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Title: Characterization and application of a laser-driven intense pulsed neutron source using Trident

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Characterization and application of a laser-driven intense pulsed neutron source using Trident

A team of Los Alamos researchers supported a final campaign to use the Trident laser to produce neutrons, contributed their multidisciplinary expertise to experimentally assess if laser-driven neutron sources can be useful for MaRIE. MaRIE is the Laboratory's proposed experimental facility for the study of matter-radiation interactions in extremes.

Neutrons provide a radiographic probe that is complementary to x-rays and protons, and can address imaging challenges not amenable to those beams. The teams efforts characterize the Laboratory's responsiveness, flexibility, and ability to apply diverse expertise where needed to perform successful complex experiments.

Campaign PI and LANSCE Rosen Scholar Prof. Markus Roth (Technical University (TU) Darmstadt, Germany), his team (Annika Kleinschmidt, Alexandra Tebartz, Victor Schanz, Gabriel Schaumann), and the Trident-based team (Cort Gautier, Randy Johnson, Russ Mortensen, Tom Shimada, Sasi Palaniyappan and Glen Wurden, all of Plasma Physics, P-24; Andrea Favalli (Safeguards Science and Technology, NEN-1) were joined by Sven Vogel (Materials Science in Radiation and Dynamics Extremes, MST-8), Ron Nelson (LANSCE Weapons Physics, P-27), Michelle Espy and James Hunter (both Applied Engineering Technology AET-6), and Adrian Losko (UC Berkeley, postdoctoral affiliate in MST-8). Scientists from Tel Aviv University (Ishay Pomarantz, Itay Kishon) and Dresden HZDR (Anna Ferrari, Fondazione Cnao and Alejandro Garcia-Laso) completed the international team and explored novel neutron detectors. Targets and neutron time of flight detectors were provided by TU Darmstadt and NEN-1.

The staff from MST-8, P-27, and AET-6 set up detectors at Trident that were developed and that are used at the Los Alamos Neutron Science Center (LANSCE), aiming to characterize the laser-driven neutrons and demonstrate various applications. Vogel provided three detector panels from the HIPPO diffractometer to attempt to collect thermal diffraction spectra. Losko installed the FP5 thermal/epithermal neutron time-of-flight imaging detector to collect data for neutron absorption resonances and Bragg-edges. Nelson, Espy, and Hunter provided a high-energy neutron imaging detector. All of these detector systems are normally used at LANSCE beam lines and added substantial value to the Trident campaign. Such specialized detector systems would be otherwise unavailable. The neutron source was moderated for many of the shots to assess the ability to produce thermal and epithermal neutrons.

Figure 1 shows a fast neutron radiograph of various objects, selected to assess resolution and discriminate contributions from neutron and gamma radiation. The radiograph was taken with a single Trident laser pulse producing neutrons and gammas. Initial analysis of attenuation by a six-step polyethylene wedge, which attenuates neutrons far more than gamma rays, indicates that the image originates predominantly from neutrons. The line pair gauge, that was not well aligned, showed resolution better than 2 mm. Both the detector configuration and the geometry can be optimized for better resolution in future work. The picture quality was surprising to the team, surpassing previous results acquired at Trident [Roth et al., *PRL* **110**, 044802 (2013)], and may already be sufficient for some applications. The high penetrating power of energetic neutrons has been demonstrated at LANSCE, and laser-driven sources show the potential for compact energetic neutron sources.

Using the LANSCE thermal/epithermal energy-resolved imaging detector, resonances from an indium foil were visible in single pulses. This may allow measurement of the temperature in bulk materials from resonance broadening, as demonstrated at the ~1,000 times more intense LANSCE neutron source a decade ago [Yuan et al, *PRL* **94**, 125504 (2005)] This technique can provide a unique diagnostic tool for MaRIE.

Based on initial results, using intense short laser pulses to accelerate ions to energies sufficient for fast neutron production can provide focused, short pulse (<60 ns depending on time-of-flight) neutrons for applications. Such sources complement and may someday replace or even surpass large, expensive accelerators such as the LANSCE linear accelerator (LINAC). At present, the $>10^{10}$ neutrons/steradian generated in each pulse with Trident are equal to the number of neutrons produced with the first neutron spallation source ZING-P at ANL in the 1970s, which enabled construction of production neutron sources at IPNS, LANSCE, and ISIS (England) only a decade later (Figure 2, left – note that all these sources operate at 10-50Hz and flux is given per second). Because lasers are much more compact than linear accelerators and require less energy, this could eventually allow a compact pulsed neutron source to be deployed on a truck. The forward directed emission of neutrons reduces the radiation shielding needed for an installation, and the short pulse enables flash neutron radiography.

Because the investment cost of lasers is at least one order of magnitude lower than a LINAC, several lasers could be combined to make a neutron source of higher emittance than even today's most powerful neutron sources. The potential to combine several synchronized laser-driven neutron producing targets into a single intense neutron source could circumvent thermal problems of present neutron sources, enabling new neutron production target designs. Figure 2, right, shows the laser power of past and present intense laser sources and the resulting proton energies as well the proton energies for future laser sources. The Extreme Light Infrastructure ELI under construction in Europe is predicted to provide laser power that will accelerate protons to energies exceeding that of the LANSCE 800-MeV linear accelerator, shifting the neutron production into the regime of spallation, where ~20 neutrons per proton are produced (the neutron production mechanisms achieved with the energies at Trident produce one neutron per proton or deuteron). For MaRIE, several intense laser-driven neutron sources could generate sub-microsecond spaced neutron pulses to characterize different sample volumes at different times during a dynamic event, providing temperature and microstructure information from neutron absorption resonance broadening and Bragg-edges, respectively.

In the past decade, some of the physical effects occurring during the interaction of the laser pulse with the target material, which boost neutron production, were theoretically predicted in computer simulations on the Laboratory’s Roadrunner supercomputer and subsequently experimentally verified at Trident. The unique combination of experimental and theoretical laser and laser-plasma expertise, plus the neutron expertise existing at LANSCE, makes Los Alamos a unique place to develop laser-driven pulsed neutron sources from proof-of-principle to applications.

The MST-8, P-27, and AET-6 work has been funded as part of an initiative to assess if laser-driven neutron sources can be used for MaRIE (LANL Capture Manager, Cris Barnes). Development of neutron imaging detectors was funded by Enhanced Surveillance, Nuclear Energy, and a Laboratory capability development grant. After the closure of the Trident laser at Los Alamos, the activities will be continued at the German PHELIX laser system, where Prof. Roth has secured experimental time in 2017.

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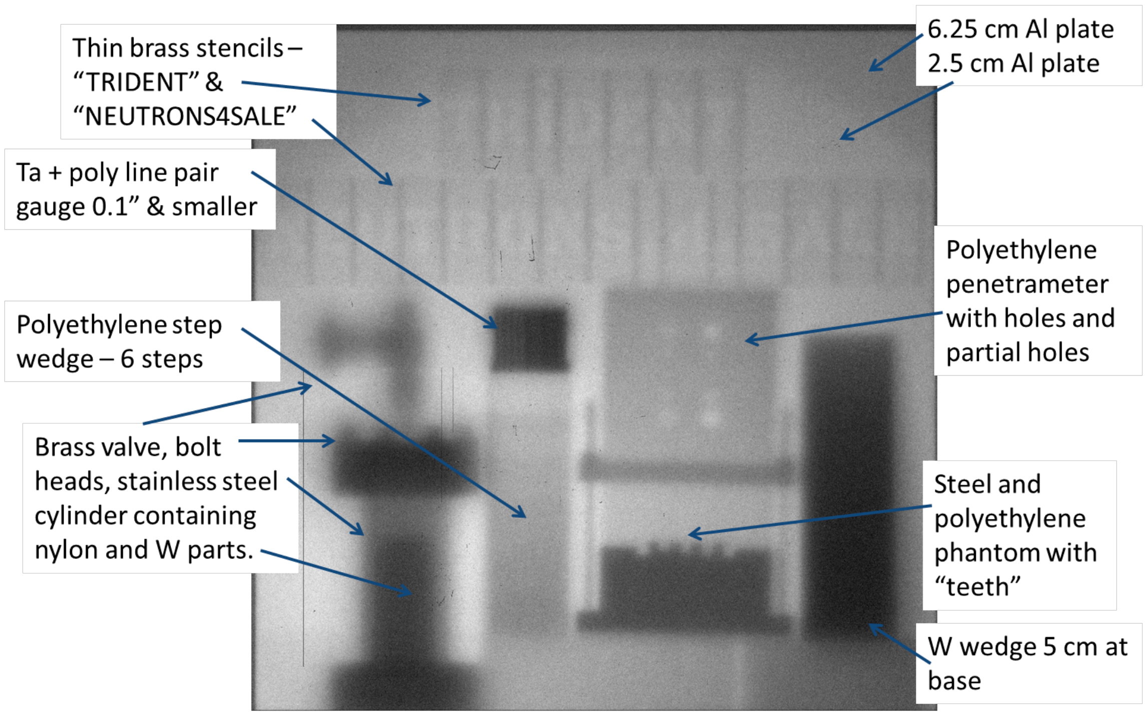
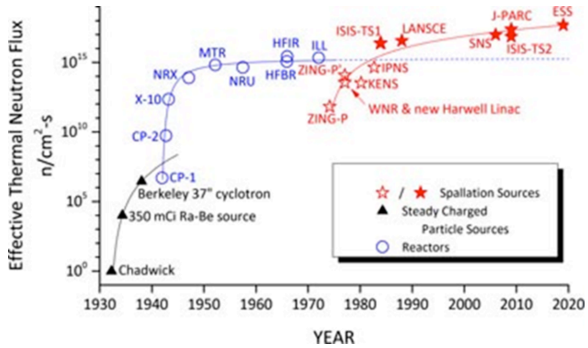


Figure 1: Radiograph from a single Trident shot viewing several objects. The objects chosen for this test reveal the resolution as well as the fraction of neutron versus gamma radiation detected by the imaging system. Initial analysis, e.g. of the image of the polyethylene step wedge, indicates that the detected signal originates predominantly from neutrons. The spatial resolution can be improved with changes in both the neutron converter screen in the detector and the geometry. The line pair gauge shows better than 2mm resolution for this proof-of-principle measurement.



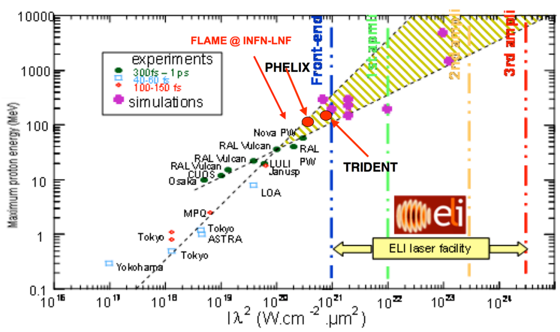


Figure 2, left: Evolution of neutron flux at various neutron sources over time [from: Mason et al., *MRS Bull*. **28**, 923 (2003)]. The 10^{10} neutrons/sr achieved per pulse at Trident are on par with the ZING-P spallation source, which paved the way to IPNS, ISIS, and LANSCE only a decade later. Right: Laser power and the resulting proton energy of past and current laser sources as well as the predicted proton energy for the European Extreme Light Infrastructure (ELI), currently under construction in Europe. When the ELI facility in Prague becomes available in a few years, proton energies exceeding the 800-MeV LANSCE accelerator will be possible. The investment cost for the ELI facility in Prague is 278 M€, including four high intensity laser sources. For comparison, the investment cost for the linear accelerator of the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory exceeded 1B$.