

Electron beam guiding by strong longitudinal magnetic fields

T. Johzaki¹, K. Mima², S. Fujioka³, H. Sakagami⁴, A. Sunahara⁵, H. Nagatomo³,
H. Shiraga³

¹Graduate School of Engineering, Hiroshima University, Higashi-Hiroshima, Japan

²The Graduate School for the Creation of New Photonics Industries, Hamamatsu,
Japan

³Institute of Laser Engineering, Osaka University, Suita, Osaka, Japan

⁴Institute for Laser Technology, Osaka, Japan

⁵National Institute for Fusion Science, Toki, Japan

E-mail: tjohzaki@hiroshima-u.ac.jp

Abstract. In electron-driven fast ignition, the guiding of fast electron beam having significantly large beam divergence is one of the most critical issues for efficient core heating. To guide the fast electron beam to the core, we consider to externally apply longitudinal magnetic fields. From the 2D PIC simulations applying uniform magnetic fields, it was shown that the field strength of 1~10kT is required for efficient guiding for the heating laser intensity of 10^{18} ~ 10^{20} W/cm².

1. Introduction

One of the most crucial issues of electron-driven fast ignition is efficient core heating by the laser produced fast electron beam. The main factors in preventing efficient heating are (1) too high fast electron energy and (2) too large beam divergence. The fast electron energy could be controlled by eliminating pre-plasma generation and by using heating laser with shorter wavelength. On the other hand, as for the beam divergence, it is difficult to control the angular spread of fast electrons since the laser-plasma interactions are the non-linear phenomena. So there are some ideas on guiding of fast electron beam with large divergence angle using self-generated [1-3] or externally-applied magnetic fields [4]. In the present paper, on the basis of 2D PIC simulations, we evaluate the effects of externally-applied longitudinal magnetic fields on fast electron generation and propagation.

2. Simulation set up

The target is initially fully ionized carbon foil, and the electron number density n_e is $100n_{cr}$ (n_{cr} is the laser critical density). The exponential-profile pre-plasma with scale length of $1\mu\text{m}$ is attached on the target front surface. The initial profile of n_e is shown in **Fig.1**. The p -polarized laser pulse with $\lambda_L = 1.06\mu\text{m}$ wavelength and $I_L = 10^{18} \sim 10^{19}$ W/cm² intensity irradiates the target from the left boundary. The transverse intensity profile is the Gaussian with a spot size of $5\mu\text{m}$ FWHM. The laser rises in $10T_0$, where T_0 is the laser period. After that the laser amplitude is kept constant during $30T_0$, and then is dropped to zero in

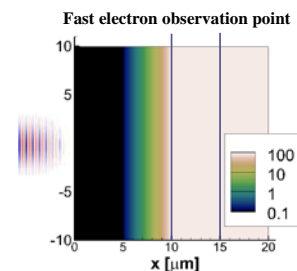


Figure 1. Initial profile of electron number density normalized by n_{cr} . The observation points of fast electrons are indicated by lines.

$10T_0$. A typical simulation time is $100T_0$, which corresponds to about 0.36 ps for $\lambda_L = 1.06 \mu\text{m}$. The external magnetic field is uniformly applied in x-direction. The generated fast electrons are observed at the two different points indicated in Fig. 1; one is the target surface, and the other is $5\mu\text{m}$ inside the target. The simulations were carried out by varying the applied magnetic-field strength $B_{x,\text{ext}}$ and I_L .

3. Results and discussion

The transverse momentum distributions (p_y, p_z) of fast electrons observed at the target surface for $I_L=10^{19}\text{W}/\text{cm}^2$ and $B_{x,\text{ext}} = 0, 1, 10 \text{ kT}$ are plotted in **Fig.2**. In 2D simulations, the momentum spread in the laser B-field direction (z-direction) is negligibly small for the case without external field ($B_{x,\text{ext}}=0$). When the external magnetic field is applied, the fast electrons gyrate in the plane perpendicular to the applied field direction. Thus, the spread in y-direction (laser polarization direction) becomes smaller, and it in z-direction larger. **Figure 3** shows the momentum distribution in p_x - p_t plane, where $p_t = (p_y^2 + p_z^2)^{1/2}$, observed at the target surface. Compared with the case without the external field, for the case with the external fields, the angular spread in the transverse direction in the momentum space becomes larger and the number of fast electrons having the momentum along x-axis is reduced because of the addition of gyration motion. These results show that the external field enhances the angular spread of fast electron beam in the momentum space.

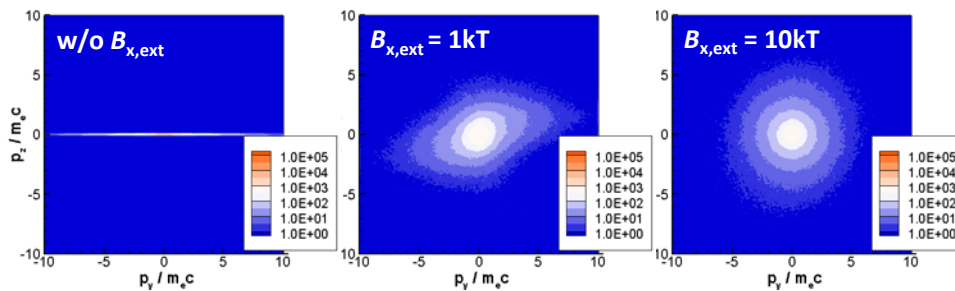


Figure 2. Fast electron momentum distribution in transverse plane (p_y, p_z) observed at the target surface for $I_L = 10^{19}\text{W}/\text{cm}^2$ and $B_{x,\text{ext}} = 0, 1, 10 \text{ kT}$.

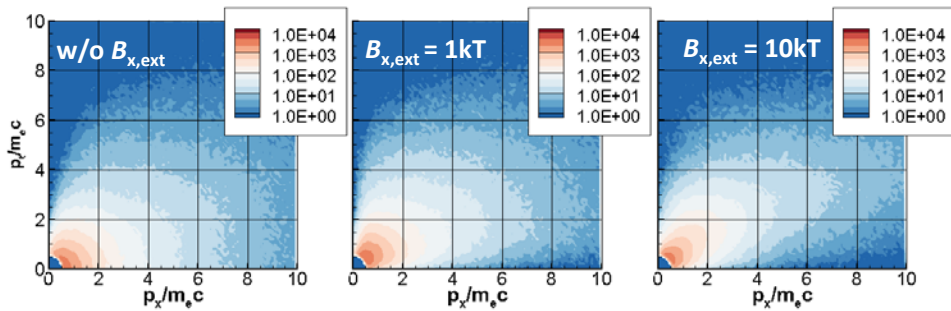


Figure 3. Fast electron momentum distribution in p_x - p_t plane, where $p_t = (p_y^2 + p_z^2)^{1/2}$, observed at the target surface for $I_L = 10^{19}\text{W}/\text{cm}^2$ and $B_{x,\text{ext}} = 0, 1, 10 \text{ kT}$.

As the role of external magnetic fields, we do not expect the reduction of angular spread but expect the suppression of spatial divergence. To evaluate the spatial divergence, we plot the spatial profiles of fast electron energy density observed at 176 fs in **Fig.4**. For the case without the external field, the fast electron beam spatially diverges with its propagation. Under the sufficiently strong external fields, however, the fast electrons are trapped by the external fields and flow along the magnetic field lines.

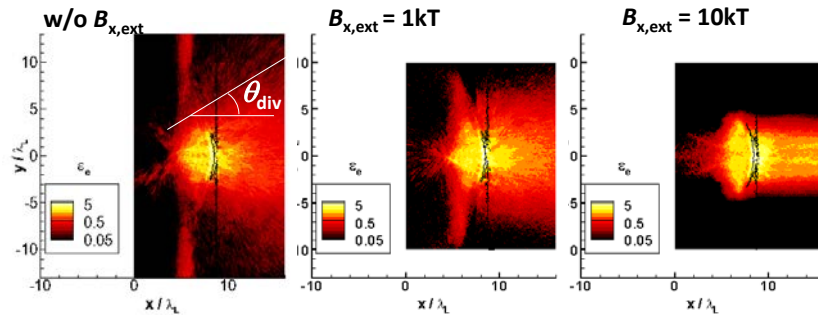


Figure 4. Spatial profiles of fast electron energy density at $t = 176\text{fs}$ for $I_L = 10^{19}\text{W/cm}^2$ and $B_{x,\text{ext}} = 0, 1, 10\text{ kT}$.

For the case with the sufficiently strong external fields, the Larmor radius becomes smaller with increasing $B_{x,\text{ext}}$, which results in smaller spatial divergence.

From the parametric simulations by varying I_L and $B_{x,\text{ext}}$, we evaluated the dependence of θ_{div} (spatial divergence angle) on $B_{x,\text{ext}}$ for $I_L = 10^{18}, 10^{19}, 10^{20}\text{ W/cm}^2$ (**Fig.5**). With increasing the laser intensity, the generated fast electron energy becomes higher, and then the required $B_{x,\text{ext}}$ for the beam guiding increases. It is found that the required magnetic field strength for beam collimation is $B_{\text{ext}} > \text{a few kT}$ for the laser intensity with $I_L = 10^{18} \sim 10^{20}\text{W/cm}^2$.

The external field strength required for $\theta_{\text{div}} \sim 0$, $B_{x,\text{ext}}^0$, is plotted as a function of I_L in **Fig.6**. It is found that $B_{x,\text{ext}}^0$ is proportional to $I_L^{1/3}$. This dependency is understood from a following simple model explanation. For the beam guiding, the fast electron gyration radius r_L should be smaller than a certain value, r_0 (for instance, the heating spot radius). The required field strength for this condition is

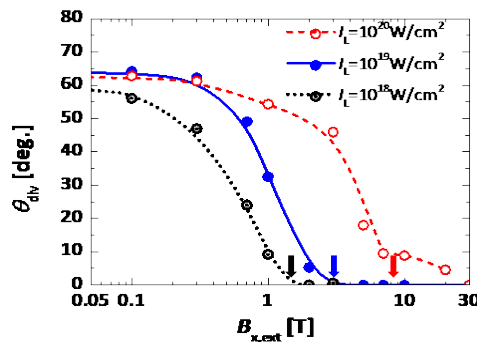


Figure 5. Dependence of spatial divergence angle θ_{div} on external field strength $B_{x,\text{ext}}$ for $I_L = 10^{18}, 10^{19}, 10^{20}\text{W/cm}^2$.

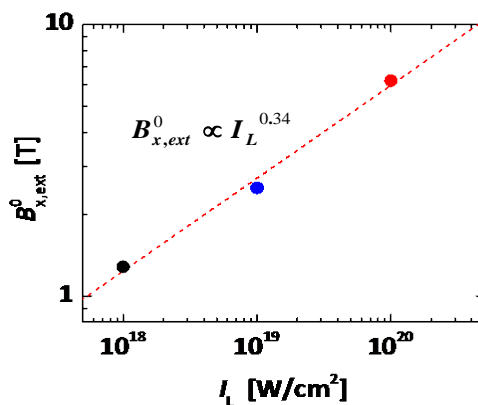


Figure 6. B-field strength required for $\theta_{\text{div}} = 0$, $B_{x,\text{ext}}^0$, as a function of I_L .

$$B_{x,ext} < \frac{p}{er_0}, \quad (1)$$

where p is the fast electron momentum. In the relativistic region, p is approximately proportional to the kinetic energy E ;

$$p = mc \sqrt{\left(\frac{E}{mc^2} + 1\right)^2 - 1} \approx \frac{E}{c}, \quad (2)$$

where m and c are the electron rest mass and the speed of light. On the other hand, the fast electron energy (*slope temperature*) evaluated here is proportional to $I_L^{1/3}$ (also, the experimental observation showed the same intensity dependency [5, 6]). The required field strength thus depends on $I_L^{1/3}$;

$$B_{x,ext}^0 \propto p \propto E \propto I_L^{1/3}. \quad (3)$$

4. Summary

For guiding of the fast electron beam with large angular divergence, we have evaluated the effects of externally-applied longitudinal magnetic fields on the fast electron generation and transport by 2D PIC simulations. It was found that angular spread in momentum distribution of fast electron beam is enhanced due to the external fields. However, the spatial divergence as the results 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. The strength of magnetic fields required for beam guiding depends on the irradiated laser intensity, $B_{x,ext}^0 \propto I_L^{1/3}$. The required field strength is 1~10kT for $I_L = 10^{18} \sim 10^{20} \text{W/cm}^2$.

Here, we assumed very simple situation (*e.g.*, uniform external fields, a plane foil target, a small laser spot, a short pulse duration and so on). Further investigation, where the more realistic situation is assumed, is required.

Acknowledgments

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