Magnetized Fast ignition (MFI) and Laser Plasma Interactions in Strong Magnetic Field

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Abstract

In this paper, magnetized fast ignition (MFI) is proposed for improving the coupling efficiency of a heating laser to a core plasma. In the MFI, the external magnetic field is applied to reduce the hot electron energy and focus the dense hot electron flux to the core. The external magnetic field higher than 100T is generated by the laser driven coil and it is amplified by the implosion. The magnetic field at the tip of the cone is expected to reach higher than 10kT and the laser plasma interaction and the hot electron transport are modified. As the results of applying the external magnetic field, hot electron energy is reduced to less than 5MeV for the laser intensity of 10^{20}W/cm^2 and the Weibel instability is suppressed to collimate the hot electron beam to the core.

1. Introduction

The critical issue of the fast ignition has been recognized to be the coupling efficiency of a short pulse laser to a hot spark. Namely, the ultra-intense laser plasma interaction (U-LPI) and the relativistic electron transport (RET) are the critical processes for the fast ignition. In the U-LPI, the generated relativistic electron energy is required to be no more than 5MeV, and in the RET, the diameter of the heating area should be less than 100μm. In this paper, the magnetized fast ignition (MFI) is proposed and the effects of a high external magnetic filed on the U-LPI are presented.

2. Concept of MFI

The schematic over-view of the MFI is shown in the Fig. 1. Here, the magnetic field higher than 10kT could be generated by using laser driven coil [1][2] and B-field compression with implosion [3]. For an example, the magnetic field at the center of a laser driven coil is assumed 1kT, then the magnetic field at the tip of the cone will be a few hundreds Tesla. When the magnetic field is compressed by 10 times in linear scale by the implosion, the magnetic field at the tip of the cone reaches a few tens of kilo Tesla, as shown in the figure 1. Here, magnetic fields are amplified by imploding plasmas, when the magnetic Raynolds number is high enough in the gas plasma contained in the capsule. Note also that magnetic field diffuses out because of the high resistivity of the shell and is carried out by the ablative flow.

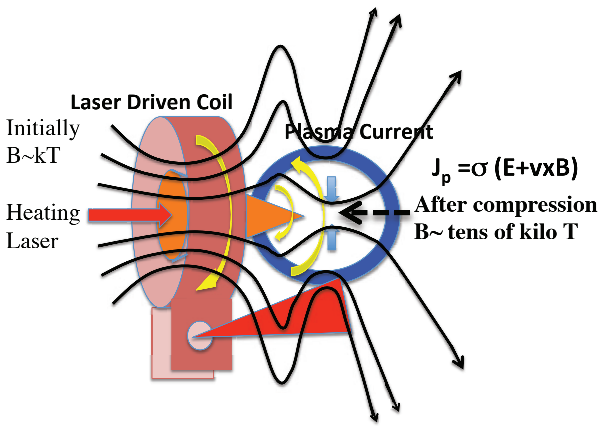


Fig.1 Geometry of Laser driven one turn coil and a cone shell target. Magnetic field is illustrated by solid lines and the circular arrows indicate induced currents in the coil and in the imploding plasma. After the compression of the magnetic field, the heating laser is injected.

In Fig. 1, the electron cyclotron frequency could be higher than the frequency of 1μm wavelength laser and a Right handed Circularly Polarized (R-CP) laser penetrates into over-dense plasmas as a whistler wave. This suggests that the laser energy is directly deposited in the over dense plasma and the average hot electron energy could be lowered. The transmittance and the reflectivity of R-CP laser for a plasma slab are estimated as follows. The refractive index of CP-em wave is given by,

$$N^2 = (\frac{ck}{\omega})^2 = 1 - \frac{\omega_p^2}{\omega(\omega \mp \omega_c)} ,$$

where ω_p is the electron plasma frequency, ω_p is the electron cyclotron frequency, and – sign (+ sign) is for R-CP (Left handed CP).

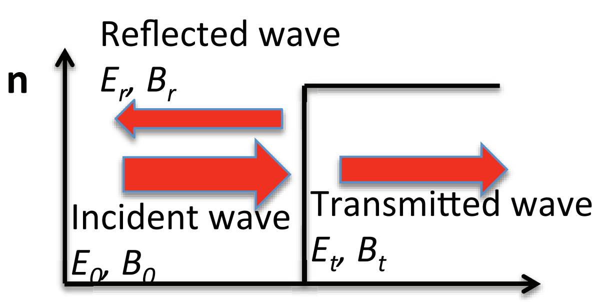


Fig.2 Geometry of laser interaction with a slab plasma. The external magnetic field is applied along X-axis.

At the boundary between vacuum and the plasma of electron density: $n>n_c$ (cut-off density), the electric fields, magnetic fields, reflectivity, and transmittance are estimated as follows.

The incident, reflected and transmitted wave electromagnetic fields are shown in Fig.2. The boundary conditions for the waves yield the relations of the amplitude of transmitted and reflected waves to the incident wave amplitude:

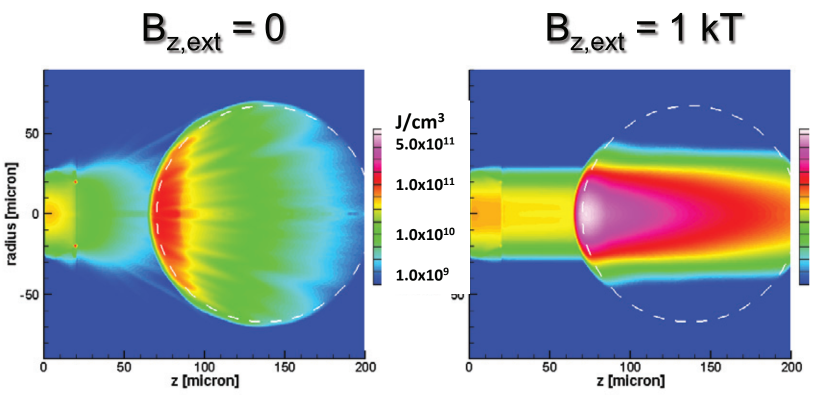
Transmitted wave: $\frac{E_t}{E_0} = \frac{2.0}{1.0+N}, \quad \frac{B_t}{B_0} = \frac{N}{(1.0+N)}$

Reflected wave : $\frac{E_r}{E_0} = \frac{1.0-N}{1.0+N}, \quad \frac{B_r}{B_0} = \frac{1.0-N}{1.0+N}$

Therefore, the reflectivity: R and the transmittance are obtained as,

$$R = \frac{(1.0-N)^2}{(1.0+N)^2} \quad \text{and} \quad T = \frac{4N}{(1.0+N)^2} \quad \text{, respectively.}$$

For an example, these relations indicate that R=0.56 and T=0.44, when $\omega_c/\omega = 2$ (20kT) and $n = 50n_c$. In this case, the electric field in the plasma is 1/4 of the incident laser electric field. Namely, the amplitude of the vector potential, a is 1/4. Therefore, the average energy of high energy electrons is also 1/4, which means the average electron energy could be 1~2MeV even for the laser intensity higher than 10^{20} W/cm^2. This will make the heat deposition efficiency higher in the hot spark. The effects of the magnetic field on the transport of the hot electrons are simulated by the hybrid simulation code[4]. It was demonstrated that the coupling efficiency could be higher than 20% for a moderate angular divergence of the hot electrons, when 1kT magnetic field is applied. The heat deposition density distributions are compared with and with out magnetic field as shown in Fig.3.



(a) (b)

Fig.3 Heat deposition profiles of the 2D hybrid simulations for without (a) and with external magnetic field.

In this hybrid simulations, we assumed that the cone is made by diamond like carbon (DLC), the total electron energy is 50kJ, the electron energy and angular spread are 3.5 MeV and 55°, respectively, and the core plasma density, the cone tip to the core edge distance is 50 μm, and hot spark density and area are 450 g/cm^3 and 40x30 μm, respectively.

The angular divergence of laser produced hot electrons may also be reduced by the sufficiently strong external magnetic field. One of the mechanisms of the enhancement of the angular divergence is the Weibel instability near the interaction region. The effects of the external magnetic field on the Weibel instability is under investigation[5]. The simulation result indicates that the growth rate of the Weibel instability is significantly reduced when the magnetic field exceeds 10kT. However, the secondary instability is not stabilized and the angular spread is reduced only for very high magnetic field higher than 20kT.

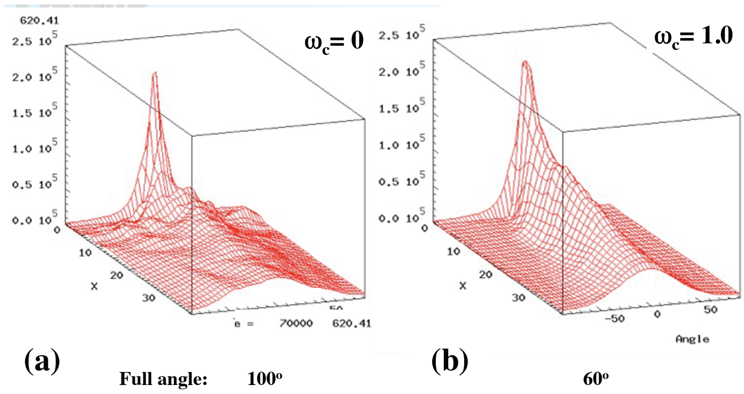


Fig.4 Angular diffusion of high energy electron in the magnetic field turbulence by the Webel instability in 40 μm propagation.
(a) Without B-field, (b) With B-field (30kT), [5]

In summary, the recent development on the laser driven coil and the amplification of magnetic field leads to a new idea: "Magnetized Fast Ignition" (MFI). In the MFI, it is expected that the heating laser penetrate into over dense plasma as a whistler wave and deposits the energy, the angular divergence of hot electrons is reduced by suppressing the Weibel instability with B-field, and the hot electrons are guided efficiently by the magnetic field. At sufficiently strong external magnetic fields, Those effects will significantly improve performance of the fast ignition.

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