Plasma heating by counter irradiating ultra-intense laser pulses

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Fast Ignition (FI) is a method of heating an assembed high-density plasma into an ignition state by using a relativistic electron beam produced form ultra-intense laser-matter interaction[1, 2]. To achieve a clear evidence of plasma heating, FI experiments were on going so far by using one-direction heating laser irradiation scheme[3, 4, 5, 6]. By using a different scheme that involving counter laser irradiating configuration to FI, we observed clear evidences of heating of plasma core preformed from a double foil target[7] and a spherical shell target[8]. A two-dimensional collisional particle-in-simulation (PIC) reveals that counter relativistic electron currents generate a mega-Gauss magnetic filaments caused by an electro-magnetic two-stream Weibel instability, contributing to trap these electrons and proposing a possibility of their energy deposition into the core[8]. In this paper, we discuss simulation results of the Weibel instability induced from counter relativistic electron beams by considering its growth rate and collisions in a bulk plasma. As the results, for bulk densities up to a few g/cc, the growth rate of Weibel instability is larger than the bulk electron ion collision frequency, so the counter relativistic electron beams can produce a mega-Gauss magnetic filaments those might induce an anomalous heating with stopping power as much as a factor of 10^3 of the classical one[9].

The two-stream Weibel instability can be occurred in the bulk plasma as far as the driving beams are collisionless. The growth rate of this instability is given by a linear theory[10, 11],

$$\frac{\partial^2 B_1}{\partial t^2} = \frac{a^2}{c^2}\omega_{be}^2 B_1, B_1 = B_{10}\exp\left[+(a/c)\omega_{be}t\right], \tag{1}$$

where B_1 is the seeding magnetic fields, a/c is the beam velocity normalized by the speed of

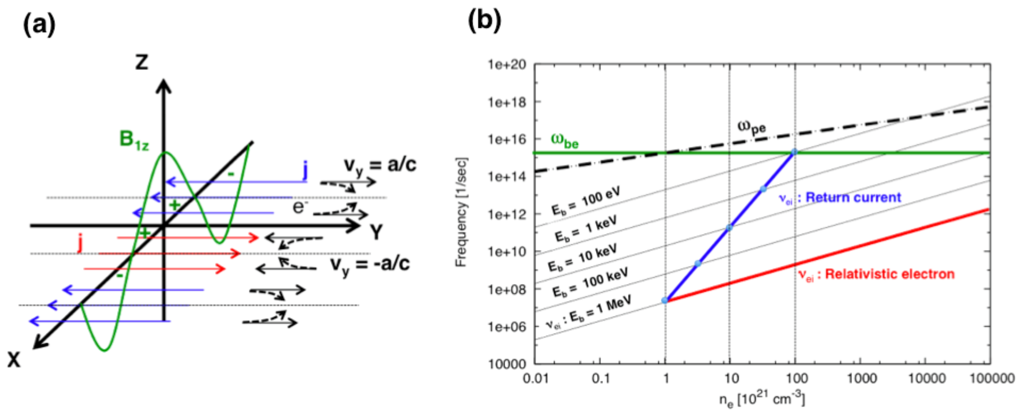

Figure 1: (a)Illustration of the instability driven by counter propagating current flow. (b) Collision frequencies as a function of bulk electron density for electron beams with energies from 100 eV to 1 MeV.

light c, and $\omega_{be} = \sqrt{e^2 n_b/\varepsilon_0 m_e}$ is the beam plasma frequency defined by the beam density of n_b, the electron charge of e, the permittivity of ε_0, and the electron mass of m_e, respectively. The growth of magnetic field described in Eq. (1) is introduced from a physics model as shown in Fig. 1 (a), where an electron beam flows along the y-axis with a velocity a/c and equal particle flux in opposite direction with a velocity $-a/c$ and these beams are curved by initial magnetic fields B_1 toward its current density j increases resulting in enhancing magnetic fields. When these counter beam flows are scattered from charged particles in the bulk plasma, the beam current concentration are suppressed preventing the growth of magnetic field. This beam scattering or momentum change is represented from an electron-ion collision frequency[12],

$$\nu_{ei} = \frac{Z n_e e^4 \ln\Lambda}{4\pi\varepsilon_0^2} \frac{1}{m_e^{1/2}(2E_{beam})^{3/2}}, \tag{2}$$

where Z is the charge state, n_e is the bulk electron density, $\ln\Lambda$ is the Coulomb logarithm, and E_{beam} is the electron beam current energy, respectively. When an ultra-intense laser is illuminated into the plasma from one-direction, a relativistic electron current produced from a laser-plasma interaction induces a return current flow in opposite direction with a equal particle flux to provide charge neutrality in the bulk plasma . For the one-direction laser illumination, this return current represents the counter beam flow with beam velocity inverse proportional to the bulk density. For a counter laser illumination, in contrast, the relativistic electron beam represent the counter beam flow with beam velocity in dependent to the bulk density. From Eq. (1) and (2), the growth of Weibel magnetic field should satisfy a condition: $(a/c)\omega_{be} > \nu_{ei}$.

For the one-direction illumination, the Weibel magnetic fields are suppressed by collisions between the return currents and the bulk plasma. Figure 1 (b) shows electron beam collision

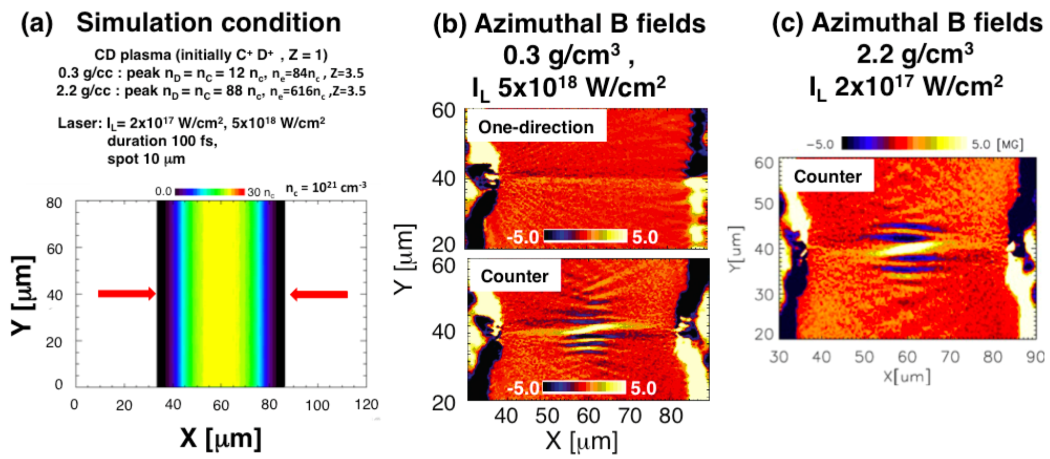

Figure 2: (a) Simulation geometry. (b) Azimuthal magnetic fields for the bulk density 0.3 g/cc with one-direction laser illumination (upper) and counter laser illumination (bottom) at t= 500 fs. (d) Azimuthal magnetic fields for the bulk density 2.2 g/cc at t= 500 fs for counter laser illumination.

frequencies as a function of the bulk electron density for electron beams with energies from 100 eV to 1 MeV. Here, we suppose a condition that the relativistic electron current driven by the ultra-intense laser illumination flows one-direction with energy 1 MeV and with the beam density of $10^{21}\mathrm{cm}^{-3}$; a laser cut-off density for a laser wavelength of 1 μm, in the bulk plasma. For counter-illumination case, the opposite counter beam flow is also represented by the relativistic electron current with energy 1 MeV driven by the ultra-intense laser illumination from the other side with the electron beam collision frequency represented as the red curve (E_b = 1 MeV) because laser-produced electron beam energy is independent of the bulk plasma. In contrast, for one-direction illumination case, the opposite beam flow is the return current with the collision frequency represented as the blue curve that closing on curves for E_b = 100 eV – 1 MeV because the velocity of return current is inverse proportional to the bulk density. For the one-direction illumination, when the bulk density reaches 10^{23} cm^{-3}, the collisions become dominant comparable to the growth rate of the Weibel instability driven by relativistic electron beam ($a/c \sim 1$); $(c/a)\omega_{be} \sim \omega_{be}$ (the green curve).

From a two dimensional PIC simulation, in a counter illumination scheme, the growth of Weibel magnetic field is confirmed for high densities up-to a few g/cc. The simulation is performed with a collisional two-dimensional PIC code, PICLS2D, that includes the ionization processes in the bulk plasma[13]. The simulation condition is shown in Fig. 2 (a), where the bulk plasma containing carbon and deuterium (CD) nuclei with an initial charge state of 1.0 has a peak bulk density at x = 0 μm with an ion cut-off density at x = 35 μm and x = 85 μm, respectively. The counter-illuminating heating pulses have a focal intensity I_L beyonds 2×10^{17} W/cm^2 with a time duration of 100 fs and a focal spot size of 10 μm, respectively. From Fig. 2 (b), for the one-direction illumination, the azimuthal magnetic field is suppressed bellow 1 MG at the center of the bulk plasma (x = 60 μm, y = 40 μm). That is a resistive magnetic field. In contrast, for the counter illumination, the magnetic fields beyond 5 MG that represents filament structures of the Weibel instability. As shown in Fig. 2 (c), as far as the counter illumination, this magnetic field also beyond 5 MG for bulk density upto 2.2 g/cc.

The induced strong magnetic fields scatter the bulk cold electron through the cyclotron motion contributing to a resistivity with an electrostatic field that might lead a anomalous heating. Sentoku reported that, in a over dense (10 n_{cr}:the laser cut-off density) plasma, the induced Weibel magnetic field arises a stochastic scattering of cold electron leading to an anomalous heating with a anomalous stopping dominates over the classical stopping by as much as a factor of 10^3[9]. As the bulk density rise up, Kemp reported that a collisional motion of cold electrons disturbs the bulk particle flows resulting in suppression of a kinetic motion or instability[14]. By using a counter irradiating scheme we propose, the strong magnetic fields are sustained by counter fast electron flows in the dense plasma that might induce the anomalous heating.

In conclusion, we discuss the Weibel instability induced from counter relativistic electron beams by considering growth rate of the instability and collisions between the beam current and the bulk plasma. For bulk densities up to a few g/cc, the counter relativistic electron beams are contributing to produce the mega-Gauss magnetic filaments those might induce the anomalous heating with stopping power as much as a factor of 10^3 of the classical one.

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