Global simulations of relativistic jets with shocks and shear-flow

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D. H. Hartmann (*Clemson Univ.*)

Magnetic Reconnection in Plasmas,
NORDITA, August 12, 2015

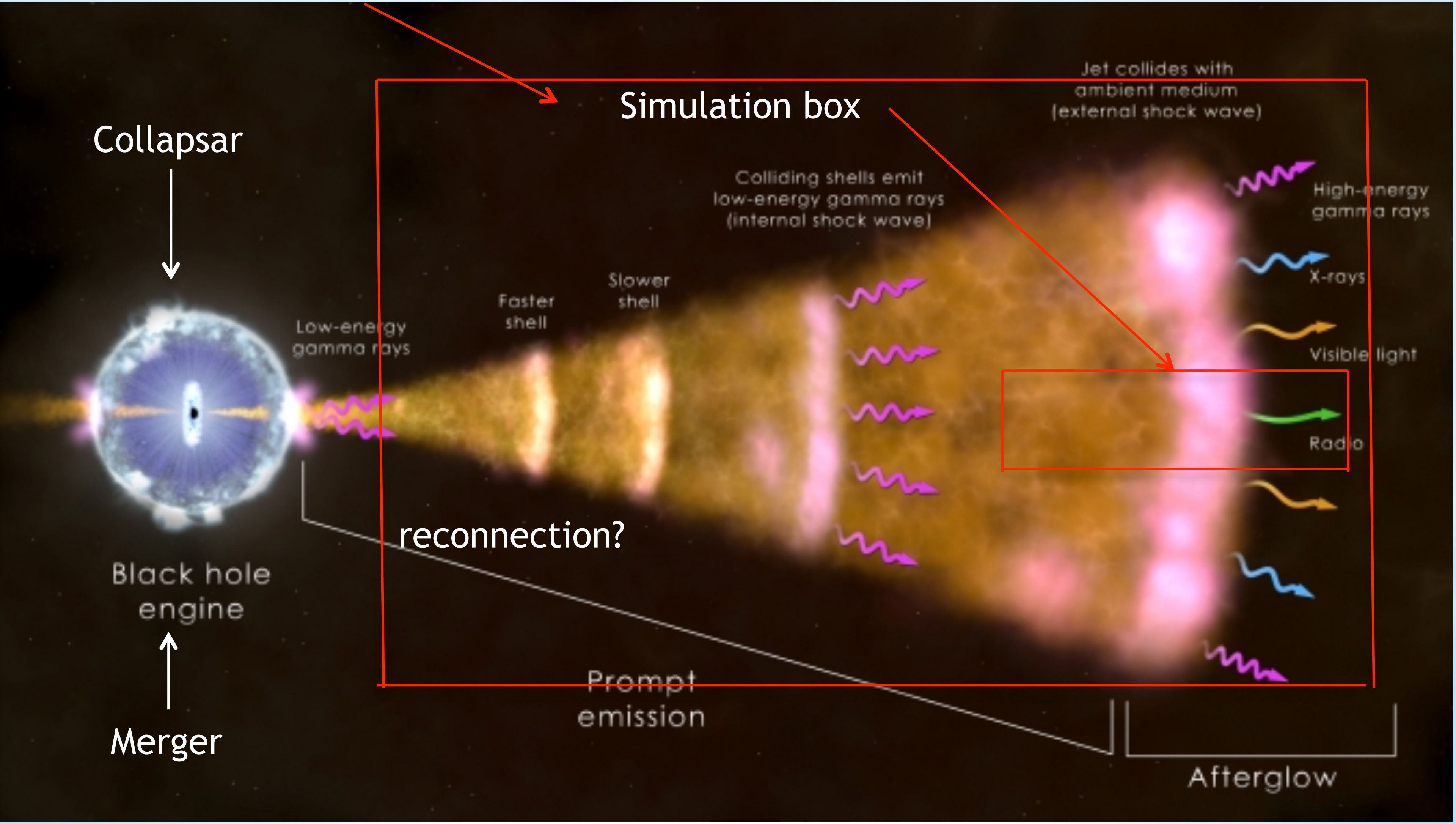
Outline of talk

1. **Introduction and Weibel instability**

2. **Recent 3-D particle simulations of relativistic jets**
   *** $e^{\pm}$pair jet into $e^{\pm}$pair, γ= 15 and**
   electron-ion (m_i/m_e = 20) into electron-ion γ= 15
   shock structures
3. **Magnetic field generation and particle acceleration in kinetic Kelvin-Helmholtz instability** (Nishikawa et al. 2014, ApJ, arXiv:1405.5247)
4. → **Global jet simulations with shock and KKHI with large simulation system**
5. **Summary**
6. **Future plans**

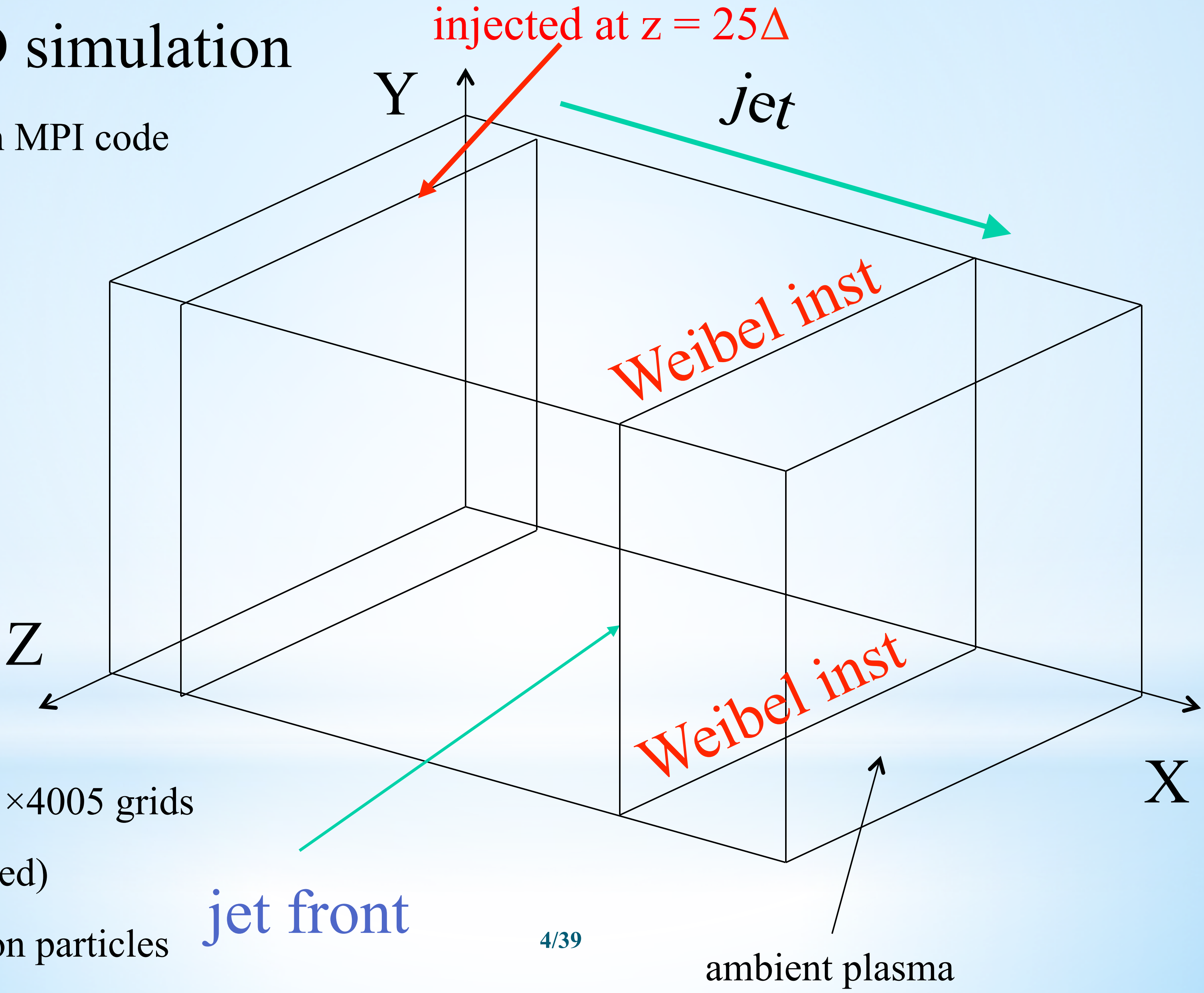
Gamma-ray bursts

Global jet simulation



3-D simulation

with MPI code



131×131×4005 grids

(not scaled)

1.2 billion particles

3D global jet simulation

NASA Pleiades

system size: 2000Δ×1000Δ×1000Δ

jet radius: 100Δ

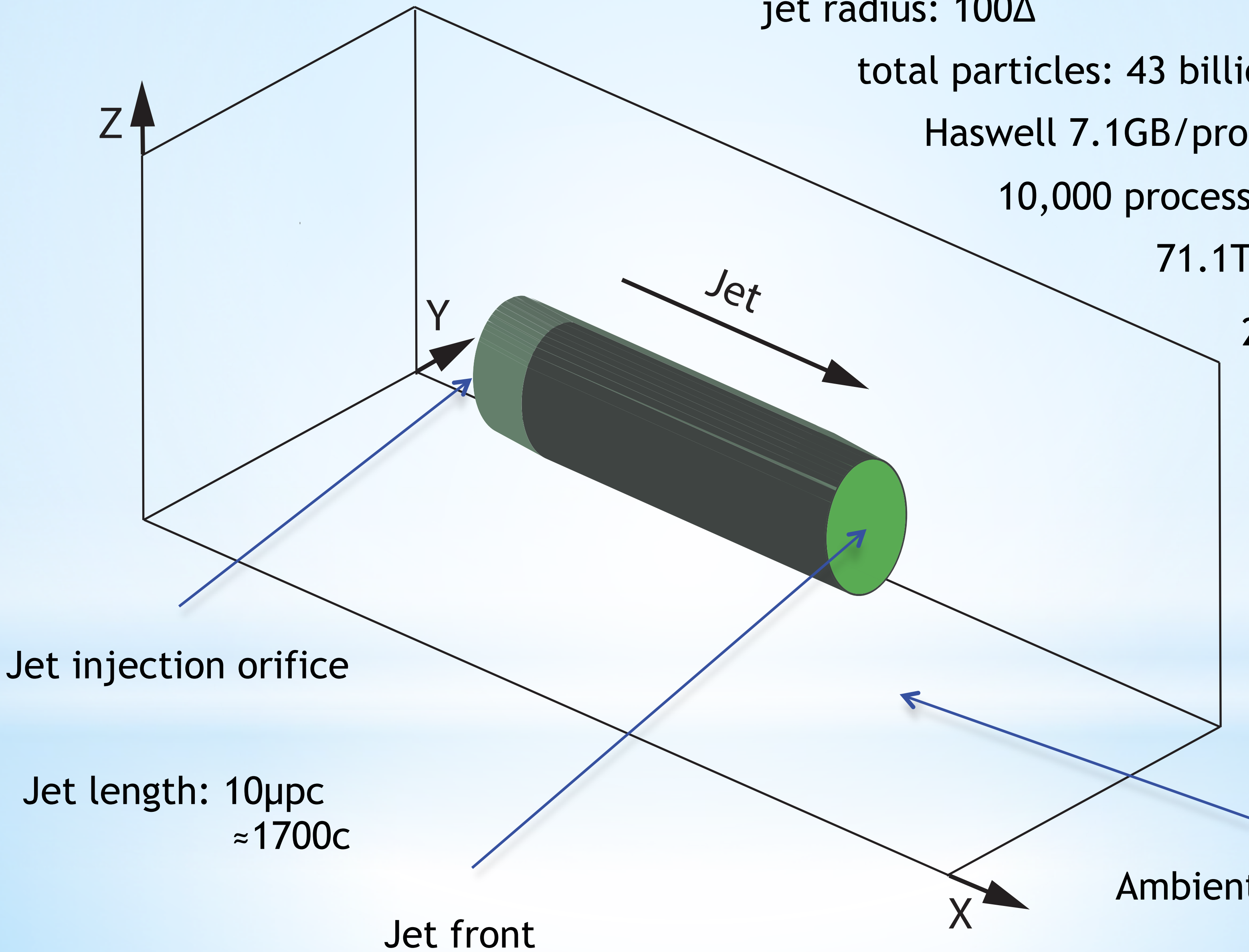
total particles: 43 billions

Haswell 7.1GB/processor

10,000 processors

71.1TB memory

2.45 hours



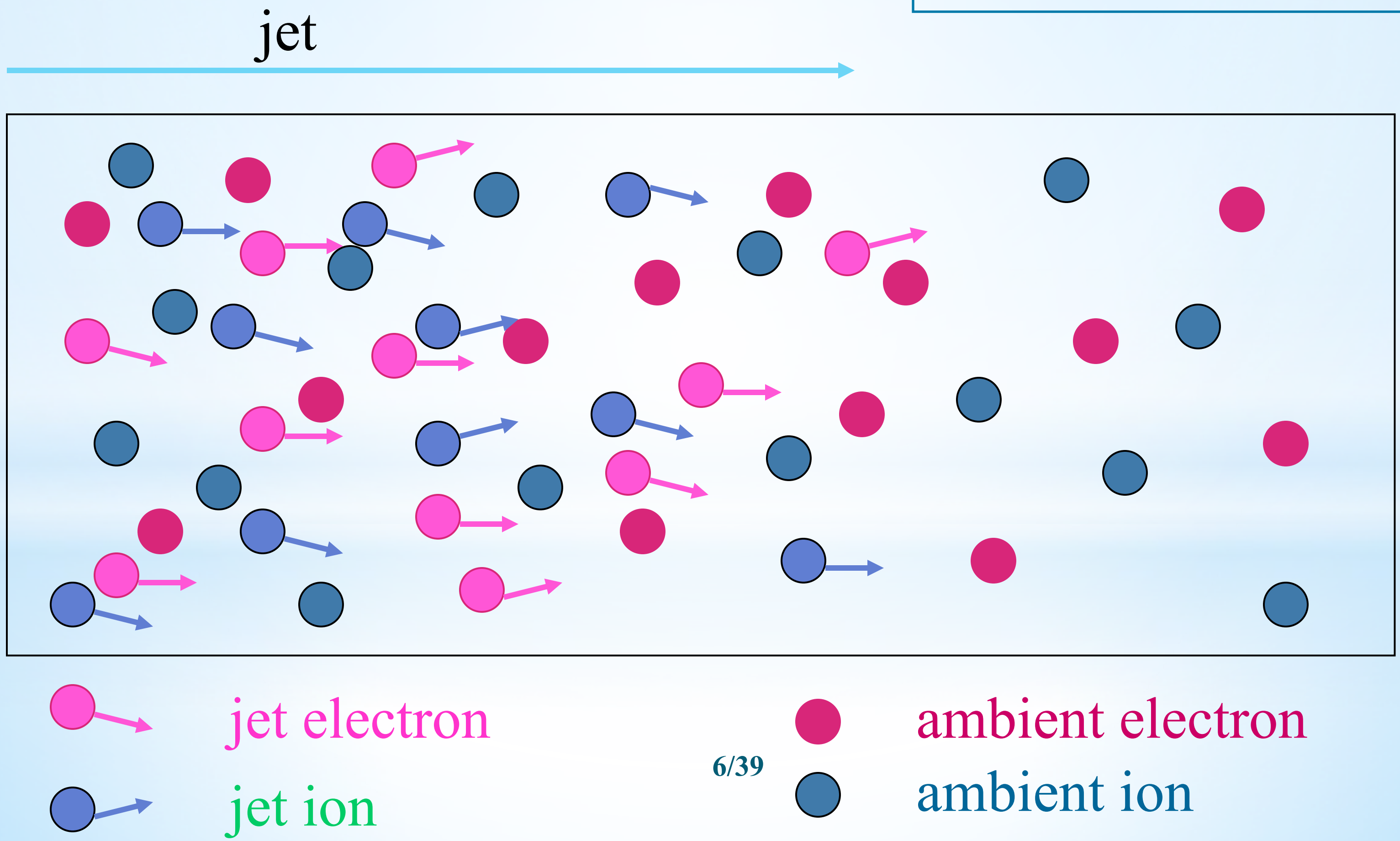
Jet length: 10μpc
≈1700c

Collisionless shock

Electric and magnetic fields created self-consistently by particle dynamics randomize particles

(Buneman 1993)

$$\partial B / \partial t = -\nabla \times E$$
$$\partial E / \partial t = \nabla \times B - J$$
$$d m_0 \gamma v / dt = q(E + v \times B)$$
$$\partial \rho / \partial t + \nabla \bullet J = 0$$



Weibel instability

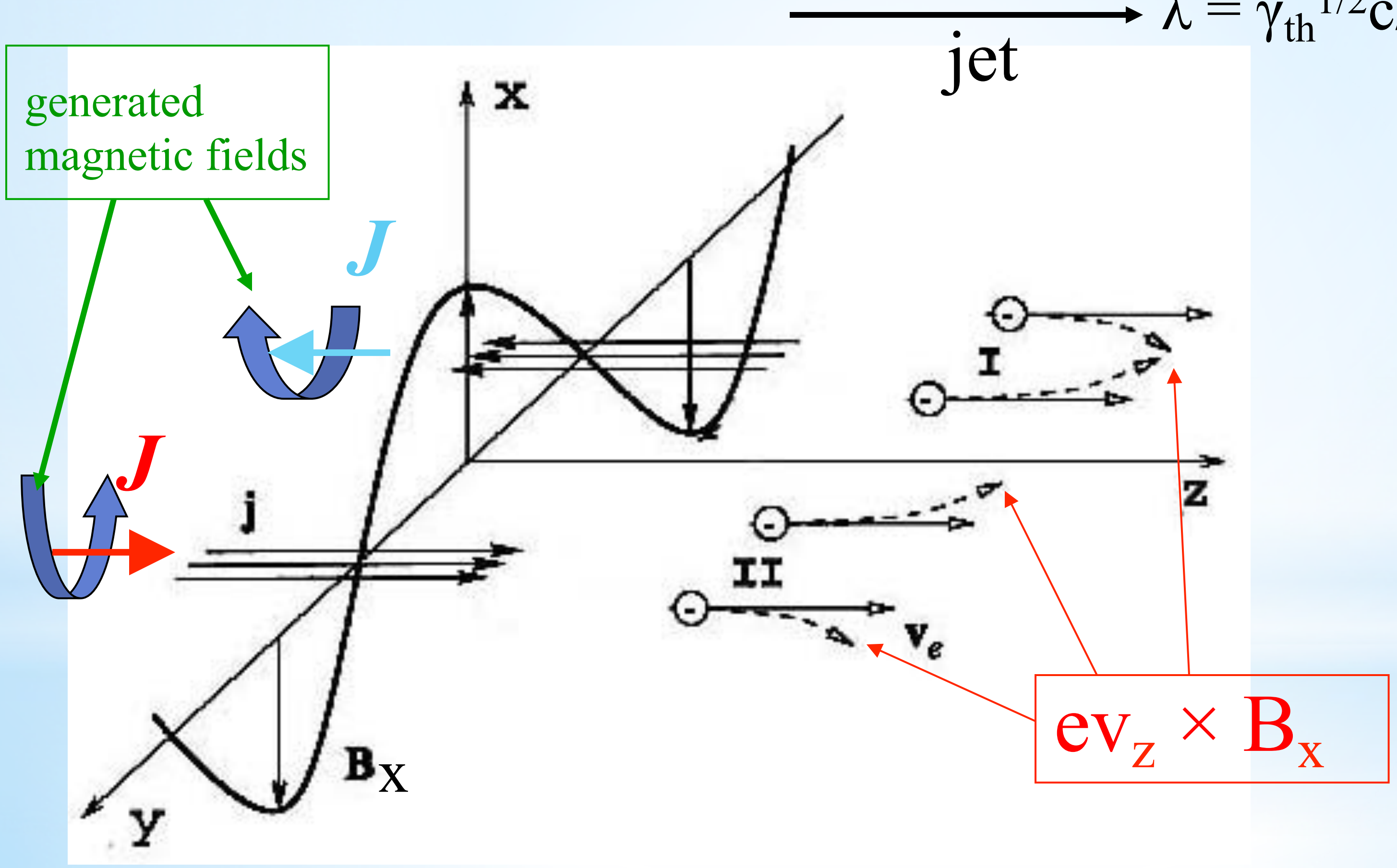
current filamentation

Time:

$\tau = \gamma_{sh}^{1/2}/\omega_{pe} \approx 21.5$

Length:

$\lambda = \gamma_{th}^{1/2} c/\omega_{pe} \approx 9.6\Delta$

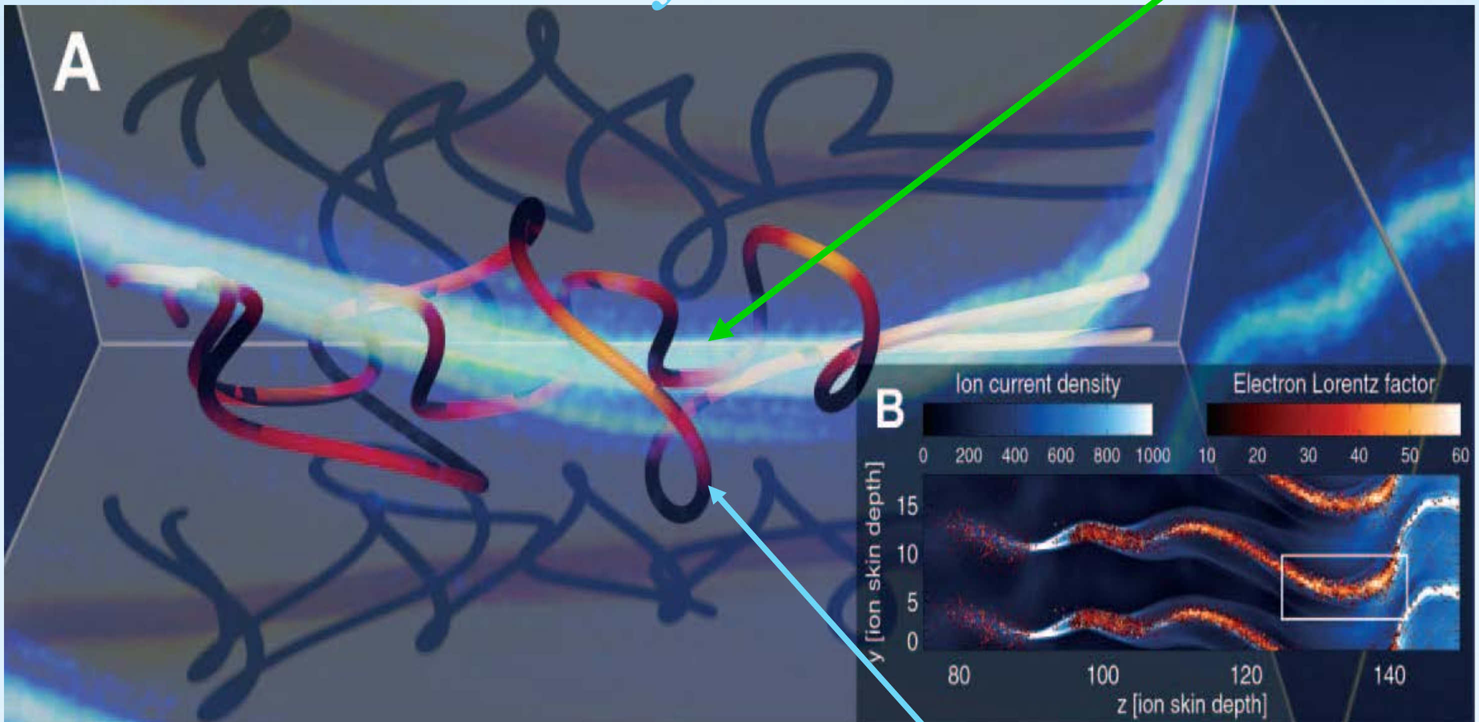


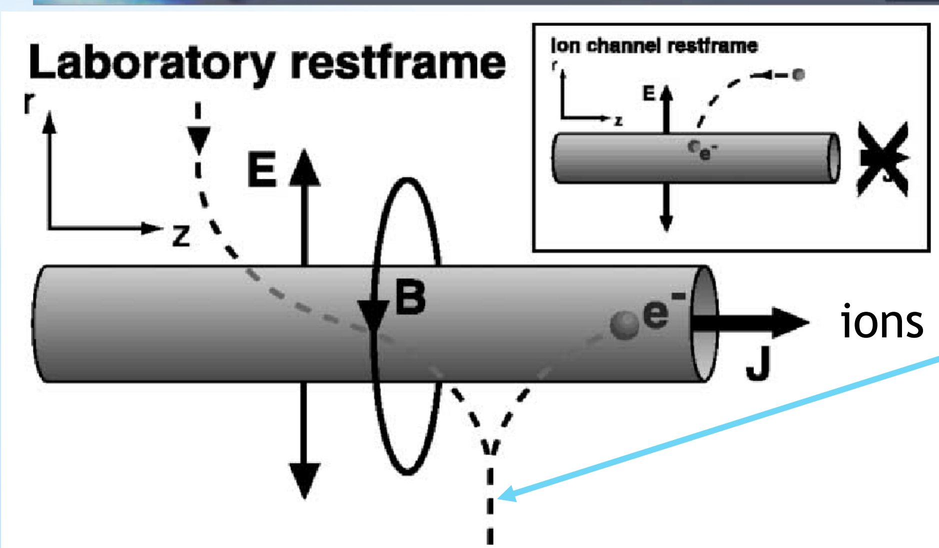
(electrons)

(Medvedev & Loeb, 1999, ApJ)

Ion Weibel instability

ion current





E × B acceleration

(Electric field acceleration)

electron trajectory

(Hededal et al 2004)

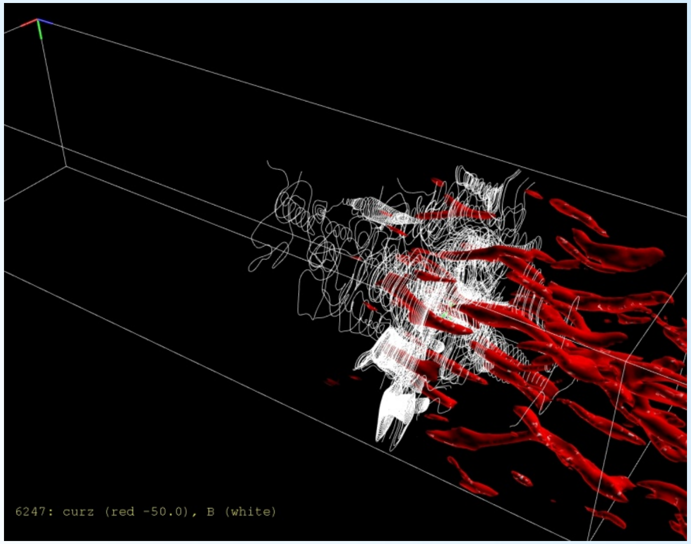
3-D isosurfaces of x-component of current J_x for narrow jet ($\gamma v_{||}$=12.57)

electron-ion ambient $t = 59.8\omega_e^{-1}$

$-J_x$ (red), $+J_x$ (blue),

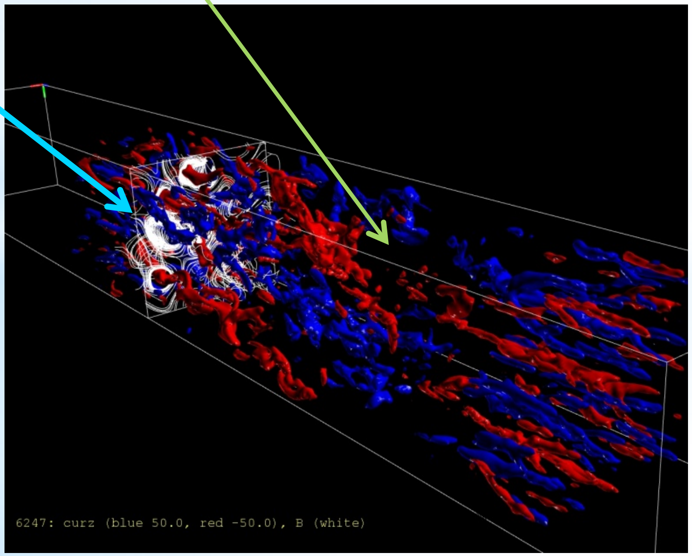
magnetic field lines (white)

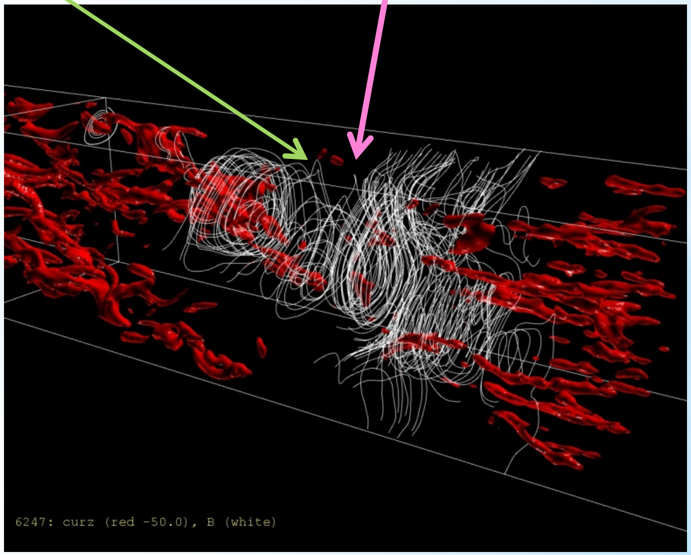
Particle acceleration due to the local reconnections during merging current filaments at the nonlinear stage

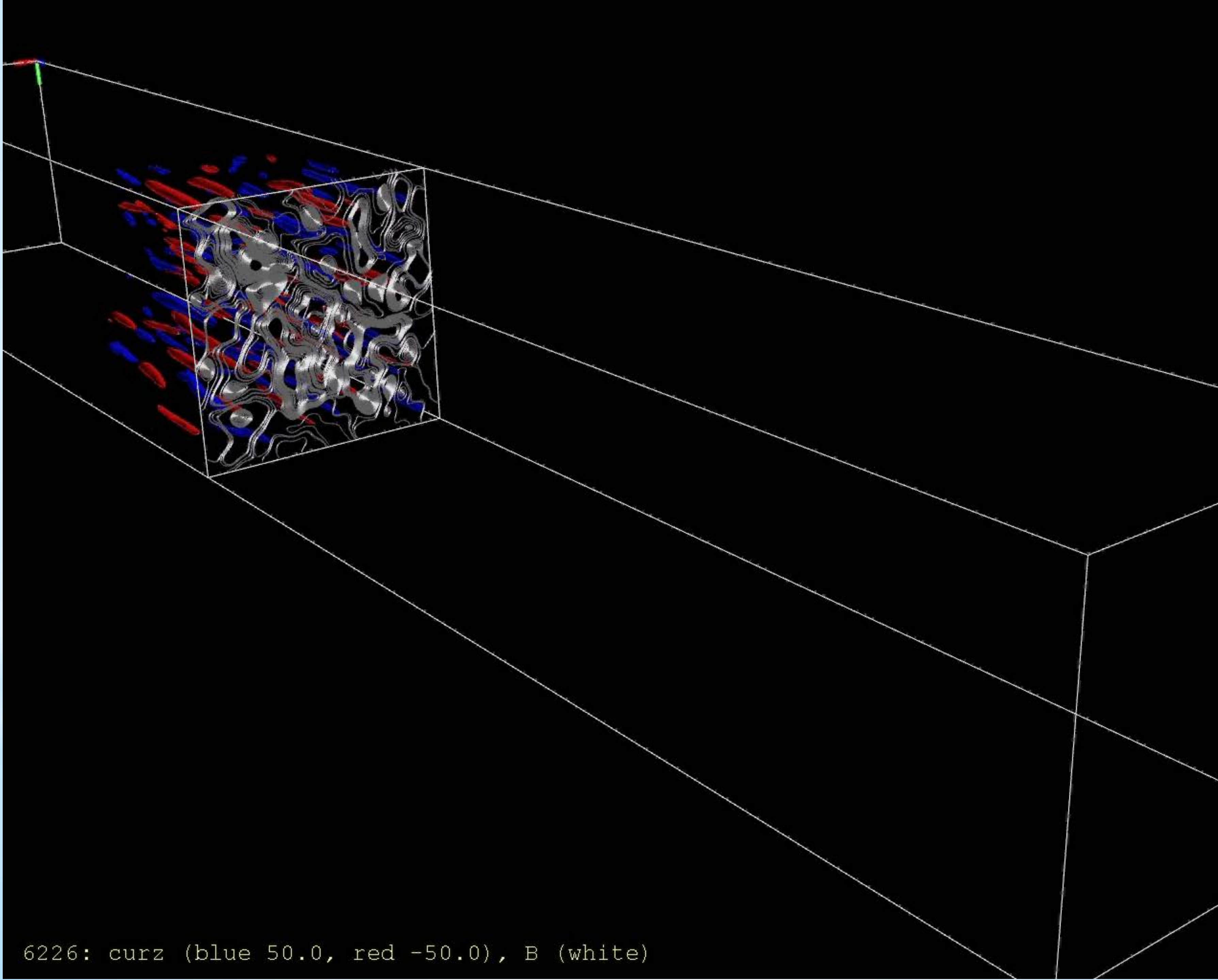


thin filaments

merged filaments



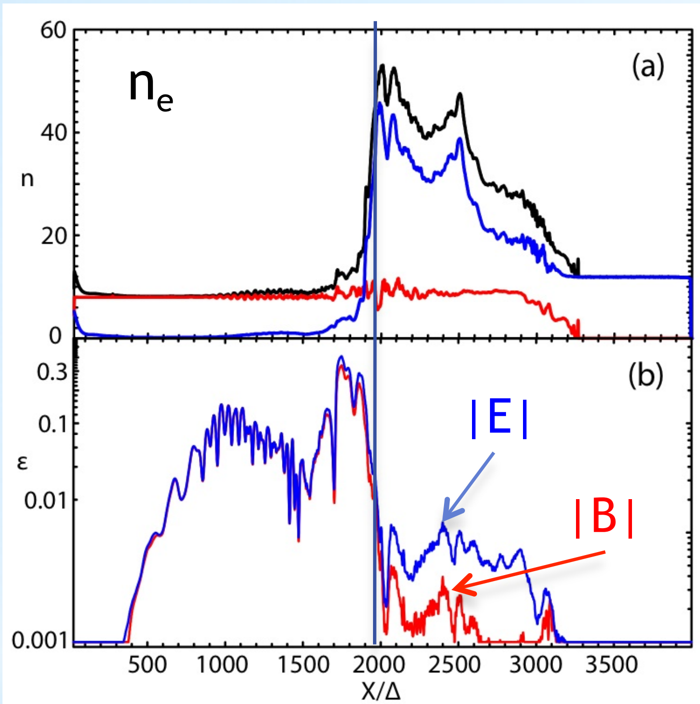


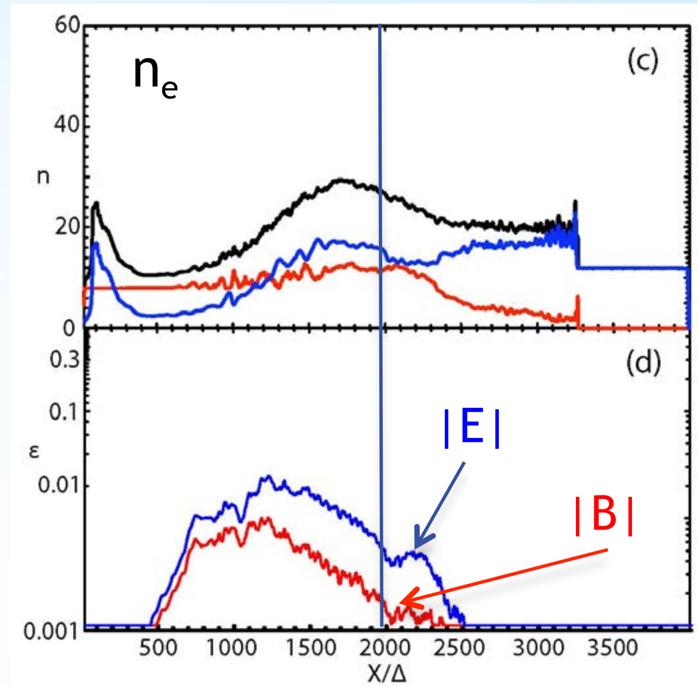

6226: curz (blue 50.0, red -50.0), B (white)

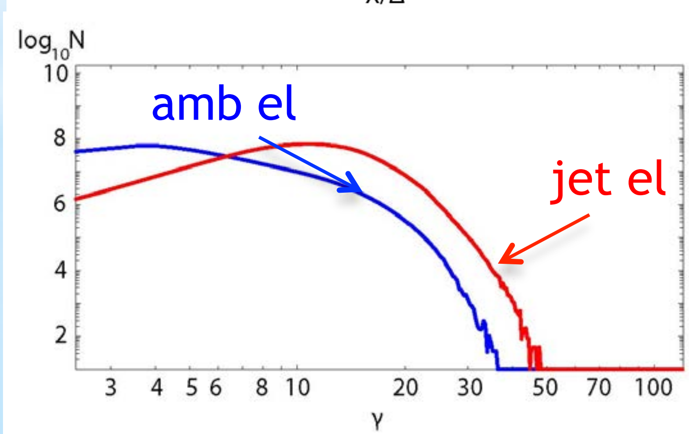
Comparison with different mass ratio (electron-positron and electron-ion)

electron-positron

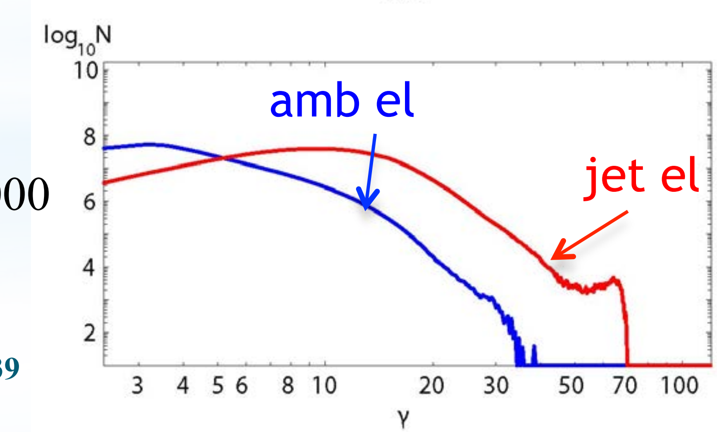
electron-ion ($m_i/m_e = 20$)





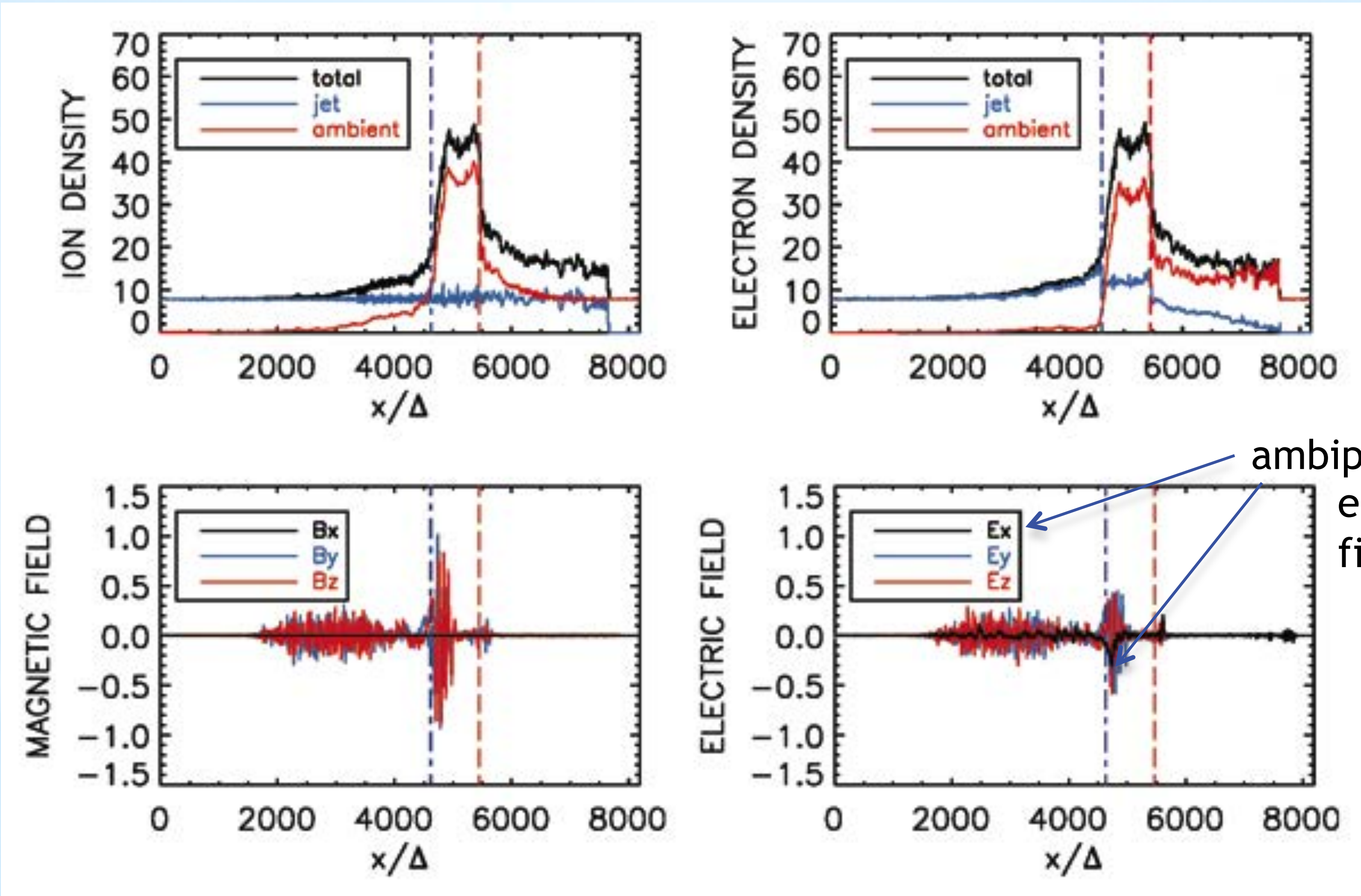


X/Δ>2000



Recent electron-ion simulation (Electrostatic shock and double layer)

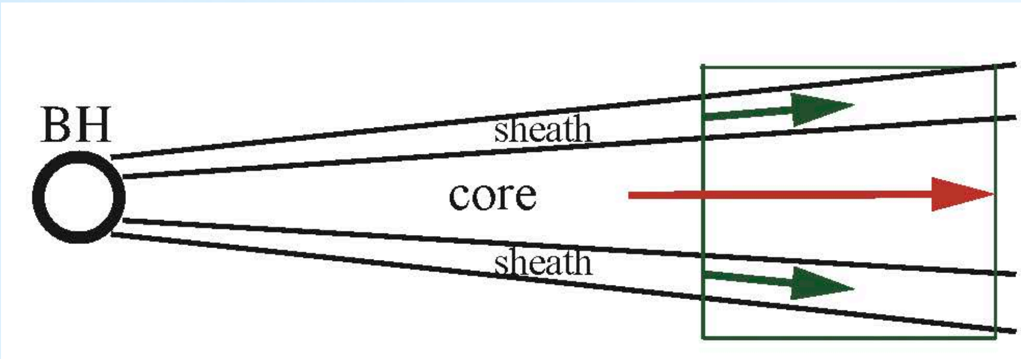
$m_i/m_e = 20$



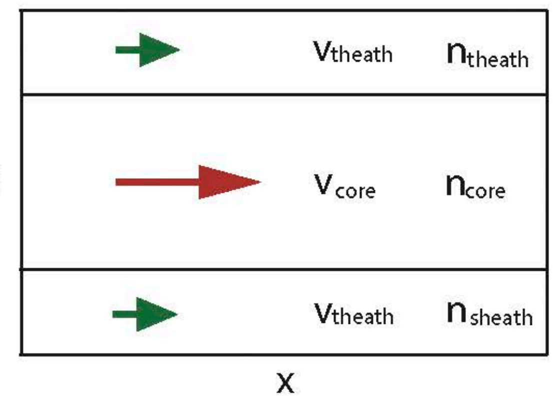
ambipolar electric field

(Choi et al. PhPl, 2014)

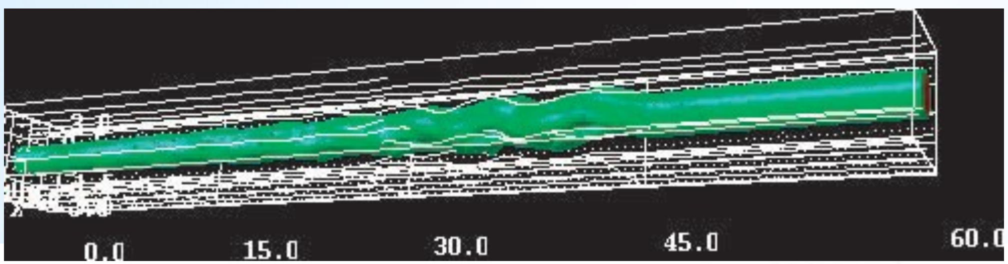
Simulations of KHI with core and sheath jets



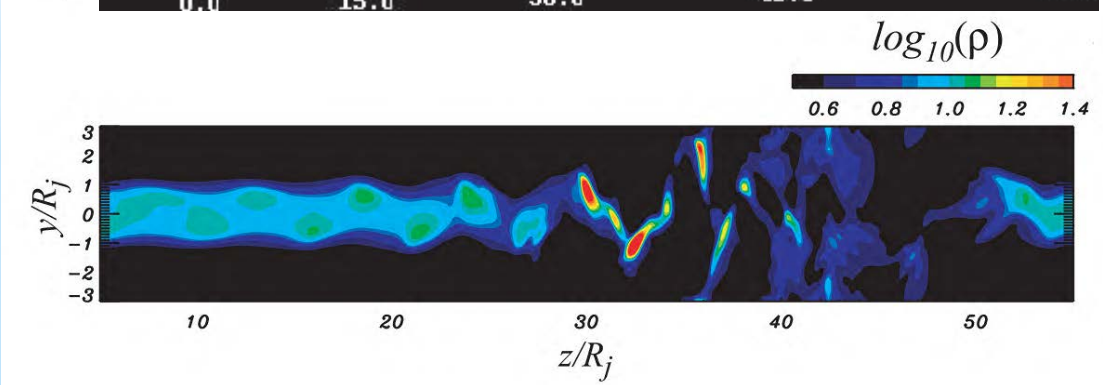
slab model

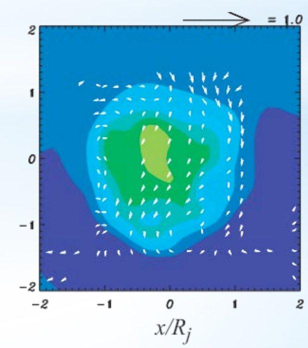


RMHD, no wind ω=0.93, time=60.0



case of V_{theath} = 0





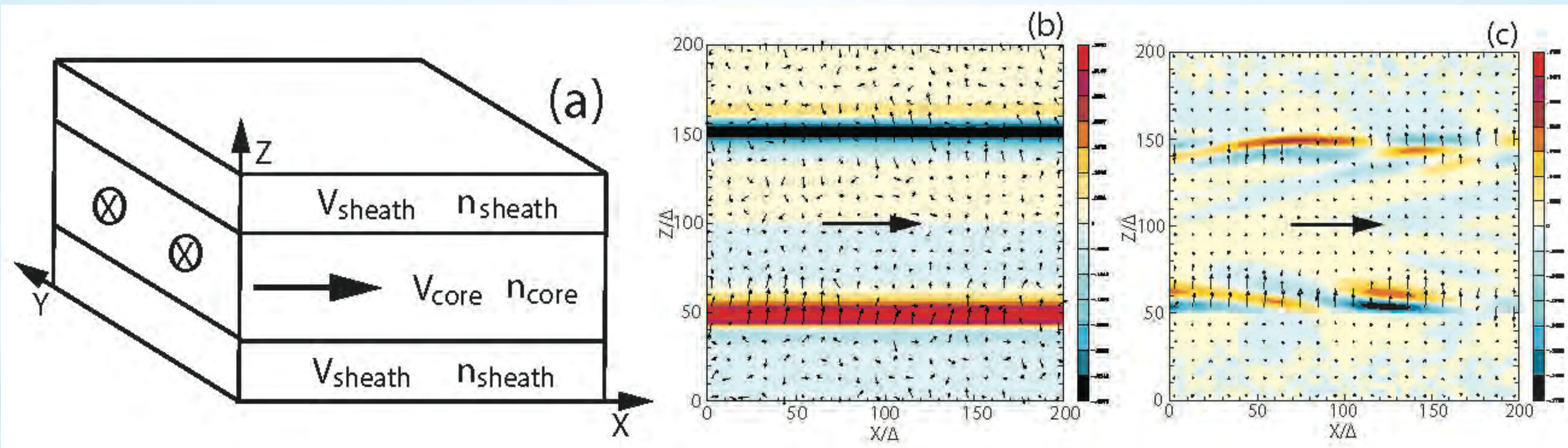
Mizuno, Hardee & Nishikawa, ApJ, 662, 835, 2007

KKHI with Core-sheath plasma scheme

$\gamma_{jt} = 15$ $t = 300\omega_{pe}^{-1}$

B_y

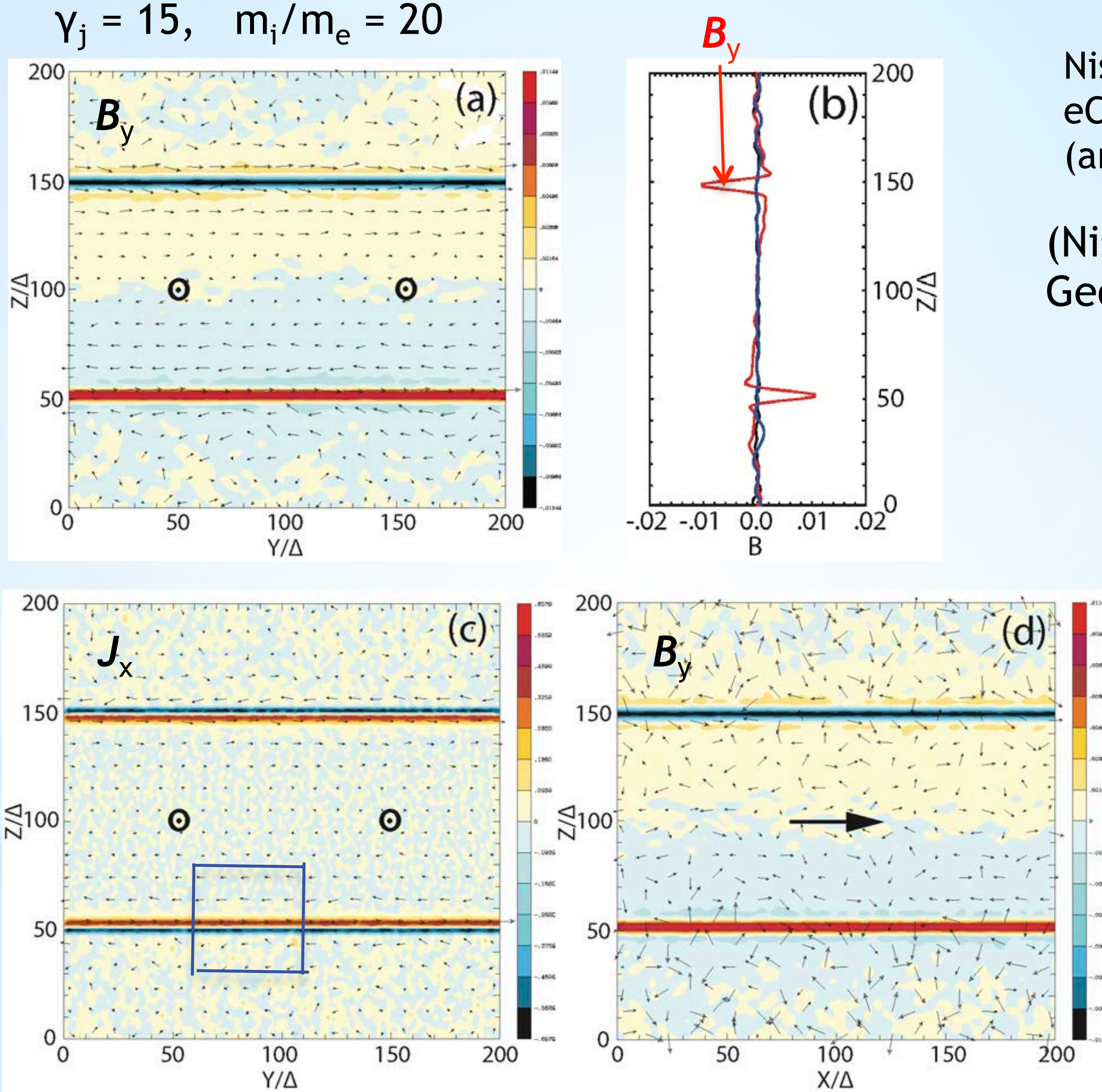
e – p (proton) $e^{\pm}$



(Nishikawa et al. 2014, ApJ)

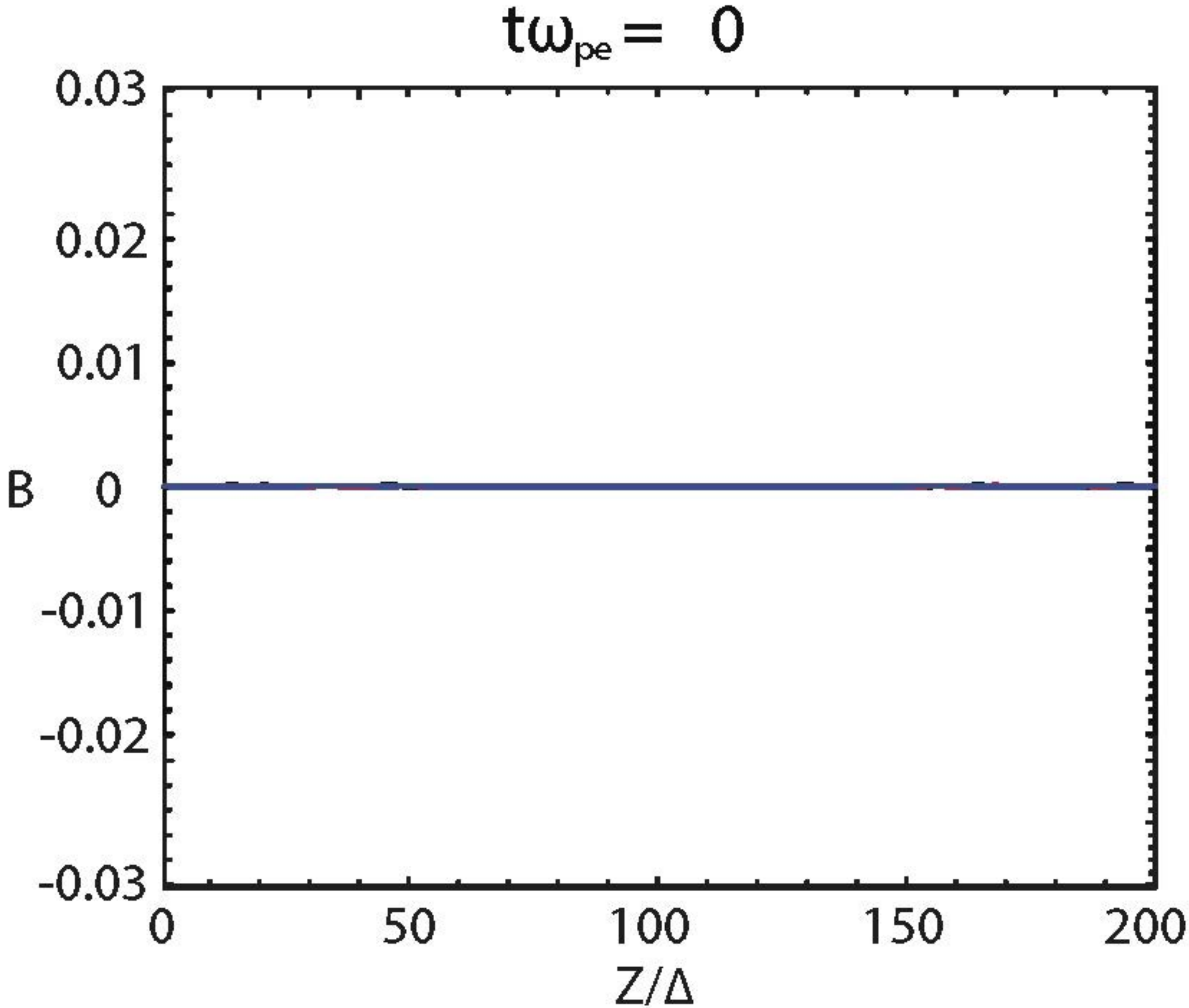
New KKHI simulations with core and sheath jets in slab geometry

$\gamma_j = 15, \quad m_i/m_e = 20$



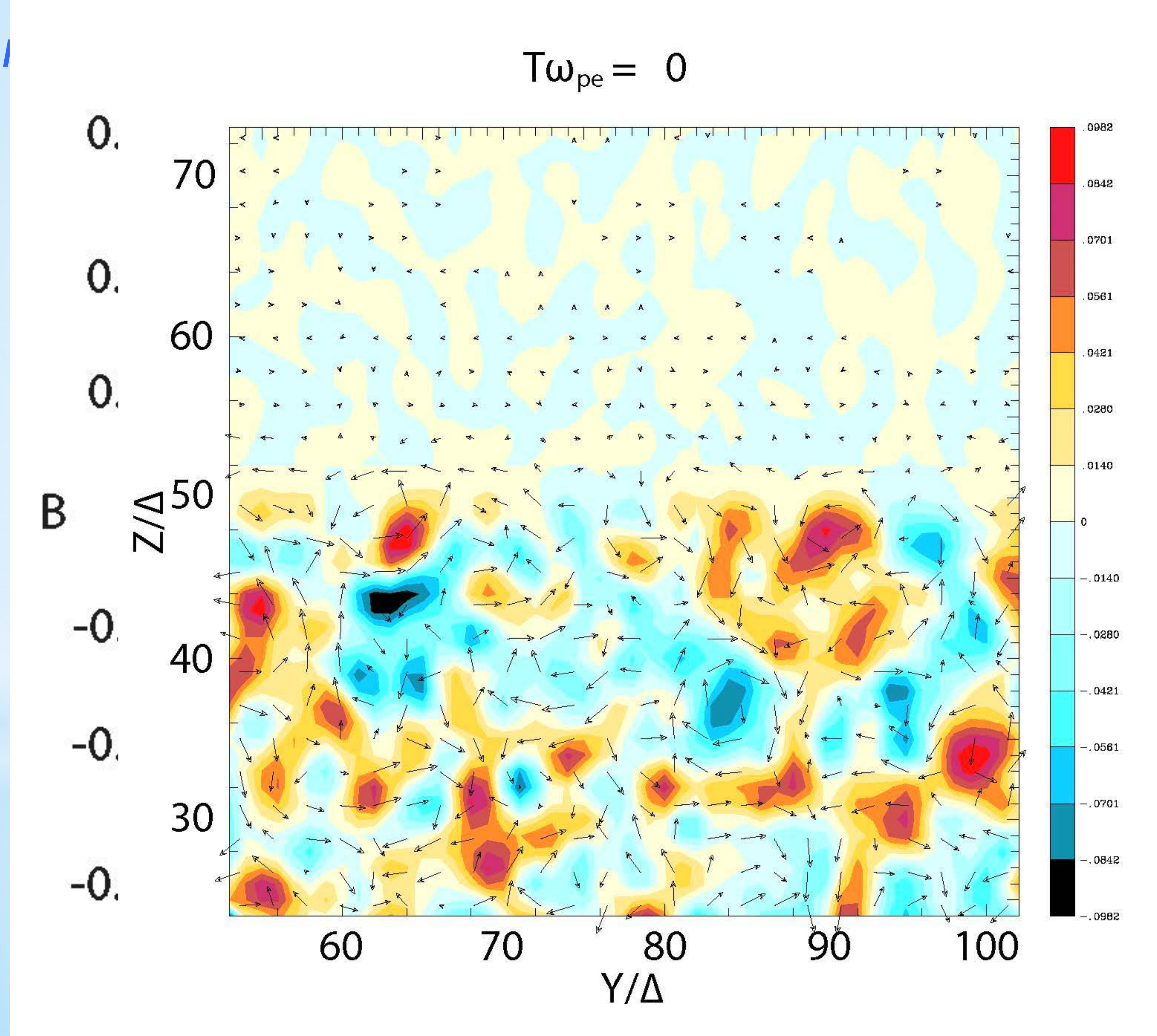
Nishikawa et al. 2013
eConf C121028
(arXiv:1303.2569)

(Nishikawa et al. Ann. Geo, 2013, ApJ, 2014)



l. 2013
3
69)

al. Ann.
J, 2014)



l. 2013
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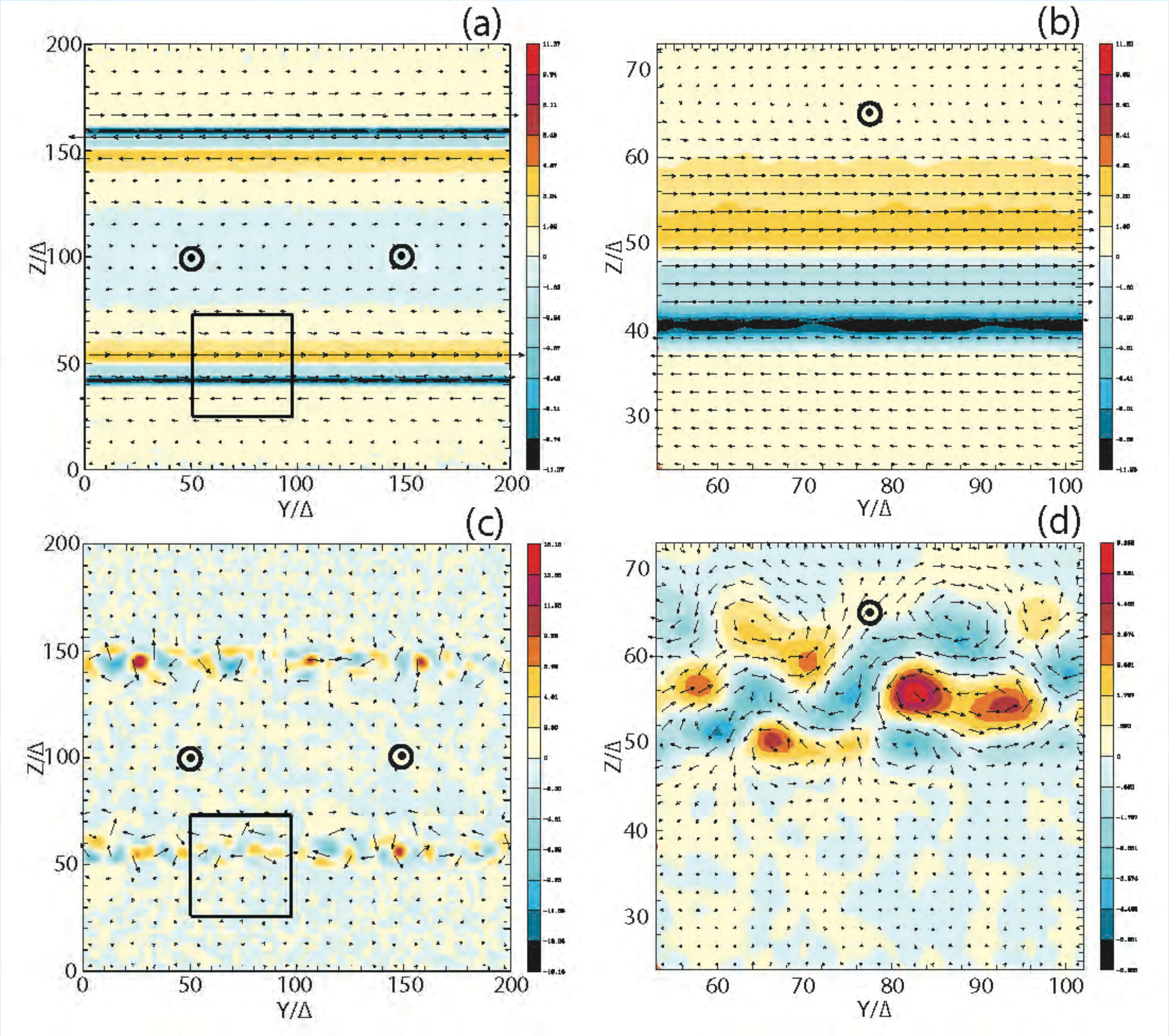
69)

al. Ann.
J, 2014)

J_x Current structures $\gamma_{jt} = 15$ $t = 300\omega_{pe}^{-1}$

e - p

e±

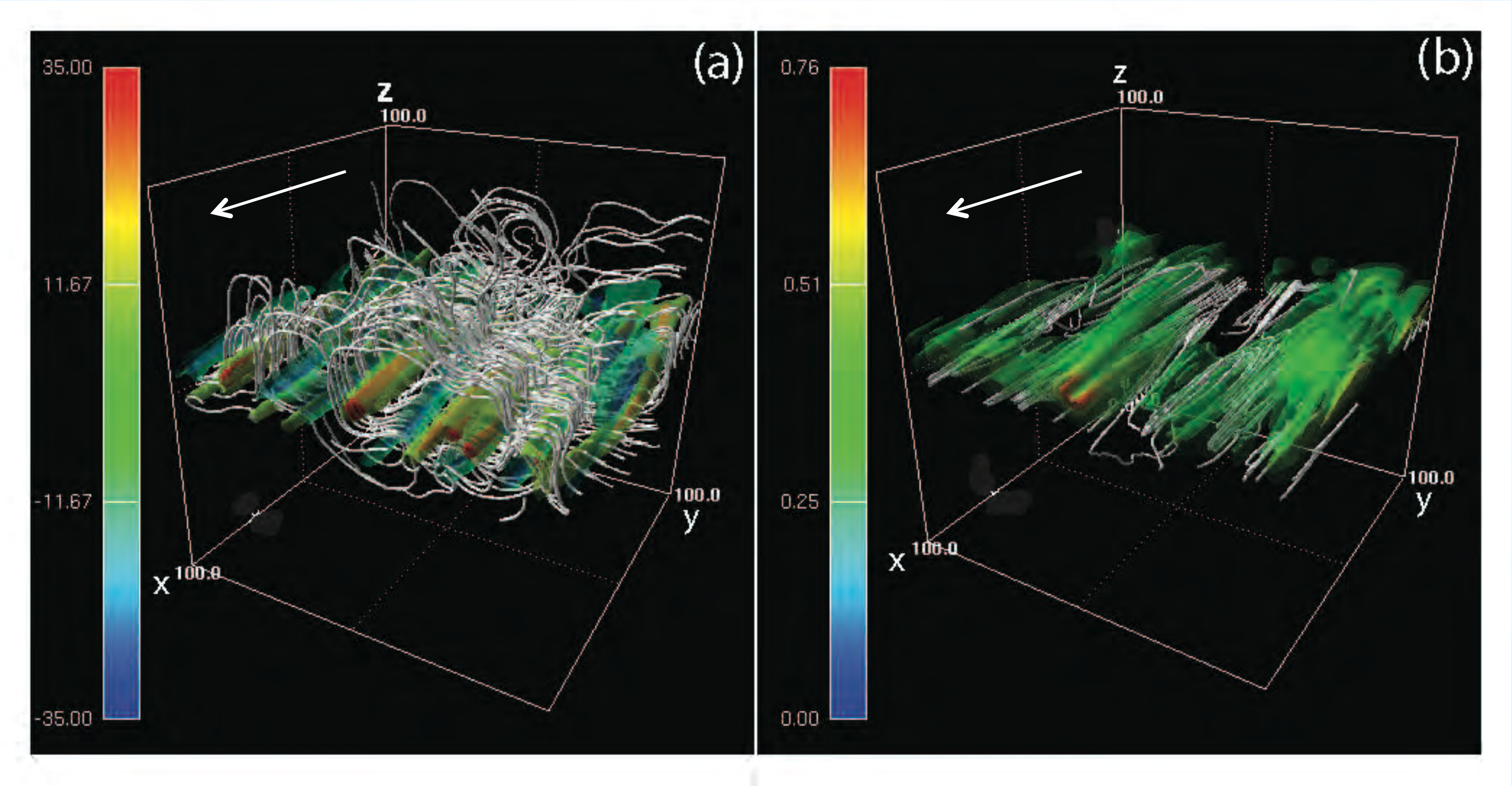


(Nishikawa et al. 2014, ApJ)

3D structure of current filaments and magnetic field

$e^{\pm}$ $\gamma_{jt} = 5$ $t = 250\omega_{pe}^{-1}$

J_x with magnetic field lines B^2 with current streaming lines

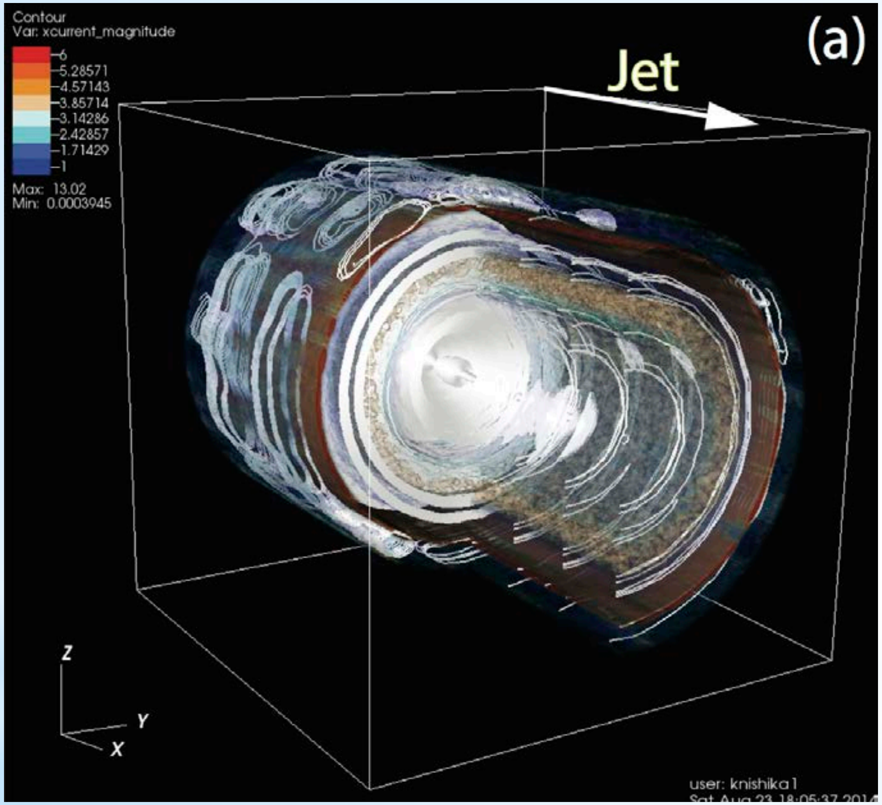


(Nishikawa et al. 2014, ApJ)

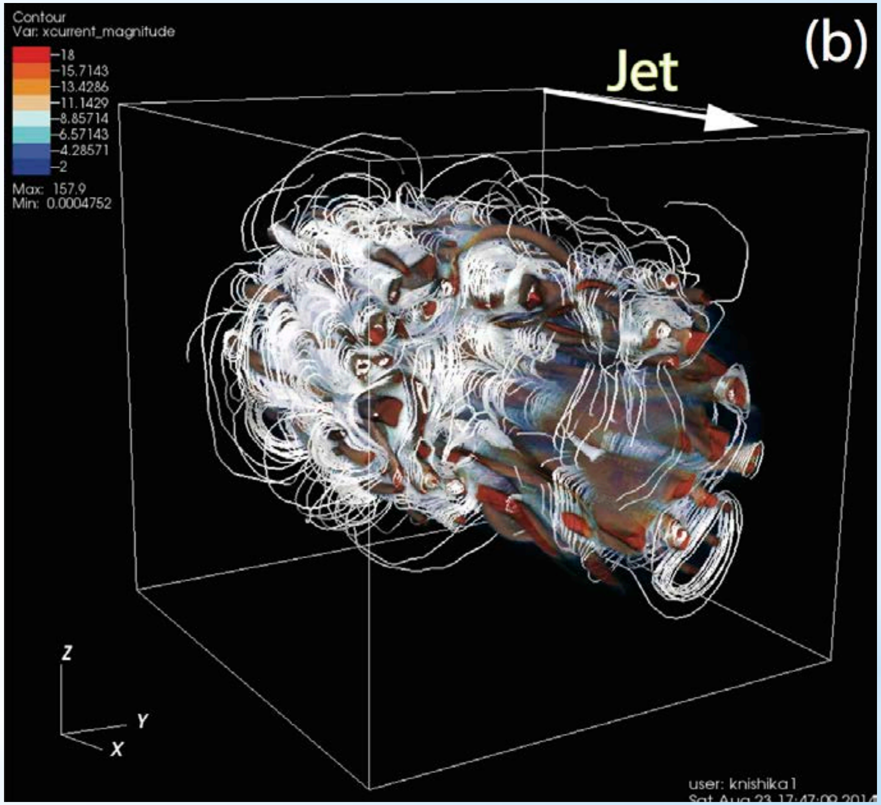
Cylindrical kKHI simulations

$\gamma_{jt} = 5 \qquad t = 300\omega_{pe}^{-1}$

e - p



$e^{\pm}$



Snap shot of electron density of global jet simulations

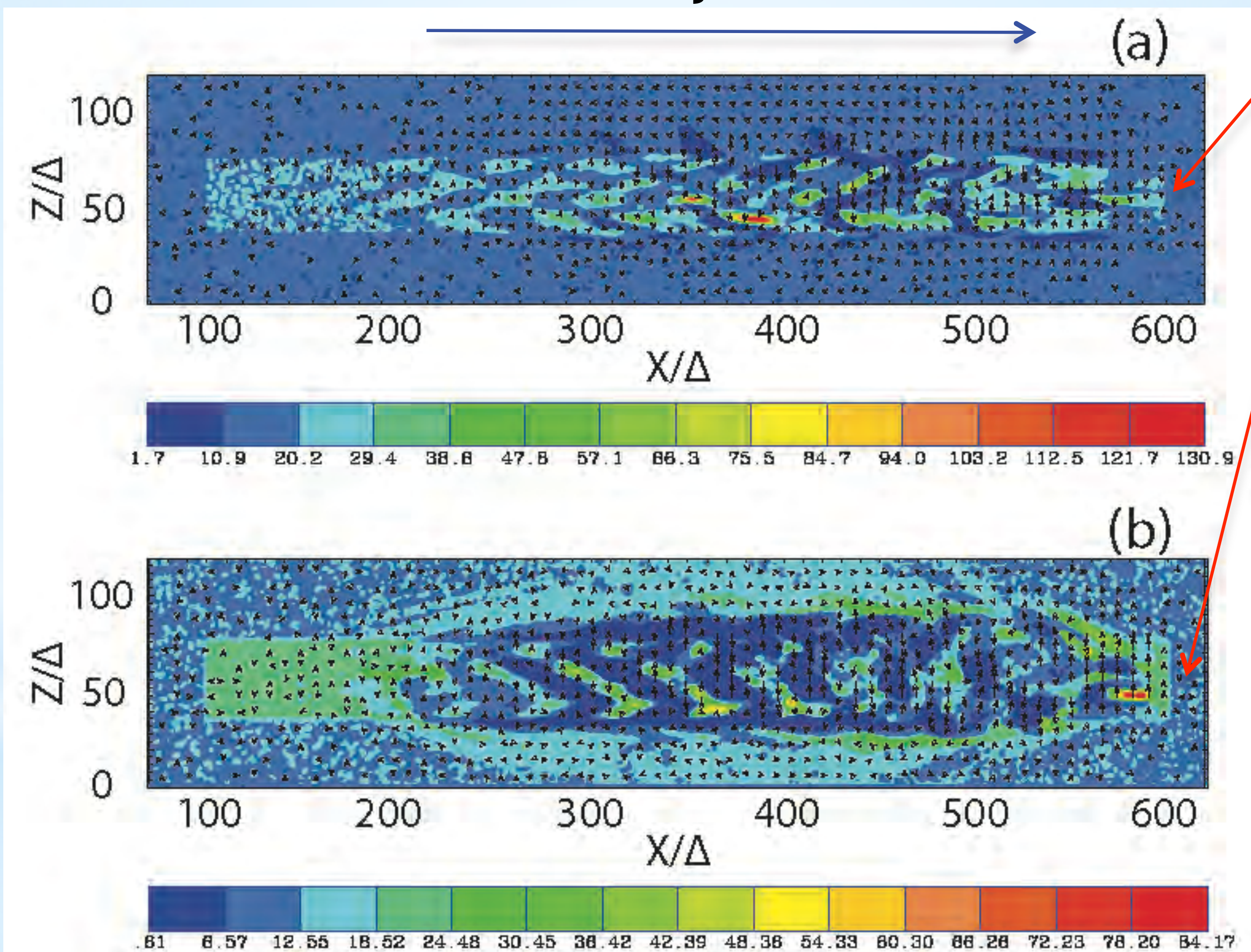
$\gamma_{jt} = 5$ $t = 500\omega_{pe}^{-1}$ $r_{jet} = 20$ 645 x 131 x 131

Jet head

jet

e - p

e±

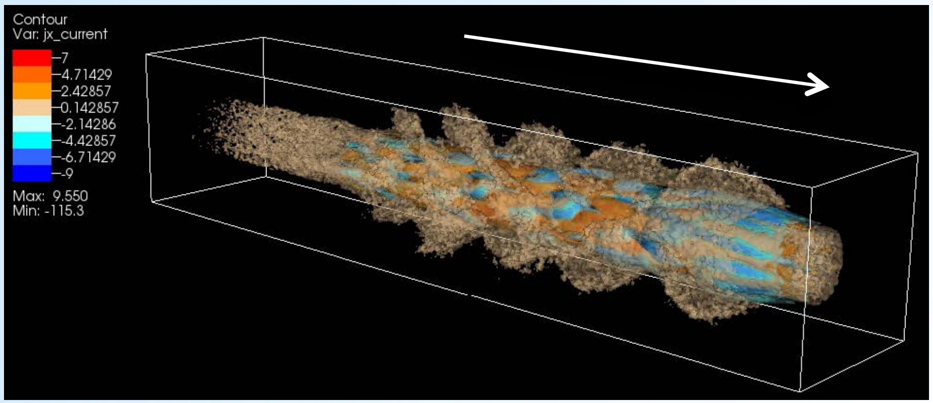


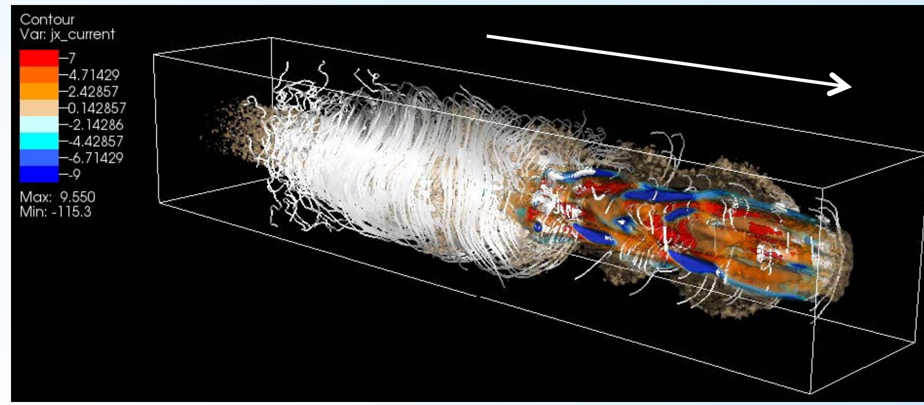
3D snapshots of current (J_x) isosurfaces with magnetic field lines

Evolution of shock and instability is different for electron-proton and electron-positron $\gamma_{jt} = 15$ $t = 500\omega_{pe}^{-1}$

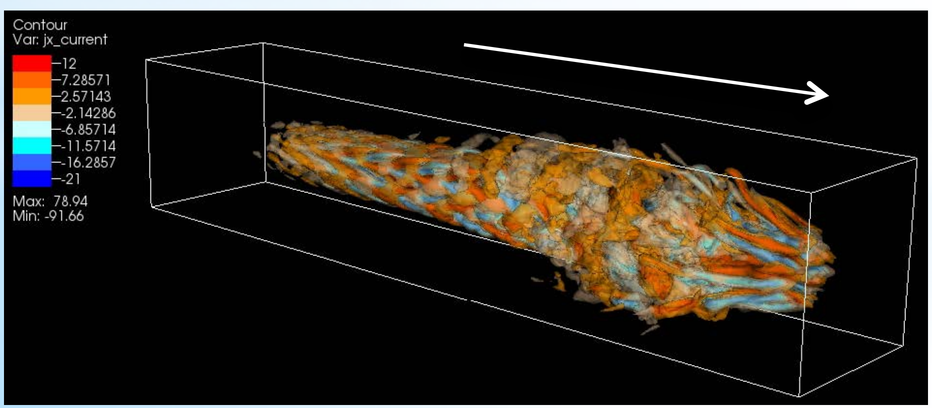
white lines: magnetic filed lines

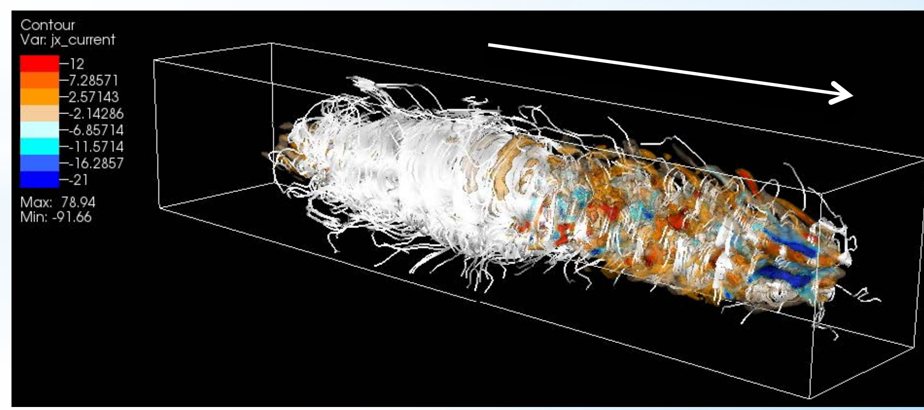
e - p



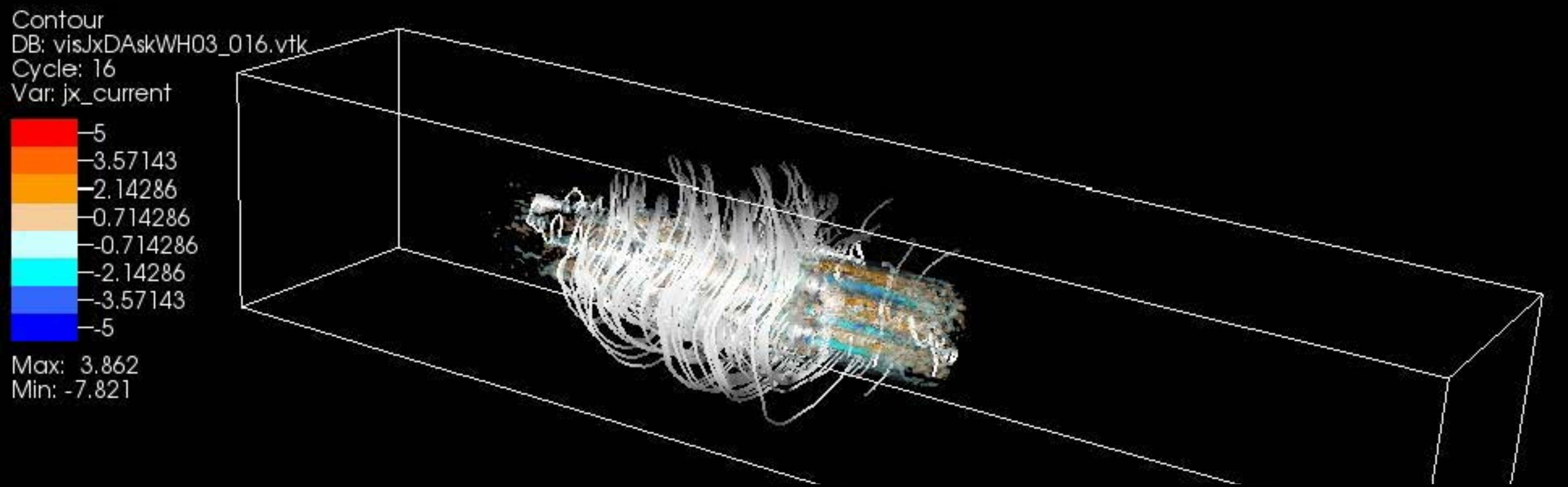


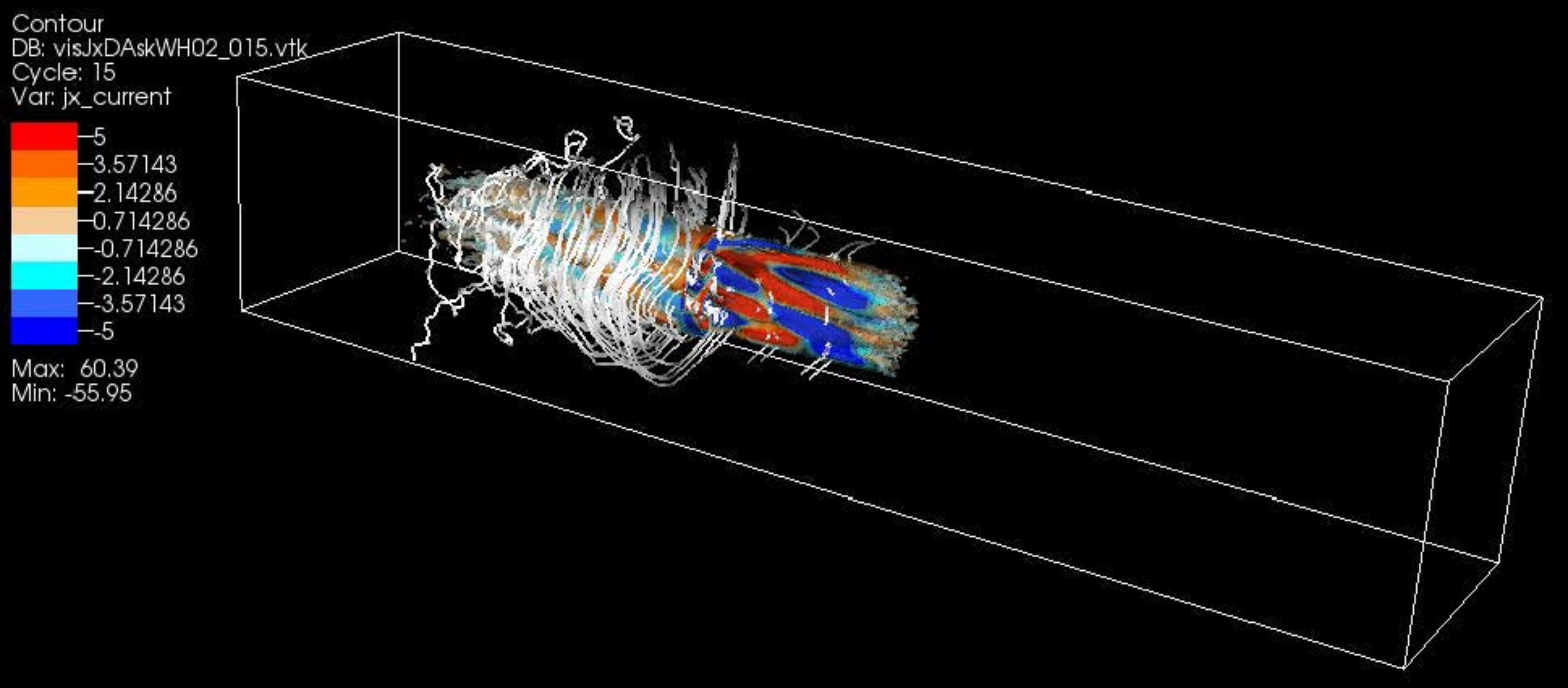
e$^{\pm}$





(Nishikawa et al. 2014)


Contour
DB: visJxDAskWH03_016.vtk
Cycle: 16
Var: jx_current
5
3.57143
2.14286
0.714286
-0.714286
-2.14286
-3.57143
-5
Max: 3.862
Min: -7.821


Contour
DB: visJxDAskWH02_015.vtk
Cycle: 15
Var: jx_current
5
3.57143
2.14286
0.714286
-0.714286
-2.14286
-3.57143
-5
Max: 60.39
Min: -55.95

3D global jet simulation

NASA Pleiades

system size: $2000\Delta \times 1000\Delta \times 1000\Delta$

jet radius: 100Δ

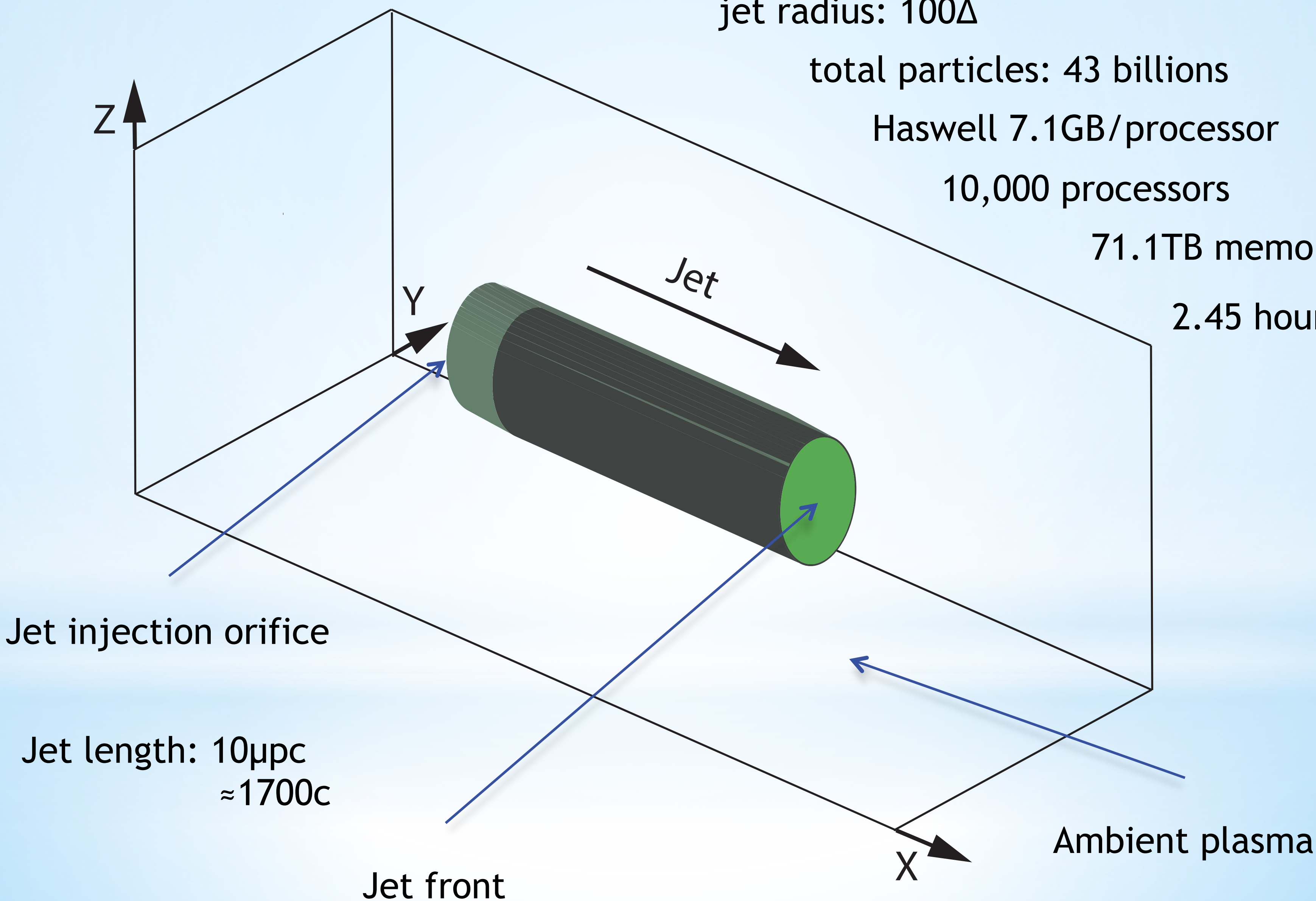
total particles: 43 billions

Haswell 7.1GB/processor

10,000 processors

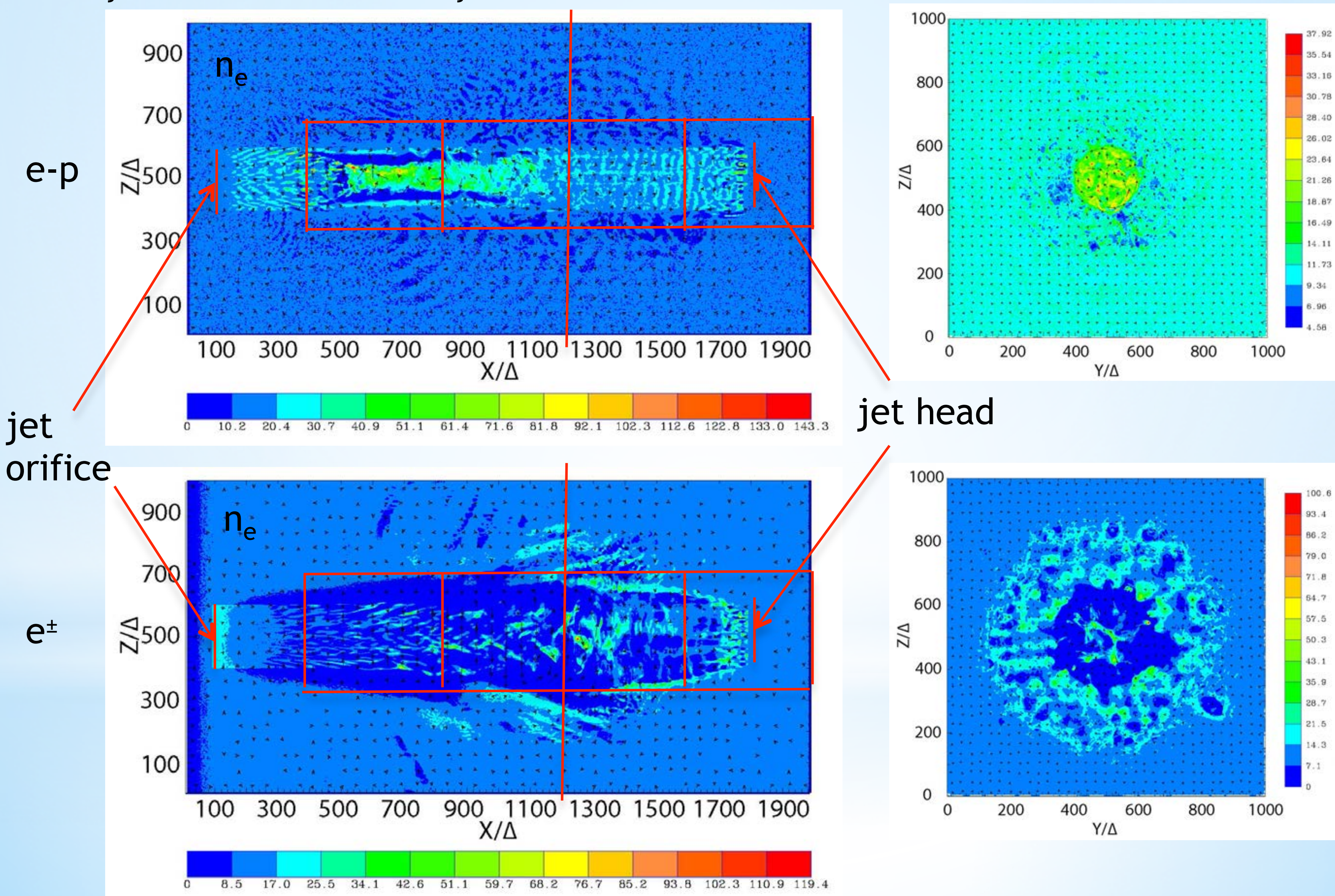
71.1TB memory

2.45 hours



Snap shot of electron density of global jet simulations with arrows ($B_{x,y,z}$)

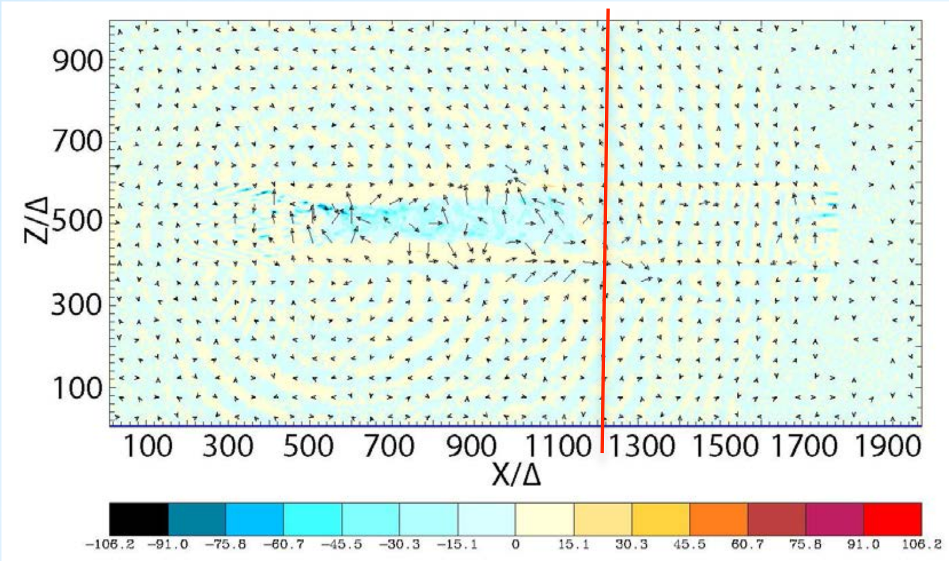
$\gamma_{jt} = 15$ $t = 1{,}700\omega_{pe}^{-1}$ $n_{jet} = 0.67n_{amb}$ at the center of the jet X/Δ=1200

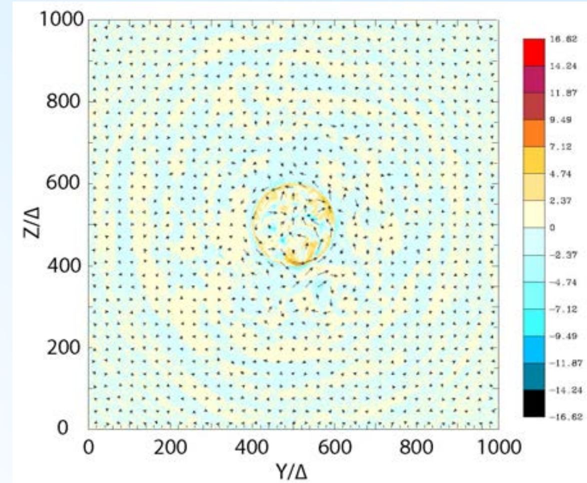


(Nishikawa et al. in progress, 2015)

Snap shot of current density (J_x) of global jet simulations with arrows ($B_{x,y,z}$)

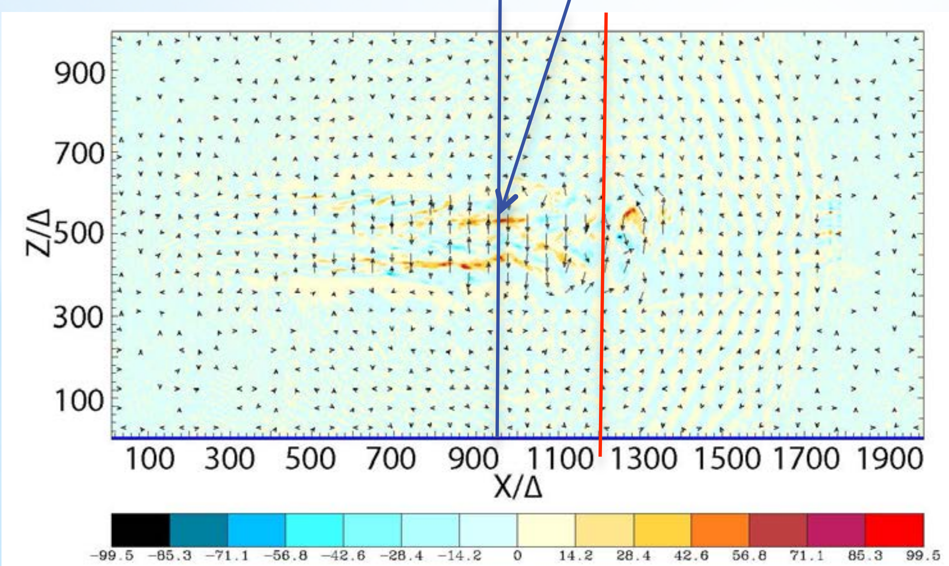
e-p

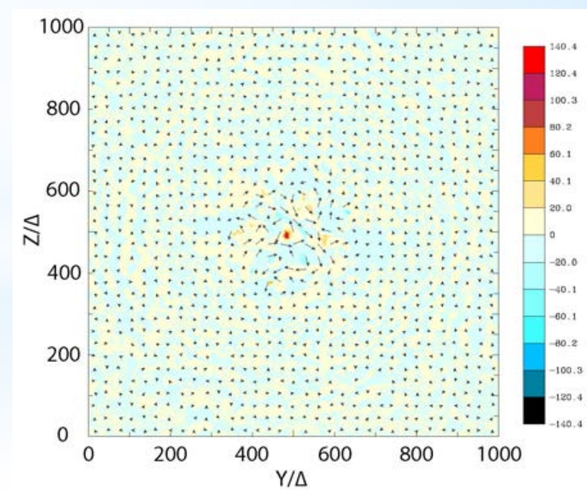




anti-parallel magnetic field: needs 3D topological analysis

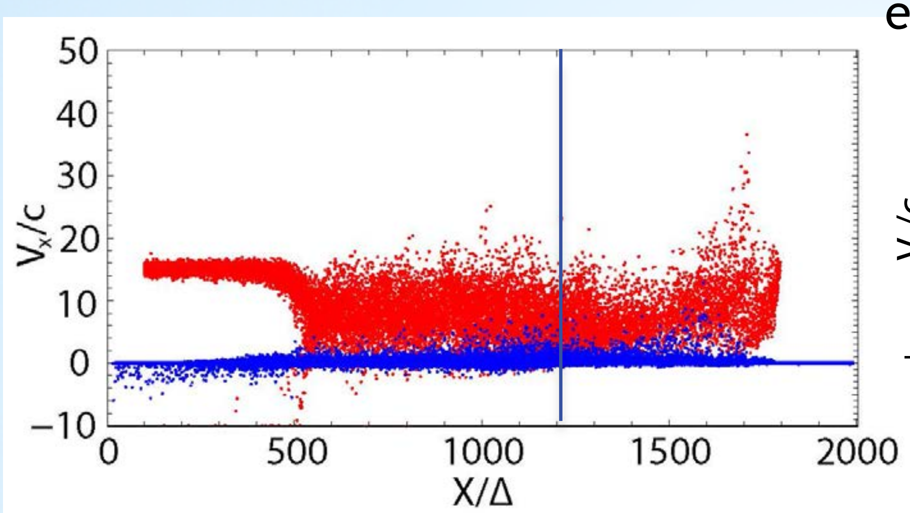
e±



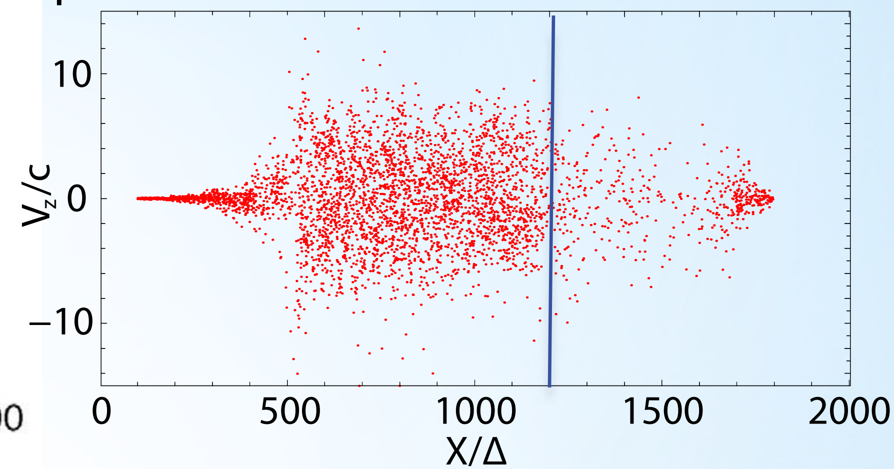


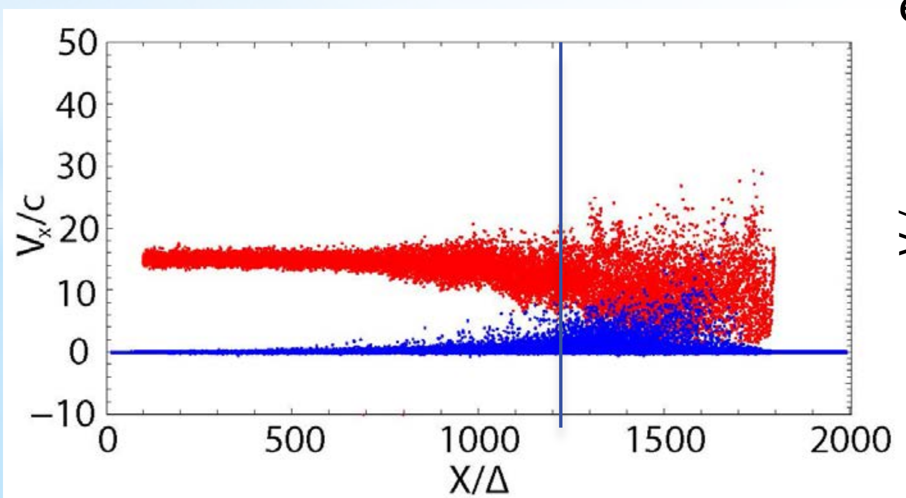
Phase-space distributions of electrons (X - Vx, and X - Vz)

red: jet electrons, blue: ambient electrons

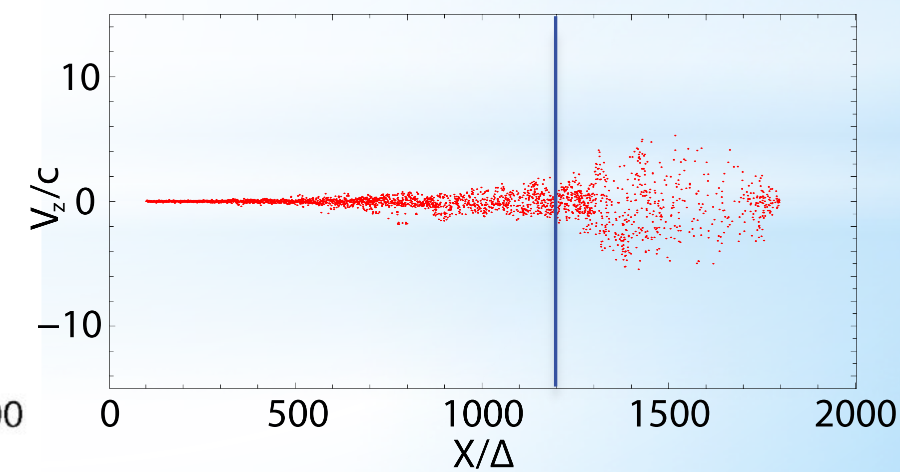


e-p





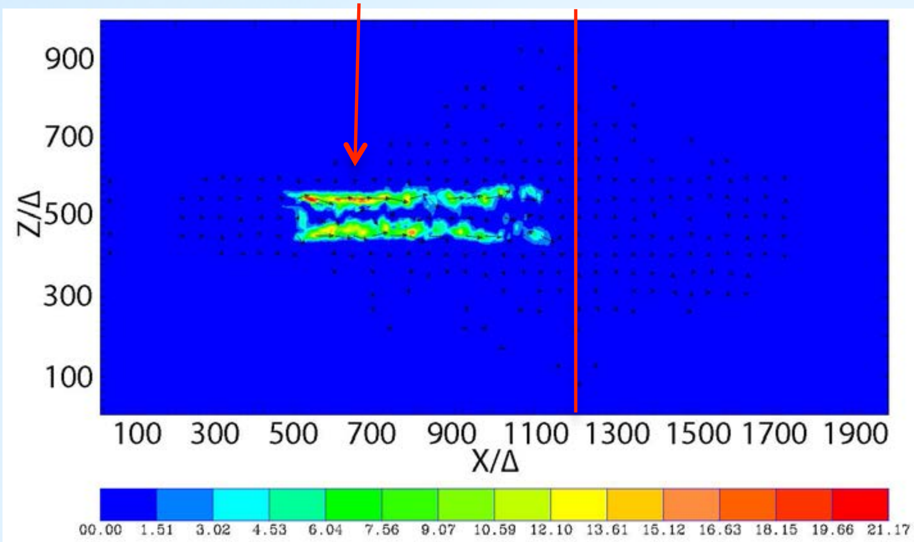
e±

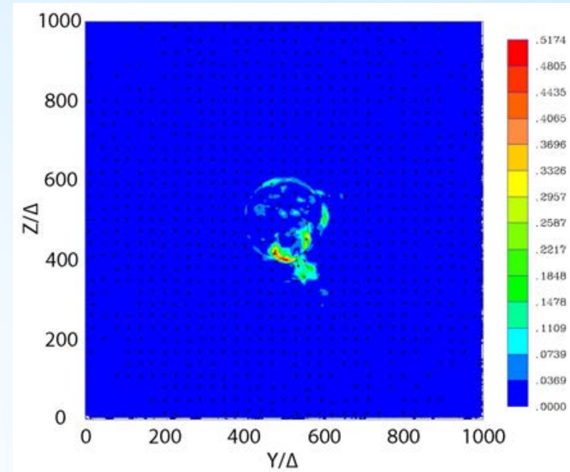


Snapshot of |ExB| in x – z and y – z planes with arrows $(ExB)_{x,y,z}$

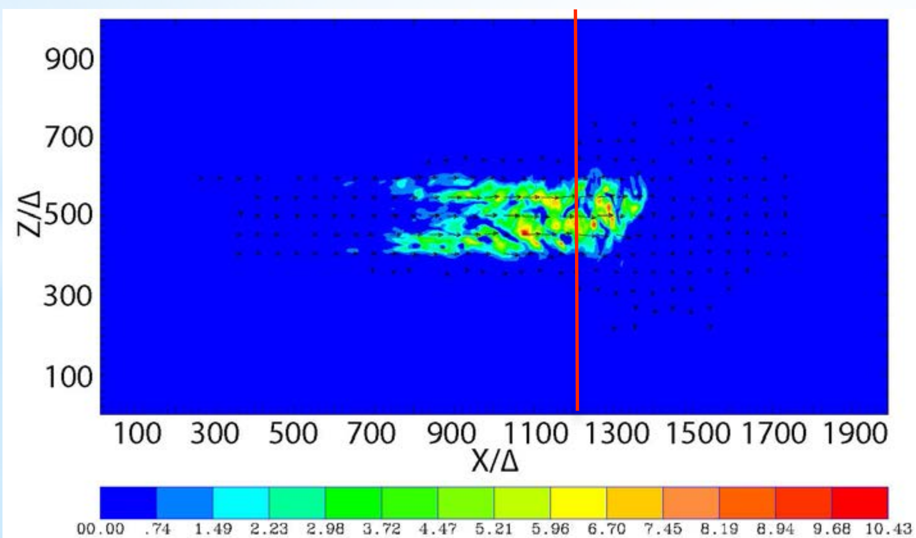
collimation due to toroidal magnetic field

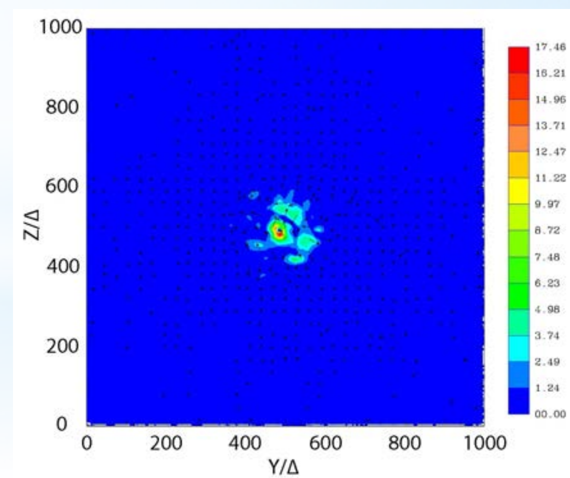
e-p





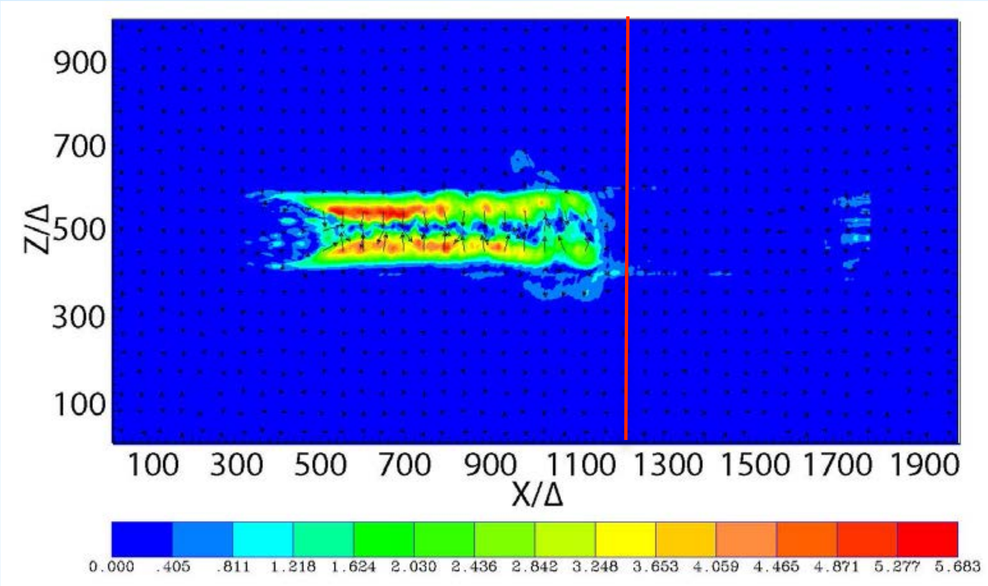
e$^{\pm}$

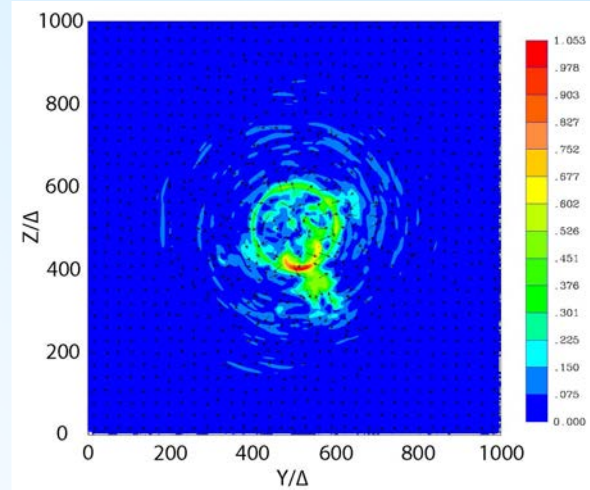




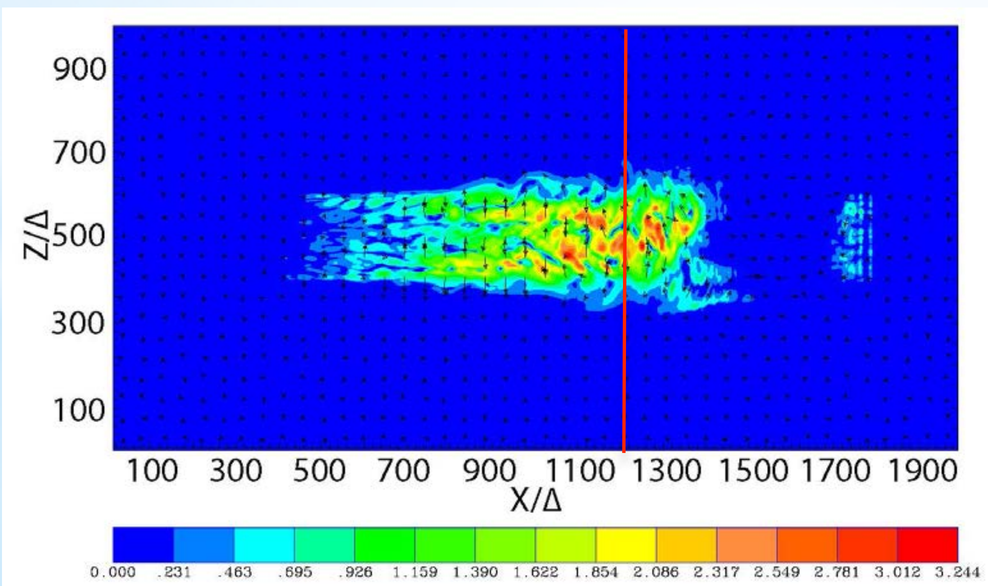
Snapshot of |B| in x - z and y - z planes with arrows ($E_{x,y,z}$)

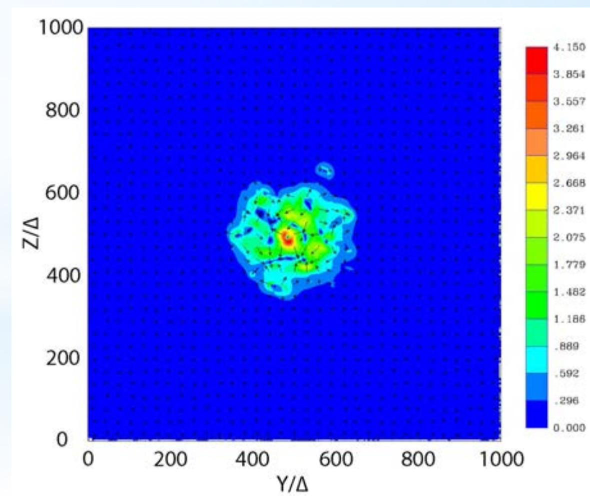
e-p





e±





3D structure of the x-component of current (J_x) with magnetic field lines

e-p $r_{jet} = 100\Delta$

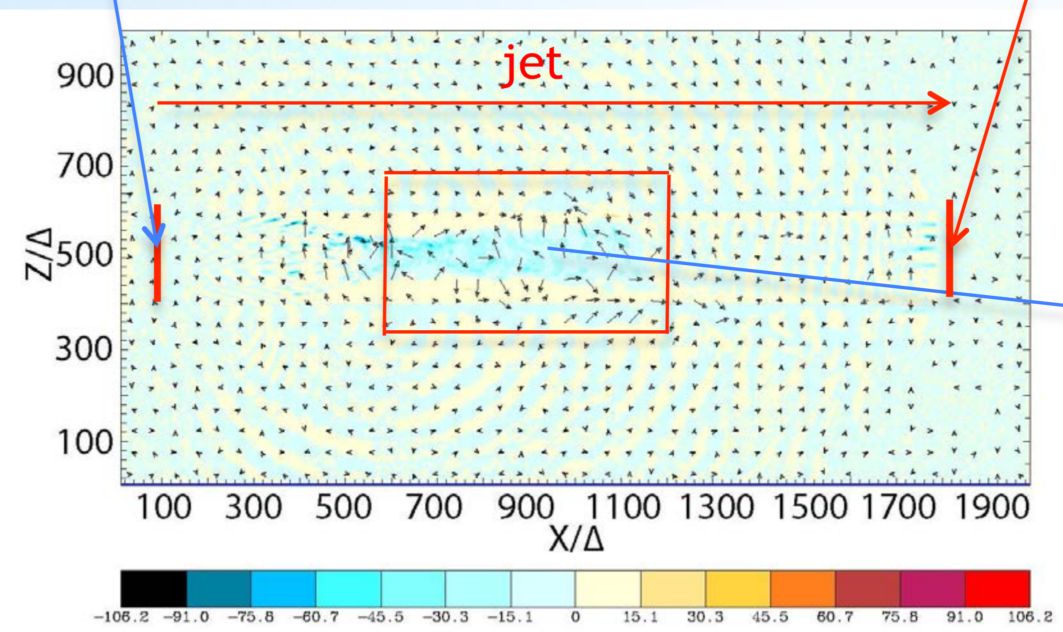
$600 < X/\Delta < 1200$,
$328 < Y/\Delta , Z/\Delta < 678$

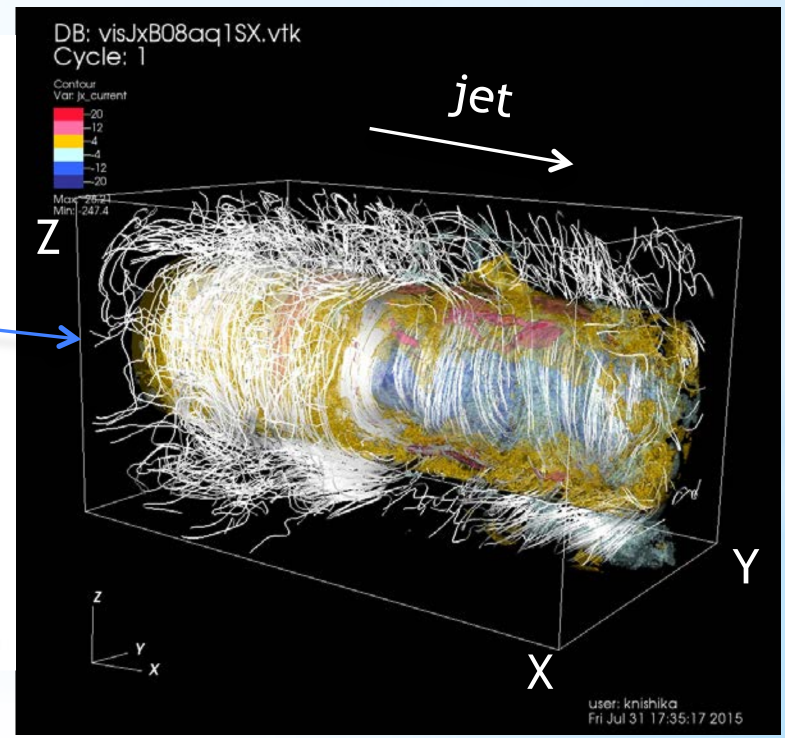
$-20 < J_x < 20$

jet orifice J_x with arrows ($B_{x,z}$)

white lines: magnetic field lines

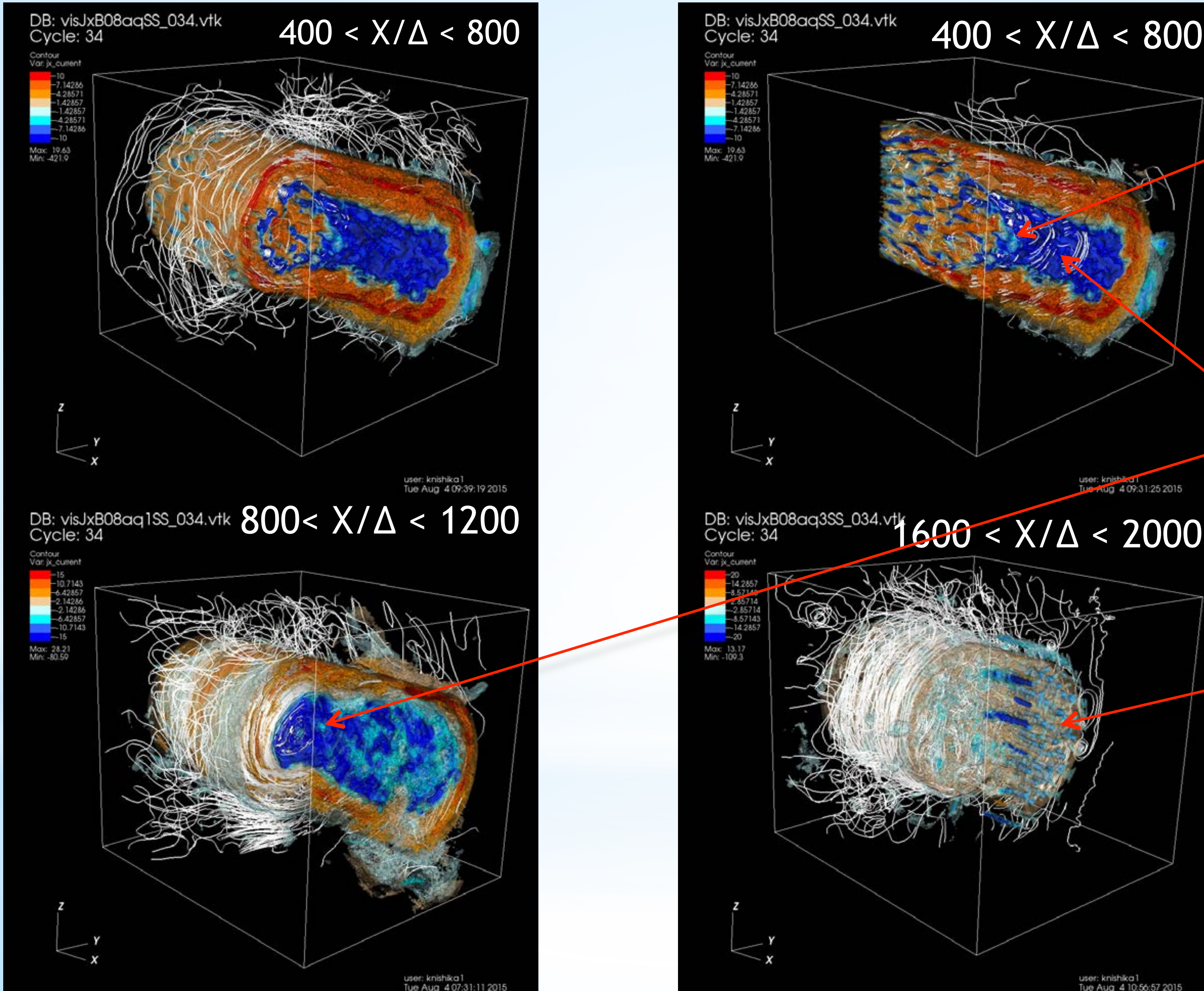
jet head





magnetic field lines are generated by kKHI

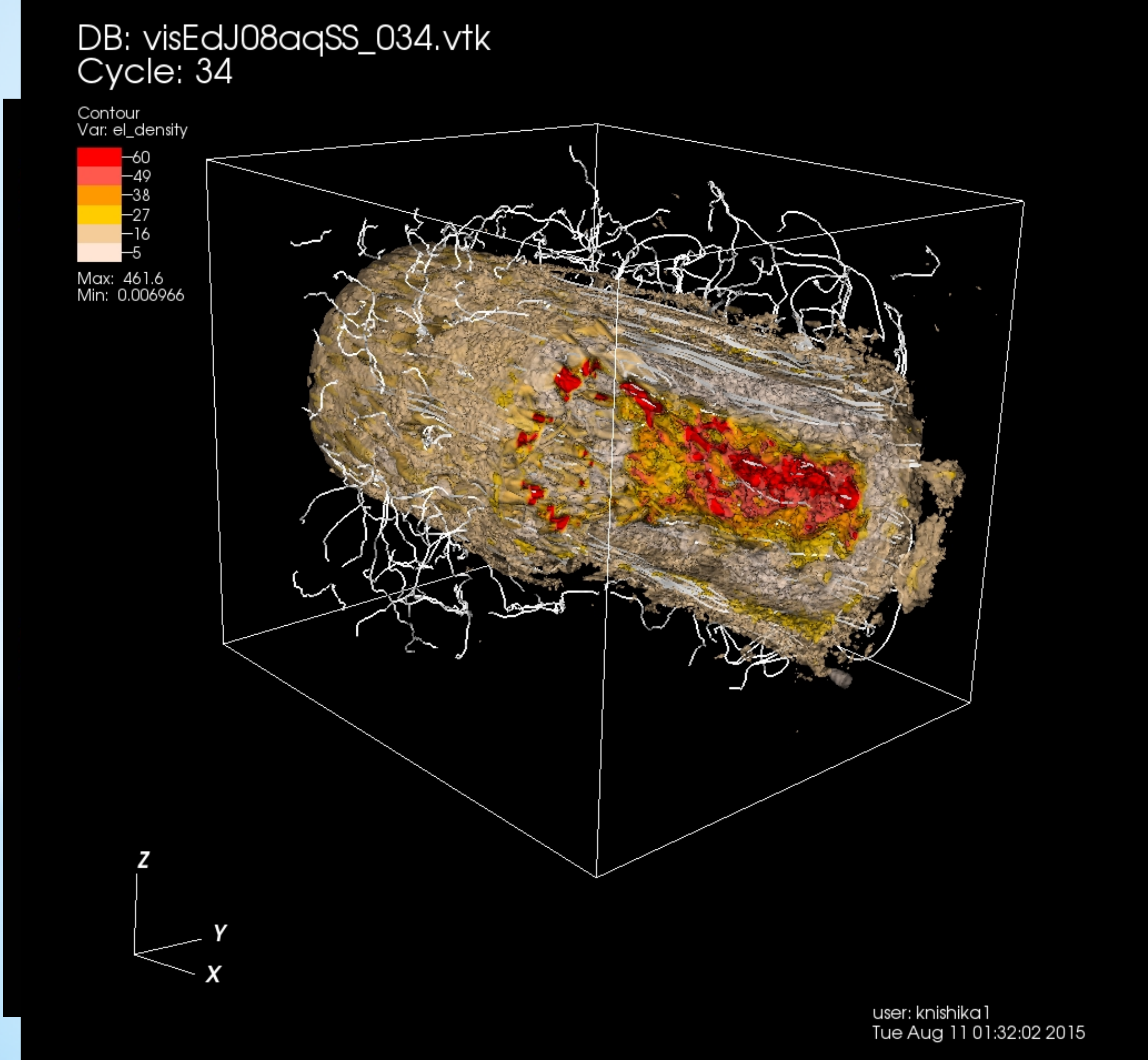
3D jet structures of J_x and magnetic field lines for e-p



current filaments disappear

jet collimates due to kKHI

current filaments remain at jet head



current filaments disappear

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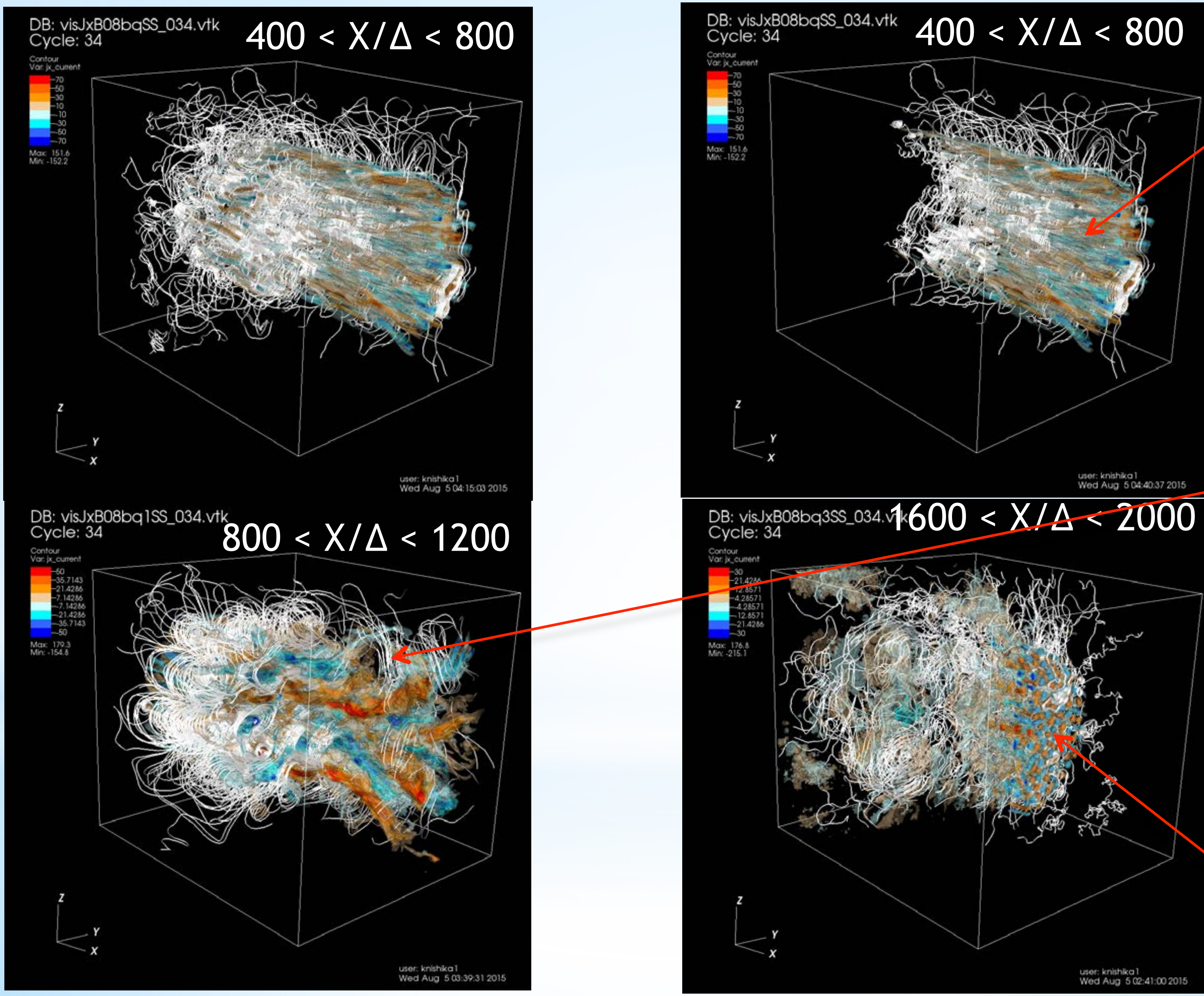
current filaments remain at jet head

3D jet structures of J_x and magnetic field lines for $e^{\pm}$



current filaments grow

current filaments move outward

current filaments remain at jet head

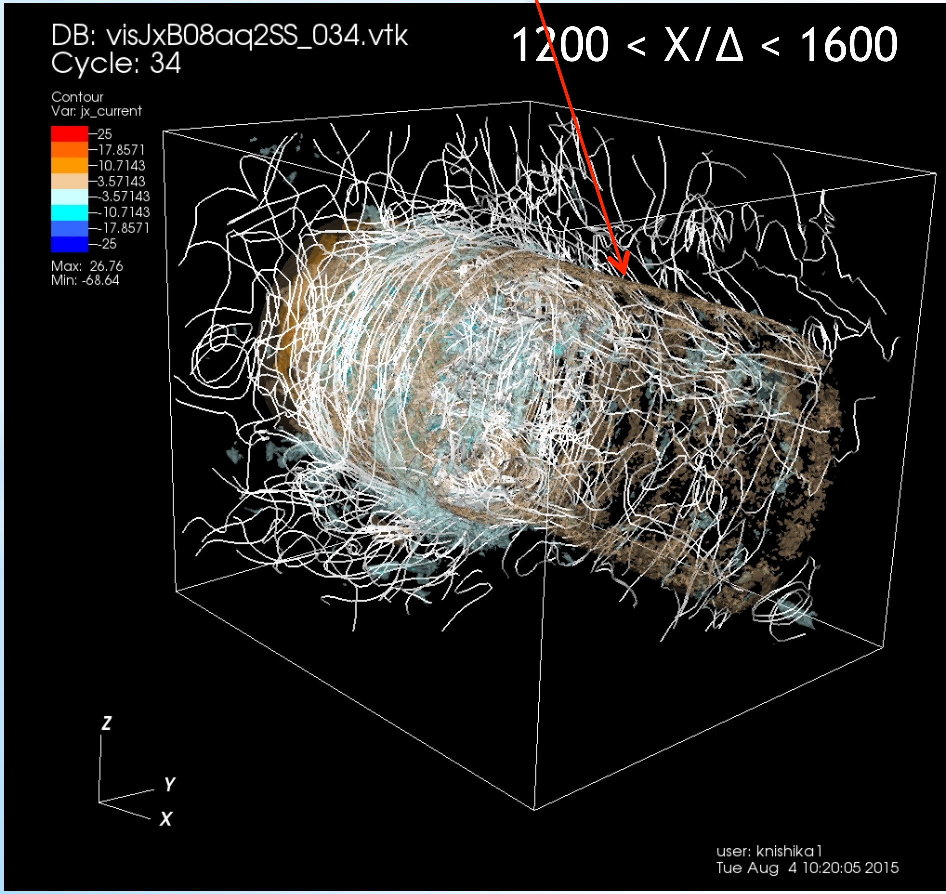
Current filaments behind the jet head

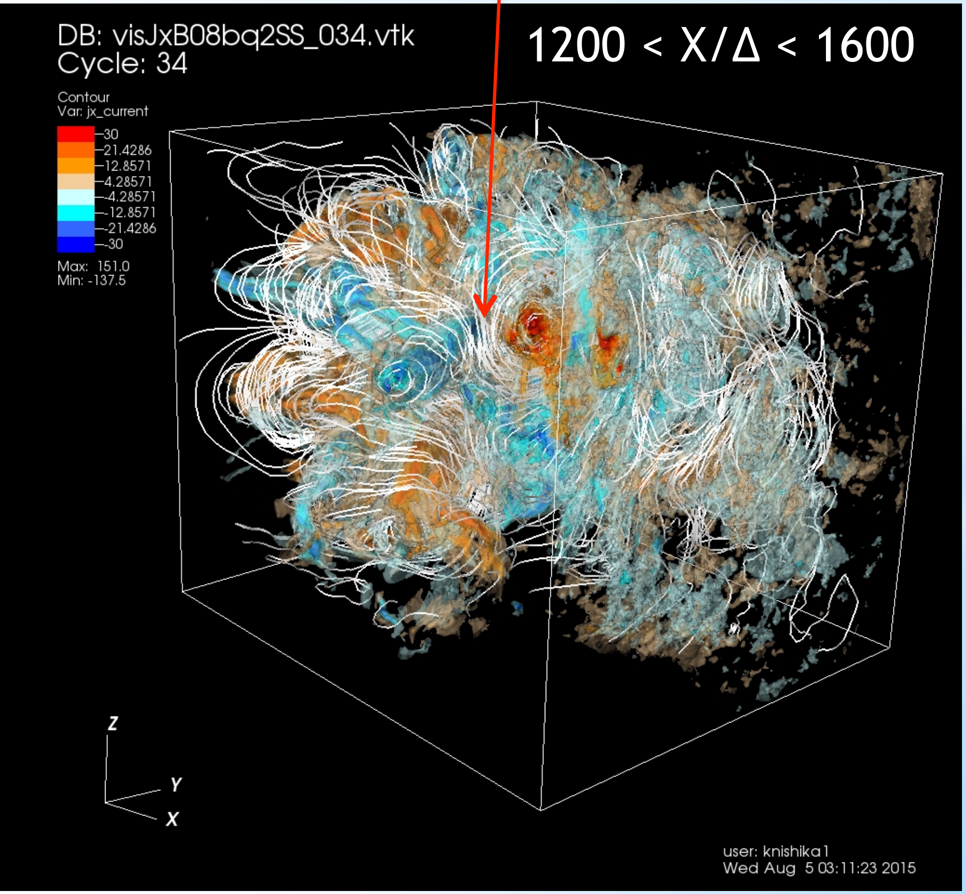
proton currents maintain the original jet boundary

current filaments twisted outward

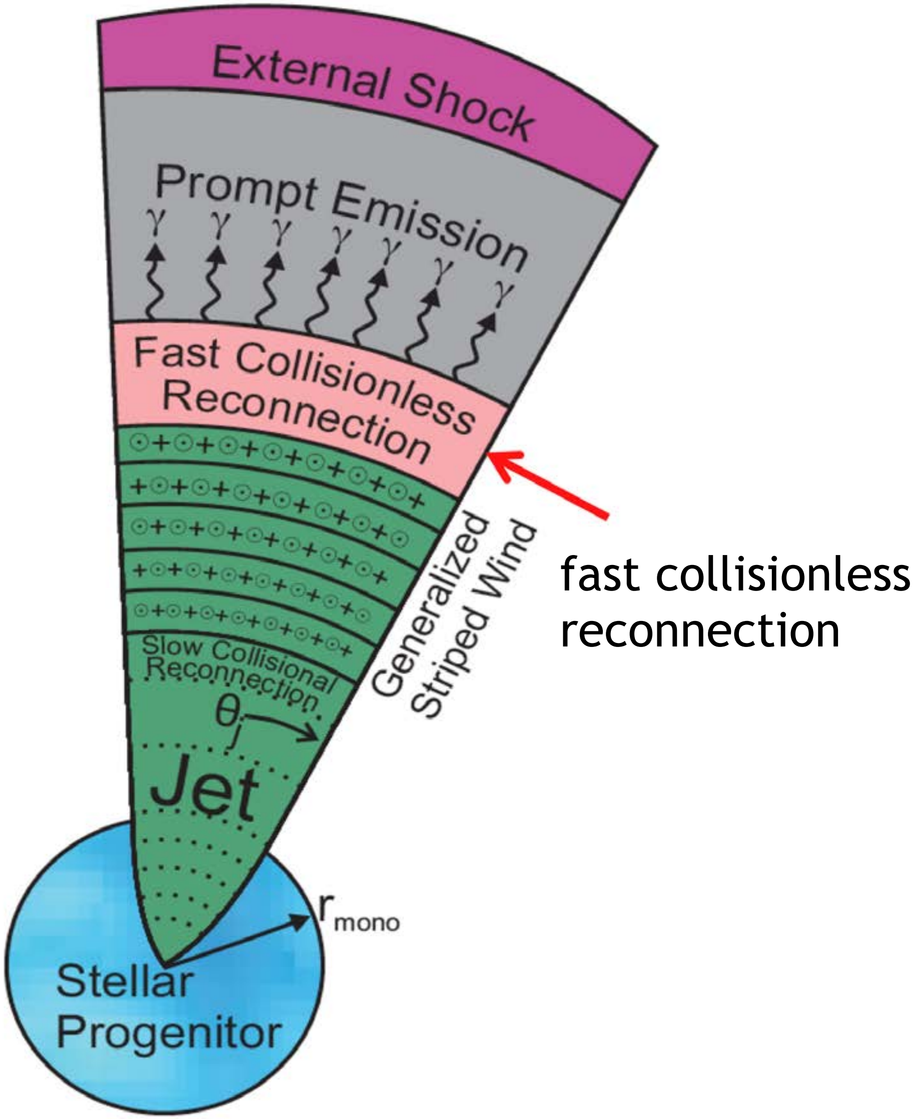
e-p

$e^{\pm}$



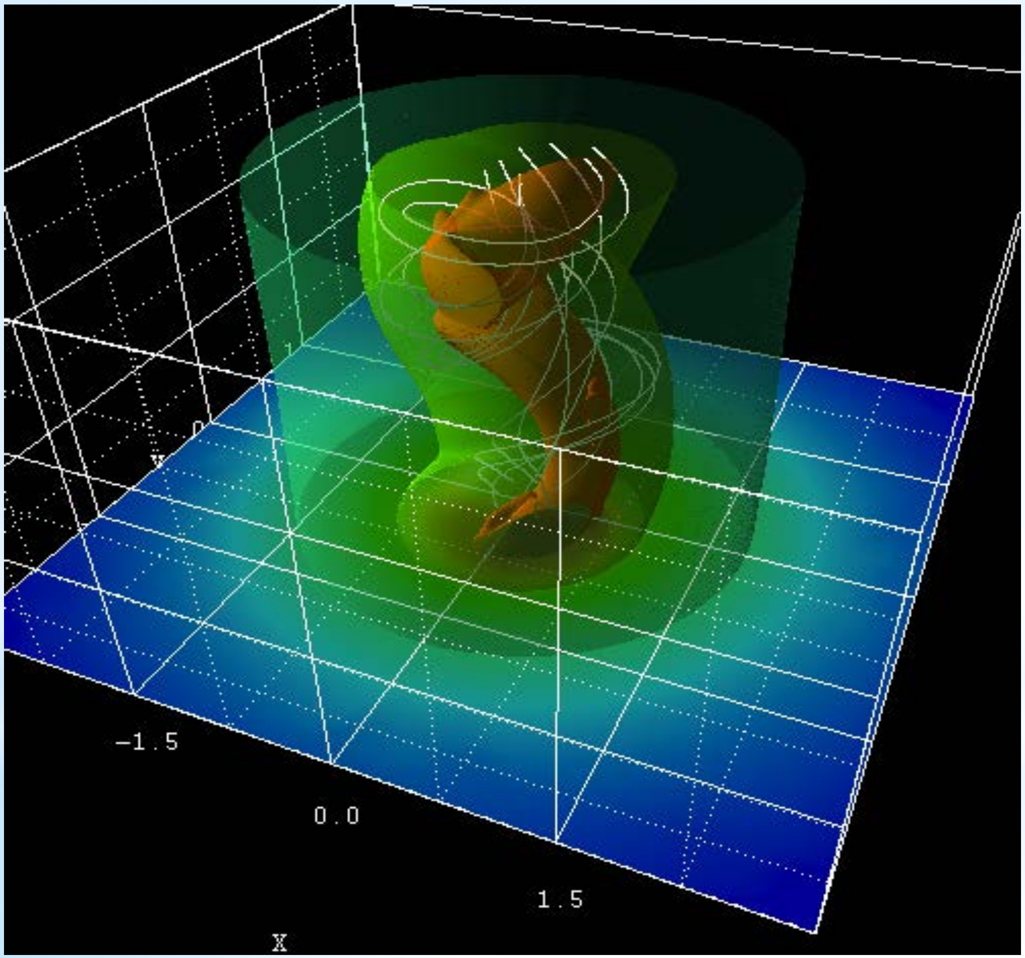


Reconnection in jet



Reconnection switch concept: Collapsar model or some other system produces a jet (with opening half-angle θ_j) corresponding to a generalized stripped wind containing many field reversals that develop into dissipative current sheets (McKinney and Uzdensky, 2012, MNRAS, 419, 573). This reconnection needs to be investigated by resistive RMHD, which is in progress within our research effort.

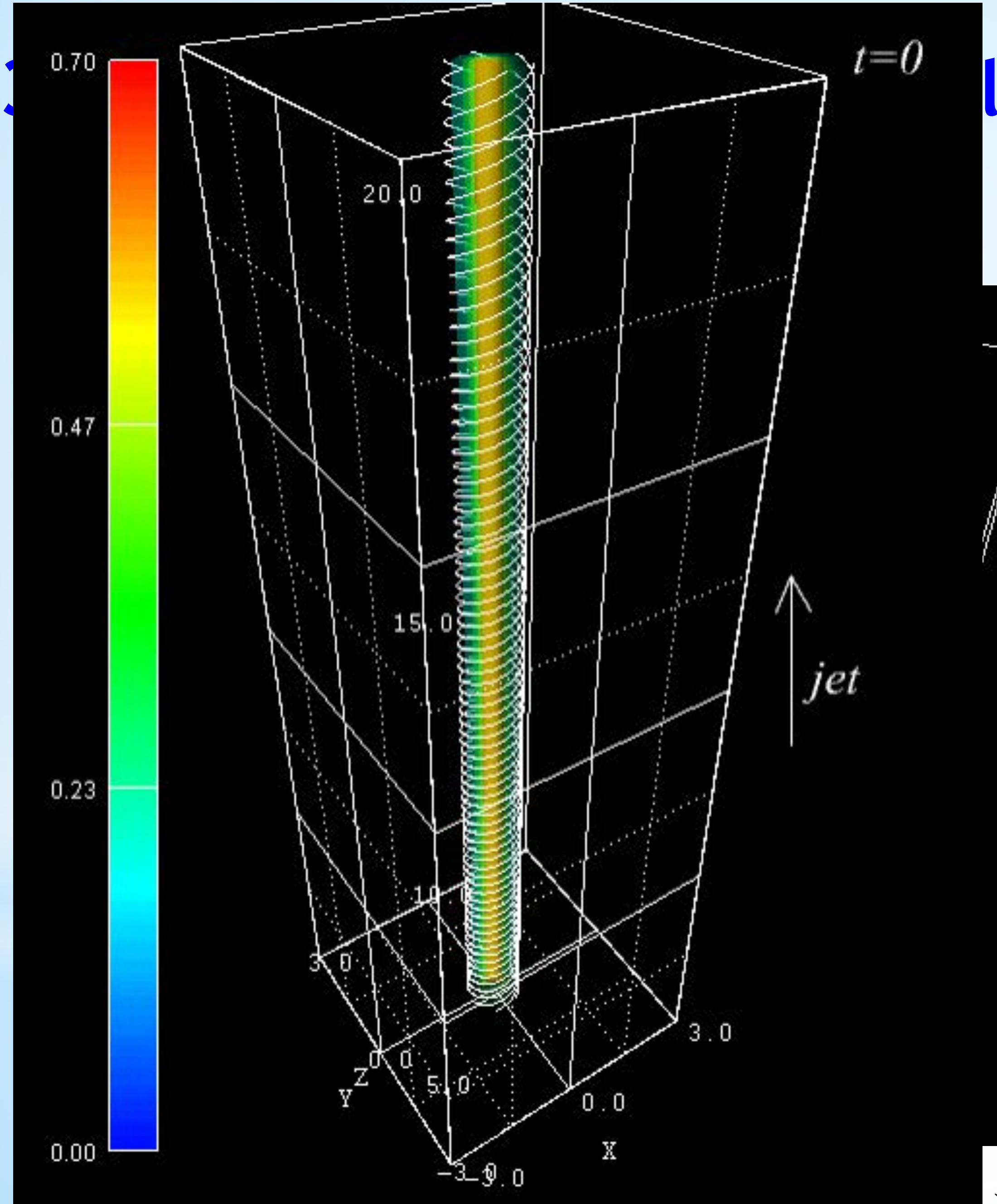
3-D kink instability with helical magnetic field



(Mizuno et al. ApJ, 734:19 (18pp), 2011)

Relativistic jet with helical magnetic field, which leads to the kink instability and subsequent reconnection, can be simulated using resistive relativistic MHD (this simulation was performed with ideal RMHD code).

lical magnetic field



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(Mizuno et al. ApJ, 734:19 (18pp), 2011)

Summary of Kinetic Kelvin-Helmholtz Instability

1. Static electric field grows due to the charge separation by the negative and positive current filaments
2. Current filaments at the velocity shear generate magnetic field transverse to the jet along the velocity shear
3. Jet with high Lorentz factor with core-sheath case generate higher magnetic field even after saturated in the case counter-streaming case with moderately relativistic jet
4. Non-relativistic jet generate KKHI quickly and magnetic field grows faster than the jet with higher Lorentz factor
5. For the jet-sheath case with Lorentz factor 15 the evolution of KKHI does not change with the mass ratio between 20 and 1836
6. Strong magnetic field will affect electron trajectories and create synchrotron-like (jitter) radiation which will be investigated
7. Global jets with combined of Weibel instability and kKHI need to be investigated further and with helical magnetic field

(for detail please see (Nishikawa et al. 2014, ApJ)

Summary for global jet simulations

- The size of jet radius is critical for the evolution of jets
- The simulations with jet radius $r_{jet} = 200\Delta$ show the clear differences electron-proton and electron-positron jets
- The electron-proton jet shows jet collimation due to the toroidal magnetic field generated by kKHI
- The electron-proton jet shows the well-defined jet boundary by the edge current by protons
- The electron-positron jet shows the growth of kKHI and the Weibel instability which generate the strong current filaments expanding outside the jet
- The electron-proton jet shows strong toroidal magnetic field in the whole jet which may contribute circularly-polarized radiation
- Further simulations with a even larger system (larger jet radius) need to be investigated

Future plans

- Further simulations with a systematic parameter survey will be performed in order to understand shock dynamics including KKHI and reconnection
- Further simulations will be performed to calculate self-consistent radiation including time evolution of spectrum and time variability using larger systems
- Investigate radiation processes from the accelerated electrons in turbulent magnetic fields and compare with observations using global simulation of shock, KKHI and reconnection with helical magnetic field in jet (GRBs, SNRs, AGNs, etc)
- Magnetic field topology analysis for understanding reconnection evolution
- Particle acceleration and radiation in recollimation shocks