Observation of mono-energetic structures in the spectrum of laser wakefield accelerated electrons

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Abstract. In recent times, the development of high power lasers has advanced such that focused intensities of up to 10^{20} Wcm^{-2} at high repetition rates are achievable using laser systems on a scale which is suitable for a university scale laboratory. It is from such advances in laser engineering that many new phenomena have been observed by many groups throughout the world. An effect of specific applicable interest is in the field of compact laser-plasma accelerators. Here we present evidence that under particular plasma conditions, it is possible to generate beams of relativistic electrons which have low divergence and a small energy spread (less than 3%). Previous results have shown laser-plasma produced electrons to be Maxwellian in energy spread [1,2,3,4].

EXPERIMENTAL

Motivation

In recent times simulations have shown that, with the correct laser and plasma parameters, non-Maxwellian electron spectra may be obtained [5,6]. Such high quality laser produced electron bunches indicate that a "table top" particle accelerator may be possible. Experimental confirmation of such high quality beams was the primary aim of the experimental work presented here.

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Instrumentation

It was noted that in order to observe fine structure in an electron spectrum, which varies from shot to shot, a high-resolution single shot measurement must be made. An electron magnet, whose magnetic field could be varied up to 1.4T, deflected the electrons onto a piece of Fujifilm image plate. The image plate works on the principle of photo-luminescence. Incident radiation excites electrons in the substrate to meta-stable states. Longer wavelength radiation in the reader de-excites the electrons and the resulting luminescence is measured [7,8].

Experimental Configuration

The multi-Terawatt Astra laser system was focused to intensities up to 2.5 x 10^{18} Wcm^{-2} into a supersonic helium gas jet to produce a plasma of various densities from 10^{18} – 10^{20} electrons per cubic centimeter. Electrons emerging from the target were analyzed using and on-axis magnetic electron spectrometer. A schematic of this complete set-up can be seen in figure 1 [9] below.

During the first experimental period, a broad range of plasma densities was used. The 9TW (360mJ in 40fs) laser was focussed into a spot of diameter 25 microns. 180mJ were contained within this focal spot. Initially, helium gas was ejected from the jet at high pressure providing plasma densities of above 2 x 10^{19} cm^{-3}. In this case a quasi-thermal electron distribution was measured. As the density was reduced below this value, it was found that the spectra no longer exhibited this type of distribution. The exponential nature of the spectrum was suppressed and ‘bunches’ of electrons with narrow energy spreads were observed.

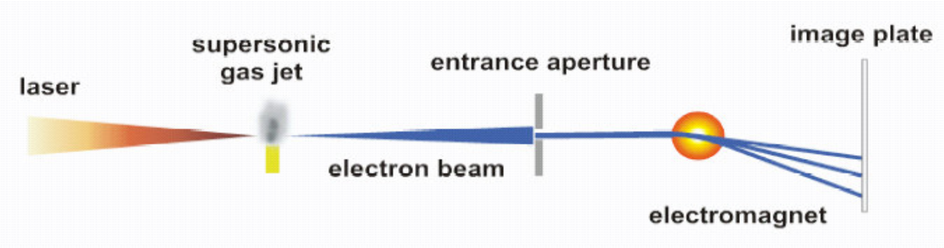

FIGURE 1. Schematic of the experimental set-up on the Astra laser system

Before the second experimental run, the Astra laser system was upgraded to provide 540mJ of laser energy in the same pulse duration. An identical experimental configuration was utilized. As a consequence of the results obtained in the first period, plasma densities around 2 x 10^{19}cm^{-3} were investigated throughout the second run. By adjusting the plasma density by small amounts, single beams of mono-energetic electrons were produced. Despite varying in energy, these electron bunches were consistently present throughout the experiment. This variation in energy can be seen clearly in figure 2 below.

Figure 2 shows four separate shots which use similar laser and plasma conditions. The x-axis is the electron energy and in all four cases ranges from 0-100MeV. If we consider the highest energy result (bottom left) we have a 78MeV electron bunch containing approximately 22pC of charge in a 3% (FWHM) energy spread.

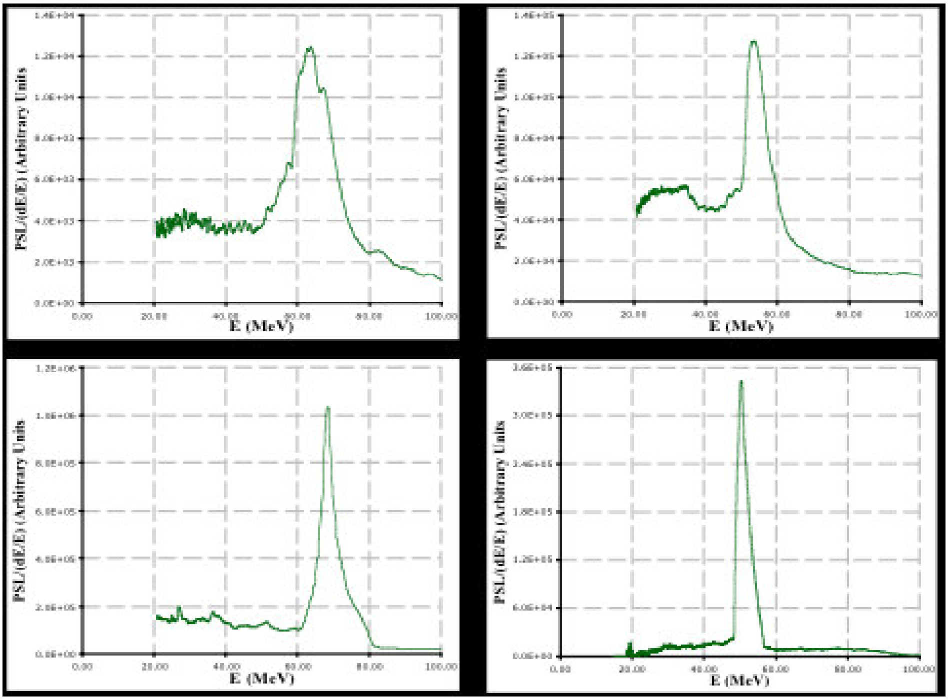

FIGURE 2. Shot to shot variation of the mono-energetic electron ‘spike’

On another shot, a beam divergence measurement was made using stacks of radiochromic film and copper foils. This showed the cone angle of the high-energy electrons (>1.25MeV) to be 40mrad and the cone angle of the whole bunch to be around 270mrad. If we assume that the source size of the electrons is equal to the focal spot size, this gives an emittance of 0.3 π mm mrad for the high-energy bunch.

SIMULATION

The particle-in-cell (PIC) code OSIRIS was used to investigate the mechanism of production of these mono-energetic electron beams. The two dimensional version of the code was used to allow a much of parameter space to be scanned. In figure 3 below, the laser pulse is moving from left to right inside a co-propagating box which travels at the speed of light in vacuum. The simulation was run in with the parameters defined as in the second experimental period. A density profile similar to the gas jet used was input.

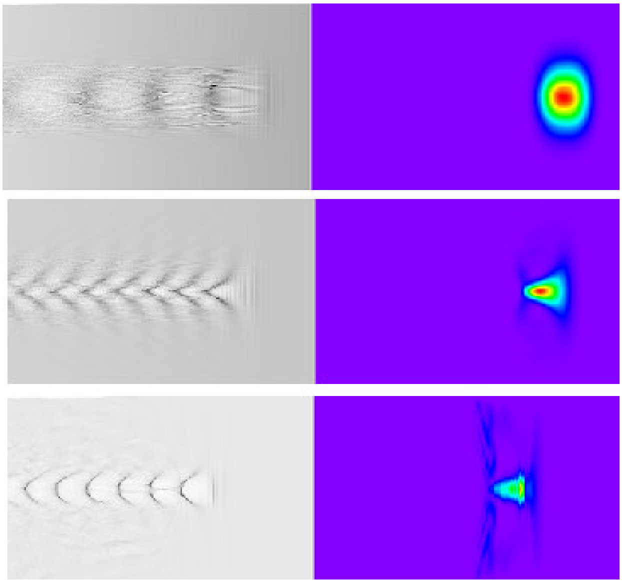

FIGURE 3. OSIRIS simulation results

Three time-steps were chosen and the electron density (left) and laser envelope (right) are displayed above. (a) shows the situation when the laser has just reached the low density plasma at the entrance to the gas jet. . In (b), the curved wakefield has caused the pulse to focus to a higher intensity which, in turn, causes the wakefield to steepen further at this point. When the plasma has evolved to the situation in (c), the back of the pulse has been eroded to the extent that the laser ponderomotive force is no longer large enough to hold out the high electron density. These electrons rush in forming a small mono-energetic bunch on axis. The curved wakefield produces an accelerating and focusing field which is conducive to the production of low emittance highly mono-energetic beam of relativistic electrons.

CONCLUSIONS

We have shown that mono-energetic beams of relativistic electrons can be produced from a laser-plasma interaction. We have modeled the experimental conditions using a two-dimensional particle-in-cell code and have found to good agreement with experimental data. Further information on this work can be found in a peer-reviewed article [10].

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