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High Quality Electron Bunches up to 1 GeV from Laser Wakefield Acceleration at LBNL

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Abstract. Experiments at the LOASIS laboratory of LBNL have demonstrated production of 100 MeV to 1 GeV electron bunches with low energy spread and low divergence from laser wakefield acceleration. The radiation pressure of a 10 TW laser pulse, guided over 10 diffraction ranges by a few-mm long plasma density channel, was used to drive an intense plasma wave (wakefield), producing electron bunches with energies on the order of 100 MeV and acceleration gradients on the order of 100 GV/m. Beam energy was increased from 100 MeV to 1 GeV by using a few-cm long guiding channel at lower density, driven by a 40 TW laser, demonstrating the anticipated scaling to higher beam energies. Particle simulations indicate that the low energy spread beams were produced from self-trapped electrons through the interplay of trapping, loading, and dephasing. Other experiments and simulations are also underway to control injection of particles into the wake, and hence improve beam quality and stability further.

Keywords: laser, plasma, accelerator
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INTRODUCTION

Laser wakefield accelerators (LWFA) have demonstrated accelerating gradients thousands of times those obtained in conventional accelerators using the electric field of a plasma wave (the wakefield) driven by an intense laser [1-13], indicating the potential for more compact accelerators. Early experiments demonstrated high gradients, but electron beam energy and quality were limited until recently by the difficulty of retaining high laser intensity over a long distance of propagation, resulting in electron bunches with 100% energy spread and an exponentially small fraction of electrons at high energy [2-8]. These experiments occurred in the self-modulated regime [1] and relied on the self-guiding of the laser pulse which occurs for powers greater than the critical power for relativistic self-focusing, P_c. The relativistic quiver motion of the electrons increases their effective mass, changing the refractive index, but the laser pulse is unstable, limiting propagation length to little more than a diffraction range, Z_R.

In 2004 experiments at LBNL demonstrated guiding of relativistically intense laser pulses over many diffraction ranges by plasma density channels, producing high quality electron beams [10]. Experiments and simulations [10,12,13] showed that the important physics of this regime is that trapping of an initial bunch of electrons loads the wake, suppressing further injection and forming a bunch of electrons isolated in phase space. At the dephasing point, as the bunch begins to outrun the wake, the particles are then concentrated near a single energy, and hence a high quality bunch is obtained by guiding the laser to this length. Described in the following are LBNL experiments and simulations at the 100 MeV level [10], and more recent results at 1 GeV [14], which demonstrate the scaling to higher energies that is needed for many applications. Channel-guided experiments retain the high acceleration gradients of previous experiments over longer distances, and beam quality is comparable to state of the art RF accelerators.

Also in 2004, two other groups [9,11] reported the production of low energy spread electron bunches with energies in the 100 MeV range, however, neither of these groups used a plasma channel. Instead, the interaction length was increased by using a larger laser spot size, which increases Z_R, but also increases the laser power needed to maintain a given intensity. Since these initial experiments, several other groups in the USA, Europe, and Asia have reported the production of low energy spread electron bunches (or at least narrow features in the electron energy spectra) in the 10-100 MeV range [15].

100 MeV EXPERIMENTS

Laser guiding at high intensities to produce a channel-guided accelerator required compensating both diffraction and plasma effects. Previous experiments demonstrated guiding for input pulse intensities at up to 2×10^{17} W/cm^2 [16-20], where a parabolic transverse plasma density profile can be matched to guide the low intensity pulse [21]. For channel guided wakefield acceleration, channels must balance diffraction, self-guiding, and instabilities for high intensity propagation over long distances.

The LOASIS Ti:Sapphire laser [5,22], operating at 800 nm with chirped pulse amplification, was used to form the guiding channel with a variation of the ignitor-heater method [18] and to drive the wake (Fig. 1A). A plasma was ionized by an ignitor pulse (15 mJ, 60 fs) from a 2.5 mm long supersonic H_2 gas jet with an atomic density of $3 - 4 \times 10^{19}$ cm^{-3}, then heated to 10's of eV by a heater pulse (using ~ 50 mJ from a 150 mJ, 250 ps beam). Plasma expansion drove a shock in surrounding gas, forming a channel with a nearly parabolic transverse density distribution [16]. This channel guided the relativistically intense drive pulse focused at its edge. To drive an intense wake and trap electrons, the drive pulse (500 mJ, 55 fs) was focused to a spot of 7 – 8.5 μm FWHM. This gave $Z_R \sim 200$ μm so that the channel was $> 10Z_R$ long. Laser propagation was monitored with an interferometer, mode imager CCD, and transmitted light spectrometer. Accelerated electrons were analyzed using a current transformer, phosphor screen, and magnetic spectrometer.

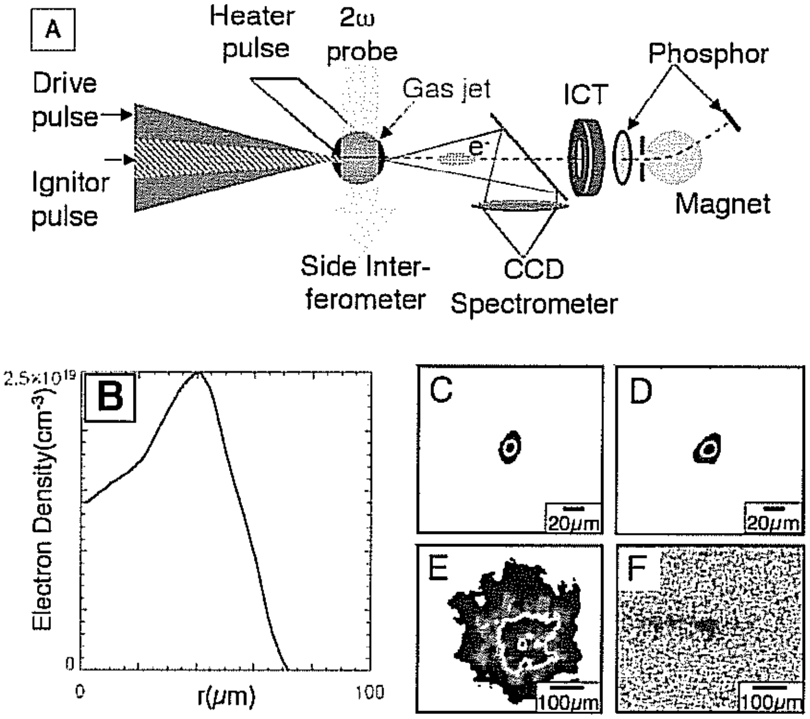

FIGURE 1. (A) Experimental setup showing the gas jet with laser beams and diagnostics. (B) The density profile of the channel obtained by Abel inversion of the side interferogram. (C-F) Mode images of laser propagation at 4 TW. The output image with the guide on (D) is indistinguishable from the input (C) indicating un-aberrated propagation at twice P_c. Unguided images show diffraction in vacuum (E) and ionization enhanced diffraction with the gas jet on (F).

Laser Guiding

The channel plasma profile was adjusted to guide the drive pulse without aberration at powers up to $2P_c$, by changing the ignitor and heater energy and timing to compensate for the presence of self-guiding [12]. With the channel tuned to match the low power guiding condition [21], aberration-free guiding of low power pulses (0.5 TW $< P_c$) was obtained.

Re-tuning the channel allowed compensation for the presence of self-guiding, and powers up to 4 TW (7×10^{18} W/cm^2) were guided without aberration. The profile of this channel (Figure 1B) is nearly parabolic, with a rise in density over the spot diameter 40% less than the low power matching condition. Figure 1C-F show mode profiles of the laser spot at 4 TW (7 μm input spot, 7×10^{18} W/cm^2). With the channel on, the output spot (D) matches the input (C). De-convolution of instrument response [12] indicated that the output is within 1 μm of the 7 μm input spot size, giving an output intensity ~ 2.5×10^{18} W/cm^2 (lower limit 1×10^{18} set by the raw observation).

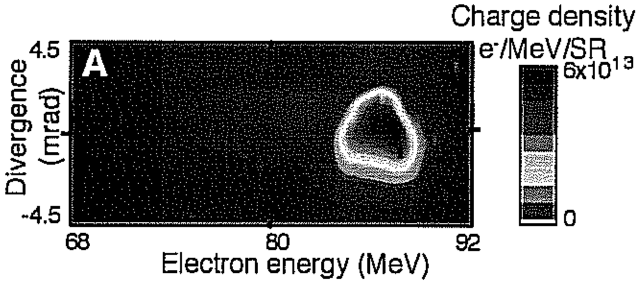

FIGURE 2. Electron bunch. The electron energy spectrum of the channeled accelerator shows the appearance of monoenergetic features, here with 2 × 10^9 electrons in a bunch with energy spread of 4% FWHM at 86 MeV. Divergence was near 3 mrad FWHM.

Transmission at 4 TW was 35%, a reduction of one third from the low power case, indicating substantial power was deposited in plasma waves. This is consistent with particle in cell simulations (below), which indicate that a plasma wave averaging 2 – 300 GV/m in the last 0.5 mm of guide length. No electrons are trapped at 4 TW, indicating a structure for controlled injection experiments [23,24], and colliding pulse injection [24] experiments are now under way which may increase beam stability.

Channeled Wakefield Acceleration

At guided drive pulse powers above 4 TW, electrons were trapped and accelerated, verifying that an intense plasma wake was driven in the channel. At 9 TW, the channel guided accelerator produced high charge electron beams at high energy with low energy spread and low divergence [10]. Figure 2 shows a bunch of 2×10^9 electrons within an energy spread of ± 2% centered at 86 MeV. Optimal performance was found in a channel with an axial density of 1.9×10^{19} cm^{-3} and with a parabolic profile with 40% less rise in density over a spot diameter than the low power matched case. The normalized geometric emittance obtained from assuming the bunch comes from a source on order of the laser spot size is 1-2 mm-mrad, competitive with state of the art RF facilities.

The accelerator was operated in the same gas jet without the guiding channel. Optimum unchanneled performance was at $n_e \simeq 4 \times 10^{19}\ \mathrm{cm}^{-3}$, producing an exponential energy distribution with a 2.6 MeV temperature below 10 MeV and an 8 MeV temperature above 10 MeV, and no detectable electrons above 40 MeV. No difference was observed between operation in a neutral gas jet and a pre-ionized (but not channeled) plasma, confirming that channeling greatly enhanced accelerator performance.

Simulations and Dephasing

Two-dimensional particle-in-cell (PIC) simulations using the code VORPAL (developed at U. of Colorado Tech X [25]) performed with parameters close to the experiment indicated that the high quality electron bunches are formed by wake

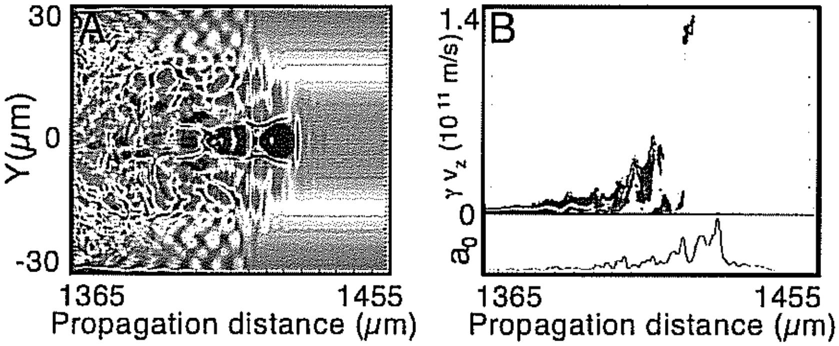

FIGURE 3. Particle in cell simulations show plasma density (A), phase space (B) and laser profile (B, lineout) for the formation of high quality bunches by dephasing.

loading and dephasing [10,13]. If laser pulse strength was just above that required to self trap electrons, loading of the wake [26] by the initial trapped electron bunch suppressed further injection. This lead to a bunch of electrons isolated in phase space (Figure 3). If this bunch was accelerated until it dephased from the wake, the leading edge of the bunch was decelerated while the tail was still accelerating, concentrating the particles in energy and forming a low energy spread bunch at the dephasing length (Figure 3B). Matching the accelerator length to the dephasing length, for the jet length and Z_R used in the experiment, required a guiding channel. A similar effect has also been seen in [27] for different plasma shapes, and quasi-monoenergetic structures were previously observed in [28] at much higher laser amplitudes.

Dephasing physics was experimentally demonstrated by using gas jets of different lengths without channeling [13], showing that the highest energies for a given density and the most monoenergetic features were obtained near the dephasing length. Consistent with this, monoenergetic beams were also observed in other experiments using a large laser spot size to increase Z_R and hence the propagation distance of the laser [9,11]. Like unchanneled experiments here, this produced lower charge and energy for a given laser power because the large spot size reduced laser intensity.

1 GeV EXPERIMENTS

Scaling laser accelerators to higher energies requires guiding over longer distances in lower density plasmas, where the dephasing length is longer. Experiments have now demonstrated production of narrow energy spread beams at energies up to 1 GeV [14], by using a hydrogen discharge capillary waveguide [29] to produce longer (3 cm) lower density (few 10^{18} cm^{-3}) channels, which were driven by 10's of TW of laser power. Figure 4 shows single-shot electron beam spectra measured by a 1.2 T magnetic spectrometer that deflected the electrons onto a phosphor screen. Figure 4(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

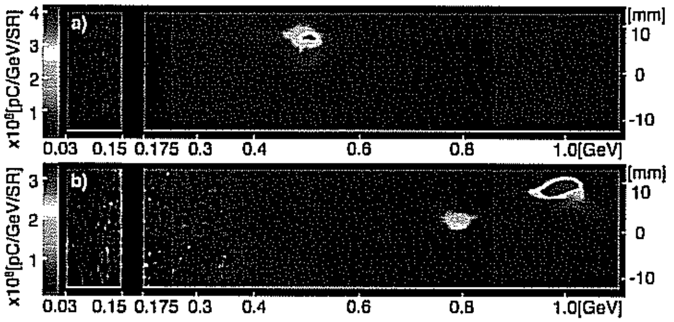

FIGURE 4. Measured single-shot electron beam spectra from a capillary-guided laser-plasma accelerator [1]. (a) 0.50 GeV electron beam produced using 12 TW input laser power and plasma density of 3.5×10^{18} cm^{-3}. (b) 1.0 GeV electron beam produced using 40 TW input laser power and plasma density of 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.

power of 12 TW (72 fs duration). Figure 4(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 a plasma density of 4.3×10^{18} cm^{-3} and an input laser power of 40 TW (38 fs duration). In Fig. 4(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. This demonstrates the anticipated scaling of channel-guided accelerators to GeV energies needed for many applications.

CONCLUSIONS

Experiments demonstrated guiding of relativistically intense laser pulses over many Z_R in plasmas, and used tailoring of the plasma profile to provide guiding without detectable aberration up to twice the relativistic self-guiding threshold [12]. Increasing density and intensity produced self-trapped electron beams of percent energy spread with several 10^9 electrons and with emittance comparable to state-of-the-art radio-frequency accelerators [10]. Energies up to 1 GeV were demonstrated [14]. This offers the possibility of new classes of experiments on laser-driven accelerators and indicates that development of high energy, high quality beams is feasible using this method. Experiments and simulations indicate these beams are formed by beam loading and dephasing [13]. Input intensities near 10^{19} W/cm^2 have been guided without self-injection of electrons. Experiments on controlled injection using the colliding pulse method are underway [24], which may further stabilize and improve the bunch quality. Radiation sources from the THz to the X-ray band are being developed using the unique ultrafast, high current properties of these laser accelerated electron bunches [30].

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