EMITTANCE AND ENERGY SPREAD MEASUREMENTS OF RELATIVISTICS ELECTRONS FROM LASER-DRIVEN ACCELERATOR

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Abstract

In this paper, we present a single-shot transverse emittance measurement for 125 ± 3 MeV electron beam using pepper-pot technique. A normalised transverse emittance as low as 1.1 ± 0.1 π-mm-mrad was measured using this method. Considering 60 consecutive shots, an average normalised emittance of $\varepsilon_{rms,x,y}$=2.2 ± 0.7, 2.3 ± 0.6 π-mm-mrad was obtained, which is comparable to a conventional linear accelerator. We also obtained high energy monoenergetic electron beam with relative energy spread less than 1%. The measured transverse emittance characterises the quality of an electron beam generated from laser-driven accelerator. Brightness, parallelism and focusability are all functions of the emittance. The low emittance and energy spread indicates that this type of accelerator is suitable for compact free electron laser driver.

INTRODUCTION

Laser-driven acceleration has been drawing much attention in the particle physics community for the past years because of its possibility to develop table-top, high-energy accelerators. This type of accelerator depends on the interaction of high intense laser ($a_o \approx 1$ for λ_{laser}=1 μm) and plasma. As the laser pulse propagates through plasma, it experiences self-compression and self-guiding as it exceeds the threshold of critical power for relativistic self-focusing,

$$P_{crit} = 17\gamma_g^2 [\text{GW}] \tag{1}$$

where $\gamma_g = \omega_o/\omega_p$ is the Lorentz factor associated with the group velocity of the laser pulse and ω_o and $\omega_p = \sqrt{n_e e^2 / m_e \varepsilon_o}$ are the laser and plasma frequencies, respectively. The relativistic self-focusing causes the intensity to grow (from a_o = 1 to a_o > 2) forcing the plasma electrons to be expelled from the laser axis. The combination of these nonlinear effects leads to the formation of plasma cavity termed as 'bubble'. The expelled electrons move around outside the bubble and if they are in phase with the field of the bubble, will be self trapped and accelerated with maximum energy of

$$\gamma_{max} = 2\gamma_g^2 a_o / 3 . \tag{2}$$

Compared to conventional linear accelerators, plasma can sustain high electric field (>100 GVm^{-1}) without breakdown; therefore accelerating high energy electrons at small scale [1]. Several groups have presented acceleration of electrons with energies ranging from 80 MeV to 1 GeV in few mm-cm acceleration lengths [2-5]. These electrons can be used as a source for synchrotron radiations having spectral range from visible to VUV [6-7]. By further improving the quality and stability (effectively increasing the brightness) of the electrons, they can be a potential driver for compact FELs producing radiation in x-ray range.

In this report, we present diagnostics to characterise the laser-driven electron beams from the Advanced Laser-Plasma High-energy Accelerator towards X-ray (ALPHA-X) beamline. We perform direct way of showing the electron beam's high-brilliance by measuring its transverse emittance and energy spread.

Beam Emittance

The brightness and quality of an accelerator is defined by the emittance. A low emittance signifies that the electron beam has high focusability and capable of propagating for a long distance at a small divergence. Knowledge of emittance allows us to determine the evolution of the electron beam at any particular location without the need of individual particles trajectories. Emittance can be loosely defined as the volume occupied by the particles in the phase space (momentum-position coordinates. In this paper, we considered the high density core of the particles distribution by getting the root mean squared (rms) value of the emittance, given as,

$$\varepsilon_{rms}^{n} = \frac{1}{m_o c}\sqrt{\langle \Delta x^2 \rangle \langle \Delta p_x^2 \rangle - \langle \Delta x \Delta p_x \rangle^2} \tag{3}$$

with m_o as the rest mass of an electron, c is the speed of light, $\Delta x = x - \langle x \rangle$ and $\Delta p_x = p_x - \langle p_x \rangle$.

For low-energy beam, quadrupole scanning is often used for measuring the transverse emittance. The beam matrix is obtained by measuring the beam size at different transport locations or by varying the focusing strength of the quadrupoles. However, for high energy electrons, pepper-pot technique is preferred because it is more robust and less prone to space charge effect. This method can give information about the beam profile and divergence at the same time in a single measurement. Similar to quadrupole scan, pepper-pot method is a destructive diagnostic tool as it introduces a screen to stop the beam. A very sensitive detecting system (with high resolution camera) is also necessary since only a small portion of the beam (~1%) is obtained.

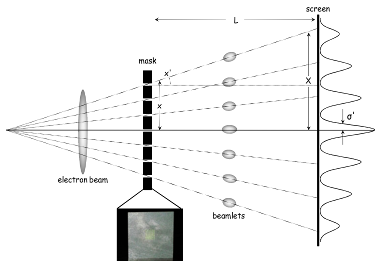

Figure 1: Schematic diagram of pepper-pot transverse emittance measurement technique.

In the pepper-pot technique, apertures are used to indirectly measure the divergence using the spatial distribution of the beam. Figure 1 shows a schematic diagram of this method. The electron beam is passed through a mask consisting of a two-dimensional array of identical apertures. The individual smaller 'beamlets' propagating through the mask are imaged onto a scintillating screen. The beam shape in each position-divergence coordinate in the trace-space is precisely known.

EXPERIMENTAL SETUP

The ALPHA-X beamline uses a CPA-driven laser system ($\lambda_{central}$ = 800mn, 35fs). It is focused to a 20 μm beam spot using an f/18 spherical mirror giving an intensity on target of $I_o = 2 \times 10^{18}$ W-cm^{-2} corresponding to a normalised vector potential $a_o = 8.5 \times 10^{-10}\ \lambda(\mu m)\ I_o^{1/2}$(W-cm^{-2}) ≈ 1.0. The laser propagates through a 2 mm supersonic Helium gas jet with an ionised plasma density of $n_e \approx 10^{19}$ cm^{-3}. The electron beam is monitored on removable LANEX phosphor screens (refer to Fig. 2).

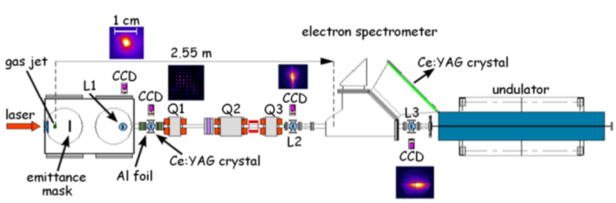

Figure 2: The ALPHA-X schematic setup. The electron beam, are imaged on the LANEX screens (L1, L2, L3) and focused through an electron spectrometer using a triplet of quadrupole lenses (Q1, Q2, Q3).

The electron energy is measured using an electron spectrometer that has a current-induced electromagnet. The design is based on Browne-Buchner where the electron beam can be focus on both the horizontal and vertical planes leading to high resolution spectrum. A combination of two triple quadrupole lenses is developed to focus the electron beam at the entrance slit of the spectrometer. A varying current is supplied to the electromagnets to scan the electron energy spectra.

The optimised design for the mask and holes for transverse emittance measurement are determined by GEANT4 simulation. The simulation predicts that a 125 μm tungsten sheet is suitable for a 125 MeV electron beam. The mask is composed of 27 x 27 laser drilled holes, each with a diameter of 25 ± 5 μm and separated by a distance of 150 μm. It is placed 29.5 cm from the gas jet and is attached to a rotation stage so that it can be removed automatically when we want to measure the electron's energy spectrum. A 100 μm thin YAG:Ce (with 10 μm resolution) crystal screen is located 61 cm after the mask to detect the outgoing electron beams. The scattering due to the laser light is blocked using a thin Al foil that is placed a few mm from the screen. At this position, the scattering effect of Al foil on the electrons is negligible compared to the beamlet size produced by the mask. The spots on the screen are then imaged onto a 14 bit CCD camera.

RESULTS

The electron beam from this accelerator shows a good pointing stability as there is less shot to shot variation of the central spot. Figure 3 shows the statistical distribution of the electron beam's horizontal and vertical positions. For 100 consecutive shots, the calculated spread is less than one spot size (σ_x = 1.4 mrad and σ_y = 1.3 mrad), implying that the electron beam is highly directional and stable. The difference in the pointing stability of x and y is expected since the laser is polarised horizontally, thus giving an additional oscillation along the x axis.

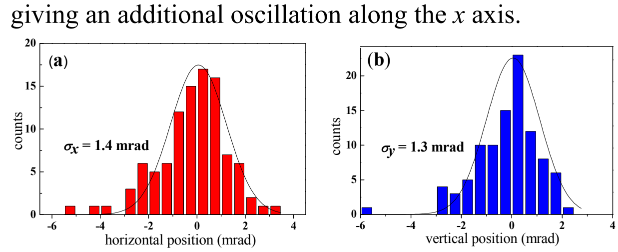

Figure 3: A statistical calculation for the pointing stability of the electron beam for 100 consecutive shots. The histograms show the distribution of the electron's centre for both the (a) horizontal and (b) vertical axes.

A false colour image of a typical pepper-pot image captured in YAG:Ce screen is showed in Fig. 4. Average values of horizontal and vertical transverse emittance are obtained for 64 out of 400 consecutive shots of 125 ± 3 MeV electron beam. To retrieve the rms emittance in equation (3) from the pepper-pot image, we used the formula derived by M. Zhang [8]. A mean values of normalised emittance, $\varepsilon_{rms,x,y}$ = 2.2 ± 0.7, 2.3 ± 0.6 π-mm-mrad are obtained for the horizontal and vertical directions, respectively, which are comparable with that of conventional linear accelerator [9]. An emittance as low as 1.1 ± 0.1 π-mm-mrad was able to measure which corresponds to the resolution limit of the current detection system.

To explain how the emittance evolves, a simulation using 2-D particle-in-cell (PIC) code OSIRIS was performed matching the experimental conditions. The simulation shows that the emittance growth is determined by the transverse forces acting on the electron before and during the trapping in the plasma bubble. Before the electrons are injected, the emittance is negligible. However, during self- injection, the electrons experience a transverse force at the back of the bubble causing them to oscillate. The oscillations change the momentum amplitude resulting to emittance growth. As the electrons' group velocity reaches nearly the speed of light, the emittance gains saturation. A growth in emittance will begin again when the electrons outrun the tail of the laser pulse. It is shown that the final emittance of the electron bunch scales with the charge and the bunch length. A detailed discussion is presented elsewhere [10].

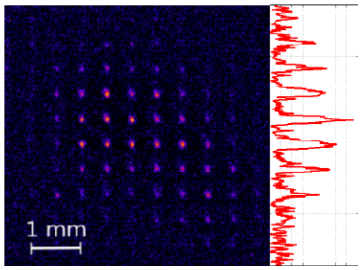

Figure 4: A false colour, background corrected, pepper-pot image produced on the Ce:YAG crystal by an electron beam after propagation through the emittance mask. A vertical lineout is shown on the right hand side.

Energy spread is also a measure of quality of the electron beam. Small energy spread relates to mono-energetic beam which is a prerequisite for most applications in LWFA such as FEL and synchrotron sources. For this set of data, the smallest energy spread measured is less than 1% (refer to Fig. 5b). However, GPT simulation shows that the resolution of our spectrometer is dependent on the emittance of the beam. It was seen that to achieve a 1% resolution, the beam must have an emittance of 0.5 π-mm-mrad [11].

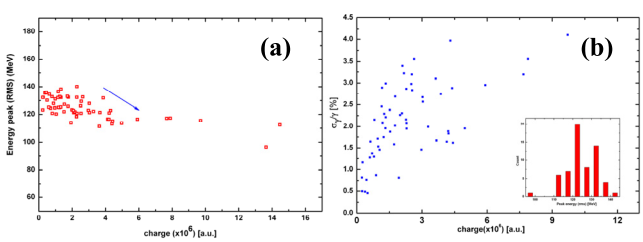

Figure 5: Scaling of (a) electron's peak energy and (b) energy spread with charge. Inset in Fig. 3b is the frequency of the peak rms central energy.

A scaling of the central energy and energy spread with the charge is observed as shown in Fig. 5. The central energy of the electron dropped with an increased in the charge. On the other, the corresponding energy spread blows up with the charge. This is a clear implication of beam loading. As the charge increases, the accelerating wake is over-loaded (due to the electron beam Coulomb field); thus, increasing the energy spread.

CONCLUSIONS

In summary, we were able to give a direct proof of high brightness of a laser-driven accelerator by measuring the emittance of the electron beam. A high resolution single shot pepper-pot technique was utilised to obtain the transverse emittance of the electrons. The mean normalised transverse emittance of 125 ± 3 MeV electron beam on horizontal and vertical directions are $\varepsilon_{rms,x,y} = 2.2 \pm 0.7$, 2.3 ± 0.6 π-mm-mrad, respectively. We also showed a charge scaling with the energy spread. Considering a 1 fs electron bunch length, the estimated peak current is around 10 kA, giving a brightness of $B=I/4\pi^2\varepsilon_x\varepsilon_y \approx 5\times10^{15}$ Am^{-1}rad^{-1}. This high brightness indicates that the LWFAs are suitable for driving a compact free electron laser that can generate coherent radiation in the VUV range.

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