Electron Self-Injection and Trapping into an Evolving Plasma Bubble: Towards Optimization of Beam Quality in GeV-Scale Laser Plasma Accelerators

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Abstract: A time-varying bubble of electron density in the wake of an ultra-intense laser pulse traps the ambient plasma electrons and accelerates them to high energy producing collimated monoenergetic beams for medical, technological, and physics applications. Quasi-static dynamics of bubble is particularly important for electron trapping if the accelerator operates with ultra-low-density plasmas (~10^{17} electrons per cm^3) and is driven by a petawatt-class laser. Desirable evolution of the bubble can be engineered through control over the nonlinear focusing of the driving laser pulse, e.g. with the help of a thin nonlinear plasma lens. Quasi-monoenergetic nC beams of few-GeV electrons with ~1% energy spread and a few mm mrad normalized transverse emittance can be thus produced in ~10 cm length plasmas without external guiding.

Particle accelerators are among the largest and most expensive scientific instruments. Thirty years ago, theorists John Dawson and Toshiki Tajima proposed an idea for making them thousands of times smaller [1]: surf the particles on plasma waves driven by short intense laser pulses. Since plasmas are free of the damage limits of conventional accelerators, much larger fields can be built up within such waves, enabling much smaller accelerators.

Just five years ago, experimentalists finally demonstrated that such laser-plasma accelerators could produce monoenergetic, collimated electron beams with quality comparable to conventional accelerators [2]. The secret was for the laser to produce a "bubble" almost completely devoid of electrons in its immediate wake that captured electrons from the surrounding plasma and accelerated them in an exceptionally uniform way [3]. Yet the precise mechanism by which the bubble captured these electrons in homogeneous fully ionized plasmas and accelerated them with such uniformity has remained one of the outstanding mysteries of this field.

Now new theoretical and computational work by scientists from the University of Texas and Commissariat à l'Énergie Atomique (CEA, France) [4-7] has shed light on this mystery. Formation of the exceptional quality electron beam is attributed to the evolution of the bubble shape which, in turn, is directly associated with the nonlinear evolution of the driving laser pulse (nonlinear focusing and defocusing).

The basic premise of this work is that the size and shape of the bubble—the cavity of electron density traveling over the positive ion background with nearly the speed of light—is determined by the spot size of the driving laser pulse. Plasma nonlinearities cause the laser to focus and defocus in the course of propagation. Once the laser diffracts, the bubble expands. Electrons that constitute a dense electron shell surrounding the bubble (and especially the inner lining of the shell) move with relativistic speeds and thus have high inertia. For some of these electrons the slippage time around the bubble becomes comparable with the characteristic time of bubble expansion. These particles fall inside the bubble, stay inside till the end of the plasma (i.e. get trapped) and finally gain multi-GeV energy. The trapped charge is proportional to the bubble growth rate. Once the laser becomes self-guided, and the spot size oscillations saturate, the injection becomes inefficient. Simultaneously, longitudinal non-uniformity of the accelerating gradient equalizes the trapped electron energy [5]. This scenario of self-injection and monoenergetic bunch formation is discovered and explored in fine detail in the 3-D particle-in-cell simulations. This is fundamentally different from the previous work which concentrated on either one-dimensional models of electron trapping or on the reduced description of transverse plasma wave breaking in planar 2-D geometry.

Bubble dynamics in the course of propagation becomes critically important for electron trapping in strongly rarefied plasmas (where the ratio of laser frequency to the electron Langmuir frequency, $\gamma = \omega_0/\omega_{pe}$, is of the order of 100). Once the bubble is driven in such plasma by a self-guided petawatt laser [6,7], γ exceeds the bubble radius normalized to the collisionless skin depth, c/ω_{pe}, by more than order of magnitude. Under these conditions, phenomenological theory [8] using the stationary model of spherical bubble forbids electron self-injection. However, once the laser and bubble dynamics is taken into account, the discussed mechanism of electron self-injection appears to be very robust. Even more, it may be responsible for one deleterious effect which in dense plasmas ($\gamma \sim 10$) has been overshadowed by other processes (beam loading, nonlinear temporal compression of the pulse, filamentation *etc*). Namely, even minimal pulsations of spot size and intensity of the self-guided laser result in periodic variations of the bubble shape and size. As a corollary, periodic self-injection and emittance dilution occur [6].

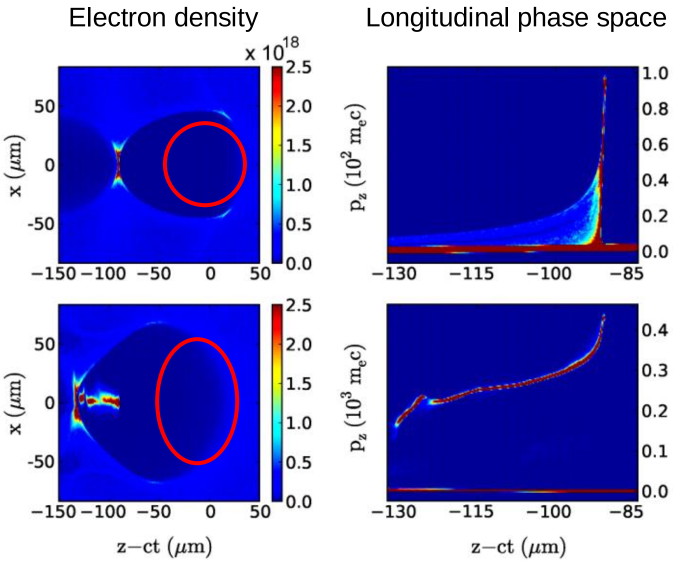

Fig. 1. Electron self-injection and acceleration in the expanding plasma bubble driven by the defocusing laser pulse (red contour) – 3-D PIC simulation by CALDER-Circ code [9]. Plasma density n_0 = 10^{17} cm^{-3}, laser power 1.33 PW and duration 150 femtoseconds (Texas Petawatt laser). As the driver defocuses, the bubble grows in size by 50% over 4 mm of propagation (from top to bottom row) and traps ~10^{10} electrons.

An appropriate modification of the plasma density (e.g. using a thin dense slab as a nonlinear lens for the laser) may cause the laser to self-focus and defocus faster, which results in a single self-injection event [7]. This kind of laser beam manipulation may lead to the generation of a few-GeV mono-energetic (~1% energy spread) electron bunch containing ~10^{10} electrons in a future experiment with the recently commissioned Texas Petawatt (TPW) laser – the most powerful laser in the world. Electron beams with such unique properties are clearly beneficial for medical applications, radiation physics (e.g. compact X-ray sources), material science, and homeland security.

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