GENERATION OF STABLE GeV-CLASS ELECTRON BEAMS FROM LASER-PLASMAS AND THEIR APPLICATIONS IN COMPACT FELS

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Abstract

Laser-plasma produced by ultraintense femtosecond laser pulses is an emerging particle acceleration technology which promises a revolutionary impact in the field of high-energy particle accelerators [1]. Here we present results that demonstrate the first generation [2] of stable and reproducible GeV-class electron beams from a few-millimetres long plasma channels produced by self-guided laser pulses in gas jet targets. Qualities of those electron beams are now approaching the requirements for applications such as compact synchrotrons and FELs. Based on our laser-plasma electron beams, we are planning on building undulators at APRI aiming to realize compact synchrotron and FEL light sources.

INTRODUCTION

Outstanding advances in laser technology have led a growing number of laboratories around the world to develop laser facilities capable of producing ultrashort laser pulses in the multi TW and up to the PW-class at a reasonable repetition rate. Laser-plasma interactions at the relativistic intensity of $\geq 10^{18}$W/cm^2 reveal interesting nonlinear optical plasma phenomena. When an ultrashort terawatt laser pulse is focused in an underdense plasma, the radiation pressure of the laser pulse excites large-amplitude electrostatic plasma waves, which can trap and accelerate electrons to relativistic energies in short distances. This is known as the laser wakefield acceleration (LWFA) mechanism [1] which is a subject of great importance for its potential in developing new generation of high-energy compact electron accelerators. Generation of high-quality electron beams produced by the LWFA mechanism depends on careful optimization of the laser-plasma parameters such as the laser intensity, pulse duration, focal spot size and quality, plasma density profile, interaction length, etc. Supersonic gas jets have been traditionally used as targets for LWFA research because they can support the propagation of the laser beam for long enough distances as a result of the effect of self-guiding. They have preference over capillary targets because they are more stable, easily aligned and the simplicity in monitoring the laser-plasma interaction volume.

In this paper, using APRI's 100 TW-laser facility and supersonic helium gas jet, we report on the generation of stable quasimonoenergetic well collimated electron beams having energies up to the GeV-class from ~ few-mm long plasma channels.

EXPERIMENTAL SETUP

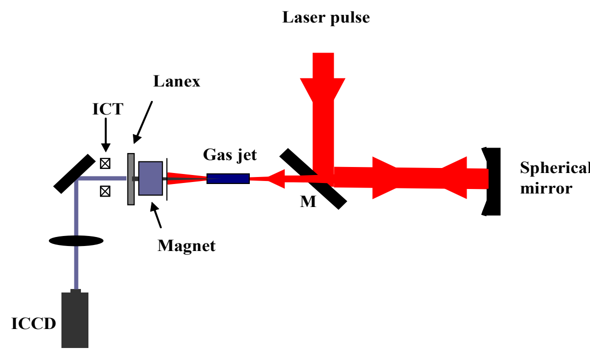

Figure 1: Schematic diagram for the laser wakefield acceleration experiment at APRI.

Our experiment was carried out at the Advanced Photonics Research Institute (APRI) using a table-top Ti:sapphire laser system based on the chirped pulse amplification (CPA) technique; the laser system delivers up to 100 TW pulses at a 10 Hz repetition rate. The laser pulse duration was 35 fs and laser power was in the range 27- 50 TW. With the help of an adaptive optics system [3], the laser beam was focused at a point above the nozzle of 4 mm-long pulsed supersonic helium gas jet; to a spot size of 22 μm full-width at half-maximum (FWHM) using a spherical mirror having a focal length of 1.5 m (Fig. 1). The Thomson scattered light emitted from the interaction region were used to monitor the laser self-guidance and channel formation. Then, the emitted electron beam energy was measured using a strong dipole magnet in conjunction with a lanex phosphorus screen imaged to an intensified charge-coupled device (ICCD), and the experiment was performed in single shot mode.

EXPERIMENTAL RESULTS

Electron Energy Scaling

At the laser power of 27 TW and the plasma density of $n_e \approx 7\times10^{18}$ cm^{-3}, the generated electron beam was quasimonoenergetic with a central energy of ~ 180 MeV, as shown in Fig. 2 (a). By increasing the laser intensity to 37 TW while the plasma density was in the range of $\approx 6.6\times10^{18}$-7.4×10^{18}cm^{-3} we could obtain electron beams having a central energy of about 260 MeV, as shown in

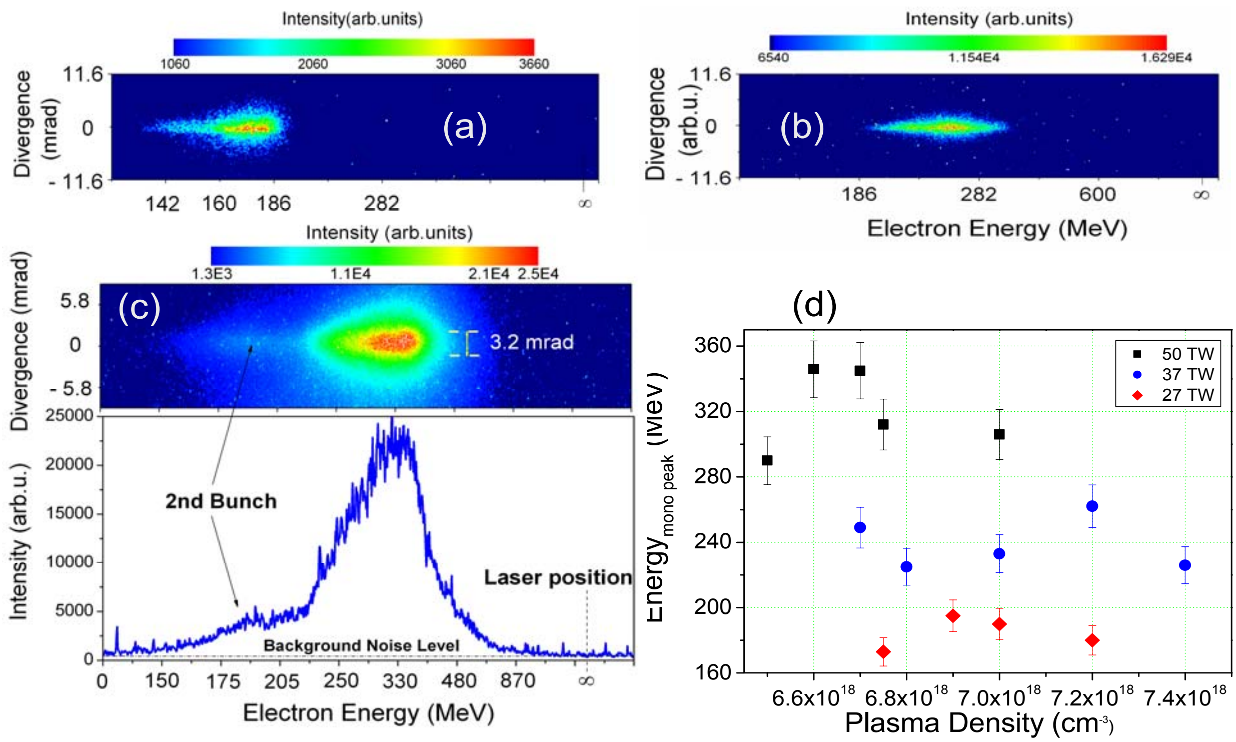

Figure 2: Quasimonoenergetic electron beams produced in 4 mm-long gas jet at various laser powers (27-50 TW) and plasma densities $6.5 \times 10^{18} - 7.5 \times 10^{18}\, cm^{-3}$.

Fig. 2(b). Again, by further increasing the laser power to 50 TW while the plasma density was ~ 6.6 $\times 10^{18}$cm^{-3}, the central energy of the quasimonoenergetic electron beam moved to 350 MeV and the maximum energy increased up to 880 MeV (GeV-class), as shown in Fig. 2 (c). The total charge of the electron beam in this case was measured to be about 500 pC and its divergence angle was about 5 mrad (FWHM). The laser-plasma channel lengths were observed to be longer at higher laser powers due the self focusing, channels of lengths (±100 μm) of 2.5 mm, 3.5 mm and 4 mm were produced at the laser powers of 27 TW, 37 TW and 50 TW, respectively. Those channel lengths were approximately equal to the dephasing lengths for the plasma densities mentioned above, and this was important in obtaining quasimonoenergetic spectrum. Experimental results of Fig. 2 clearly shows the doubling of a quasimonoenergetic electron beam energy by doubling the laser power, i.e., the electron beam energy scales as $\sim a_0^2$ (for given plasma parameters). This is an important experimental result on this scaling for the multi-hundreds MeV quasimonoenergetic electron beam generation by a LWFA.

Stability of quasimonoenegetic electron beams

3D-PIC simulations have predicted that plasma bubble regime has a highly stable particle acceleration structure. Additionally, in recent experiments [4] it was noted that long laser focusing geometries (f/ number 21.4, in our case) are necessary for the stability of the laser pulse propagation through the plasma and the generation of stable wakefields and electron beams. Motivated by those predictions, we have performed a stability test for an electron beams produced by our laser-plasma accelerator with the following parameters: laser intensity of 37 TW, 4-mm long gas jet and plasma density of 7× 10^{18} cm^{-3}. Figure 3 shows raw images of the electron beam energy spectra obtained in 10 consecutive shots. The averaged peak energy, and the energy fluctuation were ~ 237 MeV and ~ 5%, respectively. The average charge per electron bunch and the charge fluctuation were ~ 205 pC and ~ 32 %, respectively. The measured fluctuation in the laser energy during those 10 consecutive shots was ~ 4.5 % which is very close to the electron beam energy fluctuations. This leads to the conclusion that ultra stable electron beam energies can be realized by stabilizing the shot to shot laser pulse energy.

Plasma channels observed in these shots were very similar to each other and reproducible. Each channel had a single filament with a length of ~ 3.5 mm. Based on single laser pulse LWFA experiments; our stability test shows quite stable quasimonoenergetic electron generation in the energy range of 240 MeV.

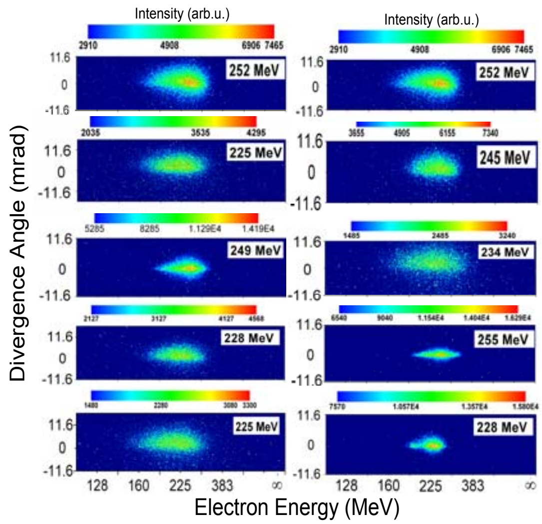

Figure 3: Quasimonoenergetic electron beams of ten consecutive shots

POTENTIAL APPLICATION TO FREE ELECTRON LASERS

Recently Schlenvoigt et al. [5] succeeded to generate synchrotron radiation by injecting an electron beam from a laser-plasma accelerator into 1-m long undulator. The electron beam parameters were: energy- 64 MeV, energy spread 5.3 %, charge- 28 pC and normalized emittance of 1.3 π mm.mrad. The synchrotron radiation wavelength was 790 nm in the visible range. In this experiment, the emission wavelength scales with the beam energy just as the theory predicts. This suggests the generation of much shorter wavelengths (EUV-x rays) by this technique is straight forward.

By extending the undulator length to 3 m, and feeding it with our electron beam of energy 350 MeV, we expect to generate synchrotron radiation of wavelength about 23 nm which can be shortened to few nm by using more compact undulator with a shorter period. So, it is clear and has been proven that the existing laser–plasma electron beams can generate synchrotron radiation, we expect this will grow in the near future as there are a lot of groups around the world generating multi-hundred MeV electron beams from laser-plasma interactions. The next important step is to use the laser-plasma electron beams for generating free electron laser. This seems possible in the future because the existing laser-plasma electron beam parameters are only about 1 order of magnitude far from the required parameters for FEL lasing. For example, the beam energy spread required for lasing is about 0.1 % while it is now about 1 % for laser-plasma electron beams. As for the beam energy and emittance, already the laser-plasma electron beams are good enough: energies up to the GeV and emittences of the order of 1 π mm. mrad are already available.

So in conclusion, we believe that the only two parameters which require to be enhanced are the beam charge and energy spread. Currently, we are entering the era of using multi-hundred TW and up to PW lasers in the laser acceleration research and this in addition to using well controlled plasma conditions, will sure lead to enhance the beam parameters to meet the FEL requirements. This will surely be a great achievement because this kind of FEL will be compact and cheap and will be applied in unlimited number of applications in science, medicine and technology.

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