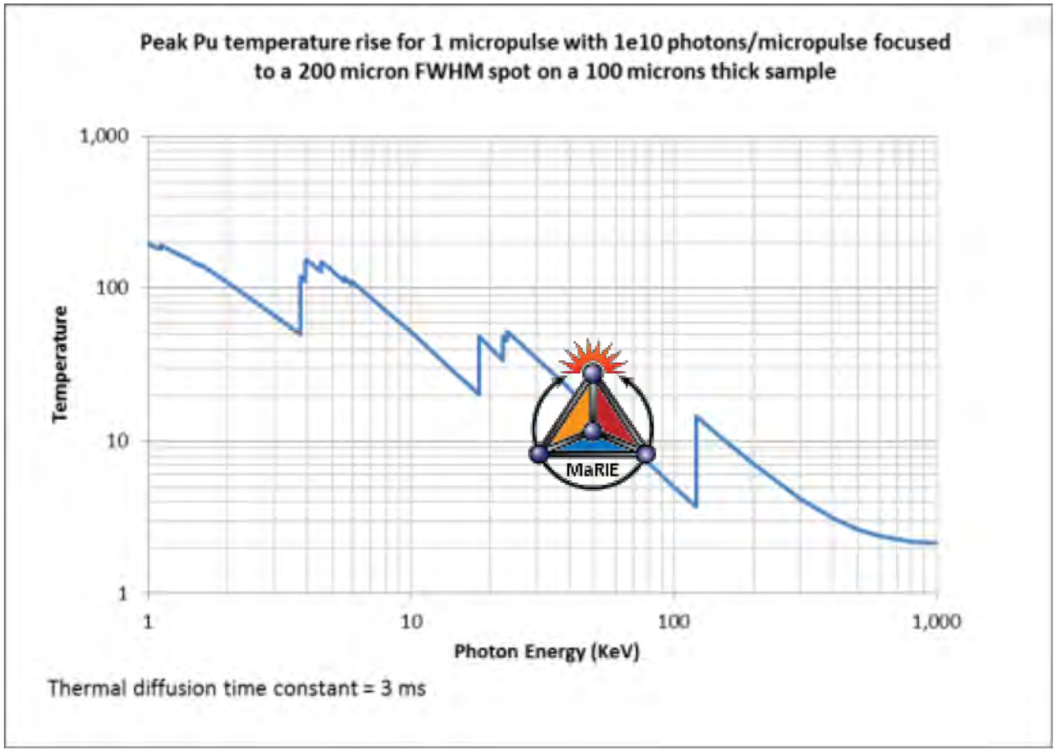
The total (solid lines) and elastic (dashed lines) x-ray cross-sections as a function of incident photon energy for various materials

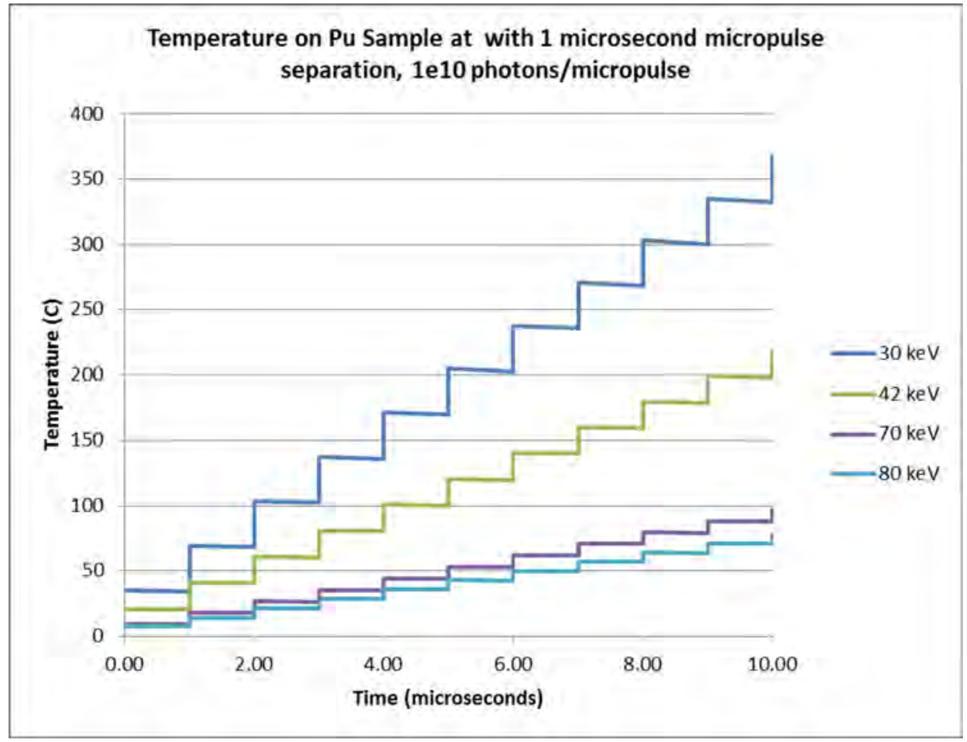


After suggestion by George Srajer, APS@ANL

J. L. Barber *et al.*, Phys. Rev. B **89** (2014) 184105

Unique Characteristic 1: > 42 keV photons allow taking multiple images of high Z materials with an acceptable temperature rise

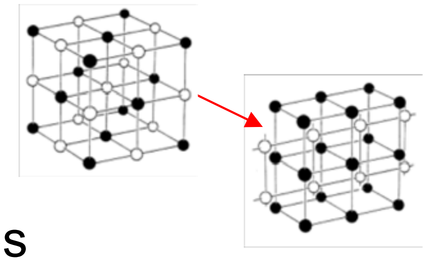




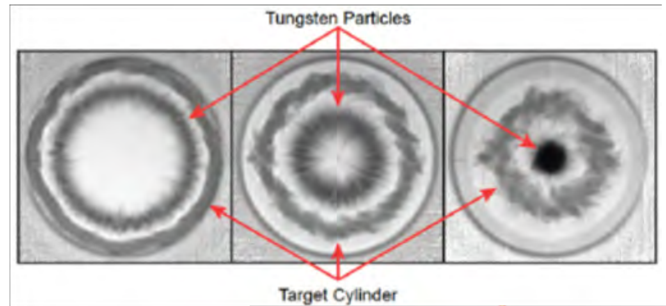
A key design requirement, that will be central to balance of cost, risk, and performance, will be the fundamental x-ray energy.

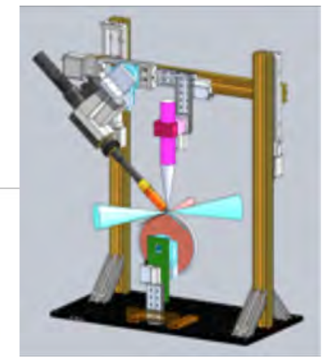
DMMSC will address materials science needs at vastly different time scales

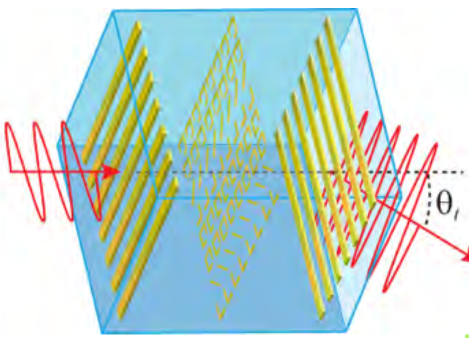
ps – ns
Metastable electronic states



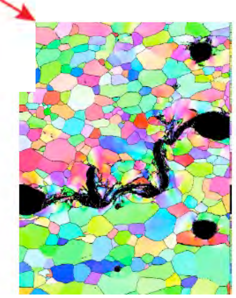
ps – 100 ns
Phase Transformations



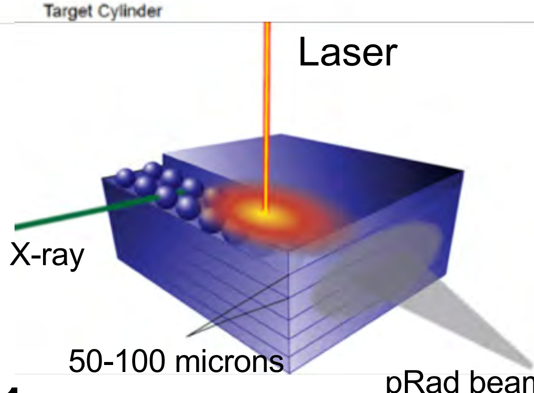




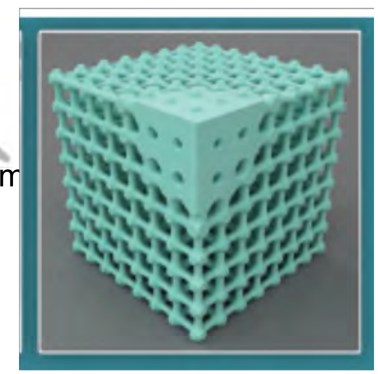
ns – 100 ns
Shock transit across grain;
Hydrodynamic instability



100 ns – 10 µs
Shock transit across sample



10 µs – 1 ms
Thermal pulse evolution

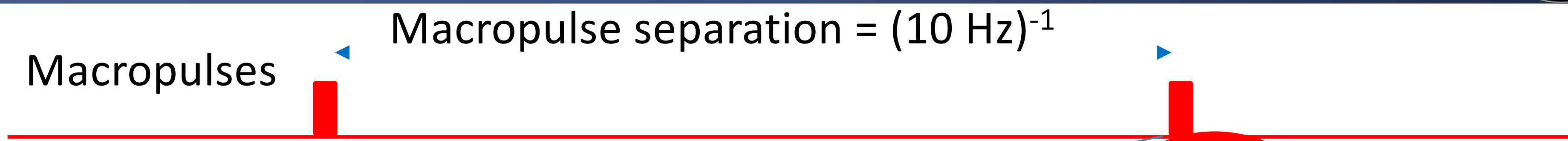


10 s – 10 hour
Additive manufacturing build

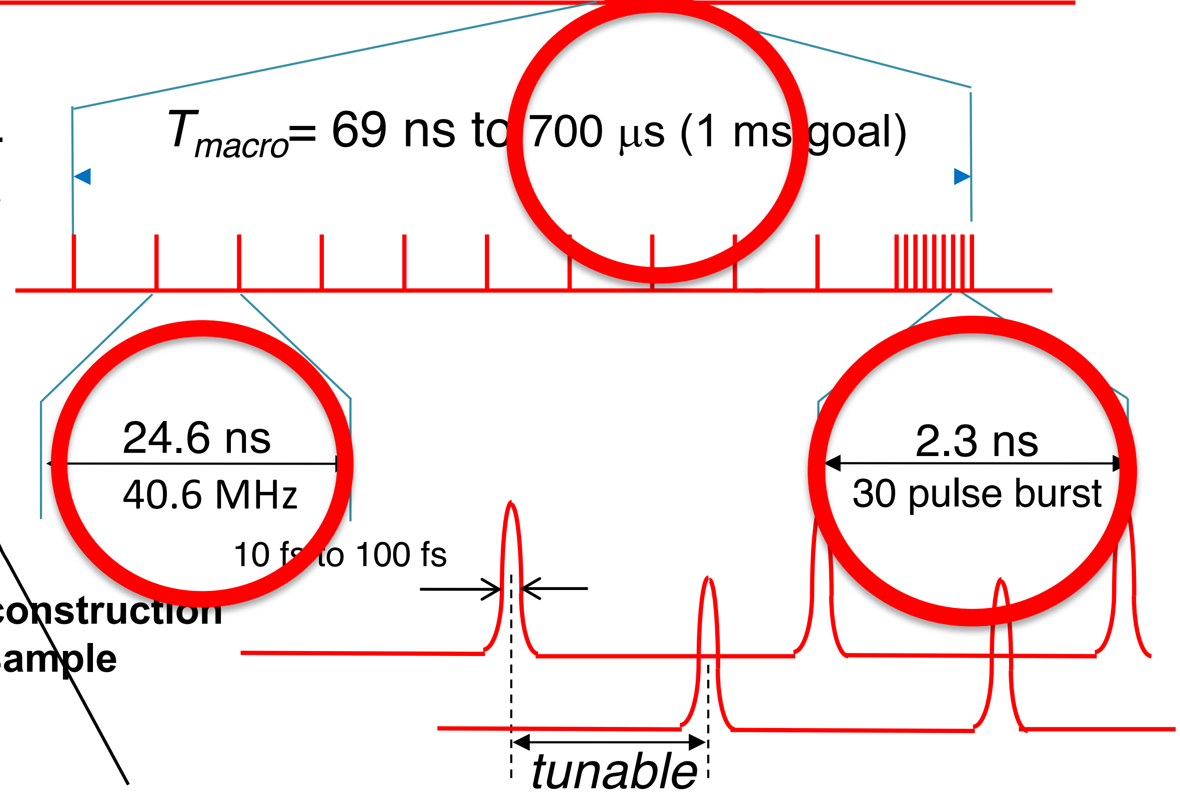
months – years
Aging effects

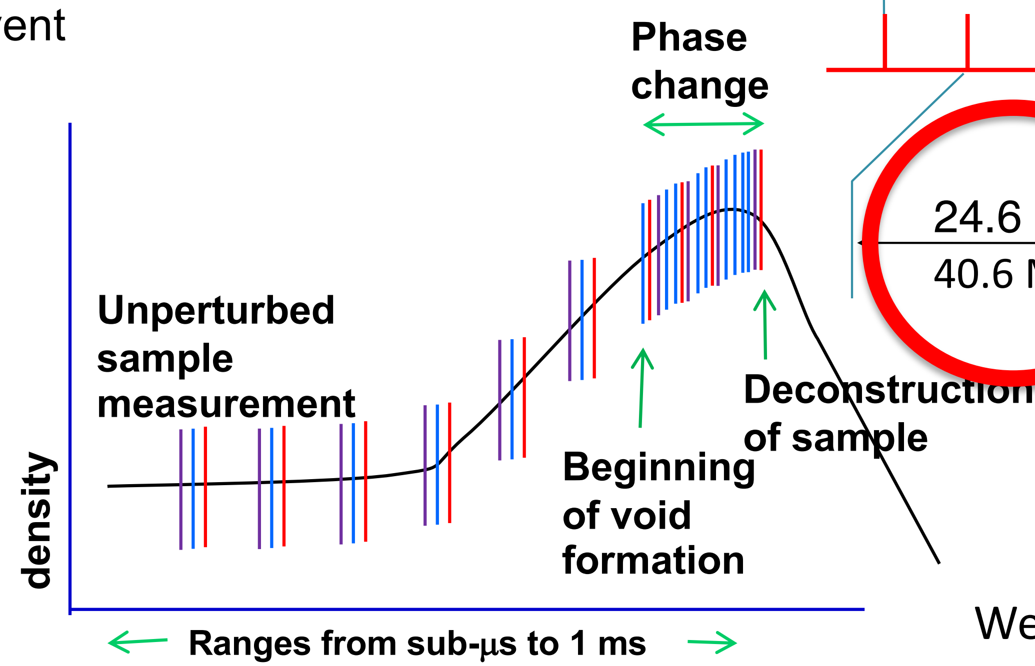
Key Requirement: a flexible linear accelerator pulse structure that can span from electronic/ionic (sub-ps) through acoustic (ns) to shock transit across samples (µs) to thermal (ms) to manufacturing (secs and above) event time scales

Unique Characteristic 2: Time-dependent control of the mesoscale requires an innovative and flexible linac pulse structure that can span from electronic/ionic (sub-ps) through acoustic (ns) to shock transit (μs) to thermal (ms) event time scales



MaRIE multiplexes 42-keV x-ray photons (blue), 12-GeV electrons (purple), and 0.8-GeV protons (red) during a single dynamic event





We plan on using an optical split and delay to generate sub-ns pulse separation

Requirements on repetition-rate and duty cycle are also critical!

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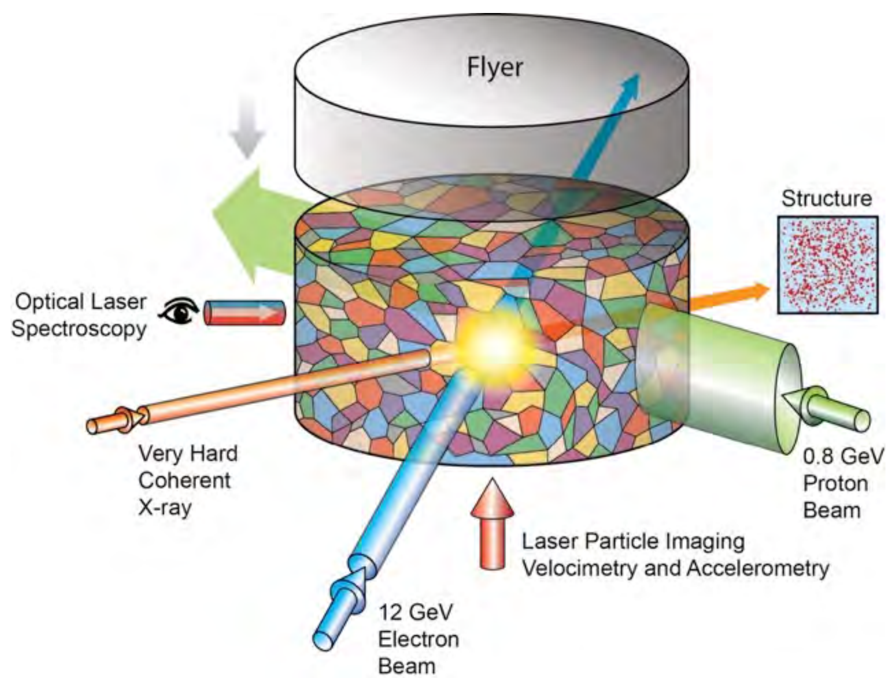
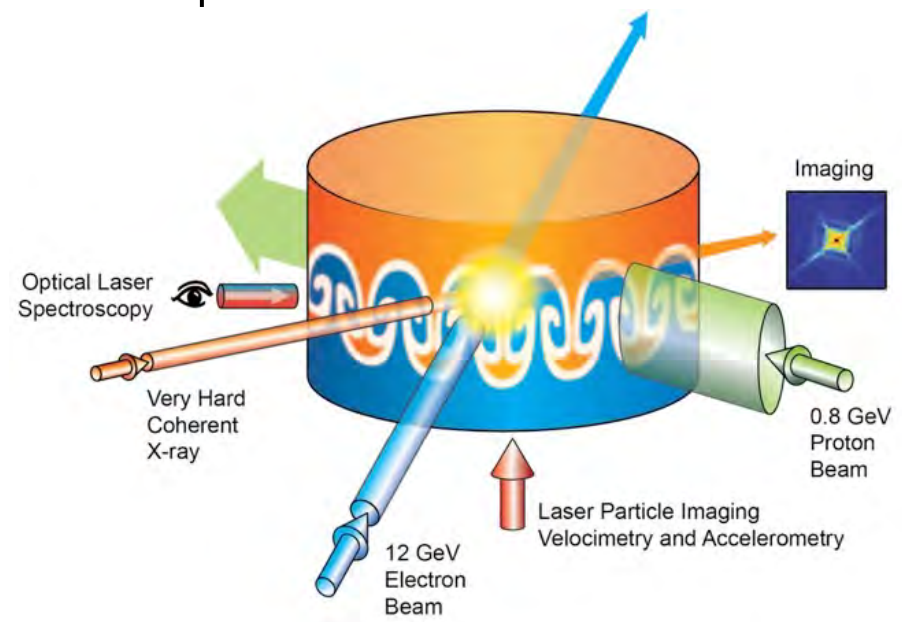
Unique characteristic #3: The need for multiple probes is driven by science

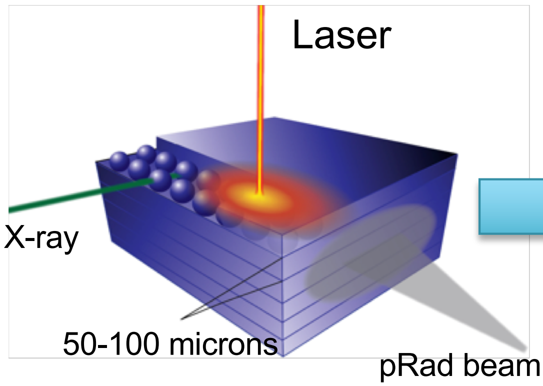
- **Phase response under failure (Bronkhorst)**
  - Broad field-of-view to determine shock location, rarefaction waves, gross grain motion
  - Narrow x-ray field-of-view to measure phase and grain plastic response

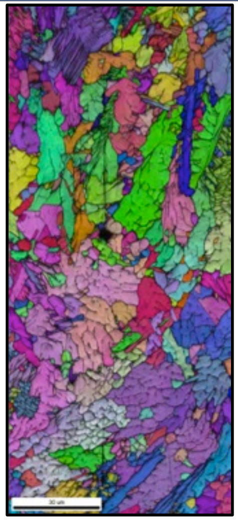


- **Ejecta evolution from Richtmyer-Meshkov jetting (Bolme)**
  - Broad field-of-view to determine bulk fluid motion and vorticity
  - Narrow x-ray field-of-view to scatter off ejecta and determine phase and structure evolution



DMMSC will provide critical data to inform and validate advanced modeling and simulation to accelerate qualification of advanced manufacturing – move from “process-” to “product-based”

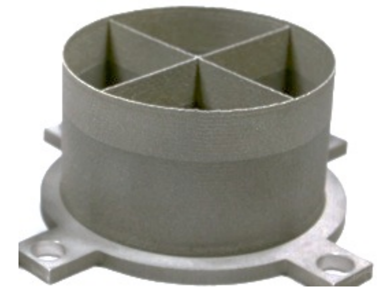




Additively Manufactured 316L Stainless Steel

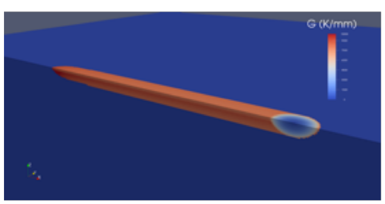
Damage under shock loading unable to coalesce leading to a tougher, more shock resistant material

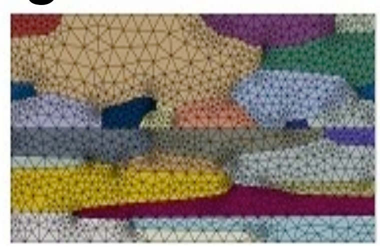
Prototype Gas Bottle

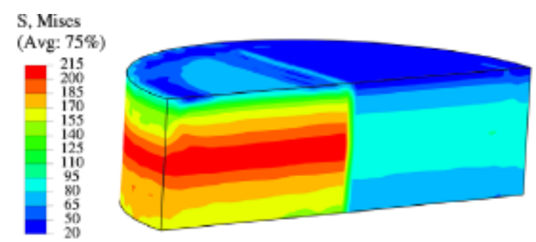


Making

Modeling







Process ⟷ Microstructure ⟷ Properties ⟷ Performance

DMMSC and Exascale will enable rapid and confident deployment of new concepts and components through more cost-effective and more rigorous science-based approaches.

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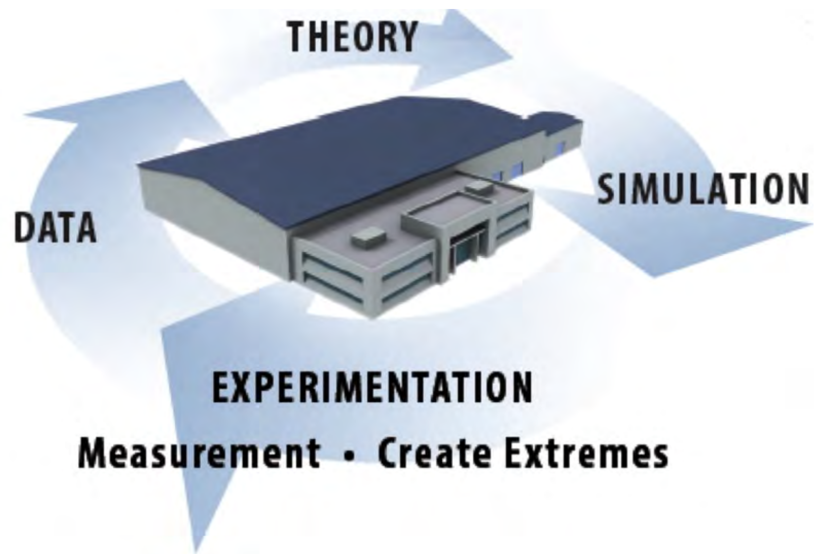
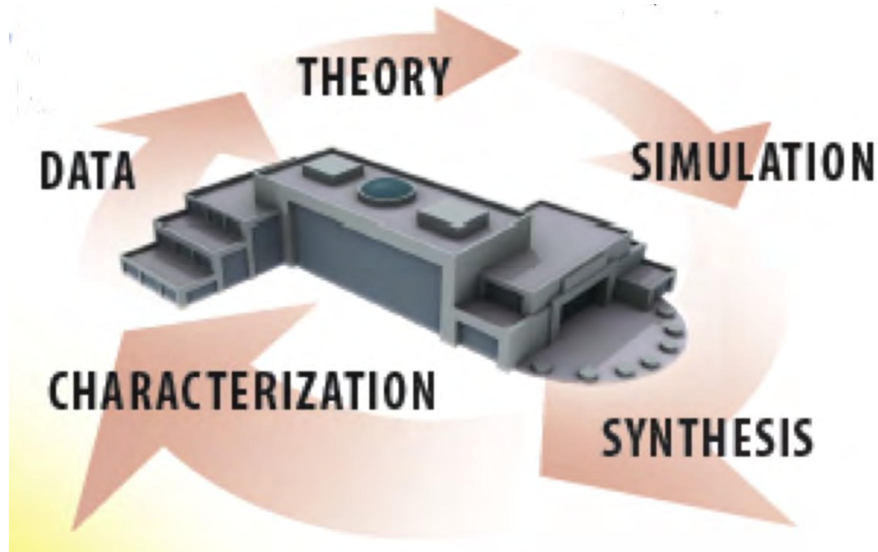
The “broader sense of co-design”: How fast can we iterate around this process?



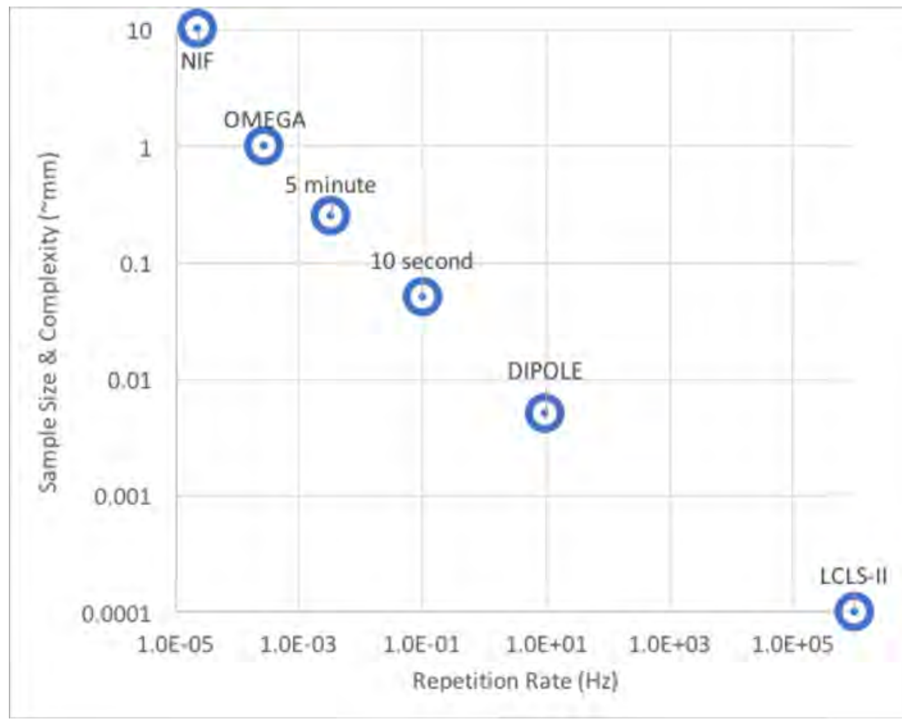


- **The experiments can now be done ”rapidly” (every few minutes to 120 Hz! And faster coming!!)**
- **The issue of “data science” is actively being attacked.**
  - Including Real-time simulation and decision-making
- **Rate-limiting step is, or is about to be, “adaptive target fabrication”**
  - 1 Hz experiment in 8-hour shift can be >20,000 targets!!

The Revolution is Hard! I claim it will be worthwhile!

Sample preparation (aka target fabrication) may, after data acquisition and analysis (aka data science), be rate-limiting step to high-throughput materials science

High-repetition-rate brilliant and coherent light sources are significantly increasing the rate at which scientific experiments can be performed. In fields of molecular biology and chemistry, fluidic methods allow large numbers of samples to be prepared. Major investments in data science and machine learning are reducing the bottlenecks on data acquisition and analysis. <u>A concomitant investment in transformative technologies to make condensed matter materials samples could enable a paradigm shift for that field as well.</u>



John Oertel and others are organizing a workshop at Texas A&M in mid-May on “Adaptive Sample Preparation and Target Fabrication for High-Throughput Materials Science”

MaRIE is a plausible facility solution that meets the DMMSC requirements – And it will be a revolutionary capability!

- The brilliance of an XFEL
- Transformative imaging techniques with coherence – "ordered light for disordered systems"
- ★ Designed for time-dependence from electronic motion (picosecond) through sound waves (nanosecond) through shock transit across samples (microseconds) through thermal diffusion (millisecond) to manufacturing (seconds and above)
- ★ High-energy to not destroy mesoscale samples with that brilliance and give that time-dependence (and perhaps provide larger reciprocal space resolution)
- ★ Not just x-ray facility, but designed for multiple simultaneous probes
- Designed with strong connection to the needs of scientific predictive capability from theory, modeling, and computation
- Providing comprehensive materials discovery capability to collaborative teams
- Enables science-based qualification and certification, leading to the "revolution in manufacturing/production science"

Maybe I'm not so crazy: Some quotes from the just-published Materials Decadal Report, 2019

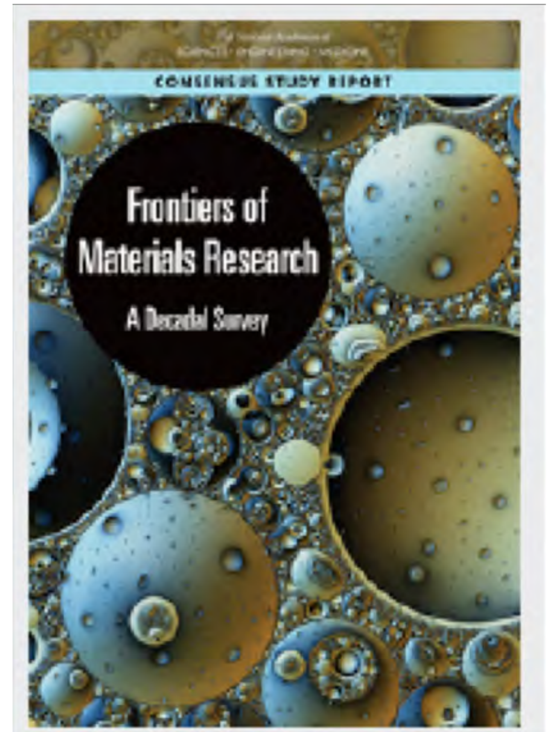
Key Recommendation: Federal agencies (including NSF and DOE) with missions aligned with the advancement of additive manufacturing and other modes of digitally controlled manufacturing should by 2020 expand investments in materials research for automated materials manufacturing. The increased investments should be across the multiple disciplines that support automated materials synthesis and manufacturing. These range from the most fundamental research to product realization, including experimental and modeling capabilities enabled by advances in computing, to achieve the aim that by 2030 the United States is the leader in the field.

Key Recommendation: The U.S. government, with NSF, DOD, and DOE coordinating, should support the quest to develop new computational and advanced data-analytic methods, invent new experimental tools to probe the properties of materials, and design novel synthesis and processing methods. The effort should be accelerated from today's levels through judicious agency investments and continue over the next decade in order to sustain U.S. competitiveness.

A principal development of the last decade has been the emergence of X-ray free electron lasers as a complement to synchrotrons, notably the Linac Coherent Light Source (LCLS) and the future LCLSII and its high-energy upgrade, LCLS-II-HE, at SLAC in the United States. New X-ray free electron lasers have been built or are under construction at DESY (Germany), PSI (Switzerland), CAS Shanghai (China), and elsewhere.

Collectively, these new ultrabright sources will drive further advances in the techniques, enabling transformative studies of materials with nanoscale resolution while under operating conditions and on ultrafast time scales. The United States had a significant fraction of all the world-leading capabilities 20 years ago, but that lead has eroded and today's landscape is one of intense competition from both Europe and Asia.

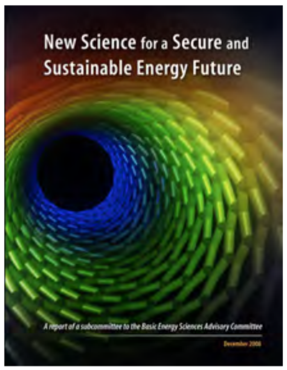
The broad photon energy range available (from the far IR to hard X ray) and the intense brightness of the beams, which allows the photon beams to be tailored to specific experimental geometries and environments, makes X-ray light sources near-ideal probes of the structure and function of materials…. As the field moves toward the capability to fully integrate computational materials science, synthesis, and advanced manufacturing for real-world performance, the microscopic characterization of structure and dynamics enabled by the next generation of instruments and upgraded sources will provide the crucial link to enable materials by design.



Honesty

LANL staff should care about MaRIE in 2009
(a slide from February 2009, 10 years ago)

DMMSC



- **MaRIE strongly support LANSCE's central role in the Lab mission**
  - (LANSCE-Refurbishment, Enhanced Lujan Neutron Scattering Center, Materials Test Station for fission energy science)
- **MaRIE enables our Materials Strategy**
  - It engages us in key national directions of material science
    - We become leaders in the transformation from the "era of observation" to the "era of control" and providers of "functionality by design"
  - It provides resources to enable strategic investment in the LANL Materials Strategy
    - Guides LDRD, provides enabling R&D support, and can re-direct programmatic interest
- **MaRIE is an experimental facility**
  - It can transform non-materials science at Los Alamos
  - It will enhance LANL capabilities for all our customers
  - 30 years from now its use will be different – just as with LAMPF

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Conclusion

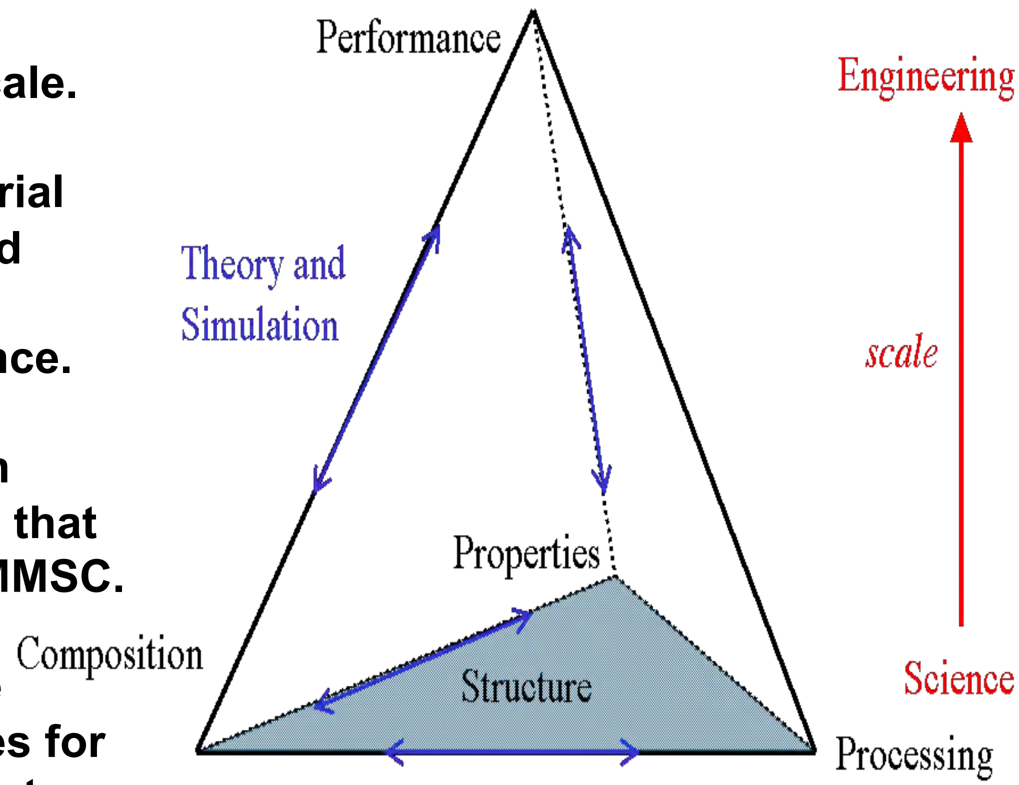
» **Big, great things take time – lots of time**

» **They are worth doing ("Do or do not, there is no try")**

» **I hope you will help us achieve this vision of a great future for our Lab.**

Bottom Line Up Front

- The Dynamic Mesoscale Materials Science Capability (DMMSC) addresses a national unmet scientific need for understanding material performance and production at the mesoscale.
- The ultimate goal is the integration of material structure and processing to achieve desired material properties and ultimately desired performance – supporting production science.
- The MaRIE (Matter-Radiation Interactions in Extremes) Facility is one plausible solution that meets all the validated requirements for DMMSC.
- The mission need for the capability and the facility project are important timely priorities for DOE/NNSA and Los Alamos National Laboratory.



Understanding process-structure-property-performance relationships requires a research capability to explore mesoscale dynamics

Backup

Hard X-ray FEL Parameters

And now Shanghai!

	LCLS-I	SACLA	EXFEL	PAL XFEL	SwissFEL	LCLS-II	LCLS-	MaRIE
X-ray energy Pulse energy photons/pulse	12.8 keV 0.93 mJ 5E11	19.5 keV 0.03 mJ 1E10	24.7 keV 1 mJ 2.5E11	20.6 keV 0.08 mJ 2.5E10	12.4 keV 1.4 mJ 7E11	5 / 25 keV 0.025 / 0.3 mJ 3E10 / 7E10	15 keV	42 keV 0.35 mJ 5E10
Undulator period K_{rms}	3.0 cm 2.5	1.8 cm 0.94	4.0 cm 1.4	2.44 cm 0.94	1.5 cm 1.1	2.6 cm 0.43 / 1.5		1.86 cm 0.86
Electron beam energy	16.9 GeV	8.5 GeV	17.5 GeV	10 GeV	5.8 GeV	4 / 15 GeV	8 GeV	12 GeV
Linac type Linac length	NCRF S-band 1 km	NCRF C-band 0.4 km	SRF L-band 1.7 km	NCRF S-band 0.78 km	NCRF C-band 0.46 km	SRF / NCRF 0.4 / 1 km	SRF 0.8 km	TBD
Gun type Cathode	NCRF S-band Cu photo	Pulsed DC CeB_6	NCRF L-band Cs_2Te photo	NCRF S-band Cu photo	NCRF S-band Cu photo	VHF / S-band Cs_2Te / Cu	same	TBD
RF pulse Rep. rate	<1 μs 120 Hz	<1 μs 30 Hz	600 μs 10 Hz	< 1 μs 60 Hz	< 1 μs 100 Hz	CW / <1 μs 930 kHz / 120 Hz	same	TBD
# pulses/RF	1-2	1-2	2,700	1-2	1-2	N/A (CW) / 1-2	N/A (CW)	TBD
Bunch charge	150 pC	30 pC	250 pC	100 pC	200 pC	20 / 130 pC	same	100 pC
Bunch length	43 fs	<10 fs	50 fs	43 fs	42 fs	20 / 33 fs		
Norm. slice nce	0.4 μm	0.6 μm	0.6 μm	<0.5 μm	0.2 μm	0.14 / 0.48 μm	same	0.2 μm