White Paper for *Frontiers of Plasma Science Panel*

Date of Submission:	19 June 2015

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Oral	X
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Title:	Laser Plasmas at the Irradiance Frontier
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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 irradiance accessible by ultra-short pulse laser facilities is approaching a level where significant new scientific challenges and opportunities emerge. During the last few decades, enormous advances were made in understanding relativistic laser-plasmas through a potent combination of advanced ultrashort pulse laser facilities and high performance computing capabilities. Some notable experimental achievements include observation of relativistic photoelectrons [1,2], generation of GeV class monoenergetic electrons [3,4,5], demonstration of all-optical betatron and Thomson x-ray sources [6], hot electron generation and enhanced neutron yields in solid targets [7], and laser acceleration of ions [8]. In many cases particle-in-cell simulations played a major role in either predicting or explaining the observed phenomena [9,10]. Early efforts were limited to one or two-dimensions or cartoon scale problems, whereas nowadays many experiments can be simulated at full scale in three dimensions.

The aforementioned relativistic regime has been investigated in a range of laser irradiance, I, between 10^{18} and 10^{21} W/cm^2, although the frequency of experiments is weighted strongly toward the lower irradiance end. Now that multi-PW lasers are under construction [11], exposing matter to $I = 10^{22}$ W/cm^2 and beyond can be seriously contemplated ($I > 10^{22}$ W/cm^2 has been achieved with sub-PW lasers [12], but the delicate focusing required tends to preclude illuminating any target other than vacuum, because of

prepulse effects). Some important opportunities and challenges associated with this new regime are as follows.

- Protons respond directly to the laser field. Although ion motion is frequently observed in the current state of the art, such motion is a result of secondary plasma fields due to the laser-electron interaction. For $I \sim 10^{23}$ W/cm^2, the quiver velocity of a proton in a near infrared radiation field becomes weakly relativistic, and ponderomotively driven ion motion results. Considering that this motion may be accompanied by collective plasma effects, the possibility of a new class of laser-plasma interaction presents itself. Note also that the ponderomotive force scales with the square of the charge, so that motion of heavy ions in a high charge state is also possible. These effects may have implications for various laser driven ion acceleration schemes.
- Radiation reaction cannot be neglected. Almost all theoretical and numerical treatments of laser plasmas neglect the recoil force on an electron when it radiates. This issue is intensely interesting because of the difficulties associated with formulating a satisfactory theory of radiation reaction. These difficulties touch on the fundamental structure of the electron as a point particle. The radiation reaction effect becomes important at the intersection of high irradiance and high electron energy, e.g., $I \sim 10^{23}$ W/cm^2 and $\gamma = 100$, with γ the relativistic Lorentz factor of the electron. Experimental observation of the radiation reaction effect is an opportunity of fundamental significance.
- New regimes of laser-ion interactions appear at the atomic scale. The extent to which a laser-ion interaction is relativistic depends on the residual charge of the ion, Q, and the normalized vector potential of the laser, a. The bound state is non-relativistic for $Q/e << 137$, and the free state is non-relativistic for $a << 1$. In the present state of the art, only the free-state side of the interaction is relativistic, since for near infrared wavelengths, the highest charge state than can be perturbed (e.g., ionized) using sub-PW class lasers is about $Q/e = 10$. For $I \sim 10^{23}$ W/cm^2, present theories predict that fully stripped krypton can be produced, i.e. $Q/e = 36$. For $I \sim 10^{25}$ W/cm^2 fully stripped gold can be produced, i.e. $Q/e = 79$.
- Effective vacuum acceleration of electrons becomes viable. Either by externally injecting electrons into an extreme irradiance laser focus [13,14], or by stripping them from high charge state ions via tunneling ionization [15], electrons can be accelerated to GeV energies, in a directional beam, using vacuum fields alone. The process occurs in a new, highly nonlinear, non-ponderomotive regime of electron trajectories in a vacuum laser field.
- As I is advanced into more speculative regimes, even more exotic effects begin to appear such as vacuum polarization, field induced pair production, and others.

These phenomena, and others, are likely to emerge in the coming decade as multi-PW laser systems are constructed around the world. Considerable effort is needed in both experimental and theoretical/numerical areas to advance the understanding of laser-plasma interactions in the ultrarelativistic regime.

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

In order to advance the frontier of ultrahigh irradiance laser plasma interactions, several experimental and theoretical challenges have to be met. Clearly, the peak power available at the world's ultrashort pulse laser facilities has to continue advancing. The commissioning of the 10 PW beamlines at the Extreme Light Infrastructure, Nuclear Physics (ELI-NP) facility in Bucharest, Romania, is projected for 2017. At present, no plans to construct a similar facility in the U.S. are known to us.

The technology to manipulate extremely high power beams needs further development in order to foster effective utilization of available laser power. Conventional optics will be meter-scale (in order to stay

below the damage threshold), resulting in lack of flexibility in focusing configurations, and increased mechanical requirements for laboratory infrastructure. Novel concepts such as plasma optics may help mitigate some of these issues. The effect of the prepulse is also likely to play a major role in experiments at the irradiance frontier. Better understanding the origin of the prepulse may require improved modeling of the ultrashort pulse laser system itself. Part of the prepulse mitigation strategy should also be to understand the effect of the prepulse on a given target through full-scale simulations or suitable experimental diagnostics. Plasma optics may play a role in mitigating prepulse effects.

The simulation tools conventionally used to model laser-plasma interactions, such as particle-in-cell codes, may require significant modification in order to be effective in the regime of extreme irradiance. In an ultrarelativistic laser field, electrons experience violent turning points, which make the splitting of electric and magnetic impulses in a conventional particle pusher ineffective. The straightforward remedy is to use much smaller time steps, but naturally this comes at the price of correspondingly longer computation time. New algorithms may be required in order to achieve high accuracy with reasonable efficiency. Effective computer codes will likely have to utilize advanced computing architectures that employ some form of hardware acceleration (e.g., graphical processing units).

In cases where relativistic ionization physics is important, it is desirable to have the capability of carrying out ab initio modeling of the ionization process itself. This requires treating a large scale separation, namely that between the Compton wavelength, ~ 10^{-12} m, and the wavelength of the laser radiation, ~ 10^{-6} m. Here again, efficient algorithms that take advantage of advanced computing architectures are needed. Moreover, interpreting the results in a way that usefully informs the inputs to classical particle codes is a non-trivial task. Unconventional concepts such as Bohmian trajectories could be used to connect the quantum and classical regimes [16].

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

Research at the irradiance frontier has potential impact in several diverse areas. Laser driven particle acceleration and heating is one of the primary outcomes of ultra-intense laser-plasma interactions, and is of interest to both the accelerator community and the fusion energy community. Laser driven particle acceleration is a potential path toward reducing the size and cost of accelerators for high energy physics. Directional particles at somewhat lower energy, whether electrons or ions, driven by ultra-intense laser pulses, are of interest in connection with the fast ignition concept. Research at the irradiance frontier also impacts physics at the atomic level, especially where extreme fields perturb or ionize relativistically bound inner shell electrons of high-Z atoms or ions. An improved understanding of the nature of the fundamental relativistic wave equations describing spin zero or one-half particles would fall out of this research.

This research might lead to advanced techniques for producing high energy particles, which have numerous applications. Electron or ion beam generation in solid targets has applications for inertial fusion energy. Laser driven proton beams could be useful for cancer therapy. High energy electrons are useful for advanced light sources, which if made compact could be useful for threat detection applications.

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Figures (maximum 1 page)

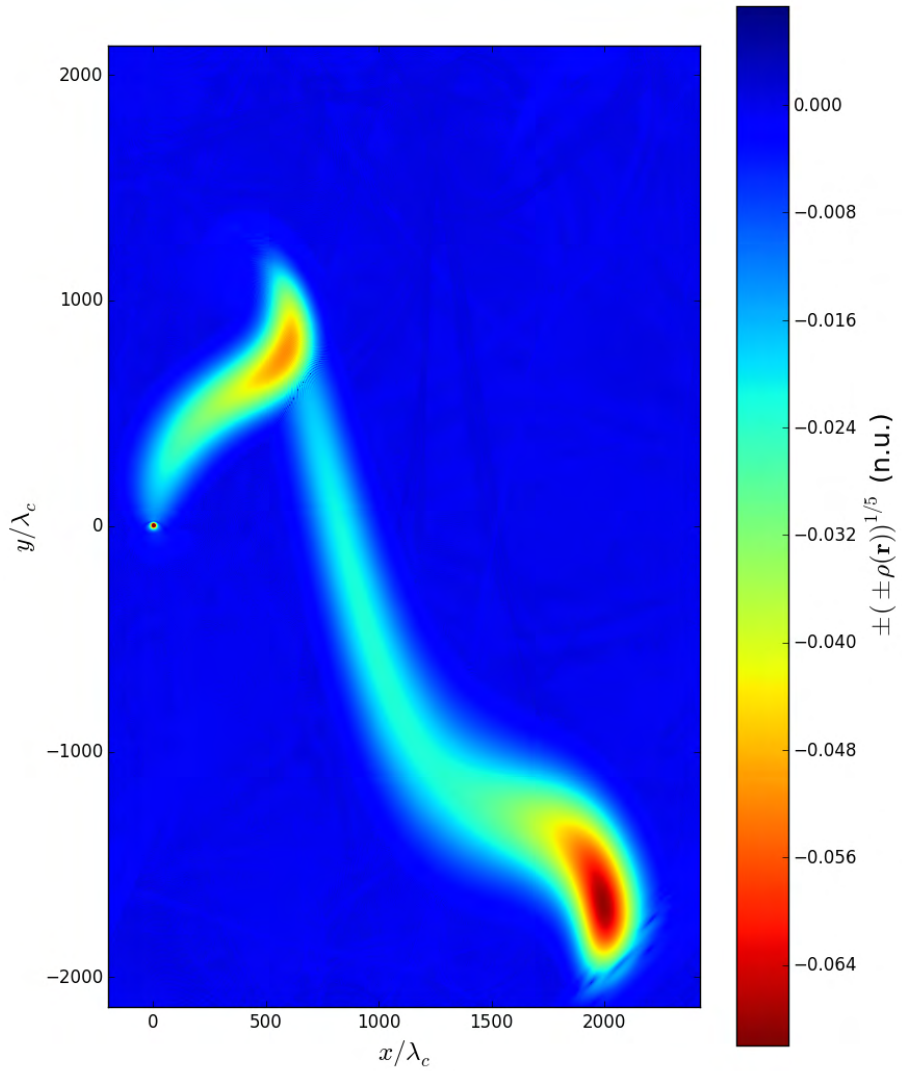

Fig. 1: Ab initio simulation of tunneling ionization of hydrogen-like xenon by a relativistically intense 1.2 nm x-ray pulse, according to the Klein-Gordon equation. The false-color scale represents the relativistic scalar analog of probability density, which is signed. The radiation field propagates in *x*, and is polarized in *y*. The small round feature near the origin is the residual ion. The much larger curving features are the two wavepackets emitted at subsequent peaks of the incident electric field. Because of the very large ionization potential of hydrogen-like xenon, tunneling ionization occurs even for x-rays. The simulation was carried out on a small cluster of graphical processing units. Similar modeling with optical wavelength radiation would require significantly greater computing resources.