§6. Electromagnetic Structure of Large-Amplitude MHD Waves and Particle Acceleration

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In the past several years we have studied the electric field parallel to the magnetic field in nonlinear magnetosonic waves [1,2]. Applying its results, we have investigated the effect of the parallel electric field $E_{\|}$ on particle acceleration [3,4] this year, in collaboration with C. Chiu and W. Horton at Institute for Fusin Studies, The university of Texas at Austin. We have also discussed multi-dimensional effects on the acceleration of trapped electrons and on the reflection of thermal ions due to oblique shock waves [5,6].

Here, we briefly describe the effect of the parallel electric field on 1) the incessant acceleration of relativistic ions, 2) acceleration of trapped electrons, and 3) positron acceleration along the magnetic field [3].

In the ideal MHD, the parallel electric field $E_{\|}$ is zero, and it was generally thought that $E_{\|}$ was quite weak in low-frequency phenomena in high-temperature plasmas; thus, the parallel pseudo potential F, which is the integral of $E_{\|}$ along the magnetic field $\boldsymbol{B}$, was thought to be small.

We have found out, however, that the parallel electric field can be strong in magnetosonic shock waves [1,2]. Our theory and relativistic, electromagnetic, particle simulations show that the magnitude of F in a small-amplitude (ε<<1) magnetosonic wave is

$$eF \sim \varepsilon \Gamma_e T_e, \quad (1)$$

in a high beta plasma, where Γ_e is the specific heat ratio of electrons, and it is

$$eF \sim \varepsilon^2 m_i v_A^2, \quad (2)$$

in a low beta plasma. For large-amplitude waves with $\varepsilon \sim O(1)$ (shock waves), it is

$$eF \sim \varepsilon (m_i v_A^2 + \Gamma_e T_e), \quad (3)$$

which is valid for both high and low beta cases. Furthermore, this work has been extended to electron-positron-ion (e-p-i) plasmas; positrons act to decrease the magnitude of F, and in a pure electron-positron plasma F becomes zero. This explains the simulation result that the positron acceleration along the magnetic field in e-p-i plasmas becomes weak as the positron density decreases [7].

The parallel electric field plays an essential role in the acceleration of trapped electrons [8] and of positrons [7] in shock waves, while it was ignored in the theory of the incessant acceleration of relativistic ions [9]. Having established the quantitative theory for $E_{\|}$, we have revisited the effect of $E_{\|}$ on these acceleration mechanisms with use of particle simulations and test particle calculations, where we obtain electromagnetic fields from the particle simulations, and using these fields we follow test particle orbits. We have used two types of test particle calculations: In one method we have used the total electric field in the relativistic equation of motion for test particles, while in the other method we have used the electric field perpendicular to $\boldsymbol{B}$.

This study [3] indicates that without $E_{\|}$, electron reflection near the end of the main pulse of a shock wave, which triggers electron acceleration and trapping, does not occur, and thus the acceleration mechanism reported in Ref. [8] does not operate (see Fig. 1). The positron acceleration in an e-p-i plasma discussed in Ref. [7] is nearly along the magnetic field, and the energy increase rate is proportional to the parallel electric field. If $E_{\|}$ =0, therefore, this type of acceleration cannot take place either. The effect of $E_{\|}$ on relativistic ions becomes small as the particle energy goes up; thus, the theoretical treatment ignoring $E_{\|}$ [9] is justified.

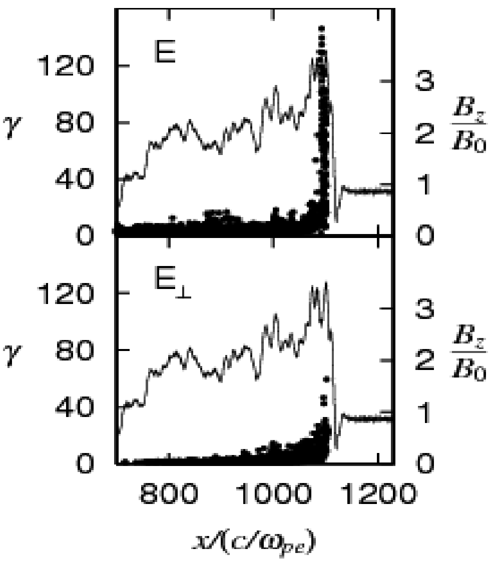

Fig. 1 Phase spaces (x, γ) of test electrons. The upper and lower panels, respectively, show test electrons calculated with total and perpendicular electric fields. There are many ultrarelativistic (γ>100) electrons in the upper panel [3].

[1] S. Takahashi and Y. Ohsawa: Phys. Plasmas **14**, 112305 (2007).
[2] S. Takahashi, M. Sato, and Y. Ohsawa: Phys. Plasmas **15**, 082309 (2008).
[3] S. Takahashi, H. Kawai, Y. Ohsawa, S. Usami, C. Chiu, and W. Horton: Phys. Plasmas **16**, 112308 (2009).
[4] S. Usami, R. Horiuchi, and Y. Ohsawa: Phys. Plasmas **16**, 122104 (2009).
[5] M. Toida and K. Shikii: Phys. Plasmas **16**, 112305 (2009); K. Shikii and M. Toida: J. Plasma Fusion Res. Ser., in press.
[6] M. Toida, R. Honma, and Y. Ohsawa: J. Plasma Fusion Res. Ser. **8**, 230 (2009).
[7] H. Hasegawa and Y. Ohsawa: Phys. Plasmas **12**, 012312 (2005); H. Hasegawa, K. Kato, and Y. Ohsawa: *ibid.* **12**, 082306 (2005).
[8] N. Bessho and Y. Ohsawa: Phys. Plasmas **6**, 3076 (1999); *ibid.* **9**, 979 (2002).
[9] S. Usami and Y. Ohsawa: Phys. Plasmas **9**, 1069 (2002); *ibid.* **11**, 3203 (2004).