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Self-Generated Magnetic Dipoles in Weakly Magnetized Beam-Plasma System

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A new self-generation mechanism of magnetic dipoles and the anomalous energy dissipation of fast electrons in the magnetized beam-plasma system are presented. Our particle-in-cell simulations show that the magnetic dipoles are self-organized and play important role for the beam energy dissipation. These dipoles drift slowly with a quasi-steady velocity depending on the magnetic gradient of the dipole and the imposed external magnetic field. The formation of dipoles provides a new anomalous energy dissipation mechanism of the relativistic electron beam, and this mechanism plays important roles in the fast ignition and the collisionless shock.

1. Introduction

The resulting two-stream instability (TSI) and the Weibel instability (WI) in the beam-plasma system have been widely investigated in the fast ignition and astrophysics. Recently, an external magnetic field is proposed to collimate the fast electrons in fast ignition [1], and strong external magnetic field of the order of kilo Tesla has already been produced in laser driven coil [2]. A variety of theoretical studies [3] indicate the important role of the inverse cascade in the nonlinear evolution of the beam-plasma system without external magnetic field. Here, we investigate the role of self-generated magnetic dipoles (MDs) in the magnetized plasma in relation with the anomalous energy dissipation [4] in the magnetized fast ignition, and suggest implications to the formation of collisionless shocks.

2. Simulations

We carry out the 2D3V PIC simulation code Ascent to study the transport of the fast electron beam in the magnetized dense plasma. The simulation plane is parallel to the external magnetic field $\mathbf{B_0}$. The simulation region is $25.6\lambda_0$ in the $\mathbf{x}$ direction and $12.8\lambda_0$ in the $\mathbf{y}$ direction. Periodic boundary conditions are applied for particles and fields in both directions. The density ratio of the beam and background electrons is $n_b/n_p=1/6$ with the drift velocities of $\mathbf{v_b}=0.978c$ for the beam and $\mathbf{v_p}=-0.163c$ for the background electrons. The total simulation time is $60T_0$. We have performed a number of simulations without and with external magnetic field of different amplitudes. (The fields are normalized to the characteristic field $mc\omega_p/e$.)

3. Results

Figure 1(a) shows the temporal evolution of the total energy of the out-of-plane magnetic field B_z and the electric field E_y and E_x, which are normalized to the initial total kinetic energy in the system for simulations with different amplitude of external magnetic field. In the linear stage of the WI and TSI, the field energies grow up exponentially at nearly the same growth rate for $\mathbf{B_0}=0.15$ and $\mathbf{B_0}=0$, as shown in Fig.1(b). In the case with strong $\mathbf{B_0}=1.0$, the growth rates are smaller. The growth rates in simulations approximately agree with the analytic analysis. Then, after the saturation and nonlinear damping due to the inverse cascade, the energy $\langle B_z^2\rangle$ reaches a quasi-steady level in the $\mathbf{B_0}=0$ and $\mathbf{B_0}=1.0$ cases. However, in the weak external magnetic field case, the energy $\langle B_z^2\rangle$ starts to grow up anomalously. The final energy in $\mathbf{B_0}=0.15$ case is nearly one order of magnitude higher than the other cases as shown in Fig.1(a). Furthermore, compare the momentum spread of the beam and background electrons in the unmagnetized and weakly magnetized cases, it is found that the beam

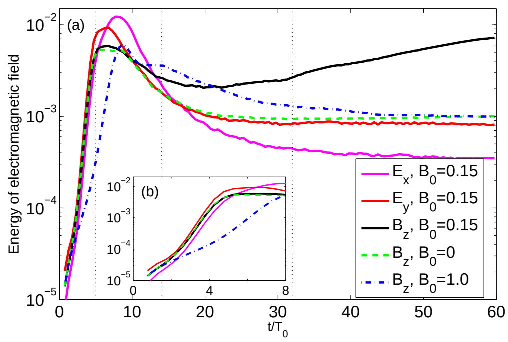

Fig.1: (a)the temporal evolution of the energy of B_z for the cases with external magnetic field of $B_0=0$, $B_0=0.15$ and $B_0=1.0$, and the energy of E_x and E_y for the $B_0=0.15$ case. The inserted figure (b) is the temporal evolution in the linear stage.

electrons are significantly decelerated together with the background electrons strongly heated up in the weakly magnetized case, and about 5.4% more total beam energy is lost in the weakly magnetized case than the unmagnetized case.

4. Analysis

Look into the dynamics of the magnetic field fluctuations in **B_0**=0.15 case, we can observe that during the initial nonlinear stage, some small MD-like structures appear due to the possible merging and crossing of current filaments (the magnetic fluctuations correspond to the current fluctuations.) These MD seeds can survive a long enough time to grow up and finally self-organize the coherent MDs shown in Fig.2(a). The grow-up of MD seeds and the formation of MDs are coincident with the slow nonlinear increase of energy $\langle B_z^2 \rangle$. In addition, these dipoles drift in the negative x direction at a quasi-steady velocity and the amplitude of the dipole gradually increases during the drift.

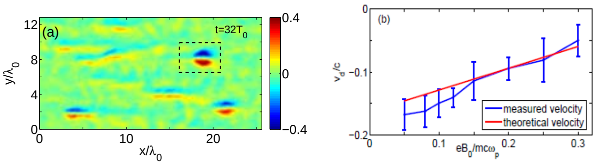

Fig.2: (a) Snapshot of the magnetic field B_z for B_0=0.15 case at t=32T_0. (b)Measured average drift velocities and the theoretical velocities of the dipoles for different amplitudes of external magnetic field.

By resorting to 2D EMHD theory, we deduce that the relationship between the drift velocity of the MDs and the external magnetic field as

$$v_d = v_b - \left(\frac{\partial b}{\partial y}\right)_{(x_0, y_0)} + \frac{k}{1+k^2} B_0 \qquad (1)$$

Here the first term is the background flow velocity, the second term denotes the magnetic gradient at the center of one vortex of the dipole, k is the curvature of the B_z field at the vortex center. It is found that the off-set linear dependence of the measured drift velocity on the external magnetic field amplitude agrees approximately with the EMHD analysis as shown in Fig.2(b).

5. Discussions

Next, we investigate the dynamics of electrons around the MDs to look for the reason of the anomalous energy dissipation. The trajectories of the beam electrons shows that due to the large B_z of the dipole, the beam electrons moving forward are deflected and focused by the Lorentz force. Similarly, the background electrons moving backward are scattered out of the MD, and the overall electron density is reduced in the MD. Thus a positive electrostatic potential well is excited

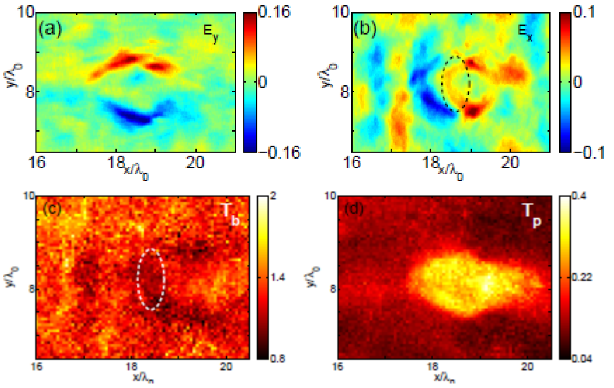

Fig.3: (a) and (b) respectively shows the detailed structure of the electric field E_y and E_x at t=32T_0 of the dipole marked in Fig.2(a). (c) and (d) represent the average energy (unit: MeV) per electron for the beam and background electrons in the same region respectively.

accordingly, and the detailed structures of the E_y and E_x are shown in Fig.3(a) and (b). It is worth noting that there is a positive E_x component in the center of the MD as marked in Fig.3(b). This field is the inductive electromagnetic component when the MD grows, and this field contributes to decelerate the beam electrons. Look at the average energy distribution of the beam electrons shown in Fig.4(c), the average energy is lower for the beam electrons in the MD, and the deceleration region corresponds to the electromagnetic Ex component. In addition, the average energy of the background electrons is dramatically high in the MD as shown in Fig.4(d), that is because some extremely low energetic background electrons trapped by the positive potential well, and gradually get accelerated during the oscillations inside the well.

In summary, we have studied the microphysics of the self-organized MDs in the nonlinear evolution stage of the instability in a weakly magnetized beam-plasma. It is found that the MDs serve as medium for the energy transfer between the beam and background electrons. Thus, the formation of MDs not only contributes to the anomalous energy dissipation in the fast electron beam transport in fast ignition, but also provides new insights that the formation of the collisionless shocks could be stronger in the weakly magnetized system.

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