HIGH QUALITY ELECTRON BEAMS GENERATED IN A LASER WAKEFIELD ACCELERATOR

W. A. Gillespie[#], SUPA, School of Engineering, Physics and Mathematics, University of Dundee, Dundee DD1 4HN, United Kingdom

A. M. MacLeod, School of Computing and Creative Technologies, University of Abertay Dundee, Dundee DD1 1HG, United Kingdom

S.P. Jamison, ASTeC, STFC Daresbury Laboratory, WA4 4AD, UK

S. M. Wiggins, G. H. Welsh, R. C. Issac, E. Brunetti, R. P. Shanks, S. Cipiccia, M. P. Anania, G. G. Manahan, C. Aniculaesei, B. Ersfeld, M. R. Islam, D. A. Jaroszynski, SUPA, Department of Physics, University of Strathclyde, Glasgow G4 0NG, United Kingdom

Abstract

A high power (900 mJ, 35 fs) laser pulse is focused into a gas jet (length 2 mm) and a monoenergetic electron beam is emitted from the laser-induced plasma density wake behind the laser pulse. High quality monoenergetic electron beams with central energy up to 183 MeV are generated. The beam is fully characterised in terms of the charge, transverse emittance, energy spread and bunch length. In particular, the energy spectrum (with less than 1% measured energy spread) is obtained using a high resolution magnetic dipole imaging spectrometer.

INTRODUCTION

The laser wakefield accelerator (LWFA) mechanism was first proposed thirty years ago by Tajima and Dawson [1] as an attractive alternative to RF acceleration technology. After three decades of research LWFAs are now capable of producing 100s of MeV electron bunches from mm-long gas jets and, more recently, 1 GeV electron bunches have been generated from a 33 mm long discharge capillary waveguide accelerating structure [2].

The first experimental demonstration of a laser wakefield accelerator as a driver of synchrotron radiation from an undulator was published in 2009 [3]. However, a major challenge is to improve the beam quality to a point where a free-electron laser (FEL) becomes feasible. Conventional RF accelerators routinely deliver beams of high charge density, low emittance, and low energy spread as drivers of the large-scale X-ray SASE FELs [4] that are now becoming operational, such as the LCLS [5]. However, LWFAs have not yet demonstrated sufficient quality beams to drive a viable FEL. Most notably, the measured relative energy spread is large, typically in the 2-10% range, but usually limited by instrument resolution [3]. Therefore the challenge is to both generate reliably and characterise carefully the LWFA electron beams in order to demonstrate the viability of the LWFA as a driver of next generation radiation sources.

EXPERIMENTAL SETUP

An experimental programme to demonstrate LWFAs as drivers of compact radiation sources is currently being conducted on the Advanced Laser-Plasma High-Energy Accelerators towards X-rays (ALPHA-X) laser-wakefield accelerator beam line at the University of Strathclyde [6]. The experimental setup is shown in Fig. 1: electrons are accelerated in a relativistically self-guiding plasma channel formed in a helium gas jet (nozzle diameter 2 mm, plasma density $\approx$ 1–5 $\times$ 10^{19} cm^{-3}) by Ti:sapphire laser pulses (λ = 800 nm, energy = 900 mJ, pulse duration = 35 fs). The laser beam has a 20 μm ($1/e^2$ radius) waist at the focus just inside the leading edge of the gas jet.
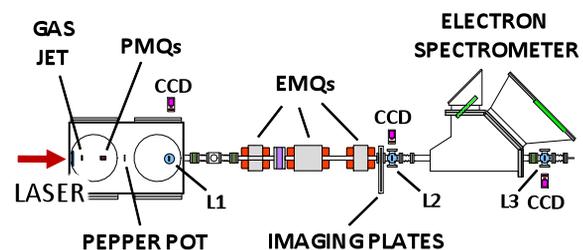

Figure 1: Setup of the ALPHA-X wakefield accelerator beam line.

Electrons are self-injected from the background plasma into the plasma density wake (bubble), trailing behind the laser pulse through the combined action of the ponderomotive force of the laser and the plasma restoring force. Permanent magnet quadrupoles (PMQs) and electromagnet quadrupoles (EMQs) are used to collimate the beam emerging from the plasma.

A suite of diagnostics allows the beam to be fully characterised. Pop-in Lanex screens (L1, L2 and L3 in Fig. 1) imaged by CCD cameras are used as beam profile monitors. A pop-in tungsten pepper-pot mask is used to measure the r.m.s. transverse emittance ε_N of the beam. This consists of a 27 $\times$ 27 matrix of holes with a 25 μm mean diameter. Measurements of the electron energy spectra have been carried out using a high resolution magnetic dipole spectrometer. Scintillating Ce:YAG crystals positioned on the focal plane are used to image electrons exiting the spectrometer field and the image is captured on a 12-bit CCD camera. Imaging plates determine the absolute charge in the beam and transition radiation, produced on passing the beam through thin metal foils, is used to estimate the bunch length.

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RESULTS

The electron beam profile, as recorded on Lanex screen L1 0.6 m after the accelerator, shows a typical beam pointing stability of 4-8 mrad both vertically and horizontally with standard deviation of 2-3 mrad along both axes. Both the angle and the fluctuation are reduced when the PMQs are in-line. This enables transportation downstream of the electron beam on almost every shot.

Absolute charge measurements have been conducted using imaging plates (Fujifilm, BAS-SR2025) inserted into the beam line, as shown in Fig. 2(a). Cross-calibration has been achieved for each Lanex screen simply with simultaneous capture on each one in turn [Fig. 2(b)]. For the YAG screens in the electron spectrometer statistical averaging over a large number of shots was performed, given the stability of the accelerator. The total beam charge can reach 30 pC, but the monoenergetic peak bunch of interest typically contains 1-10 pC. Coupled with transition radiation measurements, showing an r.m.s. bunch duration of 2 fs, it is seen that the peak current can reach a few kA.
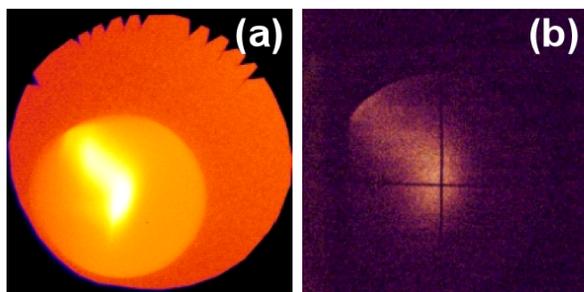

Figure 2: Electron beam image on (a) an imaging plate and (b) Lanex screen L2. The charge is 3.1 pC.

High resolution electron energy spectra have been obtained showing a central energy for the monoenergetic peak of up to 183 MeV, as shown in Fig. 3(a). The stability over a run of consecutive shots is as low as 3% while the mean central energy is tuneable in the range 80-183 MeV via control of the plasma density (gas backing pressure and position of laser with respect to gas nozzle) and/or laser parameters (energy, pulse duration and focal size).

The measured r.m.s. relative energy spread σ_γ/γ is as low as 0.4% which is very close to the resolution limit of the spectrometer. Modelling of beam transport through the spectrometer [7] has shown that the measurement of such narrow spreads implies that ε_N must be very low (less than $\sim 0.5\ \pi$ mm mrad). Simultaneous measurement of the energy spectrum and the emittance/divergence is not possible, but the actual relative energy spread is estimated to be down to $\sim 0.3\%$.

The transverse emittance inferred from the spectral diagnostic is consistent with the pepper-pot mask measurements conducted on the beam line. An example image of the mask-generated beamlets is shown in Fig. 3(b). The measured ε_N is found to be as low as 1.0 π

mm mrad with ellipticity in the beam profile evident also in the emittance measurements. Calculations show that this value is equal to the detection system limit (determined by the drift distance between mask and imaging screen, imaging screen spatial resolution and mask geometry). Future improvements to this diagnostic are in progress.
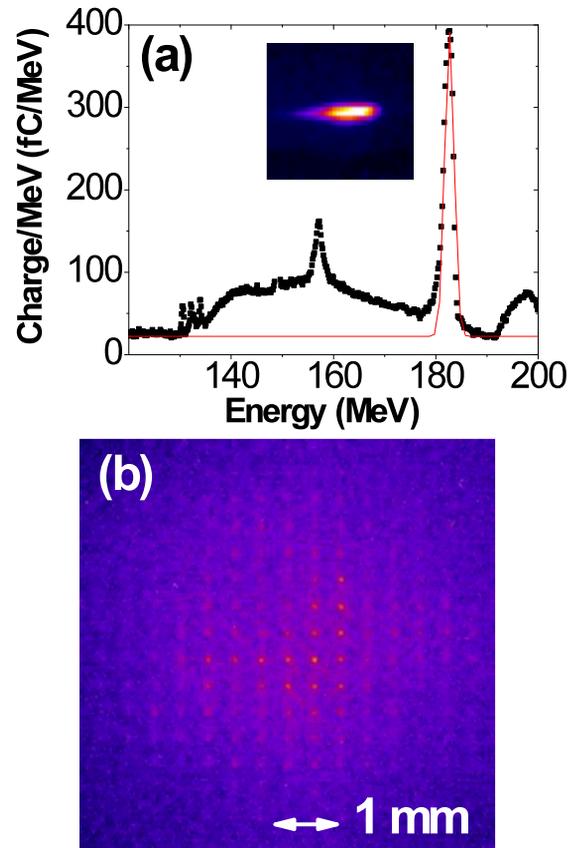

Figure 3: (a) Electron spectrum showing a bunch (YAG image inset) with central energy = 183 MeV, measured $\sigma_\gamma/\gamma = 0.5\%$ and charge = 0.7 pC obtained using the Gaussian fit shown as the red curve and (b) pepper-pot beamlet image corresponding to $\varepsilon_N = 1.3\ \pi$ mm mrad.

A direct measurement of the electron bunch duration in this facility is also under development, using the techniques of electro-optic (EO) detection of the Coulomb field of the ultrashort bunch originally developed by this group [8,9]. To obtain information on the very short time structure of the beam, our more recent technique of EO spectral upconversion [10] will be utilised to directly measure the bunch Fourier spectrum, by converting the THz field to an optical field. This technique measures the non-propagating long-wavelength spectral components which are not accessible to radiative techniques such as CSR, CTR, CDR and Smith-Purcell.

CONCLUSIONS

In conclusion, we have demonstrated the production of high quality electron beams from a laser wakefield accelerator. The relative energy spread is measured to be less than 1%, convoluted by the spectrometer resolution. The normalised transverse emittance is $1.0 \, \pi$ mm mrad, again limited by the detection system resolution. With charge in the range 1-10 pC and a bunch length of a few femtoseconds, the peak current is estimated to be ~kA. Based on our experimental parameters, FEL gain should be observable in the vacuum UV wavelength range, with extension into the XUV range on the horizon.

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