Magnetic Field Generation and Its Nonlinear Evolution of the Weibel Instability

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(Received October 11, 1999)

The Weibel instability caused by anisotropic velocity distribution may play an important role for the generation of magnetic field in the laser produced plasmas. A three dimensional electromagnetic and relativistic particle-in-cell (PIC) code is used to show the generation of magnetic field and its nonlinear evolution. As a result, we confirm that strong magnetic fields are generated with coherent structures. Loop-like magnetic fields are generated in “football-shaped” anisotropy and sheet-like magnetic fields are generated in “pancake-shaped” anisotropy.

§1. Introduction

Plasmas with anisotropic temperature are often observed in many situations such as laser produced plasmas and astrophysical plasmas. And it is well known that the temperature anisotropy causes so-called Weibel electromagnetic instability. Weibel1) showed that plasmas with anisotropic temperature is unstable, and magnetic field is generated. It is thought that this instability is important to be one of the mechanism for magnetic field generation. The generation mechanism of this instability is as follows. Electron trajectories with temperature anisotropy are bended by Lorentz force under the magnetic perturbations. The resulting currents are produced to enhance the initial magnetic fields.

In the present paper, we investigate magnetic field generation by Weibel instability using three-dimensional electromagnetic and relativistic PIC code for two anisotropy cases: football and pancake type anisotropy.

§2. Magnetic field generation and conclusion

The system size used for the simulations is $L_x = 64\Delta$, $L_y = 64\Delta$, and $L_z = 64\Delta$, where $L_x$, $L_y$, and $L_z$ are length of the system in three dimensions and $\Delta (= 1)$ is the grid size. Periodic boundary conditions are used for the particles and fields in the three directions. The initial magnetic field is zero. We investigated two anisotropy cases. The first case is football-shaped anisotropy; electron’s temperature $T_z$ in the $z$ direction is sixteen times hotter than that of other directions. The second case is pancake-shaped anisotropy; electron’s temperature $T_z$ in the $z$ direction is sixteen times colder than that of other directions. The maximum growth rate of the Weibel instability for each case is given by following equations.2), 3) We obtained

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good agreement between the theory and our simulation results.

\[
\gamma_{\text{max}} = 0.31 \frac{\omega_{pe}}{c} \left( \frac{T_{\parallel}}{m_e} \right)^{1/2} \frac{T_{\parallel}}{T_{\perp}} \left( \frac{T_{\parallel}}{T_{\perp}} - 1 \right)^{3/2}, \quad \text{(football)} \tag{2.1}
\]

\[
\gamma_{\text{max}} = \sqrt{\frac{8}{2\pi}} \frac{\omega_{pe}}{c} \sqrt{\frac{k_B T_{\perp}}{m_e c^2}} A^{3/2} A + 1, \quad \text{(pancake)} \tag{2.2}
\]

where \( A(\equiv T_{\perp}/T_{\parallel} - 1) \) is an anisotropic factor.

We confirm that strong magnetic fields are generated in both cases. \( \omega_{pe}/\omega_{ce} \) for simulation results is about 1.0 at magnetic saturation level. If we take the density as \( 10^{22} \sim 10^{24} \text{ cm}^{-3} \), we obtain that maximum magnetic field as about \( 1 \sim 10 \text{ MG} \).

Figures 1 and 2 show iso-surfaces of total intensity of magnetic field almost at the saturation level of the Weibel instability in both cases. One can find that loop-like magnetic fields are generated in football-shaped anisotropy and sheet-like magnetic fields are generated in pancake-shaped anisotropy. These structures become more larger scale in later stage of the simulation time.

The Weibel instability may play an important role for the generation of magnetic field in the laser produced plasmas. But the magnetic field strength in laser produced plasmas is about 100 MG from the observations. Therefore, it is thought that the other mechanisms are necessary for the magnetic fields in the laser produced plasmas.

Fig. 1. Iso-surface of total intensity of magnetic field (\( |\mathbf{B}|=0.05 \)) in football-shaped anisotropy at \( \omega_{pe} t = 60 \).

Fig. 2. Iso-surface of total intensity of magnetic field (\( |\mathbf{B}|=0.06 \)) in pancake-shaped anisotropy at \( \omega_{pe} t = 80 \).

Acknowledgements

This work is supported by a Grand-in-Aid for Scientific Research from the Japan Ministry of Education (11695028).

References

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