Accomplishments in the Trident Laser Facility

Trident has been an extremely productive laser facility, despite its modest size and operating cost in the firmament of high-energy, high-power laser facilities worldwide. More than 150 peer-reviewed journal articles (in 39 different journals) have been published using Trident experimental data, many in high-impact journals such as *Nature*, *Nature Physics*, *Nature Communications*, and *Physical Review Letters*. More than 230 oral presentations involving research at Trident have been presented at national and international conferences. Trident publications have over 5000 citations in the literature with an h-index of 38. At least 23 Los Alamos postdoctoral researchers have worked on Trident. In the period since its inception in 1992–2007, despite not issuing formal proposal calls for access nor functioning explicitly as a user facility until later, Trident had 170 unique users from more than 30 unique institutions, such as Los Alamos, Lawrence Livermore, and Sandia national laboratories, various University of California campuses, General Atomic, Imperial College, and Ecole Polytechnique. To reinforce its role as an important Los Alamos point of connection to the external research community, at least 20 PhD students did a significant fraction of their thesis work on Trident (see Appendix below). Such PhD students include Mike Dunne (Imperial College, 1995) – now director of LCLS and professor at Stanford; David Hoarty (IC, 1997) – scientist at Atomic Weapons Establishment, UK; Dustin Froula (UC Davis, 2002) – Plasma and Ultrafast Physics group leader at the Laboratory for Laser Energetics and assistant professor at the Physics and Astronomy Department at the University of Rochester; Tom Tierney (UC Irvine, 2002) – scientist at Los Alamos; Eric Loomis (Arizona State U., 2005) – scientist at Los Alamos; and Eliseo Gamboa (University of Michigan, 2013) – scientist at the Linac Coherent Light Source. The work performed on Trident, besides its scientific impact, has also supported the Inertial Confinement Fusion and Weapons research programs at the Laboratory. It also has advanced technologies and techniques that hold significant promise for Los Alamos initiatives, such as MaRIE (the proposed Matter-Radiation Interactions in Extremes experimental facility), and more generally for important societal applications, such as defense, global security, advanced accelerators, fusion energy, radiotherapy, and laser technology.

Specific research contributions based on Trident experiments are listed below.

Relativistic laser plasmas

1. First demonstration of laser-driven quasi-monoenergetic ion beams (Al and C) with simultaneously high ion-energy and high-efficiency [1]. These are the quasi-monoenergetic beams with the highest demonstrated energy/nucleon.
2. First demonstration of the laser-driven neutron beam with the highest yield and fluence to date: > 10^{10} neutrons within ~ 1 steradian, created in ~ 1ns [2,3]. This record performance among all worldwide high-power, high-intensity lasers is now shared with the PHELIX laser at GSI (Darmstadt).
3. First demonstration of *uniform* volumetric, isochoric heating (in ≈ 25 ps) with laser-driven ion beams of solid-matter samples [4-6] sufficiently large for warm-dense matter studies. This work, done using the laser-driven ion beams in Ref. [1], also lays the groundwork for a promising capability for dynamic materials research.
4. First laboratory demonstration of relativistically induced transparency (RIT) [7]
5. First demonstration of coherent, forward laser harmonics by coherent synchrotron emission [8]

6. First demonstration of quasi-monoenergetic laser-driven ion beams (C6+) via the novel ion soliton mechanism, achieved in the RIT regime [9,10]
7. First demonstration of laser-driven ion acceleration in the RIT regime [11]
8. First demonstration of laser-driven ion acceleration (C6+) to > 1 GeV [12], in the RIT regime
9. Characterization and development of laser-driven ion acceleration in the RIT regime, especially the novel breakout afterburner (BOA) mechanism, which enables simultaneously higher efficiency and higher ion energies [13-16]
10. First *active* measurement of relativistic electrons from a sub-μm-thick foil laser-target [17] illuminated by an intense laser (at 2 x 10^{20} W/cm^2), typical of targets in the RIT regime. The results show >50% conversion efficiency from the laser to electrons and multi-MA currents.
11. First investigation of the generation and focusing of a fast ignition (FI)-relevant laser-driven proton beam using a cone-shaped target, demonstrating focusing within the requirements for fast ignition [18]
12. First demonstration of laser-driven proton energies beyond the previous decade-long record of 58 MeV from the NOVA petawatt laser, to 67.5 MeV [19] mediated by direct laser-light-pressure acceleration of electrons, and > 90 MeV [20] with BOA
13. First observation of quasi-monoenergetic electron bunches from solid-density laser-driven targets (ultra-thin diamond foils) [21], operating in the RIT regime
14. First demonstration of ultrahigh-contrast laser pulses in a high-energy, high-power laser facility with sub-ps pulses, with a scheme based on optical parametric amplification [22]. This advance enabled access to the RIT regime
15. Implementation of “dial a contrast” capability to provide laser pulses with controllable levels of prepulse [23], in order to connect with work at other short-pulse laser facilities and with work at Trident prior to ultra-high contrast capability
16. First demonstration of controlled transport and focusing of a laser-driven ion beam with (miniature) magnetic lenses [24]
17. First demonstration of a low-energy spread (quasi-monoenergetic) laser-driven ion beam [25]
18. Use of a long-pulse laser to clean off surface impurities from a short-pulse laser foil target [26]
19. Experimental determination that protons laser-accelerated in the target-normal sheath acceleration (TNSA) regime come primarily from the rear surface of the foil target [27]
20. First measurement of beam emittance (laminarity) of TNSA laser-driven proton beams, demonstrating ultra-low emittance (high-laminarity), which enables focusing and transport [28]
21. First demonstration of proton radiography with laser-driven proton beams [29], demonstrating a ~ 2 μm resolution.
22. Systematic study of high-intensity laser-beam propagation in a coronal plasma above the critical intensity for ponderomotive self focusing, relevant for fast ignition, and comparison to dedicated modeling [30]. The study found a clear wavelength dependence, decreased transmission with increasing plasma density, and an increase in laser-beam f/number (channeling).

Laser-plasma instabilities (LPI) and basic laser plasmas

23. Initial implementation of STUD pulses at the Trident Laser and initial experiments demonstrating reduction in LPI [31, 32]
24. First demonstration of the different properties of plasma waves in the kinetic and fluid regimes [33]

25. First direct and comprehensive characterization of the ion acoustic waves driven to high levels by stimulated Brillouin scattering (SBS), using Thomson scattering measurements [34]. The results showed the kinetic effects of ion heating due to trapping, trapping then leading to SBS detuning and saturation [35]
26. First direct observation of SBS detuning by a velocity gradient with Thomson scattering measurements [36]
27. First direct observation of plasma waves from the Langmuir-decay instability in laser-plasmas [37], showing the signature frequency cascade
28. First demonstration that backward stimulated-Raman backscatter (SRS) in ignition-relevant plasmas, even with controlled, diffraction-limited (single-hot-spot) laser beams in homogeneous plasma conditions, has a non-linear onset and saturation [37]
29. First-demonstration of the non-linear onset of stimulated Brillouin scattering (SBS) in laser-plasmas with ignition-relevant multi-speckled laser beams and ignition-relevant long scale-lengths [38], in agreement with analytical theory predictions developed at LANL
30. First demonstration of laser-beam deflection by plasma flow [39]
31. First observation of the electron acoustic wave, and parametric laser scattering from it [40]
32. Full characterization of long-scale length plasmas for pioneering experiments on LPI using a diffraction-limited (single-hot-spot) frequency-tripled probe beam [41,42]
33. First observation of the two-ion decay laser-plasma instability [43]
34. First observation of spatial localization of electrostatic waves associated with backward SBS and SRS in a long-scale-length plasma [44], building on earlier observations at LULI in strong gradients or peaked profiles
35. First observation of electromagnetic seeding of backward SBS, and first demonstration that the non-linear saturation level depends on the seed level [45]
36. Generation of magnetized collisionless shocks by a novel, laser-driven magnetic piston [46]
37. Demonstration of collisionless coupling between super-Alfvénic blow-off and ambient magnetized plasmas [46]
38. Validation of kinetic plasma modeling of colliding plasmas [48]
39. First experimental observation of the ion plasma wave [49]

Dynamic Materials

40. First measurements with sufficient sensitivity to discriminate between diffusion bonded and press fit Cu/Be dynamic friction model parameters under shock-driven sliding conditions (dynamic friction) [50]
41. Highest sensitivity measurements of surface height variations induced by grain structure in shocked beryllium under consideration for ICF capsule ablators [51].
42. First in situ measurements of full field shock planarity at 10s nm sensitivity using transient imaging displacement interferometry under plate impacts driven by gas guns and by lasers [52]
43. Measurements of spall strength and phase transitions in plutonium samples, the second dynamic plutonium experimental campaign done on a laser facility [53]. These successful experiments demonstrated the ability for fast turnaround (four experiments per day) and the use of a containment vessel fully encapsulating the plutonium sample. The latter eliminates contamination to personnel and equipment, and allows equipment reuse and reduced costs.
44. Development and validation of laser-launched flyer plate and confined laser ablation methods for shock wave loading [54, 55]

45. Characterization of surface modifications in sapphire induced by long-pulse laser irradiation [56]
46. Development of quasi-isentropic compression by ablative laser loading [57]
47. Determination of shock pressures induced in condensed matter by laser ablation [58]
48. Synthesis of a novel crystalline carbon-cage structure by laser-driven shock wave loading of a graphite-copper mixture (to about 14±2 GPa and 1000±200 K) [59]
49. First investigations with simultaneous transient x-ray diffraction and velocity interferometry diagnostics of the stress at which plastic flow occurs in ns timescales for single crystals and polycrystalline foils of materials including silicon, copper, beryllium [60], iron, tantalum, nickel-titanium, nickel aluminide, and ruthenium aluminide. The results contributed to the development of time-dependent plasticity models and of simulations with explicit treatment of the motion of dislocations.

Radiation Hydrodynamics

50. Measurement of blast waves showing the transition from stability to Vishniac instability depending on the adiabatic index of the propagation medium [61, 62]
51. First experimental study (along with the Vulcan laser) of ionization fronts in the transonic regime [63]
52. First evaluation of a foam-buffered target design for spatially uniform ablation of laser-irradiated plasmas [64]
53. First study of laser-imprint saturation in foam-buffered targets [65]

Diagnostic development

54. First demonstration of a gated x-ray camera with flat response (using a Be-coated photocathode) [66]
55. Testing and characterization of the gated x-ray diagnostic (GXD) instrument for NIF at LLNL and for Orion at AWE [67], as well as cameras from earlier-generations
56. Routine testing of LANL gated x-ray cameras prior to deployment in most Omega experimental campaigns for two decades, to ensure high reliability
57. First single-shot temporal-shape measurement of high energy sub-ps optical pulses [68]
58. Testing and characterization of a novel high resolution ion wide angle spectrometer [69]
59. Testing and characterization of first spectrometer for HED experiments to measure x-ray Thomson scattering spatially resolved in 1-dimension [70, 71]. This spectrometer has been used also in experiments at the Omega laser, and is slated as a LANL contribution in kind to the HIBEF consortium for the HED instrument at the European XFEL.
60. First demonstration of an x-ray fluorescence scattering imaging as a diagnostic for laboratory hydrodynamics experiments [72, 73]
61. Demonstration of dynamic phase-contrast imaging using ultrafast x-rays in laser-shocked materials [74]
62. Development, testing and utilization of the transient imaging displacement interferometer (TIDI) diagnostic for dynamic material experiments [75]. TIDI is sensitive to surface displacements of ~ 10 nm with a resolution of ~ 5μm and a time-gate of ~ 150ps.
63. Testing, commissioning and utilization of the spatially-discriminating optical streaked spectrograph (SDOSS), also deployed at the Nova and Omega laser facilities [76]
64. Characterization and cross calibration of x-ray film [77]
65. First neutron radiograph with a laser-driven neutron-beam source [1]

66. Detection and differentiation of depleted and enriched uranium (~ kg) as well as plutonium (≈ 150g) using laser-driven neutron beams [78], laying the groundwork for a promising capability for global security
67. First use of nuclear-physics techniques to diagnose laser-driven ion beams [79]
68. First detection of a nuclear resonance (indium at 1.4 eV) with moderated laser-driven neutron beams [80], laying the groundwork for promising diagnostics for MaRIE and next generation neutron sources
69. Extensive calibration of gamma Cherenkov detectors and photomultipliers using the Trident short-pulse front end.

References:

[1] S. Palaniyappan, et al., "Efficient quasi-monoenergetic ion beams from laser-driven relativistic plasmas," *Nature Communications* **6**, 10170 (2015)

[2] M. Roth, et al., "Bright Laser-Driven Neutron Source Based on the Relativistic Transparency of Solids," *Physical Review Letters* **110**, 044802 (2013)

[3] D. Jung, et al., "Characterization of a novel, short pulse laser-driven neutron source," *Physics of Plasmas* **20**, 056706 (2013)

[4] W. Bang, et al., "Visualization of expanding warm dense gold and diamond heated rapidly by laser-generated ion beams," *Scientific Report*s **5**, 14318 (2015)

[5] W. Bang, et al., "Uniform heating of materials into the warm dense matter regime with laser-driven quasimonoenergetic ion beams," *Physical Review E* **92**, 063101 (2015)

[6] W. Bang, et al., "Linear dependence of surface expansion speed on initial plasma temperature in warm dense matter," *Scientific Reports* **6**, 29441 (2016)

[7] S. Palaniyappan, et al., "Dynamics of relativistic transparency and optical shuttering in expanding overdense plasmas," *Nature Physics* **8**, 763 (2012)

[8] B. Dromey, et al., "Coherent synchrotron emission from electron nanobunches formed in relativistic laser–plasma interactions," *Nature Physics* **8**, 804 (2012)

[9] D. Jung, et al., "Monoenergetic Ion Beam Generation by Driving Ion Solitary Waves with Circularly Polarized Laser Light," *Physical Review Letters* **107**, 115002 (2011)

[10] L. Yin, et al., "Mono-energetic ion beam acceleration in solitary waves during relativistic transparency using high-contrast circularly polarized short-pulse laser and nanoscale targets," *Physics of Plasmas* **18**, 053103 (2011)

[11] A. Henig, et al., "Enhanced Laser-Driven Ion Acceleration in the Relativistic Transparency Regime," *Physical Review Letters* **103,** 045002 (2009)

[12] D. Jung, et al., "Laser-driven 1 GeV carbon ions from preheated diamond targets in the break-out afterburner regime," *Physics of Plasmas* **20**, 083103 (2013)

[13] D. Jung, et al., "Scaling of ion energies in the relativistic-induced transparency regime," *Laser and Particle Beams* **33**, 695 (2015)

[14] D. Jung, et al., "Efficient carbon ion beam generation from laser-driven volume acceleration," *New Journal of Physics* **15**, 023007 (2013)

[15] D. Jung, et al., "Beam profiles of proton and carbon ions in the relativistic transparency regime," *New Journal of Physics* **15**, 123035 (2013)

[16] B. M. Hegelich, et al., "Experimental demonstration of particle energy, conversion efficiency and spectral shape required for ion-based fast ignition," *Nuclear Fusion* **51**, 083011 (2011)

[17] J. A. Cobble, et al., "Laser-Driven Micro-Coulomb Charge Movement and Energy Conversion to Relativistic Electrons," *Phys. of Plasmas*, in press (2016)

[18] T. Bartal, et al., "Focusing of short-pulse high-intensity laser-accelerated proton beams," *Nature Physics* **8**, 139 (2012)

[19] S. Gaillard, et al., "Increased laser-accelerated proton energies via direct laser-light-

pressure acceleration of electrons in microcone targets," *Physics of Plasmas* **18**, 056710 (2011)
[20] D. Jung, et al., "On the analysis of inhomogeneous magnetic field spectrometer for laser-driven ion acceleration," *Review of Scientific Instruments* **86**, 033303 (2015)
[21] D. Kiefer, et al., "First observation of quasi-monoenergetic electron bunches driven out of ultra-thin diamond-like carbon (DLC) foils," *European Physical Journal D*, **55**, 427 (2009)

[22] R. C. Shah, et al., "High-temporal contrast using low-gain optical parametric amplification," *Optics Letters* **34**, 2273 (2009)
[23] K. A. Flippo, et al., "The TRIDENT laser at LANL: New "dial-a-contrast" and high-contrast experimental capabilities," *EPJ Web of Conferences* **59**, 07003 (2013)
[24] M. Schollmeier, et al., "Controlled Transport and Focusing of Laser-Accelerated Protons with Miniature Magnetic Devices," *Physical Review Letters* **101**, 055004 (2008)
[25] B. M. Hegelich, et al., "Laser acceleration of quasi-monoenergetic MeV ion beams," *Nature* **439**, 441 (2006)
[26] J. C. Fernández, et al., "Laser-Ablation Treatment of Short-Pulse Laser Targets: Toward an Experimental Program on Energetic-Ion Interactions with Dense Plasmas," *Lasers and Particle Beams* **23**, 267 (2005)
[27] J. Fuchs, et al., "Comparison of Laser Ion Acceleration from the Front and Rear Surfaces of Thin Foils," *Physical Review Letters* **94**, 045004 (2005)
[28] T. E. Cowan, et al., "Ultralow Emittance, Multi-Mev Proton Beams from a Laser Virtual-Cathode Plasma Accelerator," *Physical Review Letters* **92**, 204801 (2004)
[29] J. A. Cobble, et al., "High resolution laser-driven proton radiography," *Journal of Applied Physics* **92**, 1775 (2002)
[30] J. A. Cobble, et al., "Wavelength scaling of high-intensity illumination of an exploded foil," *Physics of Plasmas* **5**, 4005 (1998)
[31] R. P. Johnson, et al., "Implementation of STUD Pulses at the Trident Laser and Initial Results," *APS DPP Conference*, Providence, RI, October 2012, http://meetings.aps.org/link/BAPS.2012.DPP.CP8.100
[32] L. Yin, et al., "Stimulated scattering in laser driven fusion and high energy density physics experiments," *Physics of Plasmas* **21**, 092707 (2014)
[33] J. L. Kline, et al., "Observation of a Transition from Fluid to Kinetic Nonlinearities for Langmuir Waves Driven by Stimulated Raman Backscatter," *Physical Review Letters* **94**, 175003 (2005)
[34] D. H. Froula, et al., "Stimulated Brillouin scattering in the saturated regime," *Physics of Plasmas* **10**, 1846 (2003)
[35] D. H. Froula, et al., "Measurements of Nonlinear Growth of Ion-Acoustic Waves in Two-Ion-Species Plasmas with Thomson Scattering, Backscatter," *Physical Review Letters* **88**, 105003 (2002)
[36] D. H. Froula, et al., "Direct Observation of Stimulated-Brillouin-Scattering Detuning by a Velocity Gradient," *Physical Review Letters* **90**, 155003 (2003)
[37] D. S. Montgomery, et al., "Recent Trident single hot spot experiments: Evidence for kinetic effects, and observation of Langmuir decay instability cascade," *Physics of Plasmas* **9**, 2311 (2002)
[38] R. G. Watt, et al., "Dependence of stimulated Brillouin scattering on focusing optic F number in long scale-length plasmas," *Physics of Plasmas* **3**, 1091 (1996)
[39] D. S. Montgomery, et al., "Flow-Induced Beam Steering In a Single Hot Spot," *Physical Review Letters* **84**, 678 (2000)
[40] D. S. Montgomery, et al., "Observation of Stimulated Electron-Acoustic-Wave Scattering," *Physical Review Letters* **87**, 155001 (2001)

[41] D. S. Montgomery, et al., “Characterization of plasma and laser conditions for single hot spot experiments,” *Laser and Particle Beams* **17**, 349 (1999)
[42] J. A. Cobble, et al., “Cyclic plasma shearing interferometry for temporal characterization of a laser-produced plasma,” *Review of Scientific Instruments* **73**, 3813 (2002)
[43] C. Niemann, et al., “Observation of the parametric two-ion decay instability with Thomson scattering,” *Physical Review Letters* **93,** 045004 (2004)
[44] J. A. Cobble, et al., “The spatial location of laser-driven, forward-propagating waves in a National-Ignition-Facility-relevant plasma,” *Physics of Plasmas* **7**, 323 (2000)
[45] J. C. Fernández, et al., “Increased Saturated Levels of Stimulated Brillouin Scattering of a Laser by Seeding a Plasma with an External Light Source,” *Physical Review Letters* **81**, 2252 (1998)
[46] D. B. Schaeffer, et al., “Generation of magnetized collisionless shocks by a novel, laser-driven magnetic piston,” *Physics of Plasmas* **19**, 070702 (2012)
[47] C. Niemann, et al., “Generation of magnetized collisionless shocks by a novel, laser-driven magnetic piston,” *IEEE Transactions of Plasma Science* **39**, 2406 (2011)
[48] D. Winske, et al., “Trident Colliding Plasma Experiments,” LANL Report LA-CP-93-0181 (1993); M. Wilke, et al., “Colliding Plasma Experiments on Trident,” LANL Report LA-CP-94-0054 (1994)
[49] B. S. Bauer, et al., “Detection of Ion Plasma Waves by Collective Thomson Scattering,” *Physical Review Letters* **74**, 3604 (1995)
[50] E. N. Loomis, et al., “High-resolution measurements of shock behavior across frictional Be/Cu interfaces,” *Journal of Applied Physics* **117**, 185906 (2015)
[51] E. N. Loomis, et al., “Investigations into the seeding of instabilities due to x-ray preheat in beryllium-based inertial confinement fusion targets,” *Physics of Plasmas* **17**, 056308 (2010)
[52] S. R. Greenfield, et al., “Transient imaging displacement interferometry applied to shock loading,” *AIP Conference Proceedings* **955**, 1093 (2007)
[53] D. L. Paisley and Carter P. Munson, “Trident Tests Dynamic Response of Plutonium,” *Nuclear Weapons Journal* **1** (2006) LALP-06-084
[54] D. L. Paisley, et al., “Laser-launched flyer plate and confined laser ablation for shock wave loading: Validation and applications,” *Review of Scientific Instruments* **79**, 023902 (2008)
[55] D. C. Swift, et al., “Laser-launched flyer plates for shock physics experiments,” *Review of Scientific Instruments* **76**, 093907 (2005)
[56] S. Luo, et al., “Sapphire (0 0 0 1) surface modifications induced by long-pulse 1054 nm laser irradiation,” *Applied Surface Science* **253**, 9457 (2007)
[57] D. C. Swift, et al., “Quasi-isentropic compression by ablative laser loading: Response of materials to dynamic loading on nanosecond time scales,” *Physical Review E* **71**, 066401 (2005)
[58] D. C. Swift, et al., “Shock pressures induced in condensed matter by laser ablation,” *Physical Review E* **69**, 036406 (2004)
[59] S. Luo, et al., “Novel crystalline carbon-cage structure synthesized from laser-driven shock wave loading of graphite,” *Journal of Chemical Physics* **123,** 024703 (2005)
[60] D. C. Swift, et al., “Simultaneous VISAR and TXD measurements on shocks in beryllium crystals,” Shock Compression of Compressed Matter–2001, M.D. Furnish, N.N. Thadhani, and Y. Horie, Eds. (American Institute of Physics, New York, 2002), AIP Conference Proceedings 620, pp. 1192–1195
[61] G. Schappert, et al., in proceedings of the Workshop on Laboratory Astrophysics Experiments with Large Lasers, Eds. B. A. Remington and W. H. Goldstein (February 26–27, 1996), LLNL Rept. No. CONF-960297, p. 164

[62] G. T. Schappert, et al., "Instabilities in Taylor Sedov Blast Waves," in LA-12901-PR, *AGEX II Technical Quarterly* **II** (July, August & September 1994)
[63] D. Hoarty, et al., "Observation of ionization fronts in low density foam targets," *Physics of Plasmas* **6**, 2171 (1999)
[64] M. Dunne, et al., "Evaluation of a Foam Buffer Target Design for Spatially Uniform Ablation of Laser-Irradiated Plasmas," *Physical Review Letters* **75**, 3858 (1995)
[65] O. Willi, et al., "Inertial confinement fusion and fast ignitor studies," *Nuclear Fusion* **40**, 537 (2000)
[66] John Oertel, private communication, in preparation for publication (2016)
[67] J. A. Oertel, et al., "Gated x-ray detector for the National Ignition Facility," *Review of Scientific Instruments* **77**, 10E308 (2006)
[68] S. Palaniyappan, et al., "Pulse shape measurements using single shot-frequency resolved optical gating for high energy (80 J) short pulse (600 fs)," *Review Scientific Instruments* **81**, 10E103 (2010)
[69] D. Jung, et al., "A novel high resolution ion wide angle spectrometer," *Review of Scientific Instruments* **82**, 043301 (2011)
[70] E. J. Gamboa, et al., "Imaging x-ray crystal spectrometer for laser-produced plasmas," *Journal of Instrumentation* **6**, P04004 (2011)
[71] E. J. Gamboa, et al., "Imaging x-ray Thomson scattering spectrometer design and demonstration (invited)," *Review of Scientific Instruments* **83**, 10E108 (2012)
[72] M. J. MacDonald, et al., "Demonstration of x-ray fluorescence imaging of a high-energy-density plasma," *Review of Scientific Instruments* **85**, 11E602 (2014)
[73] N. E. Lanier, et al., "Feasibility of fluorescence-based imaging of high-energy-density hydrodynamics experiments," *Review of Scientific Instruments* **74**, 2169 (2003)
[74] J. Workman, et al., "Phase-contrast imaging using ultrafast x-rays in laser-shocked materials," *Review of Scientific Instruments* **81**, 10E520 (2010)
[75] S. R. Greenfield , et al., "Transient Interferometric Studies of Shocked Bicrystals," *AIP Conference Proceedings* **706**, 1269 (2004)
[76] J. A. Cobble, et al., "SDOSS: a Spatially Discriminating, Optical Streaked Spectrograph," *AIP Conference Proceedings* **369**, 380 (1996)
[77] N. E. Lanier, et al., "Characterization and cross calibration of Agfa D4, D7, and D8 and Kodak SR45 x-ray films against direct exposure film at 4.0–5.5 keV," *Review of Scientific Instruments* **77,** 043504 (2006)
[78] LANL LDRD Early Career 20140580ECR final project report; Favalli, et al., "Nuclear material detection by one-short-pulse-laser-driven neutron source," LANL report LA-UR-14-28697 (2014), presented in IEEE Nuclear Symposium (Seattle, USA); Favalli and M. Roth, "Active interrogation of sensitive nuclear material using laser driven neutron beams," LANL report LA-UR-15-23312 (2015), presented in the International Workshop on Physics of High Energy Density in Matter, 2015-01-25 (Hirschegg, Austria)
[79] A. Favalli, et al., "Experimental observation of β-delayed neutrons from 9Li as a way to study short-pulse laser-driven deuteron production," submitted to *Physical Review X* (2016)
[80] S. Vogel, et al., private communication, in preparation for publication (2016)

Appendix

PhD and MS thesis based on Trident data

Michael Dunne, Ph.D. Imperial College, 1995, Advisor: Prof. Oswald Willi
David Hoarty, Ph.D. Imperial College 1997, Advisor: Prof. Oswald Willi
Akio Iwase, Ph.D. Imperial College, 1999, Advisor: Prof. Oswald Willi
Shelly Nuruzzaman, Ph.D. Imperial College, 2000, Advisor: Prof. Oswald Willi

Ronald Focia, Ph.D. MIT, 2001, Advisor: Prof. Abraham Bers
Andrew Loveridge, Ph.D. Oxford, 2001, Advisor: Prof. Justin Wark
Thomas Tierney, Ph.D. UC Irvine, 2002, Advisor: Prof. Norm Rostoker
Dustin Froula, Ph.D. UC Davis, 2002, Advisor: Prof. Richard Scalettar
Adrian Allen, Ph.D. Oxford, 2003, Advisor: Prof. Justin Wark
David Strozzi, Ph.D. MIT, 2004, Advisor: Prof. Abraham Bers
Erik Brambrink, Ph.D. TU-Darmstadt, 2004, Advisor: Prof. Markus Roth
Eric Loomis, Ph.D. Arizona State Univ., 2005, Advisor: Prof. Pedro Peralta
Jörg Schreiber, Ph.D. LMU-Munich, 2006, Advisor: Prof. Dietrich Habs
Knut Harres, M.Sc. TU-Darmstadt 2006, Advisor: Prof. Markus Roth
Frank Nürnberg, M.Sc. TU-Darmstadt 2006, Advisor: Prof. Markus Roth
Marius Schollmeier, Ph.D. TU-Darmstadt 2008, Advisor: Prof. Markus Roth
Stephan DiGiacomo, M.Sc. Arizona State Univ. 2008, Advisor: Prof. Pedro Peralta
Shima Hashemian, M.Sc. Arizona State Univ. 2008, Advisor: Prof. Pedro Peralta
Leda Wayne, M.Sc. Arizona State Univ. 2009, Advisor: Prof. Pedro Peralta
Sandrine Gaillard, Ph.D. Univ. of Nevada 2009, Advisor: Prof. Thomas Cowan
Andreas Henig, Ph.D. Ludwig Maximilians Univ. 2010, Advisor: Prof. Dietrich Habs
Dominik Kraus, Ph.D. TU-Darmstadt 2012, Advisor: Prof. Markus Roth
Daniel Kiefer, Ph.D. Ludwig Maximilians Univ. 2012, Advisor: Prof. Dietrich Habs
Daniel Jung, Ph.D. Ludwig Maximilians Univ. 2012, Advisor: Prof. Jörg Schreiber
Teresa Bartal, Ph.D. UCSD 2012, Advisor: Prof. Farhat Beg
Eliseo Gamboa, Ph.D. Univ. of Michigan, 2013, Advisor: Prof. Paul Drake
Derek B. Schafer, Ph.D. UCLA, 2014, Advisor: Prof. Christoph Niemann
Michael MacDonald, Ph.D. Univ. of Michigan, 2016, Advisor: Prof. Paul Drake
Prof. Dr. Jörg Schreiber