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Publication Date

2010-02-08

Peer reviewed

Longitudinal Density Tailoring for the Enhancement of Electron Beams in the Capillary-discharge Laser-guided Wakefield Accelerator*

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Abstract

Density perturbations in a hydrogen-filled capillary discharge waveguide have been used to control the injection of electrons into a laser wakefield. This has allowed injection and acceleration in channels of lower density than previously possible, and the production of relativistic electron beams with improved stability. For parameters of optimum stability, the mean bunch energy was $300\,\mathrm{MeV} \pm 7\,\mathrm{MeV}$ rms, with divergence $1.3\,\mathrm{mrad} \pm 0.1\,\mathrm{mrad}$ rms and pointing stability $0.8\,\mathrm{mrad}$ rms.

INTRODUCTION

Laser-driven plasma accelerators have shown acceleration gradients orders of magnitude higher than those found in conventional accelerators. Recently, GeV electron beams were produced with just 40 TW of laser power in an accelerator of length $3\,\mathrm{cm}$ [1, 2]. This was achieved by employing a lower plasma density ($4 \times 10^{18}\,\mathrm{cm}^{-3}$) than in previous experiments [3], which reduces the phase slippage between the relativistic particles and the wake [4]. In order to achieve acceleration over distances much longer than a Rayleigh range of the focused laser beam ($Z_\mathrm{R} = \pi w_0^2/\lambda$), a hydrogen-filled capillary discharge waveguide [9, 10, 11] was employed. These experiments relied on self-injection, for which the laser intensity required is high and the accelerating cavity must operate in a highly non-linear regime. If the processes of injection and acceleration can be separated, then the plasma density in accelerating cavity can be lowered further, allowing for increased electron energy, improved beam stability, and operation in the quasi-linear regime.

One method of achieving this is triggering injection using colliding laser pulses [5, 6]. Longitudinal density downramps have also been used to control injection and produce stable low-energy bunches ($1\,\mathrm{MeV}$ level), and simulations indicated that embedding such a downramp in a long plasma could produce high quality beams at high energy [7, 8]. This technique offers the advantage of a simpler setup and avoidance of possible damage to the laser system from counter-propagating laser pulses. In this paper it is shown that density perturbations in a hydrogen-filled capillary discharge waveguide can control injection and produce beams of energy several hundred MeV with significant improvement in stability over previous experiments [1, 2].

* Work supported by DOE grant DE-AC02-05CH11231 and DARPA
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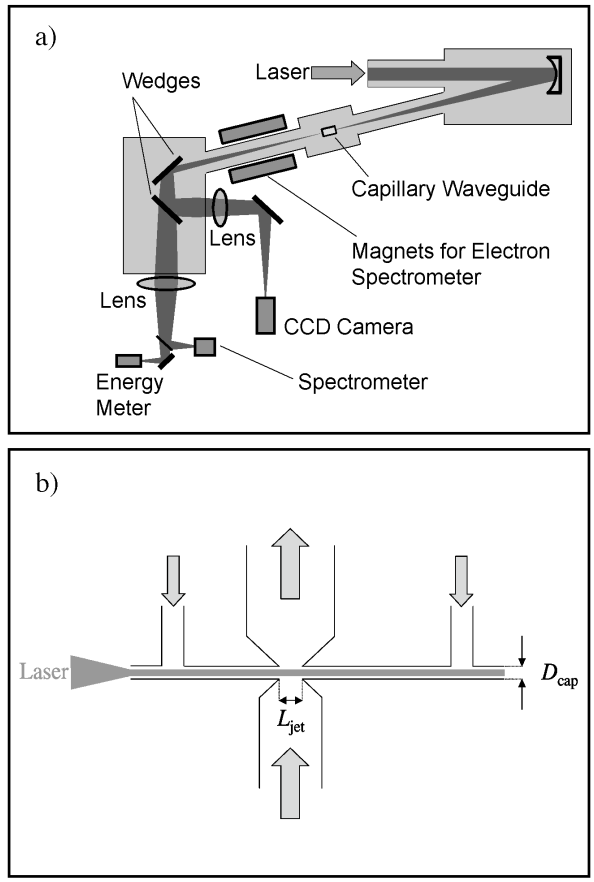


Figure 1: a) The experimental layout used for investigating electron acceleration in a hydrogen-filled capillary discharge waveguide. b) The capillary with embedded gas jet.

EXPERIMENTAL SETUP

The experimental layout is shown in Fig. 1a. Pulses from the LOASIS Ti:sapphire laser system with peak power up to $44\,\mathrm{TW}$ ($1.74\,\mathrm{J}$ in $40\,\mathrm{fs}$) were focused to a spot of size $w_0 = 25\,\mu\mathrm{m}$ by a $2\,\mathrm{m}$ focal length off-axis paraboloid used at $f/25$ at the entrance of a hydrogen-filled capillary discharge waveguide . At the maximum power used in these experiments this focusing geometry corresponds to a peak intensity of $I_0 = 2.7 \times 10^{18}\,\mathrm{Wcm}^{-2}$ and a peak normalized vector potential of $a_0 \approx 1.1$. The laser beam pointing stability was measured to be $3\,\mu\mathrm{rad}$ rms in the horizontal direction and $1.5\,\mu\mathrm{rad}$ rms in the vertical direction.

The hydrogen-filled capillary discharge waveguide has been described in detail elsewhere [9, 10], along with its use for laser wakefield acceleration of electrons to energies up to $1\,\mathrm{GeV}$ [1, 2, 13]. In the experiments described here a longitudinal density perturbation was created by adding a laser-machined gas-jet nozzle as shown in Fig. 1b. The two capillaries employed had diameter $200\,\mu\mathrm{m}$ and length $33\,\mathrm{mm}$ (which corresponds to $13\,Z_{\mathrm{R}}$). Hydrogen gas was flowed into the capillaries via slots located $2\,\mathrm{mm}$ from each end of the capillary. The on-axis electron density was calculated from the backing pressure as described in Ref. [11]. Each capillary also had hydrogen gas input from an embedded gas jet located at a distance of $11\,\mathrm{mm}$ from the entrance of the capillary. The jet nozzles were elliptical in shape, with the major axis along the capillary axis. The first jet had a nozzle with major axis $L_{\mathrm{jet}} = 0.35\,\mathrm{mm}$ and minor axis $W_{\mathrm{jet}} = 0.3\,\mathrm{mm}$. The second jet was larger, with dimensions $L_{\mathrm{jet}} = 0.80\,\mathrm{mm}$ and $W_{\mathrm{jet}} = 0.41\,\mathrm{mm}$.

The energy of electron bunches emerging from the waveguide was measured by an electron spectrometer that has been described in detail in Ref. [12]. In short, a $1.2\,\mathrm{T}$ magnet deflected the electrons onto phosphor screens imaged by four synchronously-triggered CCD cameras, enabling single-shot detection of electrons with energies in the range $0.01 - 0.14\,\mathrm{GeV}$ and $0.17 - 1.1\,\mathrm{GeV}$. Charge was obtained from the phosphor screens, which were cross-calibrated against an integrating current transformer.

Laser radiation emerging from the capillary passed through the electron spectrometer and was attenuated by reflection off two optically flat wedges. The beam was refocused by a lens of focal length $500\,\mathrm{mm}$ and diameter $100\,\mathrm{mm}$, allowing for imaging of the output of the capillary onto a 12-bit CCD camera. The energy of each laser pulse input to the waveguide was determined by a photodiode that was calibrated to the energy on target. The energy of pulses transmitted through the capillary was measured by loosely focusing the portion of the laser beam transmitted through the second wedge onto a pyroelectric energy meter that was cross-calibrated to the first.

RESULTS

For the smaller jet, the on-axis density in the bulk of the capillary was held constant at $n_{\mathrm{e}} \approx 1.3 \times 10^{18}\,\mathrm{cm}^{-3}$. The laser energy on target was $1.74\,\mathrm{J} \pm 0.07\,\mathrm{J}$ which for the laser spatial mode at focus corresponds to a peak laser intensity of $2.7 \times 10^{18}\,\mathrm{Wcm}^{-2}$ ($a_0 \approx 1.1$) for the laser pulse length of $40\,\mathrm{fs}$.

With a jet backing pressure of $105\,\mathrm{psi}$ no electrons were observed, as can be seen in Fig. 2. The threshold for injection was approximately $P_{\mathrm{jet}} = 125\,\mathrm{psi}$, where the average charge was $0.1\,\mathrm{pC}$. The maximum average charge of approximately $2\,\mathrm{pC}$ was obtained at $P_{\mathrm{jet}} = 205\,\mathrm{psi}$, where beams were observed on every shot. This result is important because it shows that a local density perturbation can be used to trigger injection into a a plasma channel of lower density, which increases the dephasing length and allows for increased energy gain. Further investigation of the many experimental parameters will be required to optimize beam energy, quality, and stability.

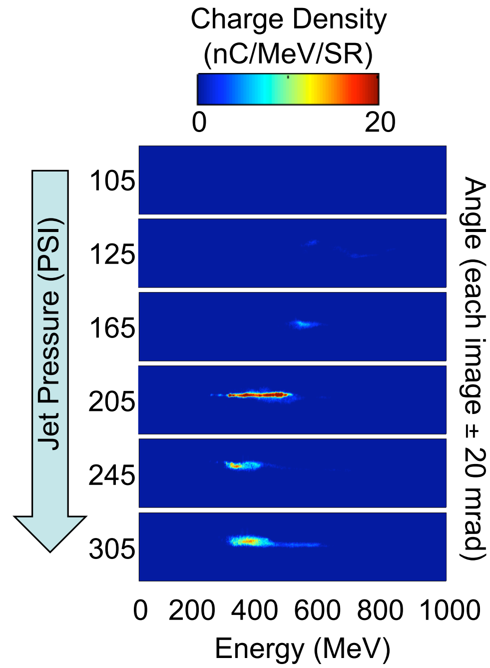
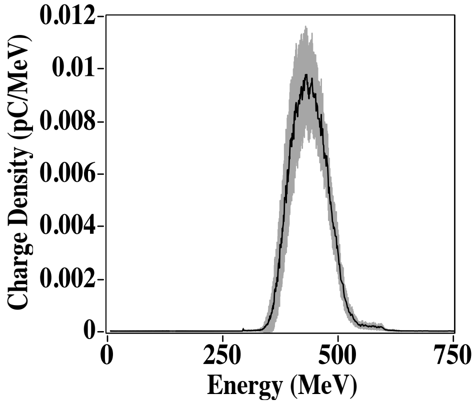


Figure 2: Electron beam spectra as a function of increasing jet pressure for experiments with the smaller jet. The vertical axis is divergence with extent of each image corresponding to $40\,\mathrm{mrad}$. The on-axis density in the capillary was $1.3 \times 10^{18}\,\mathrm{cm}^{-3}$. At $105\,\mathrm{psi}$ no electron beams were observed. The maximum charge of $2\,\mathrm{pC}$ was obtained at $P_{\mathrm{jet}} = 205\,\mathrm{psi}$, with electron beams observed on every shot.

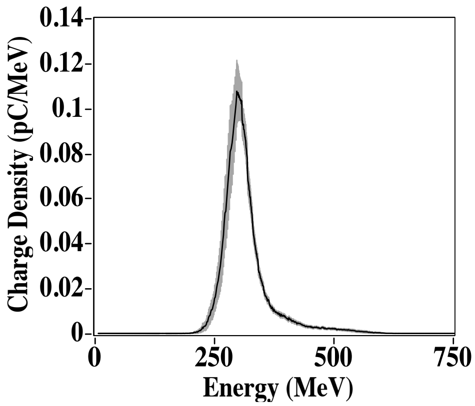
For the larger jet, the on-axis density in the bulk of the capillary was held constant at $n_{\mathrm{e}} \approx 2.1 \times 10^{18}\,\mathrm{cm}^{-3}$. The laser energy on target was $1.60\,\mathrm{J} \pm 0.05\,\mathrm{J}$ which for the laser spatial mode at focus corresponds to a peak laser intensity at focus of $2.6 \times 10^{18}\,\mathrm{Wcm}^{-2}$ ($a_0 \approx 1.1$).

Figures 3(a) and 3(b) show results for a backing pressure on the jet of $\mathrm{P_{jet}} = 105\,\mathrm{psi}$ and $145\,\mathrm{psi}$ respectively. For $\mathrm{P_{jet}} = 105\,\mathrm{psi}$, 37 consecutive shots resulted in a mean bunch energy of $E_{\mathrm{bunch}} = 437\,\mathrm{MeV} \pm 15\,\mathrm{MeV}$ rms with a mean energy spread of $\Delta E/E = 10\,\%$ rms and charge $1\,\mathrm{pC} \pm 0.4\,\mathrm{pC}$ rms. In the undispersed plane, the bunch divergence was $1.6\,\mathrm{mrad} \pm 0.3\,\mathrm{mrad}$ rms and the pointing deviation $0.7\,\mathrm{mrad}$ rms. For $\mathrm{P_{jet}} = 145\,\mathrm{psi}$, 26 consecutive shots resulted in a mean bunch energy of $E_{\mathrm{bunch}} = 300\,\mathrm{MeV} \pm 7\,\mathrm{MeV}$ with a mean energy spread of $\Delta E/E = 9\,\%$ rms and charge $8\,\mathrm{pC} \pm 2\,\mathrm{pC}$. In the undispersed plane, the bunch divergence was $1.3\,\mathrm{mrad} \pm 0.1\,\mathrm{mrad}$ and the pointing deviation $0.8\,\mathrm{mrad}$ rms.

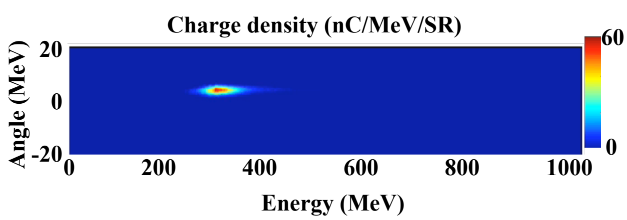
Figure 4 summarizes a scan of jet pressure for the parameters of Fig. 3 with a plot of beam energy and charge. It can be seen that increasing the pressure increases the bunch charge at the expense of bunch energy. Increased bunch charge at higher density is expected due to the slower wake phase velocity and increased laser self-focusing and steep-



(a)



(b)



(c)

Figure 3: Electron beam spectra for jet pressures of a) 105 psi and b) 145 psi. The black line is the averaged spectrum and the grey shaded area shows the rms shot to shot error. In c) is shown a sample spectrum for a jet pressure of 145 psi.

ening, all of which enhance trapping. Figure 4 also shows a decrease in laser transmission (T) that is consistent with increased pump depletion. Pump depletion lowers the intensity of the laser pulse and the amplitude of the wakefield, and could therefore explain reduced beam energy for higher jet pressure. It should be noted that the charge observed on the Lanex screen may only be a subset of the total charge injected since there may be a portion of the beam with high divergence. Thus beam loading could also be reducing the beam energy for higher pressure even though the observed beam charge would suggest beam loading is not significant.

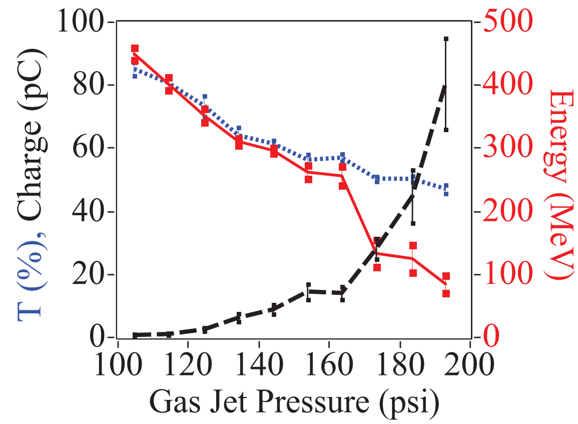


Figure 4: Beam energy (red line, right axis), laser transmission T (blue dotted line, left axis), and charge (black dashed line, left axis) as a function of jet pressure for the larger jet. Beam energy can be increased at the expense of charge.

SUMMARY

In summary, longitudinal density tailoring inside a capillary discharge waveguide was employed for the first time to inject electrons into the plasma wake, allowing for injection at densities below the usual threshold. Furthermore, it was shown that the technique can yield high-quality electron beams with significantly improved stability.

The authors would like to acknowledge the technical contributions from D. Syversrud, W. Waldron, and N. Ybarrolaza.

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