一様抵抗MHDにおけるプラズモイド不安定性（PI）は物理か？
MHD study of Plasmoid Instability (PI) with uniform resistivity

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Plasmoid Instability (PI)

- Multiple reconnection process.
- For high S (Lundquist number),i.e. weak uniform resistivity η , the reconnection process can become extremely bursty and stochastic, generating high reconnection rate η J independent of S (∝Rm∝1/η).
- In these ten years, PI became very popular. Many MHD studies (Bhattacharjee, et.al., Loureiro, et.al., Cassak, et.al., Shibayama, et.al,,,,) have been published.

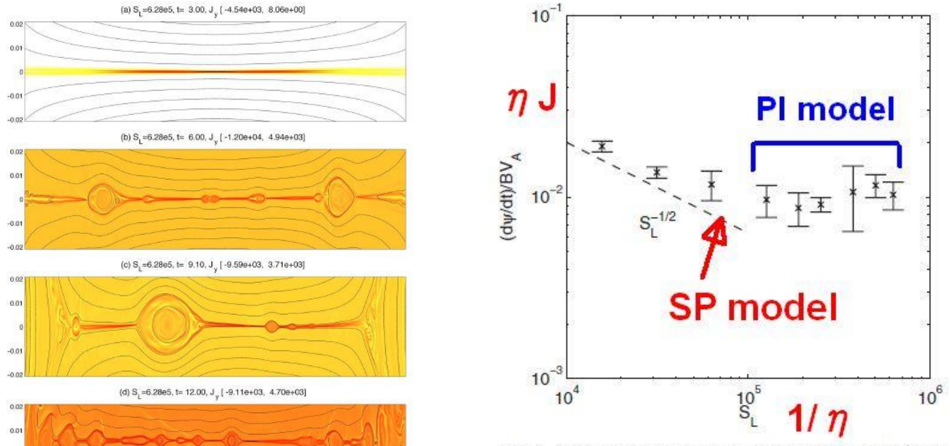
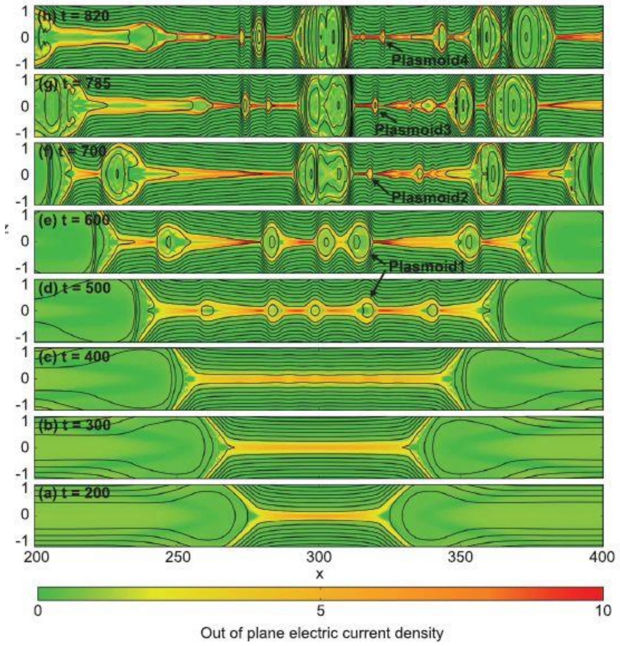


FIG. 3. Averaged reconnection rate as a function of S_L. Below $S_L \approx 3 \times 10^4$, the reconnection rate is Sweet–Parker and decays as $S_L^{-1/2}$, shown by the dotted line. Above this threshold, the reconnection rate becomes weakly dependent on S_L.

Bhattacharjee, et.al, PoP2009



Shibayama, et.al, PoP2015

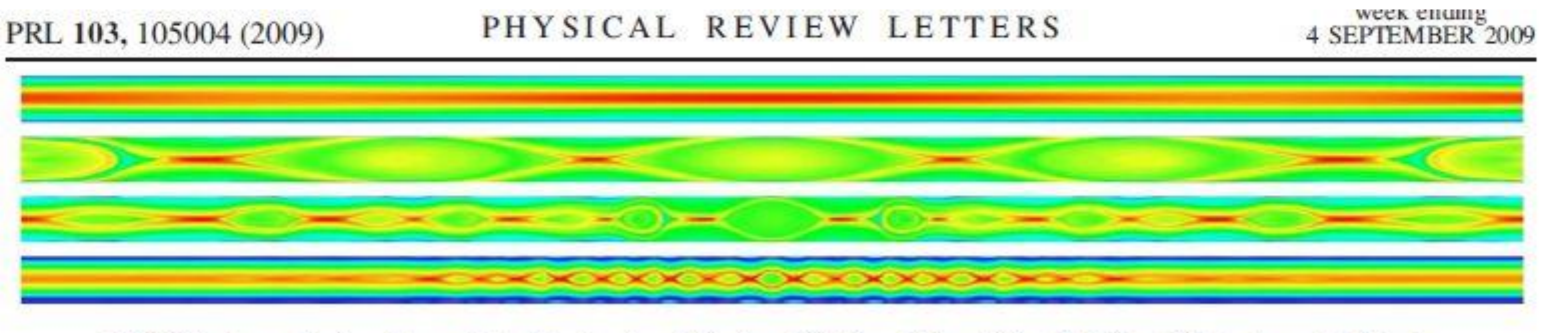


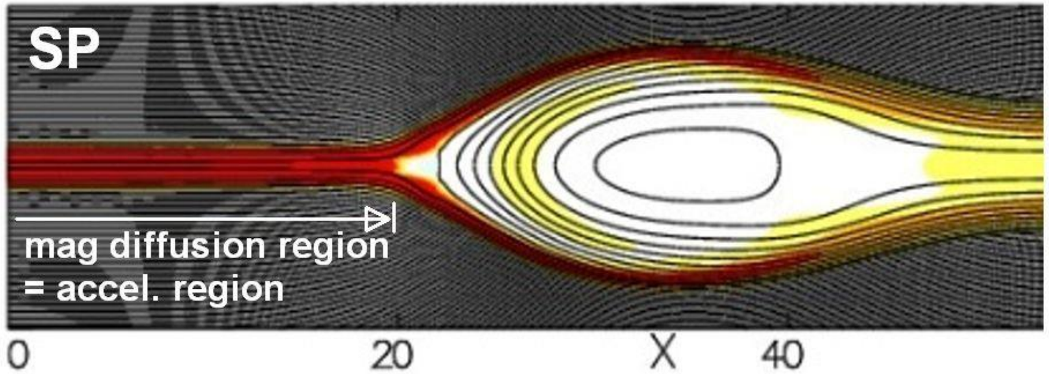
FIG. 2 (color online). Current density for $S = 10^4$, $S = 10^5$, $S = 10^6$ and $S = 10^7$. $S = 10^8$ is shown in Fig. 1.

Loureiro, et.al, PhysRevLett2009

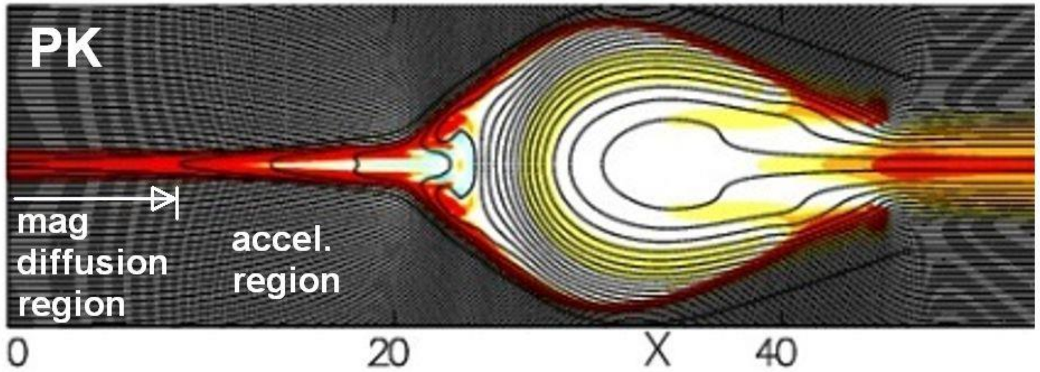
History of MHD reconnection process

<< **Theoretical** MHD models >>

- Sweet-Parker (SP) model (Sweet 1958 & Parker)➔



- Petschek (PK) model (Petschek, 1964) ➔



- FKR theory (1963) (linear tearing instability)

<< **Numerical** MHD studies >>

- Spontaneous model(Ugai,1977) vs Externally driven model(Sato, 1978)
- Uniform resistivity model vs Anomalous(non-uniform) resistivity model

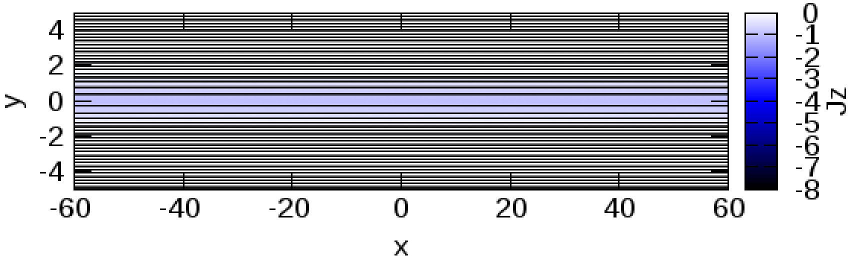
<< Our Final Goal is "What should be the "fast" mag. rec. ?" >>

- Spontaneous & Anomalous resistivity ➔ PK model
- Spontaneous, Uniform resistivity & FKR ➔ PI model (= multiple SP model)

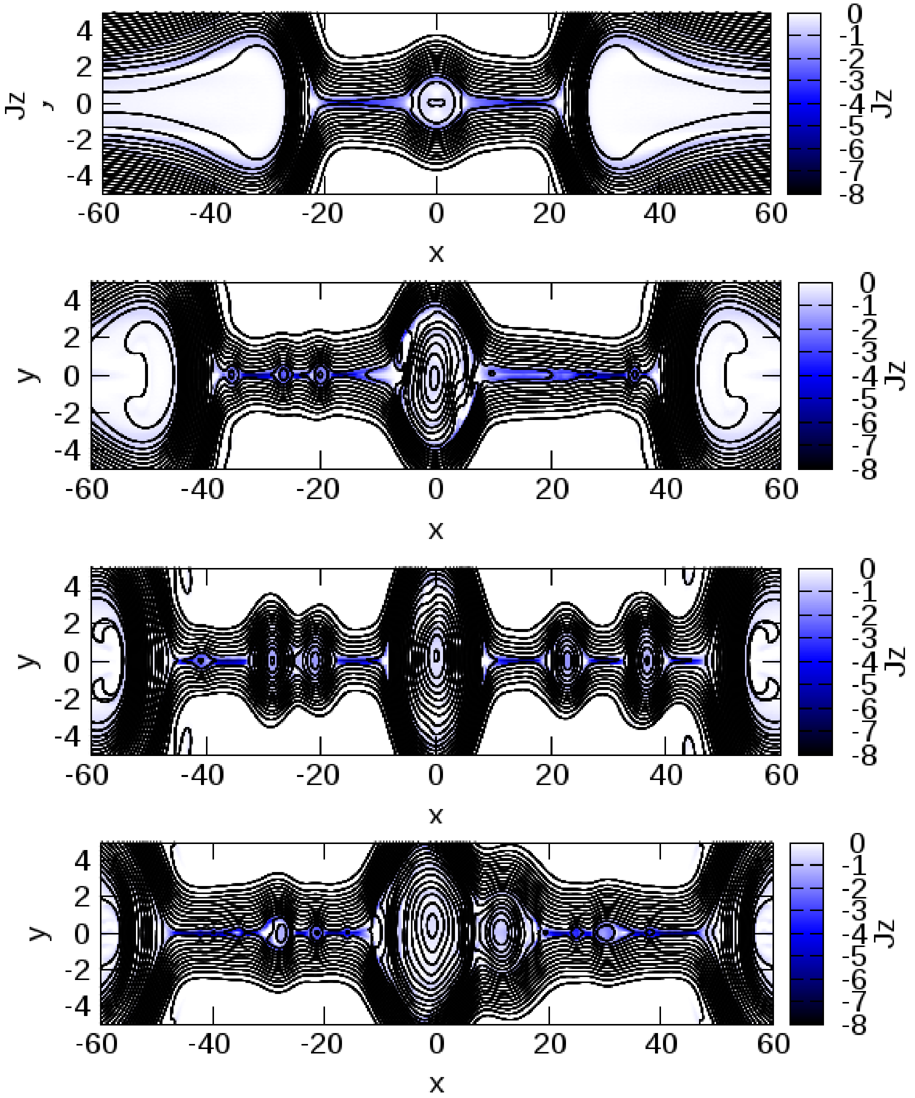
HLLD numerical scheme

- Excellent shock capturing scheme for MHD models
- Region size (Lx,Ly)=100*20
- Grid size (Nx,Ny)=3000*600～12000*2400 (e.g., Nx=3000 is dx=dy=1/15)
- HLLD setup
    - Slope limiter :minmod
    - Time marching :TVD RK2nd
    - Time step is automatically adjusted by CFL condition as time proceeds.
- Initial temperature is uniform without guide field. Initial upstream is Beta=0.15.
- Every boundary condition is symmetry, i.e. closed system model.
- For 0<T<5, a resistive disturbance to initiate mag rec is locally put around origin.
- For 5<T, the resistive disturbance is removed. Instead, uniform resistivity is maintained. Then, wait for PI.

T=130〜140　for Rm=50, 100, 250, 1000, and ∞

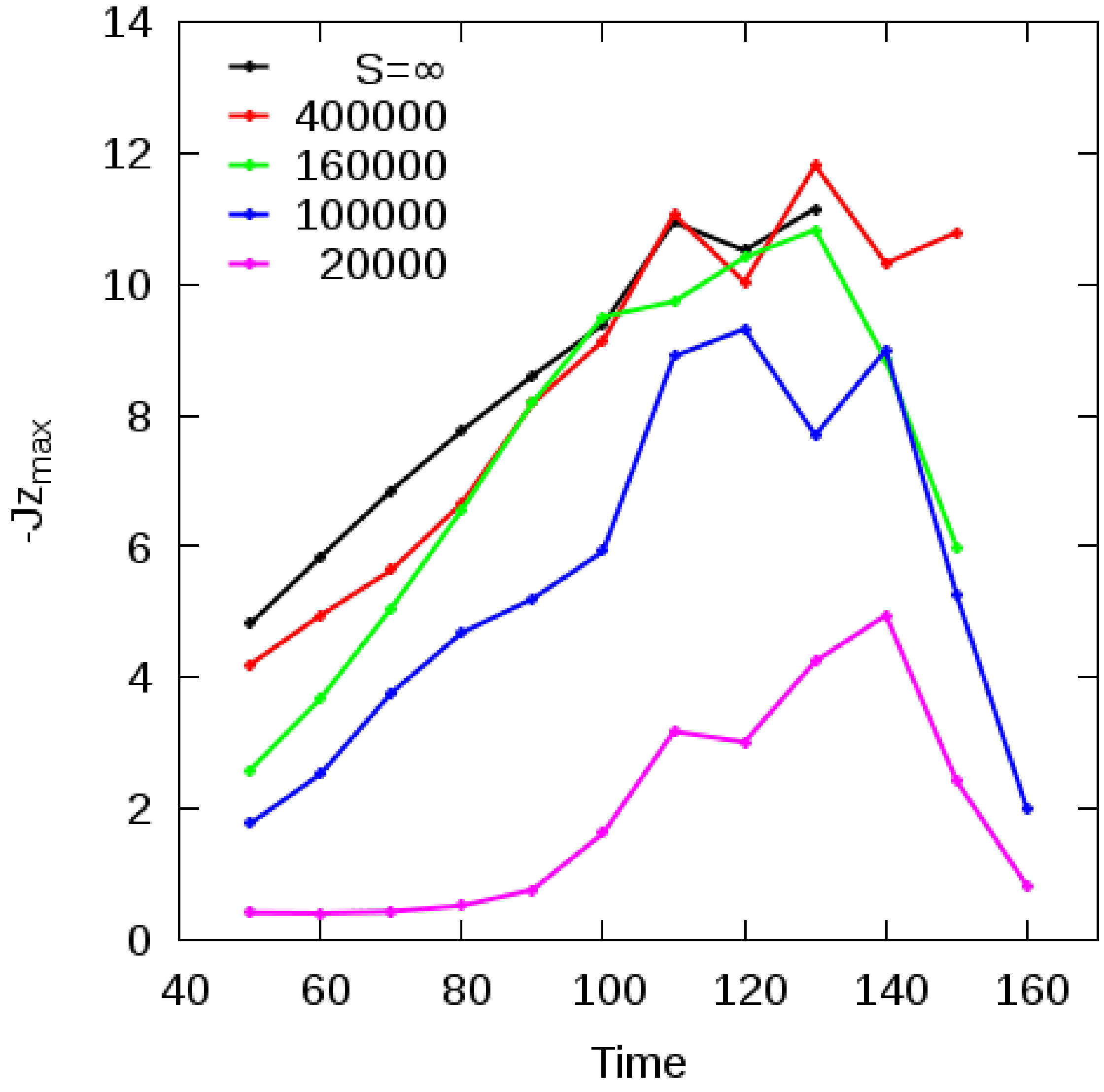


1D current sheet at T=0



- ランキスト数S(磁気レイノルズ数Rm)を上げるとテアリングが多発する。
- ただし、S(Rm)無限大でもテアリングが起こるのは明らかに数値的効果（計算誤差）。

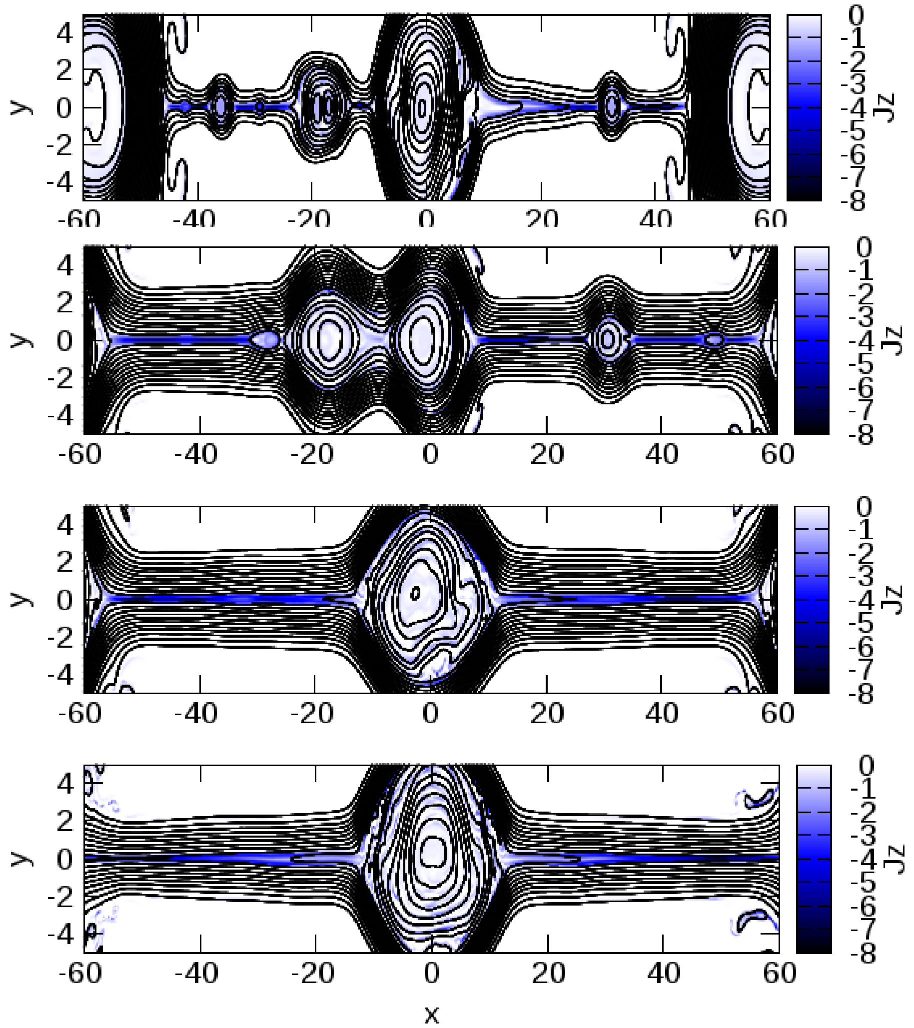
Time variations of Jz at X-point are numerically saturated.



- Jz-plot at the most active (highest Jz) X-point.
- Rm=∞　(S=∞)
- Rm=1000(S=400000)
- Rm=400(S=160000)
- Rm=250(S=100000)
- Rm=50(S=20000)
- Rm>400は

Jzの時間変化が数値的に飽和している。

As 1/dx increases from 15 to 120 for Rm=250, the plasmoid instability (PI) becomes less active.

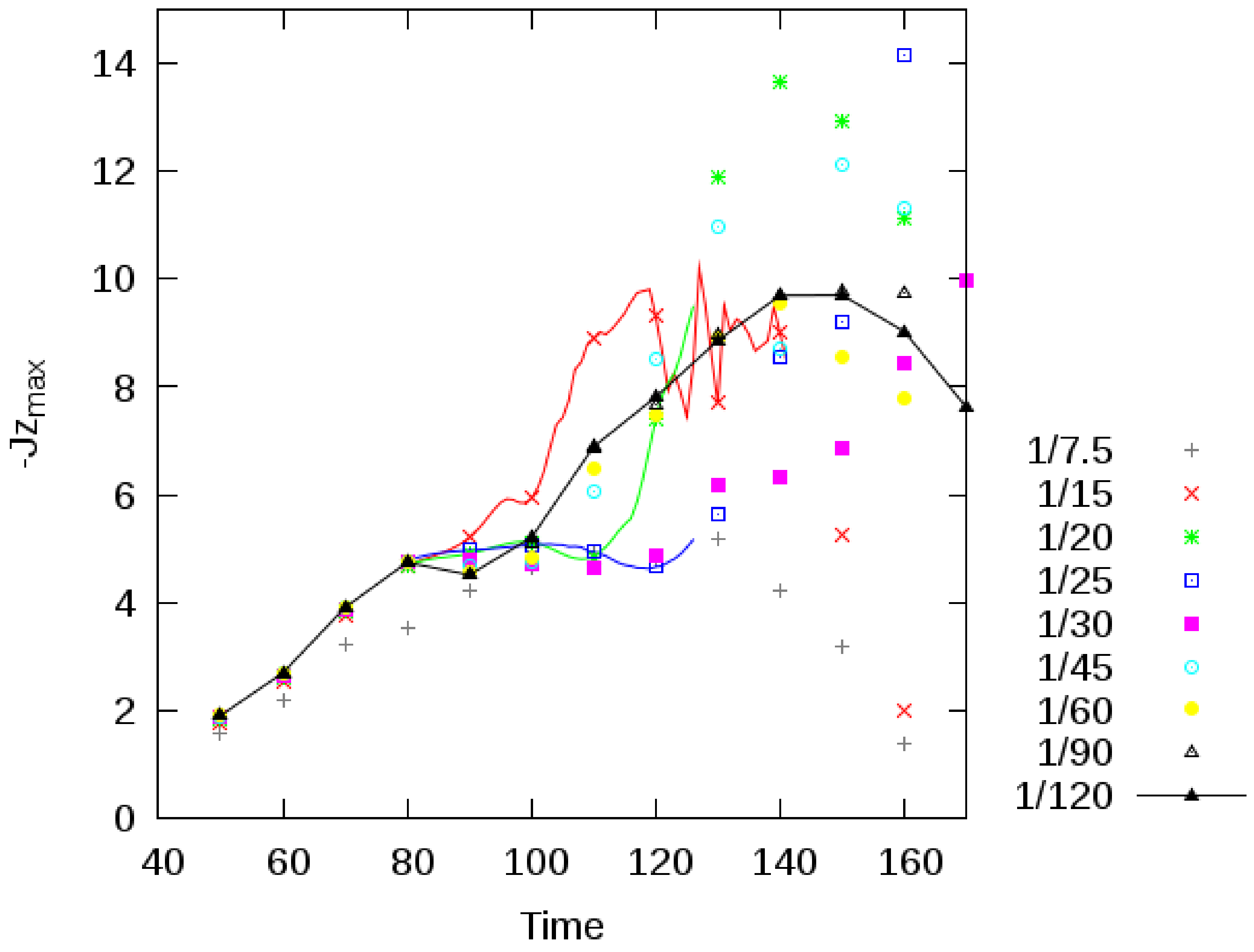


- dx=1/15, T=140
- dx=1/45, T=160
- dx=1/60, T=160
- dx=1/120, T=170
- 数値解像度1/dxを上げると
  PIは徐々に消える。

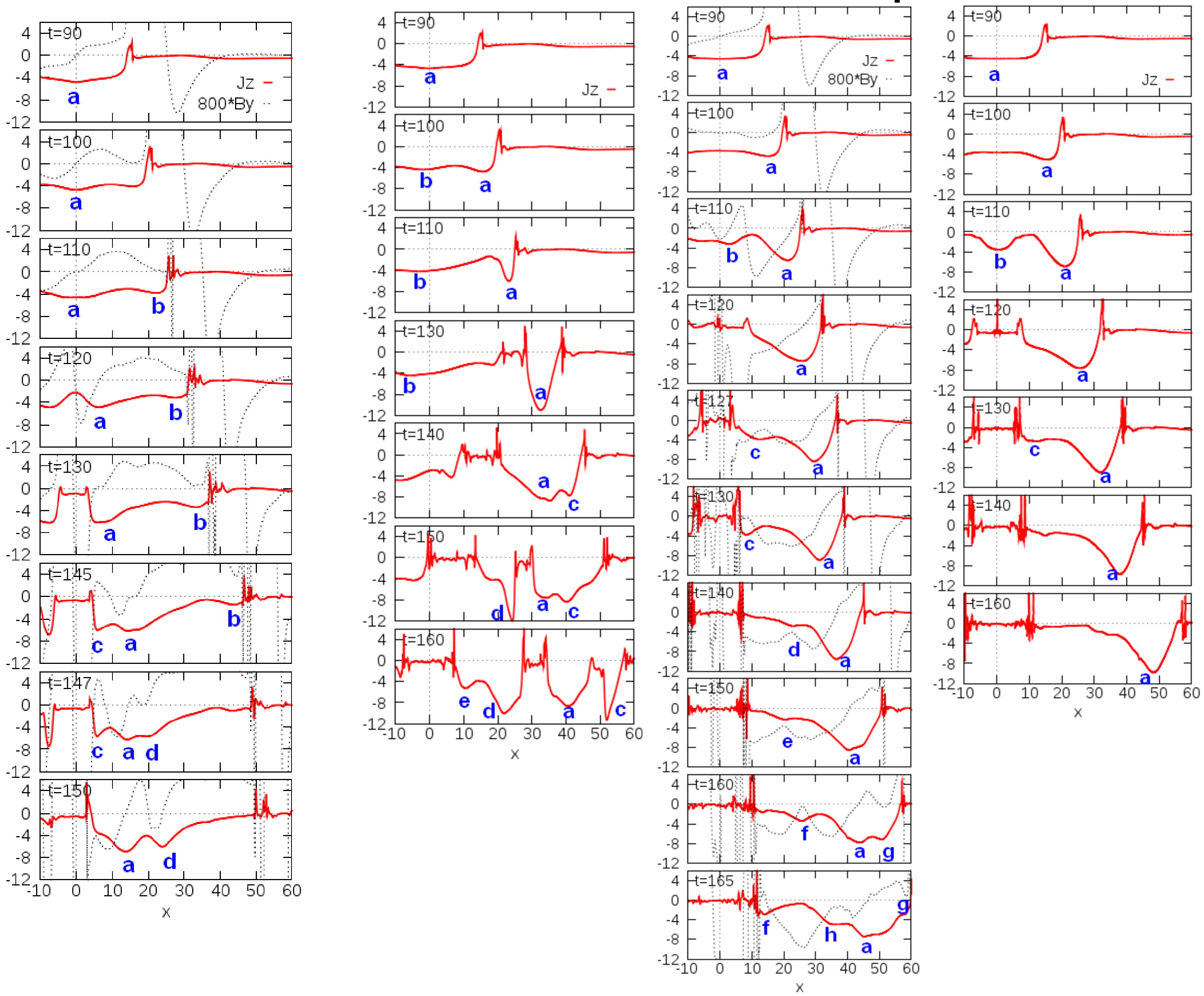
As 1/dx increases for Rm=250, the time variations of max-Jz at the most active X-point gradually converges to the black solid line.

The dx=1/120 result is numerically well-posed.
Hence, PI is NOT fully developed

1/dx増に対する数値解の収束性が見られる



Time variations of Jz-profiles on x-axis



- dx=1/30, 1/45, 1/60, 1/90の図
- ピーク（Jz<0）の高さ順にアルファベットで命名。
- dx=1/30から1/45への変化では、途中でJzピークaとb（大小）が入れ替わる（相転移）。
- **つまり、数値誤差によりある種の相転移が起こっている。**
- dx=1/45から1/90への変化は

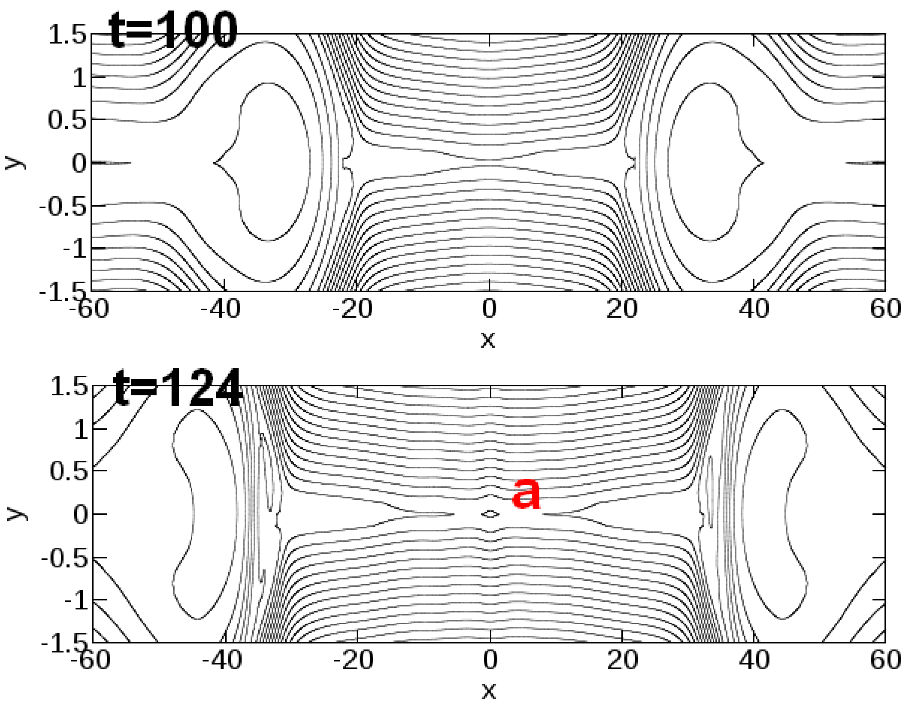
PIがless activeになる傾向。

A phase transition (drastic swtiching of Jz-peaks “a” and “b”) is observed between 1/30 and 1/45, where alphabetical order means the order of higher Jz-peaks.

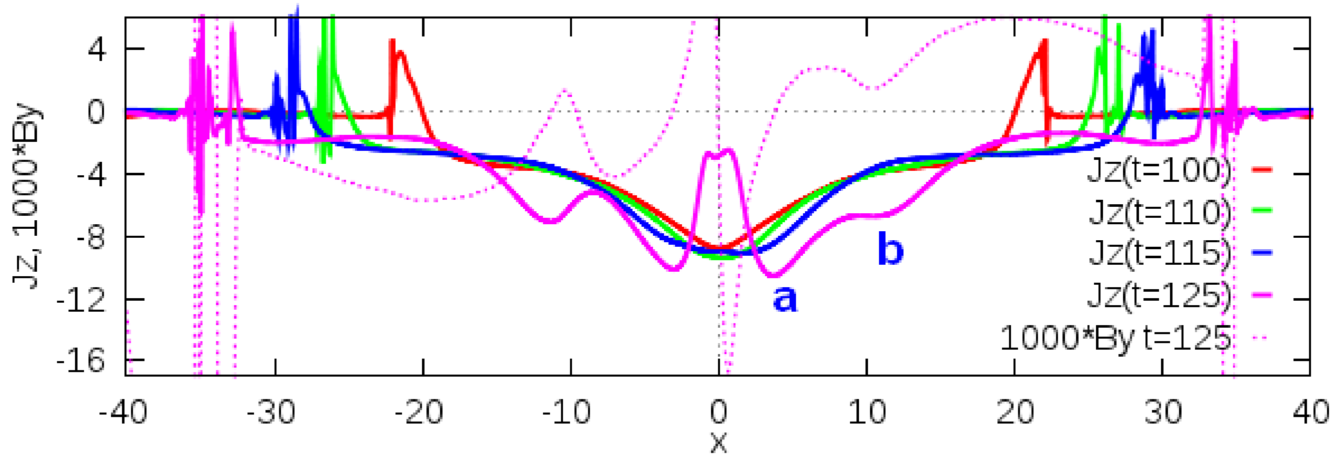
Numerical converging observed from 1/45 to 1/90 shows PI tends to be monotonically less active.

対称テアリングと非対称テアリング

symmetric and asymmetric tearing instability   (exactly, two types of Jz-peak separations)

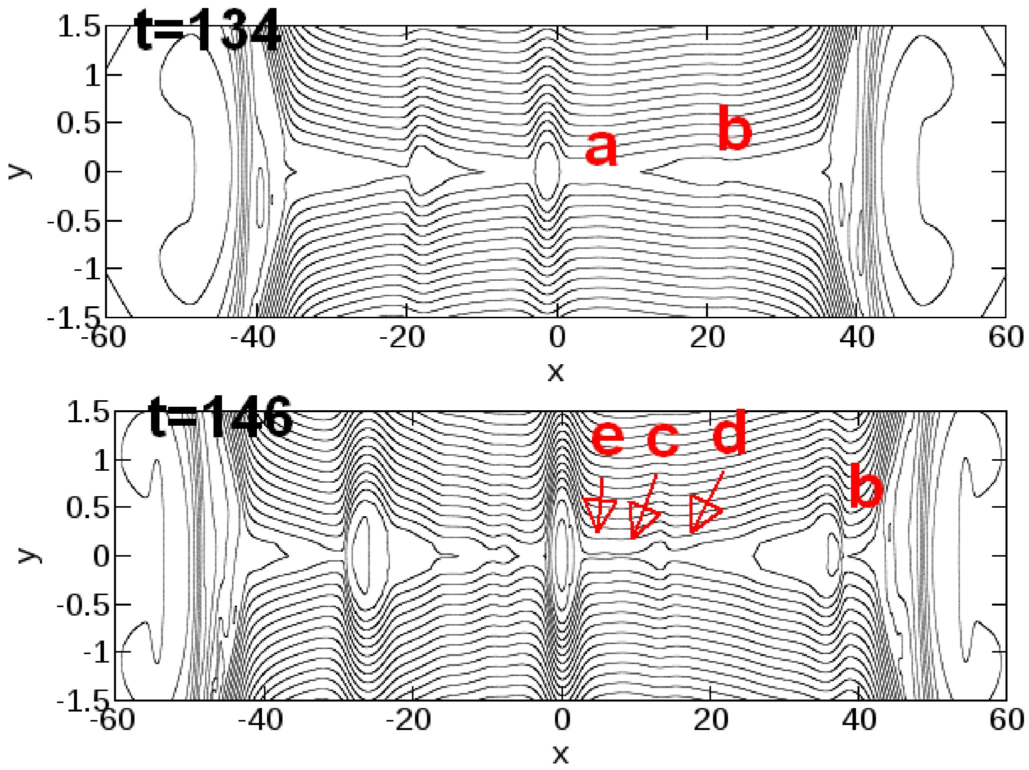


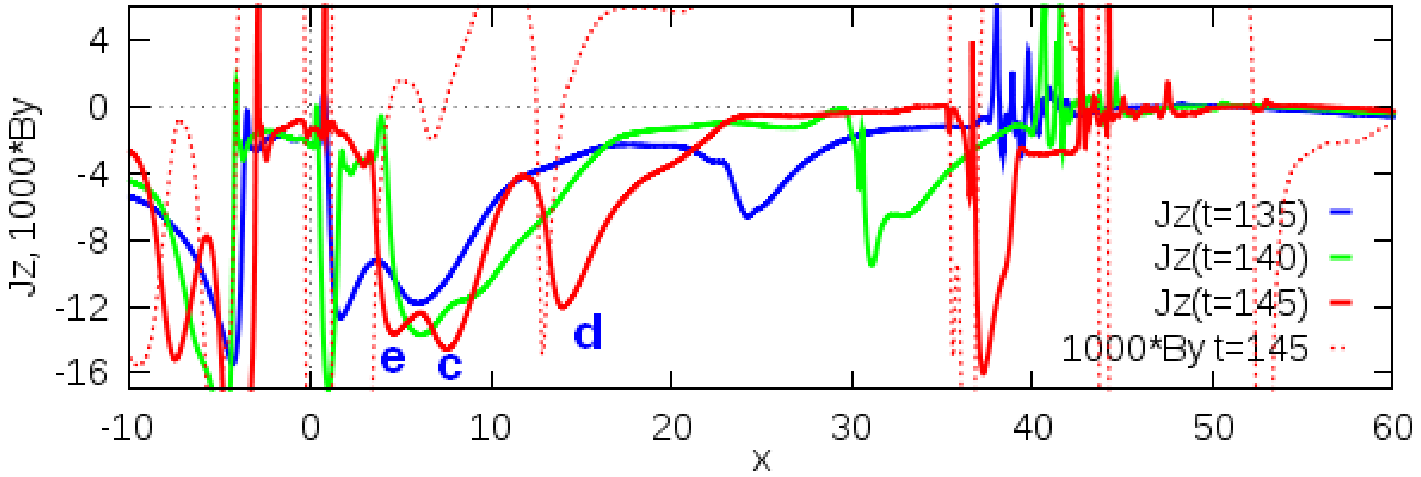
Rm=1000, dx=/90, 100<T<125



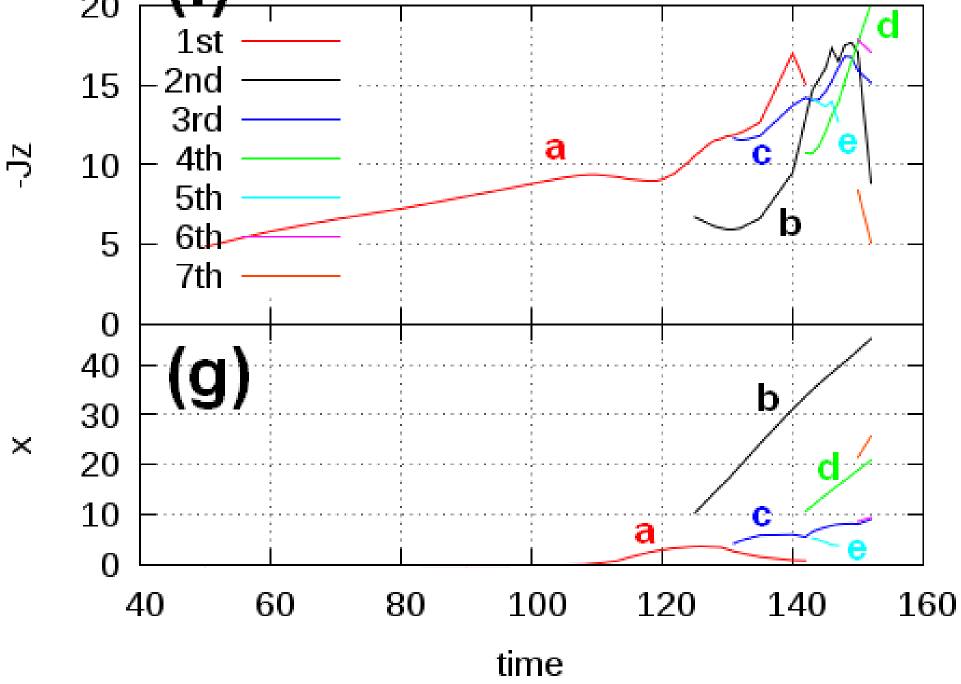
- Observe that a Jz-peak is bifurcated to two Jz-peaks.
- The bifurcation can be classified into symmetric (a) and asymmetric (b) case.
- The symmetric case (a) tends to affect a phase transition for larger 1/dx.

Rm=1000, dx=1/90, 134<T<146





(f) Time development of Jz-peaks in 40<T<150



まとめ

- 一様抵抗MHDで起こるPIは数値的な影響をうけて速い(PKライクな)リコネクションになる。
- 数値的な影響を排除すると、遅い(SPライクな)リコネクションになる。

- MHD-PI with uniform resistivity is studied with HLLD code.
- As numerical resolution 1/dx increases, PI tends to be less active where drastic Jz-peak separations may be caused as phase transitions.
- Symmetric tearing instability, i.e. symmetric Jz-peak separation tends to affect the phase transition due to numerical errors.
- We cannot numerically confirm that the fully developed PI is reproduced. It suggests that Sc (critical Lundquist number) dose not exist.