Collimation of Fast Electrons by Pre-Generation of Magnetic Field.

A.P.L.Robinson, P.A.Norreys, M.Sherlock

Central Laser Facility, CCLRC Rutherford-Appleton Laboratory, Chilton, United Kingdom

Introduction

The feasibility of Fast Ignition (FI) Inertial Confinement Fusion (ICF) depends on the efficient conversion of energy from the short-pulse laser driver to the ions in the compressed fuel. One aspect of this is ensuring that the fast electron beam has a divergence angle that is small enough to ensure that the majority of the fast electrons are incident on the compressed core. Recent experimental results [1] suggest that, at irradiances relevant to fast ignition ($\approx 5 \times 10^{19}$Wcm$^{-2}\mu m^2$), the divergence angle is around 45-50^o, which is too large. A modification to the cone-guided FI scheme is required which remedies this problem. A diverging beam is also undesirable in the case of a laser-irradiated foil acting as an x-ray source for back-lighting laser-plasma experiments, since the width of the fast electron beam determines the size of the x-ray source.

In this paper a potential solution is presented which use two laser pulses which are focussed to the same spot, but they arrive at different times. In this scheme, the first pulse (generator pulse) has an intensity of the order of 10^{18}Wcm^{-2}. The second pulse (main pulse) arrives several hundred fs after the arrival of the generator pulse. The main pulse has a much higher intensity $> 10^{19}$Wcm^{-2} and is responsible for generating the fast electron beam of interest.

Theory

The divergence angle of the fast electrons at the irradiance of the first pulse should be low (around 20^o) [2]. Previous work by Bell and Kingham [3] showed that under these conditions the fast electrons should collimate due to the self-generation of a strong magnetic field. At the higher irradiance, the large divergence angle prevents the self-generation of a strong magnetic field, and thus collimation. By pre-generating a strong azimuthal magnetic field with a low intensity short-pulse, it should be possible to collimate the fast electrons generated by the main pulse whilst only expending a relatively small amount of additional laser energy.

This can be shown by making a simple analytic estimate of the magnetic flux density that is achieved by the generator pulse. In an axisymmetric case the growth of the magnetic flux density is approximated by,

$$\frac{\partial B}{\partial t} = \frac{\eta j_f}{R}, \quad (1)$$

where η is the resistivity, j_f is the fast electron current density, and R is the scale-radius of the fast electron beam. This assumes that the fast electron current density is peaked on axis and decreases away from the axis. If one assumes a fixed resistivity of $5 \times 10^{-7}\Omega$m, $R = 5\mu$m, and a peak current density of 10^{16}Am^{-2}, then one would estimate that a magnetic flux density of 500T will be obtained in 500fs. If the fast electron beam produced by the generator pulse were to collimate then since this would lead to a contraction of the beam width, a higher magnetic flux density would be produced (i.e. this is an underestimate). However if the fast electron beam diverges then this leads to an expansion of the beam width, and the magnetic field generation gets much weaker further into the target. This magnetic flux density is sufficient to reflect 2MeV fast electrons that are travelling at 40^o to the target axis (assuming that the radial extent of the magnetic field is $\approx R$). On the basis of this argument, artificial collimation by this two pulse scheme should be viable, at least up to a certain intensity.

Simulation

The viability of this scheme has been further studied by numerical simulation. This accounts for all the effects and complexities that a simple analytic estimate cannot encompass. The code used is a hybrid-Vlasov-Fokker-Planck (h-VFP) code called LEDA. The fast electron dynamics are solved for by a VFP solver similar to the KALOS code of [3], i.e. a spherical harmonic expansion is used. The background electrons are modeled in a similar fashion to hybrid-PIC codes. The solution has thus far been demonstrated for the case of an initially cold, homogeneous solid, and is thus relevant to current laboratory experiments. Specifically an Al target was modelled using a fit to the Milchberg resistivity and a fit to a Thomas-Fermi model for the specific heat capacity. Two pulses of fast electrons were injected in succession. Each pulse was 500fs long, the injection being constant in this time. The first pulse modelled injection due to a laser pulse at 2.5×10^{18}Wcm^{-2} (half-angle of this beam was 20^o), and the second modelled injection due to a laser pulse at 5×10^{19}Wcm^{-2} (half-angle of this beam was 47^o). In both cases the laser to fast electron conversion efficiency was taken to be 30%. The laser spot radius was taken to be 5μm. A comparison run was carried out with only the main pulse.

When one compares the fast electron density at 900fs in the standard run and 400fs in the comparison run (as is shown in figure 1), one finds that without the generator pulse the fast electrons propagate as a divergent spray, whereas *with* the generator pulse the fast electrons are strongly collimated.

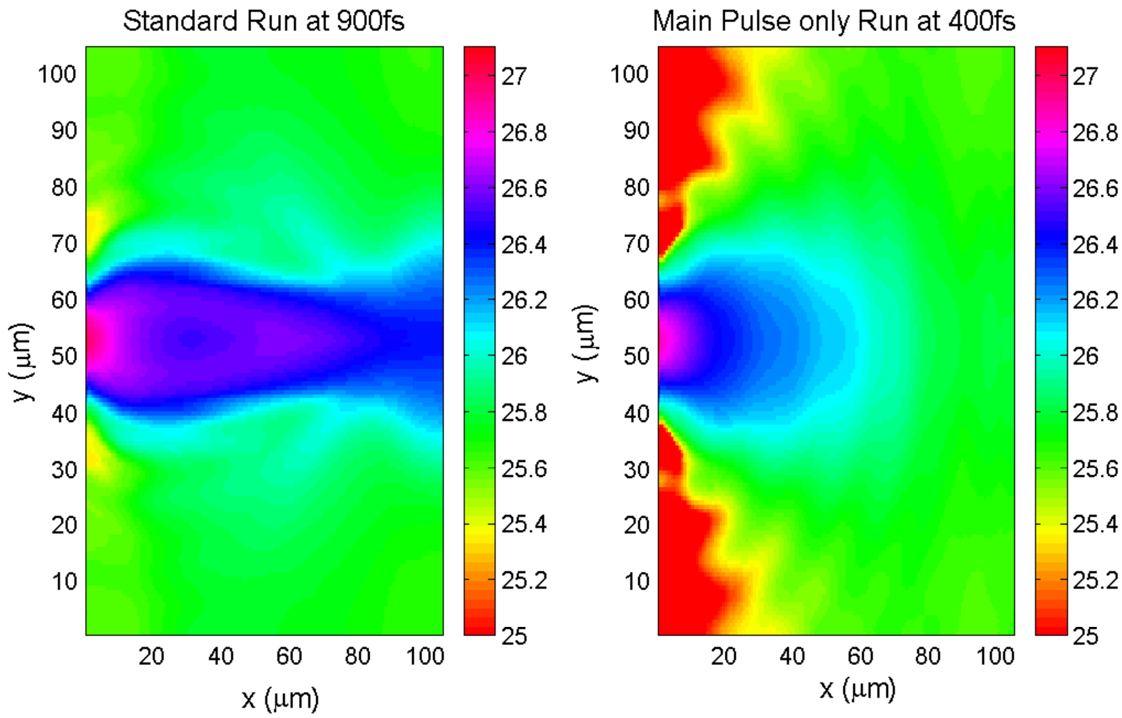

Figure 1: $\log_{10}$ of fast electron density (m^{-3}) at 900fs in the standard run (Left) and a run with only the main pulse at 400fs (Right)

This does indeed occur primarily because of the magnetic field that the generator pulse creates. However as the fast electron beam produced by the main pulse propagates deep into the target it is its self-generated magnetic field which sustains the collimation.

Further runs have been carried out to test the robustness of the scheme, i.e. how it performs under variation of the simulation parameters. This included intensity and divergence angle of the generator pulse and the main pulse. The scheme was found to be quite robust. Only when the fast electrons of the main pulse are injected isotropically or when the main pulse intensity rises significantly above 10^{20}Wcm^{-2} (assuming Wilk's scaling) does artificial collimation start to become less effective.

Finally we should note that these simulations demonstrate that this scheme works well given an increase in the laser energy 'budget' of 5%. This makes it suitable for use in FI.

References

[1] K.Lancaster et al., Phys.Rev.Lett., Accepted in February (2007)

[2] J.S.Green and P.A.Norreys, Private Communication, (2007)

[3] A.R.Bell and R.J.Kingham, Phys.Rev.Lett., **91**, 035003 (2003)