Abstract

Laser plasma acceleration (LPA) up to 1 GeV has been realized at Lawrence Berkeley National Laboratory by using a capillary discharge waveguide. In this paper, the capillary discharge guided LPA system including a broadband single-shot electron spectrometer is described. The spectrometer was designed specifically for LPA experiments and has a momentum acceptance of $0.01 - 1.1$ GeV/$c$ with a percent level resolution. Experiments using a 33 mm long, $300 \, \mu m$ diameter capillary demonstrated the generation of high energy electron beams up to 1 GeV. By de-tuning discharge delay from optimum guiding performance, self-trapping and acceleration were found to be stabilized producing 460 MeV electron beams.

EXPERIMENTAL SETUP

The schematic of the experimental setup is shown in Fig. 1. The laser that was utilized was the TREX arm of the 10 Hz Ti:Al$_2$O$_3$ system of the LOASIS facility at LBNL. The laser beam was focused by a $\theta$25 off-axis parabolic mirror providing a typical focal spot size of $r_0 \approx 25 \, \mu m$ that contains 60% of the laser energy. Here, a Gaussian transverse profile of $I = I_0 \exp(-2r^2/r_0^2)$ is assumed. Full energy and optimum compression gives $P = 43$ TW, $\tau_m \approx 40$ fs full width half maximum (FWHM) intensity, calculated peak intensity $I_0 = 2P/\pi r_0^2 \approx 2.6 \times 10^{18}$ W/cm$^2$, and a normalized vector potential $a_0 \approx 8.6 \times 10^{-10} \lambda_{\mu m} I^{1/2}$ [W/cm$^2$] $\approx 1.1$. The capillary waveguide was laser-machined in sapphire plates. Hydrogen gas was introduced into the capillary using two gas slots as shown in Fig. 1(inset). A discharge was struck between electrodes located at each end of the waveguide, using a high voltage pulsed power supply with a 4 nF capacitor charged to between 15 and 22 kV. Measurements showed that a fully ionized, approximately parabolic channel was formed on axis [6]. This fully ionized feature was also confirmed by the absence of ionization induced blueshifting of the transmitted laser spectrum when a low power ($< 0.2$ TW) laser pulse was guided. The laser energy was monitored both before and after the interaction to evaluate the guiding efficiency and guided beam quality. The laser output spectrum was measured by a broadband optical spectrometer which covers a wavelength range of 320 to 1000 nm in a single shot.

The e-beams generated were characterized by an electron spectrometer. The electron spectrometer utilized a water-cooled round dipole electro-magnet Varian 4012A, which had a 65 mm gap and was powered by a Glass-
Figure 1: Schematic diagram of the capillary discharge-guided laser wakefield accelerator and diagnostics. The detailed description of the capillary discharge unit is in the upper inset. See manuscript for detailed information of the magnetic spectrometer.

The magnetic spectrometer allowed simultaneous measurement of the laser pulse and e-beam due to its large gap. The magnetic field was measured by a Hall probe along the mid-plane, and the effective radius, defined by $R_{e,f} = \left[ \int_0^{\infty} B_x(r)dr \right]/B_z(0)$, was found to be 195 mm with peak field $B_z(0) = 1.25$ T. The magnet deflected the electrons vertically downward onto two scintillating screens (LANEX Fast Back from Kodak) mounted on the exit flanges of the vacuum chamber. Four synchronously triggered 12-bit charge-coupled device (CCD) cameras (model Flea from Point grey research) imaged a 75 cm long (bottom) and a 45 cm long (forward) screens with F number 1.4 – focal length 4.8 to 6.4 mm video lenses, allowing simultaneous single shot measurement of electrons from 0.01 GeV to 0.14 GeV (bottom) and 0.17 GeV to 1.1 GeV (forward) with a peak magnetic field of 1.25 T. Spatial resolutions of those CCD cameras were measured to be 0.6 – 1 mm for the forward screen and ≃ 2.5 mm for the bottom screen. Stray laser light was blocked by ≃ 40 µm thick aluminum foil on the back of the screens. In addition, bandpass filters [central wavelength 550 nm, width 70 nm full-width half-maximum (FWHM)] were installed in front of each CCD camera to separate fluorescent light from the infrared laser light. To avoid electrons from hitting the CCD cameras directly, first-surface mirrors were used at 45° following the exit flanges, which separated fluorescent light from the electrons.

The imaging properties of the spectrometer were determined via the edge focusing. The displacement of the dipole magnet center with respect to the laser propagation axis was carefully chosen to provide the necessary edge focusing. One can achieve the minimum energy resolution and error in the determination of the absolute energy by observing e-beams at the foci in the dispersive plane. By having the laser propagation axis below (above) the magnet center, the edges provide converging (diverging) power in the dispersive plane, and diverging (converging) power in the non-dispersive plane. The stronger converging power in the dispersive plane provides a more compact system because the foci in the dispersive plane are closer to the magnet, while it results in a smaller angular acceptance due to the stronger diverging power in the non-dispersive plane. High energy e-beams become somewhat insensitive to edge focusing due to their rigidity, and their resolutions are determined mostly by their angular divergence. For observation of high energy e-beams, the forward view was arranged to achieve the desirable angular acceptance and system dimensions. The laser propagation axis was placed 25.4 mm below the magnet center to achieve desirable foci arrangement for the dispersive plane and reasonable angular acceptance. Note that the imaging (focusing) was achieved only in the dispersive plane. The bottom view was arranged (30 degree downward from the laser propagation axis) to observe e-beams as close to the calculated first-order foci in the dispersive plane as possible.

In order for a performance evaluation, the electron trajectories on the mid-plane (reference trajectories) were computed by calculating the deflection angle based on the Lorentz force. The input midplane field was generated through a 2D interpolation of the measured field profile along the radial axis. For each trajectory, the 6-dimensional e-beam properties were calculated by using the arbitrary-order beam dynamics code COSY INFINITY (COSY) [11]. Due to the collimator-free scheme, the measured momentum resolution contained a contribution from the e-beam divergence, which depended on the accelerator configuration and parameters such as the laser energy or the capillary length and diameter. As a result, the e-beam divergence showed shot-to-shot fluctuations. Therefore, the momentum resolution and the energy spread were evaluated for each shot with the following procedure. From the computed imaging properties, the horizontal beam divergence $\sigma_{x,0}$ was calculated from the measured horizontal beam size $\sigma_{x,1}$ with a given beam size at the source, $\sigma_{x,0}$ and $\sigma_{y,0}$, which were assumed to be the same size as the laser output mode size. The effect of the source size on the image was almost negligible since the beam size at the source was smaller by an order of magnitude than the typical product of beam divergence and propagation distance. By assuming an axisymmetric e-beam profile (i.e., equal horizontal and vertical divergence), the vertical beam divergence $\sigma_{y,0} = \sigma_{x,0}$ was obtained and used to calculate the vertical beam size at the screen with a specific central energy and zero energy spread, $\sigma_{y,1,mono}$. The image size gave the intrinsic resolution of the ESM, $\delta E_{mono}$. The real energy spread of an e-beam $\delta E_{beam}$ was then calculated by deconvolving the effect of finite divergence from the measured e-beam profile $\delta E_{img}$ using $\delta E_{img} = \sqrt{\delta E_{beam}^2 + \delta E_{mono}^2}$. The momentum resolutions for $\sigma_{x,0} = \sigma_{y,0} = 1$ and 2 mrad e-beams are shown in Fig. 2, where the beam profile was assumed to be a Gaussian distribution with $\sigma_{x} = \sigma_{y} = 20$ µm. The momentum resolution is below 2% (4%) for a 1 mrad (2 mrad)
The divergence beam in the energy range of the ESM.

The collimator-free scheme also introduced an uncertainty in the determination of the absolute energy. The energy of an e-beam with positive (negative) incident angle in vertical axis would be measured higher (lower) than the actual energy. The errors in the determination of the absolute energy. The errors in the determination of the absolute energy for angles ranging from -8 mrad to +8 mrad. Horizontal axis is the kinetic energy of the electron beam for a peak magnetic field of 1.25 T. The geometrical acceptance of the spectrometer is also shown (solid line).

RESULTS

In 2006, generation of e-beams with energies of 1 GeV was reported for a 33 mm long, 300 µm diameter capillary with three gas slots [7, 8]. Similarly to these results, a parameter regime where e-beams with energies of up to 1 GeV were produced was found here for a 33 mm long, 300 µm diameter capillary with two gas slots. Representative single shot e-beam spectra are shown in Fig. 4(a)-(c). The plasma density was \( n_0 \sim 5.3 \times 10^{18} \text{ cm}^{-3} \), the laser parameters were 1.5 J (86 mJ rms), 46 fs (\( \alpha_0 \sim 0.93 \)), applied voltage was 18 kV, and the discharge delay was \( t_d \sim 580 \text{ ns} \). In this parameter regime, 51 shots were taken, and 37 shots produced electrons above 400 MeV. The mean peak energy was 713 MeV, and mean charge was 6 pC. Since e-beams were often observed with a low energy tail in this regime, electrons with energy above 400 MeV were taken into account for the analysis. The mean laser transmission was 65%.

The peak energy and maximum energy versus total charge for 33 mm long, 300 µm diameter capillary are shown in Fig. 4(d). The peak energy showed clear dependence on the charge, while the maximum energy was somewhat insensitive to charge. There are several possible

Figure 2: Momentum resolutions for \( \sigma_{x,0} = \sigma_{y,0} = 1 \) and 2 mrad electron beams. Horizontal axis is the kinetic energy of the electron beam for a peak magnetic field of 1.25 T. The input beam size was assumed to be a Gaussian distribution with \( \sigma_{x,0} = \sigma_{y,0} = 20 \mu m \).

Figure 3: Errors in the determination of the absolute energy for angles ranging from -8 mrad to +8 mrad. Horizontal axis is the kinetic energy of the electron beam for a peak magnetic field of 1.25 T. The geometrical acceptance of the spectrometer is also shown (solid line).
In experiments using a 15 mm long, 200 µm diameter capillary, the guiding performance and e-beam generation showed clear dependence on the discharge delay. The input laser parameters were 0.9 J (36 mJ rms), 41 fs ($a_0 \sim 0.8$), and the plasma density was $2.5 \times 10^{18}$ cm$^{-3}$, and the discharge delay was $\sim 680$ ns.}

Several mechanisms could be responsible for the enhancement of blueshifting, laser transmission loss, and electron trapping observed for longer discharge delay. For longer discharge delay, the degree of ionization, depth of optical spectrum. For e-beam properties, relatively high energy ($\sim 300$ MeV), low charge ($< 10$ pC) quasi-monoenergetic e-beams were observed with shorter discharge delay while broadband high charge ($\sim 100$ pC) beams were observed with longer delay. Note that by using higher density plasma ($n_0 \sim 3.7 \times 10^{18}$ cm$^{-3}$), e-beams were observed for shorter discharge delay without significant blue shift in transmitted optical spectrum.
SUMMARY

In summary, the capillary discharge guided laser plasma accelerator (CDG-LPA) system including the broadband single-shot electron spectrometer was described. The ESM has the momentum acceptance of $0.01 \sim 1.1$ GeV/c with a percent level resolution. Relativistic e-beam generation via a CDG-LPA was studied by using 15 mm long, 200 $\mu$m diameter and 33 mm long, 300 $\mu$m diameter capillaries. Generation of quasi-monoenergetic e-beams up to 1 GeV was observed from the the 33 mm long capillary, and up to 300 MeV was observed from the 15 mm long capillary. By using longer discharge delay, self-trapping was stabilized. This regime could be used to design a stable self injection CDG-LPA. While reproducible beams have been observed in tightly controlled parameter regime, a controlled mechanism for injection will be important to enhance the LPA performance, such as longitudinal density tailoring [10].

REFERENCES