CfCAユーザーズ=ミーティング

2011. 1. 11. 国立天文台三鷹

太陽フレアの
ストカスティックな電流シート中の
磁気リコネクション

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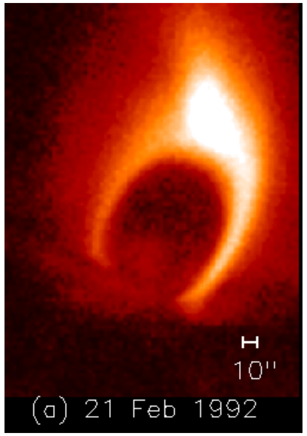
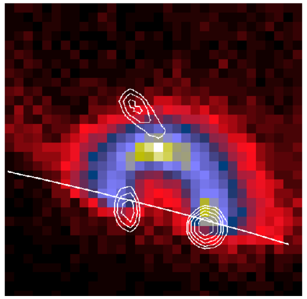
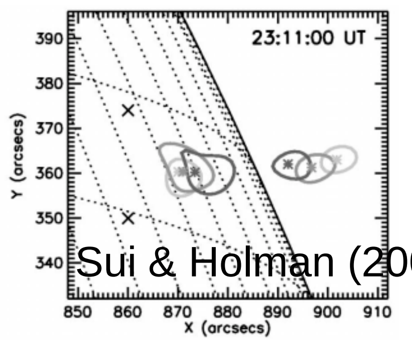
Observational evidence for the magnetic reconnection model of a flare / CME

The “CSHKP” model

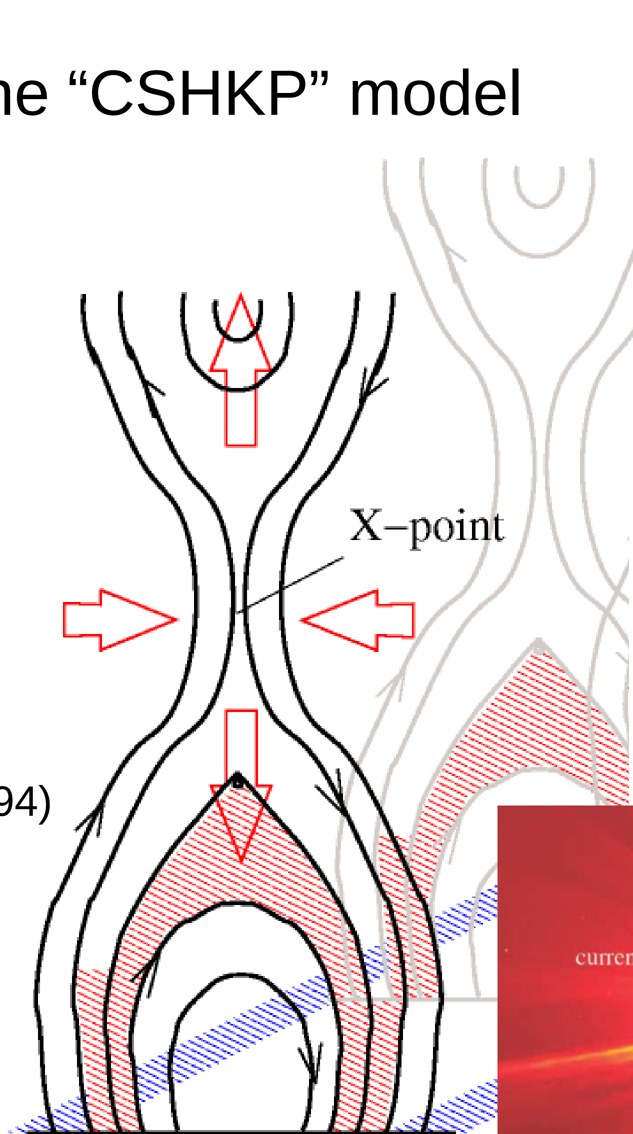


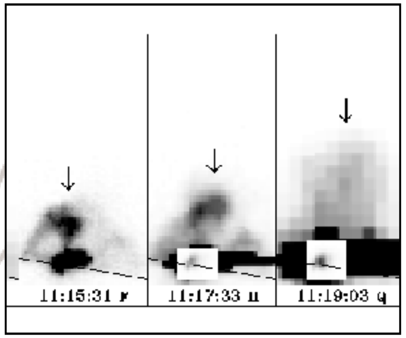
Tsuneta et al. (1992)


Masuda et al. (1994)

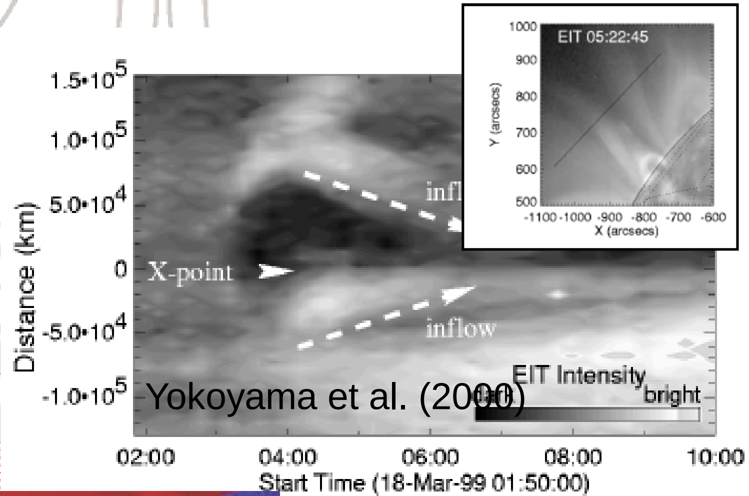


Sui & Holman (2003)

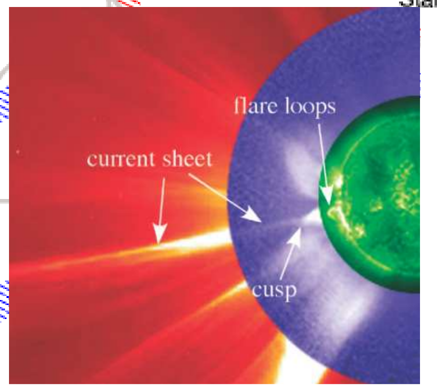


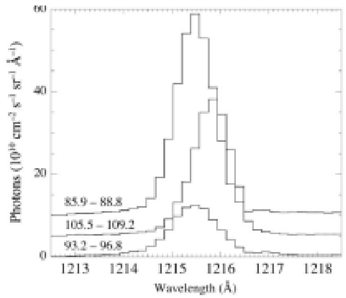


Shibata et al. (1995)



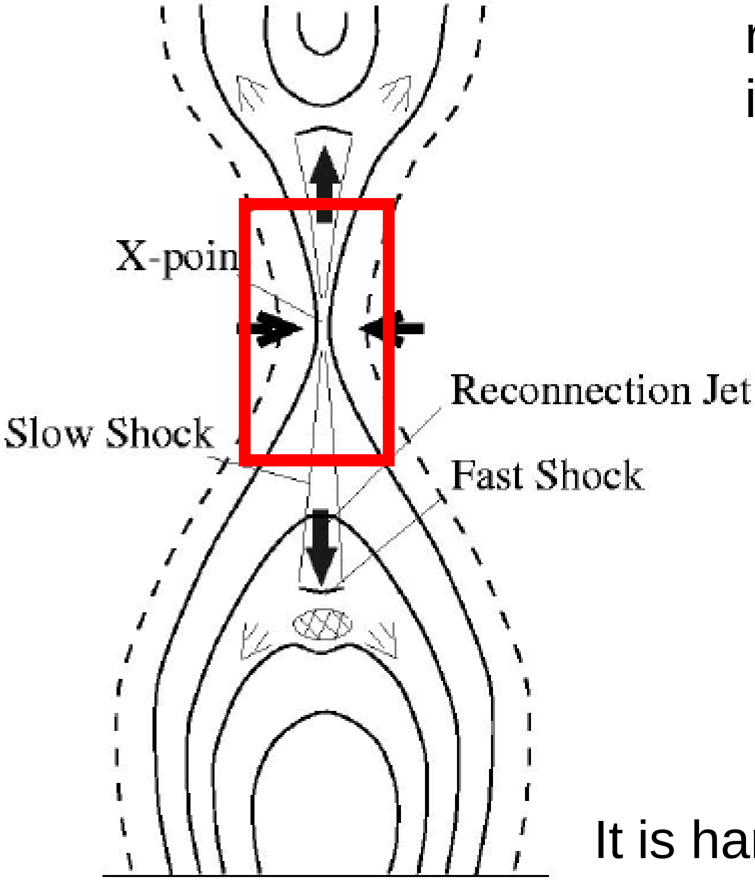
Yokoyama et al. (2000)





Lin, J. et al. (2005)

“Size-gap” problem



For a rapid energy release by the fast reconnection, an "anomalous" resistivity is expected near the neutral point.

Spatial size necessary for the anomalous resistivity:

$\delta = \rho i \sim$ <u>1 m</u>

δ; thickness of the current sheet

ρi ; ion-gyro radius

Spatial size of a flare

– $\underline{10^4 – 10^5 \text{ km}}$

Enormous gap with a ratio of 10^7 !

It is hard to believe that a laminar flow structure is sustained in a steady state manner.

The “MHD Turbulence” should play a role.

Plasmoid-induced reconnection and fractal reconnection

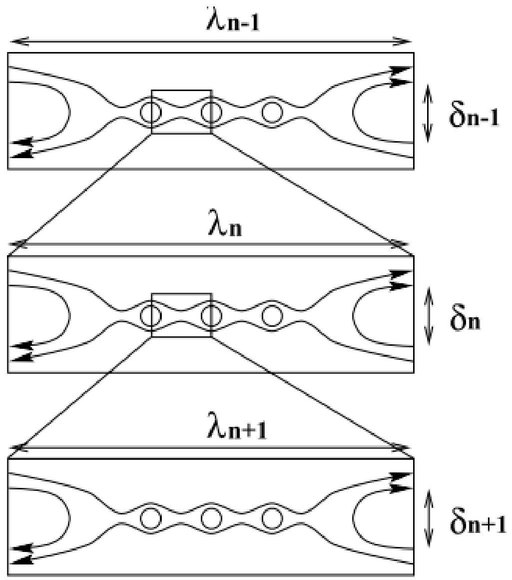
Shibata & Tanuma (2001, EPS, MR2000 proceedings)

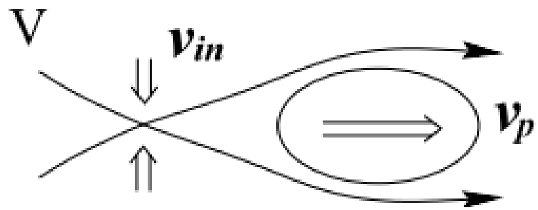
- ✓ show that the fractal structure of a current sheet is achieved via the repeated processes of the combination of sheet thinning by the tearing instability and of the Sweet-Parker sheet formation.
- ✓ suggest that the formation and ejection of a plasmoid in the current sheet play a role in the storage of magnetic energy (by inhibiting reconnection) and the induction of a strong inflow into reconnection region through a nonlinear instability.

Tanuma et al. (2001, ApJ)

- ✓ 2D MHD simulations:

Rm=150

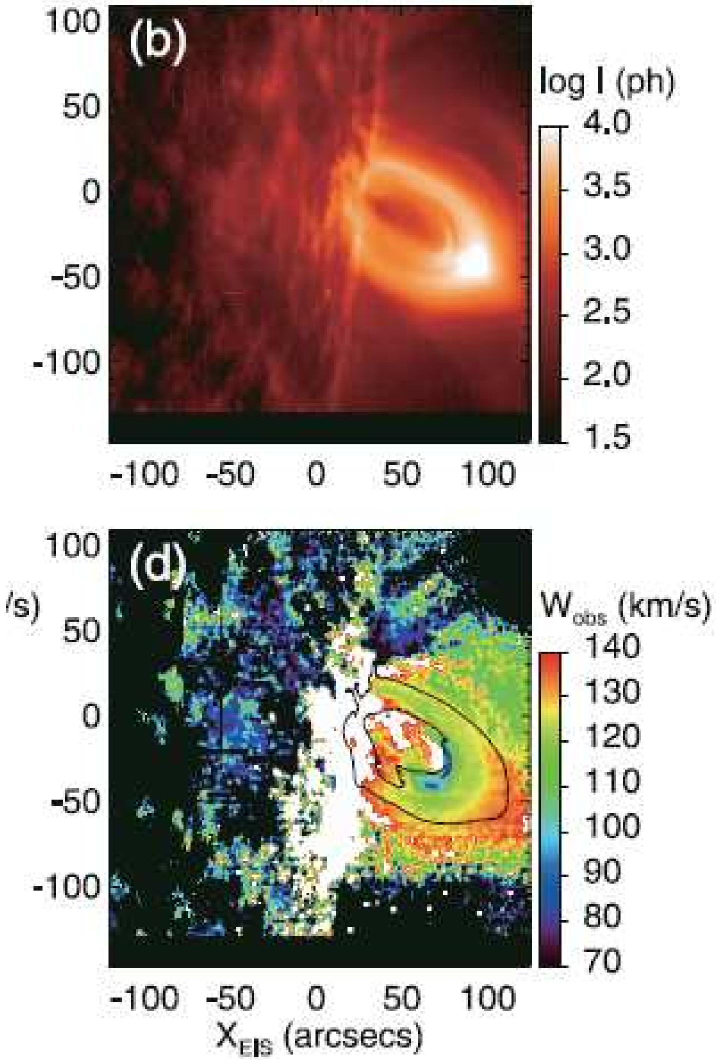




Doppler broadening at the flare loop top

Hara et al. (2008, PASJ)

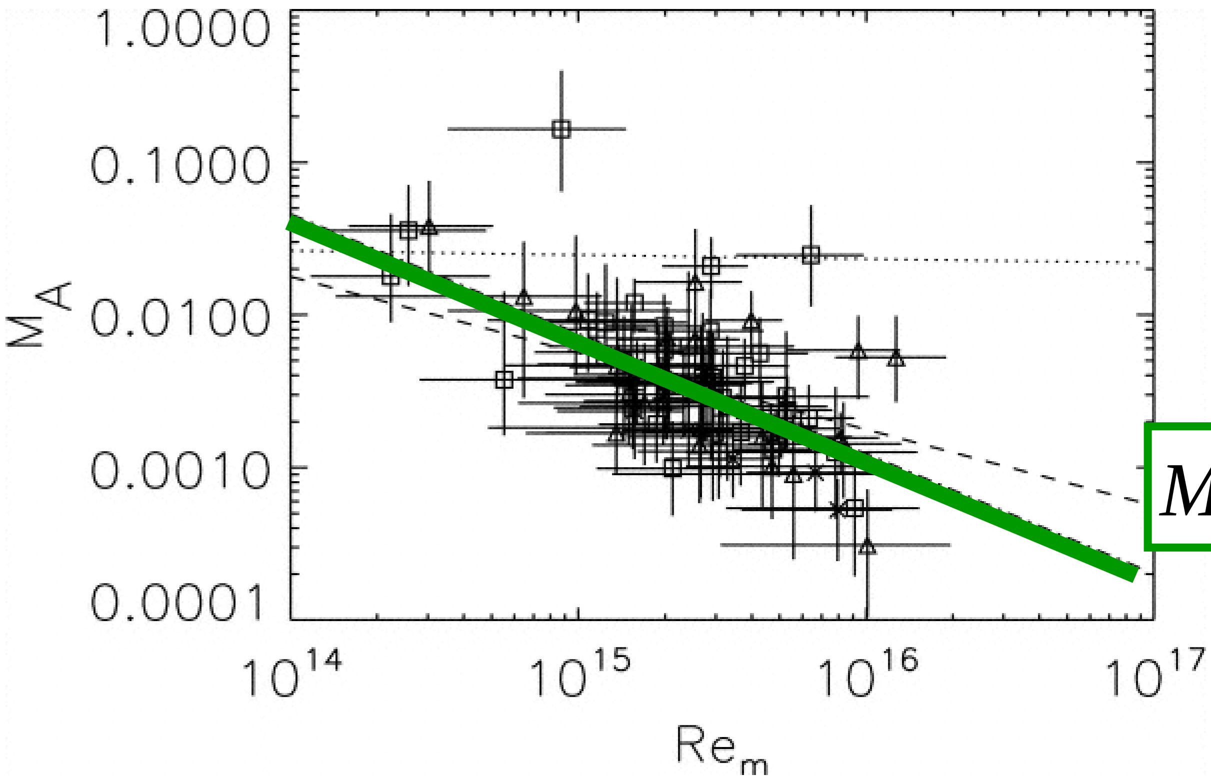
- ✓ Hinode/EIS observations of a limb flare
- ✓ Found loop-top nonthermal broadening in the CaXVII line (logTe=6.7).



Statistical Study of Reconnection Rate of Flares

Nagashima & Yokoyama (2006, ApJ)

- ✓ found that the reconnection rate is around 0.001 to 0.01 as expected by the Petschek's fast reconnection model. However, we found a relatively stronger dependence. This result suggest that the Sweet-Parker reconnection might occur with an enhanced resistivity.



$$M_A \propto R_m^{-0.8}$$

Our study

By using the 3D resistive MHD simulations, the evolution is studied about a current sheet with initially imposed finite random perturbations.

We focus on:

- (1) Evolution of 3D structures
- (2) *Global* energy release rate
- (3) Guide-field effect

Model

$$\beta = 0.1$$

$$C_{\mathrm{A}} / C_{\mathrm{S}} \approx 3.4$$

- 3D MHD eqs.
- Resistivity

$$\eta = \eta_0 + \eta_{\mathrm{randum}}(\vec{\mathbf{x}}, t)$$

η_0 : uniform resistivity

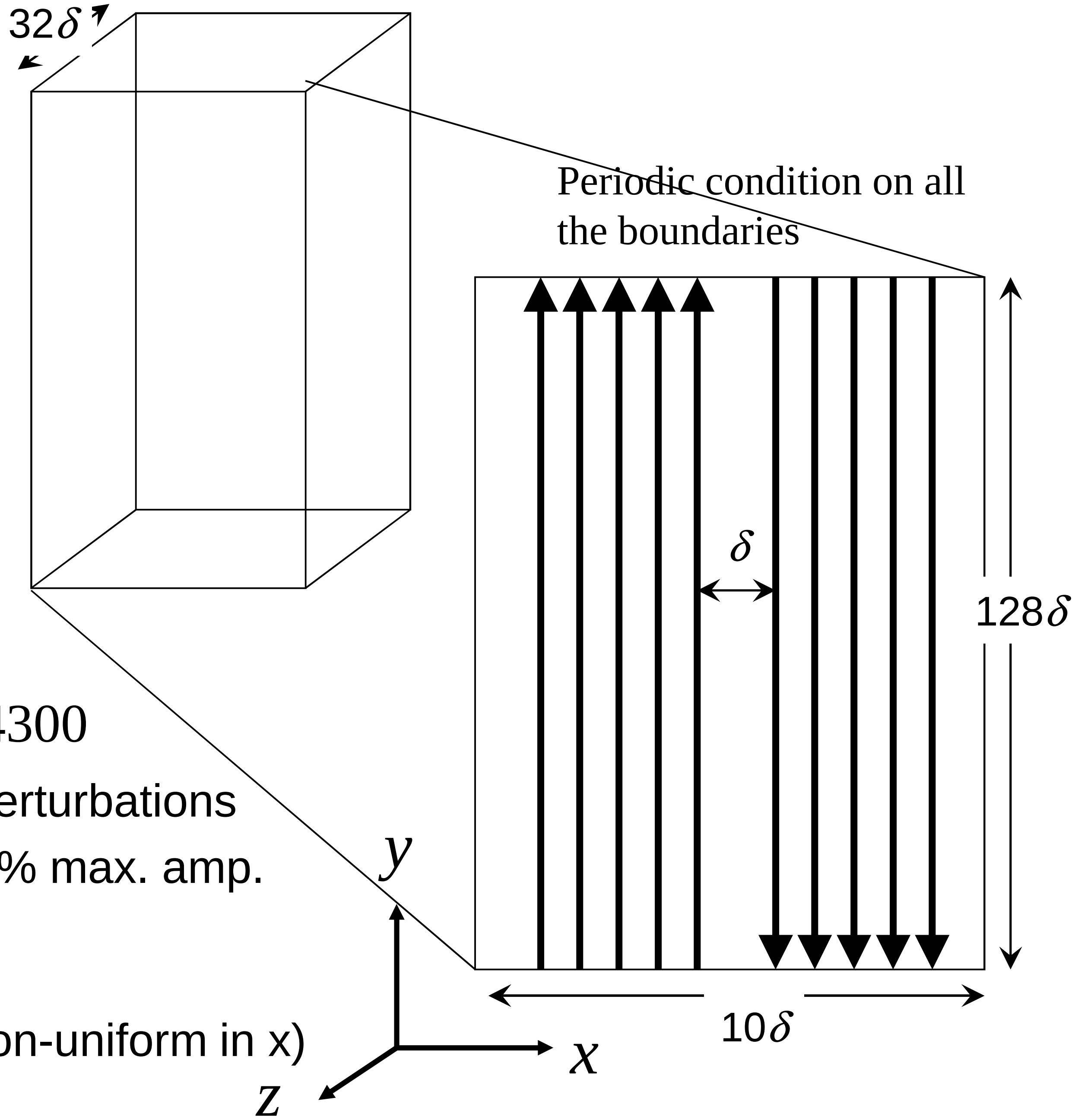
$$R_{\mathrm{m}} \equiv C_{\mathrm{A}} \delta / \eta_0 = 4300$$

$\eta_{\mathrm{randum}}(\vec{\mathbf{x}}, t)$: resistivity perturbations

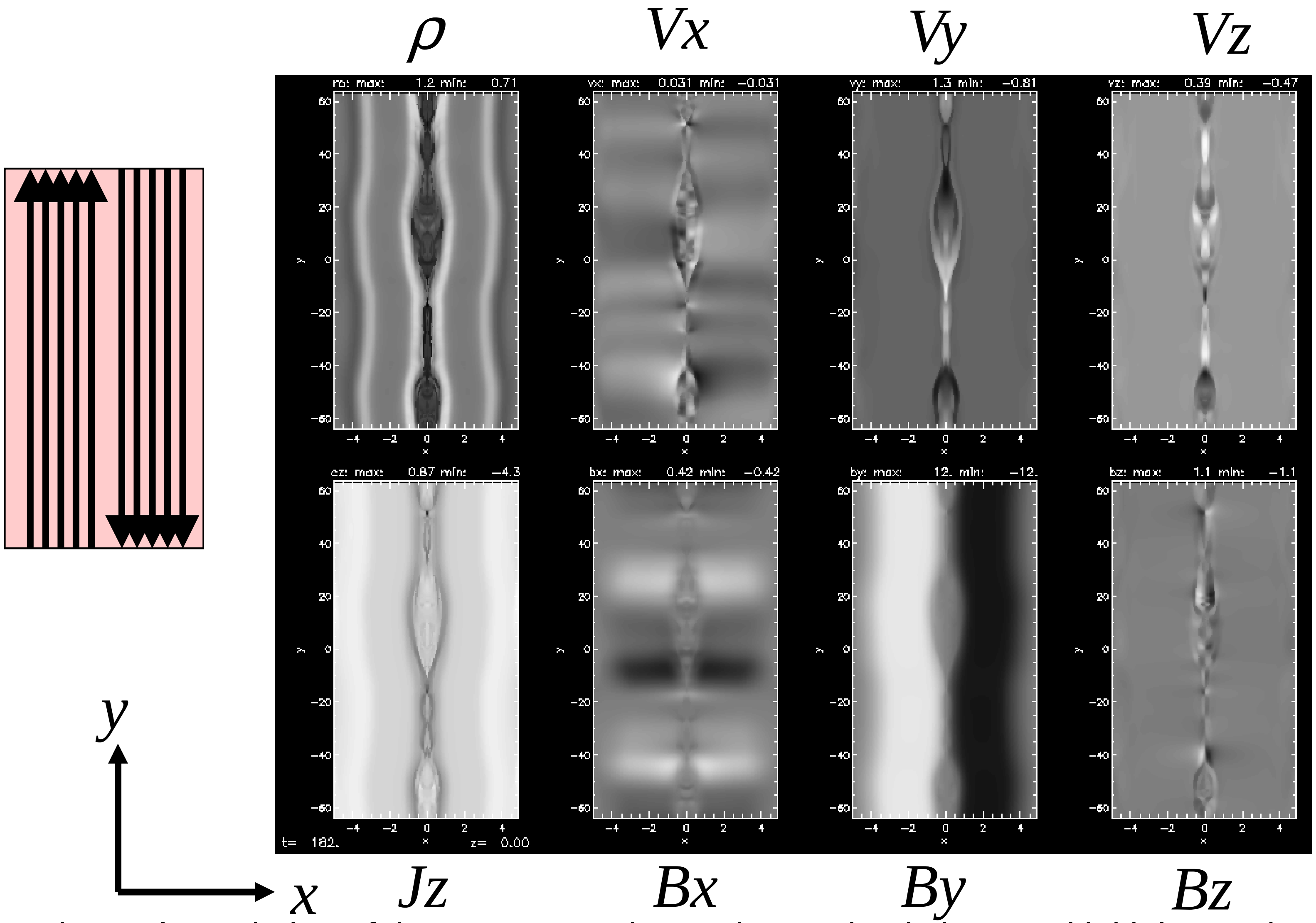
spatially random; 50% max. amp.

during $t/(\delta/Cs)<4$

grid: 256 x 256 x 256 (non-uniform in x)

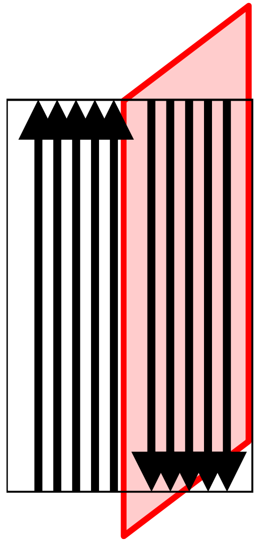


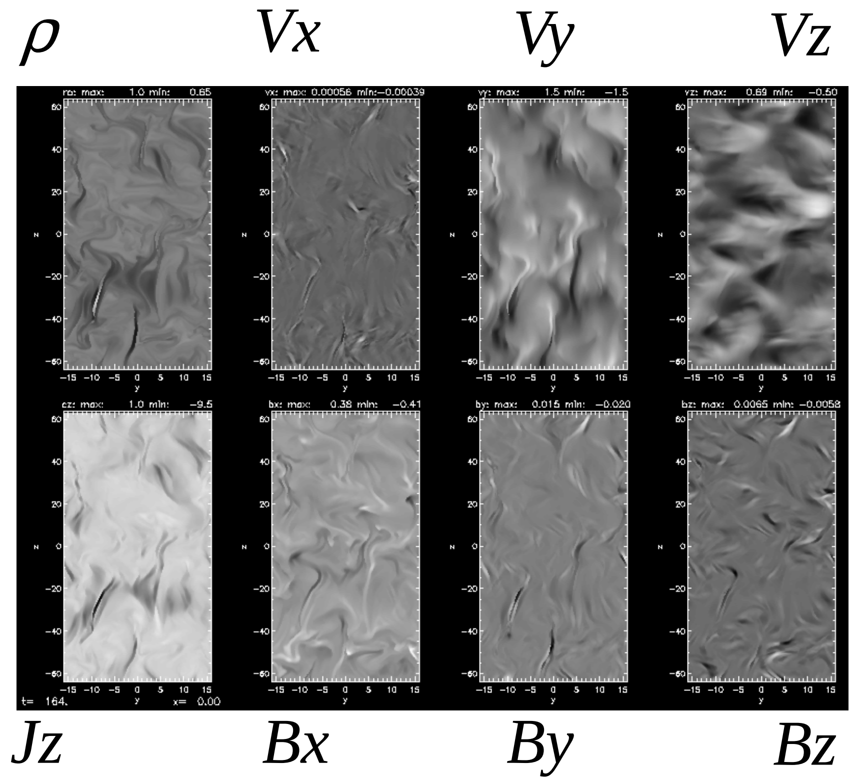
Evolution of nonlinear tearing

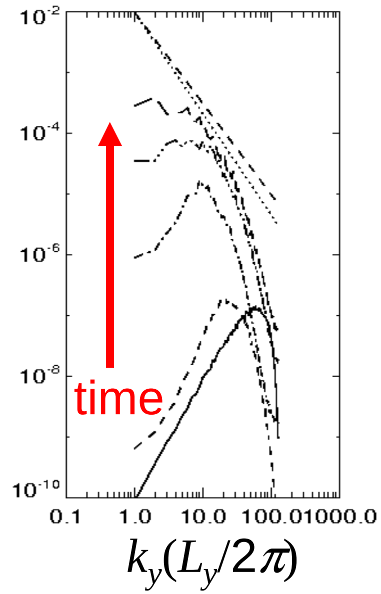


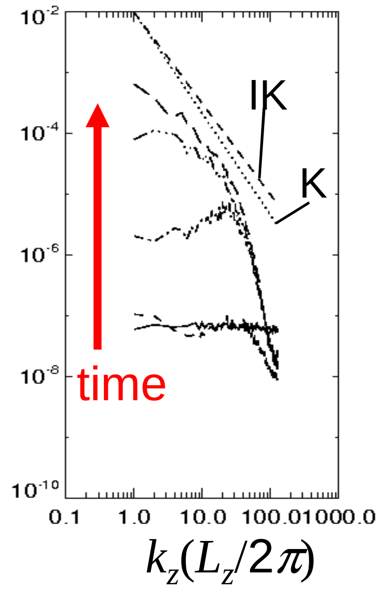
After the early evolution of tiny structures due to the randomly imposed initial perturbations, they are overcome by the larger structure, which is consistent with the growth of the tearing instability. In later phase, the magnetic islands in the sheet coalesce with each other to form a few dominant X-points.

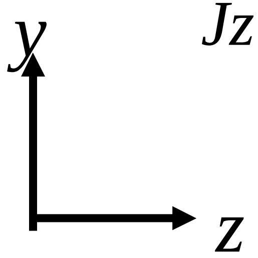
Evolution of “turbulence” in the current sheet





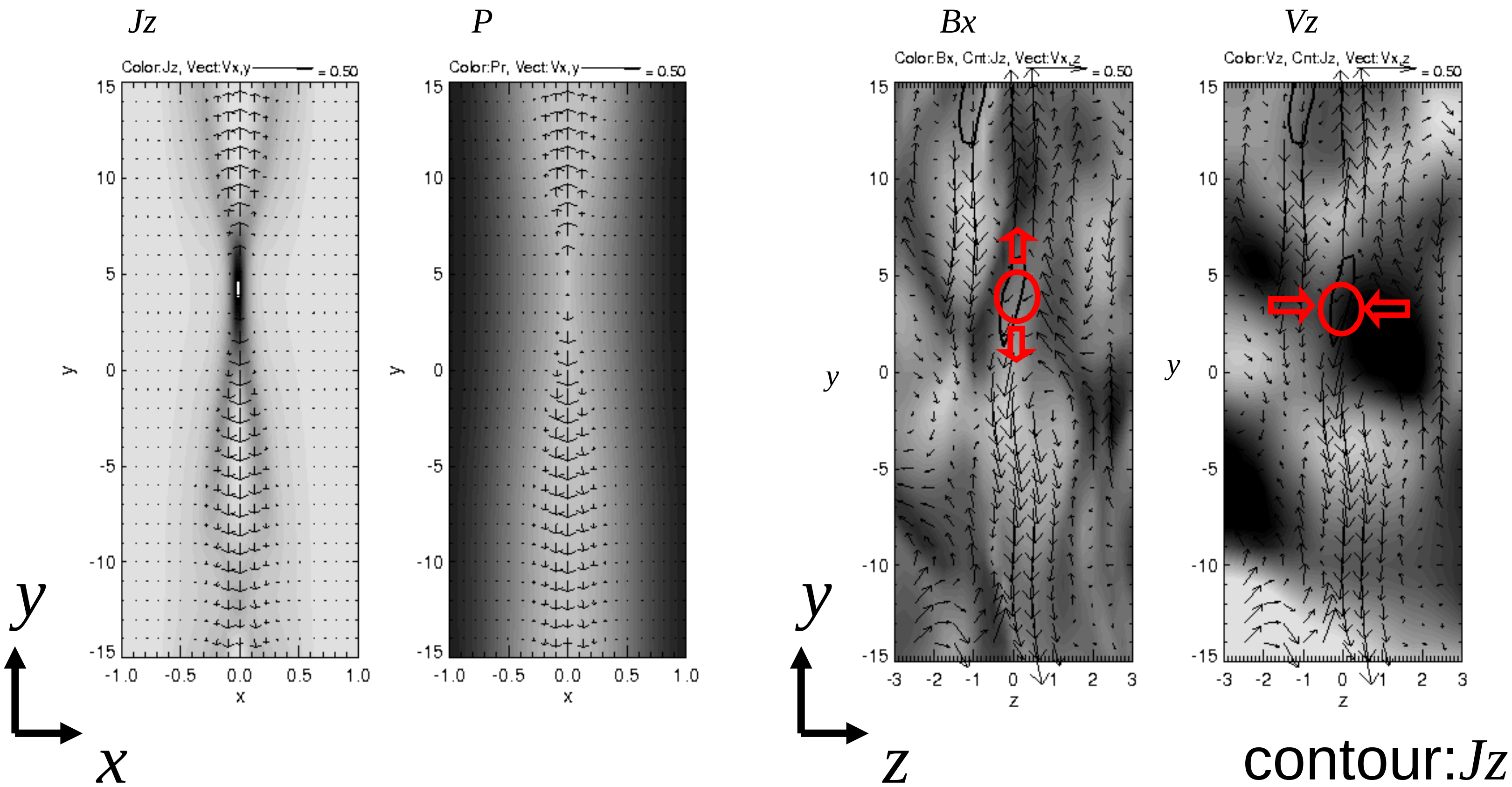






- The turbulent structure evolves in the current sheet.
- This structure evolves though the formation of vortexes by the mutual collisions of outflows from the elemental reconnection X-points.

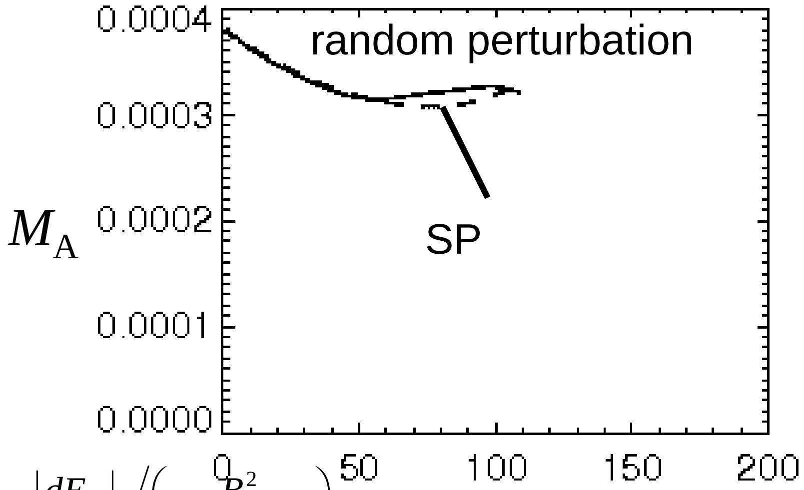
Structure of elemental reconnection X-point



• Each concentration of the electric current has our familiar Petschek-like X-point structure with inflows and outflows.

• In addition, a pair of z-directional flows into the X-point evolve. These inflows and reconnection outflows from multiple X-points collide with each other and help the evolution of turbulence.

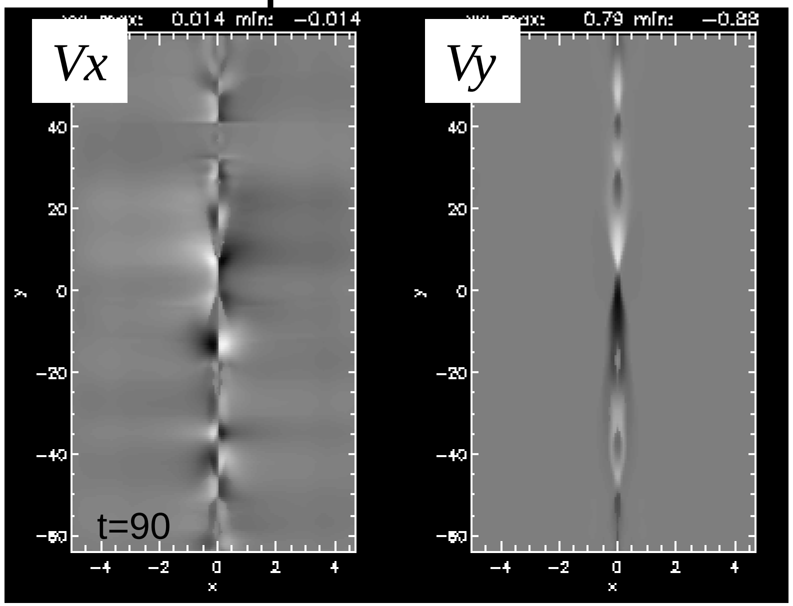
Reconnection rate



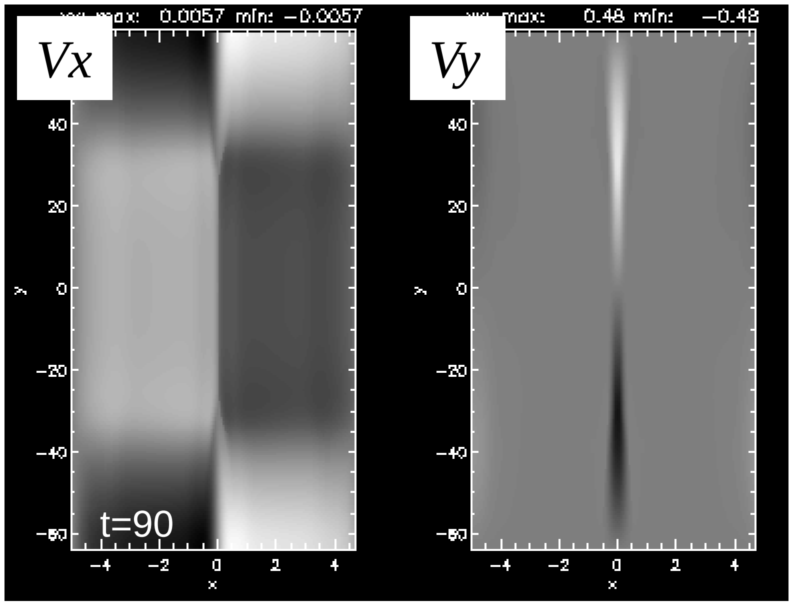
$$M_A \equiv \left|\frac{dE_m}{dt}\right| \Big/ \left(2S\frac{B^2}{4\pi}C_A\right)$$

- The energy release rate is slightly larger (by 3%) than the Sweet-Parker reconnection.

random perturbation

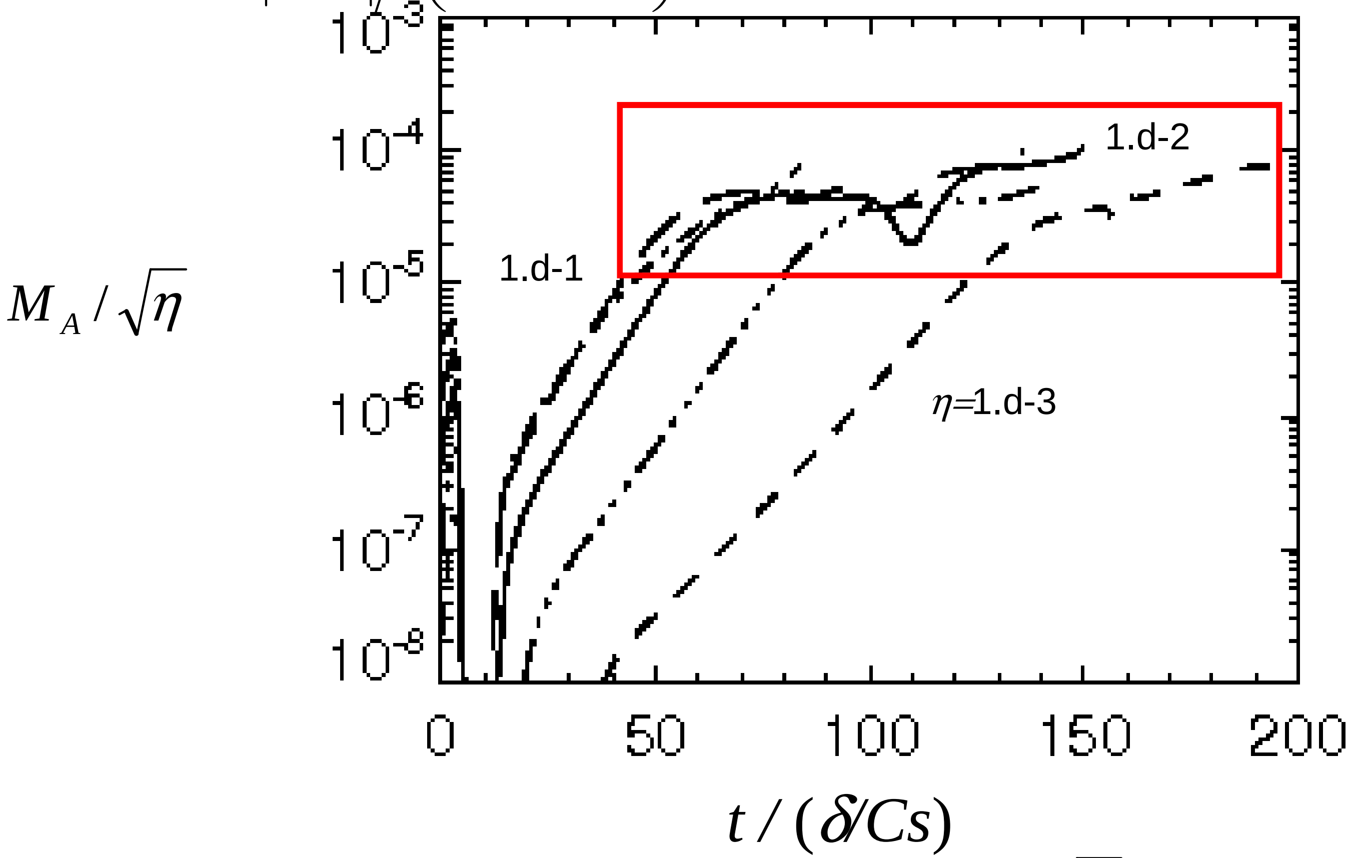


Sweet-Parker



Dependence of reconnection rate on resistivity

$$M_{\mathrm{A;ki}} \equiv \left| \frac{dE_{\mathrm{ki}}}{dt} \right| \Big/ \left(2S \frac{B^2}{4\pi} C_{\mathrm{A}} \right)$$



- The reconnection rate is: $M_A \propto \sqrt{\eta} \propto R_{\mathrm{m}}^{-1/2}$ i.e., has a Sweet-Parker like dependence on R_{m}.

Effect of the guide-field

Model

$$\beta = 0.1$$

$$C_A / C_S \approx 3.4$$

- 3D MHD eqs.
- Resistivity

$$\eta = \eta_0 + \eta_{\mathrm{randum}}(\vec{\mathbf{x}}, t)$$

η_0 : uniform resistivity

$$R_m \equiv C_A \delta / \eta_0 = 4300$$

$\eta_{\mathrm{randum}}(\vec{\mathbf{x}}, t)$: resistivity perturbations

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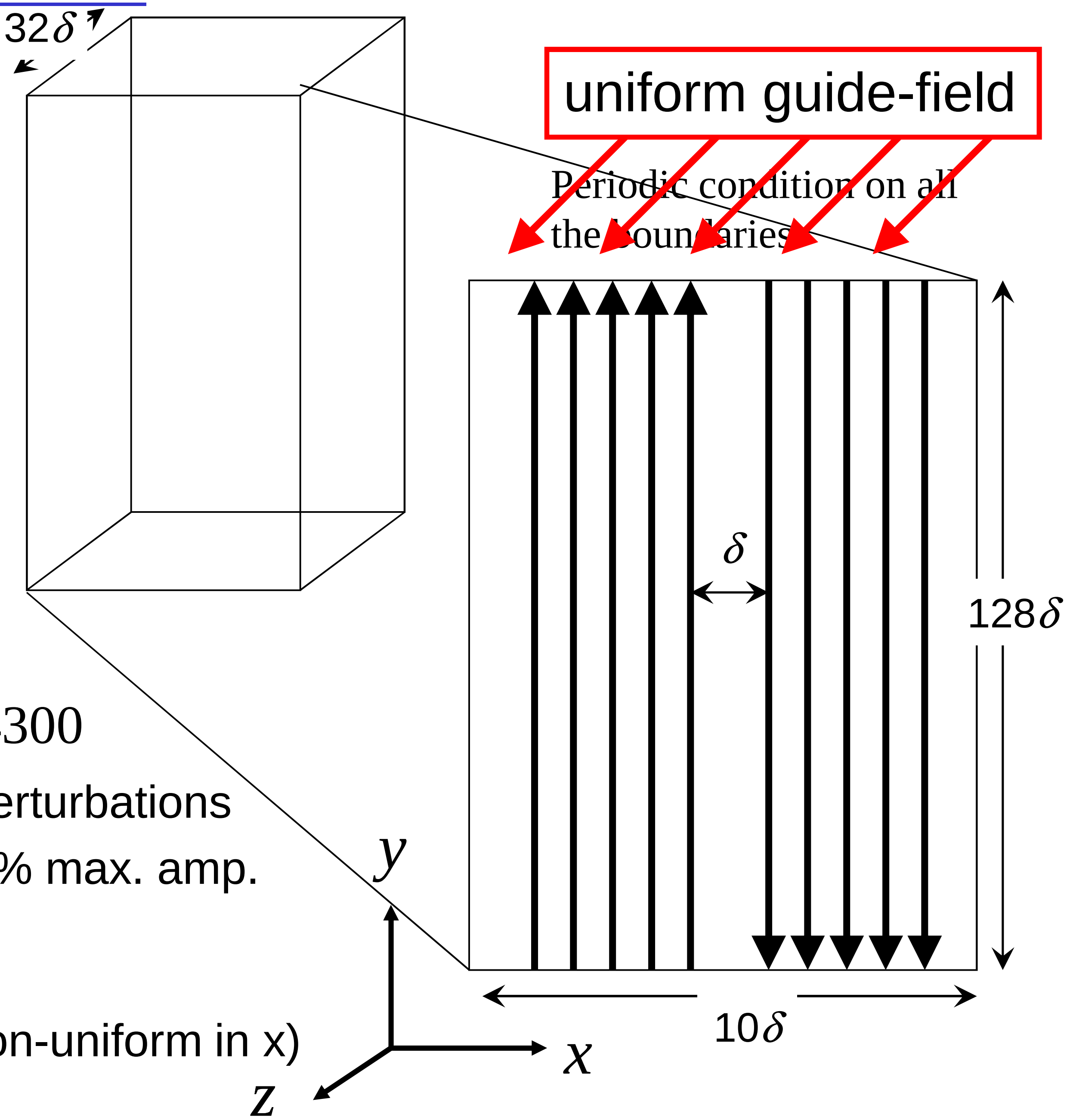
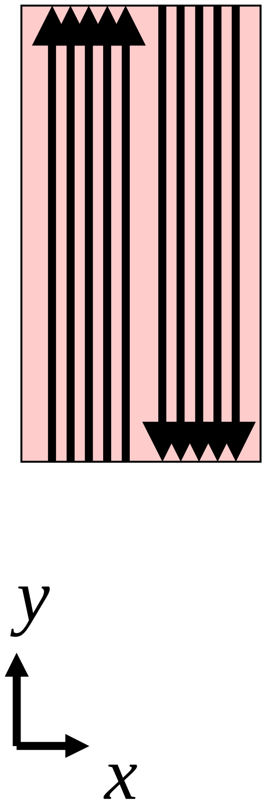
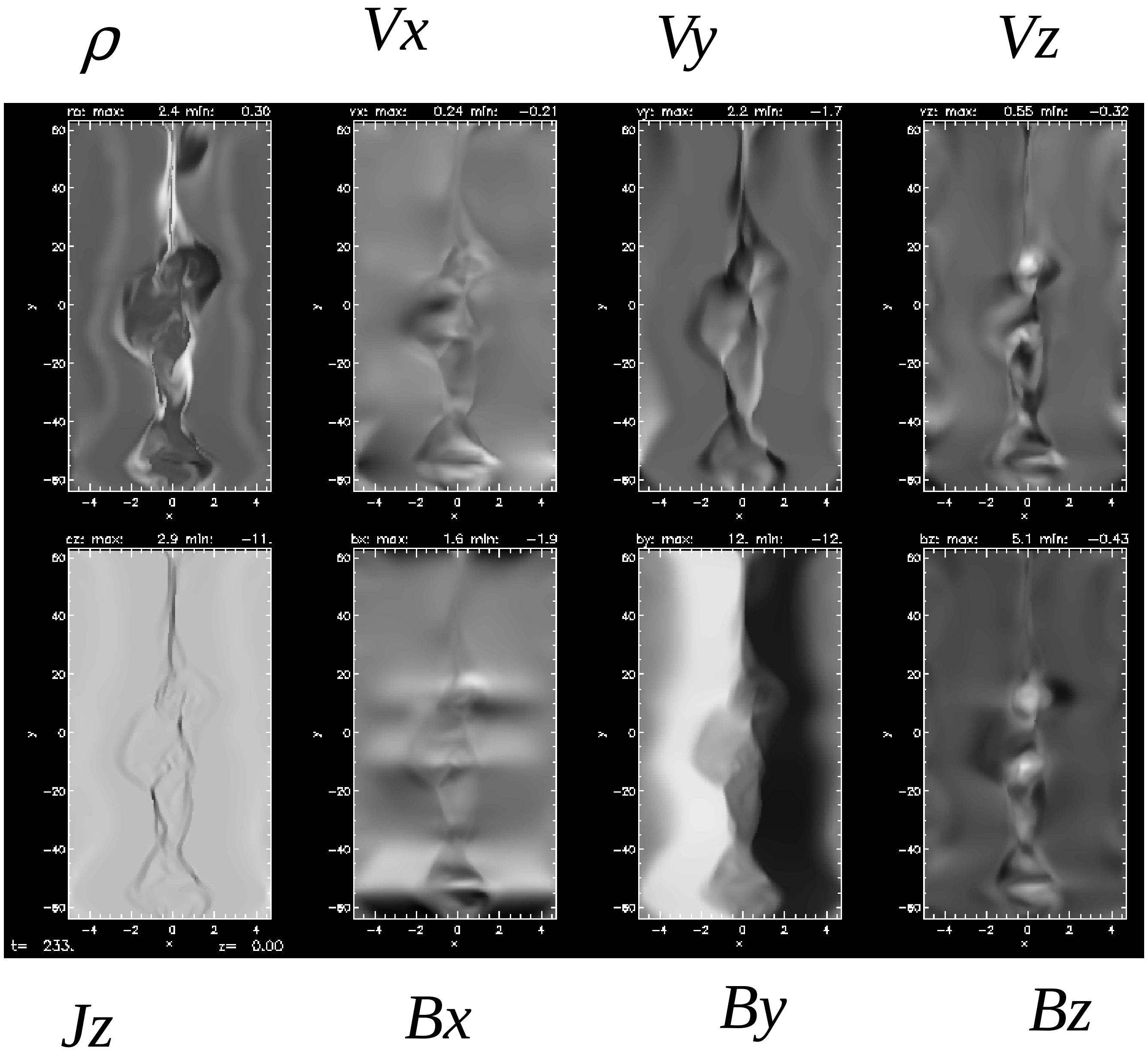


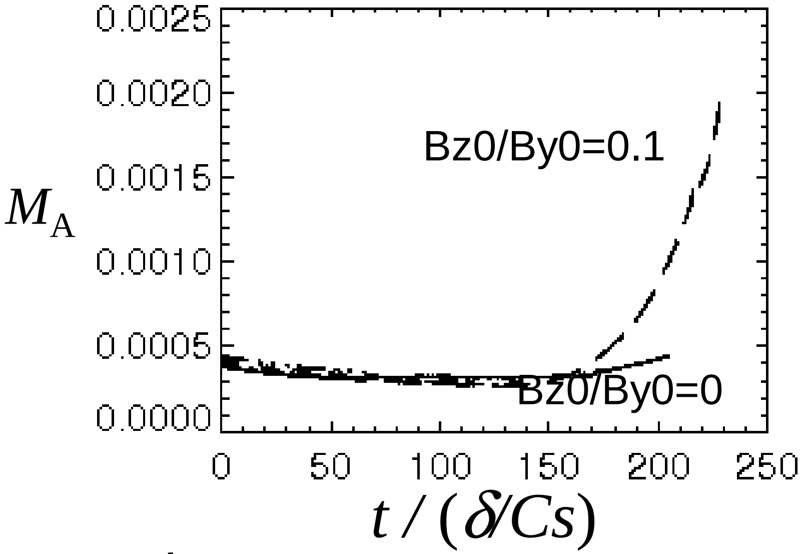
Bz0/By0=
0.1
xy-plane
(z=0)





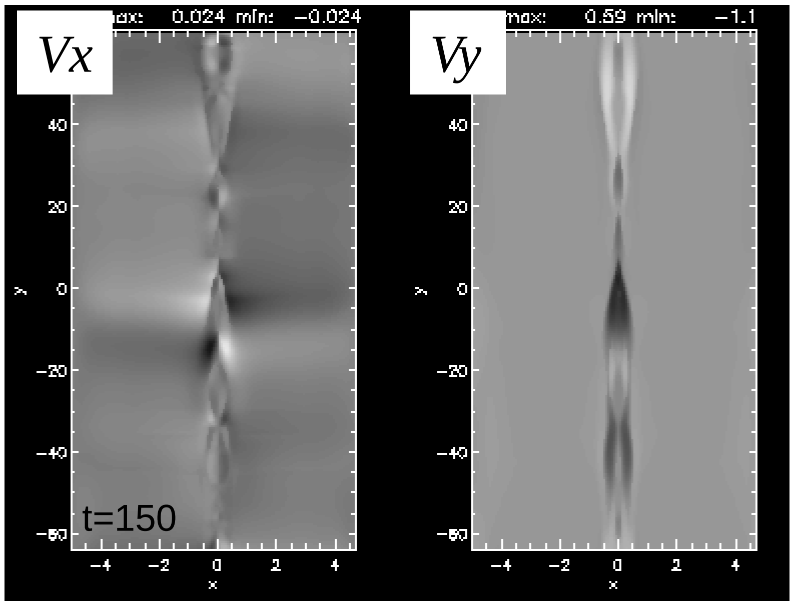
It is found that the current sheet becomes to have more turbulent nature. The magnetic islands are NOT aligned any more along the initial neutral sheet in contrast to the non-guide-field case.

Reconnection rate: influence of the guide field

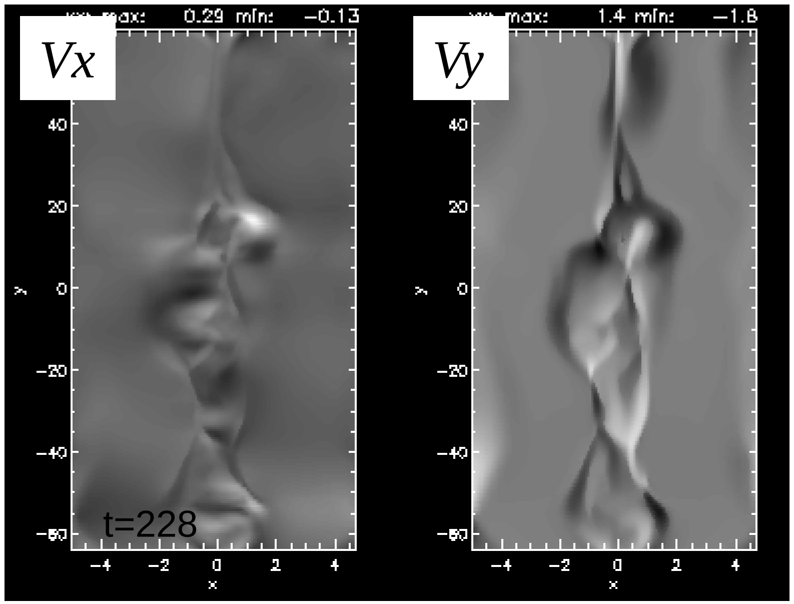


•By the influence of the guide field, at least 3 times enhancement is obtained in the reconnection rate.

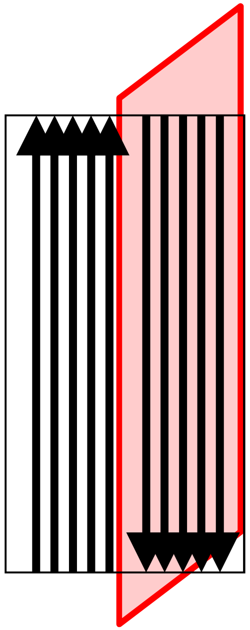
Bz0/By0=0

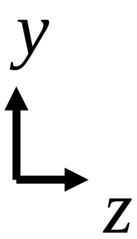


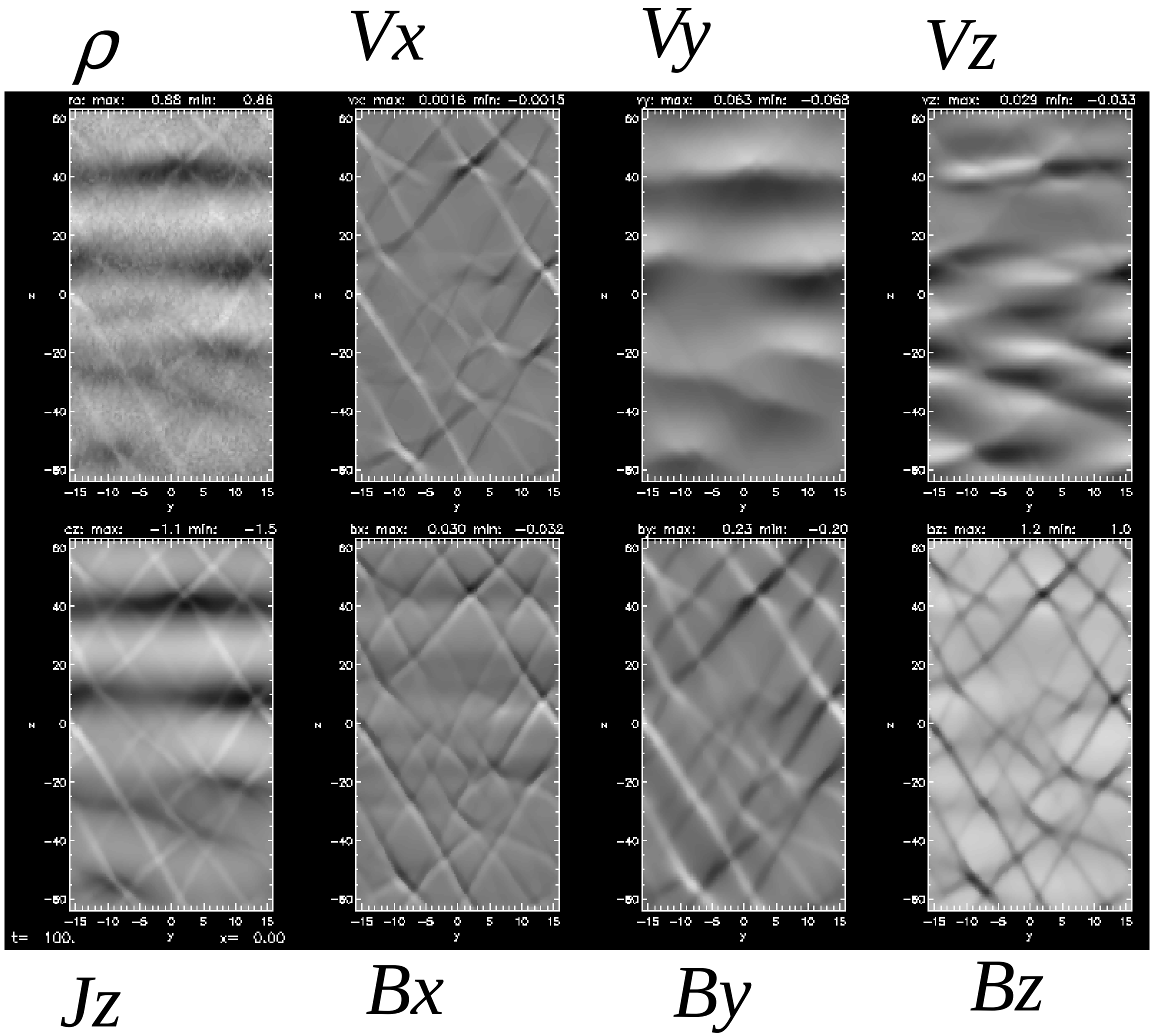
Bz0/By0=0.1



Evolution of a “network” structure in the current sheet

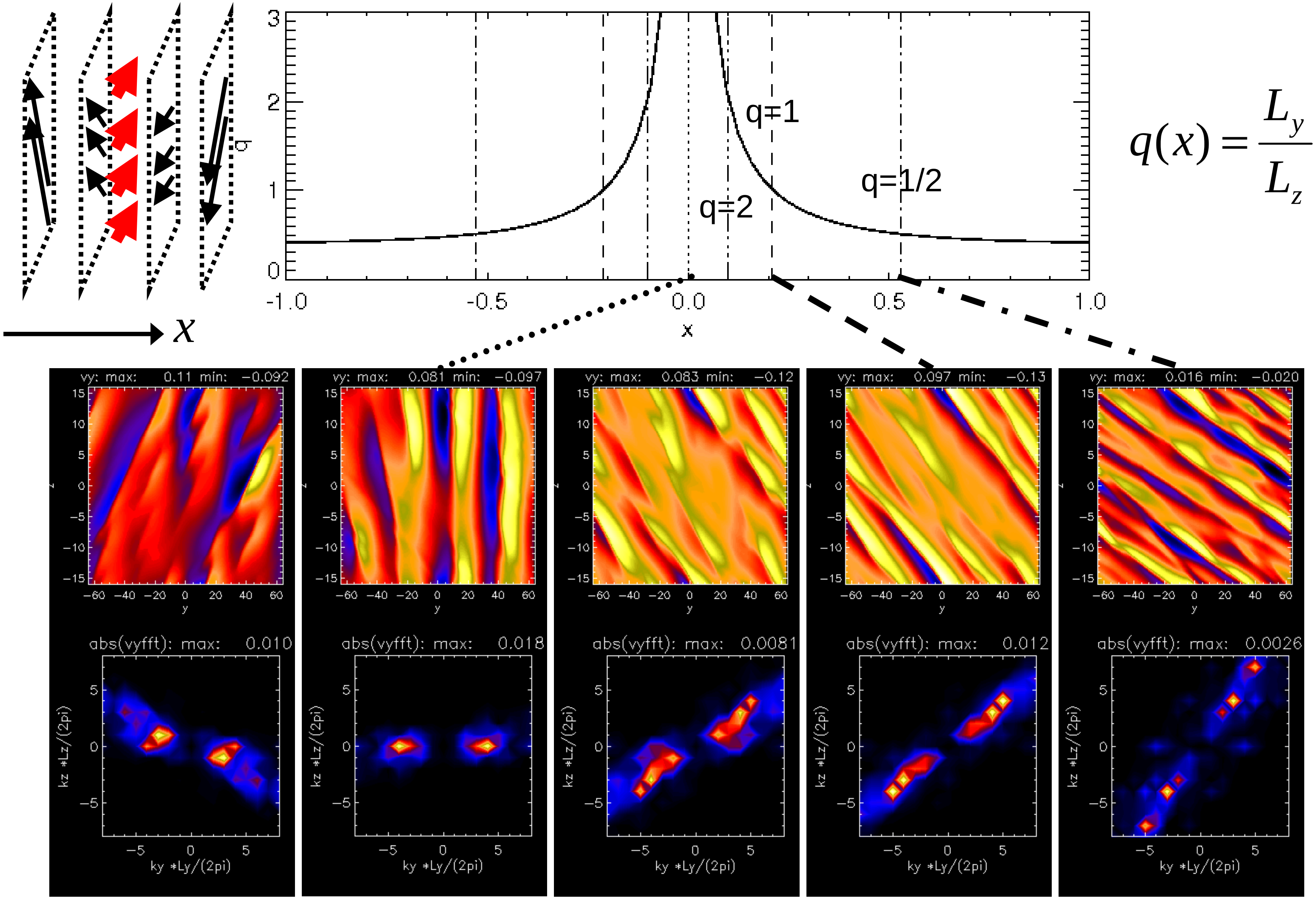






In the early phase of the evolution, a “network” structure is generated in the current sheet. This is a key to understanding the evolution of stronger turbulence in the current sheet.

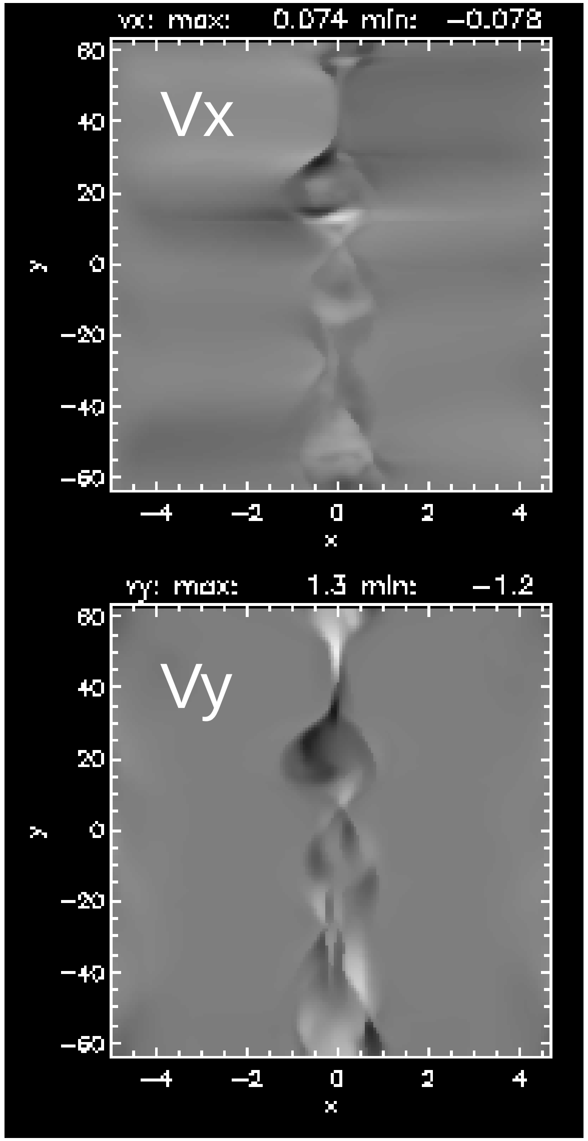
Structure in the resonant surfaces

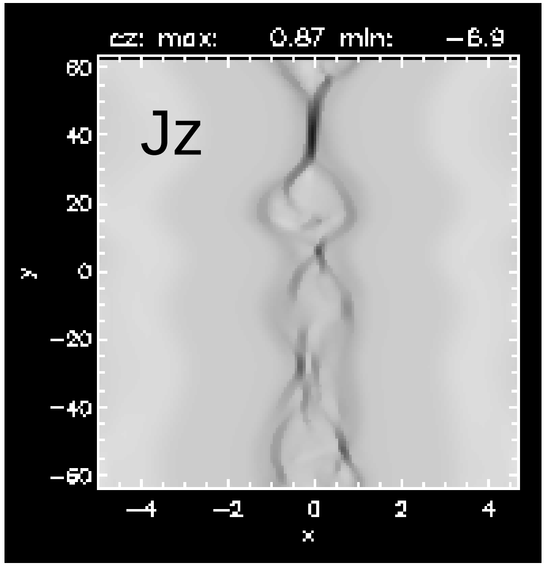


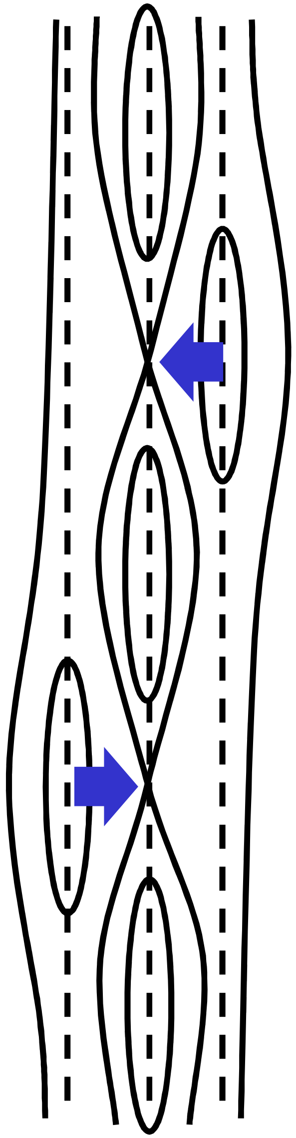
$$q(x) = \frac{L_y}{L_z}\left|\frac{B_z}{B_y}\right|$$

The amplitude of the tearing mode is larger at the “resonant surfaces” in each of which the q(x) prameter has rational value.

Interpretation: Enhancement of reconnection by interactions of magnetic islands

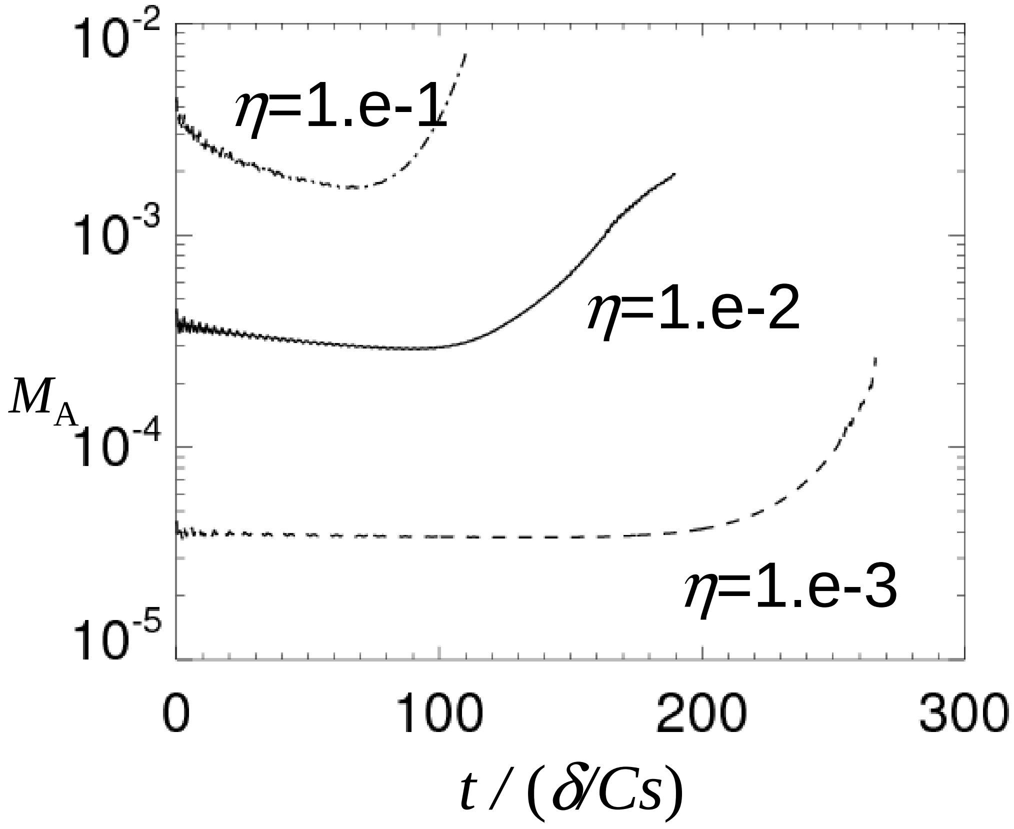






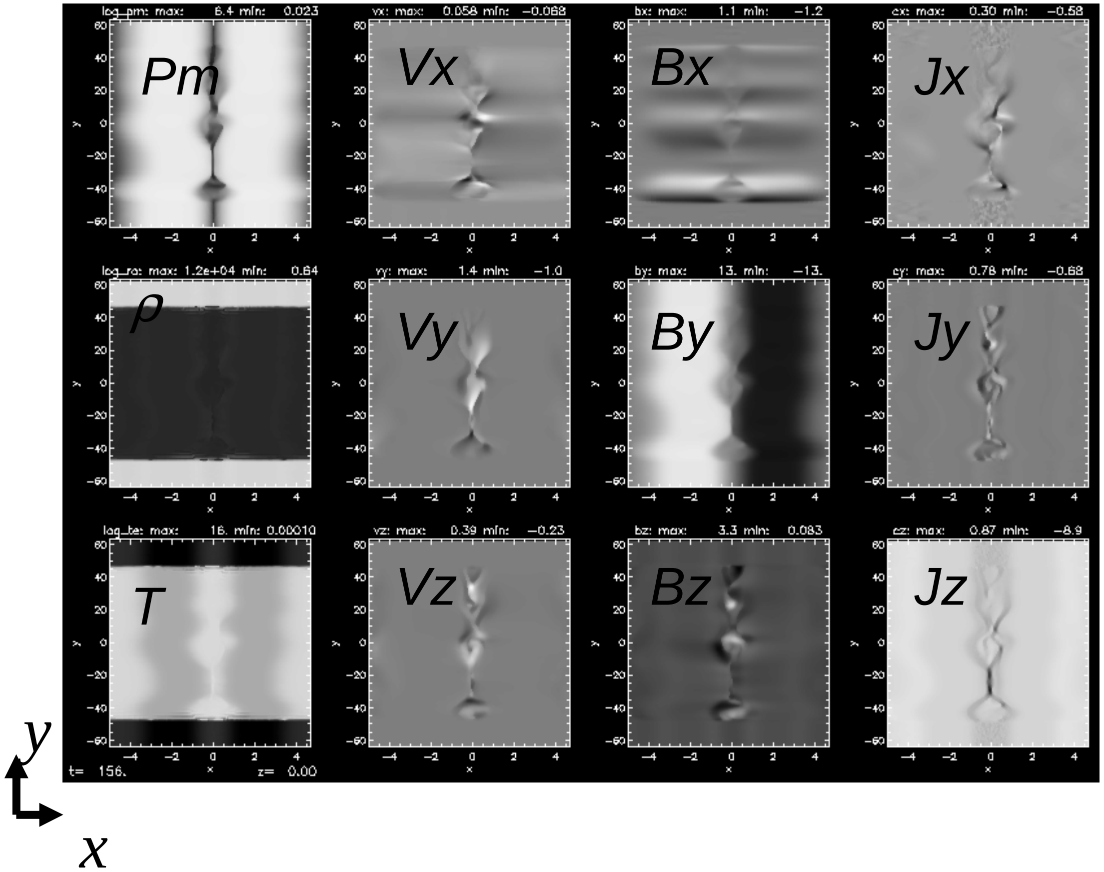
Magnetic islands are generated in multiple planes at the resonant surfaces. The generated islands push the neighboring X-points to enhance the reconnection there.

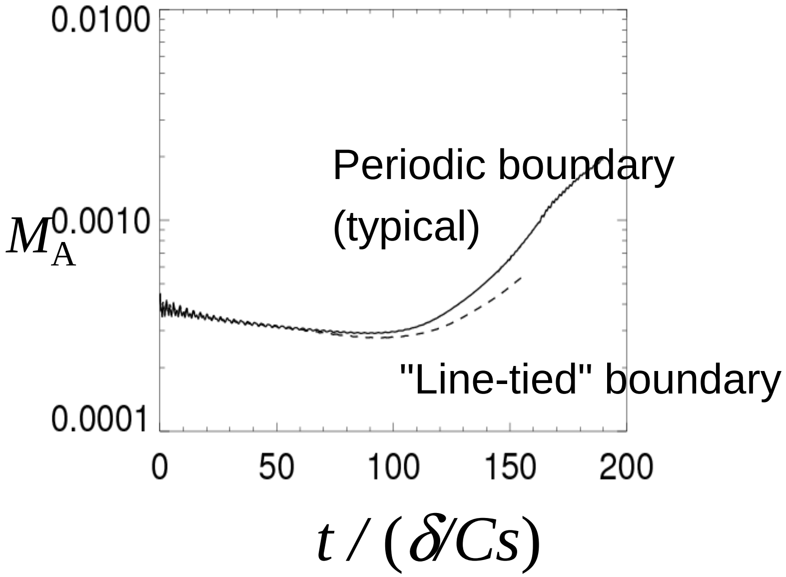
Dependence on resistivity



• Although, due to the numerical reasons, the final convergence of reconnection rate is not achieved, all the worked cases show an enhancement of the energy release.

Dependence on Boundary Conditions





- To see the boundary effect, we imposed high-density regions (|*y*/*d*|>48, r/r_0=1e4) near the y-boundaries (to mimic the line-tied boundaries along with avoiding an artificial strong current density).
- The resonance mechanism still does work even in this case though slightly weaker than the periodic-boundary (typical) case.

Summary

By performing 3D simulations of reconnection in a current sheet with initial finite peruturbations, we found:

- 3D turburent structures evolve in the current sheet via the collisions of outflows and inflows of elemental multiple reconnection points.
- Slight increase (3%) of energy-release rate above the Sweet-Parker rate is observed.
- The dependence on the magnetic Reynolds number is consistent with that of the Sweet-Parker model.
- By adding the uniform guide-field, an enhancement of reconnection rate (by several times) is found.
- The reconnection occurs simultaneously in *multiple* planes parallel to the current sheet. These planes are the resonant surfaces where the tearing mode locally has a larger amplitude. The generated magnetic islands in the inflow regions push the X-points and enhance the reconnection.