White Paper for *Frontiers of Plasma Science Panel*

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Title:	Harnessing Relativistic Laser Plasmas to Generate Intense Ion Beams
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Harnessing Relativistic Laser Plasmas to Generate Intense Ion Beams: A Plasma Science Frontier White Paper LA-UR-15-24654

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Los Alamos National Laboratory June 19, 2015

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

Optical lasers with high intensity (> 10^{19} W/cm^2), high power (> 100 TW) and high energy (> 50 J) are enabling research that is expanding the frontiers of physics. Some of the research opportunities and importance are described in several reports.[1,2,3] Here we highlight a prominent one: harnessing relativistic laser plasmas to generate intense ion beams, much more intense than it is possible with conventional particle-acceleration technology[4,5,6]. This topic is important in two ways. On the one hand, it represents exceedingly exciting science in plasma physics and extreme electrodynamics (i.e., "high-field" physics[7]). On the other hand, it enables advanced technology for advancing other fields of science, for societal applications (e.g., fast ignition[8]) and for national defense. There are tremendous opportunities for continued progress in existing laser facilities in the US (with laser intensities up to ~ 10^{21}W/cm^2, such as the Trident Laser Facility) provided modest funding support and reorientation of these lasers as national user facilities. Longer term, there are also great scientific opportunities for the US by extending our capabilities to intensities of ~ 10^{22} W/cm^2 and beyond with shaped laser pulses of intermediate duration (~ 100 fs), to complement high intensity, shorter pulse length lasers planned worldwide. Such a complementary US facility would in fact excel in the ion-beam generation mission proposed here. At ~ 10^{22} W/cm^2 and beyond, besides meeting the requirements for important societal applications of intense ion beams, novel high-field physics[7] becomes important and amenable to study. That includes e.g., radiation self-force for electrons, and direct coupling of the laser to the ions (not just to electrons and then indirectly to the ions). These new physics in turn may open new technological opportunities, such as x-ray[9] and gamma-ray-beam sources and new ion-acceleration mechanisms.

It is hard to overstate the impact of particle accelerators starting in the last century to the present. Accelerators have had profound impact in society, both as a key enabling experimental tool for the modern scientific edifice, as well as for societal applications such as cancer therapy. Conventional accelerator technology is bumping against two main limitations. One is particle energy (at a reasonable size and cost) rooted in the ~ 25 MeV/m gradient limit from electrical breakdown of conventional accelerator structures. The second is beam intensity, limited by current and space-charge stability of conventional (non-neutral) particle beams. The former issue is being addressed in ingenious ways by "dielectric accelerators" which use high-power, low-energy lasers to set up transient-high fields in dielectric microstructures. These devices promise to advance the state of the art in acceleration gradients, but of course cannot address the intensity limitations. Ultimately, the highest performance is going to require a plasma as the acceleration medium. Plasmas can support the highest accelerating potential gradients and the highest currents. Moreover, by delivering neutralized beams (ions co-moving with unbound electrons), the usual current and space-charge limits can be circumvented. Realizing the highest ion energies and intensities requires a high-power density source to drive the system. Intense, high-power, high-energy lasers represent an ideal drive source, provided the physics can be understood and controlled, i.e., a challenge proposed here. To meet that challenge, the science community can build on the significant progress over the last decade, experimentally, computationally and theoretically.[4,5,6]

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

As mentioned above, while many scientific opportunities are accessible with existing laser facilities, additional great scientific opportunities for the US become accessible by extending our

capabilities to intensities of ~ 10^{22} W/cm^2 and beyond *with* shaped laser pulses of intermediate duration (~ 100 fs). Such a unique US facility would complement other high intensity, shorter pulse length lasers planned worldwide. Such a complementary US facility at ~ 10^{22} W/cm^2 and beyond, would in fact excel in the ion-beam generation mission proposed here by meeting the requirements for important societal applications[4] and accessing novel high-field physics.[7]

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

An important societal application of these intense laser-driven ion beams is in fact squarely aligned with the fusion mission of Fusion Energy Science. These beams represent a promising and relatively untested route for Inertial Fusion Energy (IFE), specifically by demonstrating the ion beam parameters needed for high-gain, high-yield Fast Ignition (FI) of a suitably compressed DT fusion capsule[4,8]. The National Ignition Facility has delivered the necessary fuel compression but has not succeeded yet in creating the ignition hot spot. Leveraging that demonstrated capability of fuel compression, the research thrust proposed here would enable the missing piece to demonstrate DT fuel[4] ignition in the laboratory. It is well worth noting that at the LANL Trident laser, with high-intensity (10^{21} W/cm^2) but modest laser energy (~ 70J), a C-ion beam has been demonstrated[10] with the required energy spread, with half the ion energy (~ 220 MeV) and half the laser-ion conversion efficiency (5%) needed for FI.

The IFE mission is only one (albeit very important) programmatic application and societal benefit of the overarching scientific thrust proposed here. FI is in fact an extreme application of the isochoric heating technique, which allows the creation (experimental "initialization" if you will) of extreme states of matter by rapid, homogeneous bulk heating of a sample at constant density in order to field unit-physics experiments in controlled conditions. Ability to heat matter isochorically without introducing sharp gradients differs fundamentally from existing capability at NIF or Z of compression to high densities. Isochoric heating may be done all the way to warm dense matter (WMD) conditions, to probe its transient properties (transport, EOS, etc.). Important unsolved problems in plasma physics that are ripe for study with these capabilities include the basic properties of WDM (especially with ion mixtures), planetary physics, the evolution of particulates in WDM (such as in comet tails, tokamak limiters and imploding ICF capsules) and plasma-effects that enhance mixing of sharp, heterogeneous interfaces besides simple diffusion. Such ion beams are also useful to uniformly heat solid and liquid samples for exquisite control in dynamic material experiments (e.g., EOS or phase transition measurements) of interest to the shock physics and materials research communities. In general, whether for study of plasmas or dynamic materials, combining isochoric heating with conventional loading techniques (Hugoniot, isentropic, etc.) allows access to a much broader region of phase space than is possible with conventional loading alone. Intense ion beams may enable compact accelerators for cancer therapy that are affordable by regional medical centers. They have enabled new, high-energy, highly directional neutron sources[11] capable of depositing well over 100 neutrons /μm^2 within ~ 1 ns at energies in the tens of MeV range, with great potential for material science, nuclear physics, active interrogation to detect the surreptitious transport of fissile material, and scientific experiments for stockpile stewardship. Besides neutrons, laser-driven proton and ion sources are themselves directly useful and strong candidates for these missions as well.

References:

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