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kT-class Magnetic Fields in Laser Fusion Research
レーザー核融合研究における強磁場

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In fast ignition laser fusion, application of kT-class longitudinal magnetic fields to fast electron beam guiding is proposed for enhancing the core heating efficiency. From the collisional PIC simulations, we demonstrated the sufficient beam guiding performance by kT-class external magnetic fields. The effect of the magnetic mirror configuration formed via fuel shell implosion was also discussed. The beam guiding and focusing is expected for the case with the moderate mirror ratio (R_M~10). For the higher mirror ratio (R_M > 20), the refection due to mirror configuration exceeds the guiding effects, which will reduce the heating efficiency.

1. Introduction

One of the most crucial issues of fast ignition [1] is efficient core heating by 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. As for the beam divergence, some ideas of the guiding of the fast electron beam with large beam divergence have been proposed, e.g., the double cone [2-4] and the resistive guiding [5-10], where the self-generated magnetic fields are used. The guiding concept using the externally applied longitudinal magnetic fields has been also proposed [11,12]. In the present paper, on the basis of the numerical simulations, we demonstrate the effects of external magnetic fields on the fast electron generation and transport in the fast ignition condition.

2. Simulation Setup

If the sufficiently strong magnetic fields are applied, the fast electrons are trapped by the magnetic fields and move along the magnetic field lines, and then the beam guiding by longitudinal magnetic fields can be expected. The 2D collisionless PIC simulations [13] showed that several kT fields are required for beam guiding. In the simulations, however, the longitudinal magnetic fields were uniformly applied and the pulse duration was only 100fs. For more practical study, in the present paper, we carried out the collisional PIC simulations using relativistic electro-magnetic particle in cell code PICLS [14] by assuming the converging fields and longer pulse duration. The target is initially fully ionized carbon foil (30 μm width, 25 μm thickness), and the electron number density n_e is 300 n_{cr} (n_{cr} is the laser critical density). The pre-plasma with the exponential profile (3 μm scale length) is attached on the target front surface. The p-polarized laser pulse with wavelength of λ_L = 1 μm and the intensity of I_L = 3x10^{19} W/cm^2 is normally irradiated on the target surface. The transverse intensity profile is the Gaussian with a spot size of 6 μm FWHM, and the temporal profile is 1 ps flat pulse.

3. Beam Guiding under Converging Fields

In fast ignition experiments, the magnetic fields applied to the target are compressed by the fuel implosion, so that the field structure becomes a converging mirror one; the fields are weak around the fast electron generation region, and then it is intensified toward the dense core region. In such a converging structure, in addition to the guiding effects, we should concern about the reflection of fast electrons due to mirror fields. To evaluate the guiding effects under the converging fields, we carried out the simulations by assuming the converging fields with the mirror ratio R_M =1~20 as the initial magnetic field structure in PIC simulations,

Figure 1 shows the spatial profile of fast electron energy density and magnetic field structure obtained for the case with R_M = 5. Though part of the fast electrons are scattered or reflected due to the mirror fields, the beam can be collimated around the beam axis along the magnetic field lines. In addition, it is found in Fig.1(c) that the longitudinal magnetic field (B_x) around the beam axis observed at x = 37 μm, which is initially ~10 kT, becomes weaker (less than 5 kT). On the other hand, it is intensified around the beam edge (higher than 10 kT). In addition, the magnetic fields in z-direction are generated around the beam edge in a direction to confine the electron beam. So, the "magnetic pipe" [13] like structure is formed. These magnetic field evolution is basically due to the resistive effects since these structure cannot be observed in the collisionless simulations.

We evaluated the guiding effects by observing the fast electron beam energy within 4 μm width at x = 37μm, where the applied magnetic field becomes maximum. In Fig.2, the energy conversion efficiency from laser to the observed fast electrons $\eta_{L\rightarrow ob2}$ is plotted as a function of R_M. For the parallel field case (R_M=1), $\eta_{L\rightarrow ob2}$ becomes twice larger than that for the case without external magnetic field. For the moderate converging field case (R_M=5), further enhancement is observed, $\eta_{L\rightarrow ob2}$ nearly tripled. However, in further high mirror ratio region (R_M > 5), the conversion efficiency decreases with increasing R_M. For R_M = 20, the mirror refection effect is comparable to the guiding effect. Further enhancement of R_M will reduce the conversion efficiency $\eta_{L\rightarrow ob2}$ from the value for the case without external fields. These results indicate that the optimization of field configuration for the beam guiding is required. The acceptable mirror ratio of guiding fields is less than 20. Such field structure might be formed by control of applying timing of the external field to the fuel shell, and of the configuration of a fuel shell and a filed generation coil.

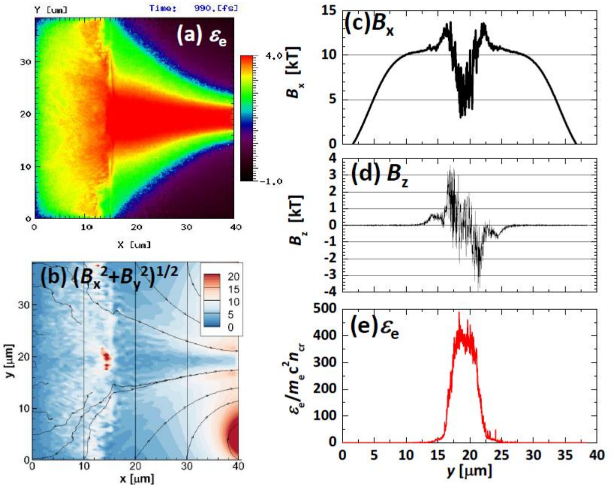

Fig.1. Spatial profiles at 990 fs for case with R_M = 5. Two dimensional profiles of (a) fast electron energy density ε_e normalized by $m_ec^2n_{cr}$, m_e and c are the electron rest mass and the speed of light and (b) $(B_x^2+ B_y^2)^{1/2}$ [100MG] and perpendicular profiles of (c) B_x, (d) B_z and (e) normalized ε_e observed at x = 37μm.

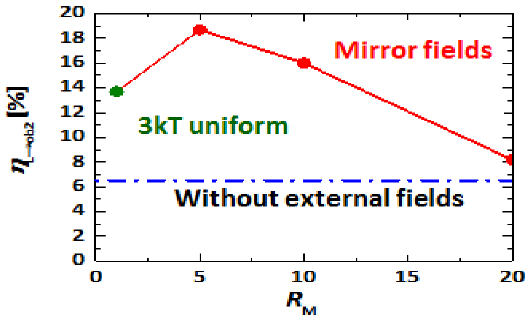

Fig.2. Energy conversion efficiency from laser to fast electrons observed within 4 μm width at x = 37 μm (maximum field region) as a function of mirror ratio.

4. Concluding Remarks

In one instance of kT-class magnetic field application in laser fusion, the fast electron beam guiding in fast ignition was referred in the present paper. Further investigation is needed such as laser intensity dependence, pulse duration dependence and formation of the optimal field structure. Also, the experimental demonstration is indispensable.

Acknowledgments

This work is partially conducted under the joint research projects of the ILE, Osaka University (FIREX-project), and with the supports of the NIFS Collaboration Research program (NIFS12KUGK057 and NIFS14KNSS054) and JSPS KAKENHI Grant Number 25400534.

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