White Paper for *Frontiers of Plasma Science Panel*

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Title:	High Intensity Laser-Plasma Interactions
Corresponding Author:	Richard Freeman
• Institution:	The Ohio State University
• email:	Freeman@physics.osu.edu
Co-Authors:	Douglass Schumacher

(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.**

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

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

High Intensity Laser-Plasma Interactions

D.W. Schumacher and R.R. Freeman
The Ohio State University

Background (Frontier and Importance)

This white paper addresses the physics of one of the fundamental problems in the experimental study of modern plasma physics: *the interaction of intense laser light with a plasma*. Hot electrons generated via the intense laser plasma interaction (LPI) initiate virtually all laser high energy density physics (HEDP) experiments and proposed applications. The study of the LPI is of fundamental interest to the plasma science community because the ultrahigh intensity laser-plasma interaction involves high temperatures,[1,2,3] enormous fields,[4] and steep gradients and the behavior of matter in this regime is exciting and not well understood. Study of the laser-plasma interaction in dense plasmas has led to the observation of dramatic and useful effects including the generation of large numbers of relativistic electrons,[5] the acceleration of electron pulses using wake fields,[6] the generation of short pulsed, MeV to GeV, ion beams via target normal sheath acceleration as well as more exotic mechanisms,[7,] and the creation of dense clouds of positrons via the Bethe-Heitler effect.[8] In turn, these effects are being considered for the role they may play in a wide range of applications and studies: cancer treatments, interdiction of nuclear materials across national borders, positronium physics, and laboratory astrophysics.

Although they play a crucial role in many envisioned applications of HEDP and have long been a focus of experiment and theory, truly fundamental and important aspects of the hot electron generation process are still not well understood. Indeed, the nature of the distributions of these electrons, both in energy and space, remains the subject of numerous published studies each year, yet there remains considerable controversy and debate concerning the role of the many physical processes involved. This is especially true concerning the explanation for the observation of the significant numbers of "superhot" electrons with energies well in excess of the ponderomotive, or Wilks, temperature, in plasma interactions of lasers with intensities greater than ~10^{18} W/cm^2; an intensity that roughly marks the boundary of relativistic interactions for the lasers currently in use.

Here we argue that a new emphasis on a systematic understanding of LPI is not only required to advance the field of laser plasma physics, but that recent advances in experimental technique,[9,] laser design,[10] and numerical modeling[11]provide a new opportunity to re-examine this problem. The emergence of high intensity lasers with clean pulses and relatively large repetition rates means that systematic measurement over a large range of laser and target conditions is no longer prohibitive and meaningful comparisons between experiments can be made.

The nature of the initial electron distribution encompasses two issues: (1) propagation of the laser through the pre-plasma (always present at some level) until it is absorbed and (2) subsequent generation of fast electrons. The laser-plasma interaction causes the laser beam to change shape spatially and temporally due to interactions such as laser modification of the index of refraction. In turn, the laser modifies the density and temperature profile of the plasma itself as gradients in the laser electromagnetic field push plasma particles.[12] The plasma-modified laser and the laser-modified plasma continue to interact until the laser is either absorbed or reflected. There are many absorption mechanisms (e.g. collisions, vacuum heating, resonance absorption, JxB heating) that assume different relative roles that vary with intensity,

density, and the density gradient.[13,14] Most absorption processes are angle dependent as well and, due to laser modification of the critical surface, the laser electric field will intersect the critical surface at a range of angles. The initial distribution of electrons formed in the pre-plasma has been the subject of intense scrutiny.[15] Current estimates of laser energy conversion into hot electrons, exceeding 1 MeV, range between 10% and 50% with the most likely value believed to be near 25%.

The initial electron distribution will propagate away from the critical surface into the target, typically with very large current densities. Large electric and magnet fields, of order GV/cm and MGauss, respectively, arise due to a wide variety of processes: the large current of the accelerated electrons; scattering of the return current of cold electrons; diffusion of electrons due to gradients in laser intensity, temperature and density and effects associated with spatially varying resistivity in the medium. These fields will greatly modify the distribution initially created by the laser both in energy and angle. As the electrons travel through solid density, the target heats up changing the ionization state. This leads to a space and time varying target charge state and, hence, a varying collision rate. Collisions with background ions and electrons dramatically change the phase space of the laser heated electrons. This will continue well after the laser pulse has been absorbed or reflected. There have been numerous efforts to obtain simple measures of the resulting electron distribution, most notably, the divergence angle of the hot electrons. These methods include thermal imaging of the front or back faces of the target, K_α imaging of fluors buried inside the target,[16,] and measurement of coherent and incoherent transition radiation.[17] Together, results span a range of inferred laser-source divergence half-angle between 20° and 90°. Much as in the measurements of conversion efficiency, the inherent complexity of the interactions complicates attempts at simple interpretations.

Approach:

With the availability of much larger computers and the increasing confidence in massive parallel PIC computing codes (e.g., EPOCH, LSP, OSIRIS, PICLS, PSC, VLPL and still others), along with recent development of clever algorithms that enable implementation of 3-D simulations, it is now realistically possible to *predict* quantitatively the outcome of well-planned laser plasma experiments. To be clear, since the physics of these interactions is so complex and so dependent upon approximations describing the targets, the likelihood of quantitative agreement is currently modest. That is the starting point. This newly developed ability to realistically treat full size targets and laser pulses and to include rich physics models permits calculation of the properties of the laser-electron/ion interactions. Comparison to experiments that can be carried out on extremely well characterized lasers at high repetition rates and hence with excellent statistics with associated fully understood diagnostics will make it possible to isolate those issues in the overall LPI problem that are the most problematical. The advent of high repetition rate lasers has not been fully taken advantage of nor has the now available suite of laser and plasma diagnostics. Finally, simulation code comparisons, common in other fields, are not typical in HEDP. The proposed approach amounts to a systematic experimental analysis of LPI physical processes leading to clear, precise 3-D simulations of realistic experiments.

Impact:

The field of laser plasma physics is now at the threshold of moving from one dominated by phenomenology to one of prediction and subsequent experimental verification or rejection. Such a transition is required for any field to make the large strides in understanding that can yield large returns in new applications and enhancement of old ones. A prime example is the now 20 year old dream to have laser driven ions replace the enormously expensive accelerator-driven ion source in cancer therapy: with a concentrated program of simulation and experiment, this dream could be realized.

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