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Electron acceleration during magnetic reconnection: Particle-in-cell simulations

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Outlook

- Introduction to magnetic reconnection
- Particle-in-cell simulation and collisionless magnetic reconnection
- Electron acceleration near the X line
- The role of magnetic island in electron acceleration
- Electron acceleration in laser plasma reconnection
- Summary

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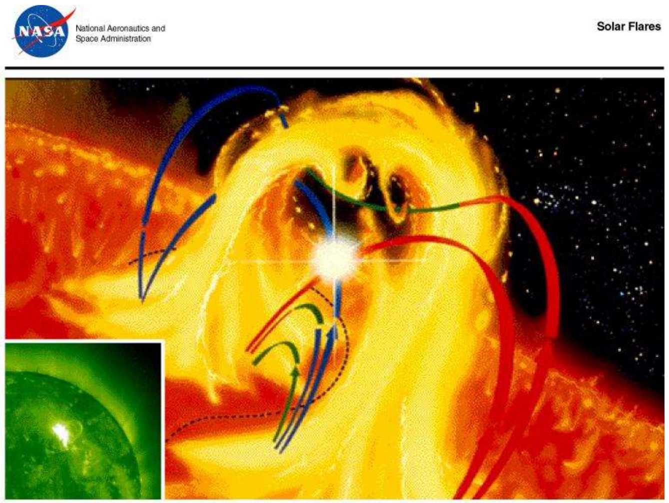
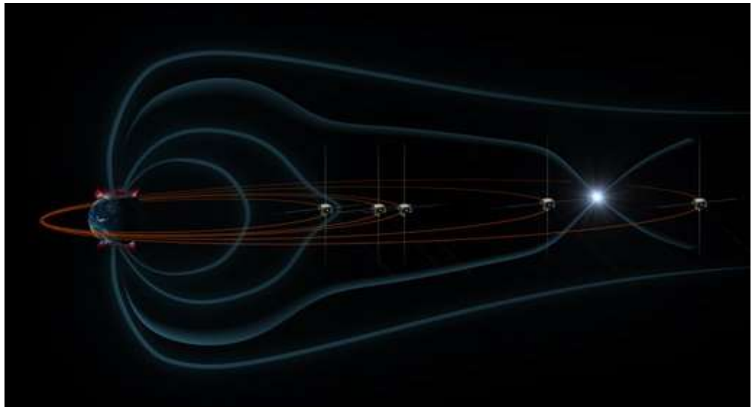
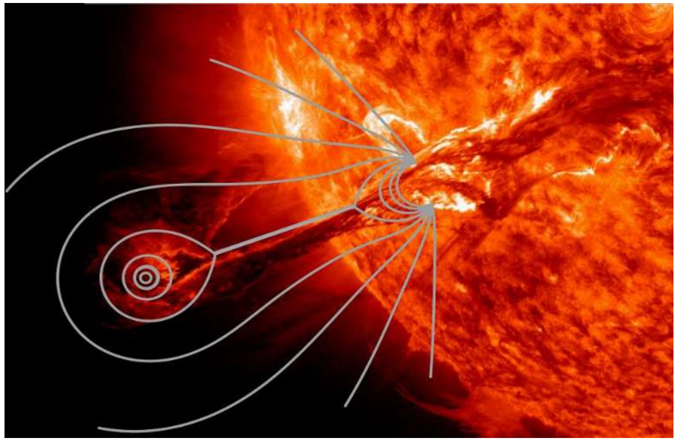
Explosive phenomena in space plasma



Solar flare



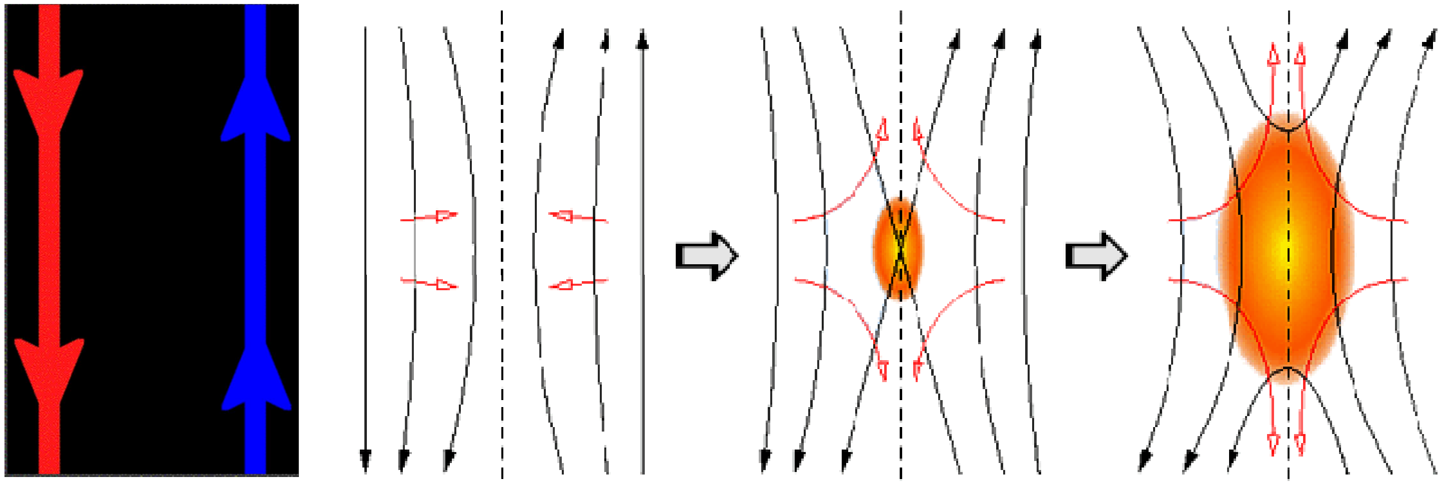
Substorm



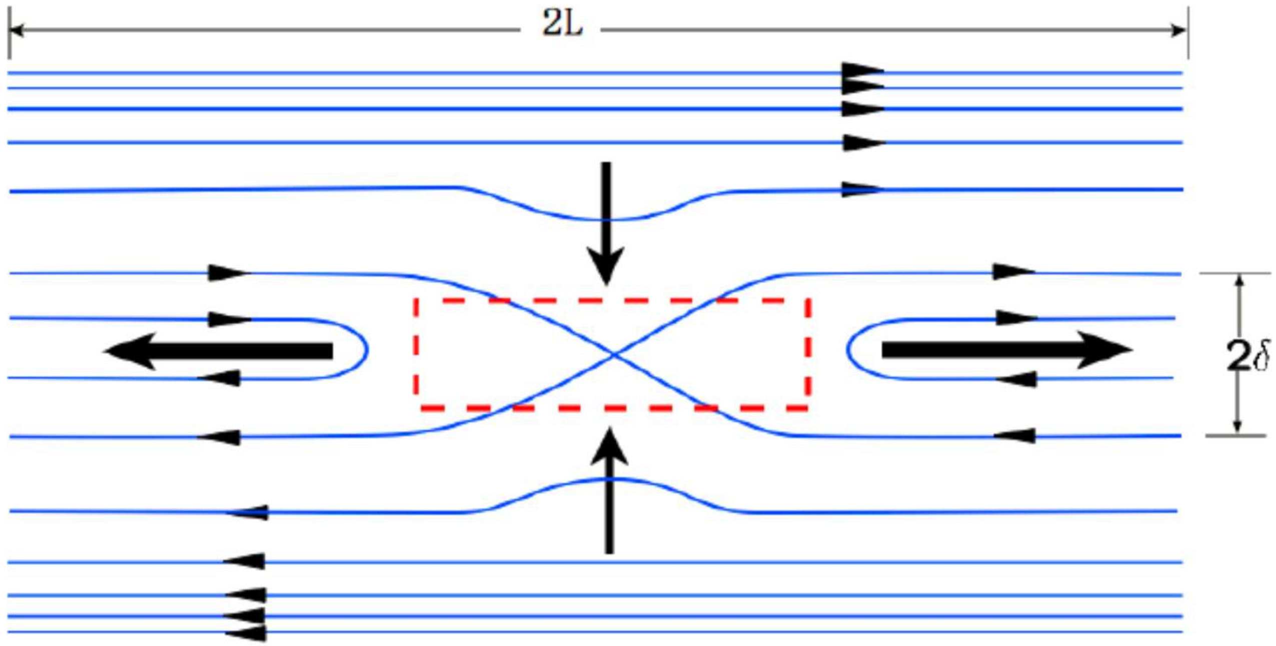
Coronal Mass Ejection（CME）

These phenomena last for about several minutes. A mechanism, which converts magnetic energy into plasma kinetic energy, is necessary to explain these phenomena.

Magnetic reconnection, where magnetic field lines are topologically rearranged, provides such a fast conversion from magnetic energy into plasma kinetic energy.



How do magnetic field lines reconnect(2D)?



In 2D picture, magnetic field lines reconnect because newly reconnected field lines move out of the diffusion region quickly due to a tension force.

Sweeter-Parker(SP) model (2D MHD)

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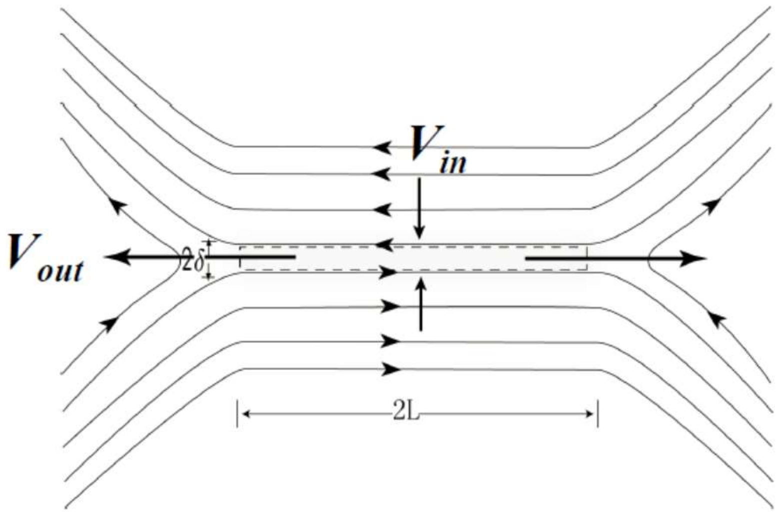
- 2D
- Steady-state
- Incompressibility



Mass conservation: $V_{in}L \approx V_{out}\delta$

Pressure balance: $\frac{1}{2}\rho V_{out}^2 \approx \frac{B^2}{2\mu_0} \Rightarrow V_{out} \approx V_A$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{V} \times \mathbf{B}) + \frac{\eta}{\mu_0}\nabla^2 \mathbf{B} \Rightarrow V_{in}B \approx \frac{\eta}{\mu_0}\frac{B}{\delta}$$

$$\frac{V_{in}}{V_A} = \frac{1}{\sqrt{S}}$$

$$S = \frac{\mu_0 L V_A}{\eta}$$

S: Lundquist number

The problems of SP model

The required reconnection time: $\tau_{reconn} \sim$ minutes

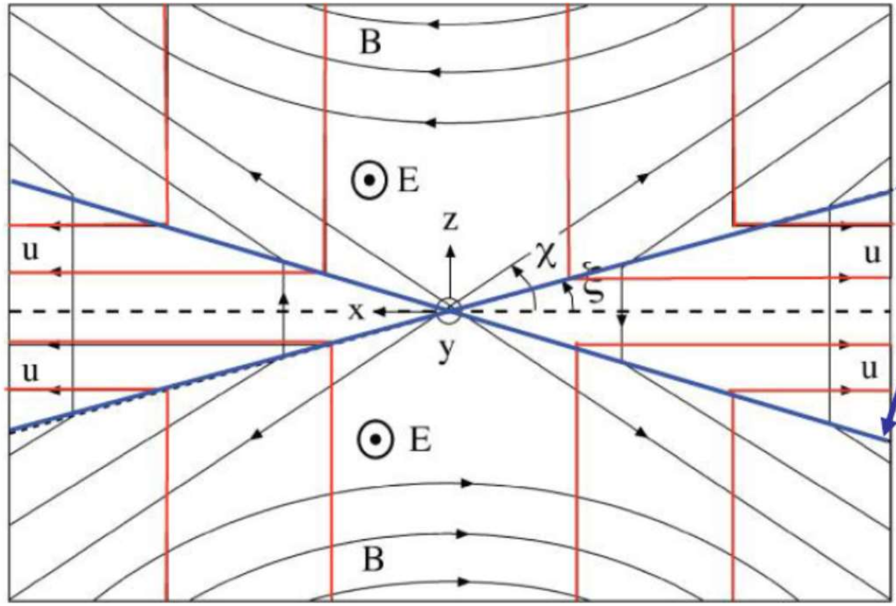
The reconnection time predicted by SP model: $\tau_{SP} \sim$ months

The width of the current sheet: $\frac{\delta}{L} \sim \frac{1}{\sqrt{S}}$

In space plasma $S \sim 10^{6-8}$, then $\frac{\delta}{L} \sim 10^{-3\sim 4}$

The SP current sheet is unstable, not steady.

Petschek model



Petschek model

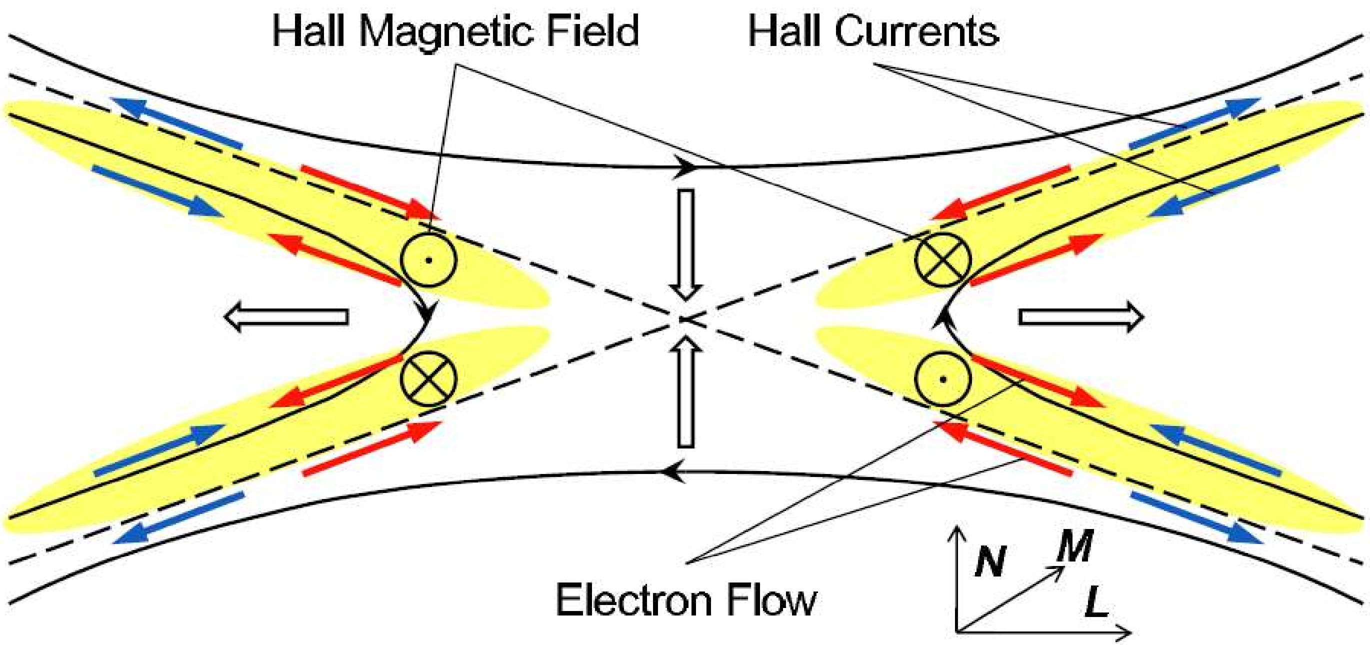
Add slow shocks in the convection region

Now the diffusion region remains small, but a much larger plasma volume can be deviated around it

$$\frac{V_i}{V_A} = \frac{\pi}{8 \ln S}$$, and the reconnection time predicted by Petschek model $\tau_P \sim$ minutes

The MHD simulations with a uniform resistivity support the development of the SP type of the current sheet rather than the Petschek type.

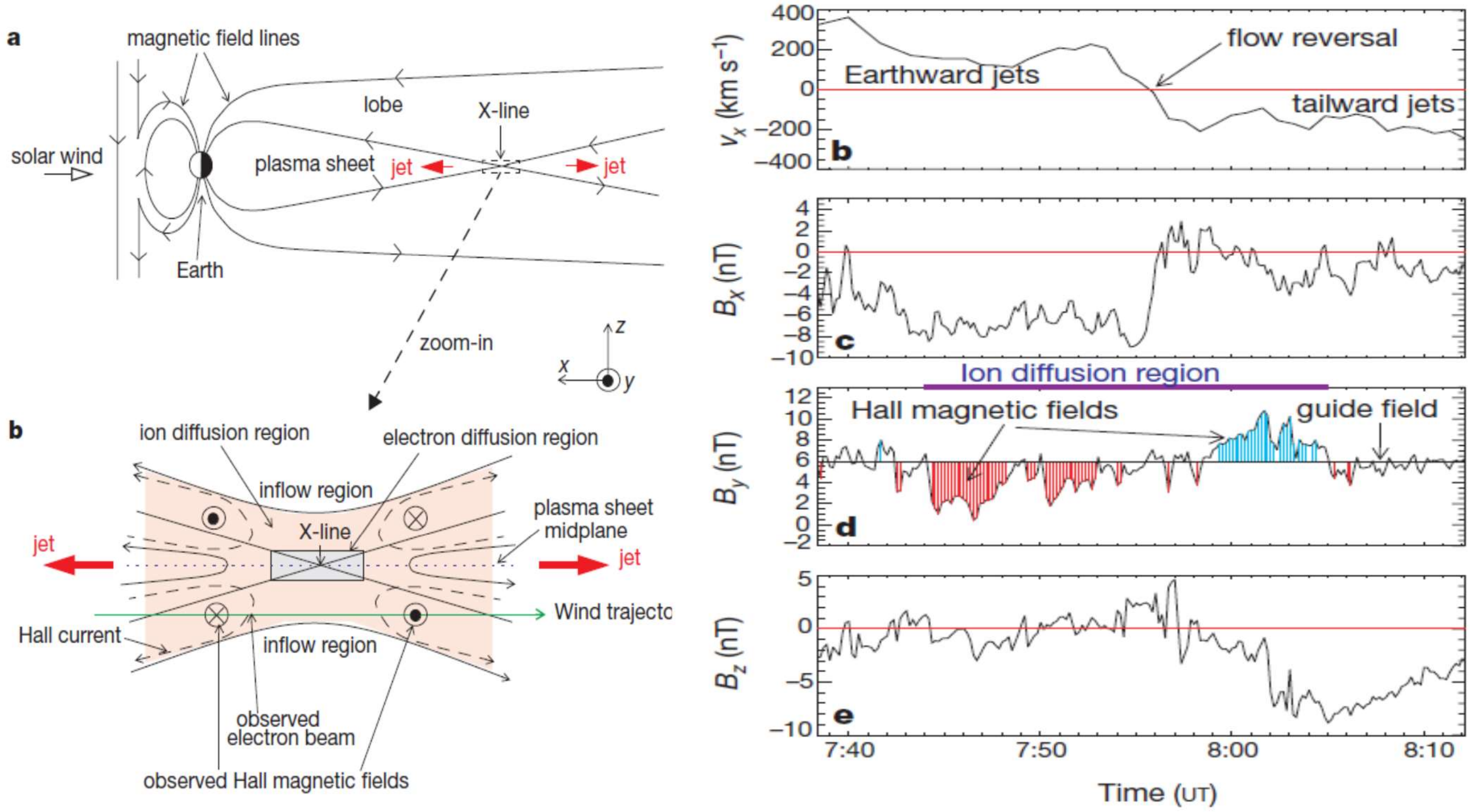
Collisionless Magnetic Reconnection



Ion diffusion region: Ions are not frozen in the magnetic field, and electrons are unmagnetized. It leads to the quadrupole structure of the out-of-plane magnetic field.
Electron diffusion region: Electrons are unmagnetized.
[Birn et al., JGR, 2001]

$$\frac{V_i}{V_A} \sim 0.1$$

Observation evidence of collisionless magnetic reconnection



In situ observation of collisionless magnetic reconnection with Wind satellite.[Oieroset et al., Nature, 2001]

Collisionless magnetic reconnection in Laboratory

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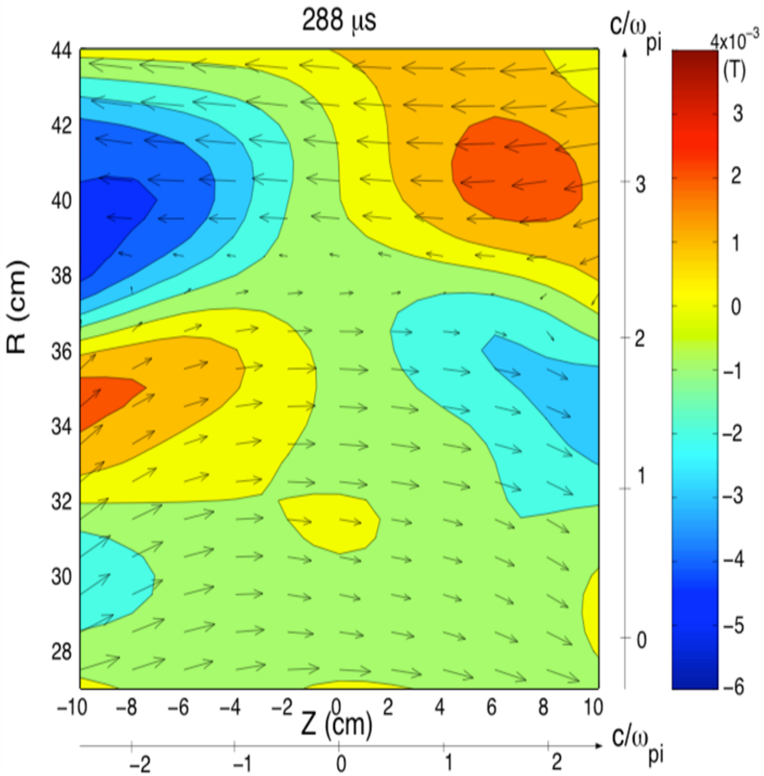
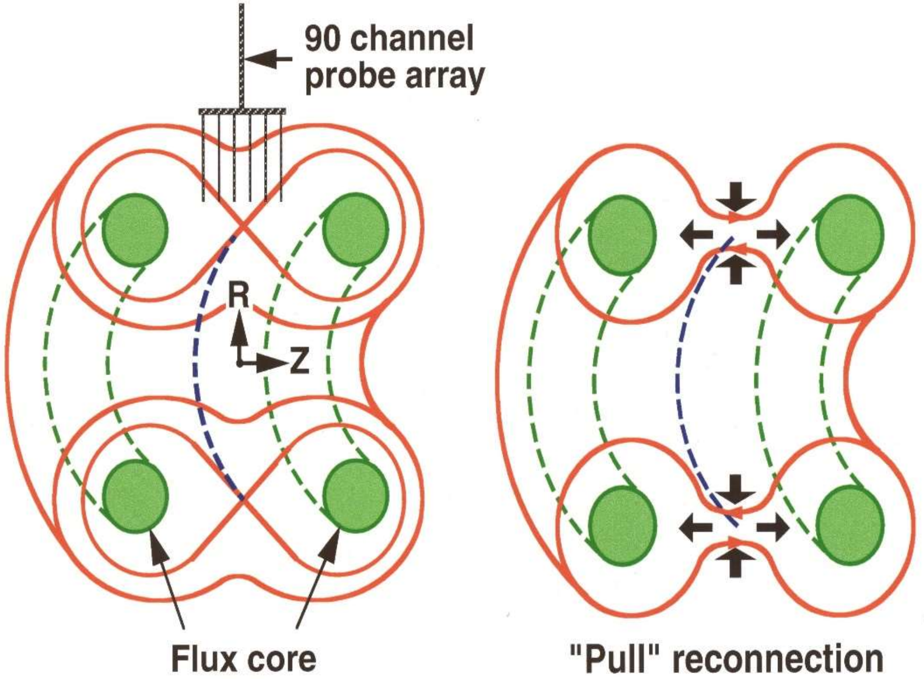


Experimental Setup in MRX



Quadruple structure of the out-of-plane magnetic reconnection is observed in Magnetic Reconnection Experiment (MRX) [Ren et al., PRL, 2005].

Energetic electrons as important signature of collisionless reconnection

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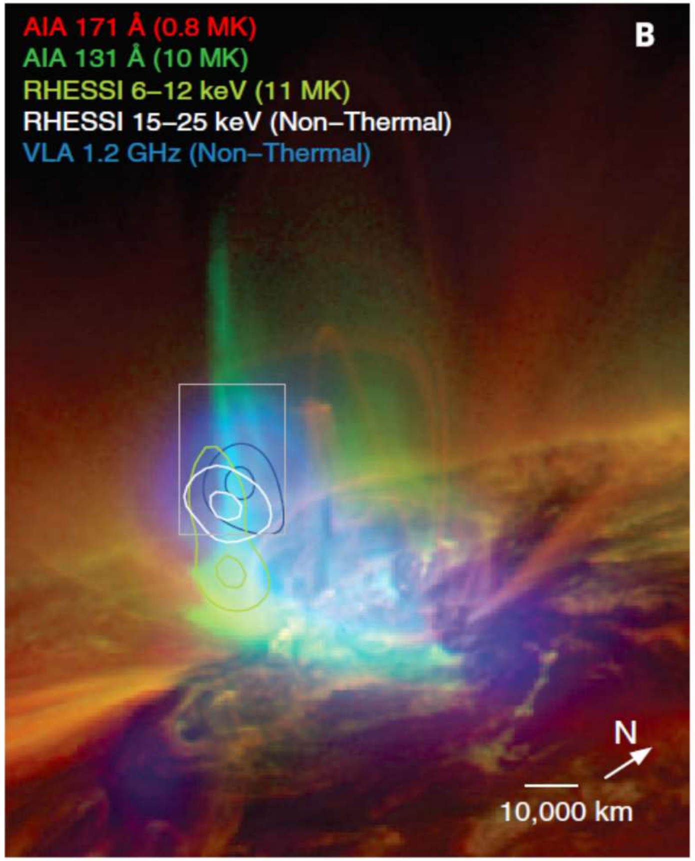

Nonthermal electrons observed by RHESSI in solar flare.

- Particle-in-cell simulations are necessary to study electron acceleration in magnetic reconnection.

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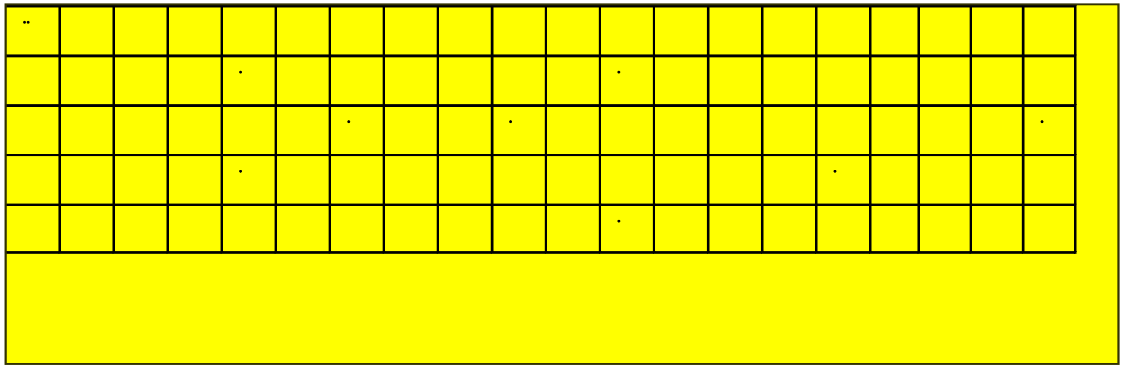
Particle-in-cell(PIC) simulations

To teat particles (ions and electrons) kinetically, a particle-in-cell simulation model is necessary.



Particles in anywhere<=======>Fields in grids

interpolation

Solve particles and fields self-consistently

PIC model governing equations

particles

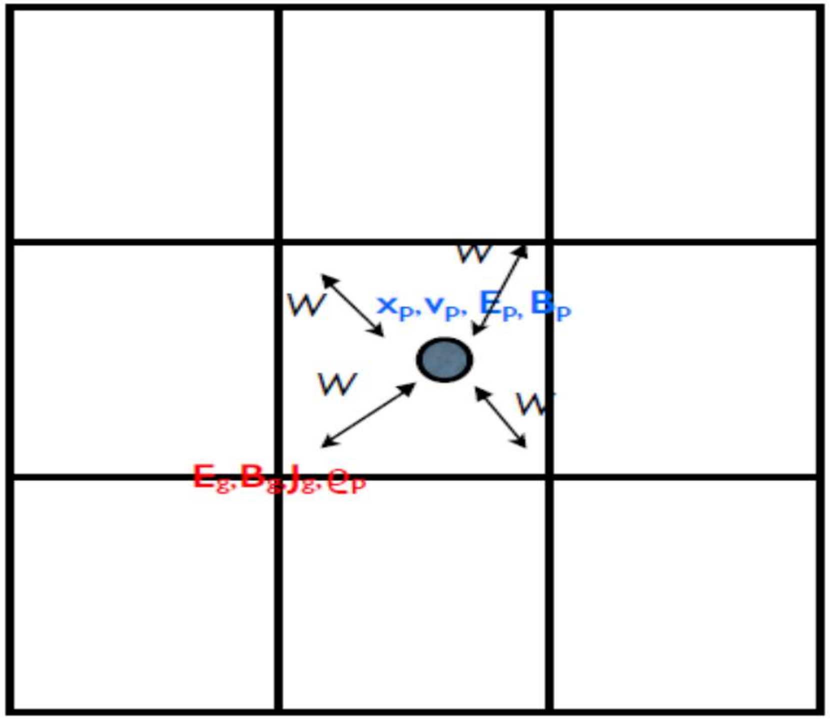
$$
\begin{cases}
\frac{d\mathbf{x}_p}{dt} = \mathbf{v}_p \\
\frac{d\mathbf{v}_p}{dt} = \frac{q_s}{m_s}\left(\mathbf{E}_p + \frac{\mathbf{v}_p \times \mathbf{B}_p}{c}\right)
\end{cases}
$$

grid

$$
\begin{cases}
\nabla \cdot \mathbf{E} = 4\pi\rho \\
\nabla \cdot \mathbf{B} = 0 \\
1/c\,\partial\mathbf{E}/\partial t = \nabla \times \mathbf{B} - 4\pi/c\mathbf{J} \\
1/c\,\partial\mathbf{B}/\partial t = -\nabla \times \mathbf{E},
\end{cases}
$$

Superparticles are used in the simulations. A superparticle with a definite shape is a computational particle that represents many real particles.

PIC algorithm

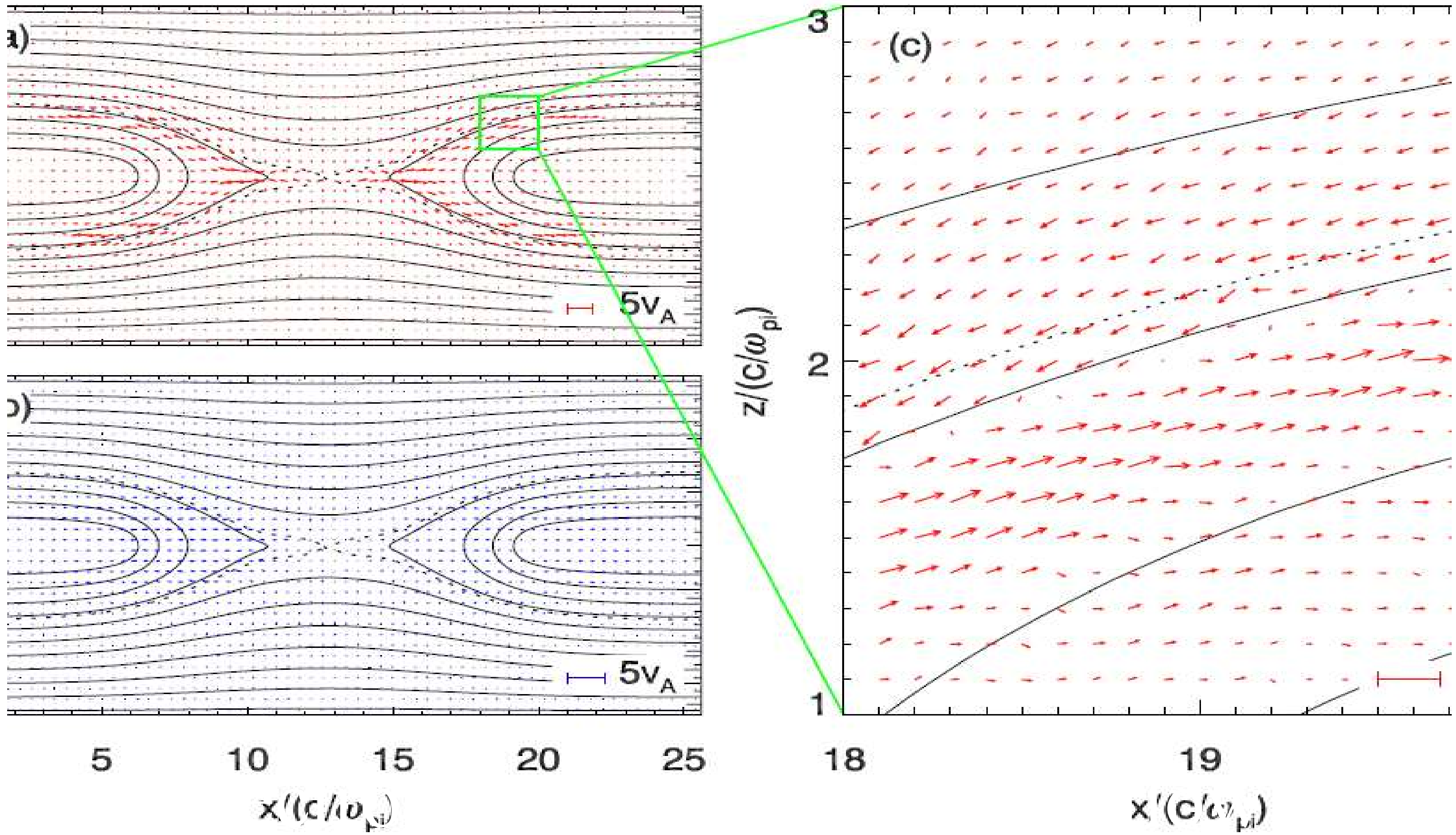


A reduced ion to electron mass ratio and light speed are used to save computational source.

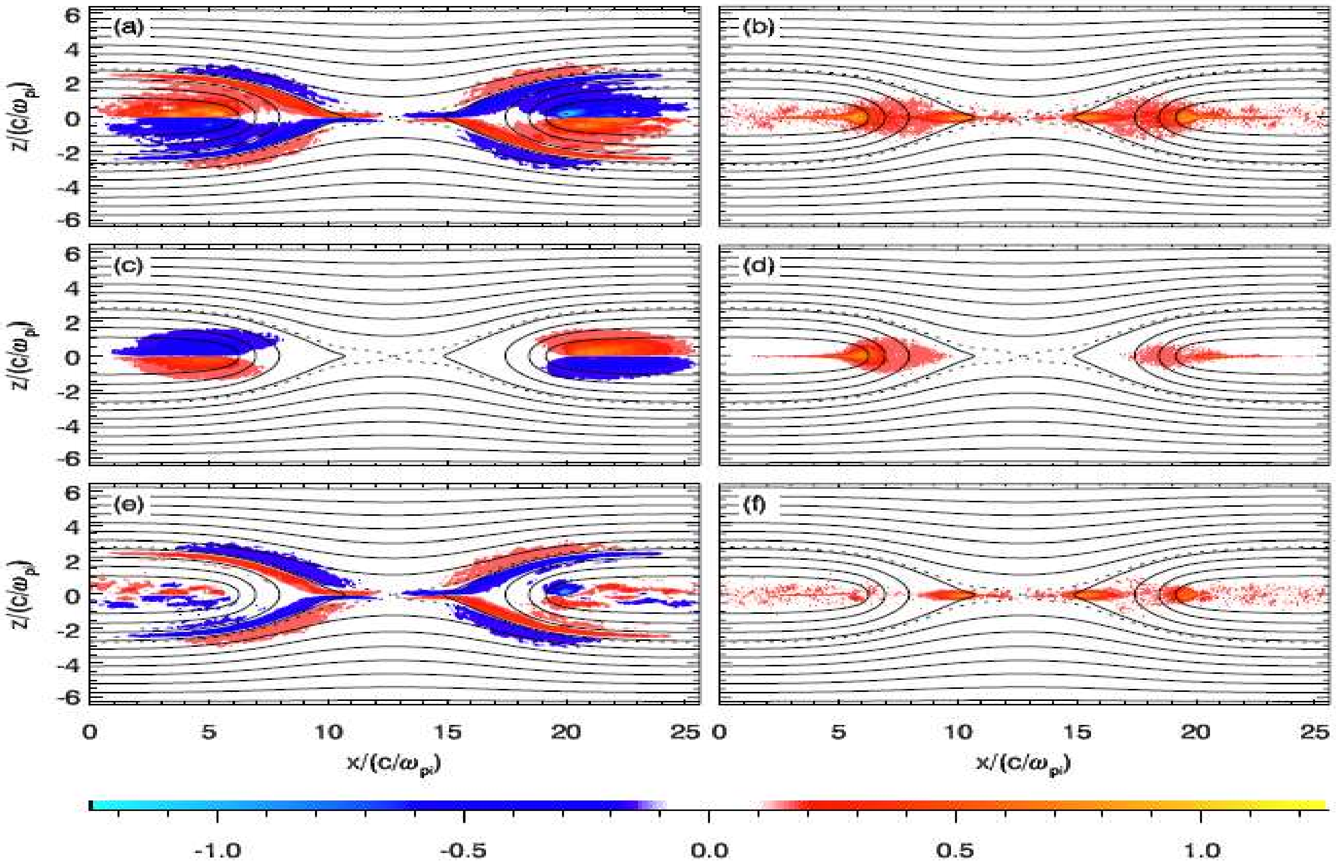
Coupling between particles and grids

$$\mathbf{E}_p = \sum_g \mathbf{E}_g W(\mathbf{x}-\mathbf{x}_p), \mathbf{B}_p = \sum_g \mathbf{B}_g W(\mathbf{x}-\mathbf{x}_p)$$

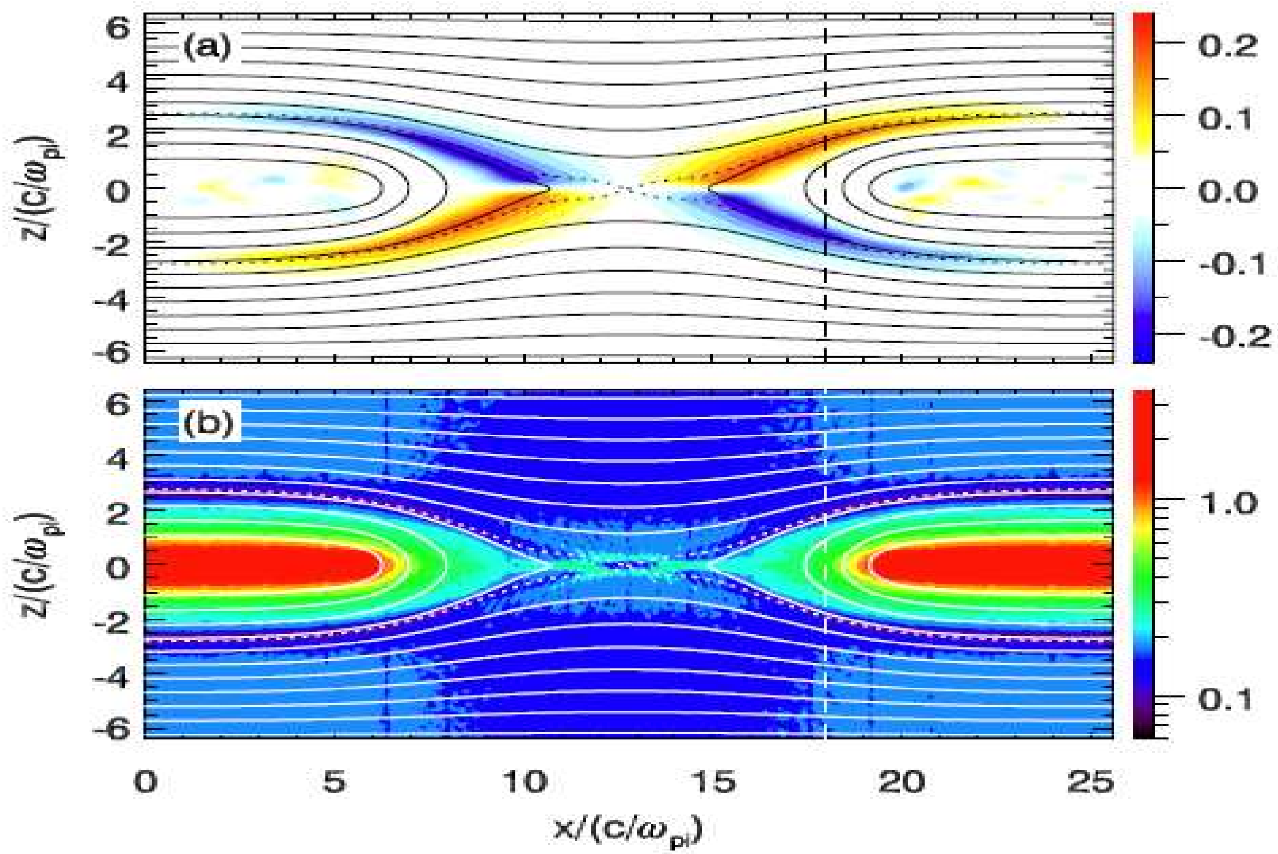
$$\{\rho, \ \mathbf{J}\}_g = \sum_s^{n_s} \sum_p^{N_s} q_s \{1, \mathbf{v}_p\} W(\mathbf{x}-\mathbf{x}_p)$$



(a) Electron flow vector, (b) Ion flow vector, based on PIC simulations [Lu et al., JGR, 2010].



(a) Electron parallel current, (b) Electron perpendicular current, (c) Ion parallel current, (d) ion perpendicular current, (e) total parallel current, (f) total perpendicular current.



Quadrupole structures of the out-of-plane magnetic field, and electron density depletion along the separatrices.

Guide Field Reconnection

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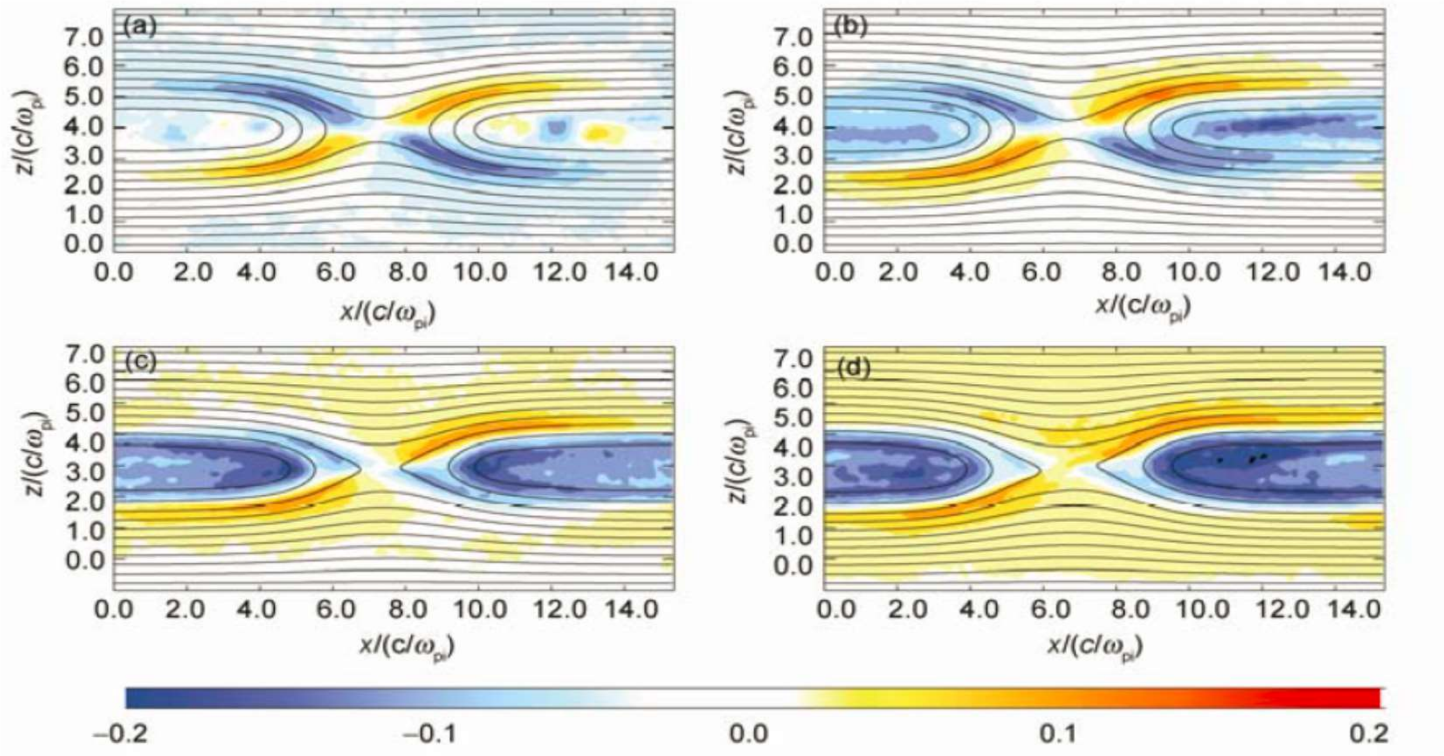

Distorted quadrupole structures of the out-of-plane magnetic field in guide field reconnection $\delta B_y / B_0$, at $B_{y0} / B_0 =$ (a)0, (b)0.2, (c)0.6, and (d)1.0. [Lu et al., CPL, 2011]

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Electromagnetic structure in anti-parallel reconnection

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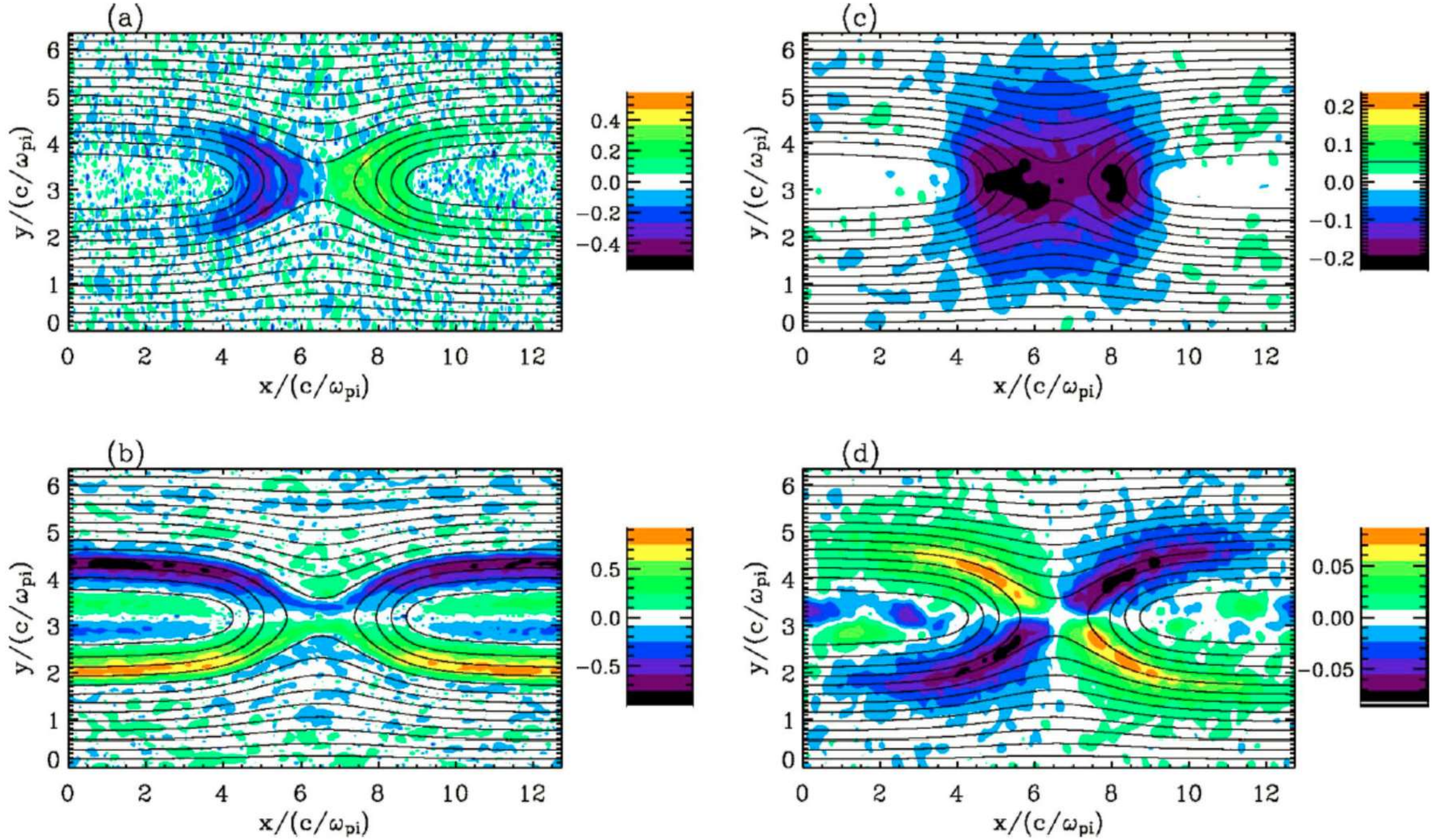
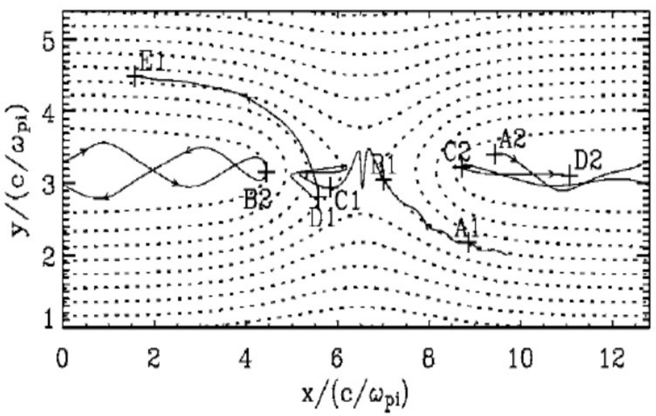
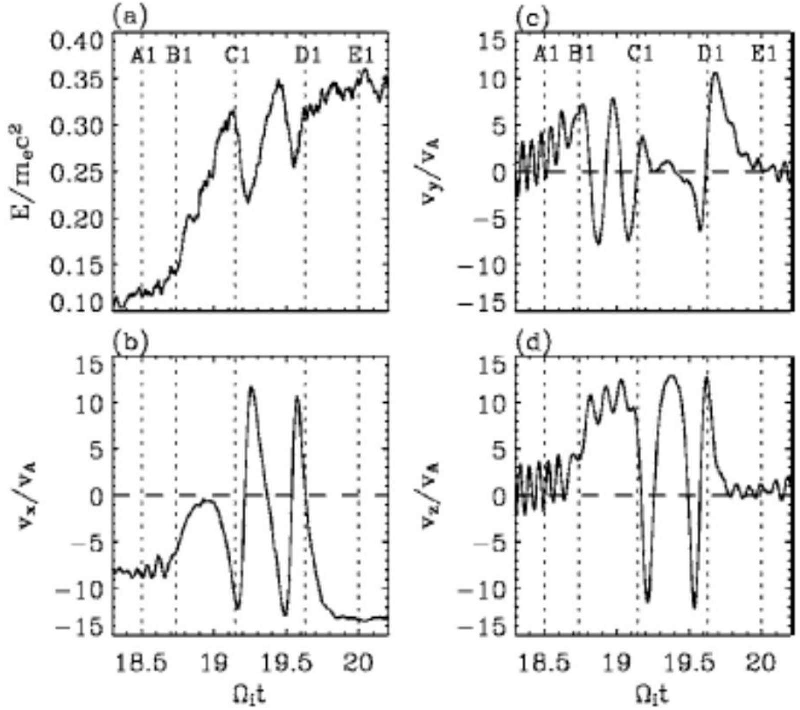


Electric and magnetic fields in anti-parallel reconnection

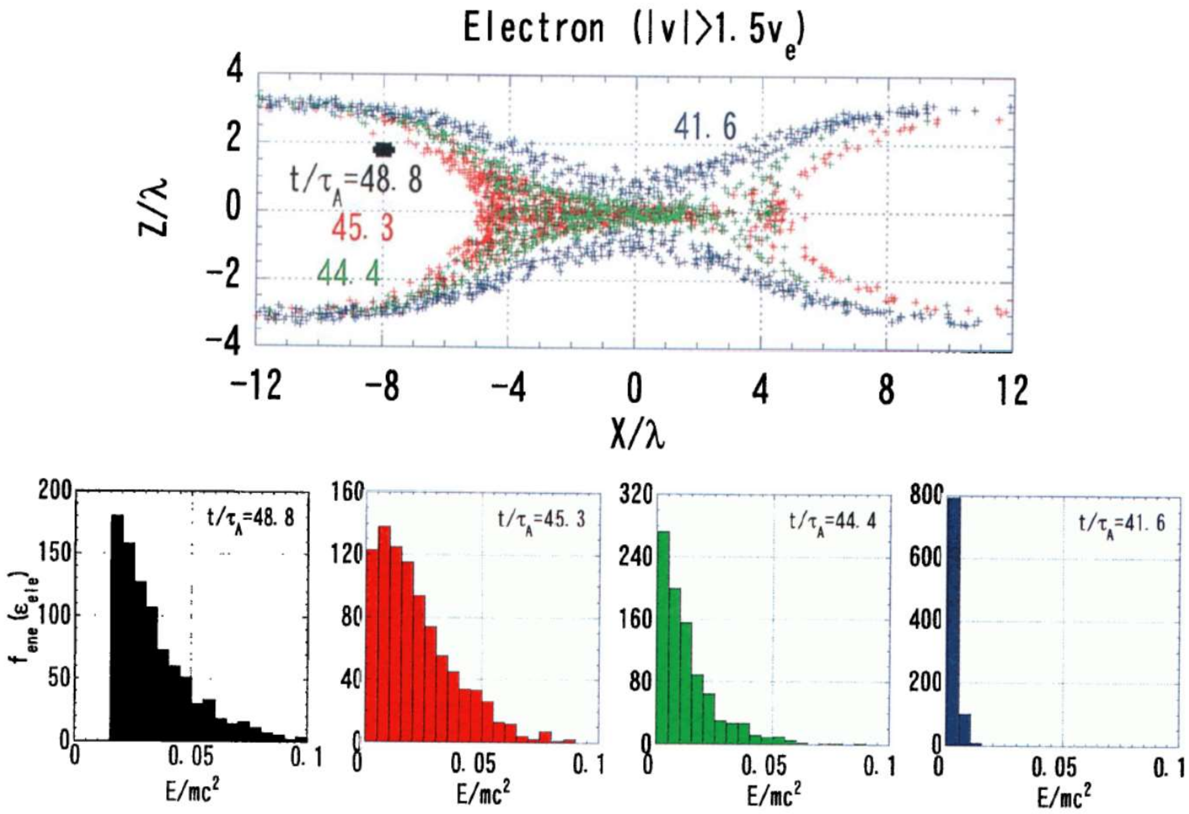
Electron acceleration near the X line

Typical electron trajectory passing through the vicinity of the[Fu et al., PoP, 2006]





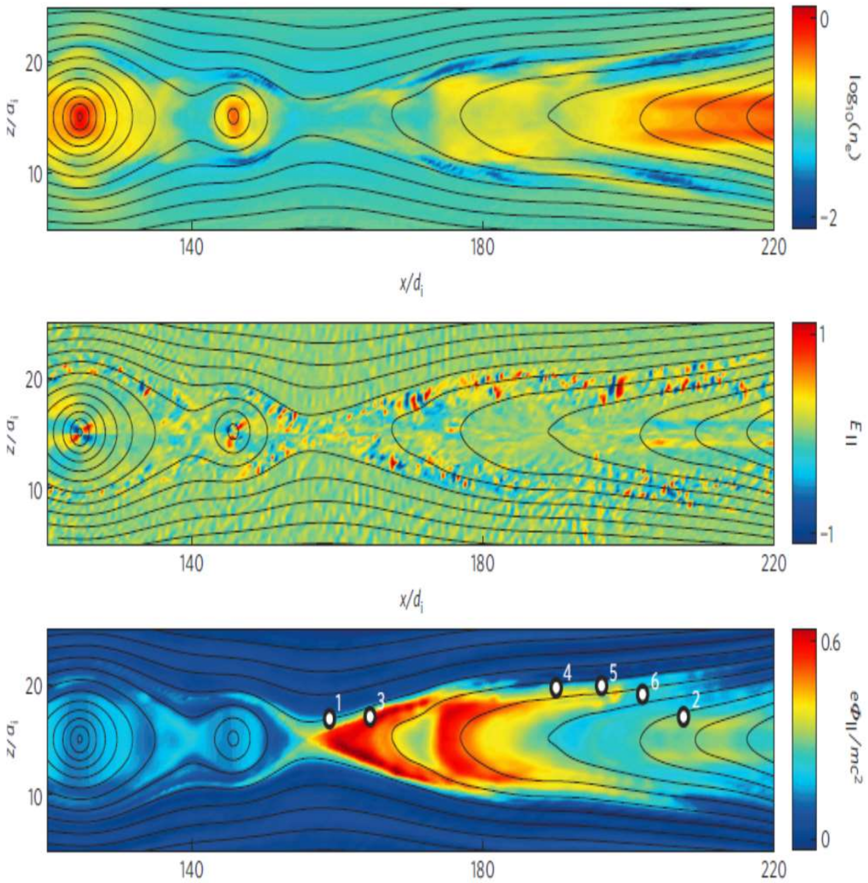
Electron acceleration in the pileup region

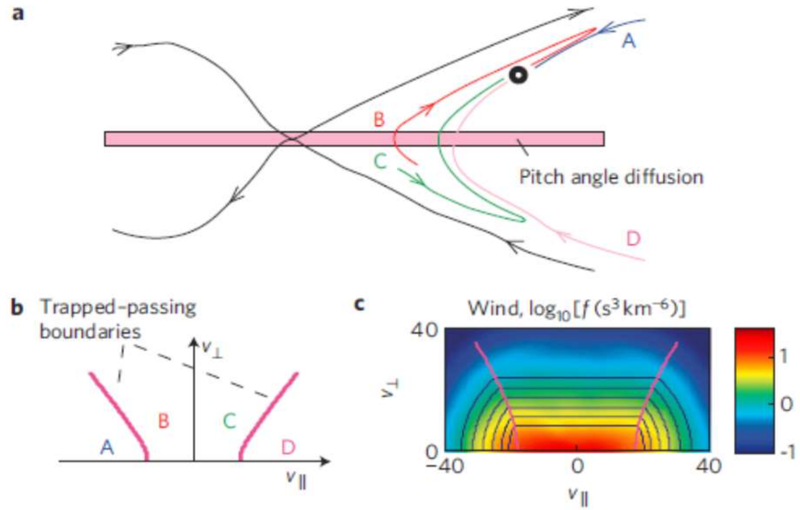


Superthermal electrons can be further accelerated in the pileup region [Hoshino et al., JGR, 2001].

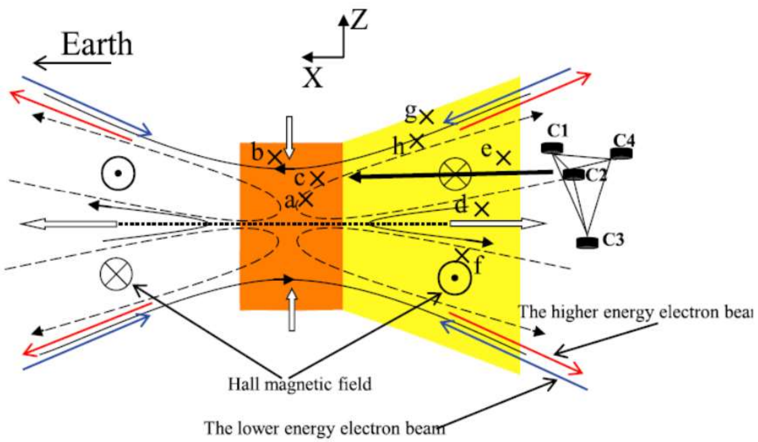
Electron acceleration in the separatrix region

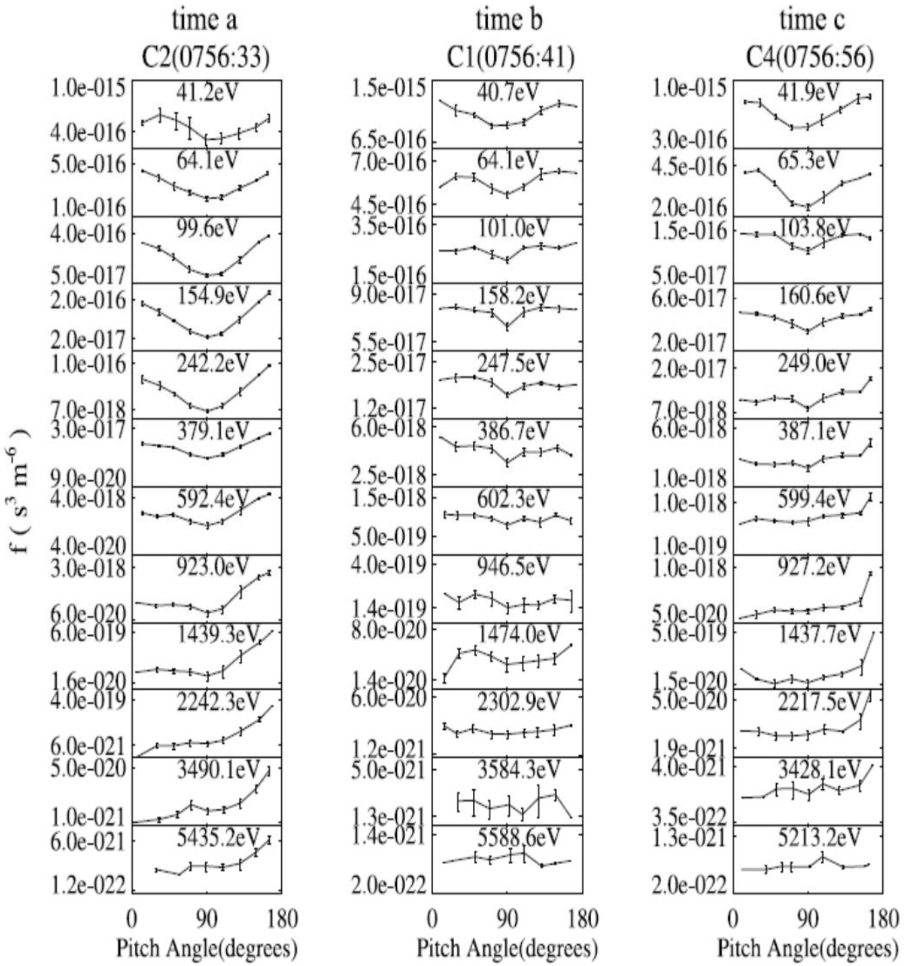
In a large-scale PIC simulation with a low beta, electron are found to be trapped by the parallel electric field around the separatrix region, and then get accelerated [Egedal et al., Nature Physics, 2012].





Observations of electron field-aligned bidirection distribution in separatrix region

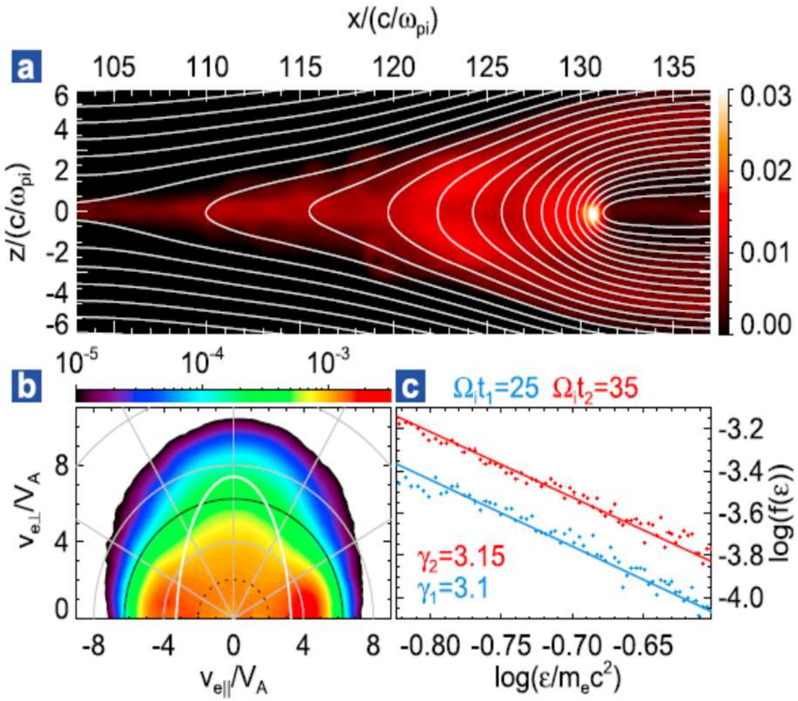


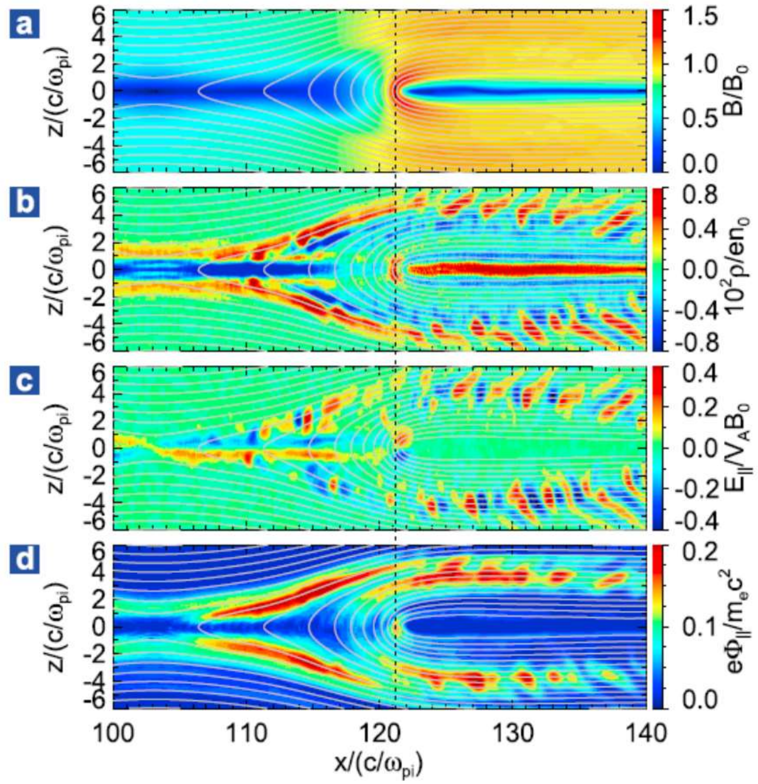


Observations of electron field-aligned bidirection distribution may be caused due to the parallel electric field or mirror force.

Electron acceleration in the depolarization front

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





Observation of multiple stage electron acceleration

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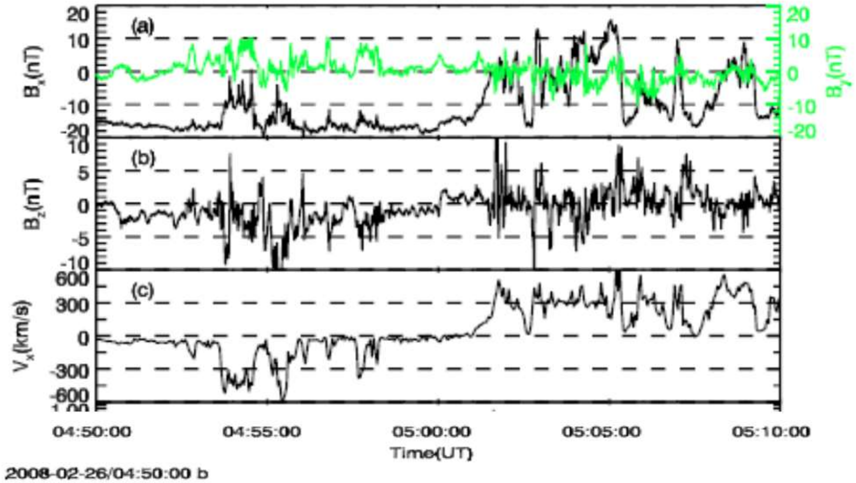
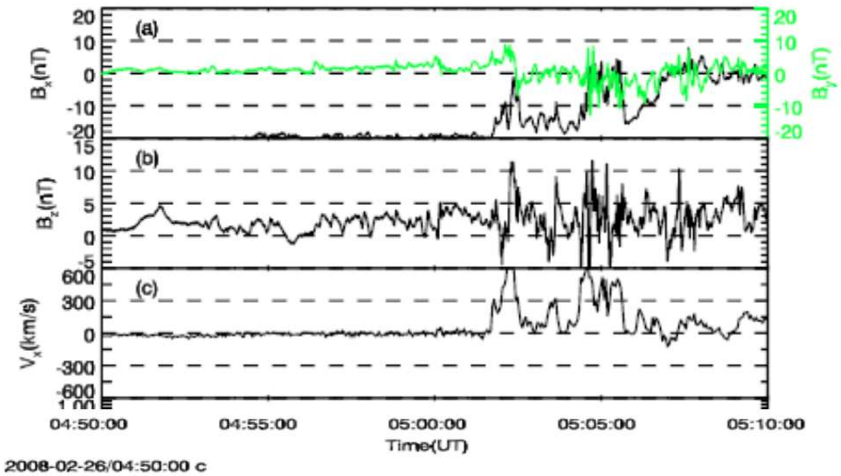
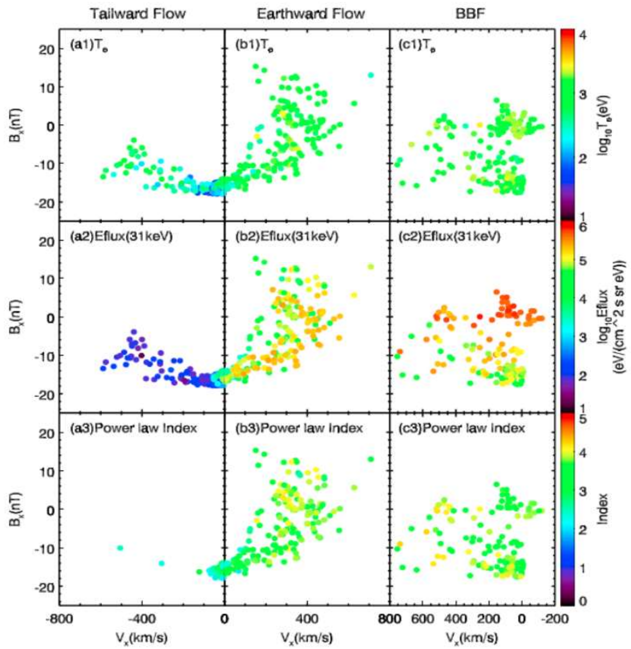
THB



THC





By analyzing a reconnection event and associated the depolarization front with THEMIS satellite, electron acceleration have three stages: the vicinity of the X line, the pileup region and depolarization front [Wu et al., JGR, 2015].

Parallel electric field/Double Layers detected near the separatrices

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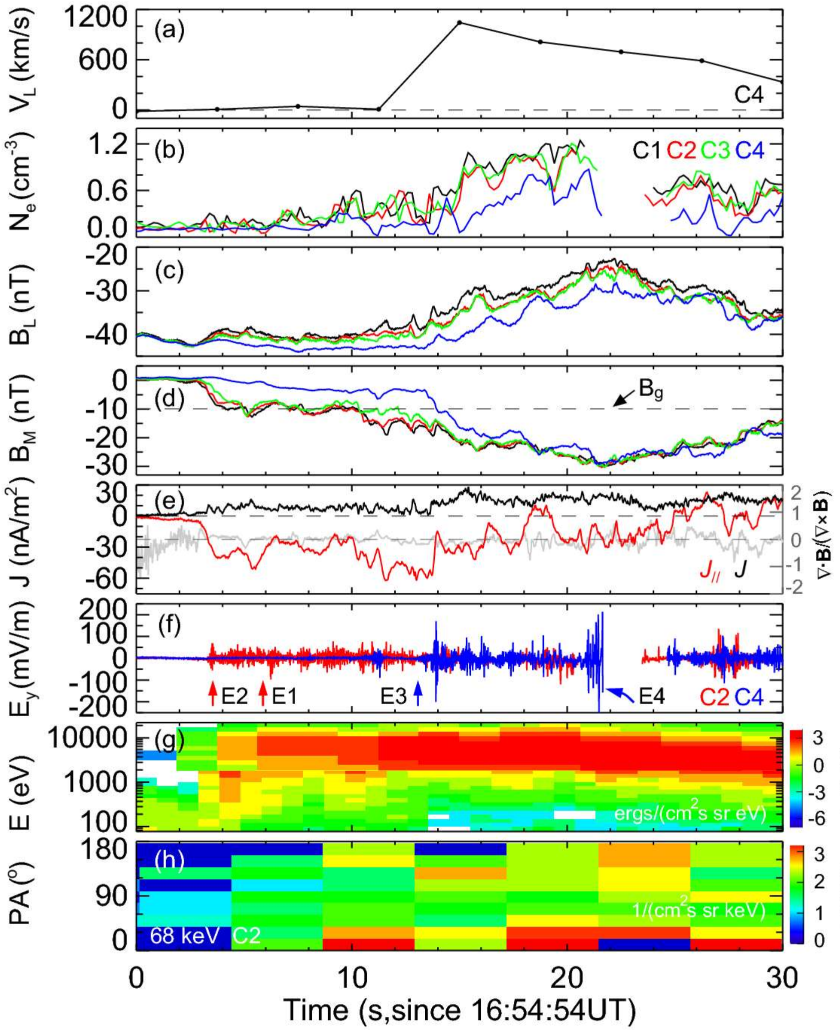
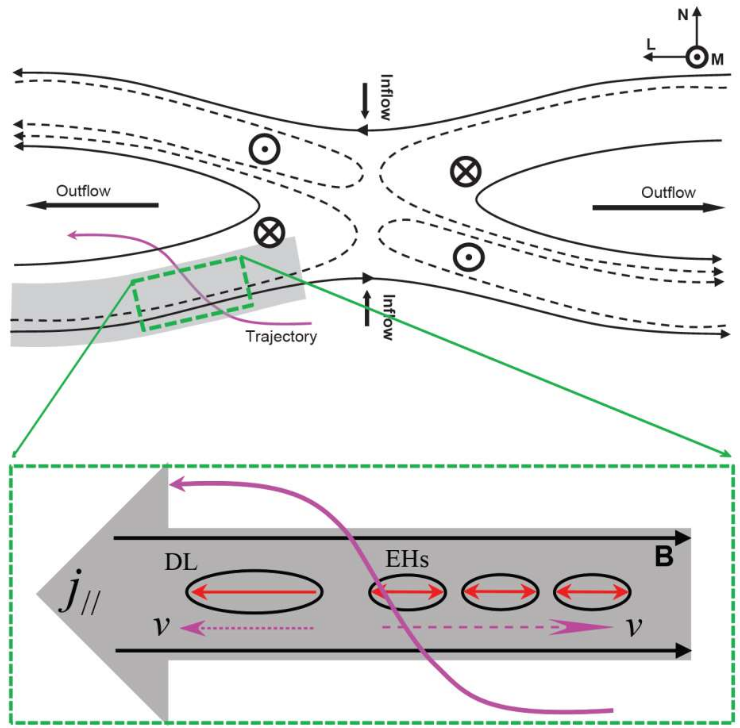
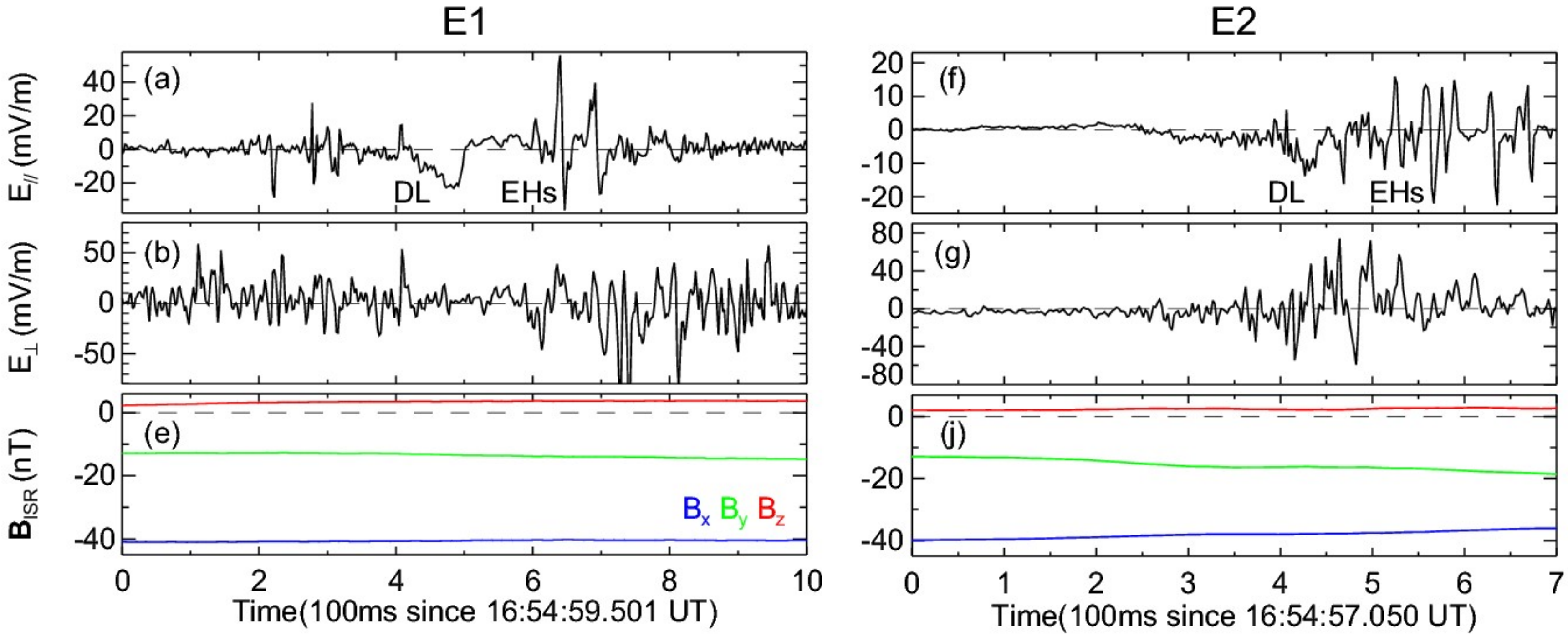


A short period of 15 sec when angles between the spacecraft spin plane and the magnetic field < 5^o, and $E_{//}$ can be estimated. Three **Double Layer**s (E1-E3) are identified in the second crossing of the separatrix.

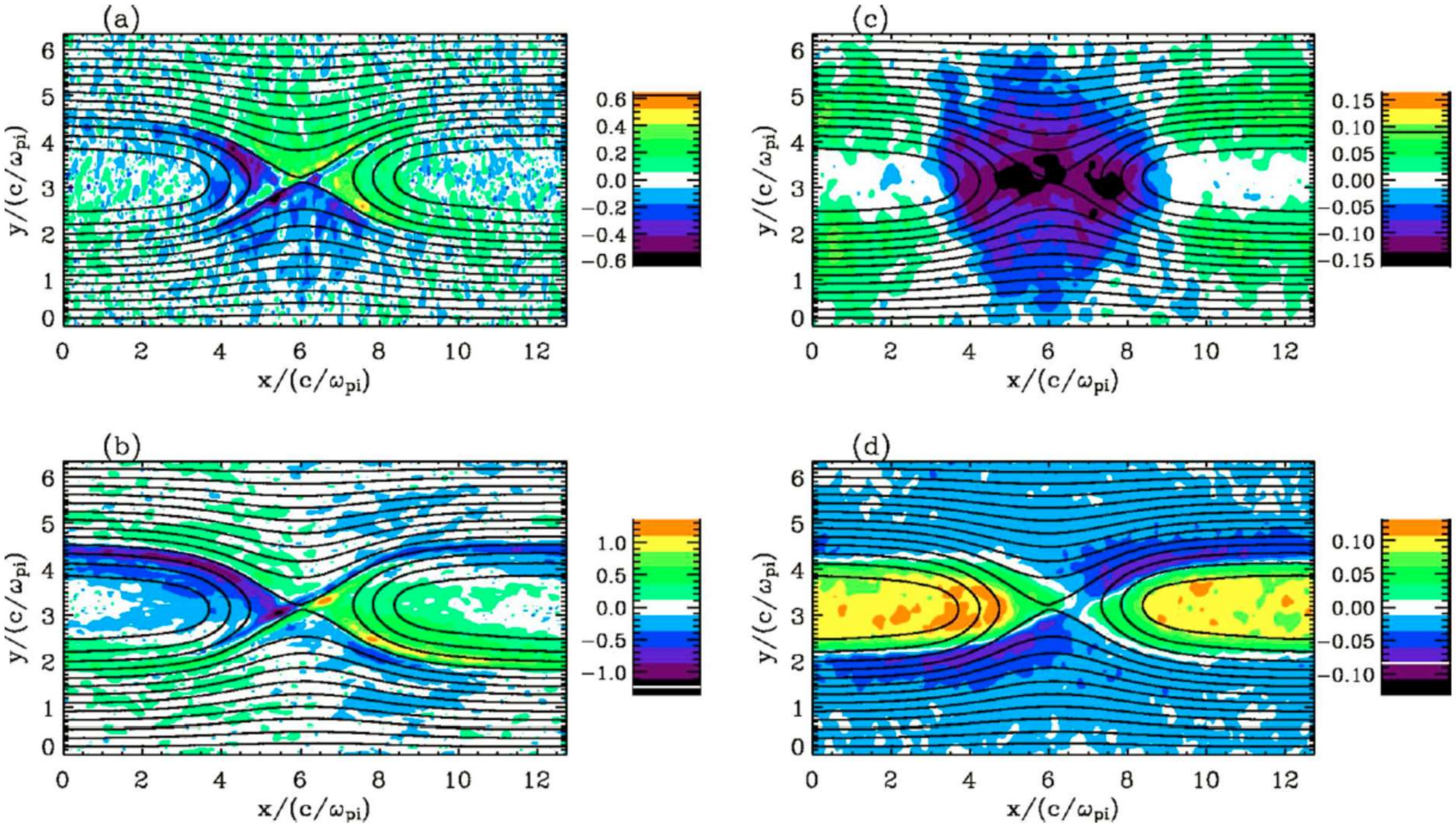


Parallel electric field/Double Layers detected near the separatrices



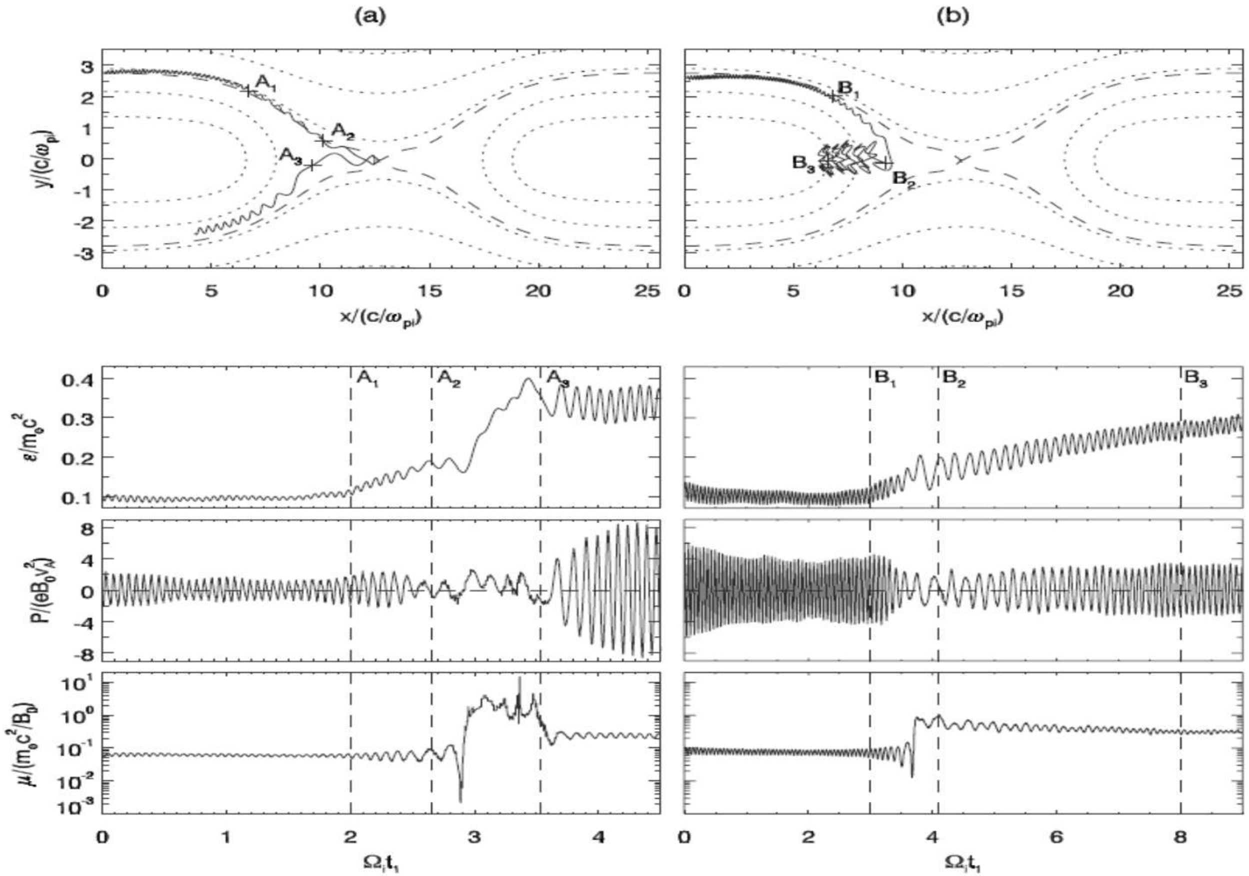
A unipolar $E_{//}$ (double layer) followed by a series of bipolar $E_{//}$ (electron hole).
The DLs are moving away from the X line [Wang et al., GRL, 2014].

Electromagnetic structure in guide field reconnection



Electric and magnetic fields in guide field reconnection

Electrons are accelerated by the parallel electric field around the X line and the pileup region, here the guide is B_0 [Fu et al., PoP, 2006].



Summary

- Electrons can be accelerated by the reconnection electric field in the vicinity of the X line, the pileup region, and the depolarization front.

- Electrons can be efficiently accelerated due to the trapping by the parallel electric field in the separatrix region.

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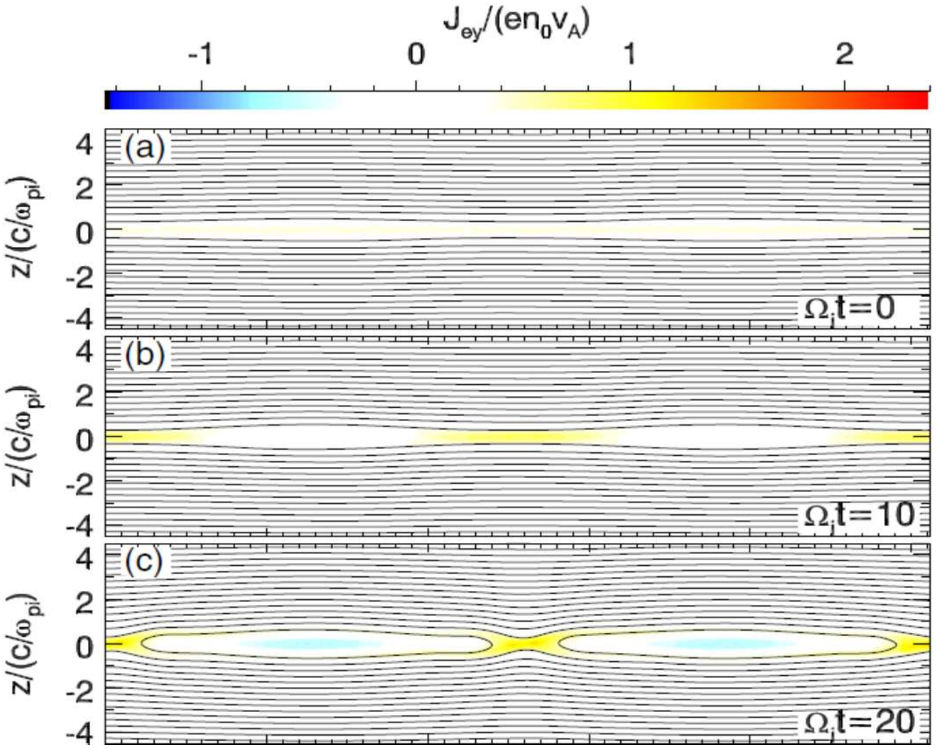
Multiple X line reconnection

Magnetic islands can be usually generated in the topologic changes of the magnetic field lines, which is associated with magnetic reconnection.

The generation of magnetic island in multiple X line reconnection.



Secondary magnetic islands in extended electron diffusion region

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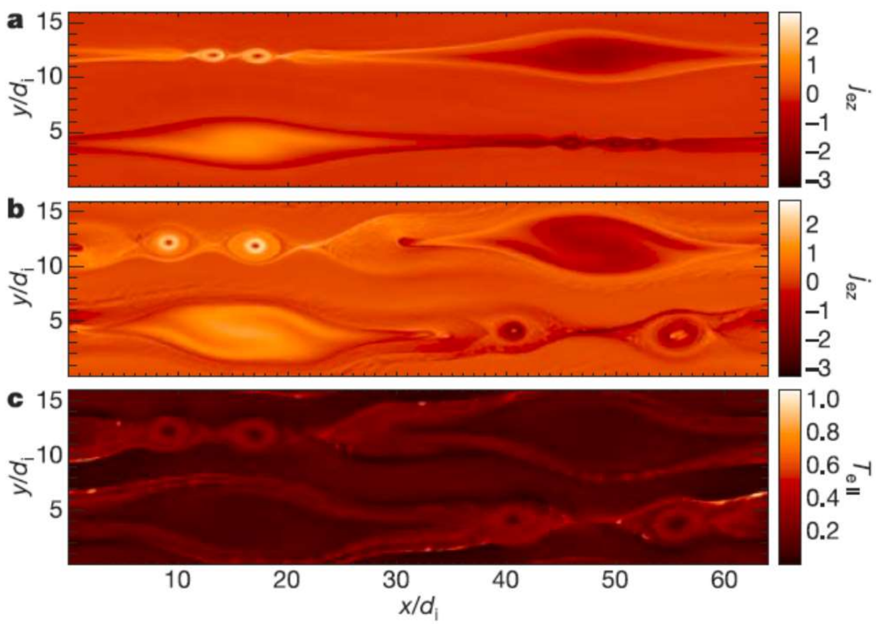
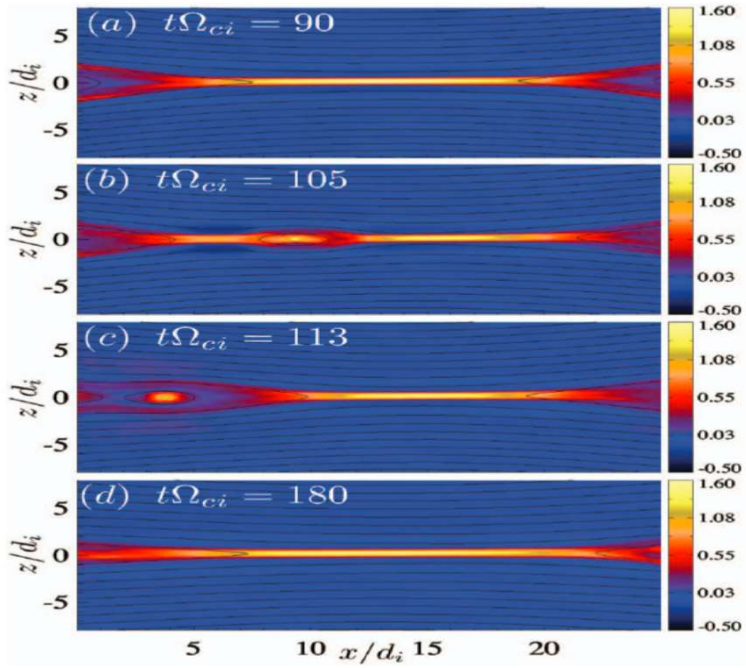
- Generation of secondary island in extended electron diffusion region, and it can enhance reconnection rate.

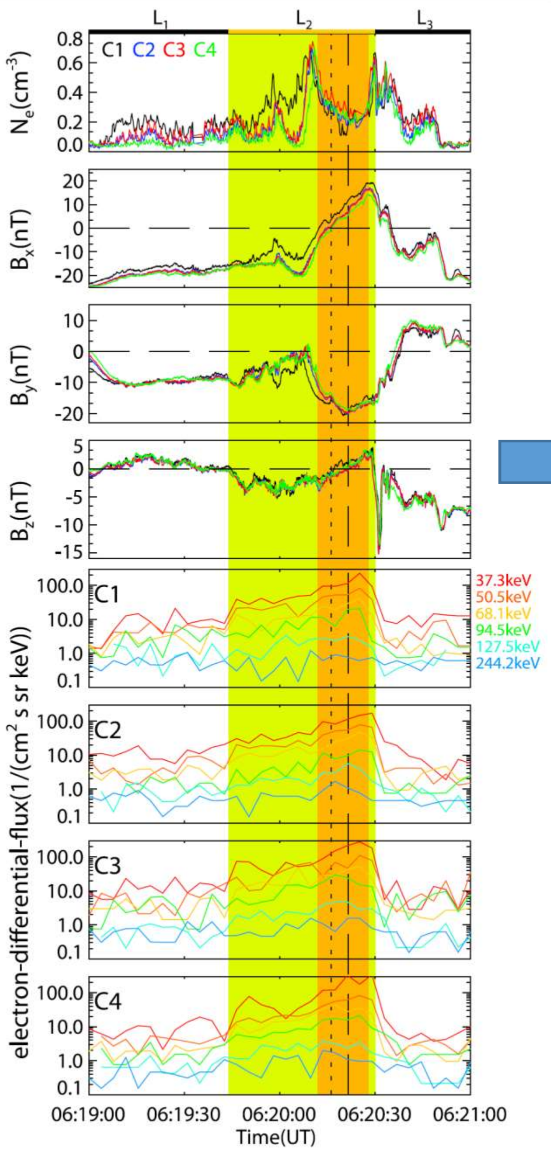


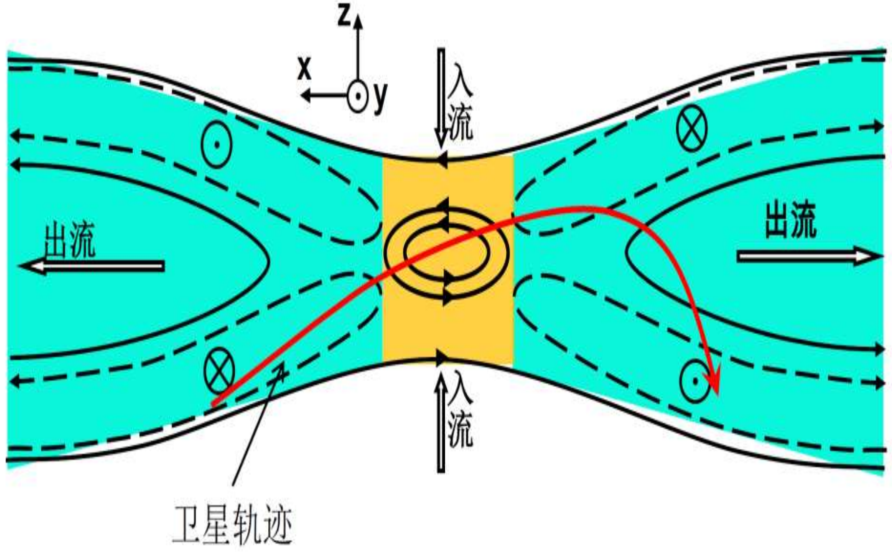


Drake et al., GRL, 2006

Daughton et al., PoP, 2006

Observation of secondary island

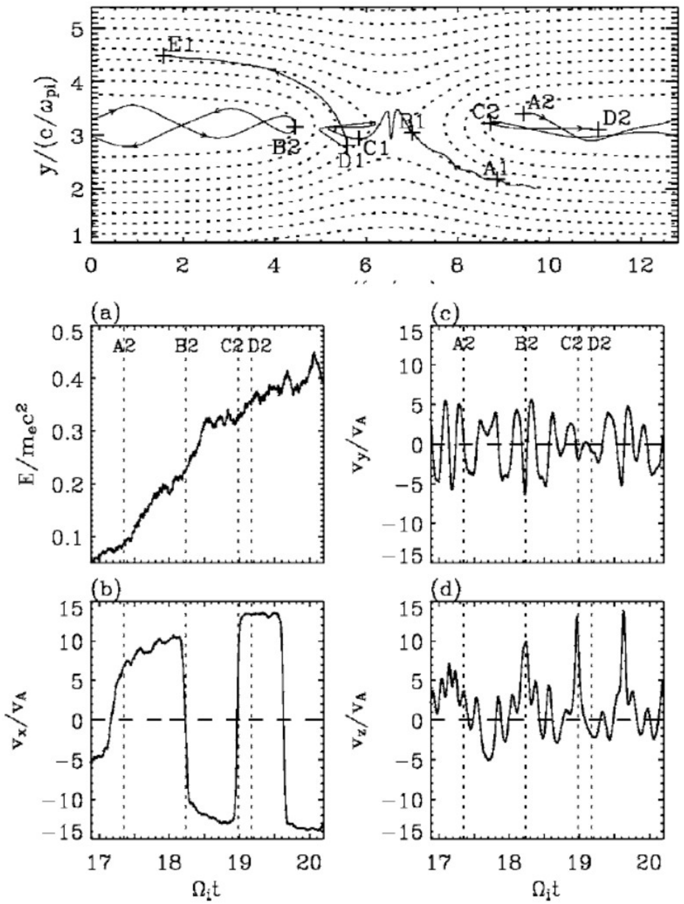




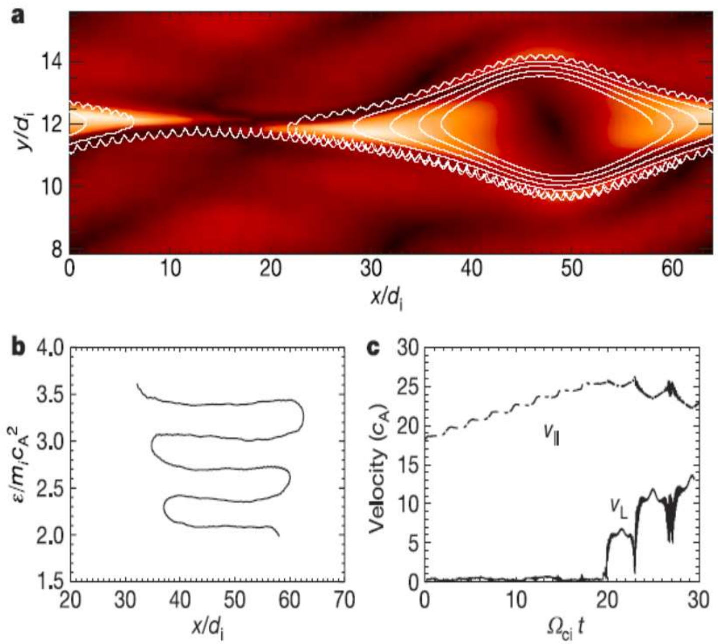
Wang et al., PRL，2010

The length of the secondary island is about $3d_i$.

Electrons are accelerated when reflected at the two ends of a magnetic island.

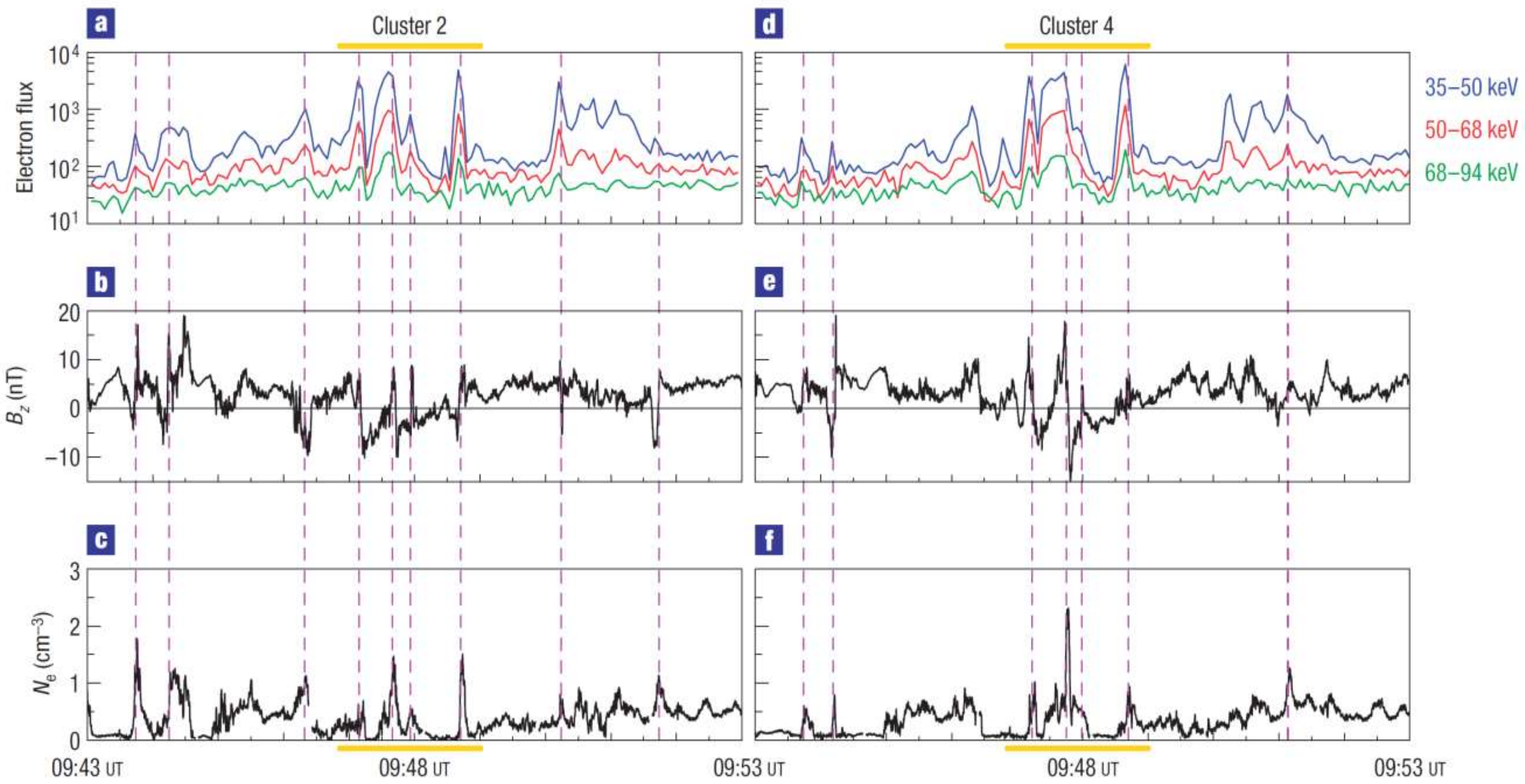


Fu et al., PoP, 2006



Drake et al., Nature, 2006

Observation of energetic electrons in islands



Chen et al., Nature Phys., 2008

Electron acceleration during island coalescence

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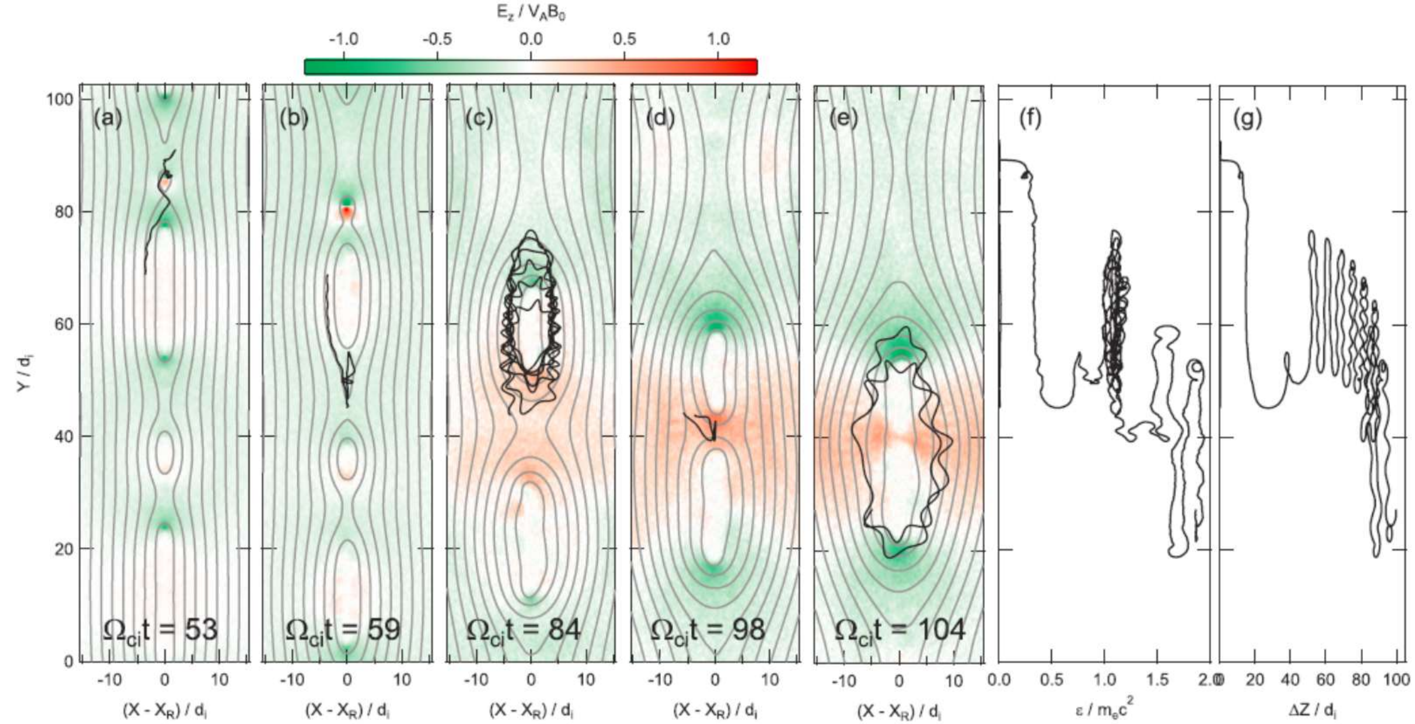
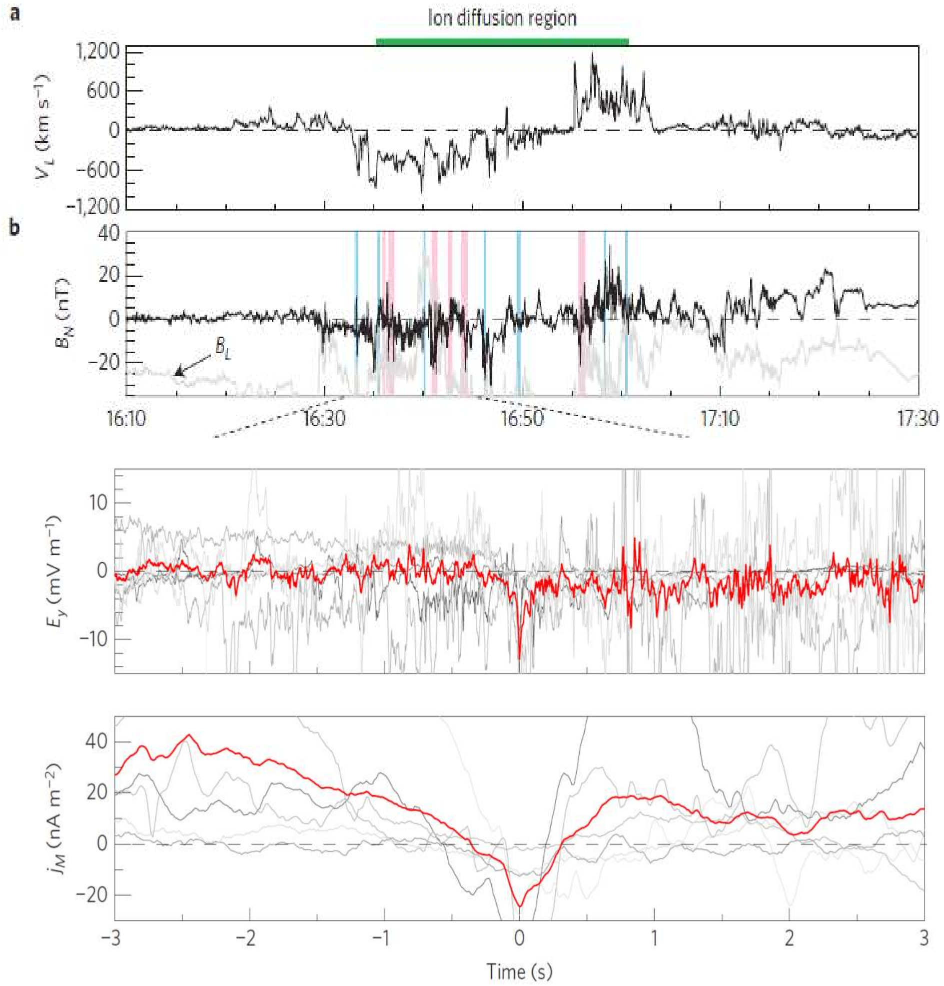
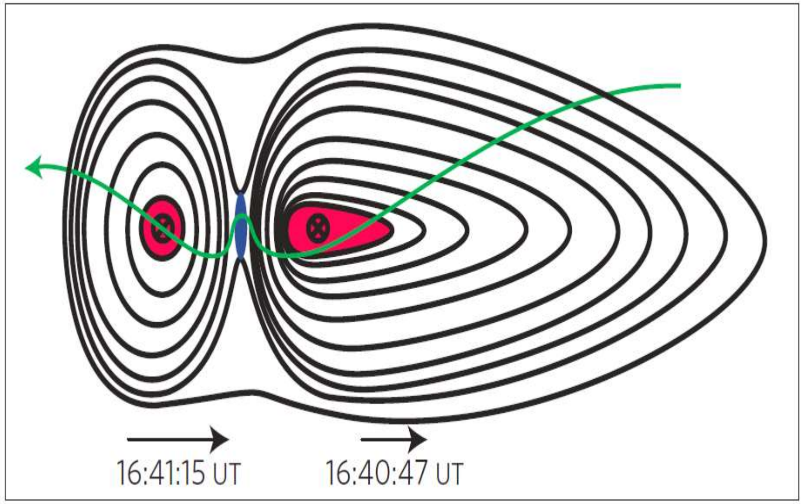
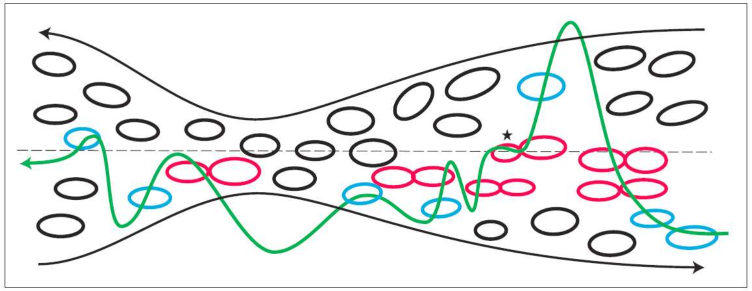


Electrons are accelerated during the coalescence of magnetic islands[Oka et al., ApJ, 2010].

Observation of coalescence of magnetic islands







Wang et al., Nature Phys., 2016

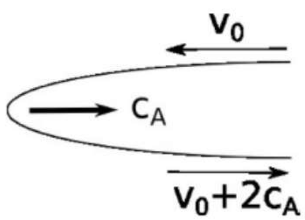
Basic mechanism for partiucle gain during magnetic reconnection

- In the guiding center limit

$$\frac{d\varepsilon}{dt} = qv_{\parallel}E_{\parallel} + q\vec{v}_c \bullet \vec{E} + \mu\frac{\partial B}{\partial t} + q\vec{v}_B \bullet \vec{E}$$

- Curvature drift (Fermi reflection): increase the parallel energy

$$v_c = \frac{v_{\parallel}^2}{\Omega}\vec{b}\times(\vec{b}\bullet\vec{\nabla}\vec{b})$$



- Grad B drift-Betatron acceleration increase perpendicular energy- μ conservation

$$v_B = \frac{v_{\perp}^2}{2\Omega}\vec{b}\times\frac{\vec{\nabla}B}{B}$$

$$\mu = \frac{mv_{\perp}^2}{2B}$$

Dahlin et al., PoP, 2014

Electron acceleration mechanisms during island coalescence

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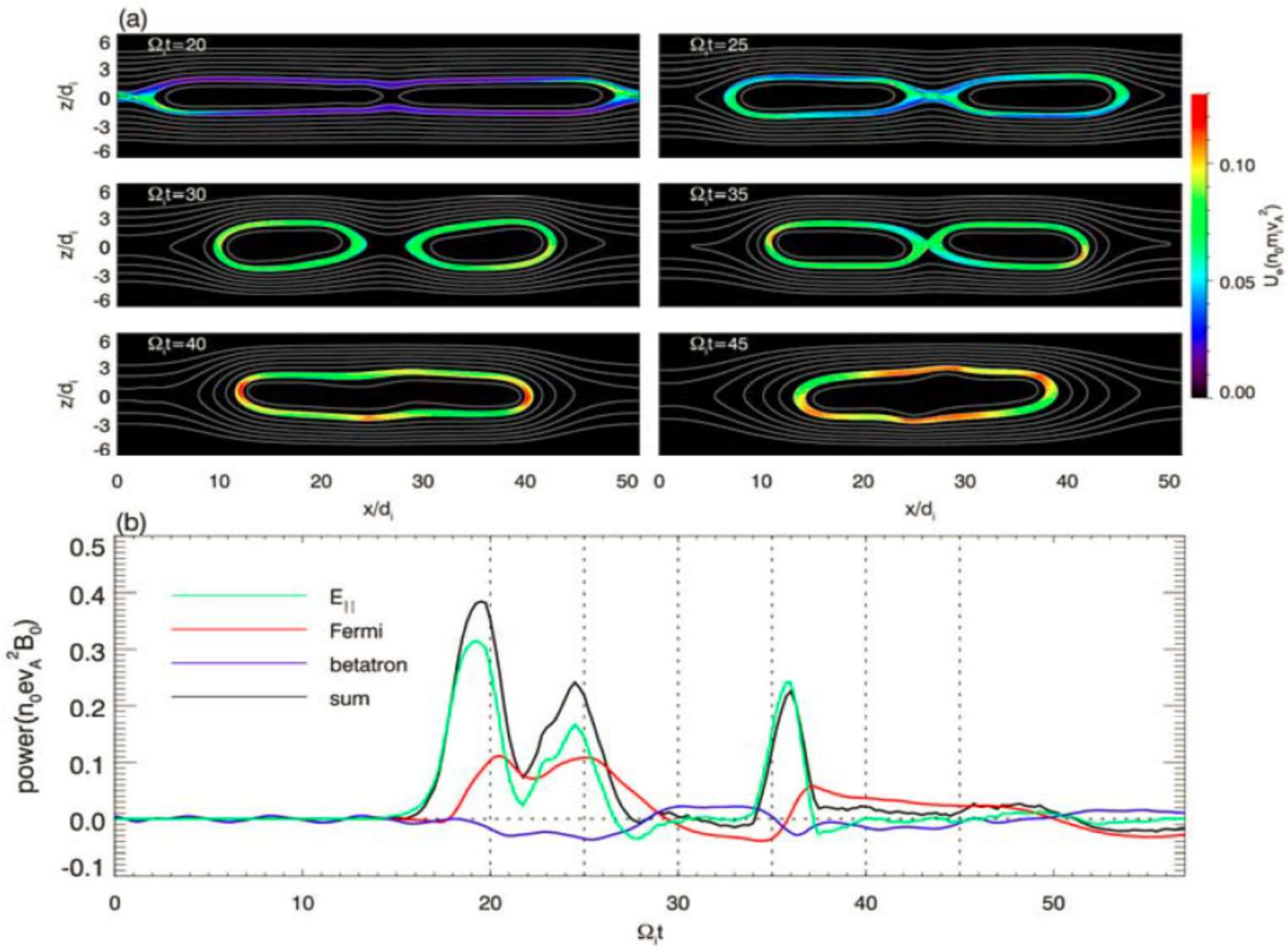
- Coalesence of magnetic islands can also lead to the production of energetic electrons.



The electron acceleration by parallel electric field, Fermi and betatron mechanisms in magnetic reconnection with a guide field.

[Wang et al., ApJ, 2016]

Distributions of electron acceleration mechanisms during island coalescence

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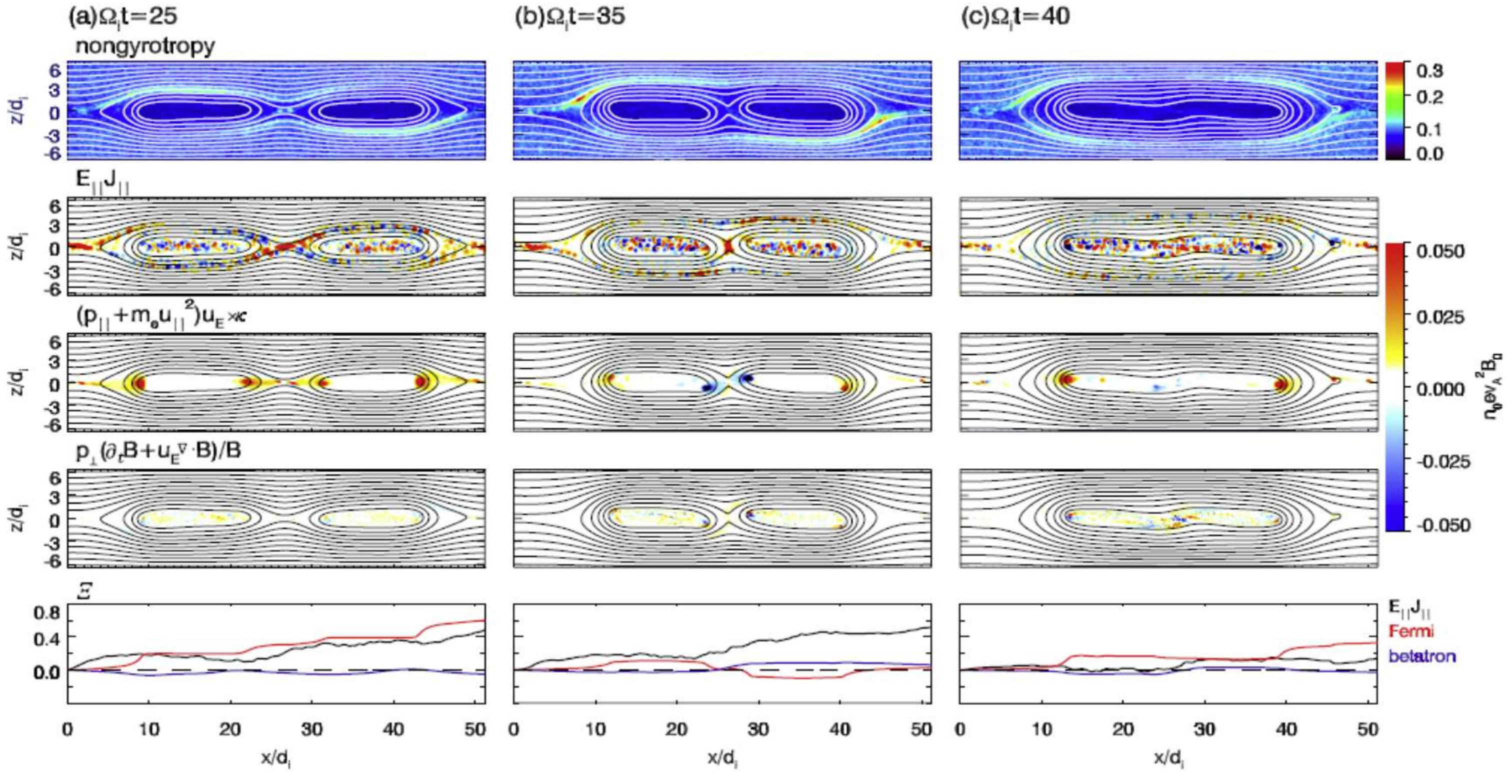
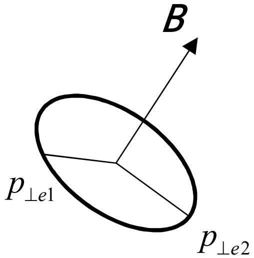


Nongyrotropy

$$D_{ng} = \frac{2\sqrt{\sum_{i,j} N_{ij}^2}}{Tr(\mathbf{P}_e)}$$

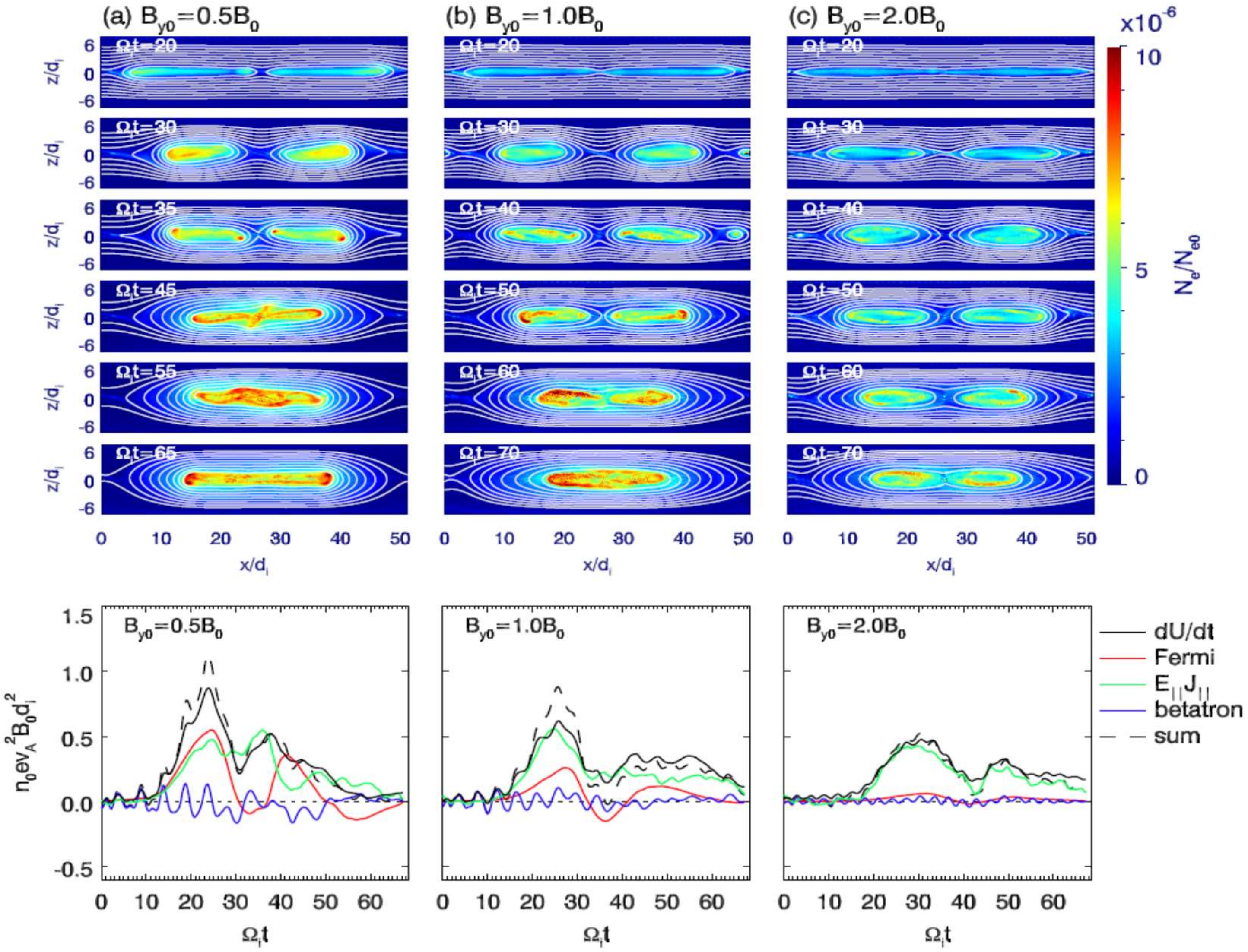


(Aunai et al., 2013)

$$\Xi(x) = \int_0^x dx' \int P(x', z, t)\, dz$$

（Dahlin et al, 2014）

The dependence of electron acceleration mechanisms on the guide field



The number of electrons with energy $\varepsilon_e > 0.1 m_e c^2$

Electron acceleration in multi-island reconnection

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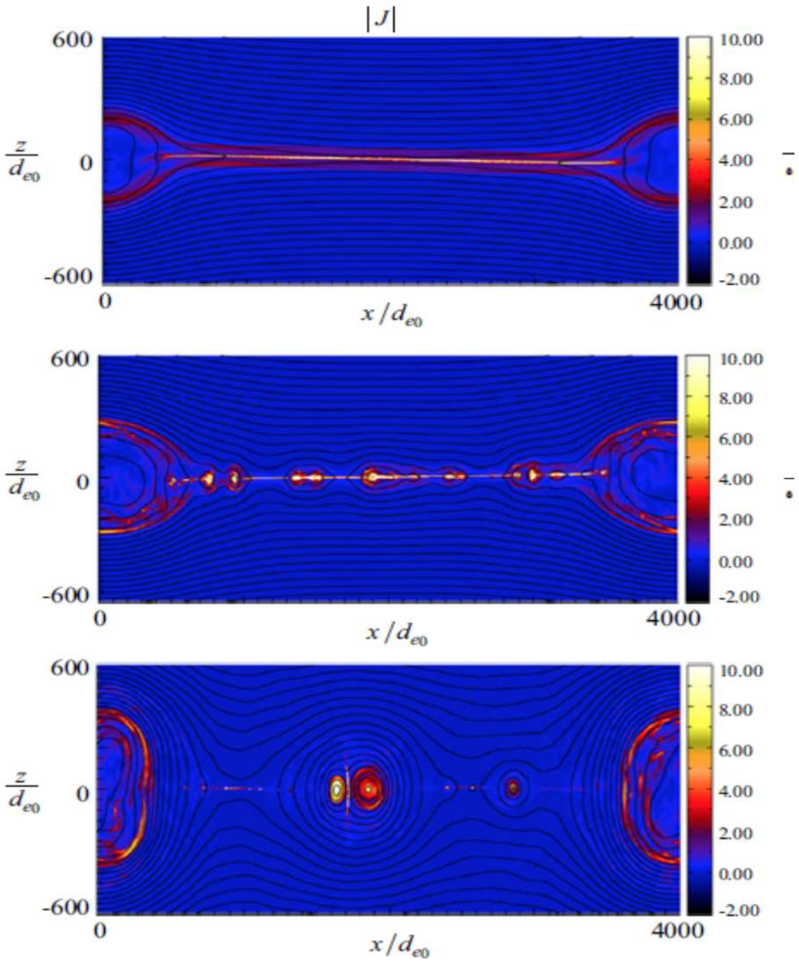
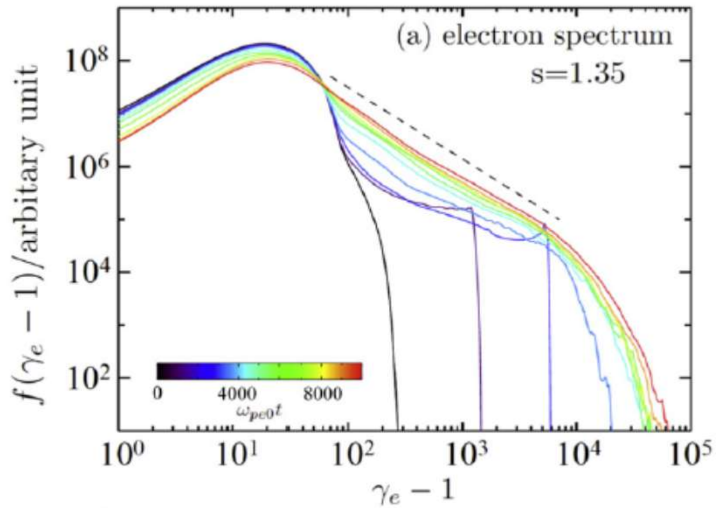
Electron trapped in contracting and merging magnetic islands undergo multiple acceleration by the parallel electric field and Fermi mechanism.



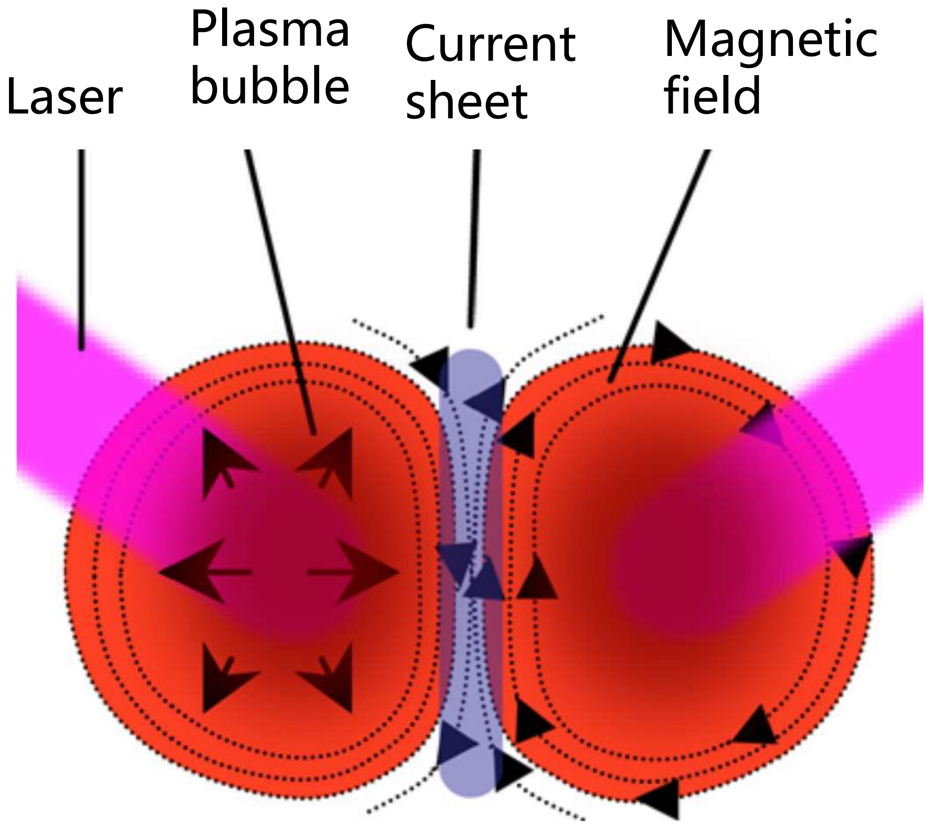


Guo et al., ApJ, 2016

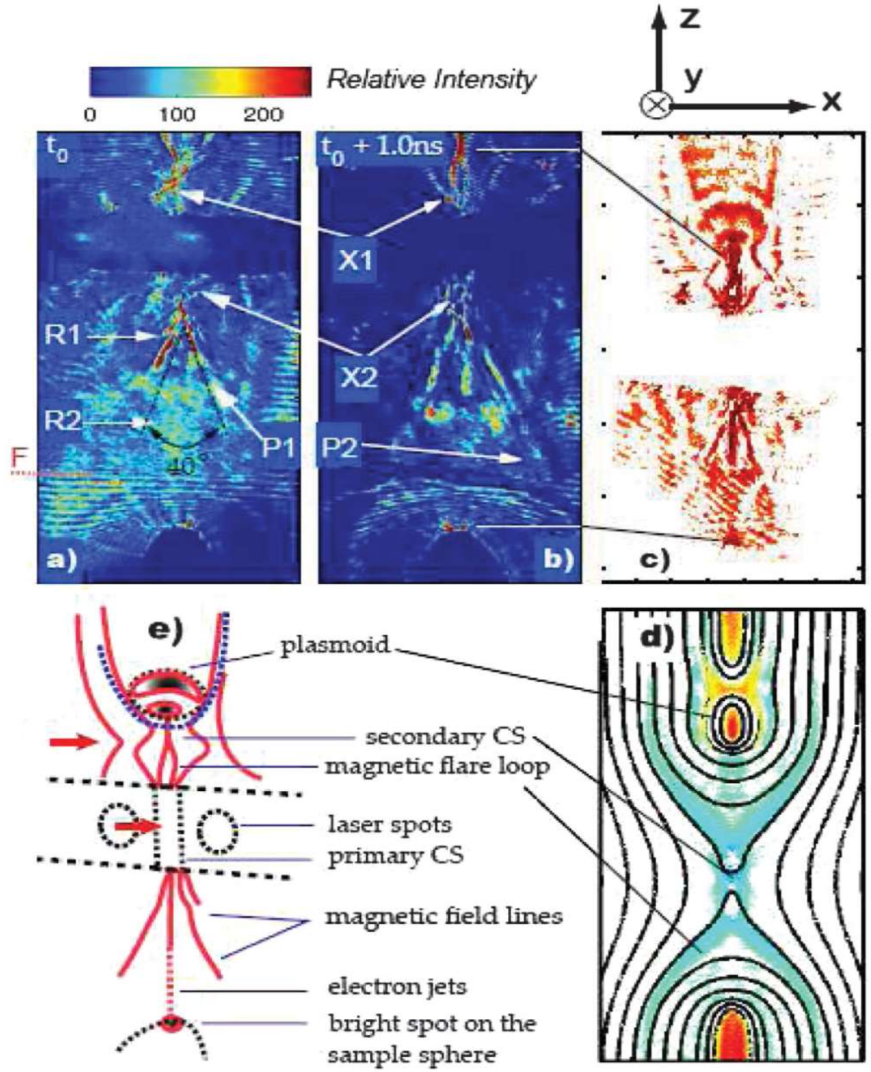
Outlook

- Introduction to magnetic reconnection
- Particle-in-cell simulation and collisionless magnetic reconnection
- Electron acceleration near the X line
- The role of magnetic island in electron acceleration
- Electron acceleration in laser plasma reconnection
- Summary

Laser plasma magnetic reconnection -Flow driven reconnection

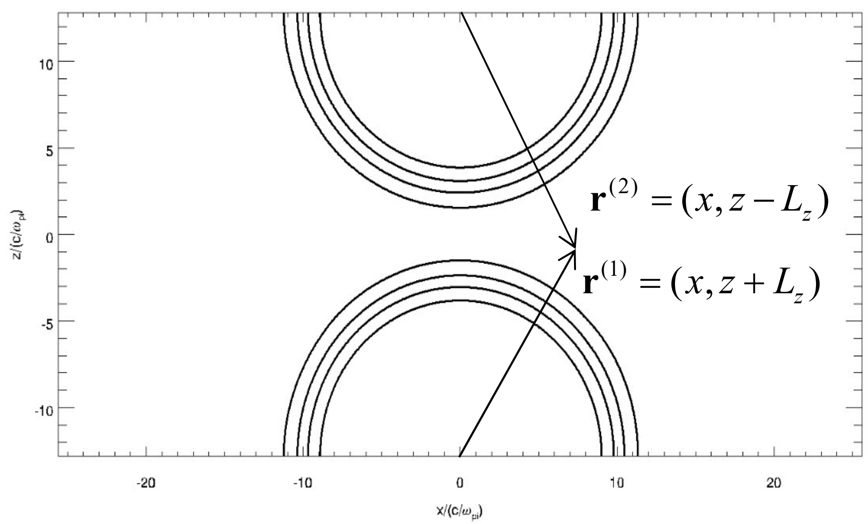


Laser-driven reconnection experiments:
Nilson et al., PRL, 2006; Li et al., PRL,2007; Zhong et al., PRL, 2010



[Dong et al., 2012]

PIC Simulation model and parameters



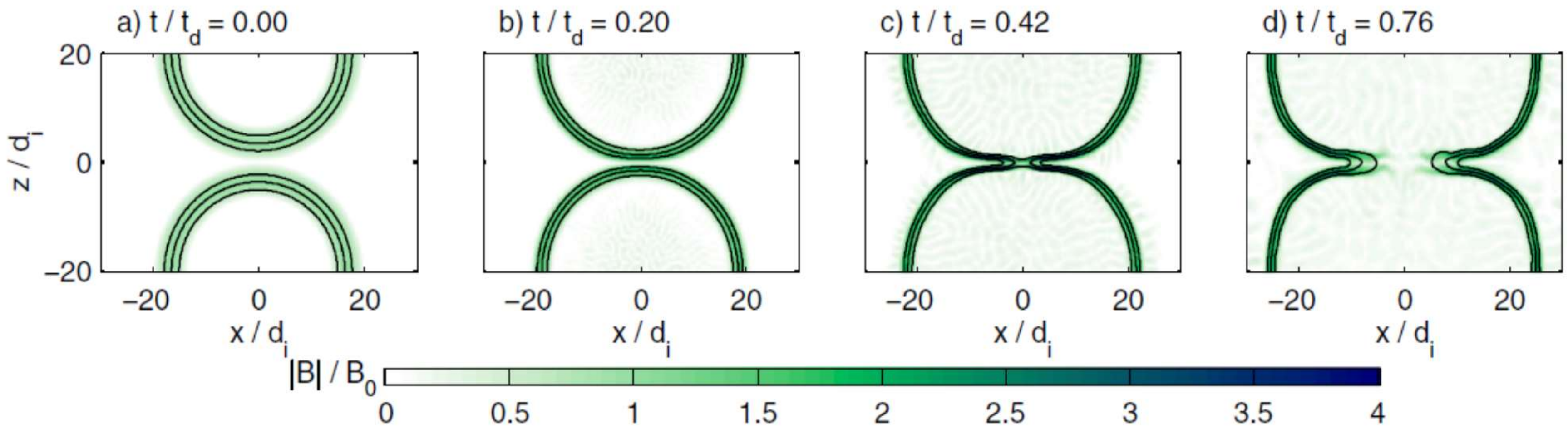
$$n_b + n^{(1)} + n^{(2)}$$

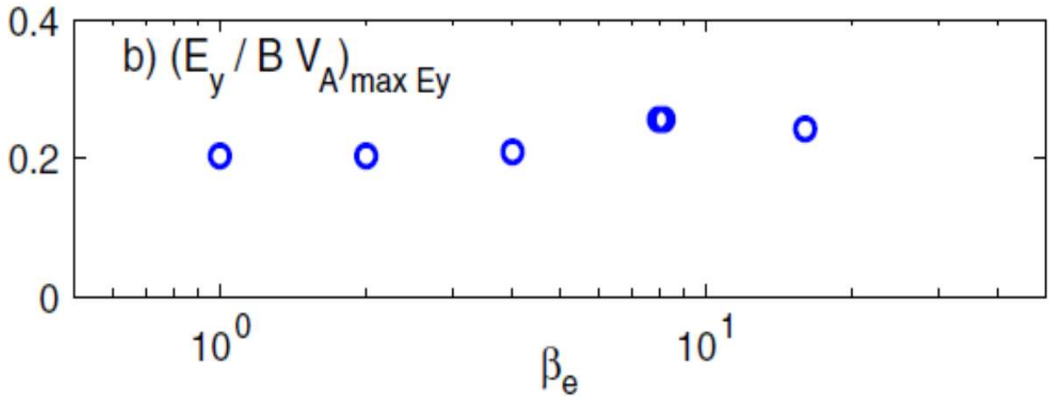
$$n^{(i)} = \begin{cases} (n_0 - n_b)\cos^2\left(\dfrac{\pi r^{(i)}}{2L_n}\right) & \text{if } r^{(i)} < L_n, \\ 0 & \text{otherwise,} \end{cases}$$

$$\mathbf{V}^{(i)} = \begin{cases} V_0 \sin\left(\dfrac{\pi r^{(i)}}{L_n}\right)\hat{\mathbf{r}}^{(i)} & \text{if } r^{(i)} < L_n, \\ 0 & \text{otherwise,} \end{cases}$$

$$\mathbf{B}^{(i)} = \begin{cases} B_0 \sin\left(\dfrac{\pi(L_n - r^{(i)})}{2L_B}\right)\hat{\mathbf{r}}^{(i)} \times \hat{\mathbf{y}} & \text{if } r^{(i)} \in [L_n - 2L_B, L_n], \\ 0 & \text{otherwise.} \end{cases}$$

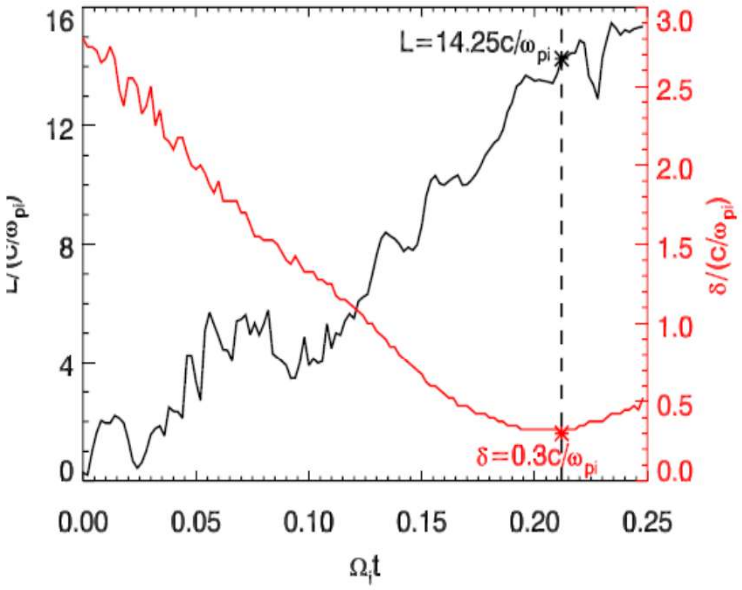
The fast reconnection rate

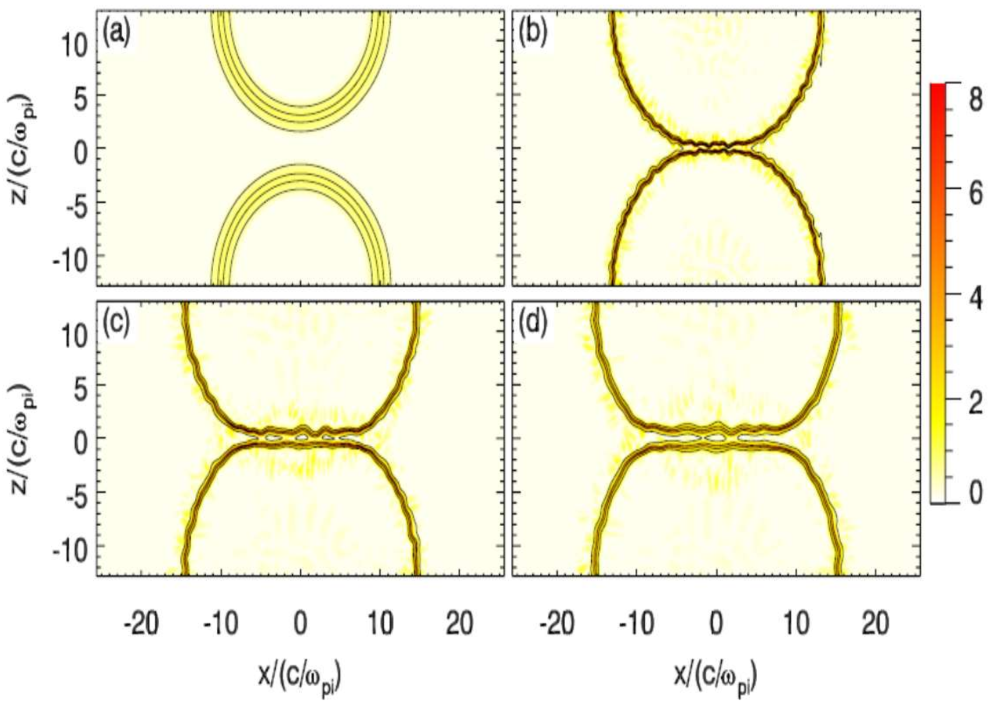


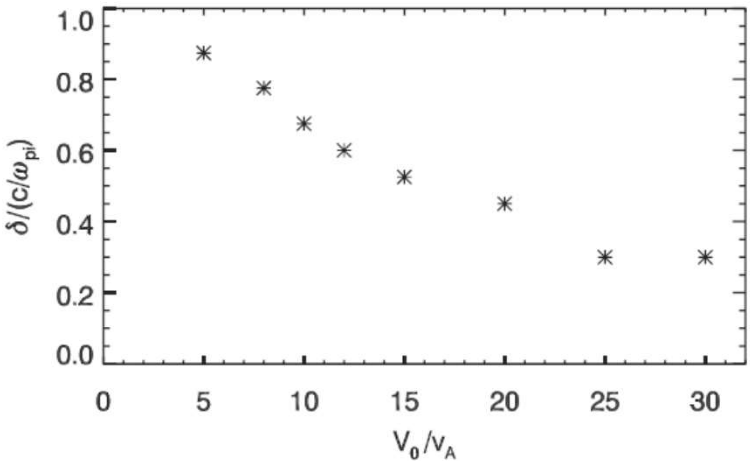


The pileup of the magnetic flux at the shoulder of the current sheet plays an important role in the fast reconnection rate[Fox et al., PRL, 2011].

Magnetic island in laser plasma reconnection







The inflow plasma with a sufficient high speed leads to the formation of a thin current sheet, which is unstable to the tearing mode instability and magnetic islands are generated [Lu et al., PoP, 2013].

Fermi and betatron acceleration in laser plasma reconnection

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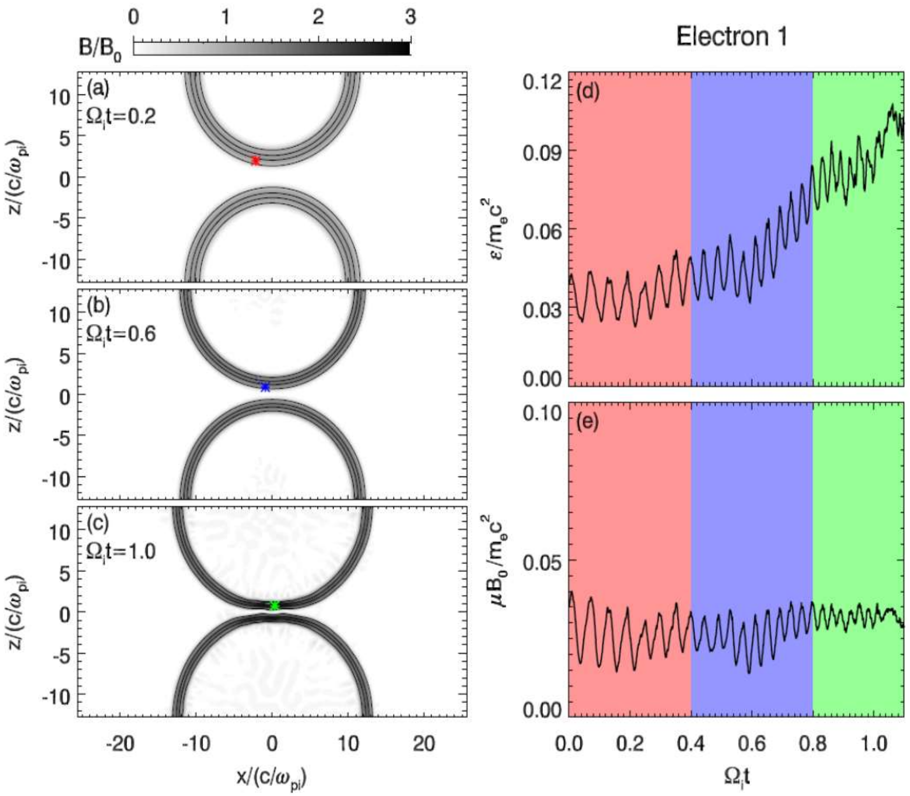
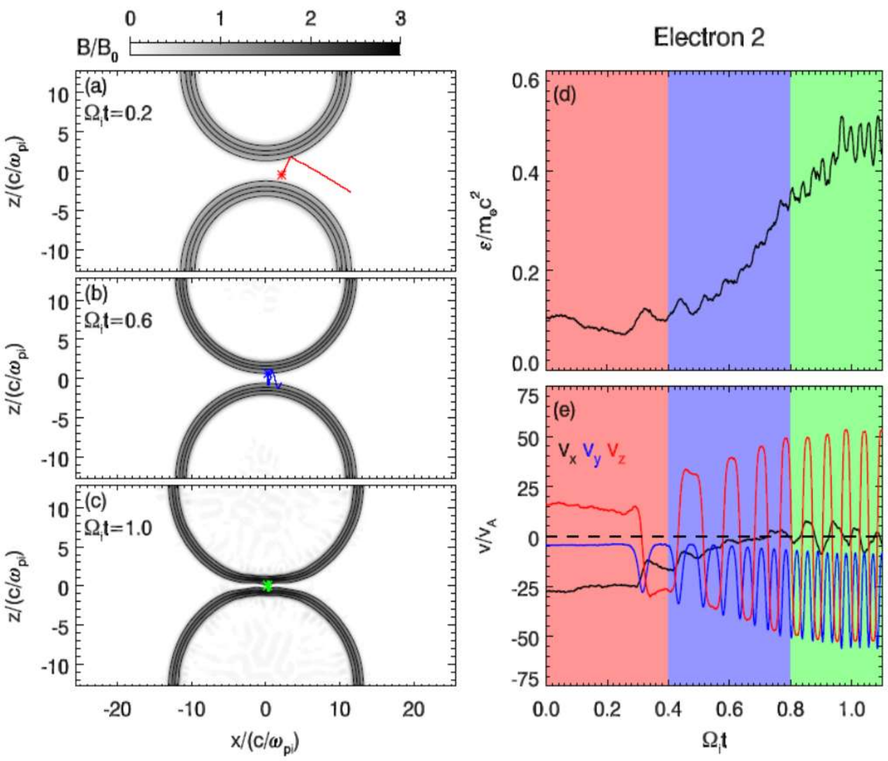
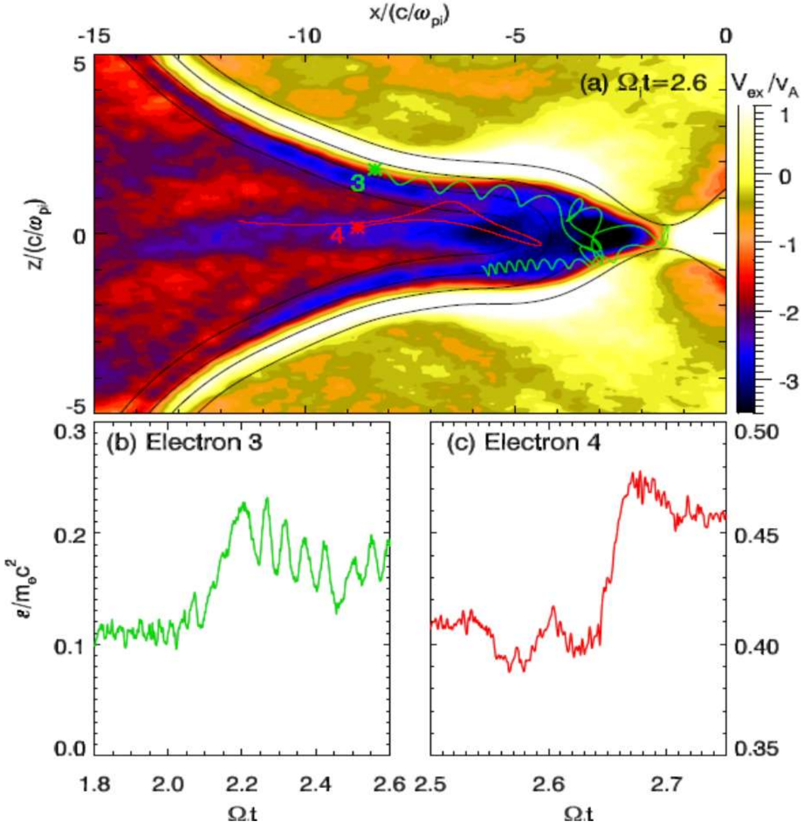


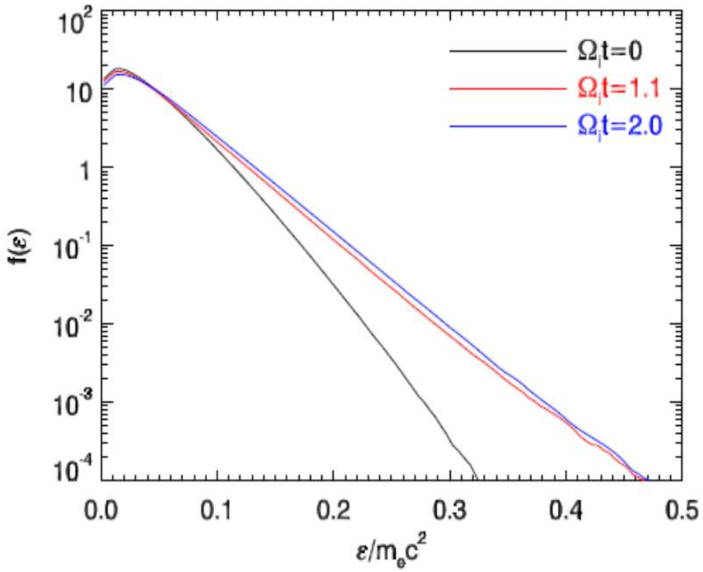


The electrons inside and between the plasma bubbles suffers from betatron and Fermi acceleration, respectively [Lu et al., NJP, 2016].

High speed electron jets

The formation of three high-speed electron jets in the outfow region, and electrons due to Fermi acceleration is most important. [Lu et al., NJP, 2014, 2016].





Introduction to Keda magnetic Reconnection eXperiment (KRX, under construction)

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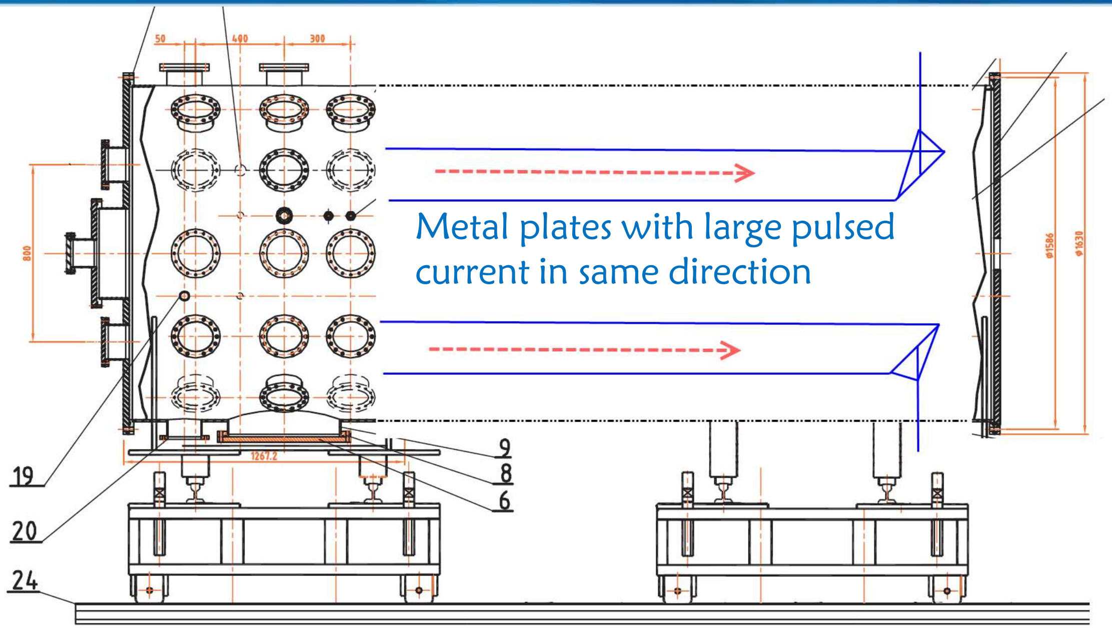
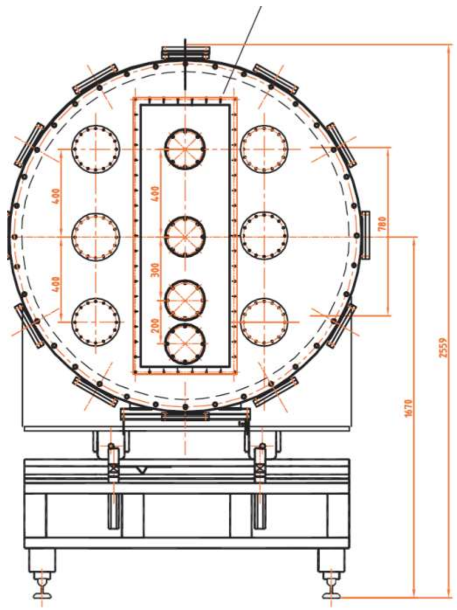


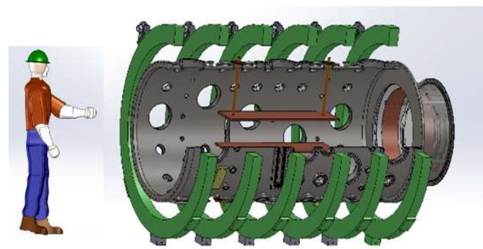


L: 6m; Dia:1.5m; B_{GF}:1000G

Plasma Column: Dia >60cm; Density $10^{13}cm^{-3}$

I_{plate}～25kA, B_{rec}～100G

RF heating: Helicon/Low-hybrid, 200kW, Te 5～100eV,



Some features about KRX

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- B dot probes & other probes
  - with high temporal and spatial resolution
- Advanced MW and optic diagnostics

✓ Laser induced fluorescence LIF / PLIF

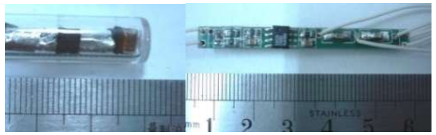
Instant 2D imaging

✓ Interferometer/polometery

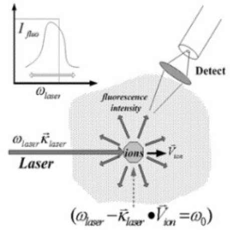
Sub mm resolution

✓ Thomson scattering

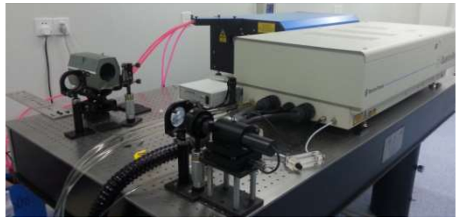
Te measurement



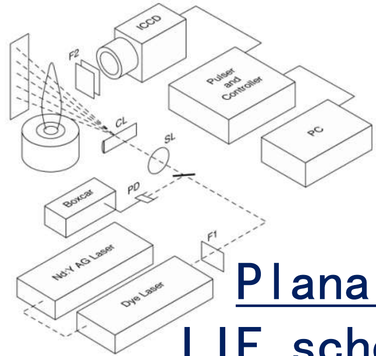
mm尺寸的磁探针及优于20MHz的射随电路



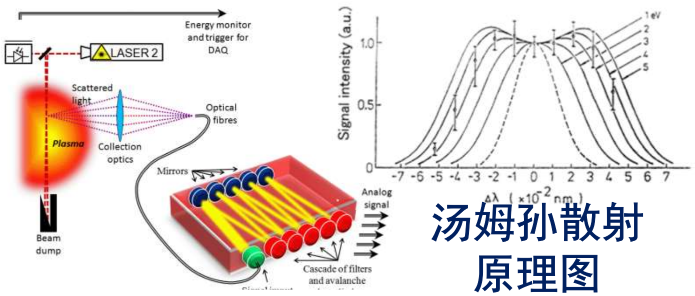
激光诱导荧光诊断原理示意图



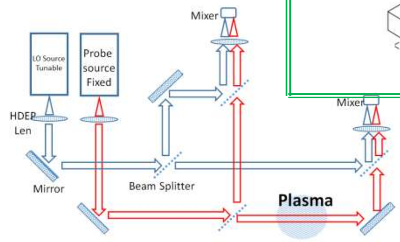
基本建成的激光诱导荧光诊断系统



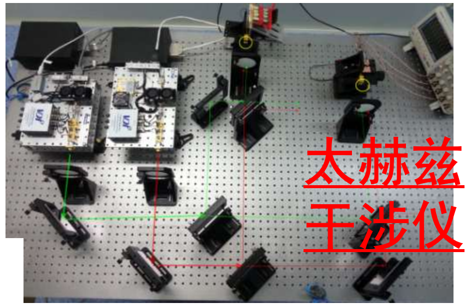
Planar LIF scheme



汤姆孙散射原理图



干涉仪结构框图



太赫兹干涉仪

Detail information from the diagnostic systems → Local/Global MR

Typical Parameter	Keda Reconnection eXperiment				
	Tuning range	Operation mode	Operation mode	Operation mode	Operation mode
Gas	H, He, N, Ar	He	He	He	H
装置特征长度L[cm]	100	100	100	100	100
等离子体密度[m^{-3}]	10^{16} ～ 10^{19}	10^{19}	10^{18}	10^{18}	10^{17}
导向磁场B[G]	0 ～ 100	50	50	50	100
电子温度Te[eV]	5 ～ 100	10	10	50	20
离子温度Ti[eV]	0.5 ～ 2	0.5	0.5	0.5	2
重联磁场B[G]	0 ～ 500	100	100	100	500
离子声回旋半径R_{ci}[cm]	3 ～ 50	6	6	14	1.3
离子惯性长度[cm] c/w_{pi}	10 ～ 100	14	45	45	100
电子惯性长度[mm] c/w_{pe}	1 ～ 10	2	5	5	17
磁扩散时间[ms]	1 ～ 200	3	3	27	19
Alfven时间[us]	0.1 ～ 10	9	3	3	0.2
等离子体归一化尺度 $\lambda=L/R_{ci}$	10 ～ 10^2	17	17	7	80
伦德奎斯特数S Lundquist number	10^2 ～ 10^5	3×10^2	10^3	10^4	1×10^5

Summary

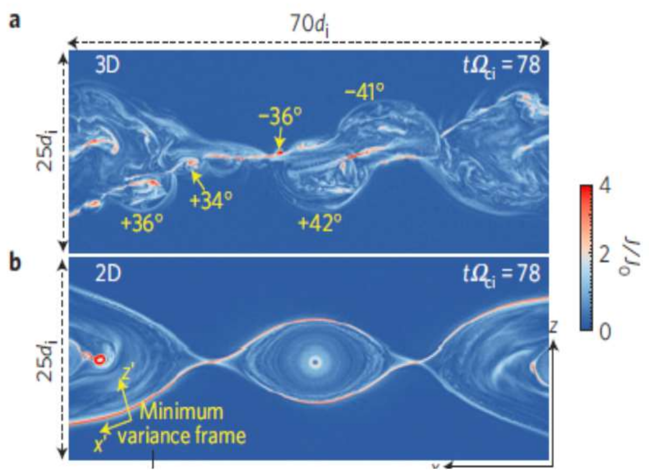
1. Electrons can be trapped and accelerated in magnetic island by Fermi mechanism.

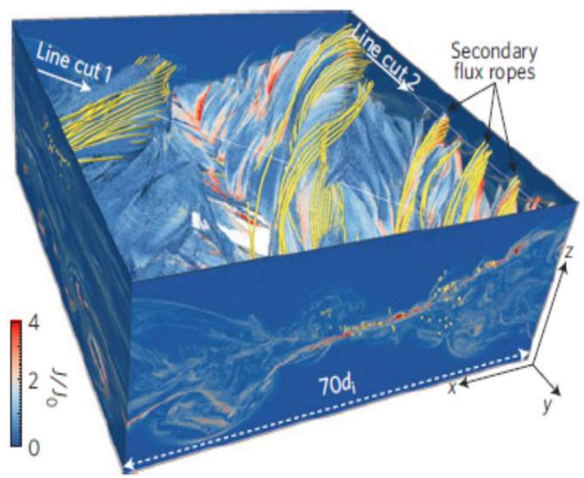
2. Electron acceleration during island merging may be more important, and electrons can be accelerated by the parallel electric field (with a guide field), Fermi and betatron mechanisms. With the guide field is sufficiently large, the parallel electric field become the primary mechanism.

Problem: when the guide field is small, how to analyze quantatively the contribution from the Fermi, betatron and the parallel electric field.

Discussion

- Electron acceleration in 3D reconnection, where magnetic islands are distorted.





Daughton et al., Nature Phys. , 2011

Discussion

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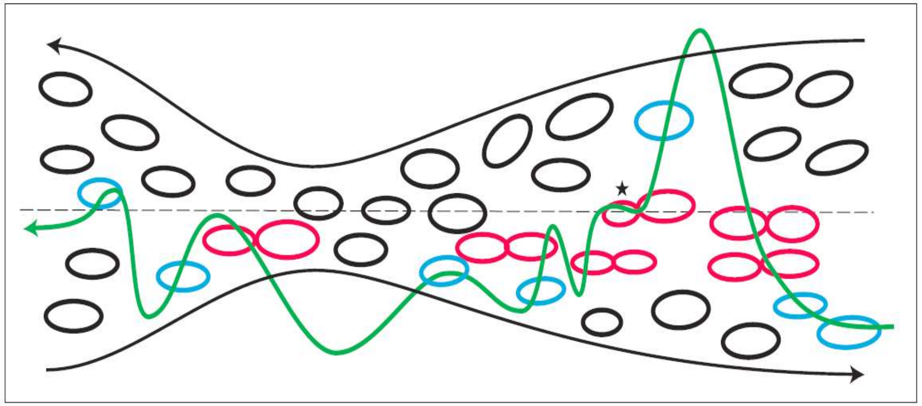
- How to quantatively study electron acceleration in a real plasma system, where energetic electrons have a power law distribution?

$$\frac{\partial f}{\partial t}+\vec{u}\bullet\vec{\nabla}f-\vec{\nabla}\bullet\vec{\vec{D}}\bullet\vec{\nabla}f+R\left(\frac{\partial}{\partial p_{\parallel}}p_{\parallel}-\frac{1}{2p_{\perp}}\frac{\partial}{\partial p_{\perp}}p_{\perp}^{2}\right)f-\gamma\frac{\partial}{\partial\xi}\left(1-\xi^{2}\right)\frac{\partial}{\partial\xi}f=0$$

merging drive pitch-angle scattering

$$R\sim 0.1\left\langle\frac{\alpha^{1/2}c_{A}}{r}\right\rangle\equiv\frac{1}{\tau_{h}}\qquad \alpha=1-\frac{1}{2}\beta_{\parallel}+\frac{1}{2}\beta_{\perp}$$

Wang et al., Nature Phys. , 2016



Thanks!