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§42. Enhancement of Coupling Efficiency in Fast-ignition Laser Fusion by Controlling Self-generated and External Magnetic Field

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In fast ignition scheme of inertial confinement fusion, collimation and guiding of the fast electron beam (FEB) is a critical to increase energy coupling efficiency from the heating laser to the fusion fuel core. The FEB is diverged due to plasma instabilities occurred in inhomogeneous and over-dense plasmas. According to several numerical studies, the divergence can be controlled by an azimuthal magnetic field (B-field) in the range of 1-10 kT, either self-generated by the FEB itself, or imposed exteriorly to the imploded capsule. The purpose of this research is to demonstrate of FEB collimation by the magnetic field. One of the most important issues is to develop a scheme to generate kT-class B-field in the laboratory. Kilo-tesla B-ield was generated with GEKKO-XII [1] and LULI facilities with laser-driven capacitor-coil targets [2]. For estimating strength of the magnetic field, we have developed a simple model base on an isothermal plasma expansion [3,4].

Laser-driven capacitor-coil target were used to generate magnetic field in this study. Two metal (nickel or copper) disks are connected by a U-turn coil. Kilojoule, nanosecond laser pulses are focused onto the first disk through a hole in the second disk. A plasma is generated at the first disk, and suprathermal hot electrons with temperatures exceeding 10 keV are emitted from the plasma corona. The hot electrons stream down the electron density gradient ahead of the expanding plasma plume and impact the second disk. The second disk acquires a negative charge, and a large electrical potential develops between the disks. That potential difference drives a current in the U-turn coil. A strong magnetic field pulse is generated in the coil.

Strength of the magnetic field generated by the capacitor-coil targets was measured with Faraday rotation of a probe laser light under the strong magnetic field, proton radiography (Fig. 1), and inductive pick-up coil. All these measurements reveals that a kT magnetic field is generated at the center of the coil. Strength of the magnetic field reaches its maximum around 1 ns after the laser irradiation, and it lasts for 3 ns.

We have developed a simple model to understand the mechanism of the B-field generation in the capacitor coil target. Isothermal expansion model was used to describe dynamics of plasma expansion between the two metal discs. Charge neutrality is not kept at the boundary between the expanding plasma and vacuum. Electric charge carried by the front surface of the expanding plasma is $\sigma = \varepsilon_0 E_{ss}$ and $E_{ss} = k_B T_e / e C_s t$, here ε_0, k_B, T_e, e, C_s t are dielectric constant of vacuum, Boltzmann constant, hot electron temperature, elementary charge, sound velocity and plasma expansion time, respectively. Sound velocity in a plasma is $C_s = (Z k_B T_e/m_i)^{1/2}$, here Z and m_i are mean charge and mass of ions, respectively. There is a relation between the plasma expansion time (t) and distance (d) between the two metal discs as $d = C_s t$ [2 ln $(\omega_{pi} t)$ + ln2 -3], here ω_{pi} is ion-plasma frequency given as $\omega_{pi} = (n_{e0} Z e^2 4\pi/\varepsilon_0 m_i)^{1/2}$. n_{e0} is hot electron density at the generation point. This density can be calculated with the energy flux conservations as $\eta I_L = n_{e0}\, k_B T_e\, (k_B T_e/m_e)^{1/2}$, here η, I_L are energy coupling efficiency from laser to hot electron and laser intensity. Total charge those are accumulated on the disc is $Q = \sigma S$, here S is an area of the disc to capture the hot electrons. Capacitance of the discs is $C = \varepsilon_0 S/d$. Therefore the electric potential differences between the discs are $V = Q/C$. V = 0.3 MV is obtained for I_L = 2.5 x 10^{16} W/cm^2 and η = 0.1. This value corresponds to 0.4 MA of the current in the wire and 1 kT of B-field at the coil center. This simple model agrees fairly well with the experimental observations.

This magnetic field will be applied to a laser-produced plasma to suppress the Weibel instabilities between counter streaming plasma and electron beam, and to guide relativistic electron beam generated by intense laser-plasma interaction. Hydrodynamic instability of high-energy-density plasma under the strong magnetic field is also an interesting research subject relevant to inertial confinement fusion and astrophysics. A Helmholtz-type coil target was designed to generate spatially uniform magnetic field in 1 mm^3 volume for benchmarking computations by magneto-hydro-dynamic codes. Electron-thermal-transport to be anisotropic in the magnetized high-energy-density-plasma, magnetic field line moves with plasma motion, therefore advection of the magnetic field affects on the development of the hydrodynamic instabilities.

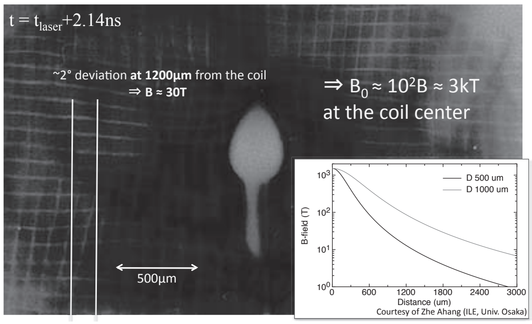

Fig 1 An example of the proton radiography of the magnetic field generated by the capacitor-coil target.

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