GeV electron beams from a cm-scale accelerator

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GeV electron accelerators are essential to synchrotron radiation facilities and free electron lasers, and as modules for high-energy particle physics. Radiofrequency-based accelerators are limited to relatively low accelerating fields (10-50 MV/m) and hence require tens to hundreds of metres to reach the multi-GeV beam energies needed to drive radiation sources, and many kilometres to generate particle energies of interest to the frontiers of high-energy physics. Laser-wakefield accelerators (LWFA)[1,2] – in which particles are accelerated by the field of a plasma wave driven by an intense laser pulse – produce electric fields several orders of magnitude stronger (10-100 GV/m) and so offer the potential of very compact devices. However, until now it has not been possible to maintain the required laser intensity, and hence acceleration, over the several centimetres needed to reach GeV energies. For this reason laser-driven accelerators have to date been limited to the 100 MeV scale[3-5]. Contrary to predictions that PW-class lasers would be needed to reach GeV energies[6,7], here we demonstrate production of a high-quality electron beam with 1 GeV energy by channelling a 40 TW peak power laser pulse in a 3.3 cm long gas-filled capillary discharge waveguide[8,9]. We anticipate that laser-plasma accelerators based on capillary discharge waveguides will have a major impact on the development of future femtosecond radiation sources – such as x-ray free electron lasers – and become a standard building block for next generation high-energy accelerators.

Although it is relatively straightforward to achieve acceleration gradients of 10-100 GV/m in laser wakefield accelerators[1,2], until recently the electron beams (e-beams) from such accelerators were of relatively low energy (below 200 MeV) and had 100% energy spread[10]. A breakthrough improvement in energy spread was obtained in 2004 by three groups[3-5], including ours[4]. In that work intense laser pulses interacting with millimetre-scale gas jets generated 70-200 MeV beams with percent-level energy spread. Two of the groups[3,5] used a relatively large laser spot size r_s such that the diffraction distance (of the order of the Rayleigh range $Z_R = \pi r_s^2/\lambda$, where λ is the laser wavelength and r_s is the $1/e^2$ radius of the laser intensity profile) roughly matched the gas jet length, which set an upper bound on the acceleration length. This approach produced, for example, 170 MeV e-beams with order 0.5 nC bunch charge using 30 fs, 30 TW laser pulses[5]. In contrast, in our previous experiments, precursor laser pulses created a 2 mm long plasma channel (parabolic transverse density profile with a minimum on axis, which functions like an optical fibre[2]) in a gas jet to guide the driving laser beam[4,11,12], enabling acceleration over many Z_R. This allowed generation of 80-150 MeV e-beams, with 0.3 nC bunch charge, using only 9 TW[4,12].

To scale laser-driven accelerators to GeV electron energies and beyond, two different approaches had been proposed: (1) operate in initially uniform plasmas[7,13] with ever more powerful laser beams and large laser spot sizes, or (2) guide the laser beam over cm-scale distances[2,14,15]. Without some form of guiding (e.g., self-focusing or preformed channels) the laser-plasma interaction length is limited to the order of Z_R, which is a few millimetres for r_s=25 μm. Relativistic self-guiding[2] 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. Obtaining GeV energies without a guiding channel therefore requires the laser spot size to be large, so as to increase Z_R, but this also increases the required laser power to PW levels[6,7]. In addition, using large laser spot sizes can result in an undesirable increase in the e-beam emittance.

A more efficient approach relies on channelling laser beams over cm-scale distances, allowing smaller spot sizes. Theory and simulations indicate that such channel guided accelerators[4] could produce GeV e-beams with only 10-50 TW of laser power[14,15], allowing the use of low-cost, compact high repetition rate lasers. However, simply making the accelerator longer is not sufficient. Phase slippage occurs between relativistic particles and the wake, because the wake has a phase velocity less than the vacuum speed of light. The dephasing length, $L_d = \lambda_p^3/\lambda^2 \propto n_p^{-3/2}$, over which electrons outrun the wake and slip into the decelerating phase, must then be extended to increase the accelerator length. Here λ_p is the plasma wavelength and n_p the plasma density. In the linear wakefield regime (laser intensity I approximately 10^{18} W/cm^2, or less), the energy gain over this length is proportional to I/n_p such that higher energy gains require lower plasma densities (n_p~10^{18} cm^{-3})[14,15]. Matching acceleration length to L_d also has been essential for the production of low energy spread e-beams[3-5].

Previously we created plasma channels[16] in a gas jet with the 'ignitor-heater' technique, in which a plasma column is first ionized and then heated by two precursor laser pulses[4,11,17]. Due to the inefficiency of laser heating at low densities, suitable plasma channels could only be produced at relatively high densities (>10^{19} cm^{-3}). Together with the small diameter (few mm) of the supersonic gas jets nozzles, this limited the acceleration length and restricted the energy of the e-beams to the 100 MeV-level energy range.

In the experiments reported here we overcame the limitations inherent to laser-induced channels in gas jets by employing a gas-filled capillary discharge waveguide[8,9] to produce longer (few cm) and lower density plasma channels. The experiments used the 10 Hz repetition rate TREX amplifier of the LOASIS Ti:sapphire laser system, operating at a wavelength of 810 nm and delivering 40 fs full width half maximum (FWHM) pulses with a peak power of up to 40 TW (Fig.1). The laser pulses were focused by a 2 m focal length off-axis parabola (f/25) to r_s = 25 μm at the capillary entrance. The capillary waveguide[8] was laser-machined in sapphire blocks and was 33 mm long and approximately 300 μm in diameter. Hydrogen gas was introduced into the capillary, and a discharge struck between electrodes located at each end of the capillary ionized the hydrogen and formed the plasma channel[18]. Measurements[8,19] and modelling[18,20] have shown that the plasma channel is essentially fully ionized and approximately parabolic. Previous experiments[9] demonstrated that waveguides of this type are able to channel laser pulses with $I \sim 10^{17}$ W/cm^2 over lengths of 30-50 mm, although these intensities were too low to generate large amplitude plasma wakes.

Laser guiding was optimized by tailoring the channel through the initial gas density and the delay between the onset of the discharge current and the arrival of the laser pulse. Under optimum conditions the on-axis density was $2\text{–}4\times10^{18}$ cm^{-3}. Figure 2 shows the laser beam profile at the waveguide exit for 40 TW laser pulses with an input intensity of order 10^{18} W/cm^2. This intensity is sufficiently high for large amplitude wake generation, self-trapping, and high-gradient electron acceleration. High-quality guiding was obtained at four times the peak power and over fifteen times the length of the ignitor-heater experiments[4,11]. The laser pulse energy transmission was observed to decrease from near 100% for input powers below 5 TW to less than 70% for input powers around 40 TW, consistent with laser energy transfer to the wake and electron beams.

The electron bunch energy was measured by a 1.2 T single-shot magnetic spectrometer that deflected the electrons onto a 1.2 m long phosphor screen, covering energies up to 1.1 GeV. The e-beam divergence and energy spread were calculated from the raw data using the imaging properties of the spectrometer, obtained from detailed magnetic field maps and a second order electron transport model[21]. The divergence was determined from the beam size in the undeflected plane, taking into account the transverse defocusing properties of the magnet. The energy spread was calculated by deconvolving the effect of finite divergence from the measured beam profile. The charge was obtained from the phosphor screen that was cross-calibrated against an integrating current transformer.

Figure 3 shows the energy spectrum of (a) a 0.52 GeV and (b) a 1.0 GeV beam, obtained with ~25 TW and ~40 TW laser pulses, respectively. In both cases the e-beams had percent-level energy spread and a divergence of 1.2-2.0 mrad (see Fig. 3 c-f). The measured energy spread at 1 GeV is comparable to the resolution of the spectrometer so that the actual energy spread may have been even lower. The bunch charge ranged between 50-300 pC. Tuning of laser power and pulse length as well as plasma density was found to affect beam charge, and hence higher charge is expected with further optimization. The e-beam energy fluctuated from shot-to-shot, due in part to the self-trapping mechanism being sensitive to small variations in the laser and plasma parameters[12]. At 40 TW, the highest energies were over 1 GeV, and narrow energy spread beams were frequently produced near 0.5 GeV, with significantly more charge than at 25 TW.

The dynamics of trapping, dephasing, beam loading[12,22] and hosing[23] may be responsible for the second spatially-displaced bunch observed near 0.8 GeV in Fig. 3b. Such features are observed in numerical simulations, owing to trapping of a second electron bunch in a wake bucket behind the first[12,22]; and these issues are being further explored.

In summary, we have demonstrated the production of high quality electron beams at 1 GeV from a centimetre-scale accelerator. This is the highest beam energy yet reported for a laser-driven accelerator, and the shortest accelerator of any type to accelerate electrons from rest to GeV energies. This was enabled by gas-filled capillary discharge waveguides that channeled relativistically-intense laser pulses over several centimetres of sufficiently low density plasma. The short wavelength of the plasma accelerating structure results in femtosecond duration bunches[24] (>10 kA peak current), that are well suited for driving pulsed radiation sources. This offers the prospect of novel, compact and intrinsically-synchronized sources of femtosecond electron pulses and radiation tunable from x-ray[25] to THz[26] frequencies, as needed for pump-probe measurements in the basic and applied sciences. Our approach offers GeV beams, enabling, for example, compact femtosecond free electron lasers producing keV x-rays using existing cm-scale period undulators, which was not possible with 100 MeV-class beams. Furthermore, it is anticipated that longer accelerating structures can be made by staging capillary discharge waveguides, thereby opening a path of compact accelerators beyond the multi-GeV level for applications in high energy physics.

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Figure 1: Schematic of the capillary-guided laser wakefield accelerator. The plasma channel was formed in a hydrogen-filled capillary discharge waveguide. The laser beam was focused onto the entrance of the capillary using an f/25 off-axis parabola (OAP). The guiding efficiency was measured using a pair of optical diodes (Diode 1&2) that monitored the amount of laser energy at the entrance and exit of the capillary. The laser beam exiting the capillary was monitored on a 12 bit CCD camera (20 μm resolution), after having been attenuated with a pair of reflective wedges and optical attenuators. The electron beam was analysed using an integrating current transformer (ICT) and a 1.2 T broad-band magnetic spectrometer (energy range of 0.03-0.15 and 0.175-1.1 GeV in a single shot).

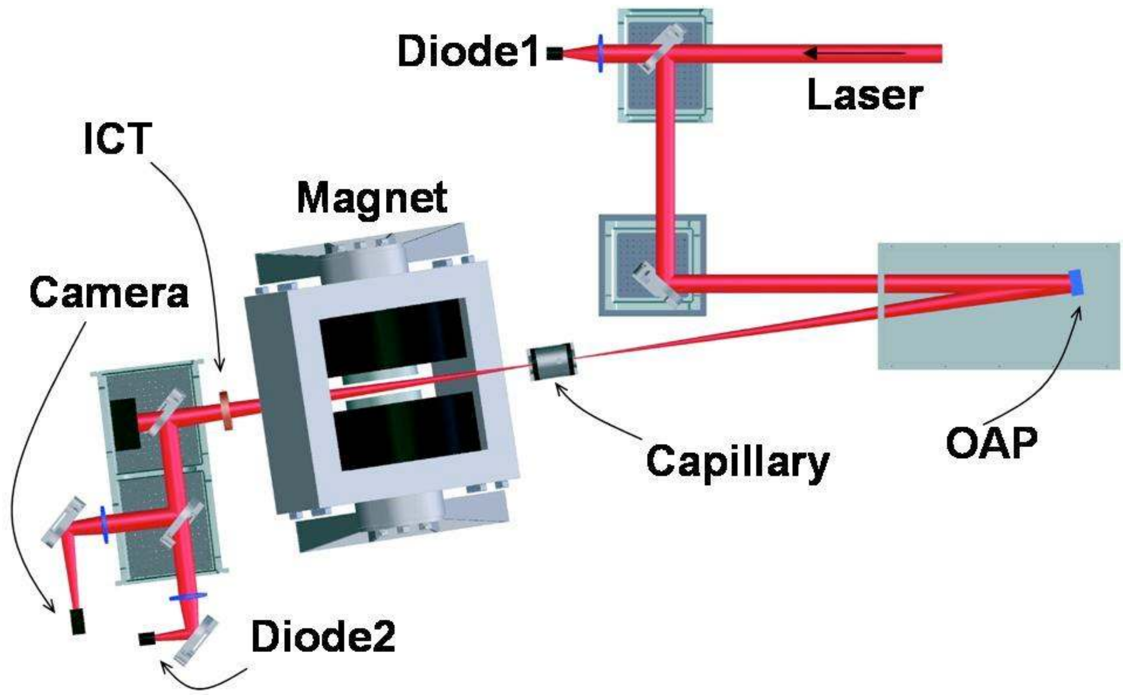

Figure 2. The measured transverse spatial profile of laser pulses with an input peak power of 40 TW at (a) the entrance (r_s = 26 μm) and (b) the exit (r_s = 33 μm) of the 3.3 cm long gas-filled capillary discharge waveguide. The small increase in spot size may be caused by imperfect mode matching.

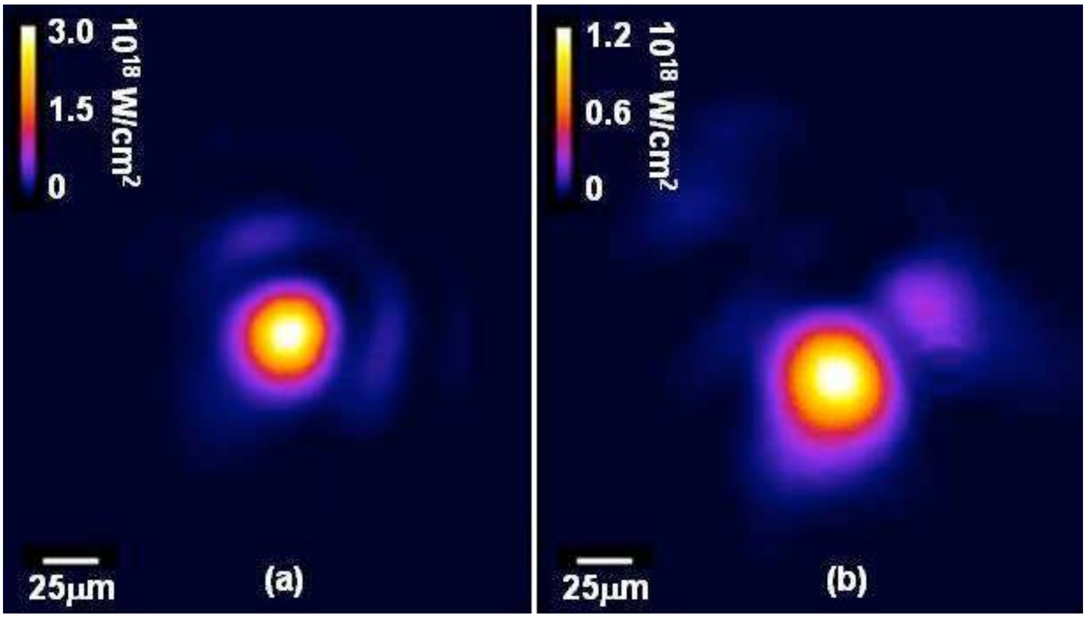

Figure 3. Single-shot electron beam spectrum of the capillary-guided accelerator. The spectrometer did not utilize an input slit, but the angular acceptance was limited by the transport beam pipe. The uncertainty in central energy associated with the finite acceptance angle is indicated.

Examples are shown of bunches at (a) $0.52^{+0.02}_{-0.015}$ GeV (4.2% rms energy spread, 1.2 mrad divergence rms, 150-300 pC charge) and (b) $1.0^{+0.08}_{-0.05}$ GeV (2.5% rms energy spread, 1.6 mrad divergence rms, 50-100 pC). The black stripe denotes the energy range not measured by the spectrometer. In (b) a second beam at 0.8 GeV is also visible.