Quasi two-temperature electron beam guiding by strong magnetic field in laser-plasma interaction using Geant4 simulation toolkit

Ghasemi S. A. [1*], Moslehi M. [2], Faghih S.[3]

[1]Plasma and Nuclear Fusion Research School, Nuclear Science and Technology Research Institute, P.O. Box: 14399-51113, Tehran, Iran
[2] Radiation Applications Research School, Nuclear Science and Technology Research Institute, P.O. Box: 11363-34861, Tehran, Iran
[3] University of Damghan, Physics Department, P.O. Box: 41167-36716 Damghan-Iran
[*] *Email: abo.ghasemi@gmail.com*

Abstract

The effect of the external magnetic field on the quasi two-temperature fast electron beams angular spread and spatial divergence in laser-solid interaction were investigated by Monte Carlo simulation using Geant4 simulation toolkit. Our simulations in the presence of an external magnetic field $B_{ext} = (0-10)\ kT$ show that the dynamics and spatial divergence of the high energy electrons are strongly affected by the external magnetic field. It was shown that for electrons with the two-temperature energy distribution, electrons with a large angular spread (and small spatial divergance) in the momentum space are trapped by the magnetic fields lines and guided toward the fuel. Comparison of the results indicates that the optimal condition is obtained for the a magnetic field of about $B_{ext} \sim 1\ kT$ with a laser wavelength $\lambda_{if} = 0.35\ \mu m$ and laser intensity $I = 10^{21}\ W.cm^{-2}$. It was presented that by increasing the external magnetic field, the angular spread of electrons becomes larger which results in smaller spatial divergence.

Keywords: Angular Spread, Spatial Divergence, Strong Magnetic Field .

Introduction

In the inertial confinement fusion with the fast-shock ignition method [1-2], collimation of MeV electrons toward dense plasma is important [3]. Electron transport in plasma is significantly influenced by external magnetic fields [4]. Considering quasi two-temperature electron energy distribution function and the main laser parameters such as the wavelength and intensity, and also the strength of the applied magnetic field seems to be challenging issues in laser-solid interaction to guide fast electron beams toward the high-density fuel surface. The purpose of this paper is to find the optimal values for minimizing the divergence of relativistic electrons under the parametric study of above-mentioned critical issues by Monte Carlo simulation using Geant4 simulation toolkit.

Monte Carlo Simulations Set Up

Simulations were performed using version 10.5 of the Geant4 simulation toolkit. The fuel geometry is schematically shown in Figure 1, in which the fuel forms a spherical shell surrounding the central hot spot.

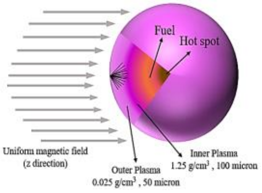

Figure 1. Spherical layers of fuel in the simulation model

There are two plasma shells around the dense fuel: The inner layer is a low-density plasma shell with a thickness of 100 μm and a density of $1.25\ g.cm^{-3}$. The outer layer is another spherical plasma shell with a thickness of $50\ \mu m$ and a density of $0.025\ g.cm^{-3}$. The density of these two plasma shells is determined by the number of ions in them. The density and radius of the fuel used in this simulation are presented in Table 1.

Table 1: Values of mass, density, and radius of the fuel [5]

$M_C\ (mg)$	$\rho_C\ (g.cm^{-3})$	$R_C\ (\mu m)$
0.261	828	43
0.524	658	58.1
1.314	490	86.6
2.094	406	108
4.190	292	152

Results and discussion

Our simulations imply that electron beam spatial divergence significantly depends on the variation of the magnetic field strength for the two- temperature energy functions.

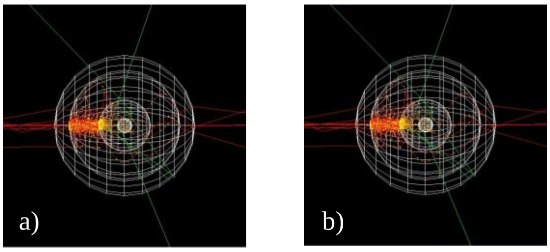

Figure 2. Results of simulation of spatial divergence of electrons with external magnetic field strength: a) $B_{ext} = 1\,kT$, b) $B_{ext} = 10\,kT$ for density $\rho_c = 490\,g.cm^{-3}$, with wavelength and laser intensity $\lambda_{if} = 0.35\ \mu m$, $I = 10^{21}\ W.cm^{-2}$.

It was shown that the variation of electron beam spatial divergence strongly affected in the interval $B_{ext} \sim 1\,kT$, as clearly shown in Figs. 2-a. By increasing the strength of external magnetic field to $B_{ext} = 10\ kT$, the impact of magnetic field on electron spatial divergence is almost constant and beam divergence does not change sensibly, Fig. 2-b. Therefore, under the sufficiently strong external fields, i.e., $B_{ext} \sim 1kT$, the fast electrons are trapped by the external fields and flow along the magnetic field lines to collimate optimally their energy toward dense fuel surface. In fact, for the case with the sufficiently strong external fields, the Larmor radius becomes smaller, which results in smaller spatial divergence and larger collimation toward fuel. The 2D simulation results of the transverse momentum distributions of fast electrons in the x-y plane (P_x, P_y) in the presence and absence of the external magnetic field for two distribution function are shown in Fig3.

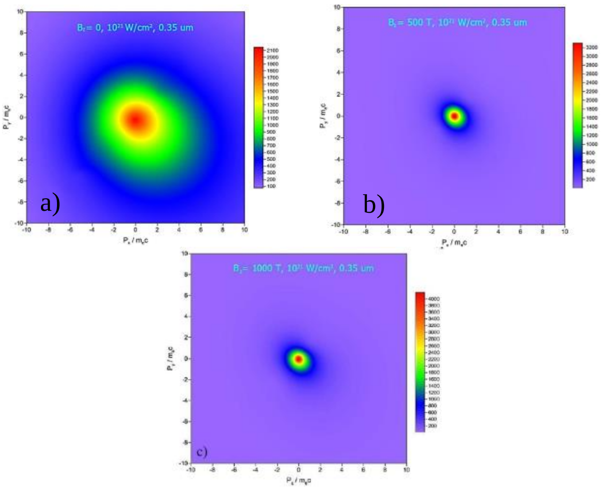

Figure 3. Transverse momentum distribution of fast electrons in the x-y plane (P_x, P_y) for quasi-two-temperature energy with laser wavelength and intensity $\lambda_{if} = 0.35\ \mu m$, $I = 10^{21}\ W.cm^{-2}$, a) without external magnetic field, and in the presence of field external magnetic intensity: b) $B_{ext} = 0.5\ kT$ and c) $B_{ext} = 1\,kT$.

Fig. 3 shows transverse momentum distributions typically in case with $\lambda = 0.35\ \mu m$, $I = 10^{21}\ W.cm^{-2}$ and $B_{ext} \sim 0.5 - 1\ kT$. The results of momentum simulation along the z-axis in the presence of an external magnetic field show that when the external magnetic field is applied, the fast electrons gyrate in the plane perpendicular to the applied field direction. Thus, the angular spread in the x-*y* direction becomes larger, and therefore spatial divergence of the electron becomes smaller and electrons centralized in z-direction which, is shown by red hot-spot localized at the centre.

Conclusions

we have evaluated the effects of externally-applied longitudinal magnetic fields on the fast electron angular spread and spatial divergence by the 2D Gean4 simulation toolkit. It was found that angular spread in the momentum distribution of fast electron beam is enhanced by applying the external fields. However, the spatial divergence as the result of the fast electron transport is significantly reduced since the fast electrons with a large angular spread in the momentum space are trapped by the magnetic fields and propagate along the magnetic field lines. Moreover, it was shown that The strength of magnetic fields required for beam guiding depends on the irradiated laser wavelength and intensity, and the optimal results are obtained for the shorter wavelength $\lambda_{if} = 0.35\mu m$ and lower intensity $I = 10^{21}\ W.cm^{-2}$ for the two-temperature energy spectrum of the electrons with the external magnetic field $B_{ext} \square 1\ kT$ for the fuel.

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