Collimation and guiding of fast electrons in laser-solid interactions

A. P. L. Robinson, M. Sherlock and P. A. Norreys
Central Laser Facility, STFC, Rutherford Appleton Laboratory, HSIC, Didcot, Oxon OX11 0QX, UK

R. J. Kingham and C. P. Ridgers
Plasma Physics Group, Blackett Laboratory, Imperial College, London SW7 2AZ, UK

M. Zepf and S. Kar
Dept. of Physics and Astronomy, Queen's University Belfast, Belfast BT71NN, UK

Contact | **alex.robinson@stfc.ac.uk**

Introduction

The fast electrons which are generated in the interaction of ultraintense laser pulse with dense plasmas can potentially transport large amounts of energy far from the laser interactions.

The details of the fast electron flow are highly important to a number of areas of active research including: ion acceleration by the TNSA mechanism, laser-driven X-ray sources, and Fast Ignition ICF. In many of these areas a highly collimated flow of fast electrons is desirable. In the case of Fast Ignition, collimation may be crucial to the energetic viability of the scheme.

Recent laser-solid experiments [7,8] indicate that the divergence of the fast electron beams might be sufficiently large for the prospects of ignition in a typical FI scenario to be questionable. This is broadly consistent with the current understanding of magnetic collimation. There is scant evidence of collimated flows (magnetic or ballistic) in any experiment. This has prompted a number of researchers to investigate schemes for artificially enforcing collimation, and this is an area that the CLF Physics group has recently been actively pursuing. This article will review and summarize our recent theoretical work in this area [1-3] using our hybrid-VFP [4-6] code LEDA.

Two pulse collimation

The first scheme that we proposed for artificial collimation employed two laser pulses separated by a delay time [1]. The 'late' pulse is the laser pulse that will generate the main beam of electrons that one wants to collimate, and it was assumed that this pulse would have a FWHM intensity in excess of 10^{19} Wcm^{-2}. The 'early' pulse has an intensity of the order of 10^{18} Wcm^{-2}. The fast electrons generated by this interaction generate a collimating magnetic field. From simple estimates using a 'rigid beam' model it was found that the collimating magnetic field could grow to such a magnitude that it would be able to initiate the collimation of a beam of MeV electrons. This means that the collimating field generated by a 10^{18} Wcm^{-2} pulse could, in principle, initiate the collimation of the fast electrons generated by a 10^{19} Wcm^{-2} pulse.

A series of numerical simulations were carried out using LEDA, a 2D hybrid-Vlasov-Fokker-Planck (h-VFP) code that was developed in the CLF Physics group. The LEDA code uses an algorithm similar to the KALOS code to describe the fast electrons [4]. This involves expanding the fast electron distribution function in terms of spherical harmonics up to a finite order (usually 20). Substituting this expansion back into the VFP equation yields a set of equations for the coefficients (which are a function of space and the magnitude of momentum). The code numerically solves these equations. There is no laser per se, with fast electrons being injected from one boundary in such a way as to model the laser as an energy deposition. The background electrons are described by a 'hybrid' approximation which is essentially the same as the hybrid method used by Davies [5,6]. The background plasma is static and is described only by a temperature, density, resistivity, and specific heat capacity. The electric field is determined by a simple Ohm's law ($E = -\eta\, j_f$), and this is substituted into the induction equation to provide an equation for the evolution of the magnetic field,

$$\frac{\partial B}{\partial t} = \eta \nabla \times j_f + (\nabla \eta) \times j_f . \quad [1]$$

The simulation series indicated that the two pulse scheme was indeed viable, at least under the somewhat idealized conditions of the hybrid model. A number of parameters were varied, including the intensities of the 'main' and 'generator' pulses, the divergence angles of the electron beams that they produced, and the initial temperature of the target.

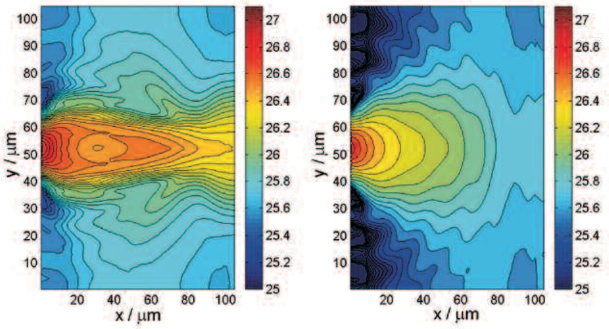

Figure 1. Fast electron densities from LEDA simulations of two-pulse scheme. (Left) Fast electron density at 900 fs (generator + 400 fs of main pulse) in two pulse simulation. (Right) Fast electron density at 400 fs in simulation with main pulse only.

Figure 1 above shows that in the case of two simulations with the same main pulse conditions, the simulation where the generator pulse precedes the main pulse results in collimation whereas the simulation with only the main pulse results in divergent flow.

Structured target collimation

The second scheme that was investigated [2] is based on target engineering, as opposed to the 'optical control' philosophy of the two-pulse scheme. The idea is to use a target consisting of a fibre which is surrounded by material that is less resistive than the fibre. From equation 1 (second term), it can be seen that the resistivity gradients at the interfaces between the two materials are in the correct sense to enhance the growth of collimating magnetic field at these interfaces. Simple analytic estimates can be made of the growth of the magnetic field, again using a 'rigid beam' model, and it is found that the magnetic field can grow to such a magnitude as to initiate collimation of the fast electrons.

This concept was further investingated by carrying out a series of 2D LEDA simulations. The targets investigated considered an Al fibre embedded in Li. The fibres extended along the entire length of the simulation box, and had a width from 5-20 µm. Figure 2 shows a plot of the target Z in one of the simulations.

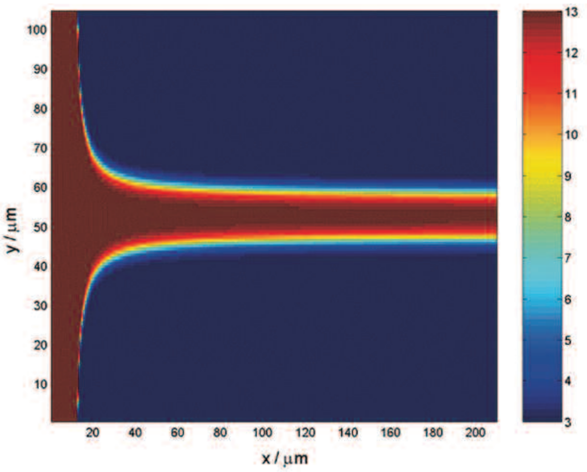

Figure 2. Plot of target Z in a typical LEDA simulation of the 'Structured Collimator' concept.

Most targets started at high temperature in the Spitzer regime of resistivity (>200 eV) which is a favourable regime for this concept as it guarantees that Al is more resistive than Li at a particular temperature. In these simulations, strong collimation along the Al fibre occurred consistently. Cold start effects were also considered with three different resistivity curves including one in which the Li was more resistive than Al over a small temperature range. Even for this case, collimation still occurred. Figure 3 shows a plot of the fast electron density in a typical LEDA simulation, which illustrates the strongly collimated flows that were observed in these simulations.

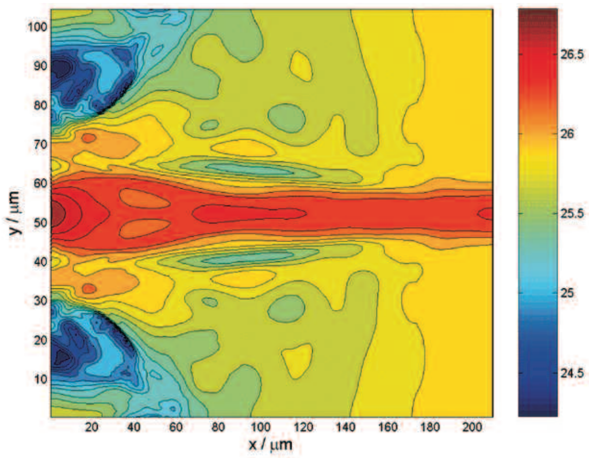

Figure 3. Fast electron density plot at 1 ps in a typical LEDA simulation of the 'Structured Collimator' concept. This shows strong collimation along the Al fibre.

Collimation and guiding due to density modulations

The third investigation [3] did not consider a scheme for artificial collimation, but was actually aimed at studying the effect small modulations to the background plasma density. In real experimental situations one cannot guarantee that the background plasma density is perfectly uniform. Therefore one wants to know to what extent small or moderate modulations can affect fast electron transport. One might argue that the effect of background density modulations should be negligible as in cold targets the resistivity is a very weak function of electron density, and in hot targets the resistivity should be almost independent of electron density (see equation 2 below).

$$\eta = \frac{10^{-4} Z \ln \Lambda}{T^{3/2}} \Omega m. \qquad [2]$$

However since modulations in the electron density implies a direct modulation of the specific heat capacity of the background plasma, when the plasma is Ohmically heated by the fast electron current the background plasma temperature must therefore be modulated as well. In the regime of Spitzer resistivity this implies that regions of high electron density will become more resistive than regions of lower electron density. Therefore the second term in equation 1 will act to generate magnetic field which will push the fast electrons into regions of high background electron density.

A series of LEDA simulations were carried out to investigate this effect. The laser that was modeled was a 1ps pulse at 5×10^{19} Wcm^{-2} with a spot radius of 5 µm. For the background density modulations we employed a sinusoidal modulation in the y-direction (transverse to the principal injection direction of the fast electrons) which grew from a uniform region close to the injection region to constant amplitude. In figure 4 we show both the background ion density and the fast electron density at 750 fs in a simulation where the modulations had a wavelength of 6.25 µm and the amplitude was 5% of the background density.

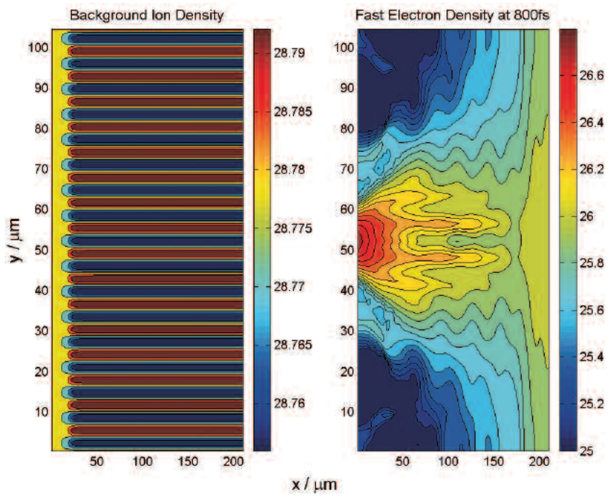

Figure 4. (Left) Background ion density in LEDA simulation. (Right) Fast electron density at 800 fs.

Figure 4 clearly shows that the fast electron beam has been broken into a number of collimated beamlets. These beamlets are being guided along the lines of high density. Given that such strong filamentation occurred even for a density modulation of 5% suggests that density modulations may have to be accounted for in the interpretation of experiments.

Conclusions

In this article we have briefly reviewed some of our recent theoretical studies of magnetically collimation in fast electron transport. These studies indicate that it might be possible to enforce magnetic collimation by either optical or target engineering. On the other hand it also suggests that the role of density modulations in fast electron transport may have to investigated in more detail.

Acknowledgements

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