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Citation: AIP Conference Proceedings **1507**, 341 (2012); doi: 10.1063/1.4773719
View online: http://dx.doi.org/10.1063/1.4773719
View Table of Contents: http://scitation.aip.org/content/aip/proceeding/aipcp/1507?ver=pdfcov
Published by the AIP Publishing

Petawatt-laser-driven wakefield acceleration of electrons to 2 GeV in 10^{17}cm^{-3} plasma

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Abstract. Electron self-injection into a laser-plasma accelerator (LPA) driven by the Texas Petawatt (TPW) laser is reported at plasma densities 1.7 - 6.2 x 10^{17} cm^{-3}. Energy and charge of the electron beam, ranging from 0.5 GeV to 2 GeV and tens to hundreds of pC, respectively, depended strongly on laser beam quality and plasma density. Angular beam divergence was consistently around 0.5 mrad (FWHM), while shot-to-shot pointing fluctuations were limited to ±1.4 mrad rms. Betatron x-rays with tens of keV photon energy are also clearly observed.

Keywords: wakefield acceleration, Texas petawatt laser, 2GeV electron, betatron radiation.
PACS: 52.38.Kd, 41.75.Jv

INTRODUCTION

Previous tabletop laser plasma accelerators (LPAs) trapped and accelerated ambient electrons quasi-monoenergetically up to 1 GeV [1], with high-energy tails extending to 1.4 GeV [2]. However, because of the need to drive LPAs resonantly using available terawatt (TW) lasers with pulse durations of tens to hundreds of fs, these LPAs operated at plasma density $n_e > 10^{18}$cm^{-3} [3, 4]. At these densities, electron dephasing length d_{ph} and pump laser depletion length d_p were limited to about 1 centimeter [5], and electron energy gain to about 1 GeV [1]. To accelerate electron to multi-GeV energy with LPA, the electron acceleration length has to be extended to multi-cm, which can be realized by reducing plasma density to ~10^{17} cm^{-3}. However, TW lasers with Rayleigh range (Z_R) of mm and pulse duration 30 – 60 fs are not sufficient to self-guide ($P/P_{cr} \sim 1$ at $n_e = 10^{17}$cm^{-3}, where P_{cr} is critical power for self-focusing) and support a plasma bubble over multi-cm lengths. To solve these problems, a PW laser [6], operating at pulse duration around 150fs, is required to satisfy the resonant driving condition and extend LPAs to multi-centimeter lengths at $n_e \sim 10^{17}$cm^{-3}. Simulation [7] showed that a 150 fs, 1 PW laser pulse could fully blow out a plasma bubble, trap electrons and accelerate them up to 7 GeV through laser self-guiding ($P/P_{cr} \sim 20$) at n_e of several 10^{17} cm^{-3}.

In this paper, we reported the performance of LPAs driven by the Texas Petawatt (TPW) laser. Plasma electrons are successfully injected into and trapped by the plasma bubble, and accelerated up to 2 GeV with a strong quasi-mono-energetic feature in the energy spectrum. In most shots with electron generation, significant x-ray emission at estimated photon energy 20 to 60 keV, due to betatatron oscillation of accelerating electrons inside the plasma bubble, is observed.

EXPERIMENTS

Fig.1 shows the setup of TPW-driven wakefield electron acceleration experiments. With an f/40 spherical mirror, a TPW laser pulse was focused on the front aperture (r_0 = 1.0 mm) of a 7 cm-long gas cell, which was prefilled with pure (99.99%) He gas at a few Torr pressure, measured with a fast sensor in the gas cell. Transversely scattered, spectrally filtered pump laser light was imaged with a lens and CCD camera. A 25 µm thick Al deflector steered the laser pulse exiting the back aperture of gas cell to a beam dump. Meanwhile, a 1.1 Tesla magnet dispersed accelerated electrons that also exited the back aperture in a horizontal plane perpendicular to the laser polarization. High-energy (E > 0.5 GeV) electrons passed through the Al laser beam deflector with minimal scatter and were recorded by image plates (IPs), lanex and plastic scintillator detectors. To eliminate ambiguity in electron energy, especially at > 1 GeV, caused by small variations in electron launch angle (few mrad), two sets of precisely

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AIP Conf. Proc. 1507, 341-344 (2012); doi: 10.1063/1.4773719

positioned fiducial tungsten wires were placed between magnet and IPs. Using the X-ray and electron shadows of fiducials on the IPs, magnetic spectrometer resolution of ±100 MeV (2σ) at 2 GeV was obtained. Low-energy (0.15 GeV < E < 0.35 GeV) electrons were recorded by a separate IP mounted before the laser beam deflector. X-rays (E ~ tens of keV) originating from betatron oscillations of accelerating electrons inside the plasma bubble co-propagated with electrons before the magnet, and were recorded by the same IP used for high-energy electrons.

To maximize laser power coupled into the plasma, the average focal plane of full power TPW shots was varied systematically with respect to the front aperture of gas cell until acceleration was optimized. At the optimized point, generation of ~GeV electron beams became about 90% reproducible from shot to shot. The rms shot-to-shot fluctuation of vertical beam position was 1.4 mrad over more than 30 shots. The peak laser power used in gathering these statistics was 500 to 800 TW, while plasma density n_e ranged from 1.7 to 6.2 x 10^{17} cm^{-3}. Electron charge and peak energy varied from shot to shot in the range of hundreds of pC and 0.5 - 2.0 GeV, respectively, and depended strongly on the focused laser beam quality, focus plane location, laser power, and plasma density for each shot. However, acceleration to GeV energy succeeded consistently at this power level (P/P_{cr} ~ 10 to 20) because of strong laser relativistic self-focusing, which triggered plasma bubble formation and size evolution, and thus electron injection and acceleration.

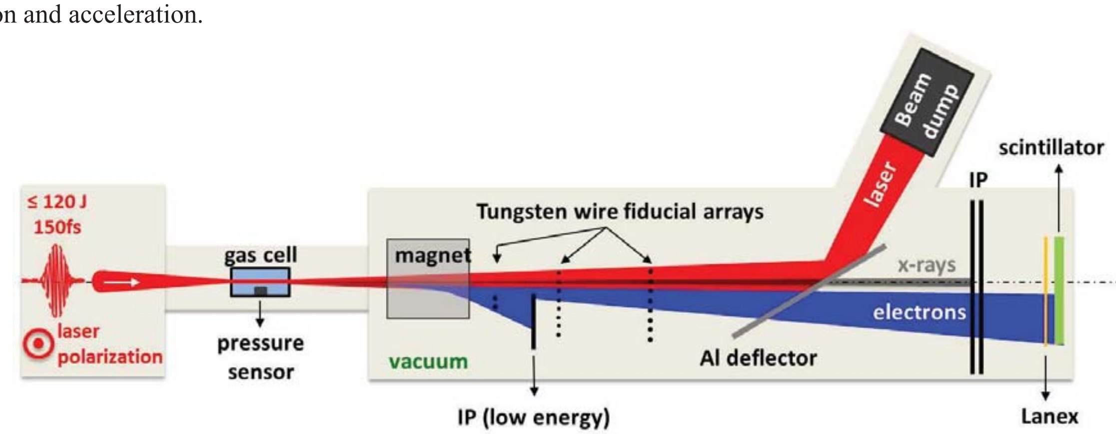

FIGURE 1. Schematic setup of Texas Petawatt laser-driven plasma electron accelerator. The distance from gas cell exit to image plates (IPs) is about 2.7 m.

EXPERIMENTAL RESULTS AND DISCUSSION

I. High Energy Electron Generation

Figure 2 presents electron energy spectra of three typical shots acquired from TPW-driven LPA experiments. Fig. 2a shows the photo-stimulated luminescence (PSL) read directly from the IP for a shot with a quasi-monoenergetic peak at ~1.7 GeV, obtained at plasma density n_e = 3.4 x 10^{17} cm^{-3}. Some dark current of lower energy electrons (0.5-1.3 GeV) is also evident, with a high charge peak around 0.4 GeV appearing in the vertically integrated spectrum in Fig. 2b. Vertical divergence of the beam is nearly energy-independent, and only ± 0.5 mrad FWHM, significantly smaller than in previous GeV LPAs [2, 4] but typical of all shots in the current experiments. The inset of Fig. 2b shows that some electrons were accelerated up to 2.2 GeV. Fig. 2c and 2d show results of two other typical shots. In Fig. 2c, one of our highest density shots (n_e = 5.2 x 10^{17} cm^{-3}), electron energy peaks at 1.3 GeV and 0.7 GeV, with more charge in the low energy peak. This indicates that electron injection was not localized --- *i.e.* one bunch was injected early and accelerated to 1.3 GeV, a second bunch with more electrons injected later and only accelerated up to 0.7 GeV. Fig. 2d shows a typical result at low plasma density (n_e = 2.1 x 10^{17} cm^{-3}), one order of magnitude lower than previous reports [4, 5]. In this shot, electrons were successfully injected and trapped in LPA and accelerated to a peak ~ 1 GeV. However, compared to the shots in Figs. 2b and 2c, the portion of charge in the low-energy background current is higher, indicating that the plasma bubble was still evolving up to the end of the plasma, and did not reach the mode-matched regime. The lowest plasma density n_e, at which we observed electron injection and acceleration, is n_e = 1 x 10^{17} cm^{-3} [8]. Results featuring quasi-monoenergetic peaks at higher energy up to 2.0 GeV will be reported elsewhere.

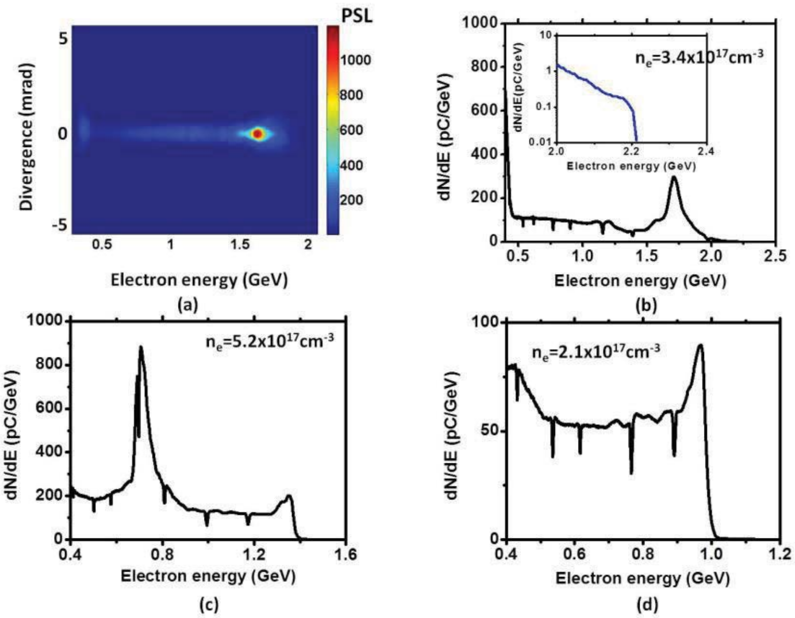

FIGURE 2. Experimental results of TPW-driven wakefield electron acceleration. **(a)** Raw IP data for a shot with quasi-monoenergetic peak at 1.7 GeV. **(b)** Vertically integrated electron energy spectrum (dN/dE) of the shot in Fig. 2a; inset: detail of energy spectrum over 2 GeV. **(c)**, **(d)** Electron energy spectra (dN/dE) of two other laser shots. Experimental conditions for those shots are: n_e=3.4x10^{17}cm^{-3}, P_{laser} = 800 TW in (b); n_e = 5.2 x 10^{17} cm^{-3}, P_{laser} = 677 TW in (c); n_e = 2.1 x 10^{17} cm^{-3}, P_{laser} = 815TW in (d). The electron energy distribution and charge are strongly dependent on the laser pulse quality, including power, focal spot and pulse duration etc., and plasma density n_e.

II. X-rays from Betatron Radiation

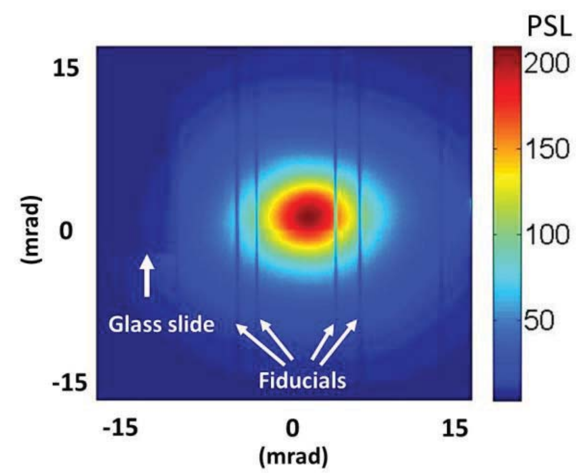

FIGURE 3. Image of betatron x-ray emission from shot in Fig. 2a, recorded with high energy IP shown in Fig.1. The darker square area on the top left is due to attenuation of a glass slide, those line shape shadows are due to attenuation of tungsten fiducial wires.

Fig. 3 shows the x-ray image acquired from shot correspondent to Fig. 2a. These betatron x-rays, generated by the high-energy electron beam wiggling in the plasma bubble, passed through the Al deflector and were detected by IP covered with another Al sheet. The total thickness of Al is around 373 μm. A 1.4 mm thick glass slide, which was placed in the x-ray path before laser beam deflector, attenuated the x-ray and left a shadow on the x-ray image (labeled with white arrow). The 127 μm thick tungsten fiducial wires, visible in the middle of x-ray profile, also significantly attenuated the x-rays, and cast clear shadows (labeled with white arrows) on the IP image. Considering the attenuation caused by glass slide and tungsten wires, the x-ray photon energy can be roughly estimated, and ranges from 20keV to 60keV. More detailed x-ray spectrum analysis requires multi-thickness layers of filters to calibrate the photon energy distribution. In practical units, the betatron radiation strength parameter α_β and critical energy $\hbar\omega_\beta$ are given by [9]

$$\alpha_\beta = 1.3 \times 10^{-10}[\gamma n_e(cm^{-3})]^{1/2} r_\beta(\mu m) \qquad (1)$$
$$\hbar\omega_\beta(keV) \approx 1.1 \times 10^{-23}\gamma^2 n_e(cm^{-3}) r_\beta(\mu m),$$

where n_e is the plasma density, γ is Lorentz factor for electron and r_β is betatron radius. In this experiment, $\alpha_\beta > 1$, therefore, the x-ray spectrum is continuous distributed with critical energy $\hbar\omega_\beta$. For values $\gamma = 2000$, $n_e = 5 \times 10^{17}$ cm^{-3}, $\hbar\omega_\beta$ is approximately 40 keV for $r_\beta \sim 2$ μm. This betatron radius is consistent with values obtained in PIC simulations of our experiment, which will be reported elsewhere. Significantly, it is much smaller than the bubble radius (~ 30 μm), and much smaller than the lateral extent of electron injection expected from inner-shell ionization of a high-Z impurity gases. This evidently accounts for the unusually small angular beam divergence observed here. In Fig. 2a and 2b, most electron charge is concentrated in the range of 0.4 - 1.5 GeV, which contributes primarily to betatron radiation at photon energies 20 – 60 keV.

SUMMARY

In summary, we observed electron self-injection and acceleration in the TPW-driven LPA at plasma densities ranging from 1.7 to 6.2 x 10^{17} cm^{-3}. High quality electron beams are quasi-monoenergetic with energy peak up to 2 GeV, well collimated (< 0.5 mrad vertical divergence), contain hundreds of pC charge and have good pointing stability (1.4 mrad rms over 30 shots). Betatron x-rays generated from high-energy electrons wiggling in the wakefield were also observed on most shots. Photon energy of betatron radiation is 20-60 keV, and appear to originate primarily from wiggling of electrons around 1 GeV.

ACKNOWLEDGEMENTS

This work was supported by U.S. DoE grants DE-FG03-96ER40954 and DE-FG02-07ER54945.

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