

Fast ignition scheme: Limiting Alfvén current in the dense plasma region

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The knowledge of the maximum current (Alfvén limit) in a plasma is of fundamental importance in the context of fast ignition of fusion pellets by lasers. A relativistic electron beam embedded in a dense plasma with non-relativistic return current is calculated. With the help of the hybrid code Petra which treats the fast electrons as a relativistic PIC and the cold background plasma as a classical non-relativistic fluid.

According to numerical studies in the past, for fast thermonuclear ignition of a precompressed pellet by laser in the optical wavelength range the intensity (energy flux density) $I = 10^{20} \text{ W/cm}^2$ represents an inferior limit [1]. For the deposition region of the laser beam around the critical density this implies that both currents, the direct fast electron stream as well as the charge neutralizing return current are relativistic. As soon as the direct beam of fast electrons penetrates into the pellet interior the return current can be treated as a non-relativistic classical fluid of very moderate temperature. Owing to the complexity of the problem in a first step it is legitimate to suppress the fast evolution in time (neglect of the displacement current, viceversa two-stream instability) and to limit all calculations to this region. The dynamics is driven by a parallel beam of relativistic electrons of Gaussian radius and length of $5 \mu\text{m}$ and $100 \mu\text{m}$, respectively, and Gaussian energy distribution. With \mathbf{j}_f the current density and η the inverse of the conductivity of the cold background electrons the governing equations are

$$\frac{\partial \mathbf{B}}{\partial t} + \mu_0 \nabla \times (\eta \nabla \times \mathbf{B}) = \nabla \times (\eta \mathbf{j}_f), \quad (1)$$

$$\mathbf{E} = \eta (\nabla \times \frac{\mathbf{B}}{\mu_0} - \mathbf{j}_f), \quad (2)$$

$$\frac{d\mathbf{p}}{dt} = -e(\mathbf{E} + \mathbf{v} \times \mathbf{B}). \quad (3)$$

Eq. (3) is restricted to the relativistic electrons in the particle-in-cell (PIC) code. In the vacuum or low density plasma a beam stops propagating when its own magnetic field B turns the electrons around. Hence, the limiting Alfvén current I_A is given by

$$I_A = \frac{4\pi}{\mu_0 e} p. \quad (4)$$

For a beam of 1 MeV electrons $I_A = 33 \text{ kA}$, for 5 MeV $I_A = 166 \text{ kA}$ [2,3]. In the dense plasma the Alfvén limit is determined by the degree of total current neutralization and must be calculated numerically. To this end various numerical runs have been performed in an Al target of thickness $d = 100 \mu\text{m}$ under the assumption of cylindrical symmetry.

In Fig. 1 we show the total current I [A] (a) and the magnetic field B_θ [Tesla] (b) in space after 1 ps, and the temporal evolution of, from top to bottom, the total energy injected minus lateral losses, the energy deposited in the target by Joule heating of the return current, the loss of the hot electrons across a coaxial test cylinder of 20 micron radius, the energy of the escaping electrons after crossing the target, the energy deposited by collisions of the fast electrons, and the losses by reflection from the entrance surface. Total current neutralization in the hot beam region is better than 10^{-3} . The calculations show that despite local violation of the Alfvén limit (4) in the lateral filaments (in red) the hot beam as a whole survives to a high degree.

In a second stage also the role of the displacement current, or equivalently, of all variants of two-stream instabilities, must be thoroughly investigated. A general conclusion which emerges already in this stage of investigations is that the Alfvén limit is less severe than criterion Eq. (4).

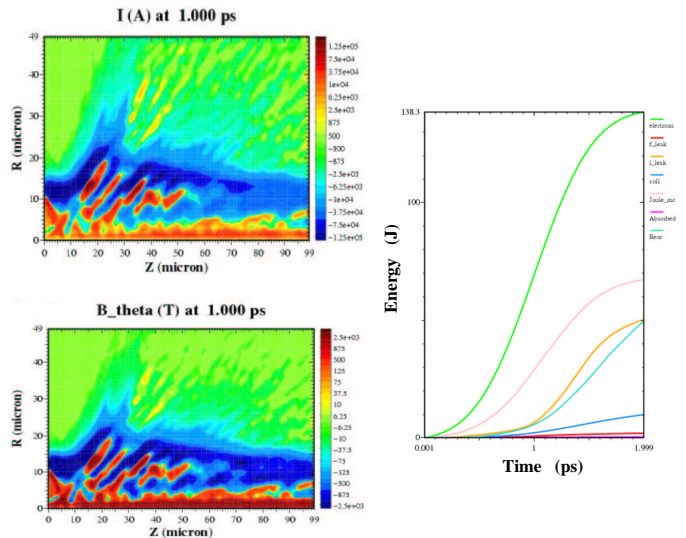


Figure 1: Total current I (a), magnetic field B_θ (b) as a function of radius $R[\mu\text{m}]$ and axial length $z[\mu\text{m}]$ after 1 ps, and evolution of energy deposition and energy losses induced by a parallel beam of electrons of 1.01 MeV mean particle energy and 5 micron radius during the time of 2 ps (c). Number of hot electrons is 9.9×10^{14} , total beam energy is 160 J. Locally the total current I exceeds the Alfvén limit Eq. (1). For additional data see text.

References

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