Laser-Plasma Acceleration of Electrons and Plasma Diagnostics at High Laser Fields

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Abstract: Laser-plasma acceleration is now entering an era of petawatt lasers, tenuous plasmas and multi-GeV electron energies. I will review initial results in this regime, and discuss plasma diagnostics needed to understand, optimize and scale them.
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1. Introduction

30 years ago, Tajima and Dawson proposed the idea of accelerating charged particles by surfing them on charge density waves propagating at light speed through underdense plasma in the wake of an intense ultrashort laser pulse [1]. Such wakes sustain space charge fields of GV/cm, thousands of times above the breakdown threshold of conventional accelerators, opening the possibility of thousand-fold smaller accelerators. Two decades of intensive experimental research, enabled by the wide availability of terawatt (TW)-class fs lasers starting in the early 1990s, has yielded a generation of self-injecting laser-plasma accelerators (LPAs) of only centimeter length [2] that have produced nearly monoenergetic electron bunches with energy as high as 1 GeV [3]. Scaling these compact accelerators to multi-GeV energy would open the prospect of building x-ray free-electron lasers and linear colliders hundreds of times smaller than conventional facilities, but until recently the 1 GeV barrier proved insurmountable.

Petawatt (PW) laser technology is now opening the era of multi-GeV LPAs. PW pulses inject plasma electrons into the laser-driven accelerator structure at much lower density ($n_e < 10^{18}$ cm^{-3}) than was possible with TW drivers, thereby overcoming the principal barriers to multi-GeV acceleration: dephasing between accelerating electrons and wake and erosion of the prow of the laser pulse by the plasma [4]. With PW drivers, self-injection has been observed at plasma density as low as $n_e = 10^{17}$ cm^{-3} [5], and electrons have been accelerated quasi-monoenergetically up to 2 GeV with unprecedented sub-milliradian angular divergence [6]. Yet this is clearly only the beginning. Simulations predict that PW pulses of currently available parameters are capable of accelerating electrons quasi-monoenergetically to nearly 10 GeV with negligible dark current [7]. Specialized injection and plasma waveguide techniques that have improved beam quality and reliability in sub-GeV LPAs have yet to be exploited in the multi-GeV regime. New laser technologies offering PW peak power together with kW average power are under development. Conversion of multi-GeV LPA beams to coherent, ultrafast x-rays, demonstrated on lower energy LPA beams, is yet to be explored. Advanced plasma diagnostics that enable direct 4D spatio-temporal visualization of the plasma structure and accelerating electrons will be critical in guiding us into this exciting future.

2. Initial multi-GeV PW-laser-driven plasma accelerator results

Figure 1 shows a typical result from a recent demonstration of quasi-monoenergetic, self-injected PW-laser-driven plasma acceleration of electrons to 2 GeV [6]. This represents the most energetic and most highly collimated quasi-monoenergetic electron bunch yet produced by an LPA, and the lowest density at which self-injection was achieved.

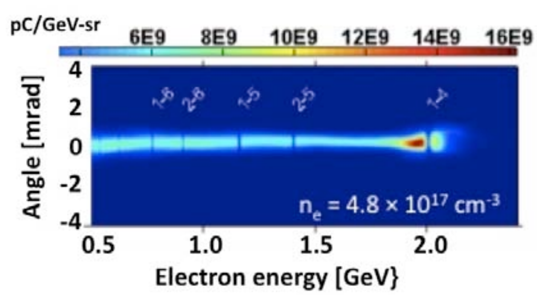

Fig. 1. Magnetically-dispersed electron spectrum recorded on imaging plates located 2.5 m downstream from a 7 cm long pure He plasma of electron density $n_e = 4.8 \times 10^{17}$ cm^{-3} driven by a 100 J, 150 fs, 1 μm laser pulse. The quasi-monoenergetic feature at 2.0 ± 0.1 GeV has energy spread ΔE/E = 0.05, 60 pC charge, and 0.5 mrad angular divergence. The dark vertical lines are shadows of precisely positioned tungsten wire fiducials placed in the electron dispersion region for the purpose of calibrating the magnetic spectrometer.

At the same time, this example illustrates the work still remaining. The 2 GeV energy, though record-setting, falls well short of ~4 GeV predicted for these nominal laser-plasma conditions, and ~7 GeV for a drive pulse of twice the power [7]. Moreover, the quasi-monoenergetic feature is accompanied by an undesirable background of lower energy electrons, and is broader ($\Delta E/E \sim 5\%$ FWHM) than desired for many applications. These shortcomings are closely tied to self-injection physics governed by subtle dynamics of the laser-driven plasma accelerator structure. The ability to see these structures directly will play a critical role in future development of multi-GeV LPAs.

3. Spatio-temporal visualization of laser-driven plasma structures

Details of evolving laser-driven plasma structures are traditionally known only through intensive computer simulations based on estimated initial conditions. I will review recently developed methods for visualizing such objects directly in the laboratory. Frequency-domain holography (FDH) --- a technique in which the object modulates a co-propagating probe pulse --- has yielded detailed snapshots of linear [9] and nonlinear [10] plasma wakes, but averages over their evolution as they propagate. Transverse shadowgraphy has yielded multi-shot movies of evolving wakes [11], but averages over transverse structure and shot-to-shot fluctuations. Recently Frequency-Domain Tomography (FDT) has shown promise for producing movie-like images of evolving laser-produced objects in a single shot. In FDT, several probe-reference pulse pairs cross the object's path simultaneously at different angles. The evolving object imprints a phase streak onto each probe, from which a single-shot, multi-frame movie is produced using tomographic reconstruction algorithms [12].

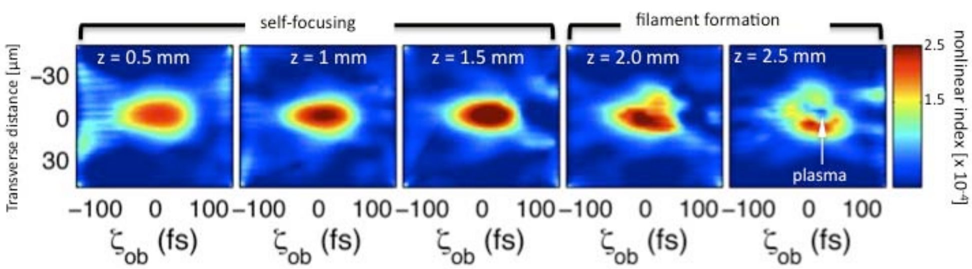

Fig.2: Five sequential movie frames (left to right) of the evolving nonlinear refractive index profile $\Delta n(\zeta_{ob},r_{ob})$ created by a pump laser pulse of energy 0.7 μJ energy propagating through a fused silica Kerr medium, produced in a single shot using Frequency-Domain Tomography. The selected frames show the profile at positions z_{ob} = 0.5, 1.0, 1.5, 2.0 and 2.5 mm into the plate. The first three frames display self-focusing, the last two filament formation and plasma generation. ζ_{ob} denotes time from peak of pump pulse. A similar technique can potentially produce single-shot movies of evolving laser wakefields.

Fig. 2 shows five frames of such a single-shot movie depicting the evolution of the nonlinear refractive index envelope of a laser pulse propagating through glass as it evolved under the competing influences of diffraction, self-focusing and plasma generation. I will describe recent developments with such techniques suited for imaging evolving plasma wakes in tenuous plasma that underlie the new generation of multi-GeV LPAs.

4. References

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