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Influence of the solenoid magnetic field on the self-modulation mechanism

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Research Article

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For the guarantee of the long-distance transport of the bunches of China Initiative Accelerator Driven System (CIADS), a new scheme is proposed that extra magnetic field is used in the accelerator-target coupling section before the windowless target to minimize the self-modulation (SM) mechanism. Particle-in-cell simulations are carried out to study the influence of the solenoidal magnetic field on the self-modulation mechanism when long proton bunches move in the background plasmas. The long proton bunches used in the simulations are similar to these in the linear accelerator of CIADS. It is found that the presence of the solenoidal magnetic field will significantly inhibit the self-modulation process. For the strong magnetic field, the longitudinal separation and transverse focusing of the long bunches disappear. We attribute these phenomena to the reason that the strong solenoidal magnetic field restricts the transverse movement of plasma electrons. Thus, there are not enough electrons around the bunch to compensate the space charge effect. Moreover, without transverse current, the longitudinal pinched effect disappears, and the long bunch can not be separated into small pulses anymore.

Introduction

In the project of CIADS in Lanzhou (Yang and Zhan, 2015), which includes three sub-systems: accelerator, spallation target, and sub-critical reactor, the proton beam from the accelerator reacts with the nuclei of the lead-bismuth eutectic. Before the proton beam is injected into the target, there is an about 100-m-long vacuum differential section. The differential section is connected to a high vacuum accelerator pipe on the one end; while the section connected to the target filled with helium at the other end where the pressure is close to atmospheric. When passing through the differential section, the high-energy beam particles will ionize the gas into plasmas. Then, the proton beam will move in plasmas over a long distance before reaching the spallation target. Normally, the plasmas will provide charge and current neutralization and compensate the transverse spreading of the ion bunches, thus providing self-pinched transport over long distance.

However, in the case that the beam radius is small compare with the plasma electron skin depth, the self-modulation (SM) mechanism (Kumar *et al.*, 2010; Lotov, 2015) appears. That is to say for a long proton beam moving in plasmas, the bunch is periodically focused and defocused and is transformed into a train of short bunches separated by the plasma wavelength. The AWAKE project reported the first experimental demonstration of the SM mechanism in plasmas, of which showed that the SM mechanism could be a possible path to the future high-energy particle physics. But in the project of CIADS, the SM mechanism caused by the unneutralized current (Kaganovich *et al.*, 2001, 2004; Polomarov *et al.*, 2007) will lead to the overcompression and destroy the stability of the beams. The overcompressed high-density beam pulse will increase the peak power density and further the temperature of target, which will greatly affect the safety of the CIADS. For the guarantee of the long-distance transport of the bunches and the safety of the system, the SM mechanism must be minimized.

The application of a solenoidal magnetic field allows the additional control of the bunches (Sefkow *et al.*, 2009; Seidl *et al.*, 2009; Hu *et al.*, 2014). The magnetic field will affect the degree of charge and current neutralization, and consequently lead to the variation of the SM mechanism. The previous study (Kaganovich *et al.*, 2007; Dorf *et al.*, 2009) shows that even a small solenoidal magnetic field will strongly change the self-field and provides the enhanced self-focusing. However, as the magnetic field increases the radial force acting on the beam ions can change sign from focusing to defocusing. Thus, if the magnetic field is carefully chosen, the overcompression caused by the SM mechanism can be minimized.

In the paper, we try to use the extra magnetic field to control the wakefield caused by the beam pulse and to minimize the SM mechanism. To achieve this, we use a simplified model here. In our simulation model, the long proton bunches, of which are similar to these in the linear accelerator of CIADS, are used to study the influence of the magnetic field when they

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move through the hydrogen plasmas. Particle-in-cell (PIC) simulations are carried out by the VORPAL (Nieter and Cary, 2004) code. The neutralization of the charge and current, the self-electric field, as well as the self-magnetic field are discussed. Section "Method" is a brief introduction of the method used in the paper. In Section "Results and discussion", we vary the solenoidal magnetic field imposed on the pulse-plasmas system. The influence on the SM mechanism of pulses propagation in background plasmas is discussed. A summary is given in the "Conclusion" section.

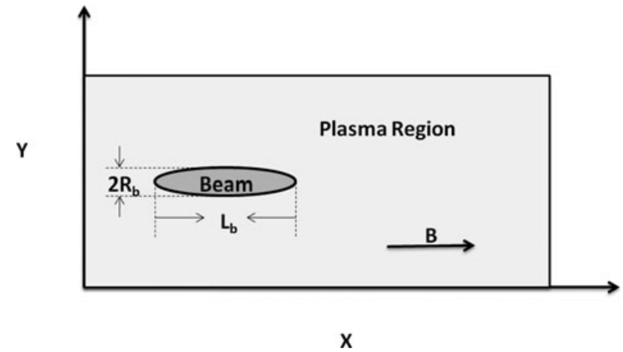

Fig. 1. A long beam pulse propagation in the plasmas with the solenoidal magnetic field.

Method

In this paper, simulations are performed by the code VORPAL, of which is an arbitrary dimensional hybrid plasma and a beam simulation code.

The kinetic model incorporated in VORPAL is based on the PIC algorithm. The electric and magnetic fields are updated by the Faraday's equation and the Ampere-Maxwell equation:

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}, \tag{1}$$

$$\frac{\partial \mathbf{E}}{\partial t} = c^2 \nabla \times \mathbf{B} - \frac{\mathbf{J}}{\varepsilon_0}, \tag{2}$$

where the particle source is

$$\mathbf{J} = \sum_j q_\alpha \mathbf{v}_j^\alpha (x - x_j). \tag{3}$$

The equations of motion for all particles involved in the simulations (plasma electrons, ions, and the injection-beam ions) are

$$\frac{d\mathbf{r}_j^\alpha}{dt} = \mathbf{v}_j^\alpha, \tag{4}$$

$$\frac{d({}_j^\alpha \mathbf{v}_j^\alpha)}{dt} = \frac{q_\alpha}{m_\alpha}(\mathbf{E} + \mathbf{v}_j^\alpha \times \mathbf{B}), \quad j = 1, 2, \ldots, N_\alpha. \tag{5}$$

Here, $\mathbf{r}_j^\alpha$, $\mathbf{v}_j^\alpha$, q_α, γ_j^α, m_α, and N_α are the position, velocity, charge, Lorentz factor, mass, and total number of plasma electrons ($\alpha = e$), ions ($\alpha = i$), and injection-beam ions ($\alpha = b$), respectively.

We use a 2D3V (x, y, Vx, Vy, Vz) PIC model in this paper. The simulations are performed in a xy-plane, as shown in Figure 1. The longitudinal (x) and radial (y) directions represent parallel and perpendicular to the direction of the beam motion, respectively. The simulation box is composed of $Nx = 6500$ grids in the x-direction and $Ny = 512$ grids in the y-direction. Periodic boundary condition in the y-direction and open boundary condition in the x-direction are adopted. The time step $dt = 2.576 \times 10^{-13}$ s by taking into count the Courant–Friedrichs–Lewy (CFL) limit and the spatial step $dx = dy = 1.486 \times 10^{-4}$ m.

A fully ionized hydrogen plasma (H+,e−) is placed in the box. The plasmas are assumed to be collisionless and uniform. The plasma density $N_{e0} = 1.0 \times 10^{17}$ m^{-3} and the temperature of electrons and ions $T_{e0} = T_{i0} = 1$ eV, respectively.

The proton bunches are in the same form with these used in the linear accelerator of CIADS. The energy of the beams is 45 MeV and the transverse emittance is zero. A hard-cutoff model is used for all protons restricting in the region of $(x - x_0)^2/(L_b/2)^2 + (y - y_0)^2/R_b{}^2 < 1$. The density profiles of the bunches are the Gaussian distribution: $N_b(x, y) = \rho_{b0} \exp(-(x - x_0)^2/L_b{}^2) \exp(-(y - y_0)^2/R_b{}^2)$, where $\rho_{b0} = 1.0 \times 10^{17}$ m^{-3}, beam length $L_b = 0.142$ m, and radial $R_b = 1.68 \times 10^{-3}$ m. To investigate how the magnetic field influences the SM mechanism, a solenoidal magnetic field is imposed in the x-direction with ranges from 0.0 to 1 T.

Results and discussion

Figure 2 shows the density distribution of the proton bunches (normalized by N_{e0}) propagation in plasmas over 0.9 m. Figure 2a shows the result when the magnetic field $B = 0.0$ T. The initial long bunch is separated into a trains of short pulses. The SM mechanism, which dominates the transport process, compresses the pulses both in the x- and y-directions. In Figure 2b when $B = 0.1$ T, the compression is inhibited. When $B = 1.0$ T, as shown in Figure 2c, the longitudinal separation disappears. Moreover, instead of transverse focus, the long bunch is defocused in the y-direction. This implies that a solenoidal magnetic field will strongly reduce the SM mechanism.

In order to further understand the phenomenon, the electric field is given in Figure 3. Figure 3a–3c shows the longitudinal electric field Ex when $B = 0.0$, 0.1, and 1.0 T, respectively. And Figure 3d–3f shows the corresponding transverse electric field Ey. When $B = 0.0$ T, the oscillation wakefield in the x-direction accelerates and deaccelerates the bunch periodically, and eventually leads to the separation of the bunch. At the same time, like the electrical field in the x-direction, periodically focusing and defocusing field is observed in Figure 3d. This means that the electrical field will focus the pulses both in the x- and y-directions. However, as B increases, the oscillation wakefield Ex and Ey decreases, as shown in Figure 3b and 3e. When B reaches up to 1.0 T, it is noted that a defocusing Ey field appears, as predicted by Dorf *et al.* (2009) and Kaganovich *et al.* (2007). The self-magnetic field Bz is shown in Figure 4. In Figure 4a when $B =$ 0.0 T, the solenoidal magnetic field around each pulse is observed. This self-magnetic field pinches the pulses. As B increases, the self-magnetic field reduces significantly and can not compensate the repulsive force from the electrical field. Thus, the defocusing phenomenon happens, as shown in Figure 2c.

As mentioned above, the SM mechanism is original from the charge neutralization and current unneutralization. To answer

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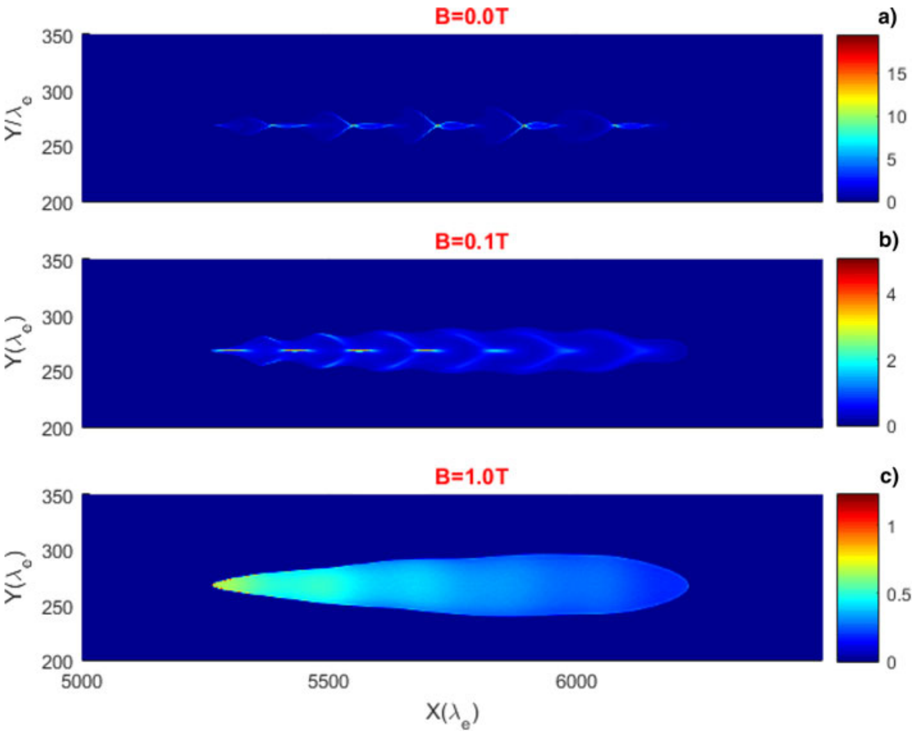

Fig. 2. The density distribution of the proton bunches (normalized by N_{e0}) propagation in plasmas when (a) $B = 0.0$ T, (b) $B = 0.1$ T, and (c) $B = 1.0$ T.

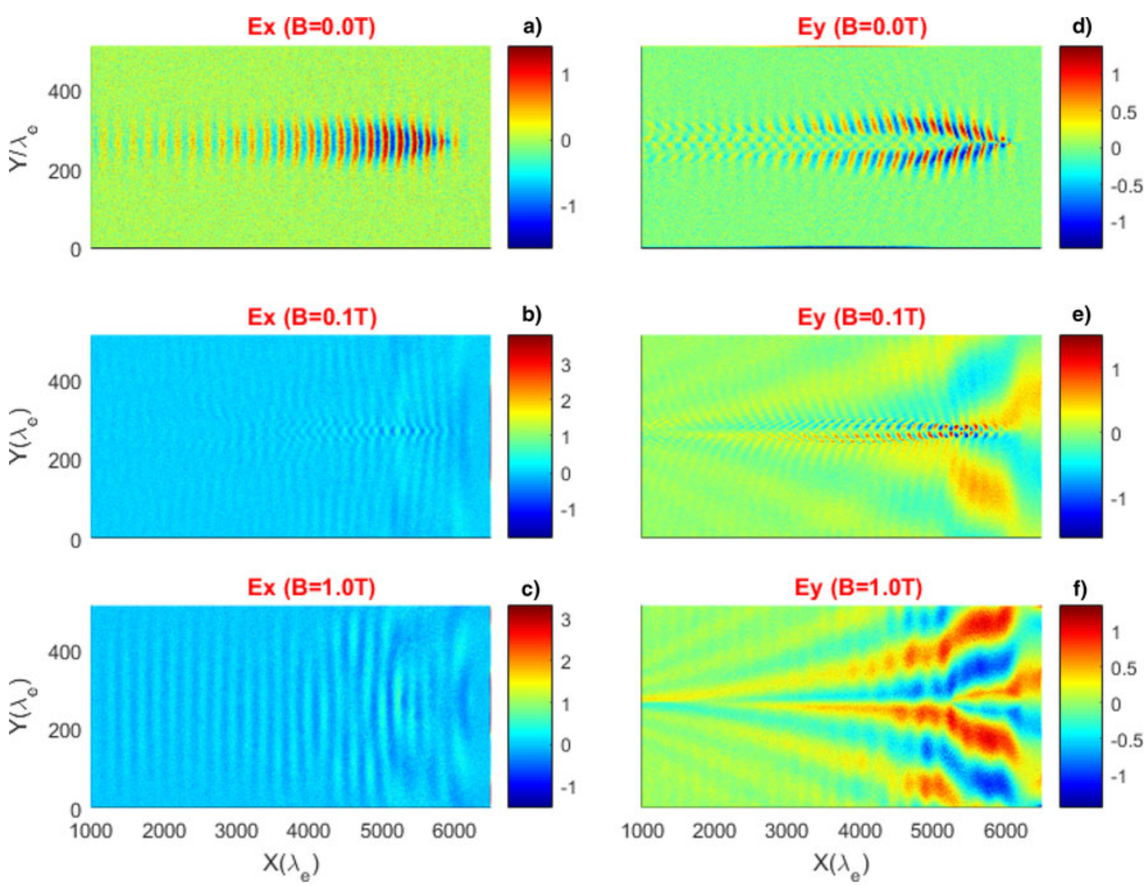

Fig. 3. The longitudinal electric field *Ex* (× 10^6 V/m) of the beam-plasma system when (a) $B = 0.0$ T, (b) $B = 0.1$ T, and (c) $B = 1.0$ T, while the corresponding transverse electric field *Ey* (× 10^6 V/m) when (d) $B = 0.0$ T, (e) $B = 0.1$ T, and (f) $B = 1.0$ T.

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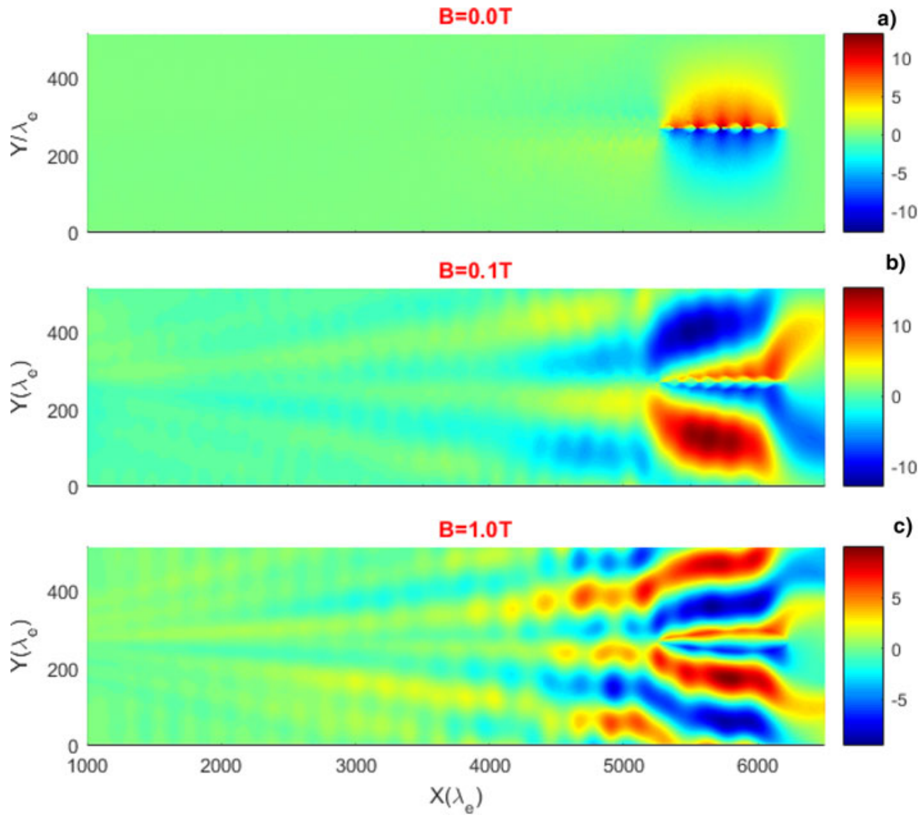

Fig. 4. The magnetic field *Bz* (*T*) of the beam-plasma system when (a) $B = 0.0$ T, (b) $B = 0.1$ T, and (c) $B = 1.0$ T.

the question how a solenoidal magnetic field influence the SM mechanism, the density distribution of the plasma electrons, as well as the current of the proton-plasmas systems are investigated. Figure 5 shows the corresponding contour plots of the electron density in plasmas. In Figure 5a and 5b, electrons assemble in the region of each pulse, providing the good charge neutralization. In Figure 5c, when B is big enough, the accumulation of electrons disappears. The space effects of the proton bunch are not compensated, of which lead to a repulsive electric field in the transverse direction, as given in Figure 3f.

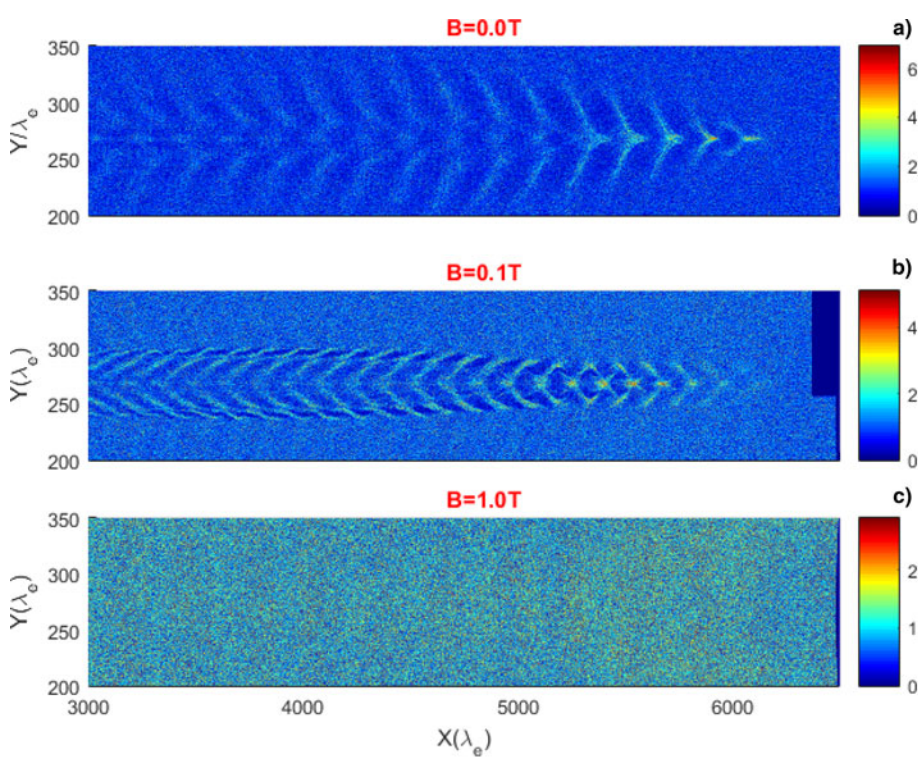

Fig. 5. The density distribution of the plasma electrons (normalized by N_{e0}) when (a) $B = 0.0$ T, (b) $B = 0.1$ T, and (c) $B = 1.0$ T.

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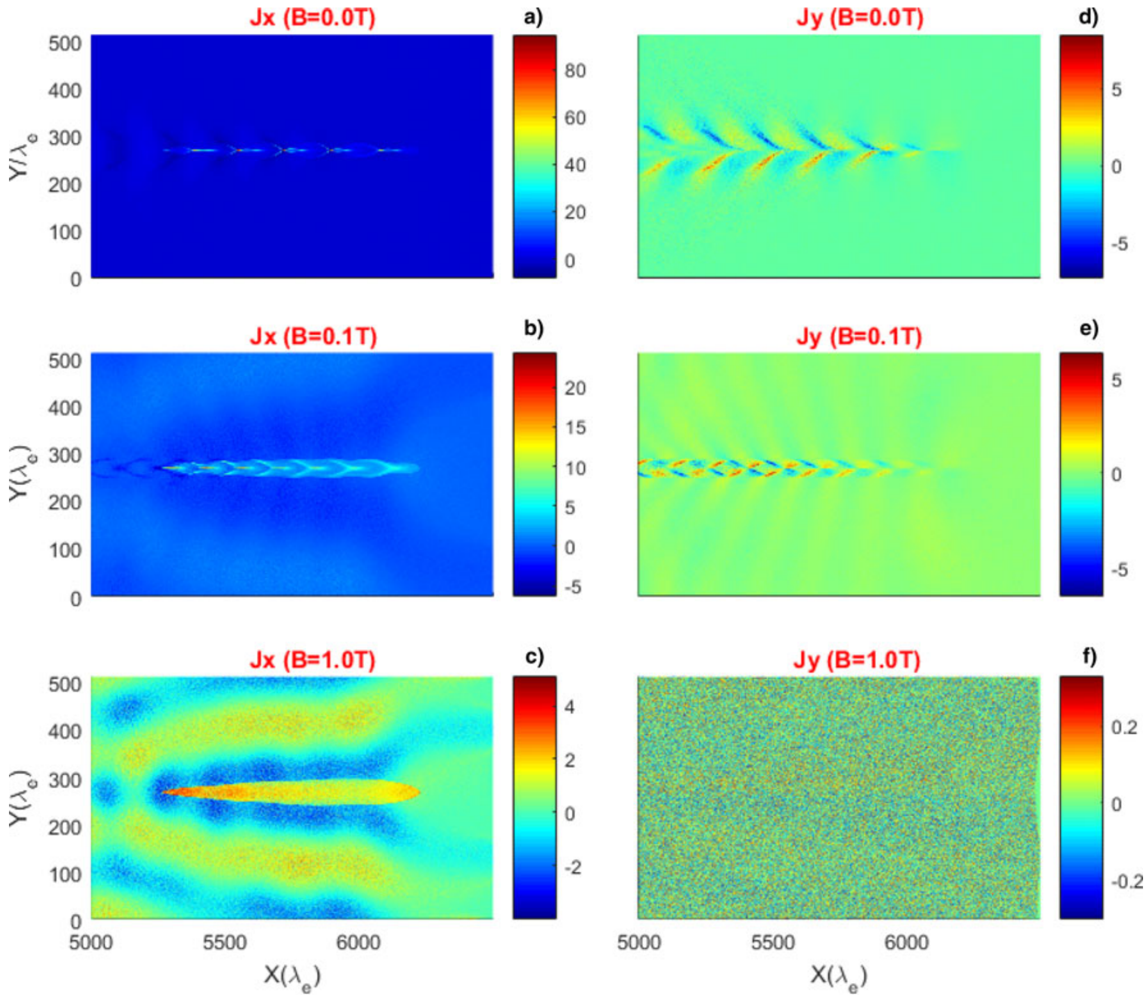

Fig. 6. The contour plot of the current density of the beam-plasma system. The longitudinal current density Jx (× 10^5 A/m^3) when (a) $B = 0.0$ T, (b) $B = 0.1$ T, and (c) $B = 1.0$ T, while the corresponding transverse Jy (× 10^5 A/m^3) when (d) $B = 0.0$ T, (e) $B = 0.1$ T, and (f) $B = 1.0$ T.

Figure 6 shows the contour plot of the current density in the beam-plasma systems. Figure 6a–6c shows the results of Jx when the solenoidal magnetic field $B = 0.0$, 0.1, and 1.0 T, while Figure 6d–6f shows the results of Jy. In Figure 6a–6c, the longitudinal currents are not compensated in all cases as predicted before (Kaganovich *et al.*, 2001; Polomarov *et al.*, 2007), while the difference is from Jy. When $B = 0.0$ T, electrons move toward the pulses in the y-direction, as shown in Figure 6d. This leads to two phenomena: (1) Electrons will assemble in the region of pulses, and the good charge neutralization is expected. (2) In the presence of both Jx and Jy, the self-magnetic field envelops the pulses and pinches them both in the x- and y-directions. However, when $Bx = 1.0$ T, as shown in Figure 6f, the magnetic field is strong enough and electrons are restricted transversely. Thus, Jy disappears. This also leads to two phenomena: (1) There are not enough electrons to compensate the space charge effect, so the repulsive electrical field appears. (2) Without Jy, there is no more pinched effect in the longitudinal direction. The long bunch can not be separated into small pulses anymore.

Conclusion

In this paper, a new scheme is proposed to minimize the SM mechanism in the accelerator-target coupling section in the windowless target design of CIADS. We use 2D3V PIC simulations to study the influence of a solenoidal magnetic field to the SM mechanism. Our results show that the solenoidal magnetic field will significantly inhibit the SM process. In the presence of a strong magnetic field, the transverse focusing, as well as the longitudinal separation of the proton bunches, disappear. We attribute these phenomena to the reason that a strong solenoidal magnetic field will restrict the transverse movement of plasma electrons. Thus, in the region of proton bunches, there are not enough electrons to compensate the space charge effort. Moreover, in the absence of transverse current, the plasmas could not pinch the bunch in the longitudinal direction, either. For a long ion bunch moving in plasmas, a carefully chosen magnetic field will minimize the SM mechanism, avoid overcompression and provide the guarantee of stable transport over long distance.

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