Magnetic Reconnection in the Magnetotail: Onset Mechanisms and Structure of Exhaust Jets in 3D

P. L. Pritchett - UCLA

- Onset Problem in Presence of Finite Normal B_z
- 3D Structuring of Exhaust (Dipolarization) Fronts

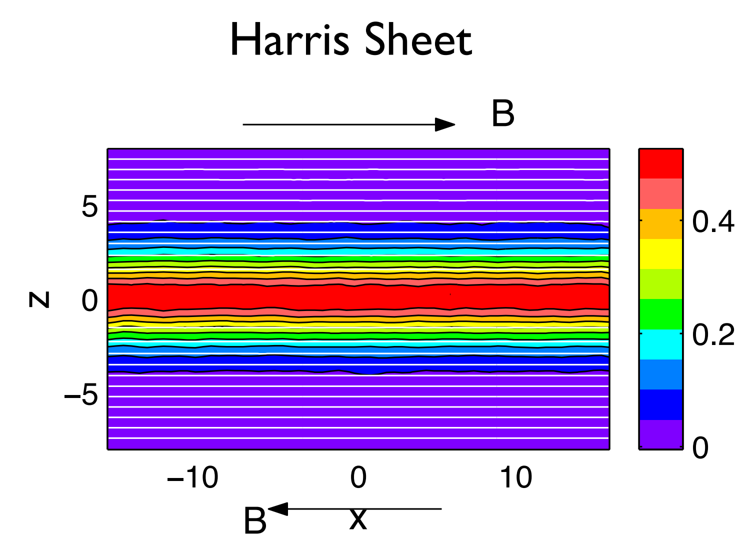
Reconnection Onset in Presence of B_z

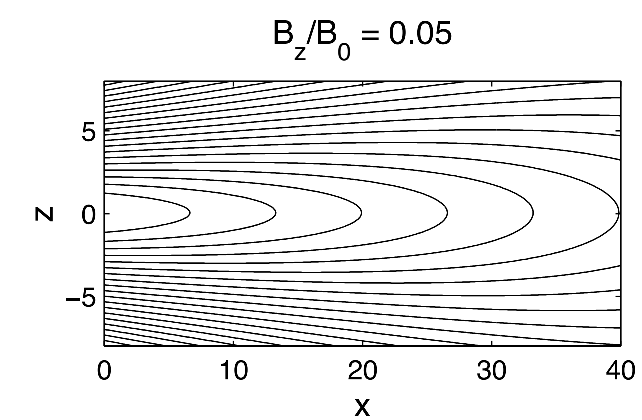
- Usual Reconnection Configuration: Harris Current sheet; not directly applicable to magnetotail due to B_z.

- Electron Tearing Instability: not viable since cyclotron motion removes electron Landau resonance.

- Ion Tearing Instability (Schindler, 1974)?
  - Unless half width comparable to d_i, growth rate too small to overcome ion magnetization.
  - Electron stabilization effect: Either electron adiabaticity (Lembège & Pellat, 1982) or simply conservation of P_y in 2D system (Pellat et al., 1991) ensures that tearing mode EM field produces strong compression of electron density. Energy associated with this compression exceeds free energy in reversed B configuration.
  - Condition for electron stabilization: $k\rho_{en} < 1$, which is satisfied for very small $B_z \sim 0.01 - 0.1$ nT.

- Spontaneous tearing instability unlikely to occur in the magnetotail.





- Multi-Scale Current Sheet (Sitnov and Schindler, 2010)

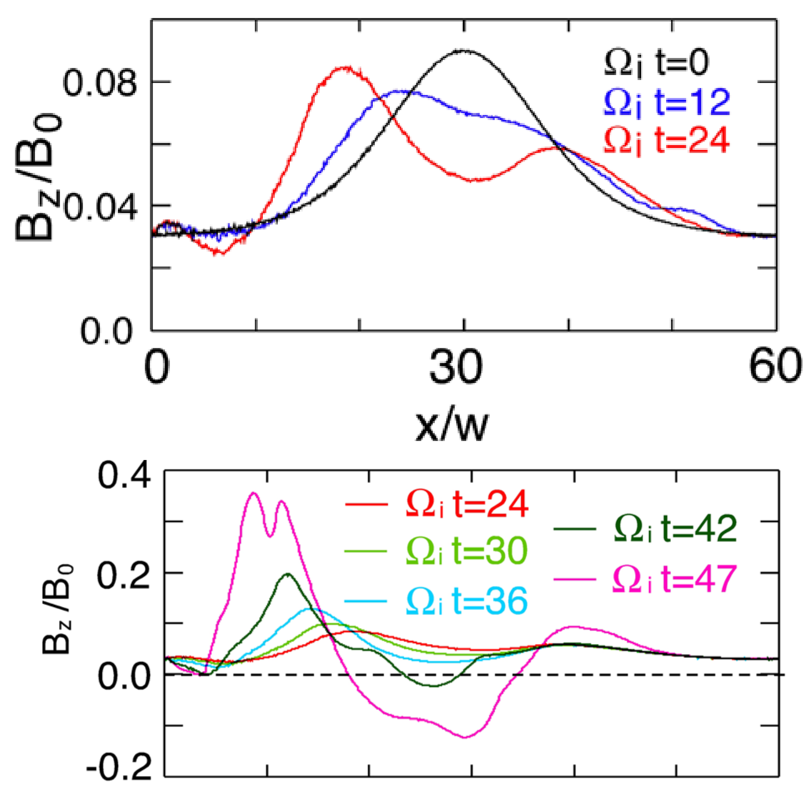
Sufficient stability condition for tearing mode with wavenumber k_x in 2D current sheet can be written as

$$k_x L_z/\pi b > (V B_z/\pi L_z)^2 \equiv C_d^2,$$

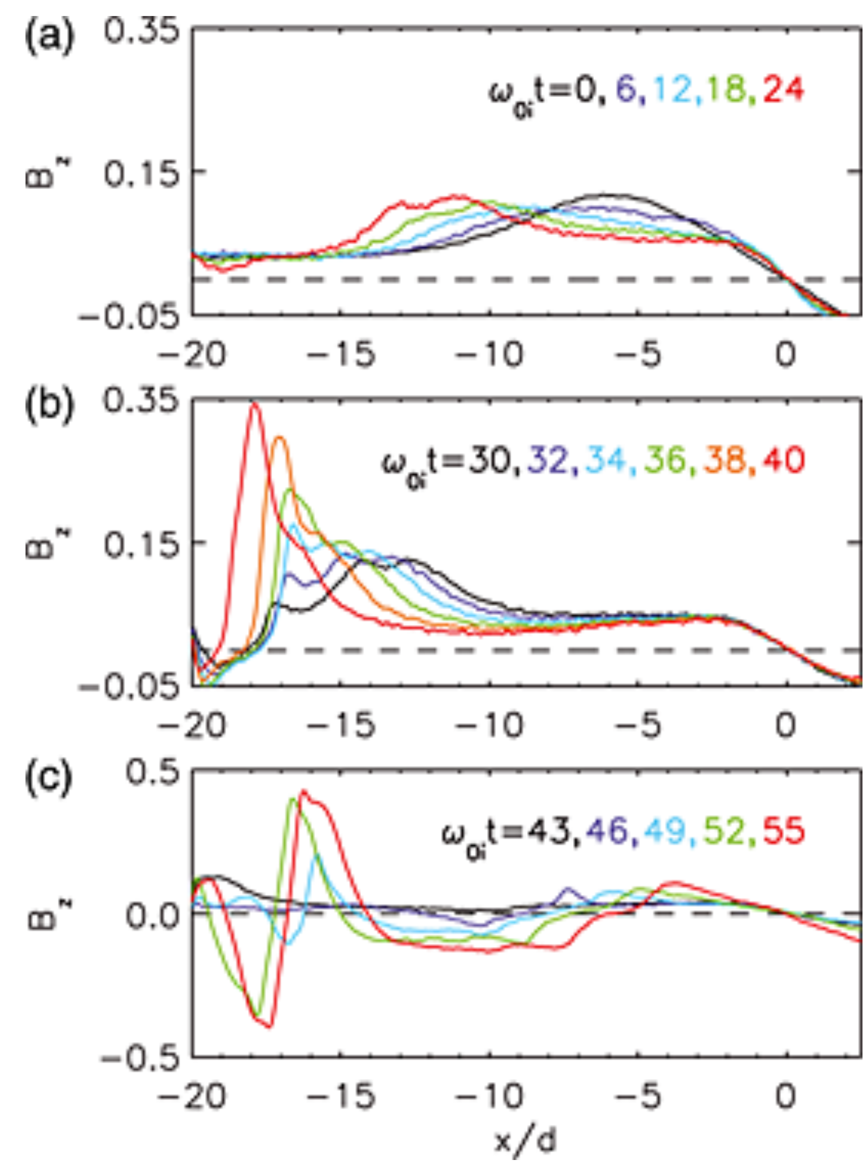
where flux tube volume $V = \int dl/B$. If $C_d < 1$, then mode is stable within WKB limit $k_x L_z/\pi b > 1$. Only way to obtain $C_d > 1$ and thus allow possibility of instability is with an accumulation of B_z flux at tailward end of current sheet.

2D PIC Simulations with open boundaries

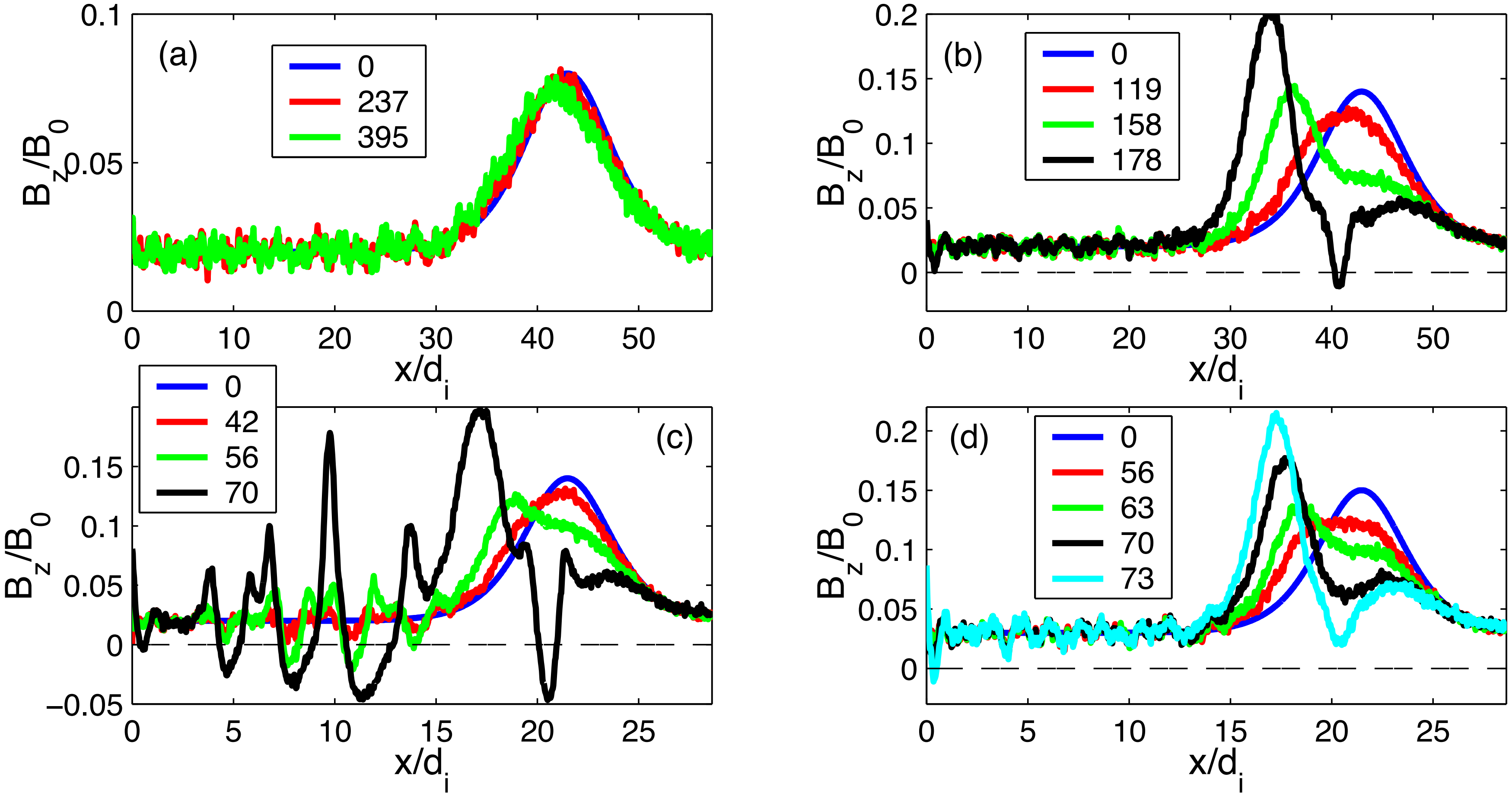
Bessho & Bhattacharjee, 2014



Sitnov et al. 2013



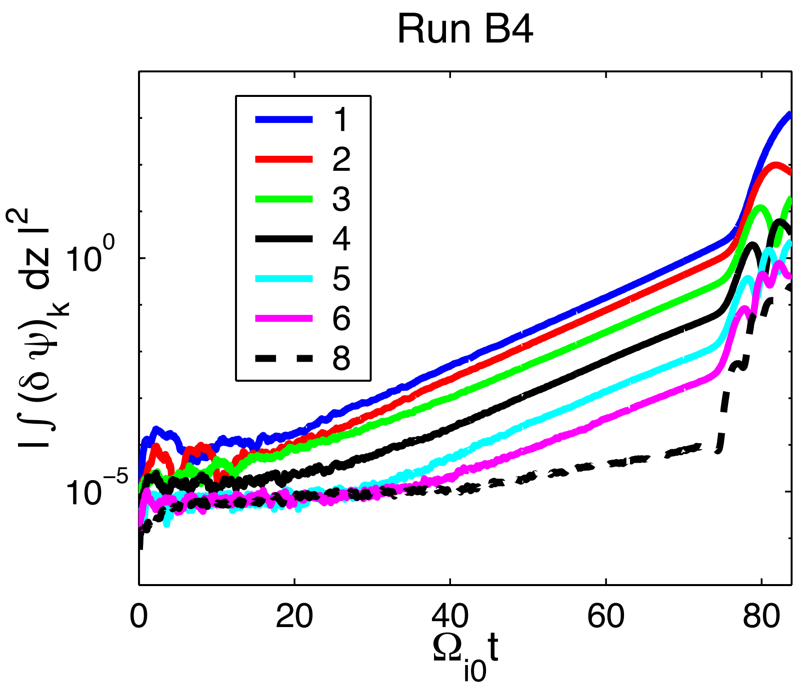
Stability of Current Sheets with a Localized B_z Hump



$m_i/m_e = 64$
$L_z/d_i = 1.43$

$m_i/m_e = 128$
$L_z/d_i = 0.72$

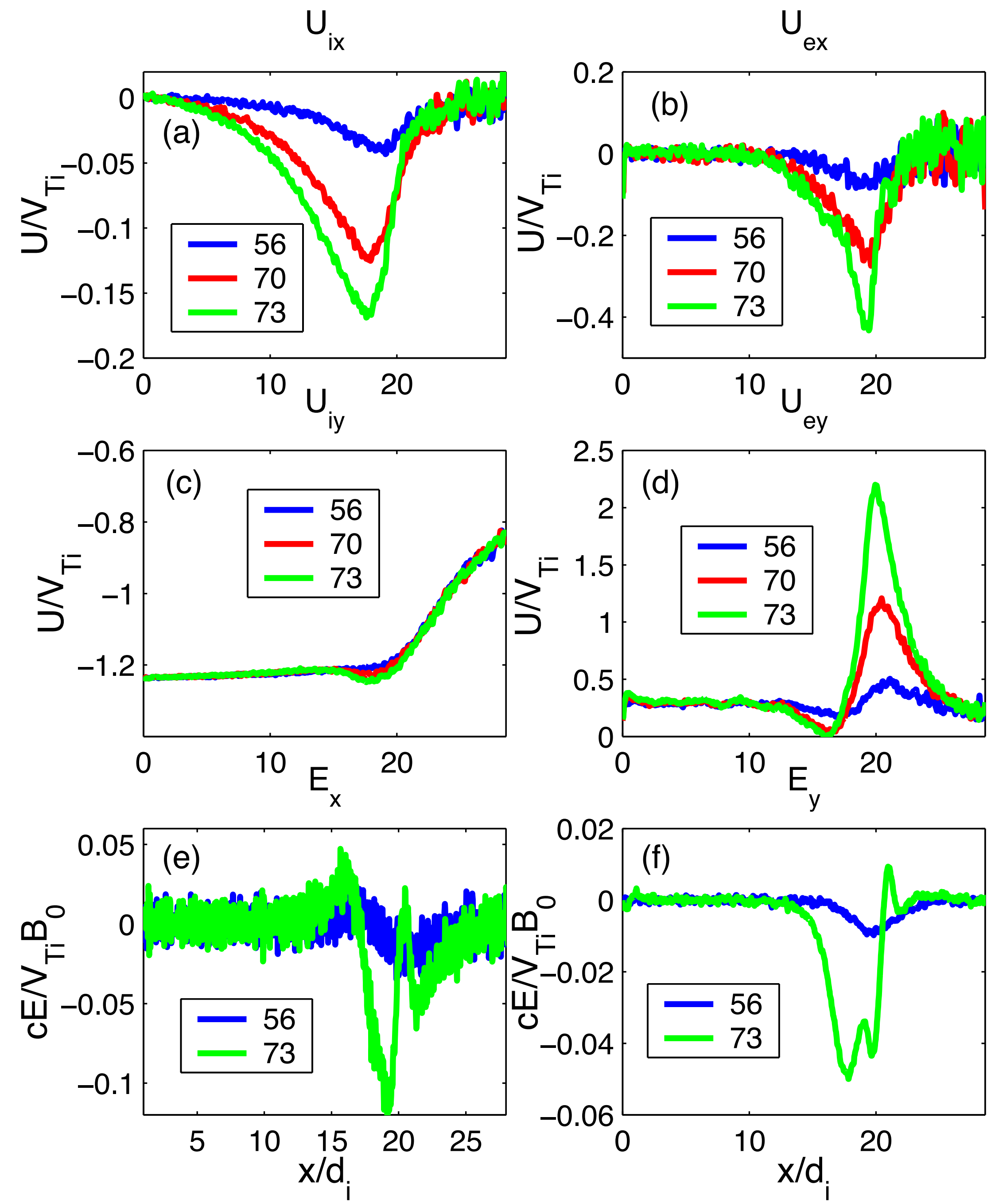
- 2D PIC with closed boundary conditions; hump is well isolated from earthward boundary.
- Ideal-like mode observed: earthward shift of hump and erosion of tailward side. Eventually leads to formation of X line near original hump position; no activity in extended low-B_z region prior to this.
- Possible case of internally driven reconnection onset ("flux starvation").



- No tearing instability, but a coherent development over many modes.

	B4	B2
γ/Ω_{i0} =	0.086	0.031
γ/Ω_{iL} =	0.022	0.011

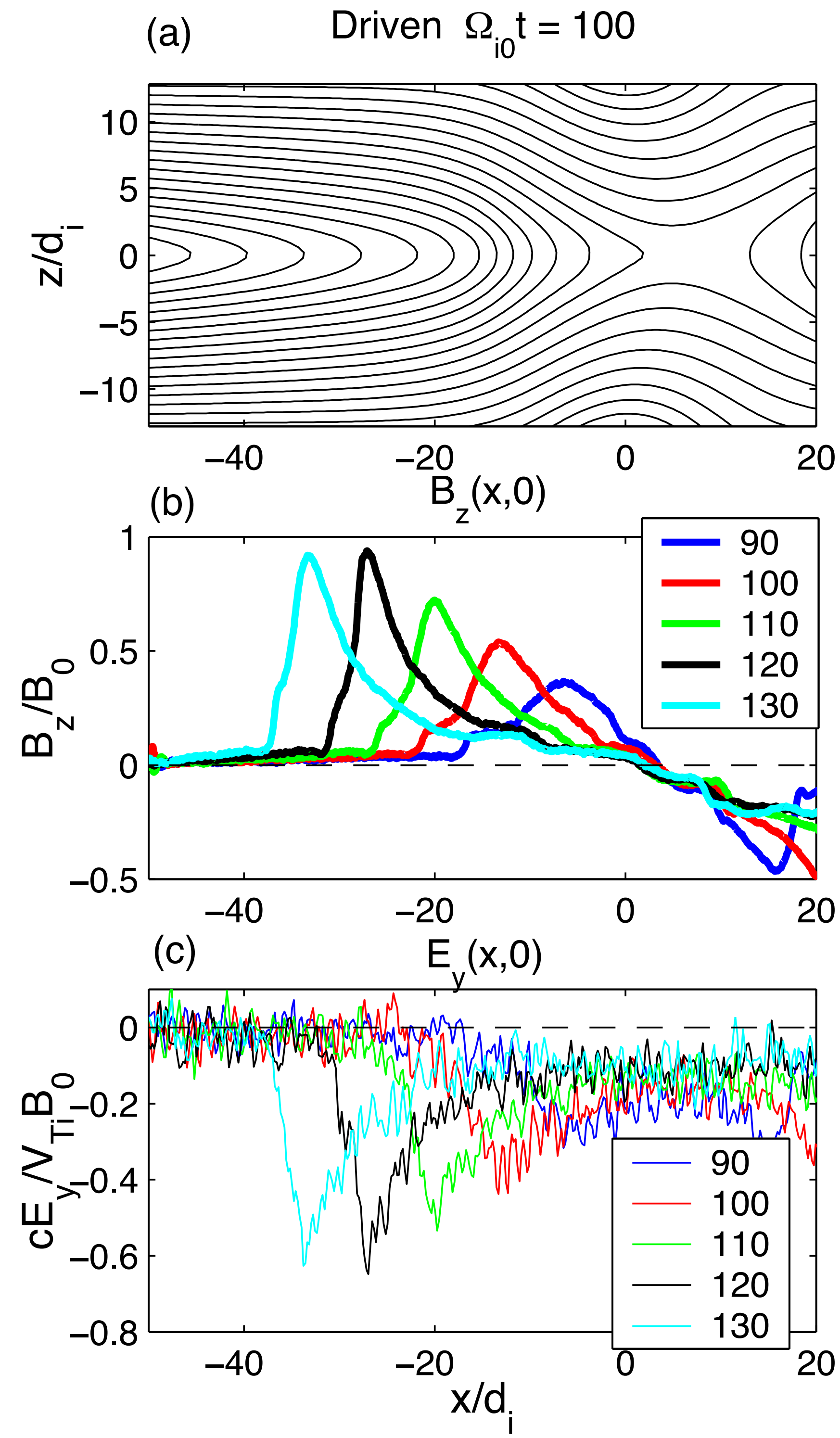
- In open system growth rate is an order of magnitude larger; initial equil. begins to move in less than an ion gyroperiod based on the asymptotic B_x field at hump.



- Flows concentrated in hump region, but U_{ix} extends further earthward; mode can be stabilized by a too close boundary.
- No development of E field outside of hump region prior to X line formation.

Relation Between Reconnection Jets and the Hump Configuration

- Perform driven 2D PIC simulation ala Newton Challenge (finite boundary displacement) with open boundaries starting from a Lembege-Pellat current sheet with $B_z/B_0 = 0.02$, $L_z/d_i = 2.0$.
- As time progresses, the B_z jets steepen (up to $0.9\ B_0$) and the leading thickness decreases.
- On the trailing side are regions of low $B_z/B_0 \sim 0.2$ and reduced $|E_y|$; no sign of B_z evolving toward 0.
- Ongoing reconnection at the X line leads to replenishment of trailing B_z.
- Spontaneous decay of hump configuration may not be a good model to investigate magnetotail dynamics.



Dipolarization Fronts in the Magnetotail

- Earthward transport of mass, energy, and magnetic flux in magnetotail mainly associated with brief periods of fast plasma flow (300 - 400 km/s) (BBFs).

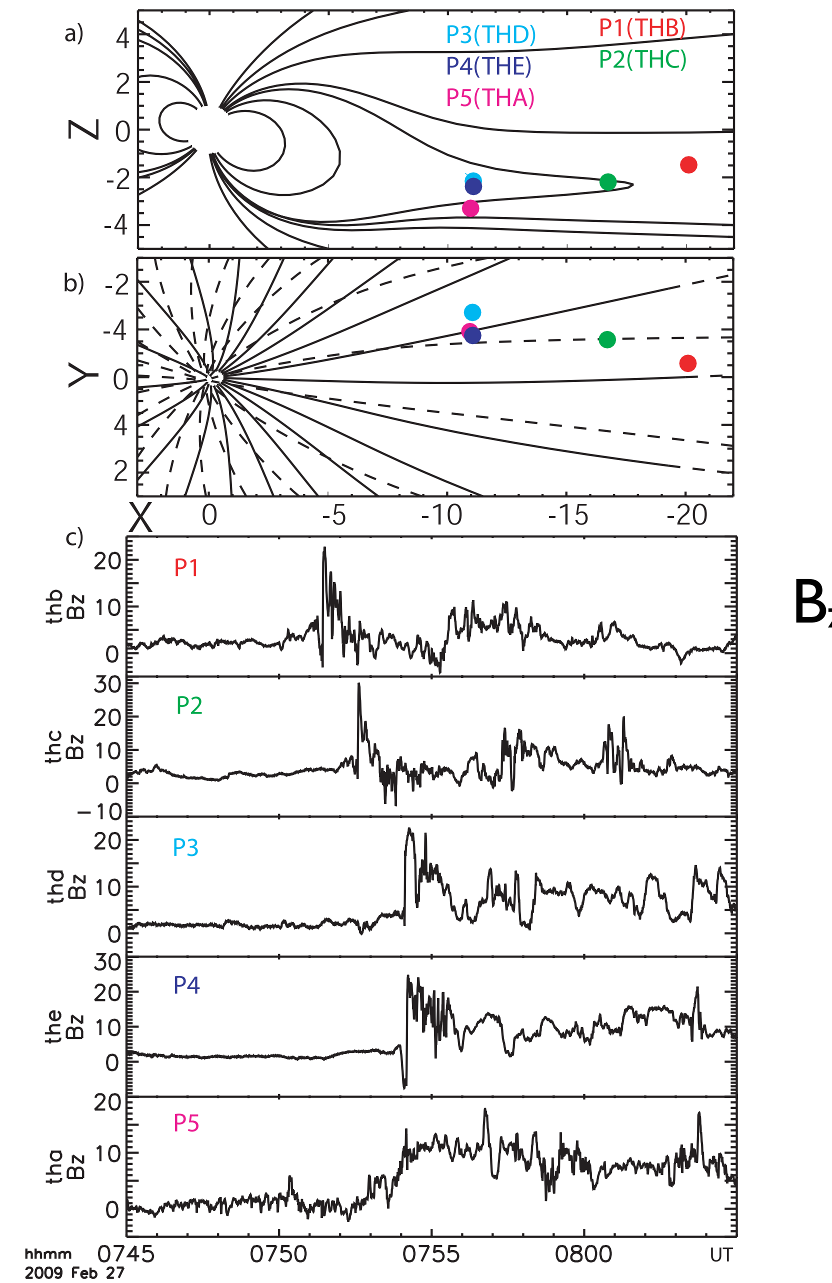
- BBFs confined to flow channels with cross-tail width ~ 1 - 3 R_E.

- Common feature at leading edge of BBF is sharp increase of B_z (termed a dipolarization front - DF) frequently preceded by a smaller negative variation.

- From THEMIS observations Runov et al. [2009] identified these DFs as coherent plasma/flow structures proagat-ing over distance ~ 10 R_E.

- Front thickness ~ d_i or ρ_{i0} (several hundred km).

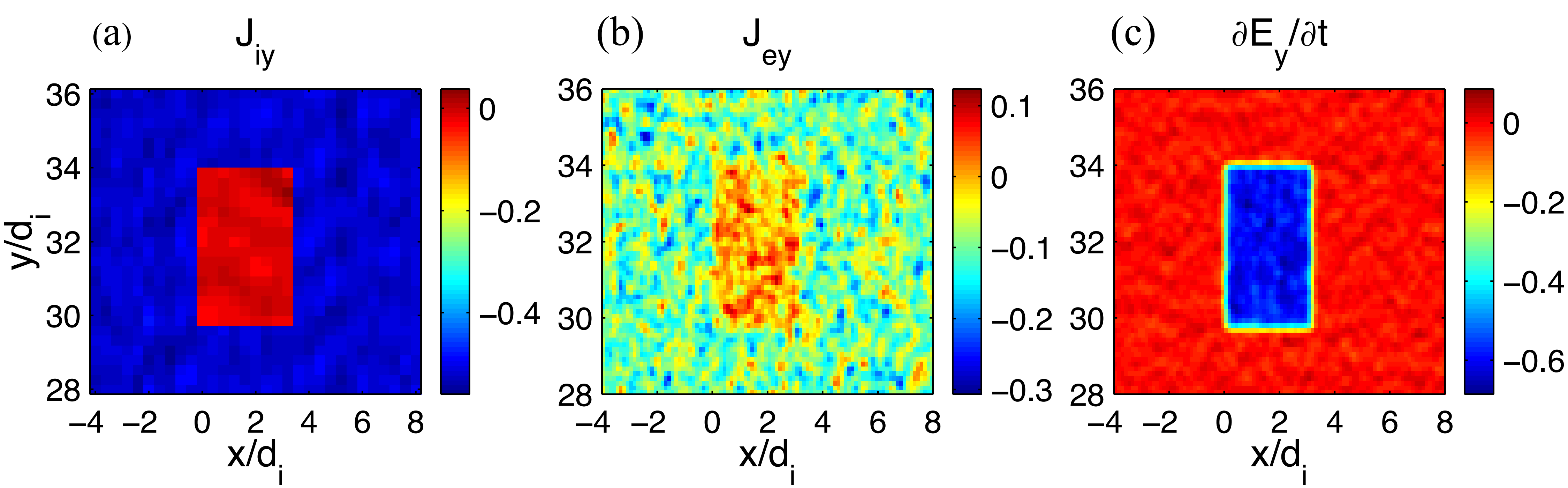
- 2D reconnection simulations produce outflow jets with many of the features of DFs. What about the width?



Runov et al., 2009

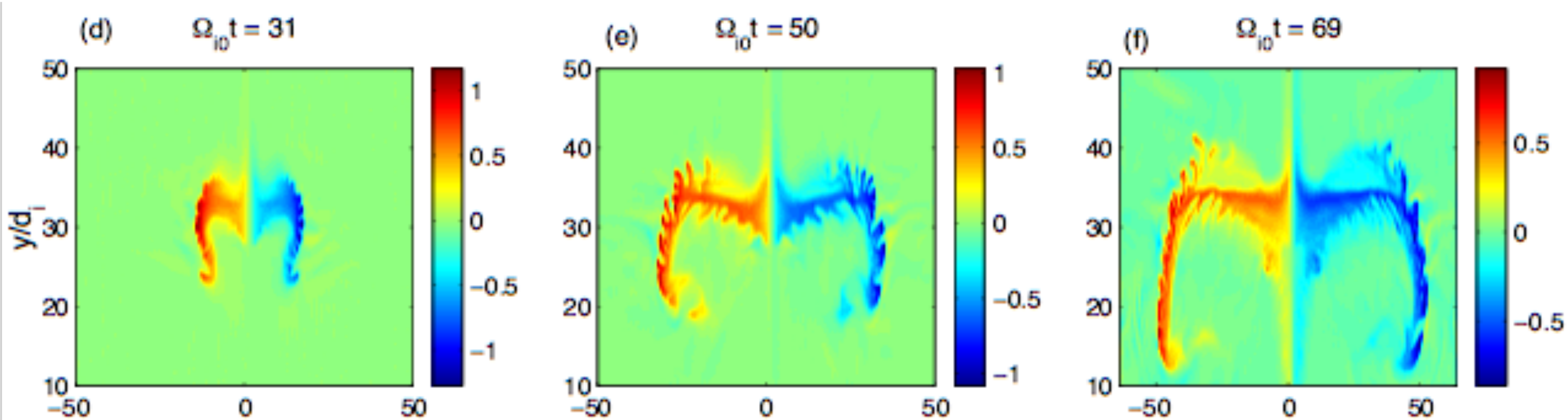
3D Simulation Configuration

- 3D Particle-in-Cell: Full dynamics for both electrons & ions, $m_i/m_e = 64, T_i/T_e = 5$
- Localized (in y) reconnection initiated by imposition of a localized blocking region that removes J_y and acts as an effective anomalous resistivity [Pritchett & Coroniti, 2002]
  - Blocking region: $0 < x < 3d_i$, y width varied between $4d_i$ and $48d_i$; open x boundary
  - System size: $-64d_i < x < 64d_i$, $0 < y < 128d_i$, $-16d_i < z < 16d_i$
- Initial configuration: Harris current sheet,
  half-thickness $L = 1.6d_i$,
  background density $n_b/n_0 = 0.1$
- Caution: Coordinate system: x increases tailward, y increases dawnward



Expansion of a Narrow Reconnection Jet

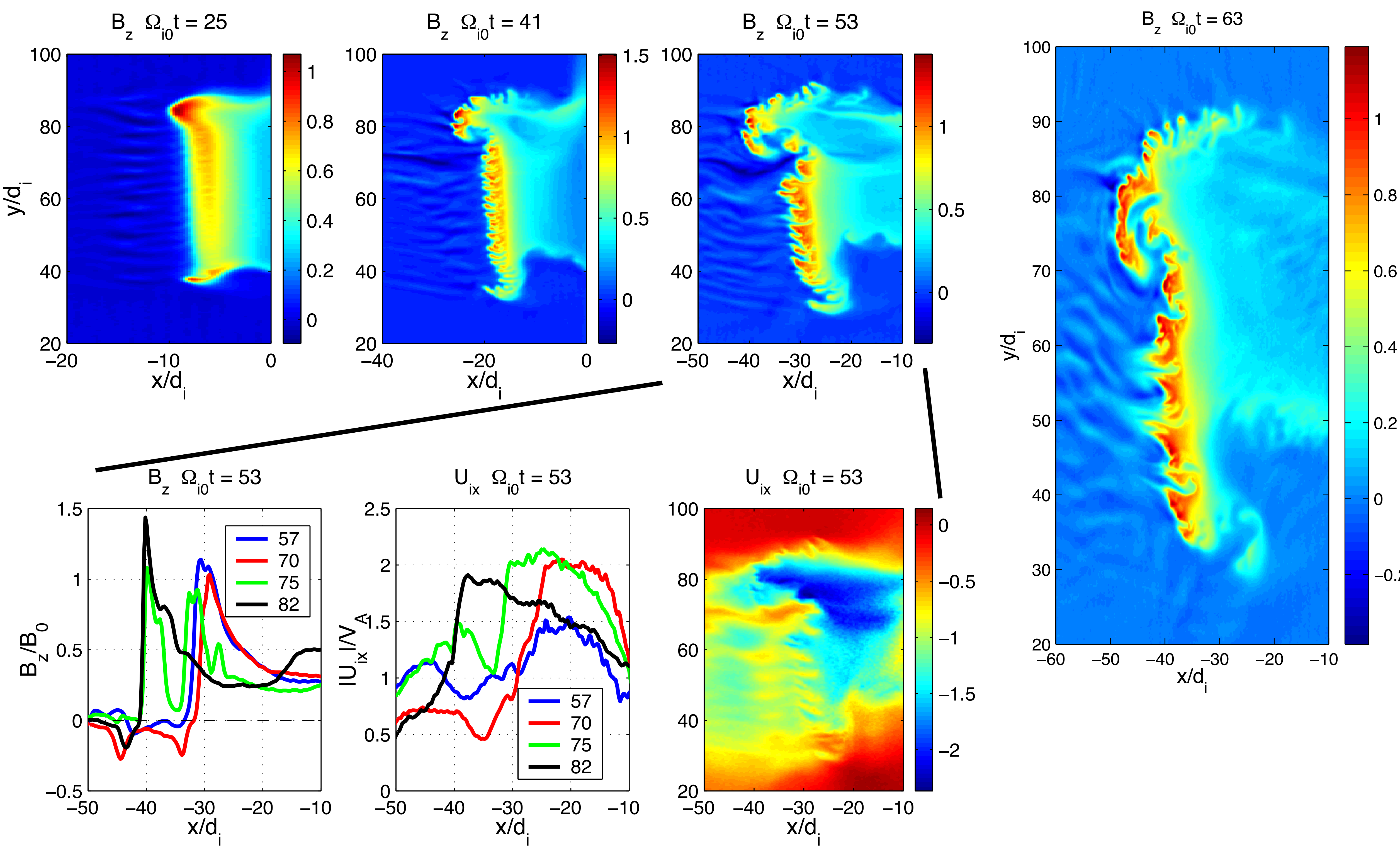
w = 8d_i



- Initial expansion: rather laminar with slight dawnward drift despite $T_i/T_e >> 1$.
- At later times, pronounced expansion of the front duskward, reaching an extent 15-20 d_i.
- Front breaks up on scale of 1-2 d_i. Compatible with excitation by the ballooning/ interchange instability.

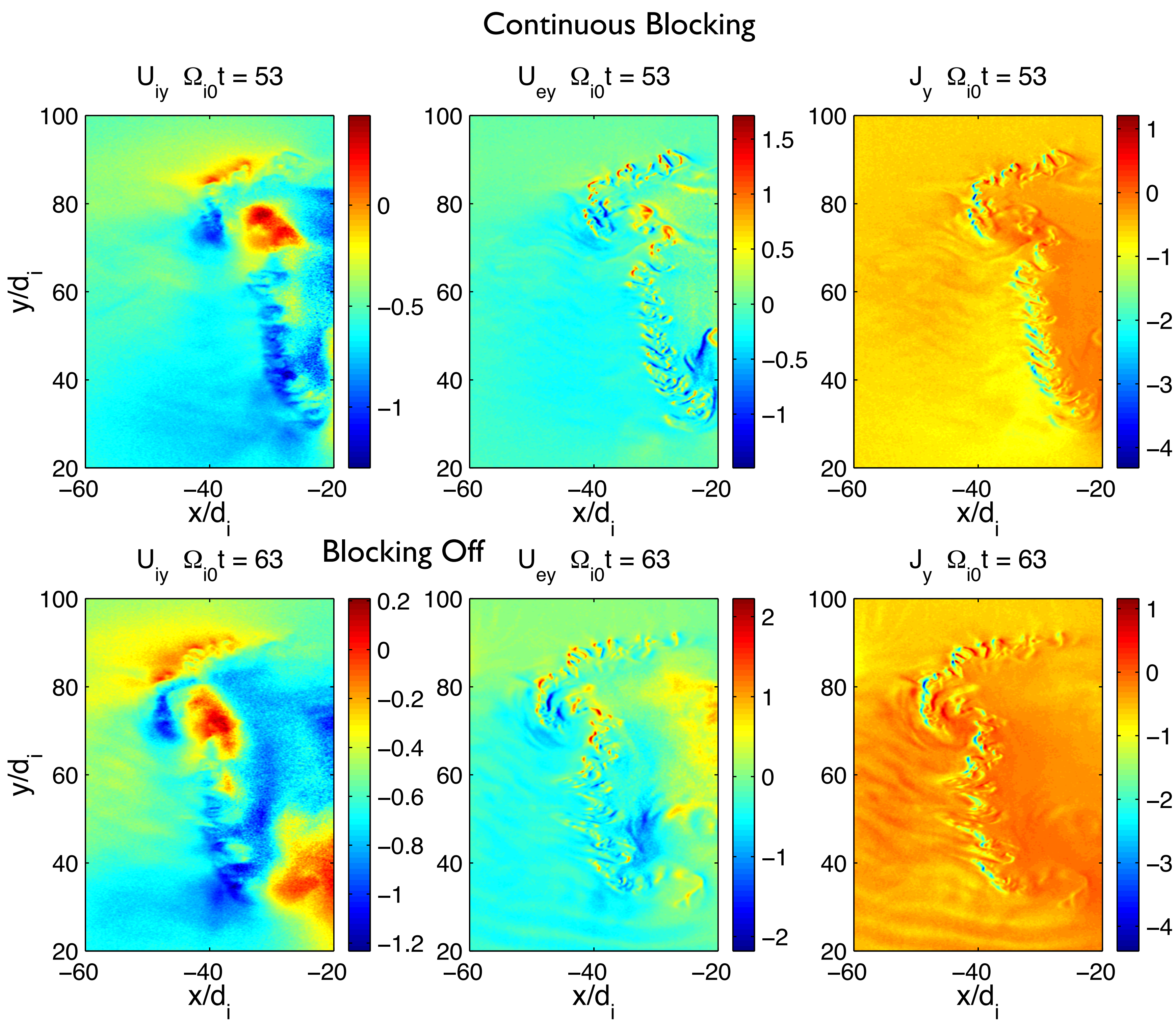
Behavior of w = 48 d_i Reconnection Jet

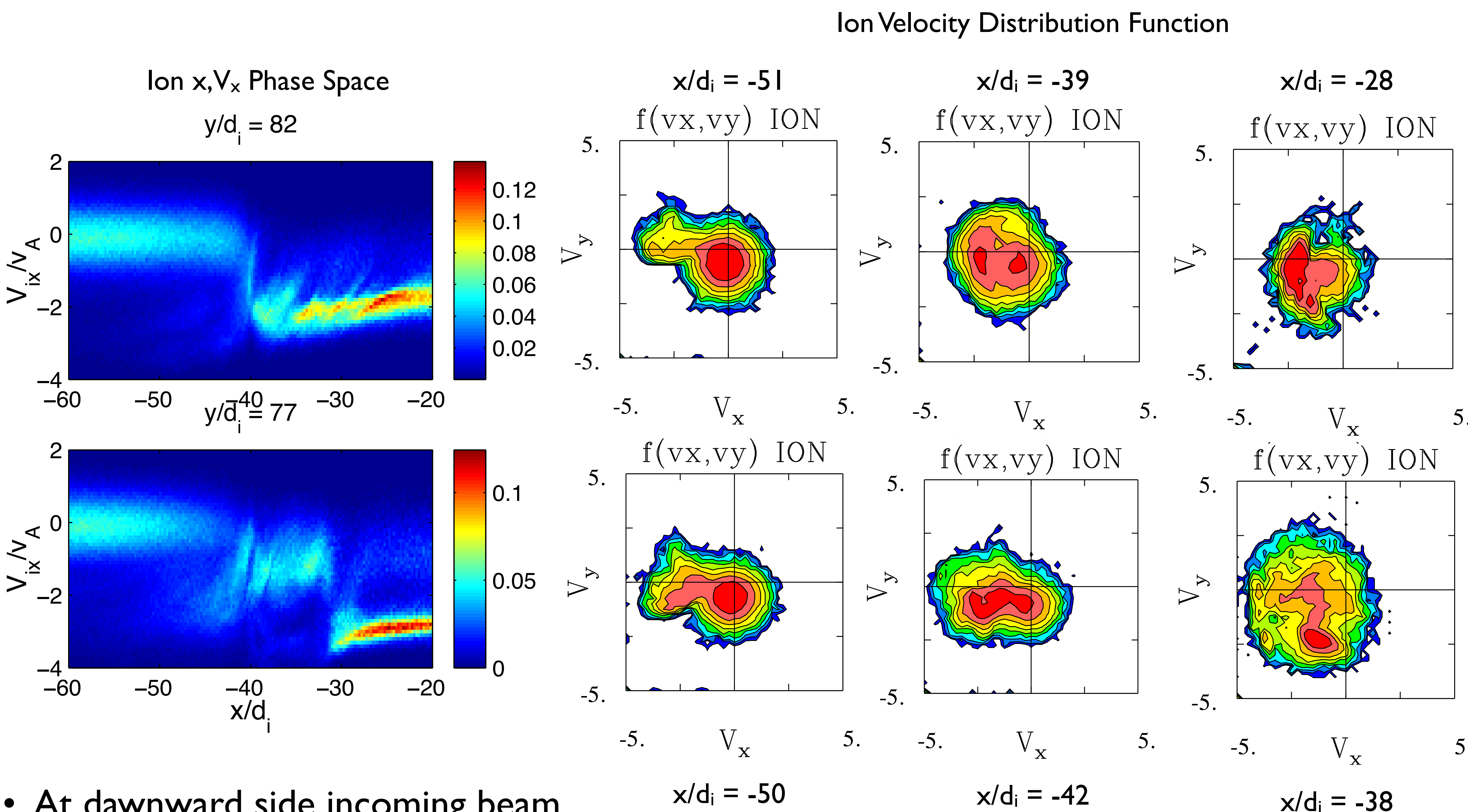
Blocking off at $\Omega_{i0}t = 19$



Small-Scale Structure

- Main ramp up in B_z associated with thin (~d_i) J_y current layer. Current carried mainly by electrons.
- Ion current not negligible but broader scale (several d_i).
- Localized J_y structures ahead of front produce blips and dips in B_z ahead of front.





- At dawnward side incoming beam is slowed sharply; reflected ions appear downstream but are only small portion (~15%) of the total and do not determine net y drift.
- Behind front is a slower turbulent region with strong localized duskward drift structure.

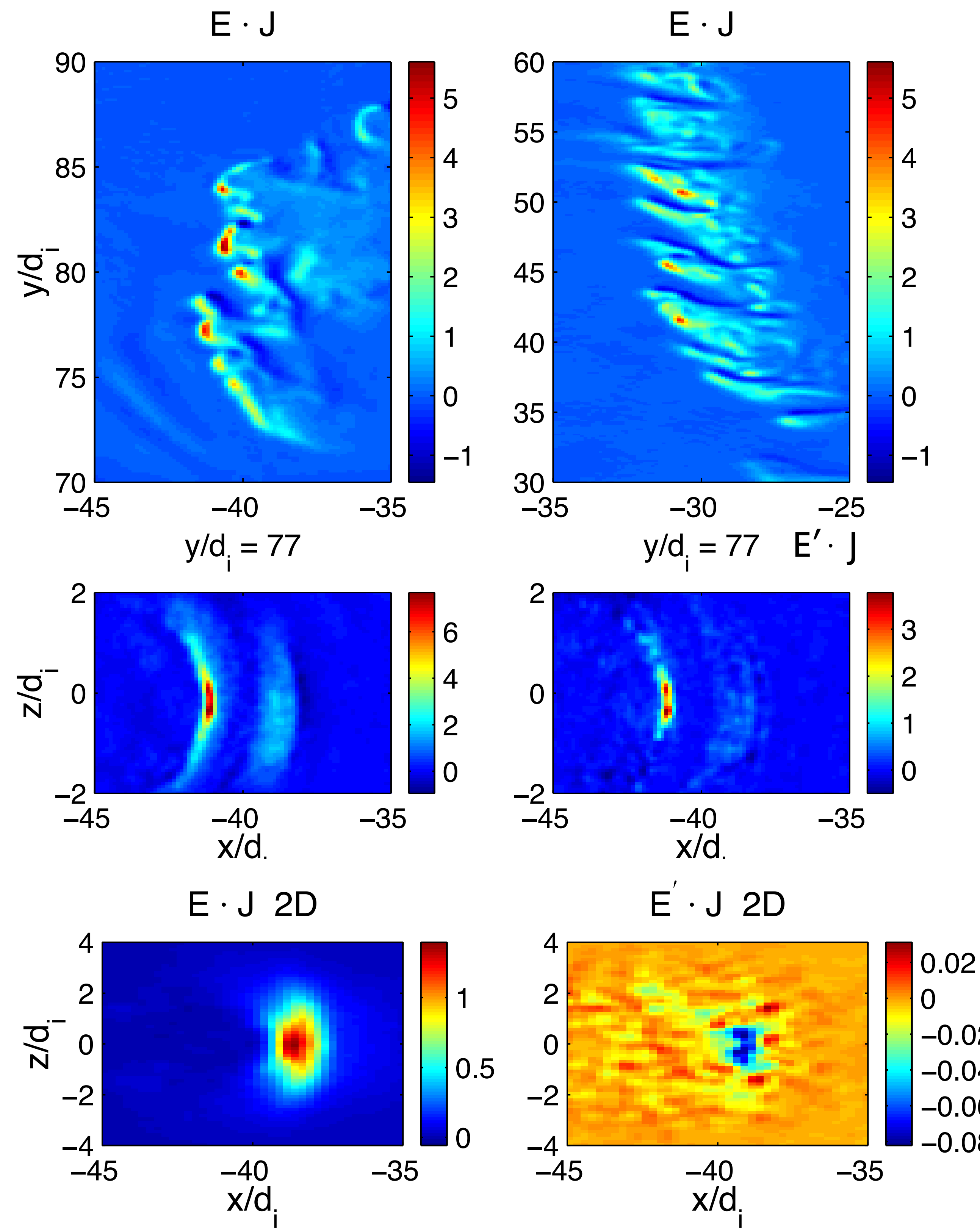
Dissipation at the Front

- There are isolated small-scale regions of intense dissipation $E \cdot J > 0$ at the front, primarily on the dawnward side. Dimension $d_e << L << d_i$. Strength ~ 1 - 2 nW/m^3. Consistent with Angelopoulos et al. (2013).

- Interspersed between and behind the load regions are weaker generator regions.

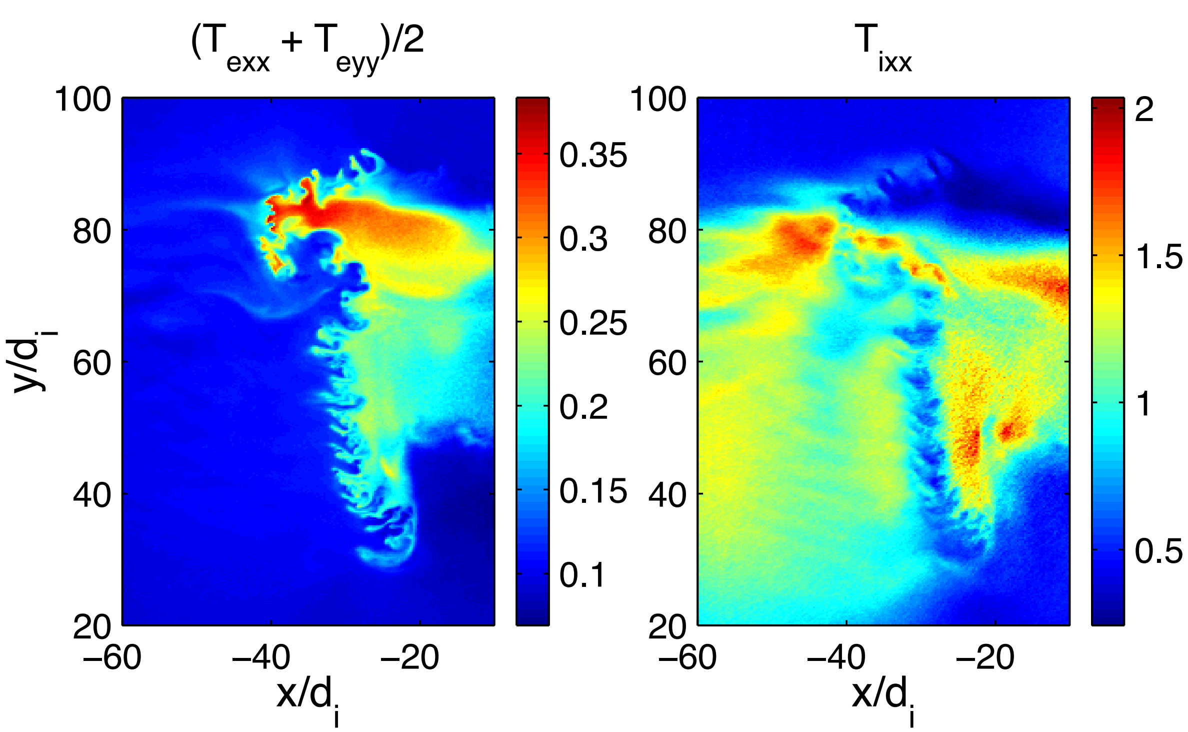
- Removing the bulk plasma flow to give $E' \cdot J$ ("Joule dissipation") reduces the magnitude by a factor ~ 2. Probably associated with only partially magnetized ions.

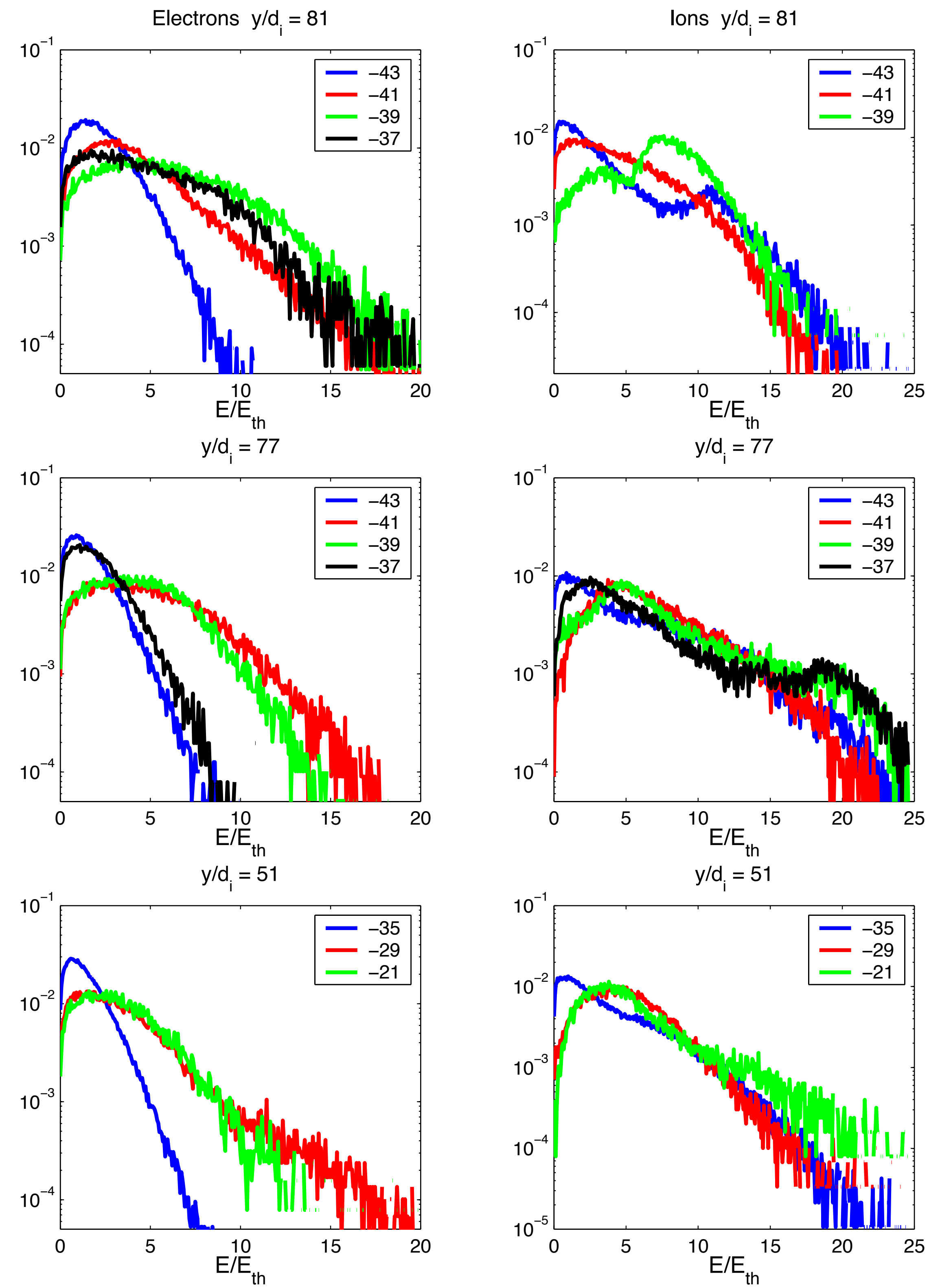
- In 2D result was quite different: $E' \cdot J \approx 0$ at front. 2D values for energization may be inaccurate.



Particle Energization

- T_{ixx} and $T_{e\perp}$ increase substantially at front, particularly on dawnward side.
- On duskward side T_{ixx} has max/min/ max structure.
- Substantial increase in both elec & ion fluxes at 15 - 20 times thermal.





SUMMARY

Reconnection Onset

- Closed 2D PIC simulations indicate that B_z hump type current sheet can be unstable as suggested by Sitnov & Schindler [2010].

- Growth localized near peak of hump; it shifts peak earthward and erodes field on tail-ward side of hump. No development of a dipolarization front.

- Growth rate is order of magnitude smaller than in previous open BC PIC simulations.

- Nonlinear development can lead to formation of X line and onset of reconnection as demonstrated by Bessho & Bhattacharjee [2014]. Internally driven reconnection due to flux starvation.

- For case of externally driven reconnection, the formation of an X line behind the front is unlikely to occur due to the replenishment of the trailing B_z field by ongoing reconnection.

Structure of Reconnection Jets

- Used 3D PIC simulations to investigate structure of exhaust jets produced by reconnection localized (4 - 48 d_i) in out-of-plane direction.

- Narrow fronts (<10d_i) expand in ion drift direction to width of 15-20d_i.

- Broader fronts (>25d_i) form a 10-15d_i higher-speed structure on dawn side of jet.

- In all cases fronts filament into substructures of 1-2d_i width (ballooning/interchange instability). On longer time scales they clump into ~5d_i structures.

- Ramp up in B_z associated with thin (~d_i) current layer carried mainly by electrons.

- DF is site of strong mixing between jet and ambient plasma with production of reflected and transmitted ions at speeds of 2-4 V_A.

- Ion energization occurs in front of and behind the DF; electron energization occurs at front.

- Dissipation (1-2 nW/m^3) concentrated in small scale regions $d_e << L << d_i$, similar to observations of Angelopoulos et al. [2013]. $E' \cdot J$ much larger at front than in 2D.