An Electron Heating in the Downstream Region of the X-type Neutral Line

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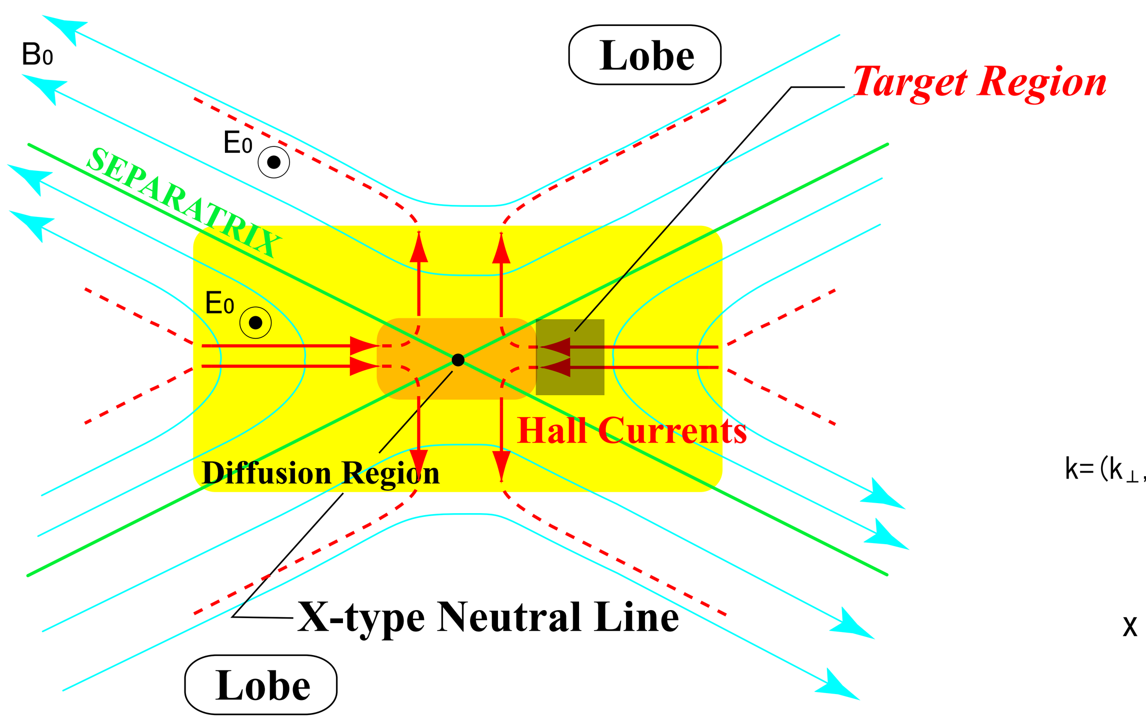
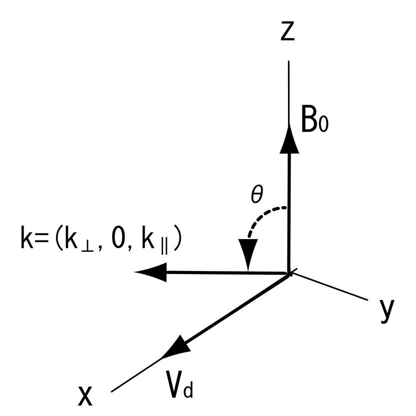
Introduction

In the outflow region outside the electron diffusion region around the X-type neutral line, electrons are frozen-in to the ambient magnetic field while ions are unmagnetized.
In this region, it is known that the electron motion is basically described by the $E\times B$ motion and electrons can be accelerated up to "the electron Alfven velocity" defined as $V_{Ae}=B_L/(\mu_0 m_e n_{ps})^{1/2}$, beyond the ordinary Alfven velocity ($V_A=B_L/(\mu_0 m_i n_{ps})^{1/2}$).
On the other hand, ions are unmagnetized so that the accelaration is not effective. Thus it is expected that a large relative velocity between electrons and ions across the ambient magnetic field (the Hall current) exists inside the ion diffusion region.

In this paper, we investigate possible instabilities and the anomalous electron heating caused by a cross-field super Alfvenic relative motion between electrons and ions.
(Notice that the following study is conducted *in the electoron frame*.)





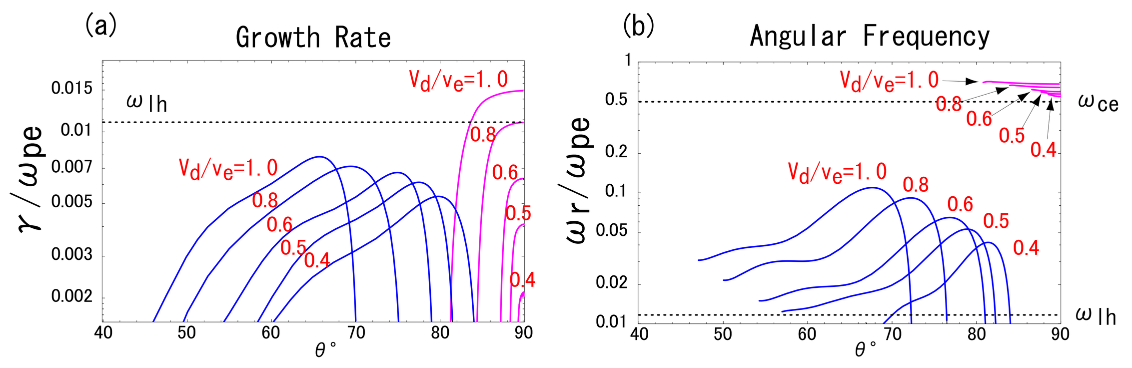
Kinetic Linear Theory

In order to identify the instabilities inside the diffusion region, we solved the kinetic linear dispersion relation numerically.

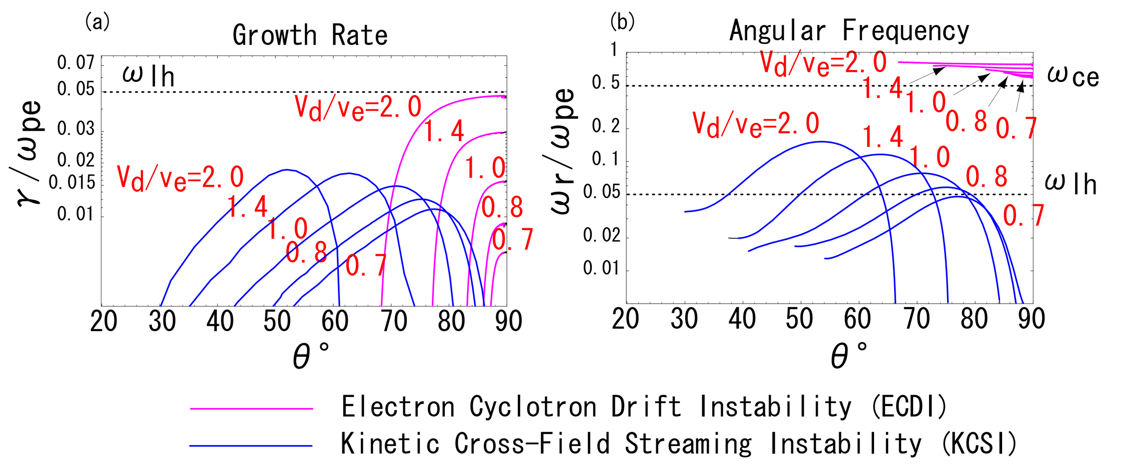
$$D_{11}+\frac{\frac{2k_\perp^2}{k^2}D_{12}D_{13}D_{23}+D_{12}^2D_{22}-\frac{k_\perp^2}{k^2}D_{23}^2D_{22}}{D_{22}D_{33}+\frac{k_\perp^2}{k^2}D_{23}^2}=0$$

$\omega_{ce}/\omega_{pe}=0.5,\quad T_i/T_e=8.0,\quad \beta_i=1.0$

In the case of $m_i/m_e=1836$



In the case of $m_i/m_e=100$



Prospective unstable mode varies according to the electron-ion relative velocity, V_d.

The Kinetic Cross-field Streaming Instability (KCSI) is dominant when $V_d < V_{cr}$.
The Electron Cyclotron Drift Instability (ECDI) is dominant when $V_d > V_{cr}$.

$V_{cr} \fallingdotseq 0.6\, v_e$ for the case of $m_i/m_e=1836$

$V_{cr} \fallingdotseq v_e$ for the case of $m_i/m_e=100$

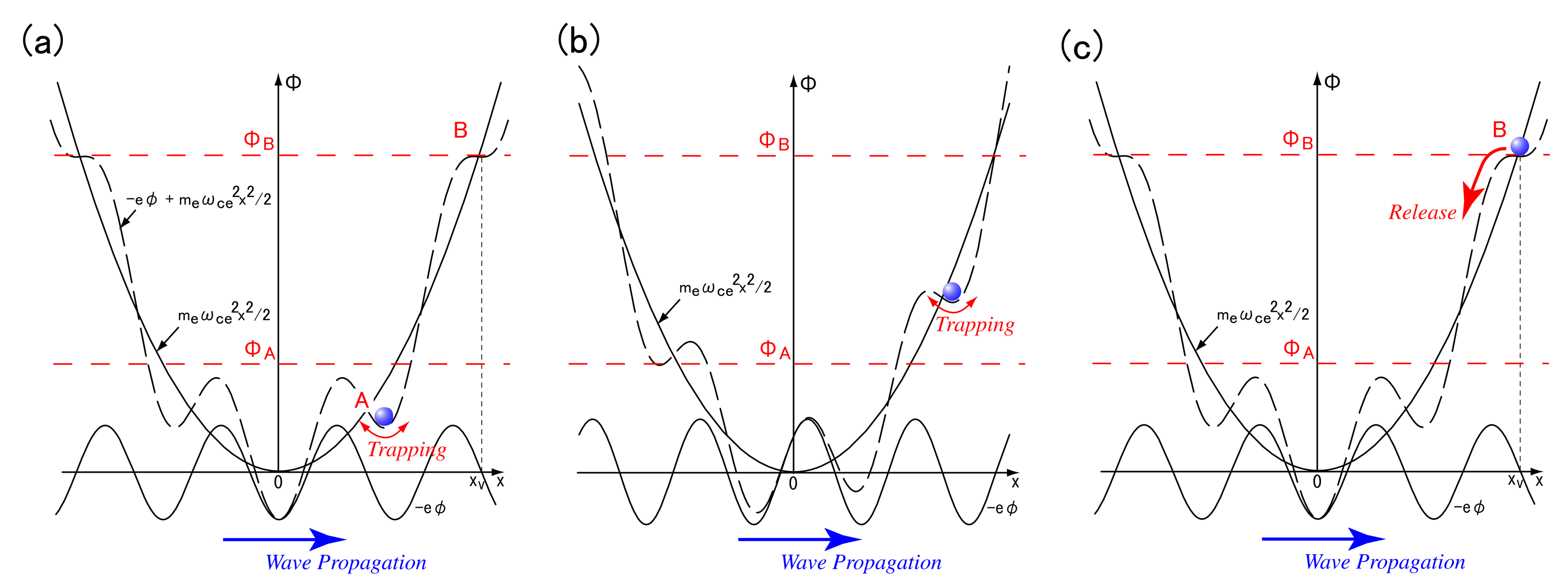
An electron trapping by electrostatic wave propagating perpendicularly to the magnetic field is simply described with the use of effective potential.

$$\frac{dv_x}{dt}=-\frac{e}{m_e}E_x-\omega_{ce}v_y,\qquad \frac{dv_y}{dt}=\omega_{ce}v_x.$$

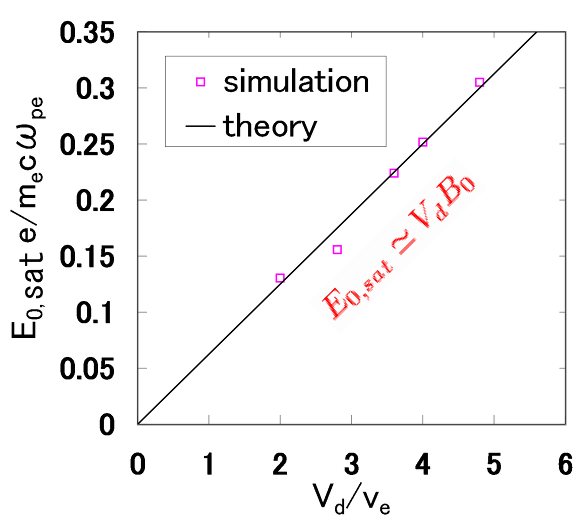
$$F_x=-\frac{\partial}{\partial x}\left[-e\phi(x,t)+\frac{1}{2}m_e\omega_{ce}^2x^2\right]=-\frac{\partial\Phi}{\partial x}$$

$$\Phi=-e\phi(x,t)+\frac{1}{2}m_e\omega_{ce}^2x^2$$

[*Chen and Birdsall, 1973*]



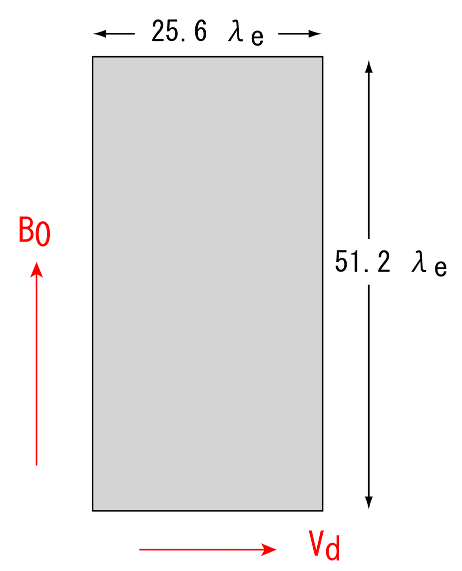
$$x_v=\frac{ek\phi_0}{m_e\omega_{ce}^2}$$



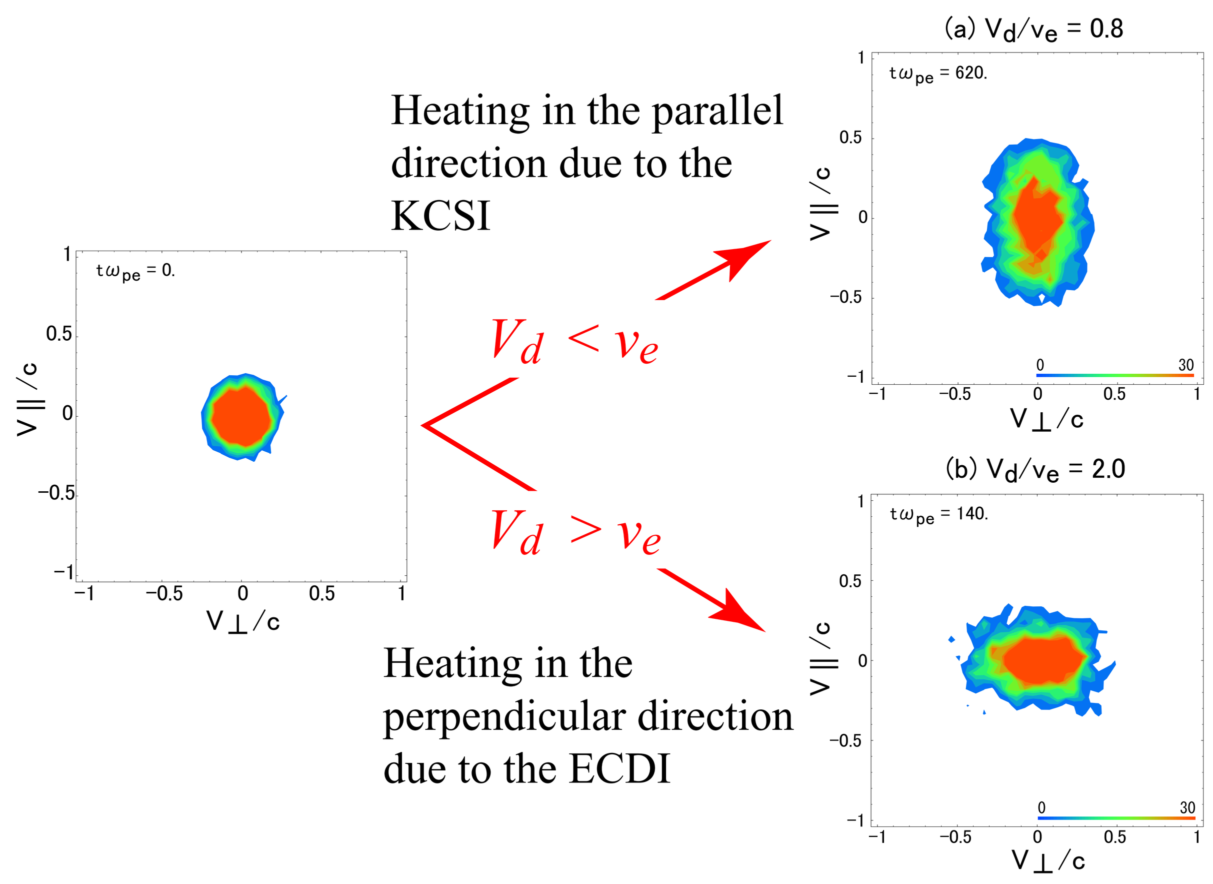
The theoretical prediction well agrees with the simulation results, which justifies the above model.

Electron Heating

We next study the electron heating due to the unstable waves, making use of 2-1/2 dimensional electromagnetic particle simulation.



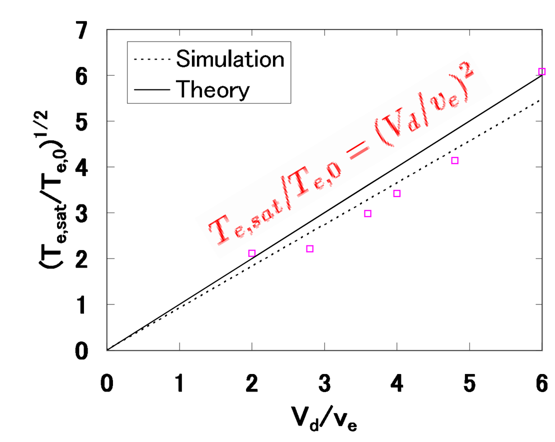
- Particle-In-Cell method
- Dobly periodic boundaries
- 256 × 512 grids
- $\Delta x=\Delta z=\Delta\lambda_{De}$
- $\omega_{ce}/\omega_{pe}=0.5,\quad T_i/T_e=8.0$
  $m_i/m_e=100,\quad \beta_i=1.0$



Electrons are easily trapped along the magnetic field line by the obliquely propagating waves.

Electrons are trapped by the perpendicularly propagating waves.

Saturation Temperature



Wave amplitude saturates when the electron thermal velocity reaches the drift velocity, which is nearly equal to the phase velocity of the most unstable wave.

Summary

A linear analysis and 2-1/2 dimensional particle simulations are performed to investigate mechanisms of electron heating due to the strong Hall current.

- The numerical solution of the kinetic dispersion relation indicates that the prospective unstable mode varies according to the electron-ion relative velocity.
  KCSI for $V_d < V_{cr}$, ECDI for $V_d > V_{cr}$.
- Our simulation results show that the electron heating mechanism varies according to the dominant instabilities.
  Parallel heating by the KCSI,
  Perpendicular heating by the ECDI.
- The perpendicular heating by the ECDI is expected to be ineffective when $V_d < v_e$, because unstable waves with the ECDI are likely to be resonant with large number of electrons and dumped before they grow to enough amplitude to trap electrons and heat them effectively.