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Title: Accomplishments in the Trident Laser Facility

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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.

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Appendix

PhD and MS thesis based on Trident data
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