Kinetic simulation of electron transport using electron magnethydrodynamic structures

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Abstract. Recent researches show the possibility that dipolar vortex structures, which are moving solutions in electron magnetohydrodynamic model, are generated by laser plasma interaction and they are applicable to electron transport in high-density plasma. However, the consideration of immobile ion and zero temperature employed in the electron magnetohydrodynamic formalism is pretty restrictive. Therefore the kinetic effects due to finite electron temperature on propagation of electron magnetohydrodynamic dipolar structures have been firstly explored using two-dimensional Particle-In-Cell simulation. Results show that the dipolar structures propagate damping the magnetic fields and its lifetime becomes longer in the case of lower temperature.

1. Introduction

In fast ignition scheme, various heating methods have been proposed [1,2,3]. Application of a laser-produced electron beam is one method to ignite the core, but it is difficult to produce the directional electron beam because electron beam generated by interaction between high-intensity laser and solid matter has originally large divergence angle [4]. Another method is the use of ion beam that is easy to be directive compared to the electron beam but conversion efficiency is not so good. Although it is not clarified that which method is the best way, we pay attention to electrons as the medium for core heating. It is because electron magnetohydrodynamic structures may be able to be used for electron transport [5]. In the two-dimensional electron megnetohydrodynamics (EMHD), a variety of localized solutions are permitted [6,7]. For example, there are stationary monopolar rotating electron vortex solutions in the 2-D plane. A combination of two counter-rotating electron vortices brought within a distance of the electron skin depth, forms a structure of a dipolar form, which propagates at a constant speed towards the direction of central flow if the strength of the two vortices is the same. There is the possibility that dipolar structures are generated by laser plasma interaction and applicable to electron transport in high-density plasma [5,8]. The consideration of immobile ion and zero temperature employed in the EMHD formalism, however, is pretty restrictive. Therefore, the role of kinetic effects due to finite electron temperature on EMHD structures needs to be investigated. In the previous related work, the kinetic effects on robustness of EMHD monopolar structures had been investigated [9]. As the next step, the kinetic effects on the propagation of EMHD dipolar structures have been firstly explored in this paper.

2. Electron magnetohydrodynamic structures

The EMHD model is relevant to phenomena for which the typical time scale of variations lies between the electron and ion gyroperiods and the length scale is in between the electron and ion gyroradii. The governing equations for EMHD can be obtained from: (i) the electron momentum equation, (ii) the expression for current in terms of the electron velocity (immobile ion), and (iii) Ampere's law, in which the displacement current is neglected. When the current and its variation are confined in two dimensions, namely the x-y plane, the equation for EMHD is simplified. Simplified equation permits exact stationary solutions. A typical solution in cylindrical coordinates (r,θ,z) can have the following form:

$$\begin{aligned} b &= \exp\left(-\frac{r^2}{R^2}\right) \\ v_\theta &= -\frac{2r}{R^2}\exp\left(-\frac{r^2}{R^2}\right) \end{aligned}, \qquad (1)$$

where $\mathbf{v}_e = v_\theta \mathbf{e}_\theta$ because $\mathbf{B} = b(r)\mathbf{e}_\mathbf{z}$, and R represents a typical size of the structure. The solution consists of the vortex electron flow (currents) and its associated magnetic fields. The simplified 2-D EMHD equation also has dipolar solution that is moving solution. This solution consists of Bessel function that was derived by Ishichenko *et al* in Ref. 7 and approximate solution can be given by putting closely two-opposite monoploar solutions.

3. Two-dimensional Particle-In-Cell simulation of EMHD dipolar structures

3.1. Initial condition

To estimate the kinetic effects on the propagation of EMHD dipolar structures, we perform kinetic simulations using 2-D Particle-In-Cell code, FISCOF-2D [10]. We suppose high-density plasma over the critical density for the Nd: glass laser. In this case, 9.92×10^{20} electrons per cm^3 are the critical density for the laser wavelength of 1.06 μm. A rectangular plasma slab, whose electron density is 20 times the critical density, is placed at $-1.0 < X$ [μm] < 4.0 and $-1.0 < Y$ [μm] < 1.0 and surrounded by a vacuum, where ions are the stationary background and simulation box is defined at $-1.2 < X$ [μm] $<$ 6.2 and $-1.2 < Y$ [μm] < 1.2. Normally, electrons that move out over the edge of the plasma return via self-generated sheath fields and they cannot reach the boundary of the simulation box. Initial electron currents and magnetic fields of the dipolar structures are given by putting closely two-opposite monoploar solutions that follow Eq. (1). Both structure size and distance between two monopolar solutions are set to 0.15 μm. Maximum magnetic field is set to 500 mega gauss. Initial electron velocity distribution is followed by locally shifted Maxwellian, where the drift velocity is given by the fluid velocity of the EMHD solution. Three cases of the temperature of 1, 4, and 16 keV are simulated. Simulation time is 400 fs that is enough to see kinetic effects on the simulated EMHD structures.

3.2. Results

Figure 1 shows 2-D spatial profiles of magnetic field in the z direction in the case of (a) 1, (b) 4, and (c) 16 keV at t = (1) 0, (2) 50, (3) 100, (4) 150, and (5) 200 fs. It is clearly shown that dipolar structures move in high-density plasma and one of them collapses in the case of high temperature, namely 16 keV. It is noted that the moving speed seems not to depend on the electron temperature. In those cases, the moving speeds are estimated at 0.005–0.006 μm/fs. Figure 2 shows two examples of electron orbits in the cases of (a) 1 and (b) 16 keV, where black and blue lines indicate orbits of electrons that are initially inside the dipolar structure and purple line indicates the orbit of electron that is initially outside the structure. Background contour is initial two-dimensional spatial profile of magnetic field in the z direction. In the case of 1 keV, electrons that are initially inside the structure do not run away outside the structure, therefore the structure does not collapse much. On the other hand,

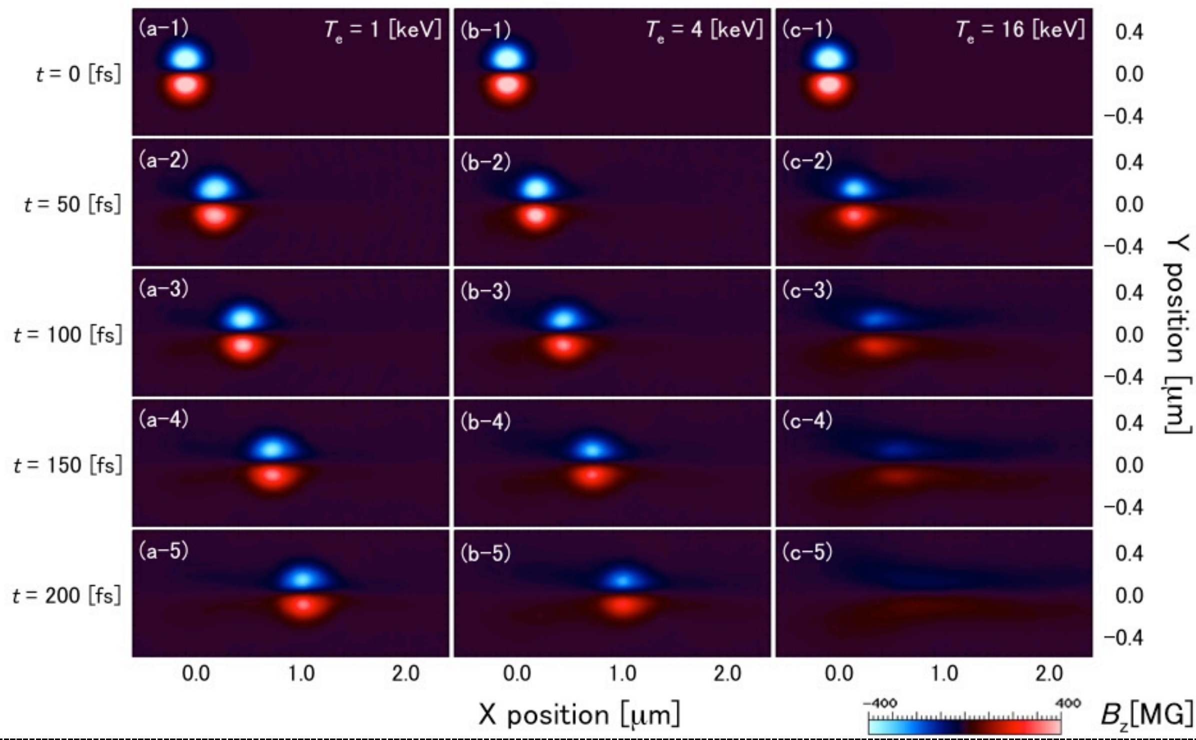

Figure 1. 2-D spatial profile of magnetic field in the z direction in the case of (a) 1, (b) 4, and (c) 16 keV at t = (1) 0, (2) 50, (3) 100, (4) 150, and (5) 200 fs.

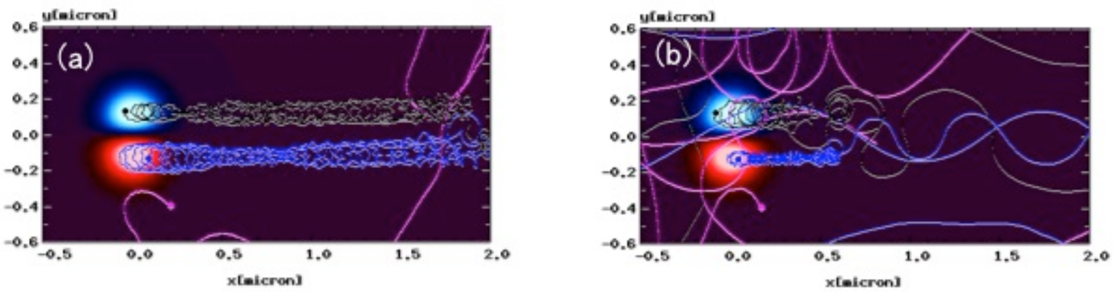

Figure 2. Electron orbits in the case of (a) 1 and (b) 16 keV, where black and blue orbits indicate the electrons that are initially inside the dipolar structure and purple orbit indicates the electron that is initially outside the structure.

in the case of 16 keV, electrons that are initially put inside the structure are trapped inside the structure for a while but they run away outside the structure within the simulated time, therefore the structure gradually collapses. Figure 3 shows that time evolution of magnetic energy within the circle with the radius of three and half times the structure size ($3.5R$) from the center of the structure, where red, blue, and green lines indicate the cases of 1, 4, and 16 keV, respectively. The decay times of the magnetic energy, which are estimated from Figure 3 assuming the exponential decay and summarized in Table 1, are shorter for lower temperature, but that for higher temperature is longer.

Table 1. Decay times of the magnetic energy assuming exponential decay

Simulation case	1 keV	4 keV	16 keV
Decay time	315 fs	193 fs	65 fs

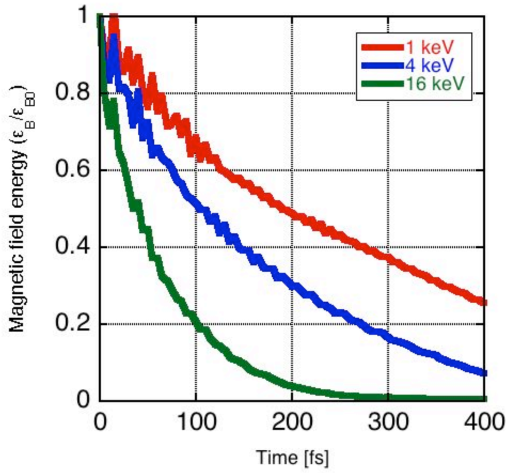

Figure 3. Time evolution of magnetic energy within the circle with the radius of three and half times the structure size ($3.5R$) from the center of the structure, where red, blue, and green lines indicate the cases of 1, 4, and 16 keV, respectively.

4. Summary and discussion

Kinetic simulations of electron transport using EMHD dipolar structures have been performed and kinetic effects due to finite electron temperature on the propagation of these structures have also been explored. Under the finite electron temperature, the dipolar structure can survive for a while and its lifetime is seemed to depend on the electron temperature. The finite temperature effects cause the damping of the magnetic field and finally its collapse. Collapsing of the dipolar structure is crucial issue for the application to the fast ignition scheme because this structure may collapse before reaching the core. Actually, simulated structures must collapse during the propagation of few microns. However, this issue can be cleared because it is considered that the larger structure has longer lifetime according to Ref. 9.

References

[1] Tabak M, Hammer J, Glinsky M E, Kruer W L, Wilks S C, Gampbell E M, Perry M D and Mason R J 1994 *Phys. Plasmas* **1** 1626–34
[2] Roth M, Cowan T E, Key M H, Hatchett S P, Brown C, Fountain W, Johnson J, Pennington D M, Snavely R A, Wilks S C et al. 2001 *Phys. Rev. Lett.* **86** 436
[3] Hegelich B M, Jung D, Albright B J, Fernandez J C, Gautier D C, Huang C, Kwan T J, Letzring S, Palaniyappan S, Shah R C et al. 2011 *Nucl. Fusion* **51** 083011
[4] Hata M, Sakagami H, Johzaki T and Nagatomo H 2013 *Laser Part. Beams* **31** 371–7
[5] Yadav S K, Das A and Kaw P 2008 *Phys. Plasmas* **15** 062308
[6] Isichenko M B and Marnachev A M 1987 Sov. Phys. JETP **66** 702
[7] Das A 1999 *Plasma Phys. Controlled Fusion* **41** A531
[8] Nakamura T, Bulanov S V, Esirkepov T Zh and Kando M 2010 *Phys. Rev. Lett.* **105** 135002
[9] Hata M, Sakagami H and Das A 2013 *Phys. Plasmas* **20** 042303
[10] Sakagami H and Mima K 2002 *Proc. 2nd Int. Conf. on Inertial Fusion Sciences and Applications* 380–383