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

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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

The multi-Terawatt Astra laser system was focussed 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 centimetre. Electrons emerging from the target were analysed using and on-axis magnetic electron spectrometer. A schematic of this complete set-up can be seen in figure 1 below.

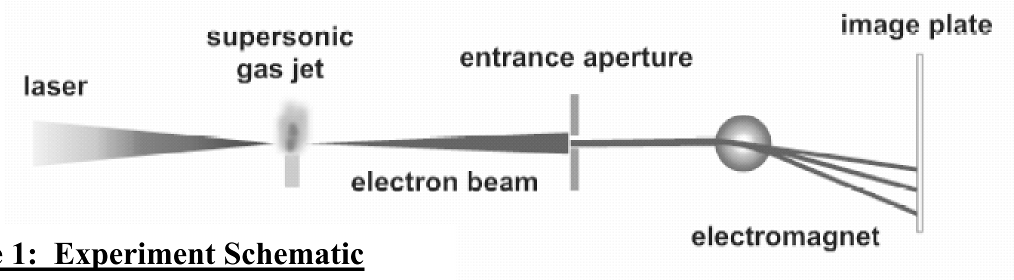
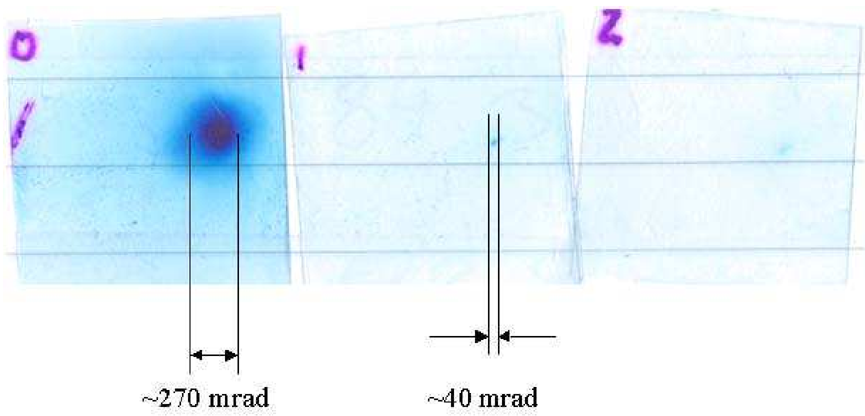


Figure 1: Experiment Schematic

During the first experimental period, a broad range of plasma densities was used. 9TW of laser power was focused with half the energy being deposited in a focal spot 25 microns in diameter. This gave a vacuum intensity of 3 x 10^{18} Wcm^{-2} on a supersonic jet of helium gas. As the density was varied, there appeared to be a noticeable qualitative change in the electron spectrum. For plasma densities greater than 2 x $10^{19}cm^{-3}$ a quasi-thermal electron distribution was noted. As the density was reduced below this value, many of the spectra did not display the same type of distribution. The exponential nature of the spectrum was suppressed and ‘bunches’ of electrons with narrow energy spreads were observed. These spikes on the spectrum were often orders of magnitude larger than the Maxwellian background. This, and all other data mentioned in this paper, will be available for viewing in a peer-reviewed publication in the near future[5].

In the second experimental period, the system was able to deliver 16TW of laser power to the target in a similar configuration as previously used. The region of parameter space around the plasma density of 2 x $10^{19}cm^{-3}$ was investigated further. In this set of experiments it was found that by tailoring the plasma density correctly, it was possible to obtain a mono-energetic beam of electrons which varied in energy but was consistent in presence. One such electron bunch was measured to be 78MeV with an energy spread of approximately 3% (FWHM). This bunch contained approximately 22pC of charge. To measure the bean divergence, stacks of radiochromic film and copper were placed 25mm behind the target. The opening cone of the beam for all the electron energies was 270mrad, whereas the cone angle for the relativistic

Figure 2: Divergence measurement



Estimated emittance: ~2.1 π mm mrad ~0.3 π mm mrad

electrons (E > 1.25 MeV) was ~40 mrad. This result can be seen in Figure 2. If we assume the source to be equal to the focal spot of the laser, we can estimate the emittance of this high-energy component as being 0.3 π mm mrad.

Simulation

To determine a mechanism for the production of these mono-energetic features the Particle-In-Cell (PIC) code OSIRIS was used. The code was run in a two dimensional configuration to allow rapid scanning of parameter space. The simulation shown here shows the laser pulse propagating to the right inside a moving window which moves to the right at the speed of light in a vacuum. The parameters used mimic those during the second experimental period described above. The density profile used watched the experimental gas jet density profile.

Figure 3 shows the electron density (in grayscale) and the laser envelope (in colour) at three points in time. (a) shows the situation shortly after it has entered into the plasma. The laser envelope has not evolved much and there is a wake forming in 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 as 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.

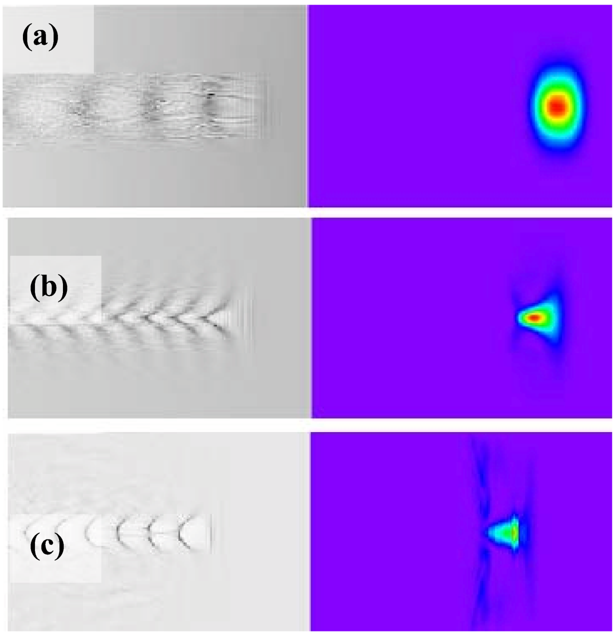


Figure 3: OSIRIS simulation results

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 (yet to be published).

Acknowledgements

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