GeV electron beams from a laser-plasma accelerator

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***Abstract*— High-quality electron beams with up to 1 GeV energy have been generated by a laser-driven plasma-based accelerator by guiding a 40 TW peak power laser pulse in a 3.3 cm long gas-filled capillary discharge waveguide [1].**

I. Introduction

GeV electron accelerators are used in synchrotron radiation facilities and free electron lasers, and as modules for high-energy particle physics. Conventional radio-frequency (RF) accelerators are limited to relatively low accelerating fields (10–50 MV/m) due to material breakdown, requiring tens to hundreds of meters to reach the multi-GeV beam energies needed to drive light sources, and many kilometers to generate particle energies of interest to high-energy physics.

Plasma waves can produce accelerating fields on the order of $E \sim m_e c\omega_p/e$, where $\omega_p = (4\pi n_e e^2/m_e)^{1/2}$ is the plasma frequency with n_e the electron number density. For plasma densities 10^{18}–10^{19} cm^{-3} the fields can be of the order ∼100 GV/m, several orders of magnitude greater than conventional RF accelerators. Such plasma waves can be ponderomotively driven by relativistically intense (>10^{18} W/cm^2), short pulse (tens of fs, such that the pulse duration $\sim \omega_p^{-1}$) lasers, enabling extremely compact accelerators [2], [3].

One challenge for laser-driven plasma-based accelerators is maintaining the laser intensity that drives the plasma wave. Without guiding (e.g., via self-focusing or using preformed plasma density channels) the laser-plasma interaction length is limited to the order of the Rayleigh range, Z_R, (e.g., a few mm for $r_s = 25$ μm, where r_s is the laser spot size). Relativistic self-guiding [3], [4] can extend the propagation distance of high-power pulses due to self consistent modification of the plasma refractive index, but is limited by nonlinear effects such as the erosion of the leading edge of the laser pulse.

In past experiments, the required laser intensity was not maintained over the distance needed to reach GeV energies, and hence acceleration was limited to the 100 MeV scale [5]–[7]. In these previous experiments [5]–[7], an ultra-intense ∼10^{19} W/cm^2 laser pulse focused on a gas jet, with typical length of a few millimeters. Obtaining GeV energies without a plasma channel to guide therefore requires large laser spot sizes that increases Z_R, but also increases the required laser power to PW levels.

A more efficient approach relies on using a plasma channel (a positive plasma density gradient away from the axis of propagation) to guide laser beams with smaller spot sizes over cm-scale distances. Theory and simulation indicate that such channel guided accelerators could produce GeV electron beams with 10–50 TW of laser power [3], [4], [6].

Demonstration of high-quality electron beams with up to 1 GeV energy, generated by a laser-driven plasma-based accelerator via guiding a 40 TW peak power laser pulse in a 3.3 cm long gas-filled capillary discharge waveguide (plasma channel), has recently been achieved at LBNL [1].

II. Channel-guided laser wakefield accelerator

Laser-plasma-based accelerators have previously demonstrated generation of low energy spread, ∼100 MeV electron beams [5]–[7] using an ultra-intense laser pulse focused on a gas jet with typical length of a few millimeters. The limitations of gas jet experiments can be overcome by employing a gas-filled capillary discharge waveguide [8], [9] to guide relativistically intense laser pulses in cm-scale, lower density plasma channels.

The experiments preformed at LBNL used a 10 Hz repetition rate Ti:sapphire laser system ($\lambda = 810$ nm) delivering as short as 38 fs (FWHM) pulses with up to 40 TW peak power. These pulses were focused by a 2 m focal length off-axis parabola (f/25) to $r_s = 25$ μm at the capillary entrance. The capillaries [8] were laser machined into 33 mm long sapphire blocks with diameters ranging from 190 μm to 310 μm. Hydrogen gas, introduced through holes near the capillary ends, was ionized by striking a discharge between electrodes at the capillary ends. Measurements [8] and modelling [10], [11] showed that a fully-ionized, approximately parabolic (with density minimum on axis) plasma channel is formed.

Intense laser pulses guided in the plasma channel excite plasma waves (wakefields) with phase velocities approximately equal to the group velocity of the drive laser pulse. These plasma waves can trap background plasma electrons and accelerate them to relativistic energies. A fundamental limitation to the energy gain is due to phase slippage between the trapped electrons and the plasma wave. The linear dephasing length, $L_d = \lambda_p^3/\lambda^2 \propto n_e^{-3/2}$, over which electrons outrun the wake and slip into a decelerating phase, limits the distance over which acceleration occurs. Here λ_p is the plasma wavelength and λ the laser wavelength. For laser intensities $I \leq 10^{18}$ W/cm^2, a rough estimate of the electron energy gain over a distance L_d in a channel-guided laser wakefield accelerator [3], [4] can be obtained from $W[\text{GeV}] \sim 0.4 I[\text{W/cm}^2]/n_e[\text{cm}^{-3}] \sim 0.9(k_p r_s)^{-2} P[\text{TW}]$; the energy gain in the laser-plasma-based accelerator scales approximately linearly with laser power P.

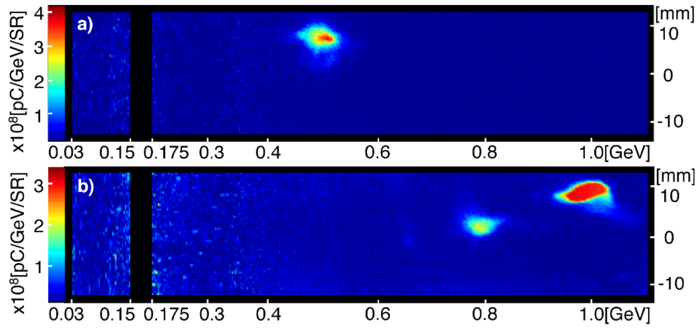

Fig. 1. Measured single-shot electron beam spectra from a capillary-guided laser-plasma accelerator [1]. (a) 0.50 GeV electron beam produced using 12 TW input laser power and plasma density of 3.5×10^{18} cm^{-3}. (b) 1.0 GeV electron beam produced using 40 TW input laser power and plasma density of 4.3×10^{18} cm^{-3}. The horizontal axis is the beam energy and the vertical axis is the beam size (in the plane undeflected by the magnetic spectrometer). The color scale denotes the bunch charge in pC/GeV/sr.

In recent laser-plasma accelerator experiments at LBNL using plasma-channel-guiding in a cm-scale capillary, high quality electron beams with GeV energies were generated [1]. Figure 1 shows single-shot electron beam spectra measured by a 1.2 T magnetic spectrometer that deflected the electrons onto a phosphor screen. Figure 1(a) shows an electron beam with energy of $0.50^{+0.02}_{-0.015}$ GeV (5% rms projected energy spread, 2.0 mrad rms divergence, and 50 pC of charge) generated in a 3.3 cm capillary (225 μm diameter) with a plasma density of 3.5×10^{18} cm^{-3} and input laser power of 12 TW (72 fs duration). Figure 1(b) shows an electron beam with energy $1.0^{+0.08}_{-0.05}$ GeV (2.5% rms energy spread, 1.6 mrad divergence rms, and 30 pC of charge) generated in a 3.3 cm capillary (310 μm diameter) with plasma density of 4.3×10^{18} cm^{-3} and input laser power of 40 TW (38 fs duration). In Fig. 1(b) a second beam at 0.8 GeV is also generated. Experimental results using 2 J of laser energy have produced 1 nC electron beams at 0.5 GeV.

III. Conclusion

These laser-plasma accelerator experimental results [1] open the possibility of a new class of compact accelerators. Such a laser-plasma accelerator could be used to drive a high-peak flux, x-ray free-electron laser in which the conventional RF accelerator (10–100 m length) is replaced by a GeV-class laser-plasma accelerator (several cm length), greatly reducing the size and cost of such light sources [12]. The electron bunches emerging from a laser-plasma accelerator have naturally short durations on the order of the plasma period (tens of fs) [13], and are intrinsically synchronized to the short-pulse laser driver, making such a source ideal for ultra-fast pump-probe applications. Future staging of GeV laser-plasma accelerator modules may open the possibility of achieving energies of interest to high-energy physics experiments.

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