Formation of power law spectra of energetic electrons during multiple X line reconnection with a guide field

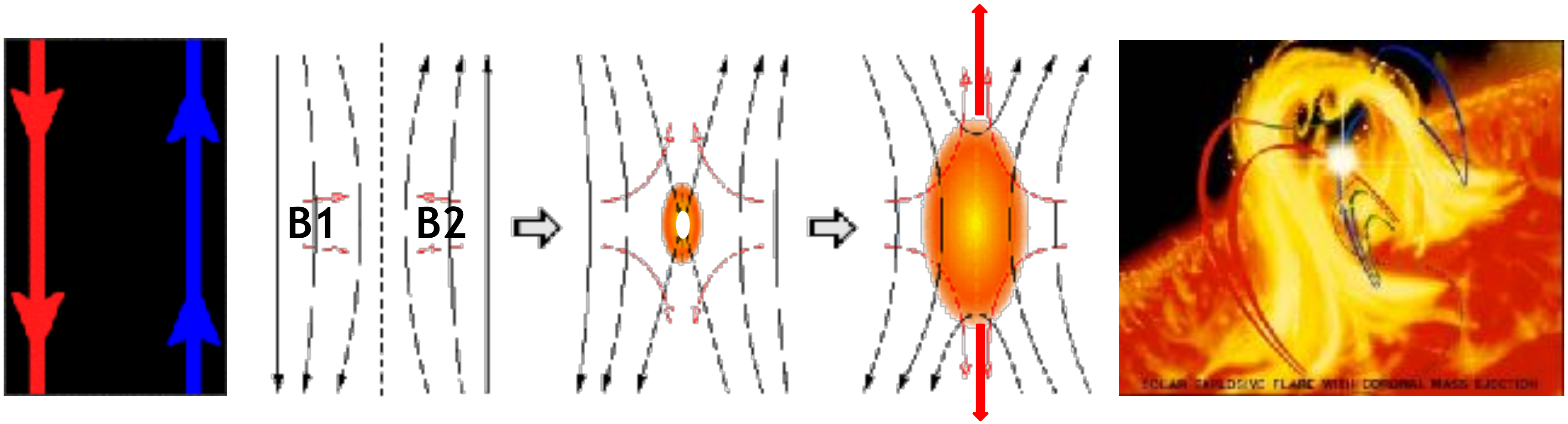
Quanming Lu(陆全明), Huanyu Wang, Rongsheng Wang

School of Earth and Space Sciences, University of Science and Technology of China(USTC), China

Outline

- Mechanisms of electron acceleration during reconnection
- Electron acceleration in multiple X line reconnection
- Power-law spectra of energetic electrons
- Summary

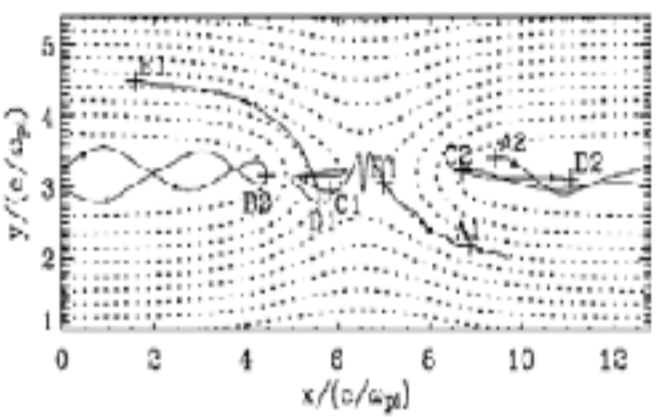
Magnetic Reconnection

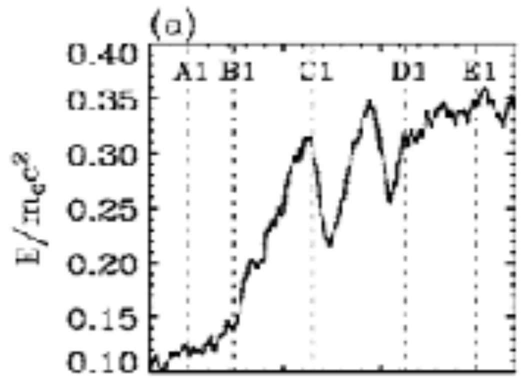


Magnetic reconnection converts magnetic energy into plasma kinetic energy, and it is accompanied with topological change of magnetic field lines and energetic particles.

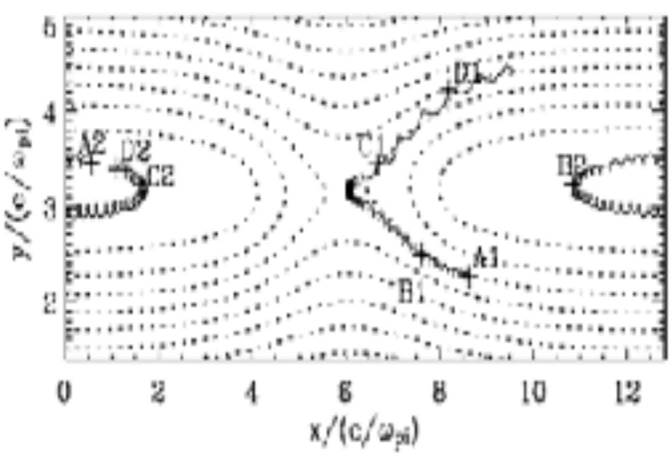
Electron acceleration near the X line

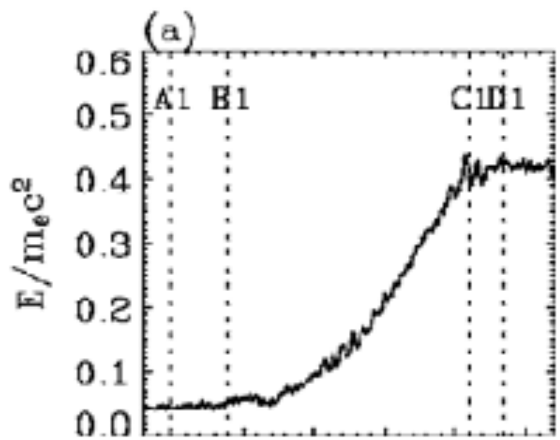
Typical electron trajectory passing through the vicinity of the X line, and it is accelerated by the reconnection electric field.[Fu et al., PoP, 2006; Huang et al., PoP, 2010]





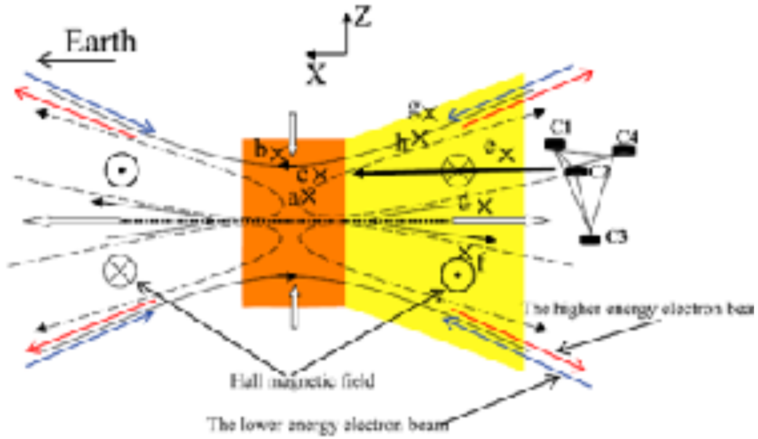
Without a guide field



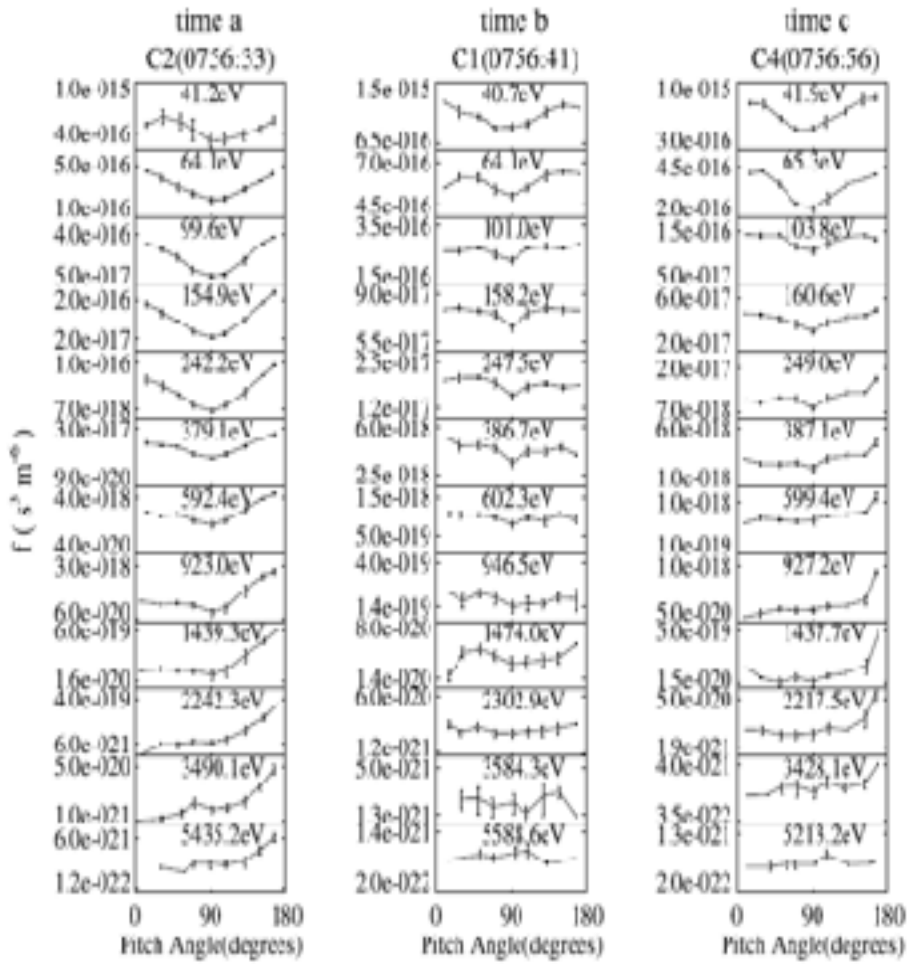


With a guide field

Observations of electron field-aligned bidirection distribution in separatrix region

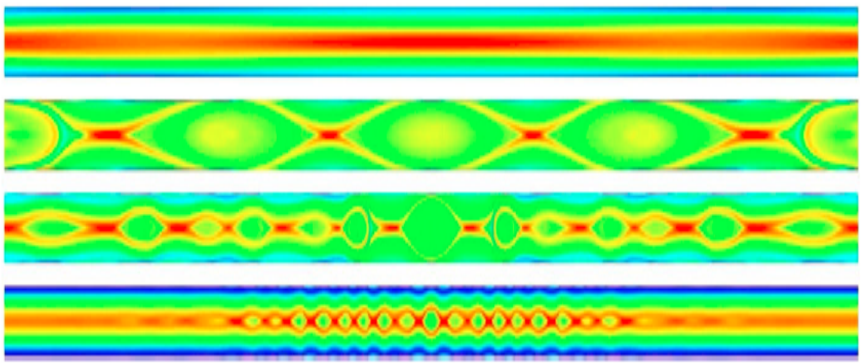


Observations of electron field-aligned bidirection distribution may be caused due to the parallel electric field or mirror force.



.[Wang et al., JGR, 2010]

Generation of magnetic islands during reconnection

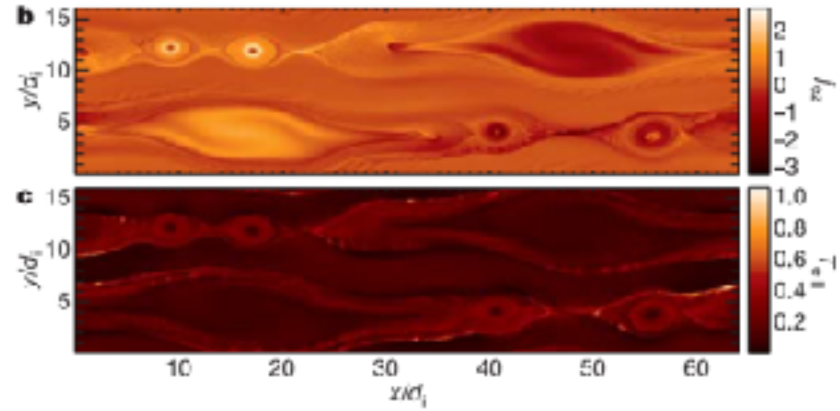


S $=10^4$

S $=10^5$

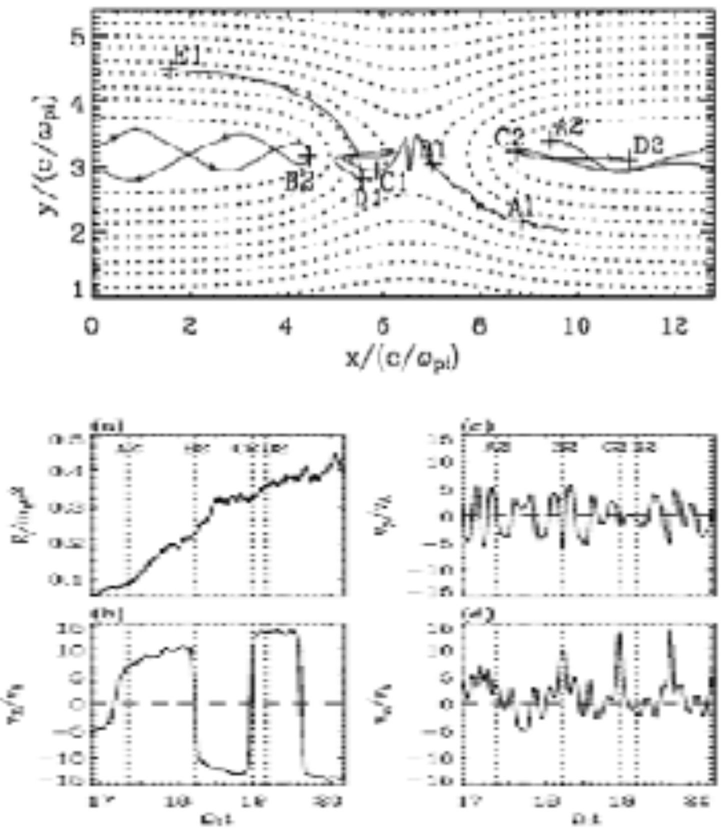
S $=10^6$

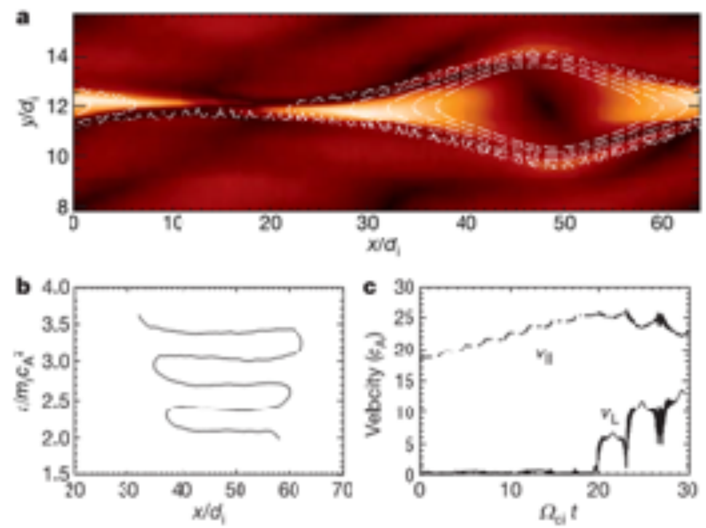
S $=10^7$



Primary magnetic islands and secondary islands are usually generated during magnetic reconnection, in MHD simulations with a large Lundquist number or kinetic simulations.[Samtaney et al., 2009; Drake et al., 2006]

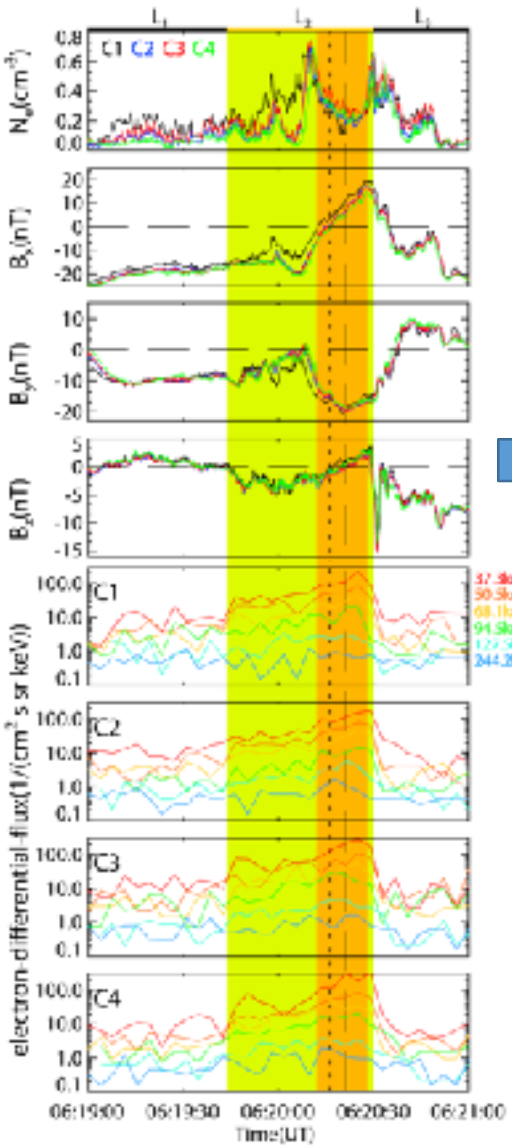
Electron acceleration in magnetic island

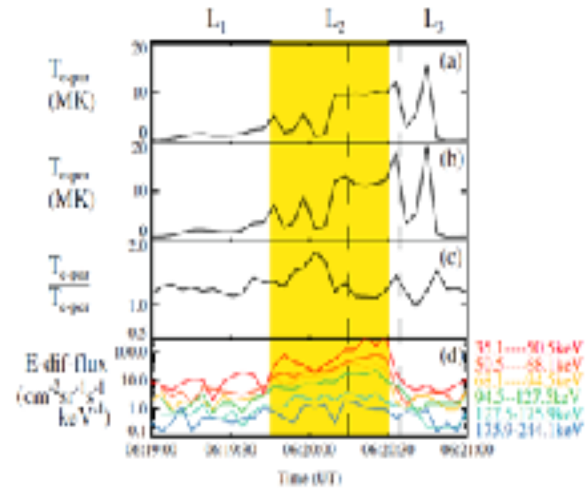


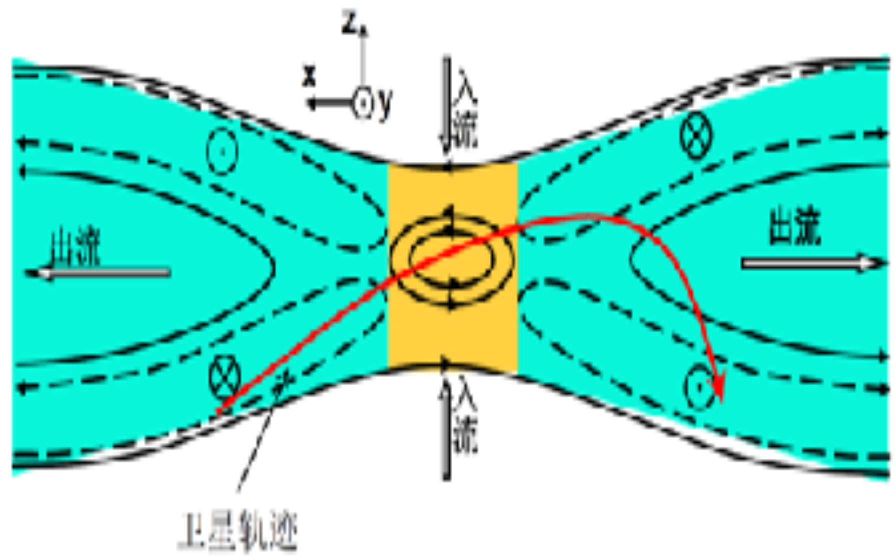


Electrons can be accelerated when they are trapped/reflected at the two ends of a magnetic island[Fu et al., 2006; Drake et al., 2006].

Observation of energetic electron in magnetic island

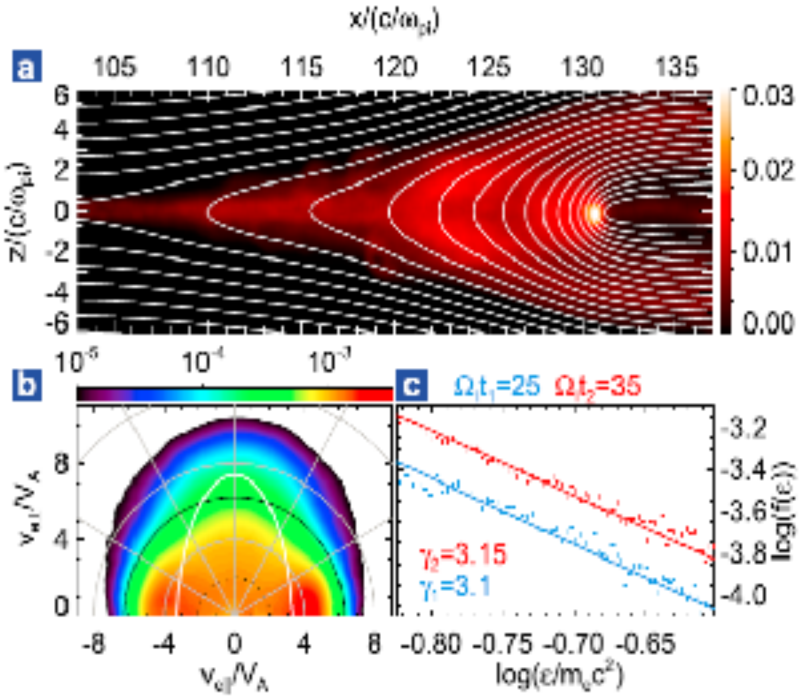


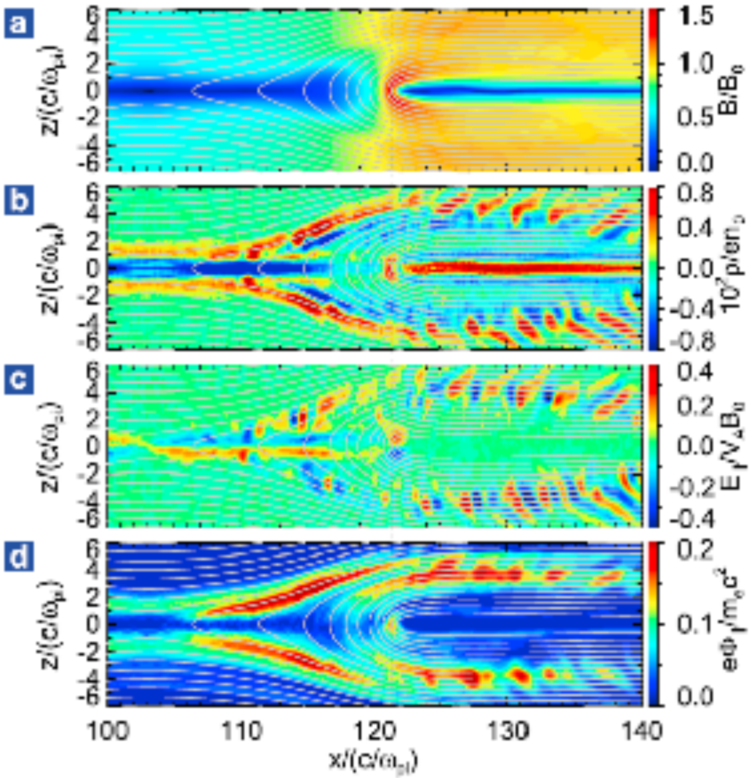




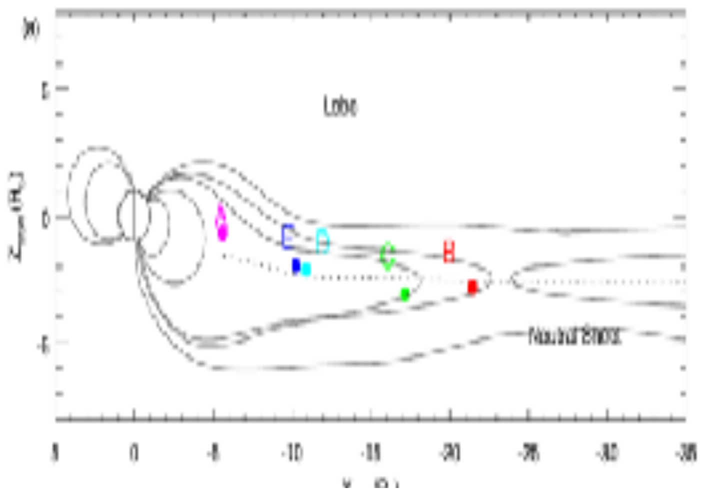
Wang et al., PRL，2010

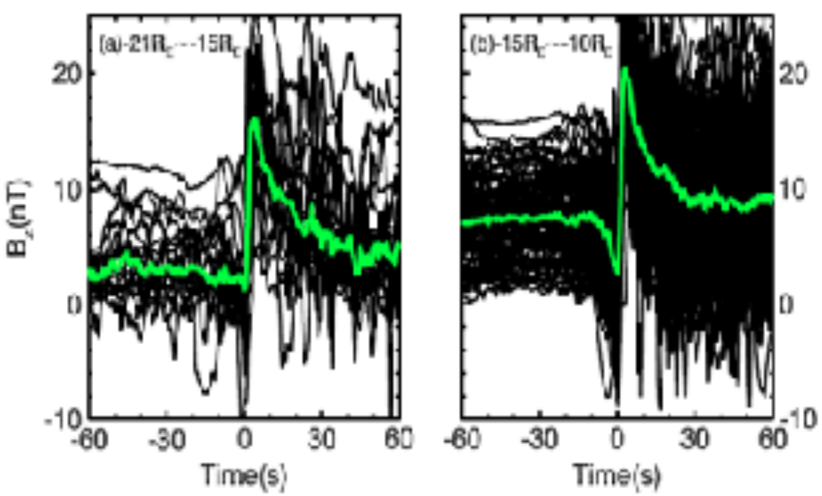
Electron betatron acceleration in the dipolarization front
[Huang et al., JGR, 2015]

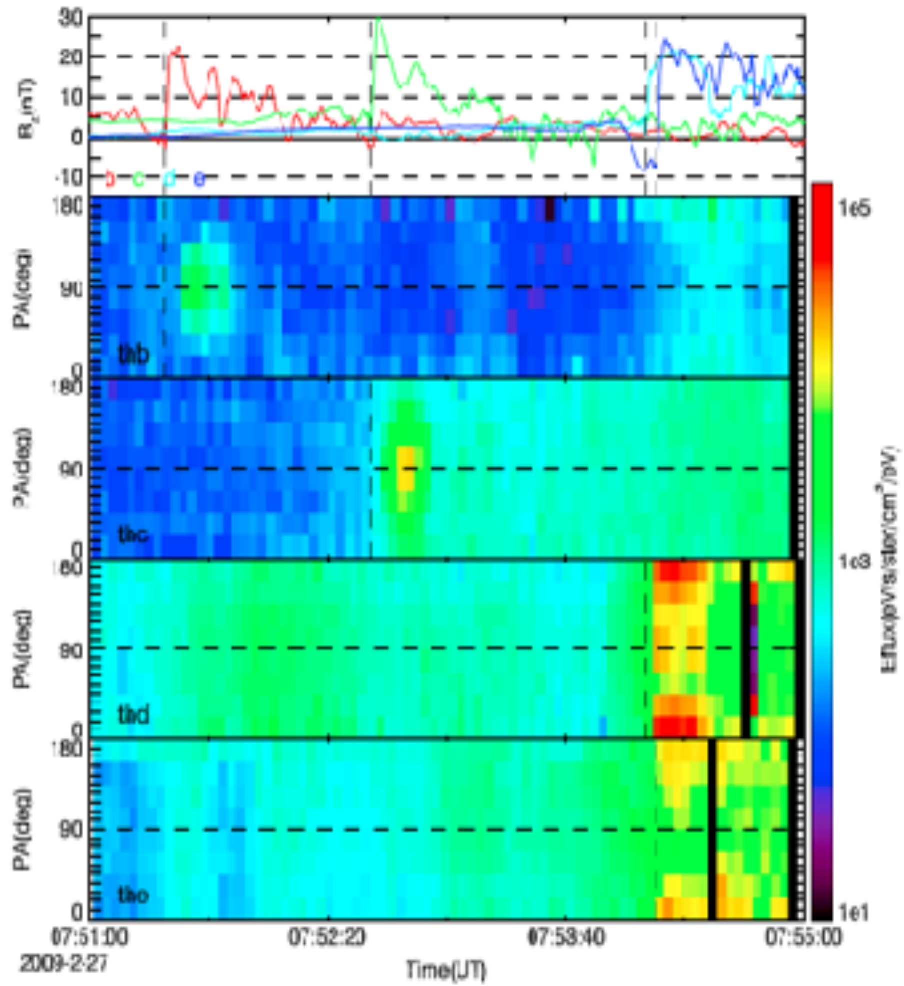


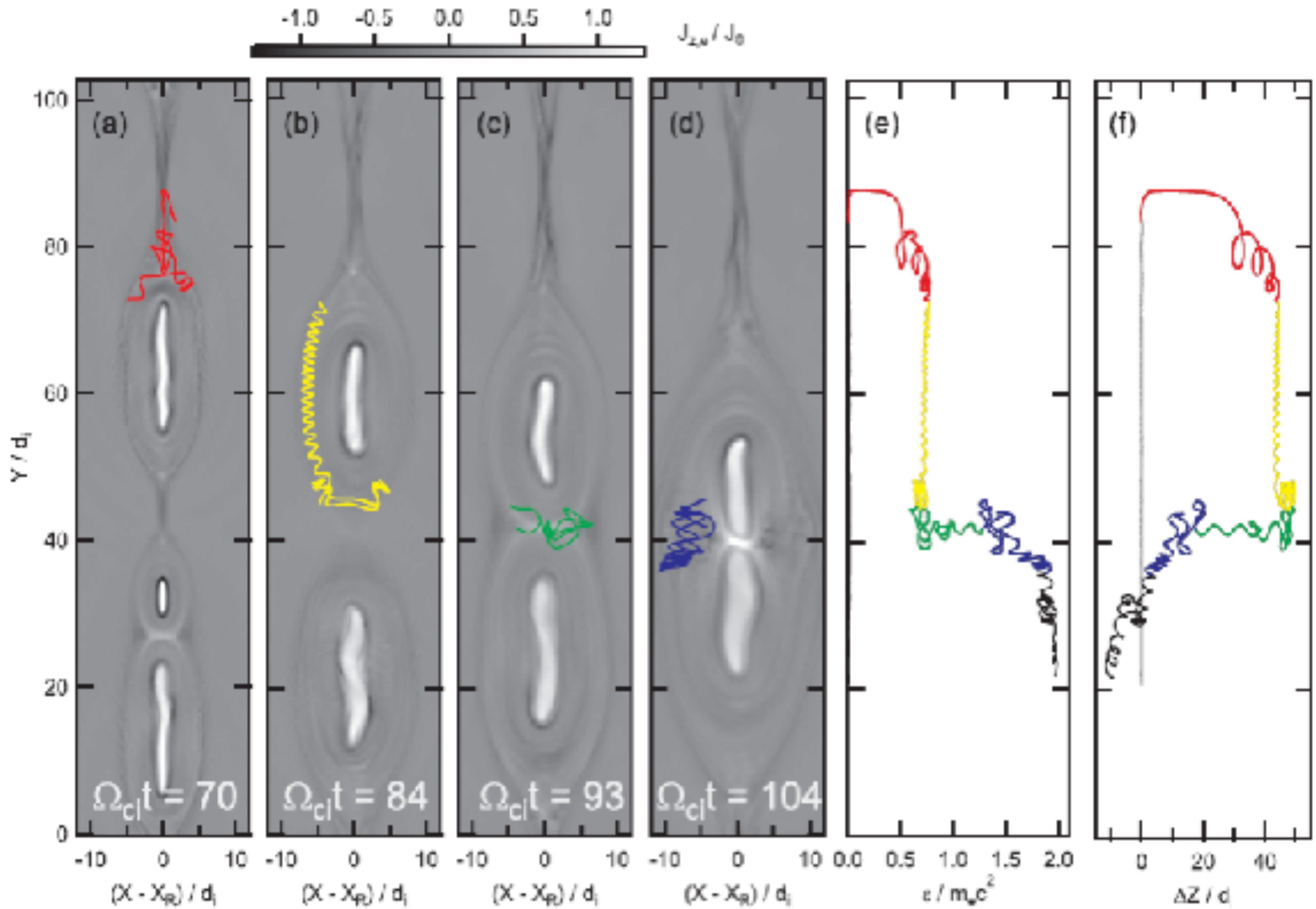


Observations of Fermi and betatron acceleration in the magnetotail
[Wu et al., JGR, 2013]





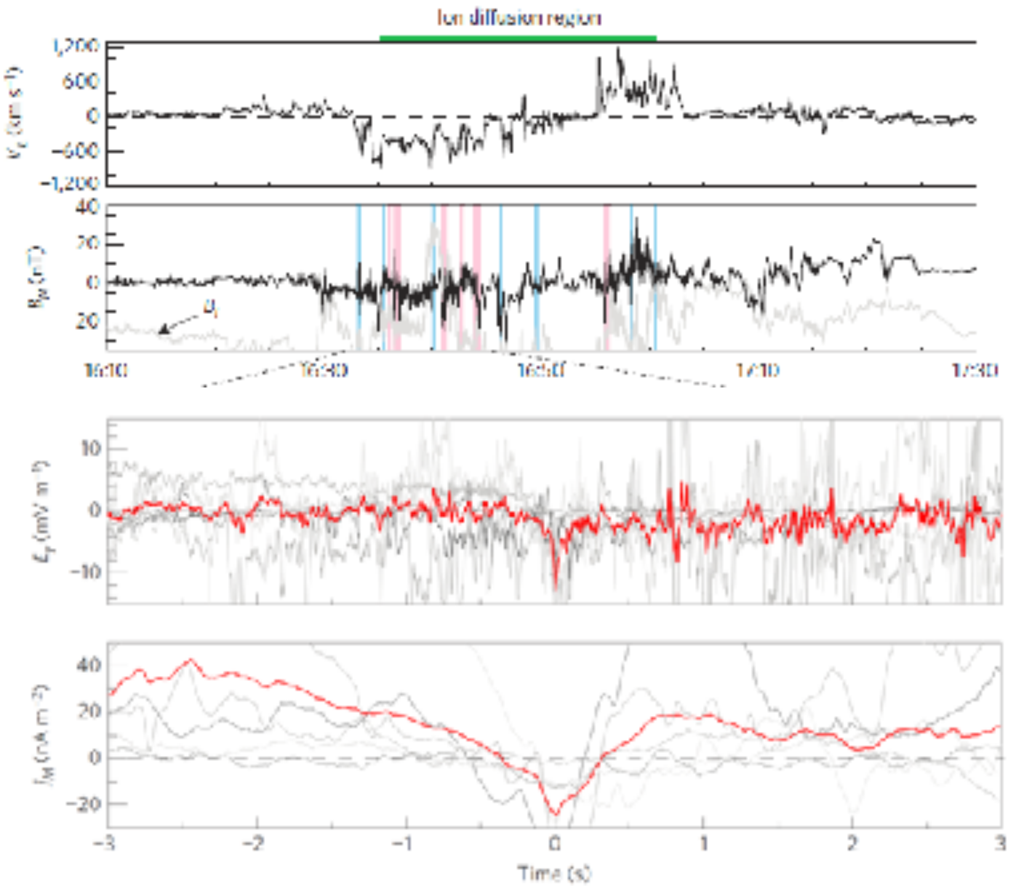


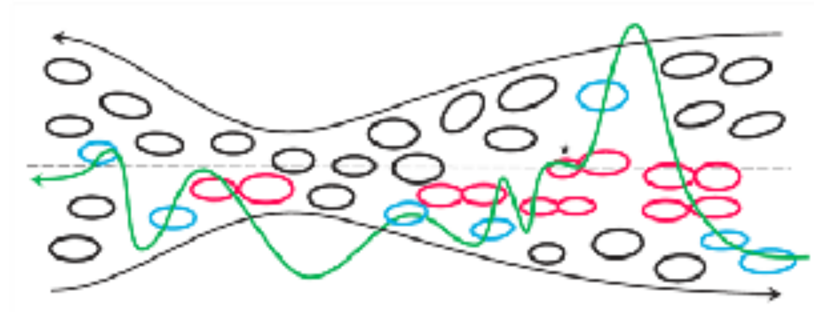


Electron acceleration during the coalescence of magnetic islands **[Oka et al., 2010]**

In situ evidence for coalescence of magnetic islands

6 coalescence events in ion diffusion region

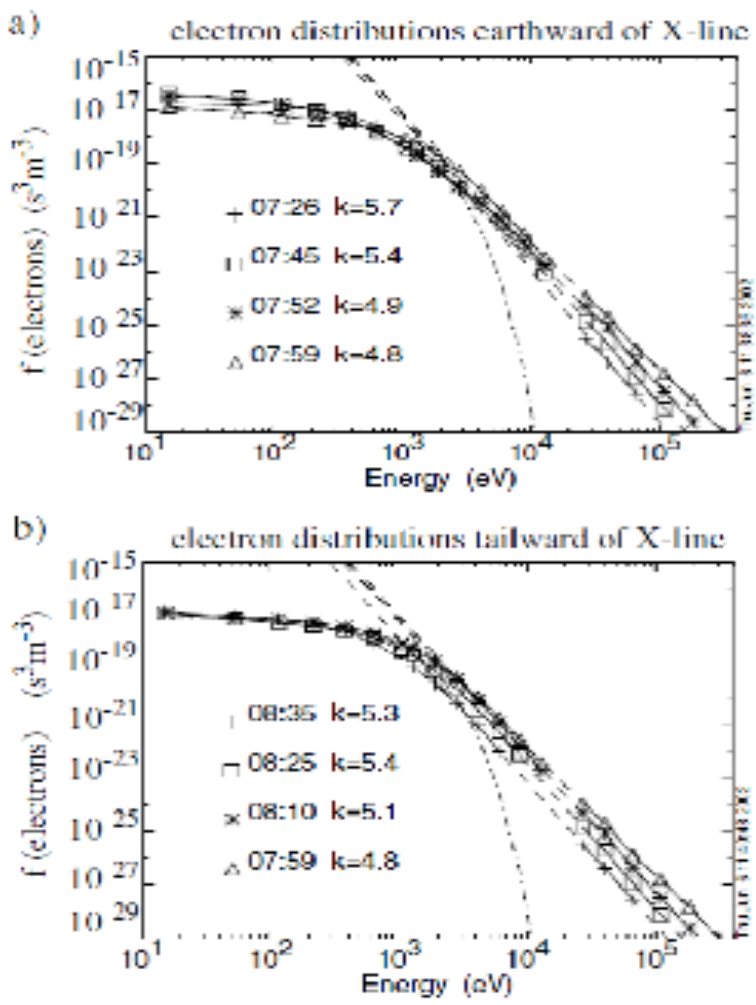




Wang et al., Nature Phys. 2016

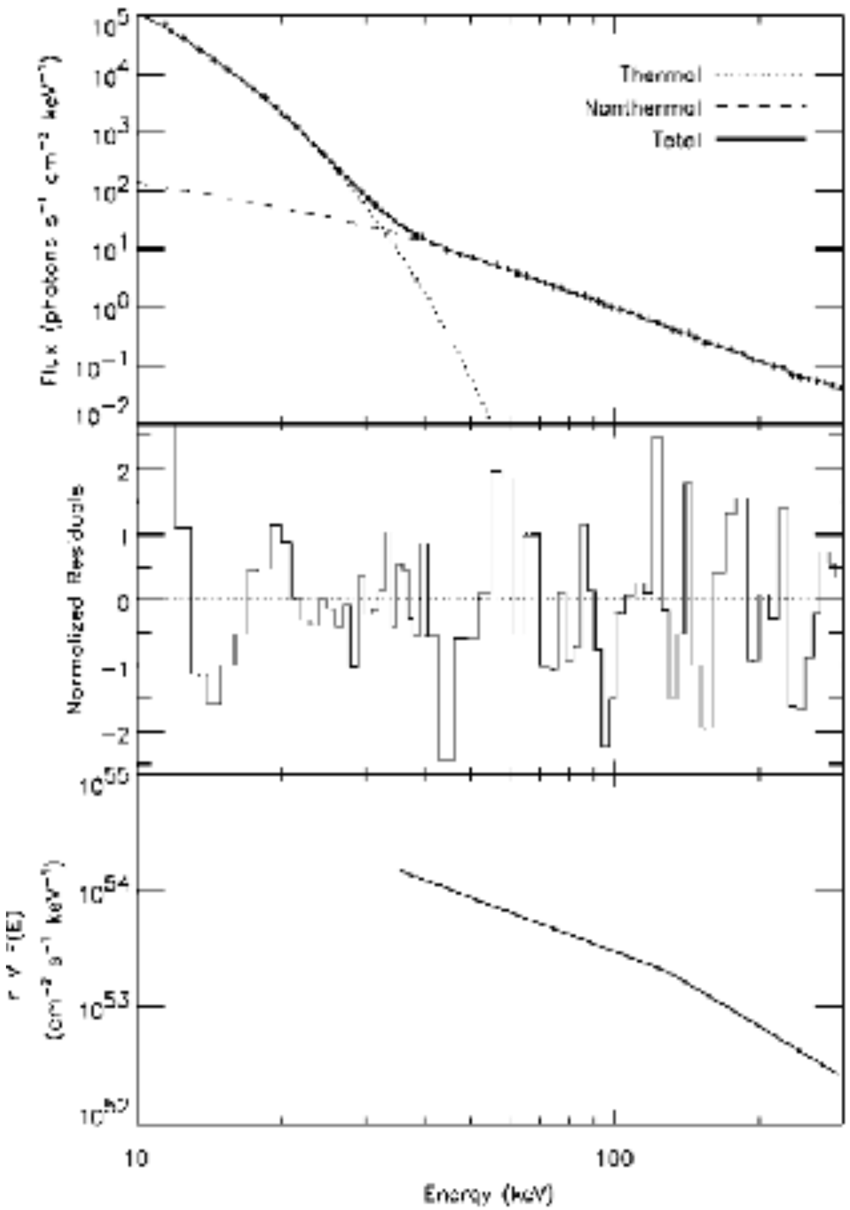
A superposed epoch analysis of E_M and J_M for the 6 coalescence events, E_M and J_M are enhanced in the merging point.

Power law spectra of energetic electrons observed associated with magnetic reconnection



The higher energy tail of the electron distributions can be fitted as a power law spectrum. The power k varies from 5.7 away from the diffusion region to 4.8 near the center of the diffusion region. [Oieroset et al., PRL, 2002]

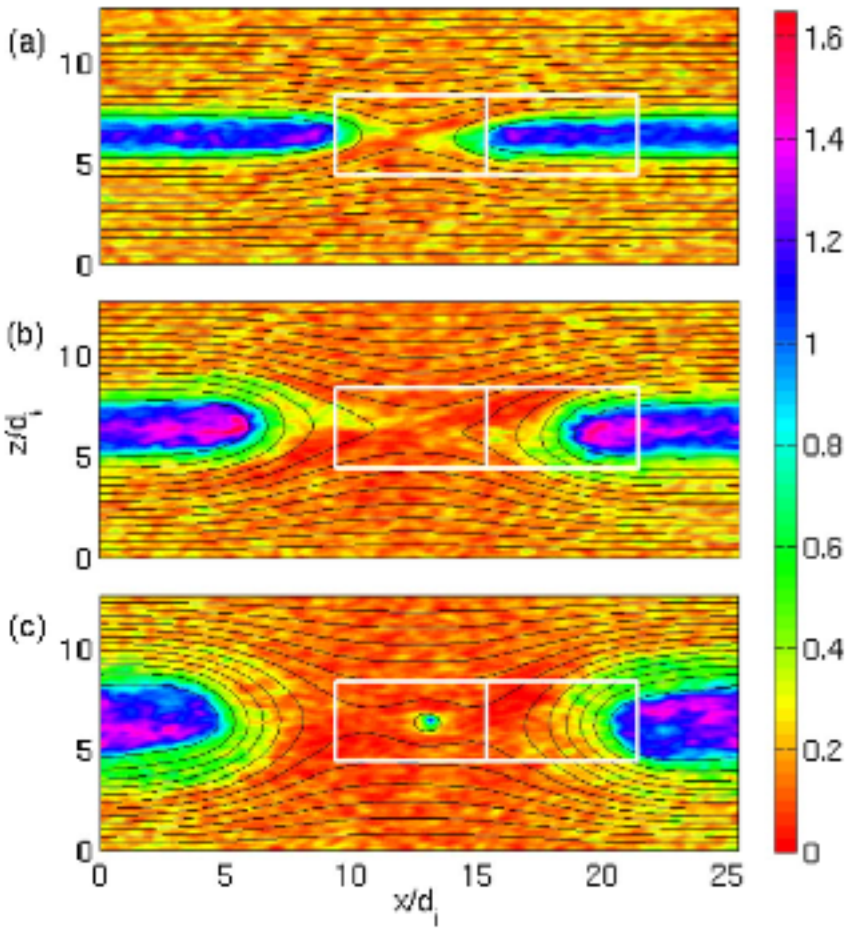
Magnetosphere

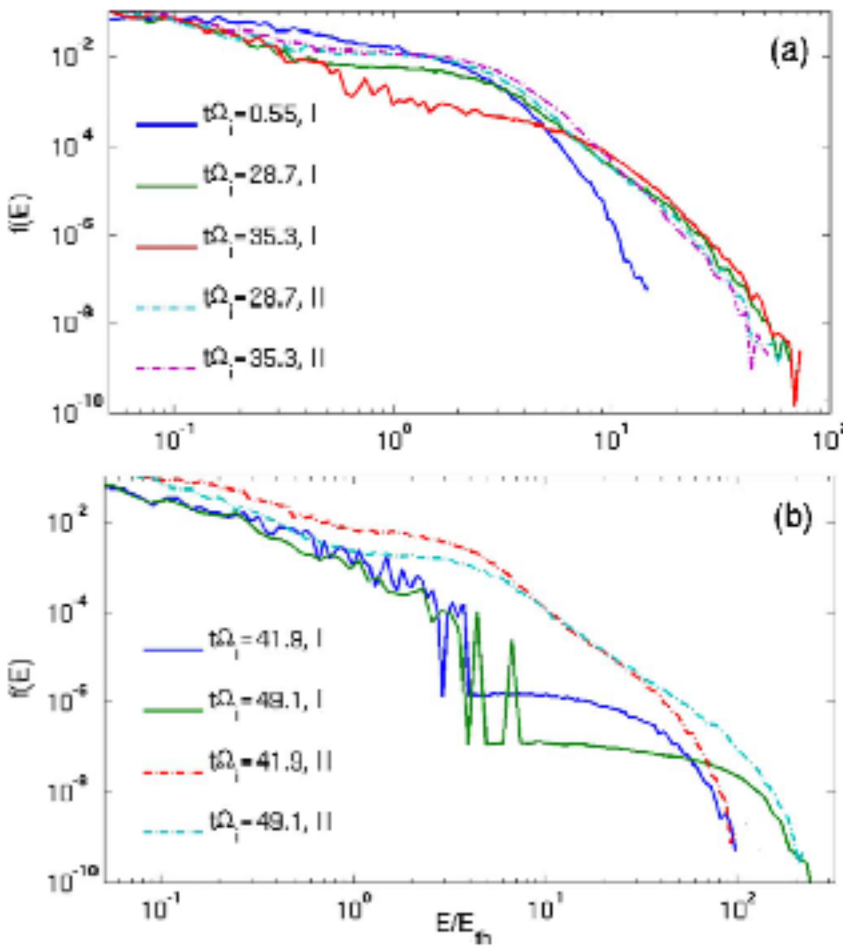


By analyzing High-resolution hard X-ray spectra from the 2002 July 23 solar flare. The beat-fit parameters are T=37MK, E_C=34KeV, the power k=1.5, E_B=129KeV, the power k=2.5。
[Holman et al., ApJL, 2003]

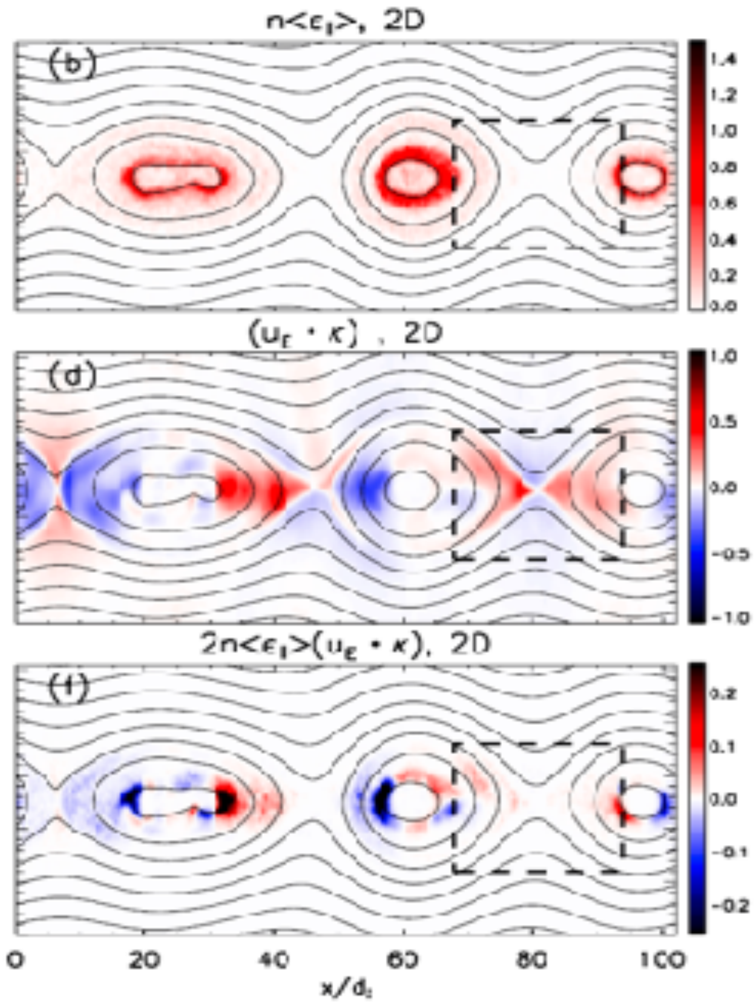
Solar atmosphere

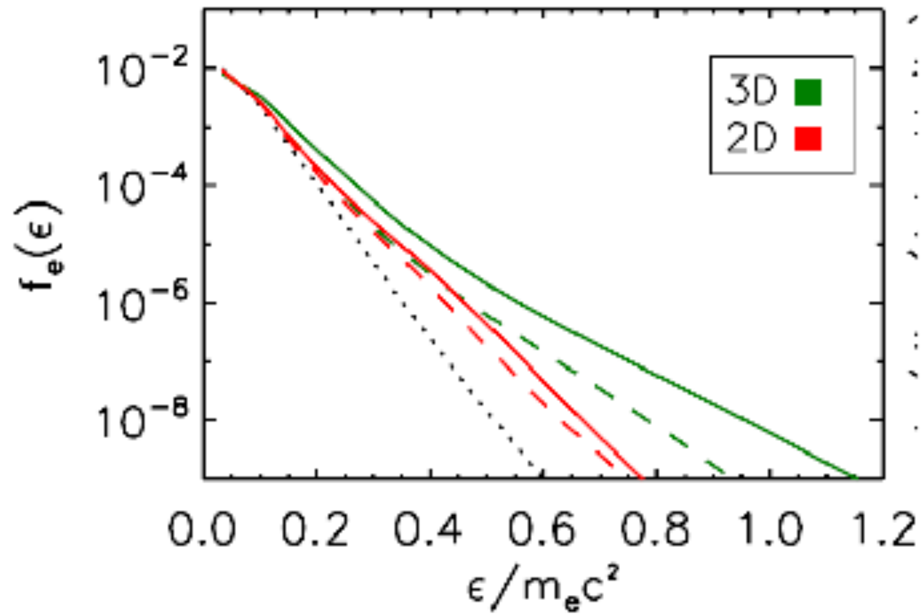
Particle-in-cell simulations of energetic electrons during magnetic reconnection





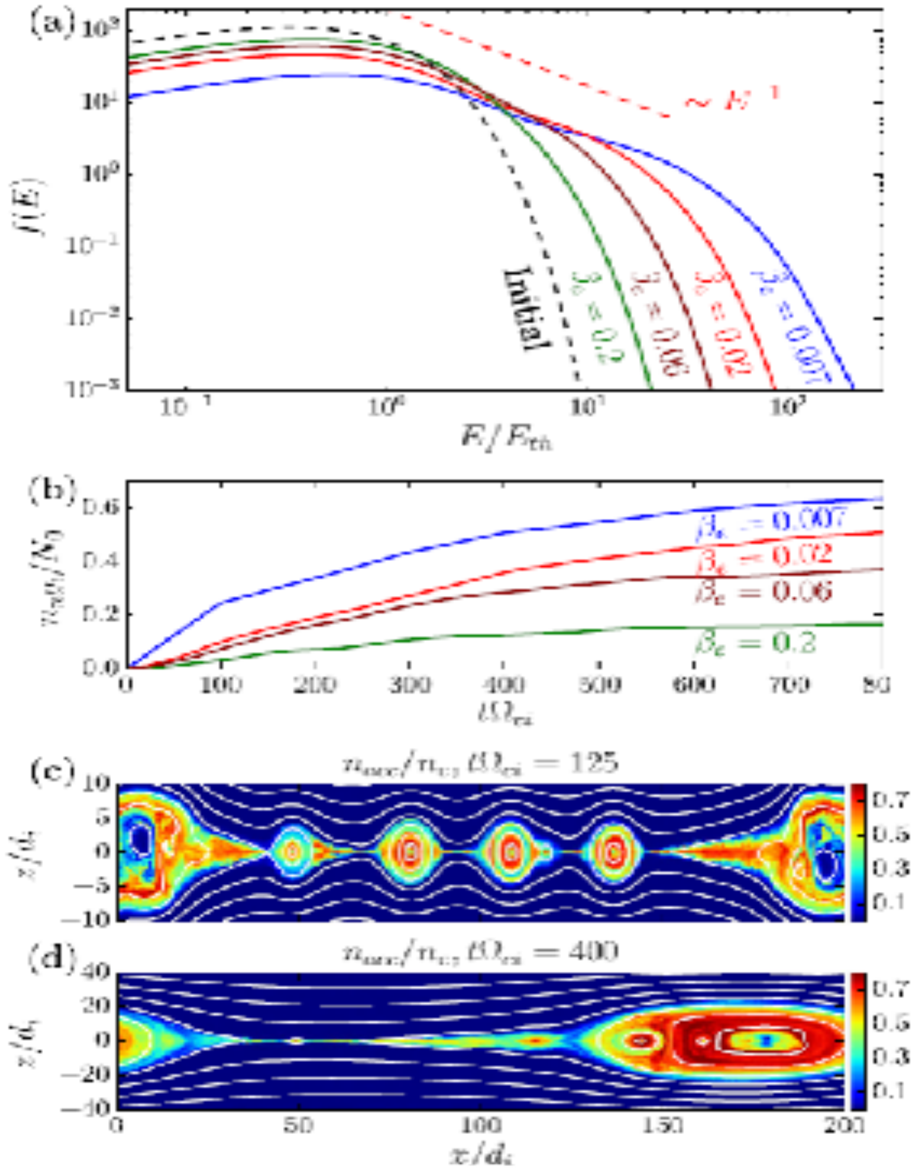
[Wan et al., PoP, 2008]





No Power Law!!

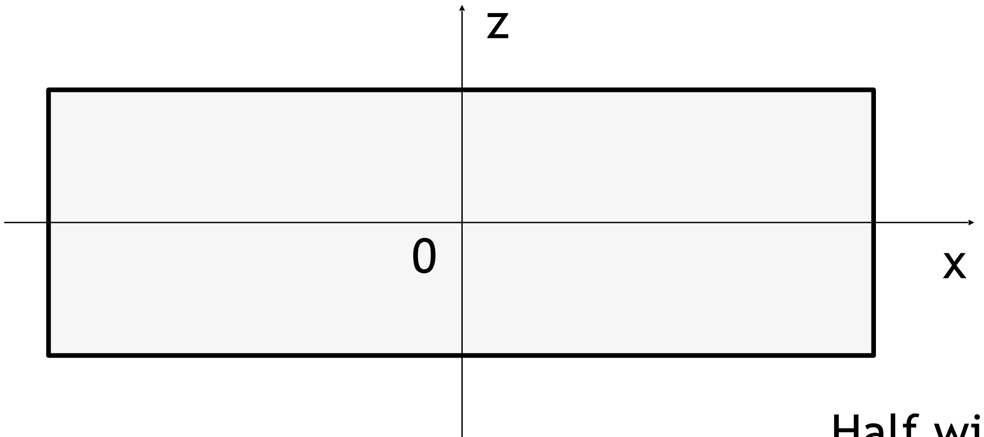
[Dahlin et al., PoP, 2017]



Power law spectra of energetic electrons are formed in low beta plasma.

[Li et al., ApJ, 2015]

Simulation model

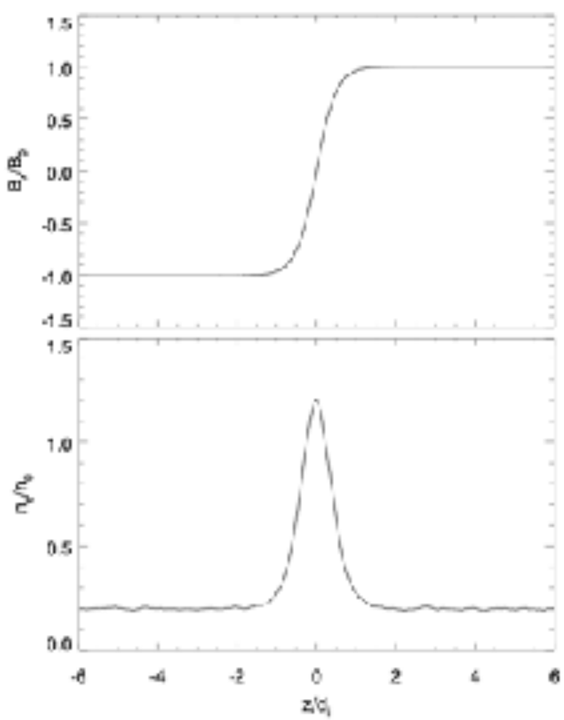


Harris current sheet:

$$\mathbf{B}_0(\mathrm{z}) = B_0 \tanh(z/\delta)\mathbf{e}_x + B_{y0}\mathbf{e}_y$$

$$n(z) = n_b + n_0 \mathrm{sech}^2(z/\delta)$$

Initial state:



Half width of current sheet: $\delta = 0.5 d_i$

Background plasma
density for each species: $n_b / n_0 = 0.2$

Simulation domain:

$$L_x \times L_z = (51.2 d_i) \times (12.8 d_i)$$

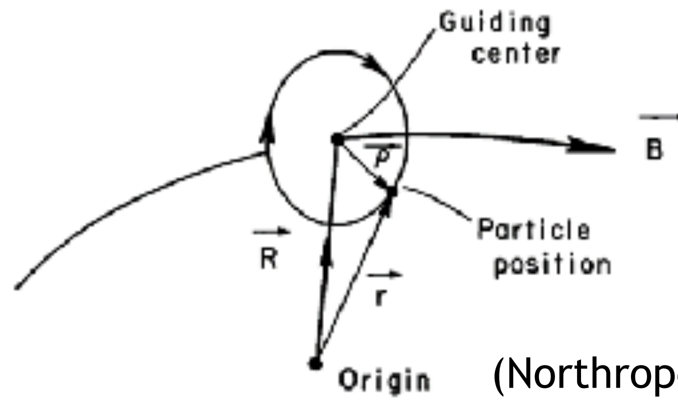
Mass ratio: $m_i / m_e = 100$

Initial guide field:

$$B_{y0} = 0.5B_0, 1.0B_0, 2.0B_0$$

Adiabatic theory for electron acceleration

Electron energy:



(Northrope, 1963)

$$\varepsilon = \frac{1}{2} m_e R^2 + \mu B$$

guiding center motion

gyro-motion around guiding center

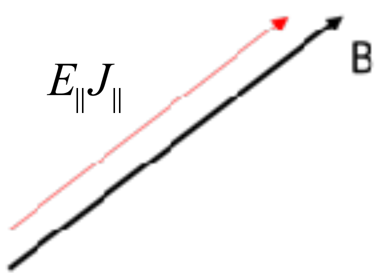
Power terms: $$\frac{d\varepsilon}{dt} = -e\left(v_\parallel \boldsymbol{b} + \boldsymbol{v}_c + \boldsymbol{v}_g\right)\cdot\boldsymbol{E} + \mu\,\partial_t B$$

guiding center along magnetic field

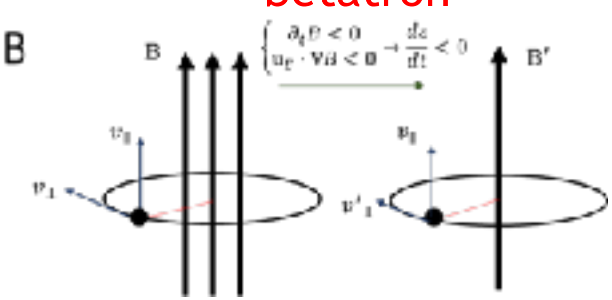
drift motion

sum over large amount of electrons

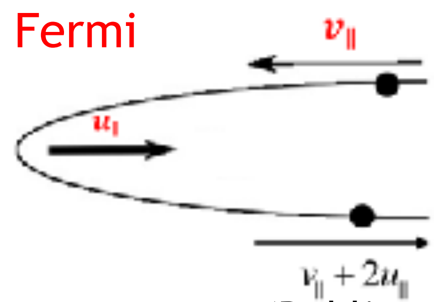
$$\frac{dU}{dt} = E_\parallel J_\parallel + \frac{p_\perp}{B}\left(\frac{\partial B}{\partial t} + \boldsymbol{u}_E\cdot\nabla B\right) + \left(p_\parallel + m_e n u_\parallel^2\right)\boldsymbol{u}_E\cdot$$



betatron



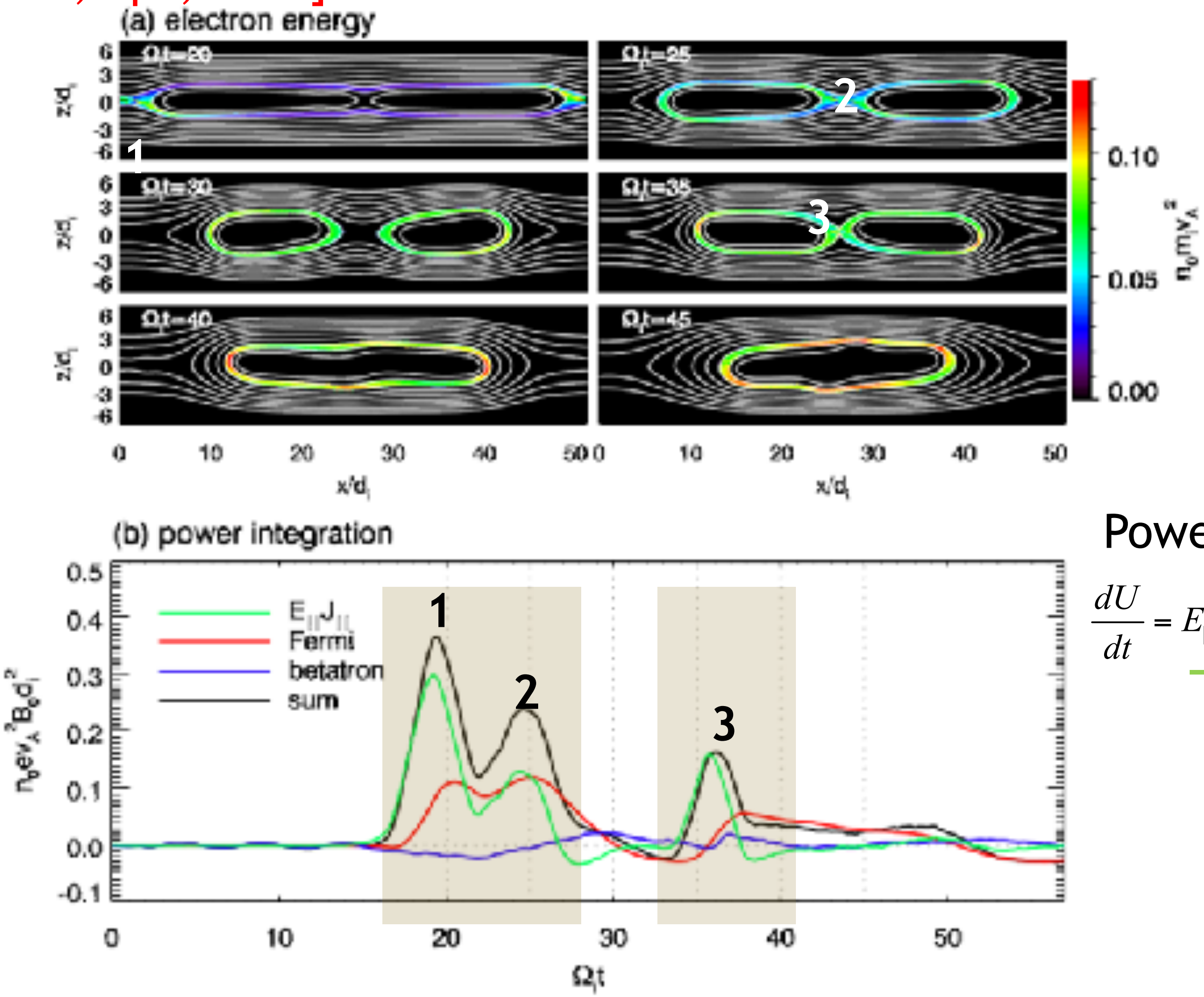
Fermi



(Dahlin et al. 2014

Simulation results

Simulation case with initial guide field: $B_{y0} = 0.5B_0$. The enhancement of energetic electrons due to the parallel electric field and Fermi mechanism[Wang et al., ApJ, 2016].



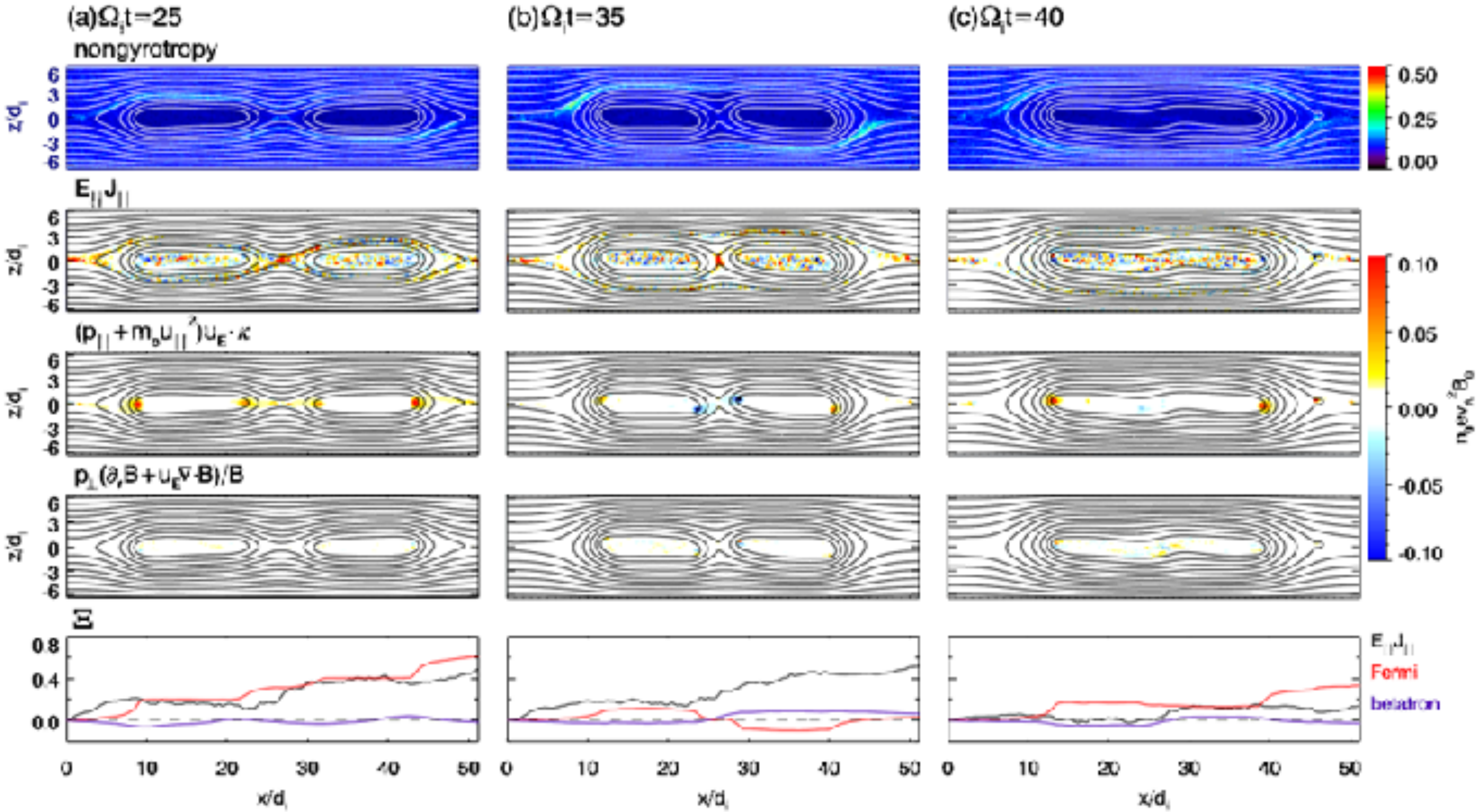
Power terms:

$$\frac{dU}{dt} = E_{\parallel} J_{\parallel} + \frac{p_{\perp}}{B}\left(\frac{\partial B}{\partial t} + \boldsymbol{u}_E \cdot \nabla B\right) + \left(p_{\parallel} + m_e n u_{\parallel}^2\right) \boldsymbol{u}_E \cdot$$

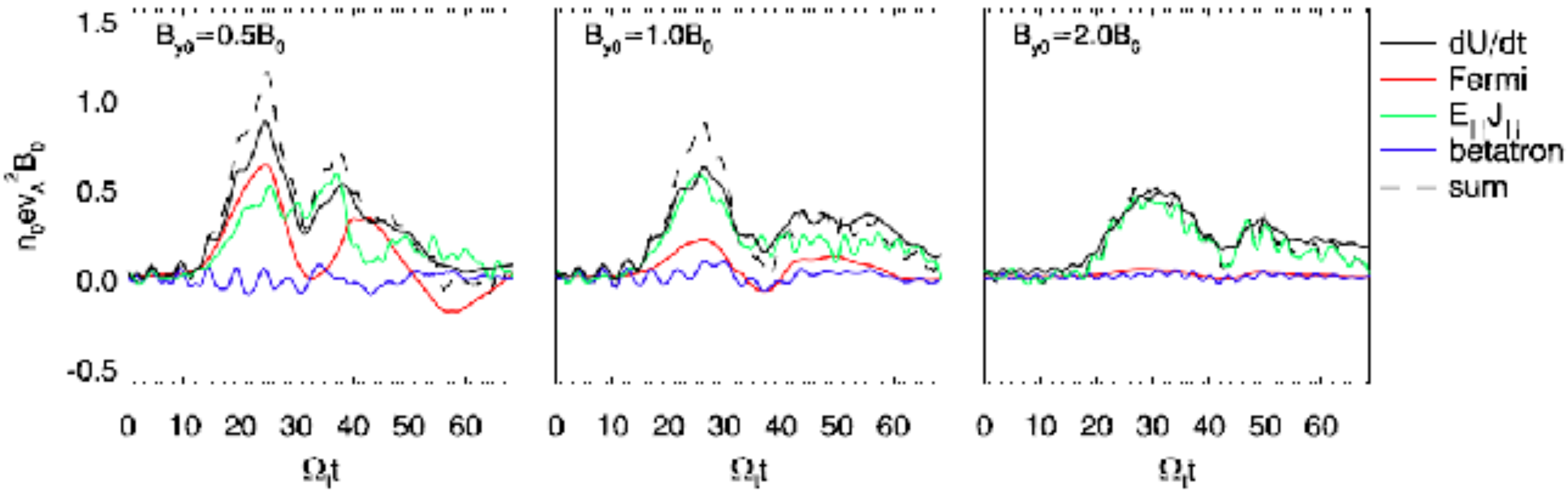
betatron

Fermi

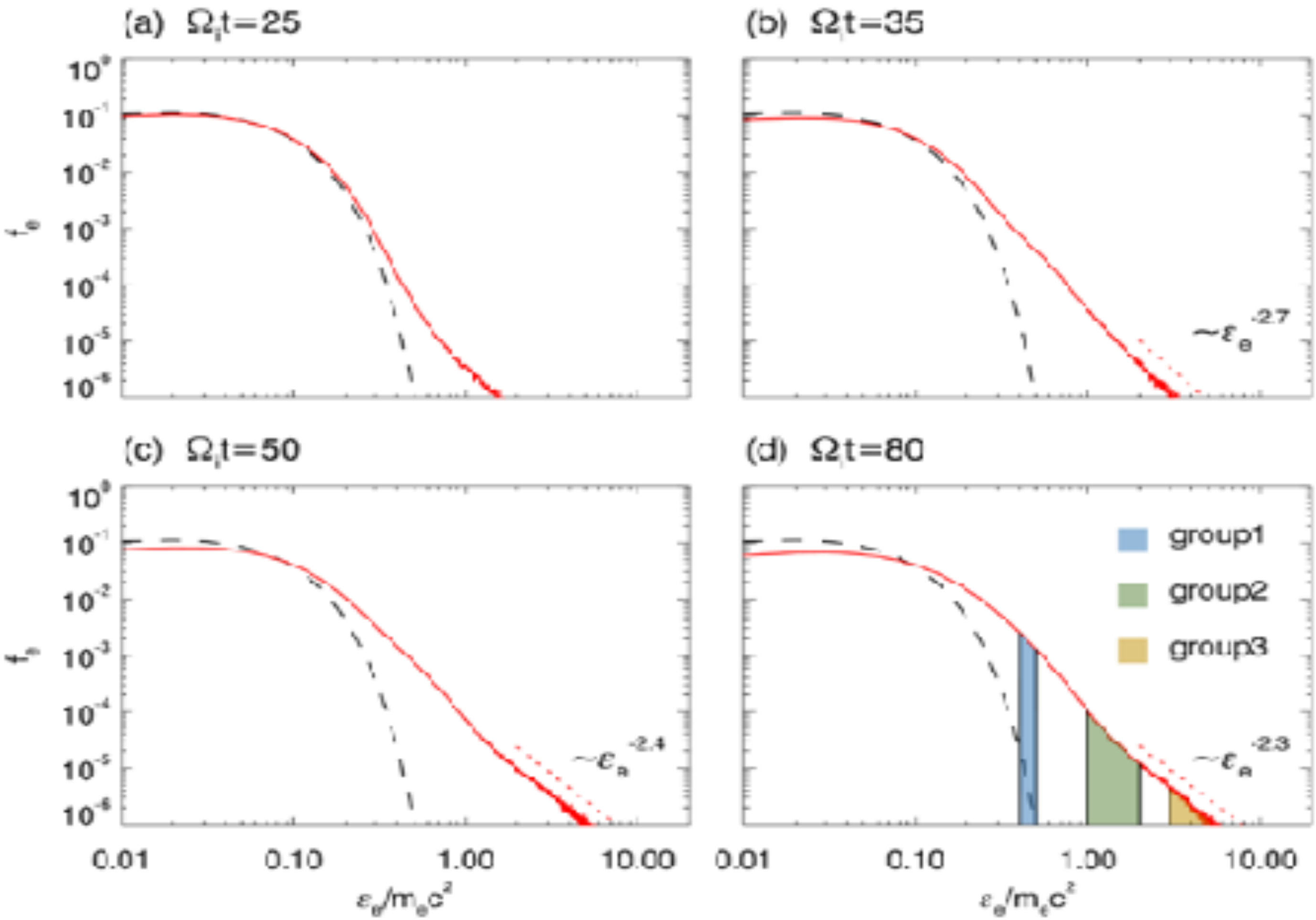
Spatial distributions of power terms



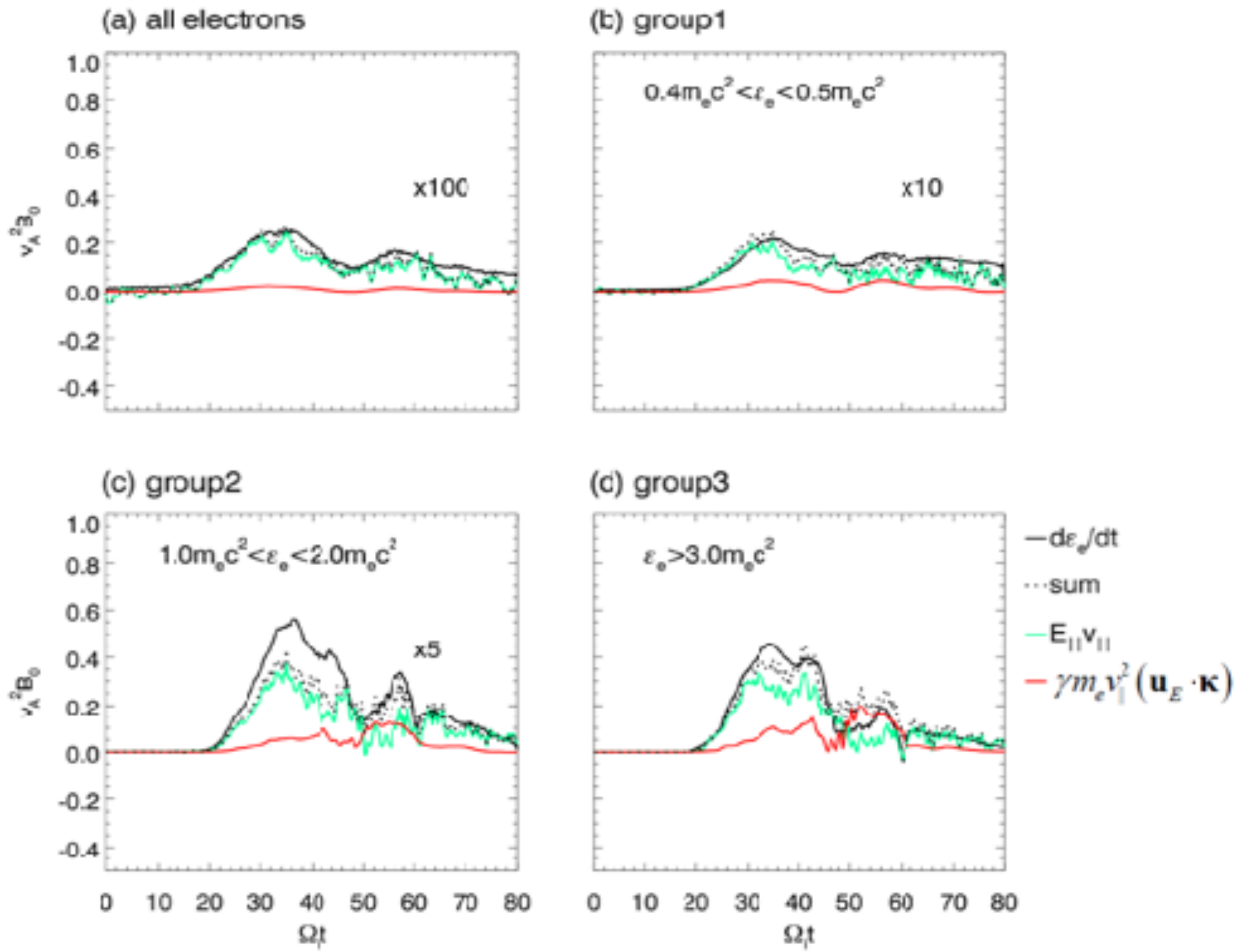
The contribution of the parallel electric field is concentrated near the X point, and Fermi mechanism is concentrated at the two ends of magnetic islands.



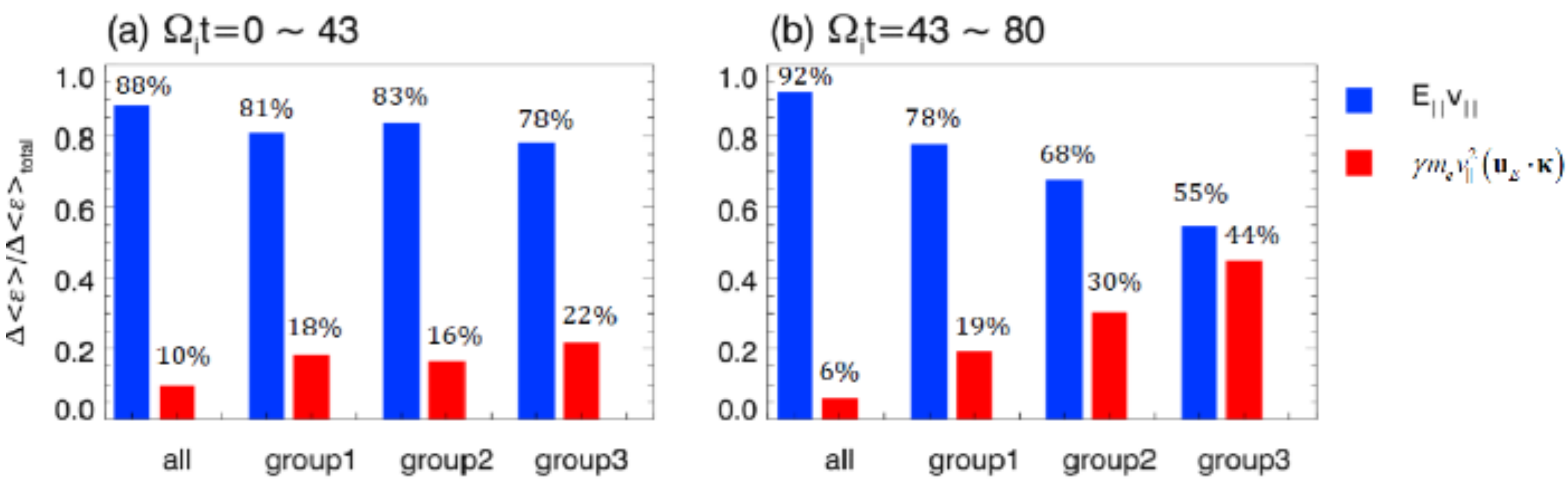
Parallel electric field acceleration become the most important mechanism in strong guide field case



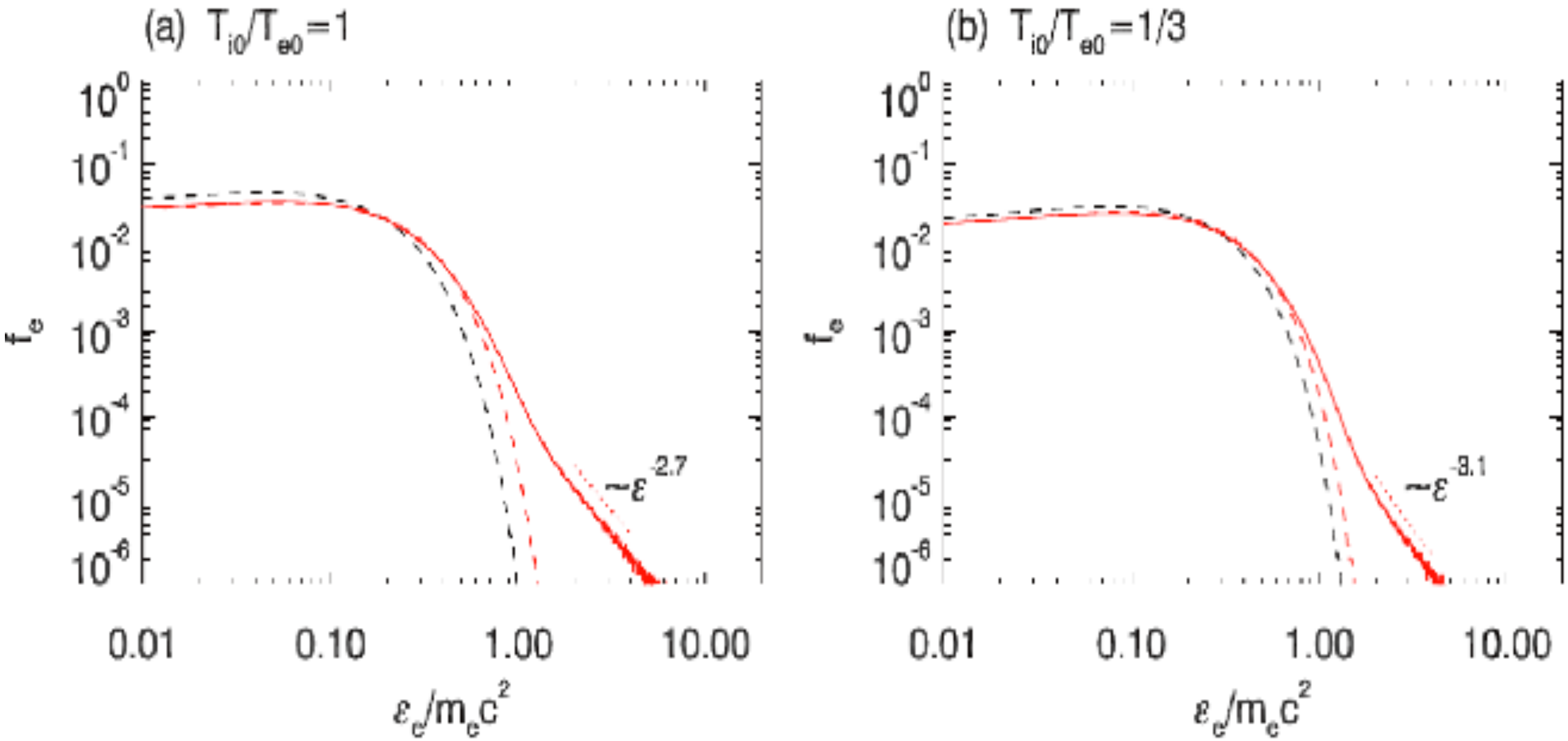
The electron energy spectra at different times for the case with $B_{y0} = 2.0B_0$
A power-law distribution of energetic electrons are formed.



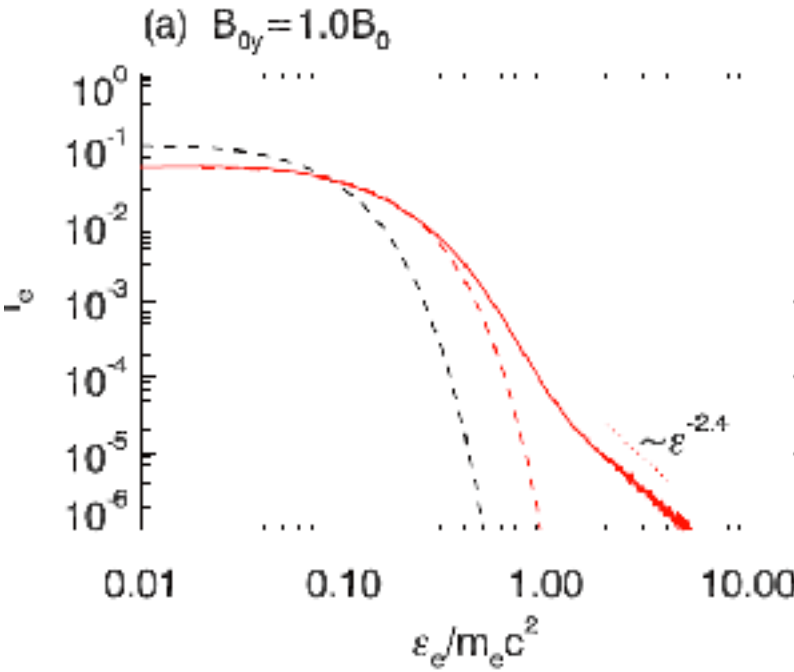
The time evolution of contributions of parallel electric fields ($\sim \varepsilon_e^{1/2}$) and Fermi mechanism ($\sim \varepsilon_e$) with energies for the case $B_{y0} = 2.0B_0$. With the increase of electron energy, the contribution of Fermi mechanism becomes more and more important.



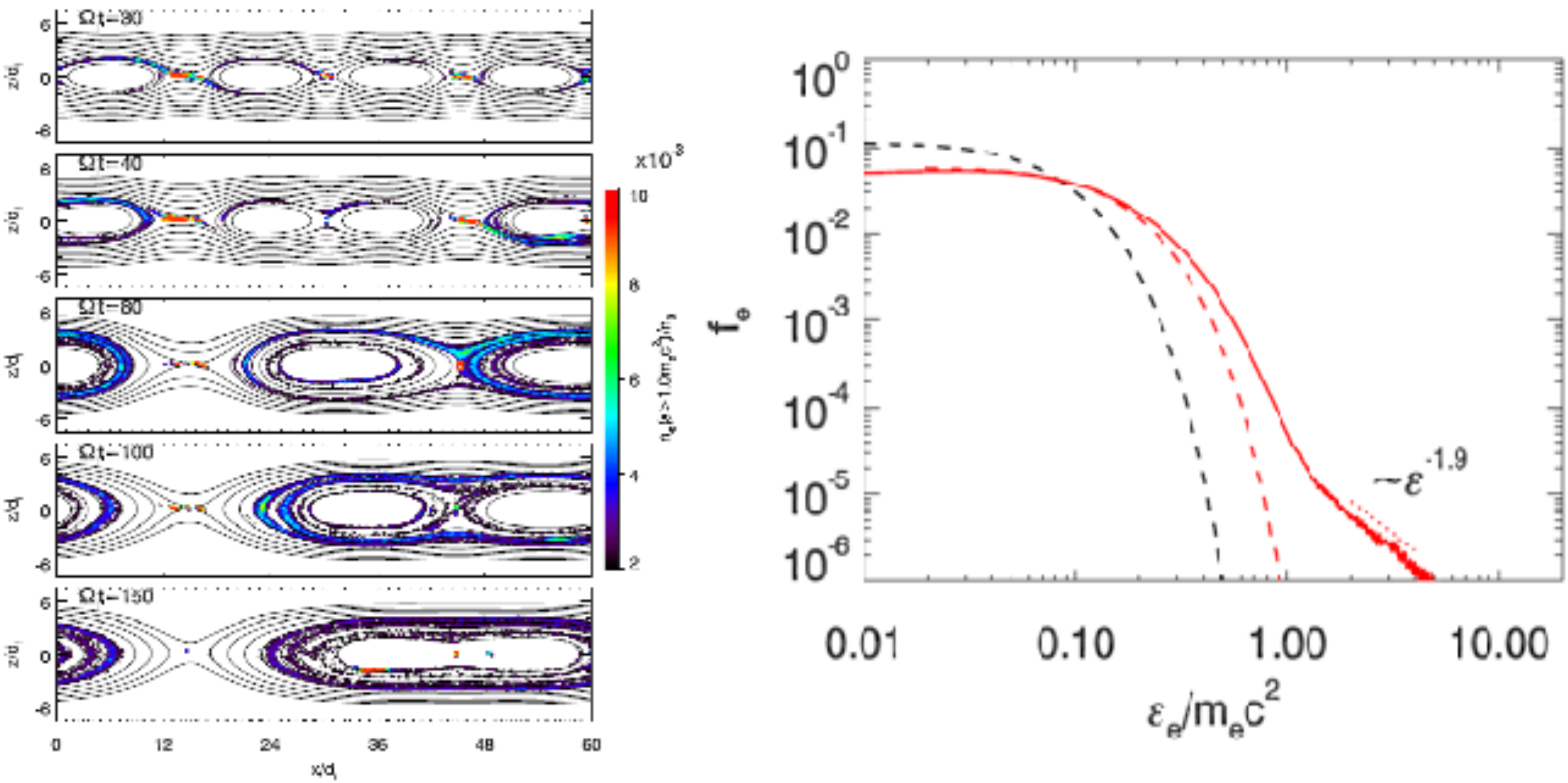
The percentage of the contributions from the parallel electric field and Fermi mechanism at two stages: the generation of two magnetic islands and coalescence of two islands.



(a) $T_{i0}/T_{e0}=1$
(b) $T_{i0}/T_{e0}=1/3$
f_e
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$\sim\varepsilon^{-2.7}$
$\sim\varepsilon^{-3.1}$
0.01
0.10
1.00
10.00
ε_e/m_ec^2



(a) B_{0y}=1.0B_0
(b) B_{0y}=0.5B_0
f_e
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$\sim\varepsilon^{-2.4}$
$\sim\varepsilon^{-3.2}$
0.01
0.10
1.00
10.00
ε_e/m_ec^2



Ωt=30
Ωt=40
Ωt=80
Ωt=100
Ωt=150
z/d_i
x/d_i
0
12
24
36
48
60
x10^-3
f_e
~ε^-1.9
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
0.01
0.10
1.00
10.00
ε_e/m_ec^2

Summary

1. Power law spectra of energetic electrons can be formed in multiple X line with a guide field.

2. Electron acceleration has two stages: the appearance of X line, and merging of magnetic island. In the first stage, parallel electric field is more important. In the second stage, with the increase of electron energy, Fermi mechanism become more and more important.

Thanks for your attention!