ELECTRON BEAM QUALITY MEASUREMENTS ON THE ALPHA-X LASER-PLASMA WAKEFIELD ACCELERATOR*

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Abstract

The Advanced Laser-Plasma High-Energy Accelerators towards X-rays (ALPHA-X) programme at the University of Strathclyde is developing laser-plasma wakefield accelerators to produce high energy, ultra-short duration electron bunches as drivers of radiation sources. Coherent emission will be produced in a free-electron laser by focussing the ultra-short electron bunches into an undulator. To achieve net gain, high peak current, low energy spread and low emittance are required. A high intensity, ultra-short pulse from a 30 TW Ti:sapphire laser is focussed into a helium gas jet to produce femtosecond duration electron bunches in the range of 80 - 200 MeV. Beam transport is monitored using a series of Lanex screens positioned along the beam line.

Measurements of the electron energy spectrum, obtained using the ALPHA-X high resolution magnetic dipole spectrometer, are presented. The maximum central energy of the monoenergetic beam is 90 MeV and r.m.s. relative energy spreads as low as 0.8% are measured. The mean central energy is 82 ± 4 MeV and mean energy spread is 1.1 ± 0.4%. We also present pepper-pot measurements of the normalised transverse emittance where mono-energetic electrons are passed through an array of 52μm diameter holes in tungsten. The analysis of the pepper-pot results sets an upper limit for the normalised emittance at 5.5 ± 1π mm mrad for an 82 MeV beam. With further acceleration to 1 GeV, the relative energy spread will reduce giving beam parameters that indicate the feasibility of a compact X-ray FEL driven by a plasma-wakefield accelerator.

INTRODUCTION

Conventional accelerators use radio frequency (RF) excited conducting cavities as accelerating structures. These are limited to ~100 MV/m due to ionisation of the walls of the cavity under the high electric field. The duration of the electron bunches used in these accelerators are relatively long at >100 fs, limiting their application in ultra-fast physics. A potential and very attractive alternative to RF acceleration technology is the laser wakefield accelerator (LWFA) mechanism, first proposed thirty years ago by Tajima and Dawson [1]. In a LWFA, the ponderomotive force of a high intensity laser pulse propagating in under-dense plasma drives strong plasma waves that lead to the formation of electrostatic accelerating “cavities” with electric field strengths in excess of 100 GV m^{-1}, i.e., 3 orders of magnitude greater than in RF accelerator cavities [2]. The first quasi-monoenergetic electron bunches from a LWFA were reported in 2004 [3-5]. These experiments used mm scale gas jets to generate electrons in the 100 – 200 MeV energy range. More recent, experiments have demonstrated the production of 1 GeV electron bunches from a 33 mm discharge capillary [6,7]. By utilising currently available terawatt laser systems, LWFA as a standard accelerator is becoming a reality.

The LWFA is a very attractive potential driver of a synchrotron light source or free-electron laser. One of the advantages is the short electron bunch length, recently shown to be as short as 32 fs [8], and subsequent ultra-short radiation pulse that is produced. The first experimental demonstration of a LWFA to generate synchrotron radiation pulses in an undulator has recently been published [9,10]. These initial demonstrations of the scaling and also the observation of harmonic emission, show the viability of a brilliant X-ray source. More recent observations of VUV radiation [11] confirm these initial observations. .

Producing an FEL at X-ray wavelengths [12] is challenging and requires excellent properties of the electron beam e.g. low emittance and small energy spread, high current etc..

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EXPERIMENTAL SETUP

Experiments to measure the electron beam properties have been conducted on the ALPHA-X laser-wakefield accelerator beam line in the Terahertz to Optical Pulse Source (TOPS) facility [13] at the University of Strathclyde. Electrons are accelerated in a relativistically self-guiding plasma channel formed in a helium gas jet by a Ti:sapphire laser pulse (wavelength $\lambda = 800$ nm, energy = 0.9 J, duration = 35 fs). An F/18 spherical mirror focuses the laser pulse to a spot size of 40 µm (1/e^2 diameter) just inside the leading edge of the gas jet, giving a peak intensity $I = 2 \times 10^{18}$ W cm^{-2}.

The gas jet nozzle is 2 mm long and on ionisation the plasma density is $n_e \sim 3 \times 10^{19}$ cm^{-3}. Relativistic electron beams emitted from the plasma are imaged downstream using a series of translatable Lanex phosphor screens positioned along the beam line axis at 0.6 m (Lanex 1), 2.2 m (Lanex 2) and 3.3 m (Lanex 3) downstream of the plasma accelerator.

Measurements of the electron energy spectra are carried out using a Browne-Buechner magnetic dipole spectrometer range of 50 – 200 MeV. Spectra are observed on scintillating Ce:YAG crystals positioned at the focal plane of the spectrometer and the image is captured on a 12-bit CCD camera.

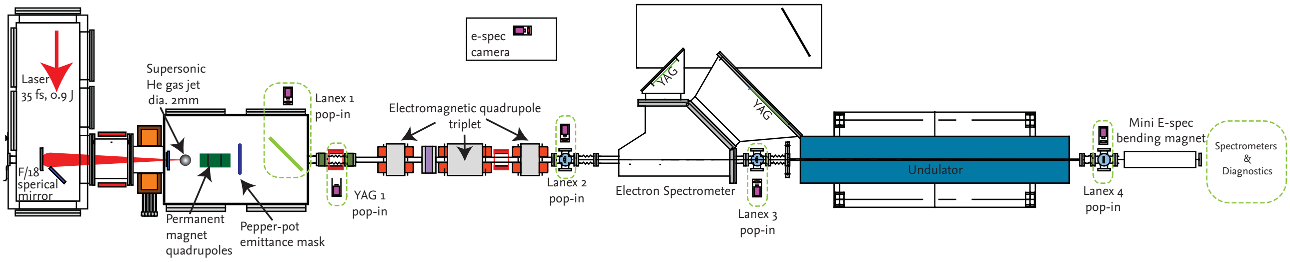

Figure 1: A detailed schematic of the ALPHA-X laser wakefield accelerator, showing the positioning of the gas jet relative to the key detection systems.

RESULTS

Energy Spread Measurement

The ALPHA-X spectrometer provides strong focusing in both the horizontal and vertical plains, which enables excellent energy resolution to be maintained over a wide energy range (from < 1% at the lower end to ~10% at 600 MeV).

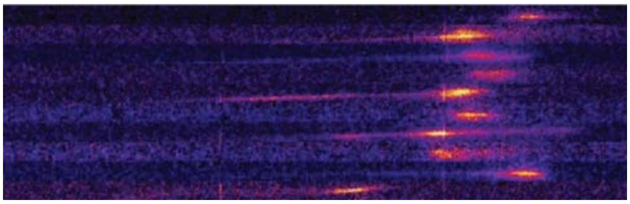

Figure 2: False colour images of five representative electron spectra captured on the YAG screen when operating without additional quadrupole fields. The energy range shown is 60-100 MeV (left to right).

Typical measured electron spectra are displayed in Figure 2, which shows false colour images of ten electron spectra captured on the YAG screen when no quadrupole fields along the beam line turned on. Figure 3 shows images when the quadrupole triplets are used.

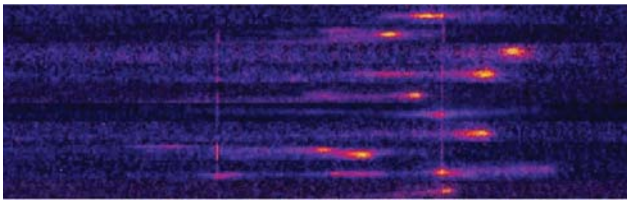

Figure 3: False colour images of five representative electron spectra captured on the YAG screen when operating with quadrupole fields turned on. The energy range shown is 60-100 MeV (left to right).

The energy range in both cases is 60-100 MeV (left to right). An analysis of 10 shots yields, in this case, gives an average central energy of 82 ± 4 MeV and r.m.s. relative energy spread, σ_γ/γ, of only 1.1 ± 0.4%. In these measurements the maximum energy was 89 MeV while the minimum r.m.s. energy spread was 0.8%.

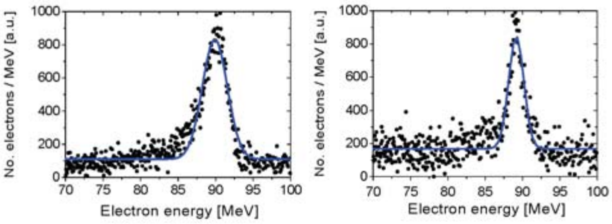

Figure 4: Detailed energy spectrum profiles of a single shot (of Figure 2) compared with a measurement with quadrupole fields turned on (from Figure 3).

The energy spectra plots (Figure 4) show a best-fit Gaussian curve for beams transported without quadrupole fields (left) showing σ_γ/γ is 1.9% and a centre wavelength of 89.2 MeV, compared with a measurement with quadrupole fields turned on (right) σ_γ/γ is 0.8% and a centre energy of 90.0 MeV.

Emittance Measurement

The beam emittance, which is a measurement of the phase space volume occupied by the particles, gives a good indication of the quality of beams from a particle accelerator. The "pepper-pot" emittance measurement technique is the preferred method for laser wakefield accelerator electrons as it is single shot. This method uses a mask to block most of the electron beam while splitting the beam into beamlets which allow the correlated momentum and phase space position to be determined. At relativistic energies the beamlets experience little space charge forces. Previous emittance measurements were performed on low energy Maxwellian distribution LWFA electrons beams [14]. Here, a slit was scanned over the electron beam, after it had passed through a collimator and an electron spectrometer, to provide an average emittance for a small energy range. In contrast, we present single shot measurements of the transverse emittance for mono-energetic LWFA electrons beams.

In our experiment a mask consists of an array of 11 x 11 holes drilled in tungsten is placed 29 cm from the gas jet. A slight taper of the holes gives an effective hole diameter of 52 ± 7 µm. The pepper-pot mask is mounted on a rotation stage to allow the mask to be inserted into the beam line. The mask is aligned using a HeNe (aligned to the beam line). The transmitted and back reflected light is used to ensure that the mask is normal to the electron beam. The electron bunch transverse profiles are measured on Lanex 1 (Figure1), which is placed a further 30 cm from the pepper-pot mask.

The normalised emittance is determined from the electron images observed on the lanex screen. By measuring the distribution of size and position of an individual beamlets, the beam emittance can be deduced [15]. Figure 5 shows two typical beamlet images measured on Lanex 1. The normalised emittance has been calculated to be 5.5 ± 1 π mm mrad and 7.8 ± 1 π mm mrad respectively. The errors are determined from the uncertainty in the hole size and the electron beam energy. These uncertainties and the resolution limit of the Lanex screen imply that the measured emittances correspond to an upper limit of the emittance. The actual emittance could be an order of magnitude lower, as expected from simulations.

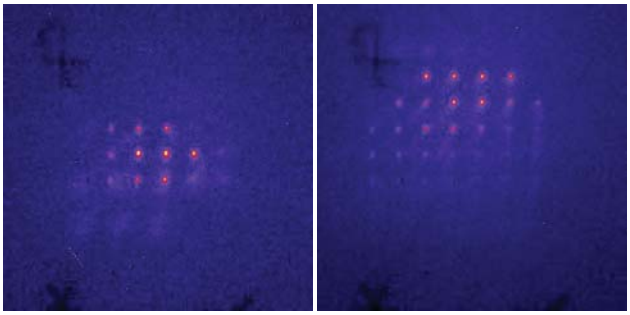

Figure 5: Images from pepper-pot emittance measurements for a 4 mrad divergence beam (left) and a 10 mrad divergence beam (right). The normalised r.m.s. emittance for 82 MeV electrons (corrected for hole size) is 5.5 ± 1 π mm mrad (left) and 7.8 ± 1 π mm mrad (right) respectively.

CONCLUSION

In conclusion, we have demonstrated the production of electron bunches with a central energy of 90 MeV and energy spreads as low as 0.8%, which would be reduced further at higher energies. The resolution of the spectrometer used in these measurements places an upper limit to the energy spread. We have also presented pepper-pot measurements of the normalised transverse emittance from a LWFA, which show that the actual emittance must be less than 5.5 ± 1 π mm mrad.

These beam parameters, along with our previous measurements of the bunch charge in the range 1 – 50 pC, demonstrate that with increase in the beam energy a compact X-ray FEL should be feasible.

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