White Paper for *Frontiers of Plasma Science Panel*

Date of Submission:	***17 June 2015***

Indicate the primary area this white paper addresses by placing "P" in right column.
Indicate secondary area or areas by placing "S" in right column

	"P", "S"
• Plasma Atomic physics and the interface with chemistry and biology	P
• Turbulence and transport	P
• Interactions of plasmas and waves	P
• Plasma self-organization	P
• Statistical mechanics of plasmas	S

Indicate type of presentation desired at Town Hall Meeting.

	"X"
Oral	X
Poster	
Either Oral or Poster	
Will not attend	

Title:	The Omega Laser Facility: A High-Energy-Density-Physics User Facility
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(Limit text to 3-pages including this form. Font Times Roman size 11.
1 page of references and 1 page of figures may also be included. *Submit in PDF format.*)

- ***Describe the research frontier*** **and importance of the scientific challenge.**

The Omega Laser Facility at the University of Rochester's Laboratory for Laser Energetics (LLE) is the nation's most versatile and prolific high-energy-density-physics (HEDP) research facility. The Facility consists of two laser systems, OMEGA and OMEGA EP. The OMEGA Laser System became operational in 1995.[1] It consists of sixty 351-nm wavelength beamlines that can each produce energies up to 0.5 kJ in 0.1 to3.9-ns pulses with complex shaped temporal profiles. The beams are arranged symmetrically over the surface of a sphere in a truncated icosahedron pattern, similar to the carbon atoms in a Buckminsterfullerene molecule and to the vertices of a soccer ball. The OMEGA beams have sophisticated temporal and spatial "beam smoothing," a technology pioneered by LLE for solid-state lasers. Flexible pulse shaping, pulse delays, and pointing configurations allow for a large variety of HEDP experiments to be performed, including those exploiting optical, x-ray, and particle probes. The OMEGA EP Laser System was completed in 2008.[2] It consists of four NIF-like beamlines [3] that can be configured in various ways. Each beamline can produce up to 6.5 kJ of 351-nm light in 0.1 to 10-ns pulses. The beamlines can have different pulse shapes and arbitrary temporal separations. They are incident on a planar target 23° from its normal. Two of the beamlines can be operated in chirped pulse amplification (CPA) mode.[4] In this case, the 1053-nm wavelength beams can have pulse durations of 0.7 to 100 ps, with ~2 kJ each in a 10-ps laser pulse with a prepulse intensity contrast of greater than 10^9. The beams can be propagated normal and/or tangent to the planar target surface in the OMEGA EP target chamber, or co-propagated to the OMEGA EP or OMEGA target chamber. The peak intensity exceeds

10^{21} W/cm^2. The two lasers comprising the Omega Laser Facility produce approximately 2000 target shots in a typical year, while operating at 80% of full capacity. Both facilities are extensively diagnosed with a wide range of optical, x-ray, and particle (ions, electrons, and neutrons) diagnostics. Externally applied magnetic fields exceeding 10 T can be used in experiments.

The Omega Laser Facility is operated by LLE as an HEDP User Facility for National Nuclear Security Administration's (NNSA) Office of Inertial Confinement Fusion. Approximately 2/3 of the target shots are devoted to programmatic research that supports NNSA's Stockpile Stewardship Program. The remaining shots are available for fundamental science research. There are two peer-reviewed programs, the National Laser Users Facility (NLUF)[1] and Laboratory Basic Science (LBS).[2] The NLUF program began in 1979 to provide access for University/Business Users. The solicitation is managed by NNSA. NNSA provides research funding to the NLUF participants to cover some of the incremental costs of performing experiments using Omega (e.g. travel, etc.). In FY15, this funding is $1.6 million. NNSA also provides funding for targets. LBS, started in 2008, provides fundamental science access to Omega for scientists at NNSA's weapons laboratories and LLE. This allows non-programmatic (e.g., LDRD) experiments to be performed using Omega. There is no additional funding for the LBS program. There is no charge to the Users for the cost of the Omega shot time and operational staff support for either the NLUF and LBS programs.

Fundamental Science experiments using the Omega Laser Facility span the HEDP phase space [5] including questions related to astrophysical phenomena such as the origin of galactic magnetic fields and the nature of gamma-ray bursters, the properties of solar and extrasolar planets, the properties of materials under extreme conditions such as warm dense matter, hydrodynamic and magnetohydrodynamic instabilities, laser-plasma interactions, relativistic laser-plasma interactions, energetic particle generation, nuclear physics, and development of new capabilities for HEDP experiments. The breadth of HEDP research being performed on the Omega Laser Facility can be seen in LLE's Annual Reports.[3] While it is not possible to provide a comprehensive summary, two examples are provided below.

The development of the galactic magnetic fields is not fully understood. It is assumed that they grow as a result of the magnetic dynamo, but the origin of the seed fields is unknown. One possible source is the development of fields during the nonlinear stages of the Rayleigh-Taylor instability through the Biermann Battery effect.[6, 7] Experiments on OMEGA [8, 9] and OMEGA EP [10-12] have observed the development of magnetic fields during the nonlinear evolution of the Rayleigh-Taylor instability. Figure 1 shows a late-time proton radiograph of a target driven into the nonlinear phase of the Rayleigh-Taylor instability. The structure shows the magnetic fields wrapped around the bubbles and spikes.[10] The bubbles grow and merge as was independently observed with x-ray radiography.[13]

One possible origin of gamma-ray bursters is the recombination of electron-positron plasmas. A series of experiments, carried out, primarily on OMEGA EP, have developed a platform that produces a beam of quasi-monoenergetic relativistic positrons.[14-19] Figure 2 shows a positron energy spectrum that was produced using a 1 kJ, 10 ps OMEGA EP beam interacting with a solid gold target. The conversion efficiency from laser energy to positron energy was 0.3%. The positron beam is created by target normal sheath acceleration.[20] The addition of axial magnetic field focused the positrons and co-moving electrons, leading to a beam where the electron and positron densities are nearly equal.[19] The next step will be to magnetically trap this beam, creating a relativistic electron-positron plasma.

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[1] http://www.lle.rochester.edu/about/nluf.php
[2] http://www.lle.rochester.edu/media/documents/laboratory_basic_science.pdf
[3] http://www.lle.rochester.edu/publications/annual_report/

- ***Describe the approach to advancing the frontier and indicate if new research tools or capabilities are required.***

The self-organized Omega Laser Facility Users Group (OLUG),[4] with more than 400 members from 55 Universities and 35 centers and national laboratories, was founded in 2008. It holds an annual 2½-day workshop at LLE in the spring. One of the goals of the workshop is to develop a set of findings and recommendations to improve Omega as a User Facility. This often includes capability improvements (operational issues, laser, and diagnostics) that will enhance the research opportunities for the Users. Some of the recommendations can be found by following the link in footnote 4. Unfortunately, many of these requests require funding beyond that provided by NNSA for the facility. For example, OLUG has requested that LLE provide dedicated "beamline scientists" who would help Users develop their experiments, including providing simulation and experimental support. This would include opportunities for external scientists and graduate students, including those not familiar with HEDP facilities, to work with LLE scientists to develop proposals for the fundamental science programs. LLE submitted a proposal to OFES to create such a program, but the Joint Program in High Energy Density Laboratory Plasmas did not fund it. This capability would greatly benefit, facilitate, and expand the HEDP community.

The capabilities of the Omega Laser Facility could be greatly expanded by using two OMEGA EP beams to pump an optical parametric amplifier line (EP OPAL).[21] This system could be housed within the current OMEGA EP laser building. EP OPAL is predicted to produce 1.6 kJ in a 20-fs duration laser pulse that would provide a focused laser intensity of ~10^{24} W/cm^2, an order of magnitude higher than proposed for the first stage of the billion-dollar-scale Extreme Light Infrastructure (ELI) that is being constructed by the European Union.[5] The intensity contrast is expected to be greater than 10^{10}. An advantage of this system is that the two remaining long-pulse 351-nm or short-pulse 1053nmnm OMEGA EP beams would be available for target conditioning or pump-probe experiments (shown schematically in Figure 3). The proposed system would be world-leading in areas such as attosecond physics, x-ray source generation, tests of quantum electrodynamics, electron and ion acceleration, and THz wave interactions with matter. With the emphasis on fundamental science, the system would provide an opportunity for the Office of Science to retake the world leadership in high-intensity laser-matter interaction experiments.

- ***Describe the impact of this research on plasma science and related disciplines and any potential for societal benefit***.

The Omega Laser Facility provides a broad impact on HEDP, with many significant advances, as described above. In addition to the multitude of experiments that are performed, the Facility provides an important training ground for HEDP graduate students and postdocs. Many of the young PhD's, from the University of Rochester and the universities participating in NLUF, are hired by the nation's nuclear weapons laboratories, providing the workforce that will support the Stockpile Stewardship Program, an important societal benefit. In addition, the science and technology associated with HEDP research has numerous applications outside of fundamental plasma science. Examples include the development of extreme ultraviolet lithography (EUV) that originated from HEDP research; the development of ultrahigh brightness lasers for a wide range of applications including laser accelerators and novel radiation sources for material interrogation, "femtosecond" precision machining, and numerous national security applications related to directed energy such as high-power solid-state lasers and high-performance, damage-resistant optics.

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[4] http://www.lle.rochester.edu/about/omega_laser_users_group.php

[5] http://www.eli-laser.eu/

Figures (maximum 1 page)

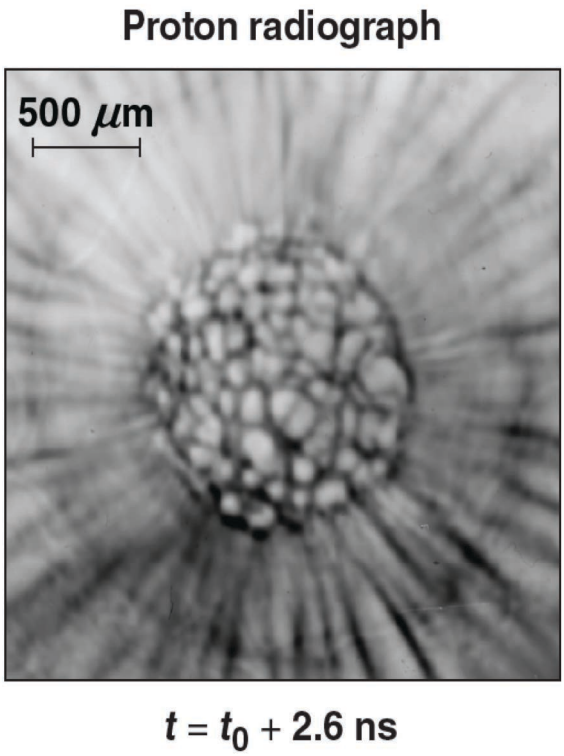

Fig. 1: Proton radiograph showing magnetic field generation during the nonlinear phase of the Rayleigh-Taylor instability (from Ref. 10).

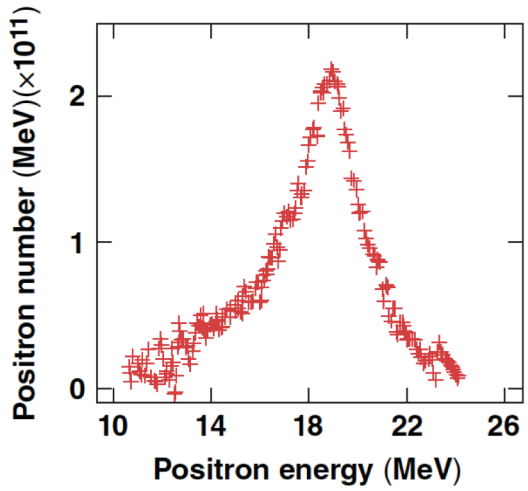

Fig. 2: Positron energy spectrum resulting from an OMEGA EP beam interacting with a mm-thick gold target.

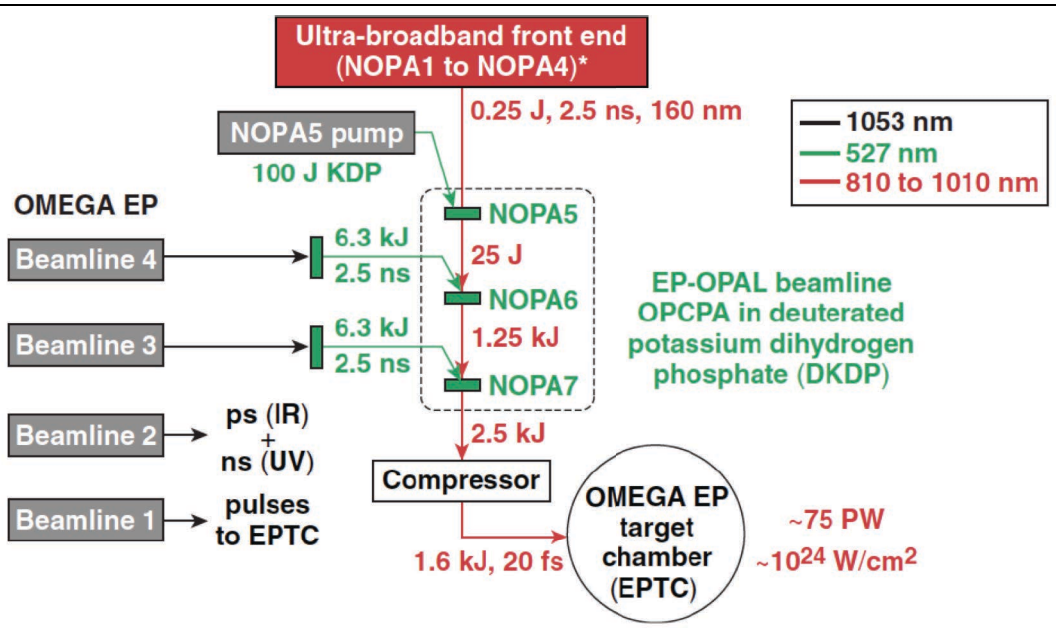

Fig. 3: Schematic of potential ultrahigh-intensity laser system pumped by OMEGA EP. (NOPA is noncollinear optical parametric amplifier.)

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