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Study on the transport of a relativistic electron beam in plasmas

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Abstract.

In the fast ignition scheme, in order to deliver enough energy (10kJ) into the pellet in 10ps, the ignition laser beam should reach the intensity of \( I_0 \approx 10^{20} \text{W/cm}^2 \) if the coupling from the laser to the core plasma is about 20% for a well-collimated beam. However, studies have shown that the electron divergence increases with the laser intensity. Of particular importance is the possibility of collimating the fast electron beams with the size of the compressed core. In this work, we will introduce two ways to obtain the collimated electrons: 1) collimate fast electrons in specially engineered targets with the spontaneously generated magnetic field during its transportation; 2) collimate fast electrons with imposed magnetic field.

1. Introduction

Fast ignition [1] is an attractive option for inertial confinement fusion because it relaxes the requirements on the symmetry of the implosion and the compression energy. One task is how to produce and transport enormous numbers of high-energy and high-quality charged particles. However, recent studies revealed that the relativistic electron beam produced from the interaction of an intense laser pulse with a solid-density target may be strongly divergent. [2, 3] If the beam divergence is large, then the coupling efficiency could not be large and the required ignitor pulse energy can rapidly become unfeasibly large. State-of-the-art integrated simulations and experiments indicate that the coupling efficiency of short-pulse energy into the compressed deuterated-plastic (CD) core is only 3.5 ± 1.0%. [4] Therefore, of particular importance is the possibility of collimating the REBs with the size of the compressed core.

To date, several mitigation works have been done regarding the control of the divergence of REBs, including self-generated magnetic field at the resistivity boundary in sandwich target, [5] high-resistivity-core-low-cladding targets,[6] and switchyard target, [7] two laser pulses, [8] double cone target, [9], imposed axial magnetic field, [10], and so on. Altogether, the fast electrons are collimated by the azimuthal magnetic field or axial magnetic field. In this paper, we will introduce two ways to obtain the collimated electrons and discuss the possible influence of axial and azimuthal field on fast electrons in the fast ignition scenario.

2. Magnetic collimation of fast electrons in specially engineered targets

Firstly, we find two different kinds of sandwich targets can produce magnetic fields with different generation mechanisms to collimate electrons. One is the large resistivity gradient along the
interfaces between different materials, the other is nonparallel density gradient and fast electron current at the interfaces. The former is consistent with the hybrid-Vlasov-Fokker-Planck’s simulation results [7] and experimental results [5, 6]. The latter will be discussed with our analytical model. From the electron fluid equations (the continuity equation and force balance equation), we can get the relationship between the self-generated magnetic field and electron flow velocity [11], \( \mathbf{B} = \frac{1}{c} \nabla \times \mathbf{p}_{e} \), where \( \mathbf{p}_{e} = m_{e} \mathbf{v}_{e} \gamma_{e} \mathbf{v}_{e0} \) is the momentum of the background electron flow and \( \gamma_{e} = 1/\sqrt{1 - v_{e0}^2/c^2} \) is the relativistic factor. Maxwell’s equations for the self-generated electric and magnetic fields, \( \mathbf{E} \), and \( \mathbf{B} \), are given by \( \nabla \times \mathbf{B} = -\frac{4\pi}{c} (n_{e0} \mathbf{p}_{e}/m_{e} \gamma_{e} + n_{b} \mathbf{v}_{b}) + \frac{1}{c} \frac{\partial \mathbf{E}}{\partial t} \). Here, for a long beam with pulse length \( l_{b} \gg v_{h}/\omega_{p} \), where \( v_{h} \) and \( \omega_{p} \) are the fast electron beam velocity and background plasma frequency, the displacement current \( \frac{1}{c} \frac{\partial \mathbf{E}}{\partial t} \) is of order \( (v_{h}/\omega_{p} l_{b})^2 \ll 1 \) compared to the electron current. In the following discussion, the displacement current \( \frac{1}{c} \frac{\partial \mathbf{E}}{\partial t} \) is neglected. Therefore, we obtain the equations for self-generated magnetic field, 

\[
\frac{m_{e} c^2}{4\pi e^2} \nabla \times \left( \frac{\gamma_{e} \nabla \times \mathbf{B}}{n_{e0}} \right) + \mathbf{B} = -\frac{m_{e}}{e} \nabla \times \left( \frac{\gamma_{e} n_{b} \mathbf{v}_{b}}{n_{e0}} \right),
\]

One can see that the source term is \( \nabla \times \left( \frac{\gamma_{e} n_{b} \mathbf{v}_{b}}{n_{e0}} \right) \approx -\frac{\gamma_{e}}{n_{e0}} \nabla n_{e0} \times \mathbf{j}_{b} \), which means the generation of self-generated magnetic field is due to the nonparallel density gradient and fast electron current.

Figure 1(a) shows the spontaneous magnetic field at time \( t = 500fs \); (b) A slice of spontaneous magnetic fields at \( x = 15\lambda_{0} \), the solid line is for simulation result, and the dash-dotted line for the analytical result. The unit of the magnetic field is \( m_{e} \omega_{0} c/e \) (1 unit = 100MG).

Figure 1. (a) The spontaneous magnetic fields at time \( t = 500fs \); (b) A slice of spontaneous magnetic fields at \( x = 15\lambda_{0} \), the solid line is for simulation result, and the dash-dotted line for the analytical result. The unit of the magnetic field is \( m_{e} \omega_{0} c/e \) (1 unit = 100MG).

3. Effects of the imposed magnetic field on the production and transport of relativistic electron beams

The effects of the imposed uniform magnetic field, ranging from 1MG up to 50MG, on the production and transport of relativistic electron beams (REBs) in overdense plasmas irradiated by ultraintense laser pulse are investigated. This study gives clear evidence that the imposed magnetic field is capable of effectively confining the relativistic electrons in space even when the source is highly divergent since it forces the electrons moving helically. In comparison, the spontaneous magnetic fields, generated by the helically moving electrons interplaying with the current filamentation instability, are dominant in scattering the relativistic electrons. In Fig.
2 the energy density distributions of electrons with energy between $0.5 \leq E[\text{MeV}] \leq 5.0$ are plotted. It is clearly seen that the produced fast electrons are very divergent for the case without imposed magnetic field. Alternatively, in the cases with imposed magnetic field, the electrons are collimated in space. The spot of the electron beam becomes smaller in the higher imposed magnetic field case. It seems that the high energy electrons are confined much better in the higher imposed magnetic field case. Actually, when the imposed magnetic field $B_0 > 3MG$, the overall coupling from laser to the relativistic electrons which have the potential to heat the compressed core in fast ignition was found to increase from 6.9% to 21.3%.

We next check the effects of imposed and spontaneous magnetic fields on the divergence angle of the electrons. In our simulations, the laser plasma interaction region locates at $x = 11 \sim 13\lambda_0$, while the local angular distribution function of the fast electrons was extracted at the positions $15\lambda_0$, $25\lambda_0$, and $55\lambda_0$. In order to distinguish the divergence angle of the fast electrons from that of the background electrons, only the electrons with energy higher than 200keV and propagating through the diagnostic positions at time interval $t=(667, 1000)$fs were considered. The local dispersion has been characterized by a Gaussian function $f(\theta) = A \exp[-(\theta - \theta_r)^2/\Delta\theta^2]$, where $\theta = \tan^{-1}[p_y/p_x]$, $\theta_r$ is the local electron mean propagation angle, and $\Delta\theta$ is the local divergence angle.

| $B_0$ (MG) | 0 | 1 | 3 | 5 | 10 | 20 | 30 | 40 | 50 |
|------------|---|---|---|---|----|----|----|----|----|
| divergence angle | $63^\circ$ | $64^\circ$ | $72^\circ$ | $64^\circ$ | $67^\circ$ | $60^\circ$ | $71^\circ$ | $76^\circ$ | $90^\circ$ |

Table 1 presents the divergence angle of fast electrons diagnosed at position $x = 15\lambda_0$ for different imposed magnetic fields. Here, only the electrons in the region $y = (-8\lambda_0, 8\lambda_0)$ and $t = (667, 1000)$fs are diagnosed.
field. However, when the imposed magnetic field $B_x$ reaches as high as 50MG, which is the same order of the spontaneous magnetic field due to the current filamentation instability in the interaction region, the divergence angle rapidly increases to 90°. This means that the imposed magnetic field can result in larger divergence angle. Altogether, taking into consideration of the conversion efficiency and the electron divergence angle, we may conclude that $B_0 = 3 \sim 30MG$ is more suitable to collimate the fast electrons.

![Figure 3. Integrated simulations coupling a hydrodynamic code, a hybrid-fluid-code, and a PIC code.](image)

Summary
In summary, we have shown two ways to collimate fast electrons and improve beam quality. It is found that huge surface magnetic field, which can collimate fast electrons, is generated due to the the nonparallel density gradient and fast electron current for the specially engineered low-density-core-high-density-cladding structure targets. However, this collimation scheme also bring some complexity for the target design. On the other hand, we found when the imposed magnetic field was increased from 1MG to 50MG, overall coupling from laser to the relativistic electrons which have the potential to heat the compressed core in fast ignition was found to increase from 6.9% to 21.3%. The simulations show that imposed magnetic field of the value of 3 \sim 30MG could be more suitable to fast-ignition inertial fusion. Further analysis of the integrated efficiency will be carried out by the our newly developed integrated simulation codes combining particle-in-cell code ASCENT, 2D radiation hydrodynamic code LARED-S, and hybrid-fluid-PIC code HFPI (see Fig. 3) in the near future.

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