Cylindrical fast electron beam in a plasma density gradient

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A theoretical study of a uniform fast electron beam propagating in a plasma density gradient targets (low density core-high density cladding) is presented. The self-generated magnetic field is calculated using a rigid beam model in cylindrical geometry. It is found that the spontaneous magnetic field peaks at the interface and evanesces exponentially into the outer target over a characteristic skin depth. This method is used for reducing the transverse angular distribution of a fast electron beam (control of the divergence of fast electron beams).

Interaction of ultra-intense laser with solid targets and generated fast electrons in this process have many applications in different fields that including: fast-ignition, x-ray production, compact particle accelerators. One of the most attractive applications of such laser generated electron beams relate to the fast ignition that great attention has been paid to it. In the concept of fast ignition, high intensity (∼10^20 W/cm^2), high energy (∼100 kJ), short (∼10ps) laser pulse irradiates spherical pellet (containing a Deuterium-Tritium mixture), relativistic electrons can be produced at the edge of the pellet, (which is usually ∼50 μm away from the dense core), through the different mechanisms. These energetic electrons can propagate through the bulk solid and transfer their energy to dense core with various mechanisms [1, 2]. Over the years, this scenario has been investigated from different aspects. In order to trigger fusion reactions, effective energy transfer efficiency of the REB through dense plasma should be achieved. However, results of various studies confirmed that the produced relativistic electron beam from the interaction of an intense laser pulse with a solid-density target have the transverse angular distribution. In order control of the divergence of fast electron beams, alternative works have been done. One of these methods is the use of targets with density gradient. Targets that have a low-density-core–high-density-cladding structure have been showed that can generate megagauss interface magnetic field, which fast electrons collimates.
An analytical model for the self-generated magnetic field using a rigid beam model for the target structure (low-density core–high density cladding) by considering a cylindrical geometry for the target structure and an annular laser beam is presented to investigate the influences of target geometry in collimating fast electrons beam. The system is described by the electron fluid equation that with Maxwell’s equations comprise a complete system of equations that response to the propagating fast electron beam.

\[
\frac{∂n_e}{∂t} + \nabla \cdot (n_eV_e) = 0 \tag{1}
\]

\[
\frac{∂p_e}{∂t} + (V_e, \nabla)p_e = -e \left( E + \frac{1}{c}V_e \times B \right) \tag{2}
\]

\[
\nabla \times B = \frac{4\pi}{c} \left( -en_e \frac{ρ_e}{meV_e} + j_h \right) \tag{3}
\]

Finally, the following equation is obtained:

\[
\frac{m_eV_e^2}{4\pi e^2} \nabla \times \left( \frac{γ_eV_e^2}{n_e} \right) + B = \frac{m_eγ_e}{ne^2} \left( \frac{1}{n_e} \nabla × j_h - \frac{1}{n_e^2} \nabla n_e × j_h \right) \tag{4}
\]

It is clear from Eq. (4) that, such structures with density gradient should produce strong magnetic fields at the boundary between a low-density core and high-density cladding, which cause to collimate the flow of fast electrons.

Figure 1 show the geometry of the target. Due to different density of the regions of target, the ion density numbers are different, \( n_{i1}, n_{i2}, n_{i3} \) for \( 0 < r < r_0 \), \( r_0 \leq r \leq 2r_0 \), and \( r > 2r_0 \), respectively.

![Density profile of target in cylindrical geometry.](image-url)
The following Bessel differential equation describe (in cylindrical geometry) the velocity of electrons.

\[
\frac{m_e c^2}{4\pi e^2} \left[ \frac{d^2 V_e(r)}{dr^2} + \frac{1}{r} \frac{dV_e(r)}{dr} \right] = n_e V_e(r) + n_h V_h
\]  

(5)

So,

\[
V_e(r) = c_1 I_0 \left( \frac{r}{\delta_{p1}} \right) - \frac{V_{h1} n_{h1}}{n_1} \quad \text{for} \quad 0 < r < r_0
\]

\[
V_e(r) = c_2 I_0 \left( \frac{r}{\delta_{p2}} \right) + c_3 K_0 \left( \frac{r}{\delta_{p2}} \right) - \frac{V_{h2} n_{h2}}{n_2} \quad \text{for} \quad r_0 \leq r \leq 2r_o
\]

\[
V_e(r) = c_4 K_0 \left( \frac{r}{\delta_{p3}} \right) - \frac{V_{h3} n_{h3}}{n_3} \quad \text{for} \quad r > 2r_o
\]

and then the magnetic field can be obtained

\[
B_\theta(r) = -m_e c \left[ \frac{c_1}{\delta_{p1}} I_1 \left( \frac{r}{\delta_{p1}} \right) \right] \quad \text{for} \quad 0 < r < r_0
\]

\[
B_\theta(r) = -m_e c \left[ \frac{c_2}{\delta_{p2}} I_1 \left( \frac{r}{\delta_{p2}} \right) - \frac{c_3}{\delta_{p2}} K_1 \left( \frac{r}{\delta_{p2}} \right) \right] \quad \text{for} \quad r_0 \leq r \leq 2r_o
\]

\[
B_\theta(r) = m_e c \left[ \frac{c_4}{\delta_{p3}} K_1 \left( \frac{r}{\delta_{p3}} \right) \right] \quad \text{for} \quad r > 2r_o
\]

Result and Conclusions

Our analytical results indicate that sandwich targets can collimate the fast electrons. in the sandwich target, density gradient, will produce the spontaneous interface magnetic field that lead to guiding of the fast electrons. Fig. 2 shows that that the maximal magnetic field appear at the interface and it penetrate into the inner region over a characteristic skin depth. the spontaneous interface magnetic field is proportional to the fast electron current and
inverse proportional to the square root of the density of the inner region. This special array for target shows that may provide different design of target possibility of convergence of fast electron for effective ICF.

![Graph of normalized magnetic field](image)

Fig. 2 The magnetic field as a function of the normalized radius.

REFERENCES