Test particle simulations at tearing of null-point current sheets

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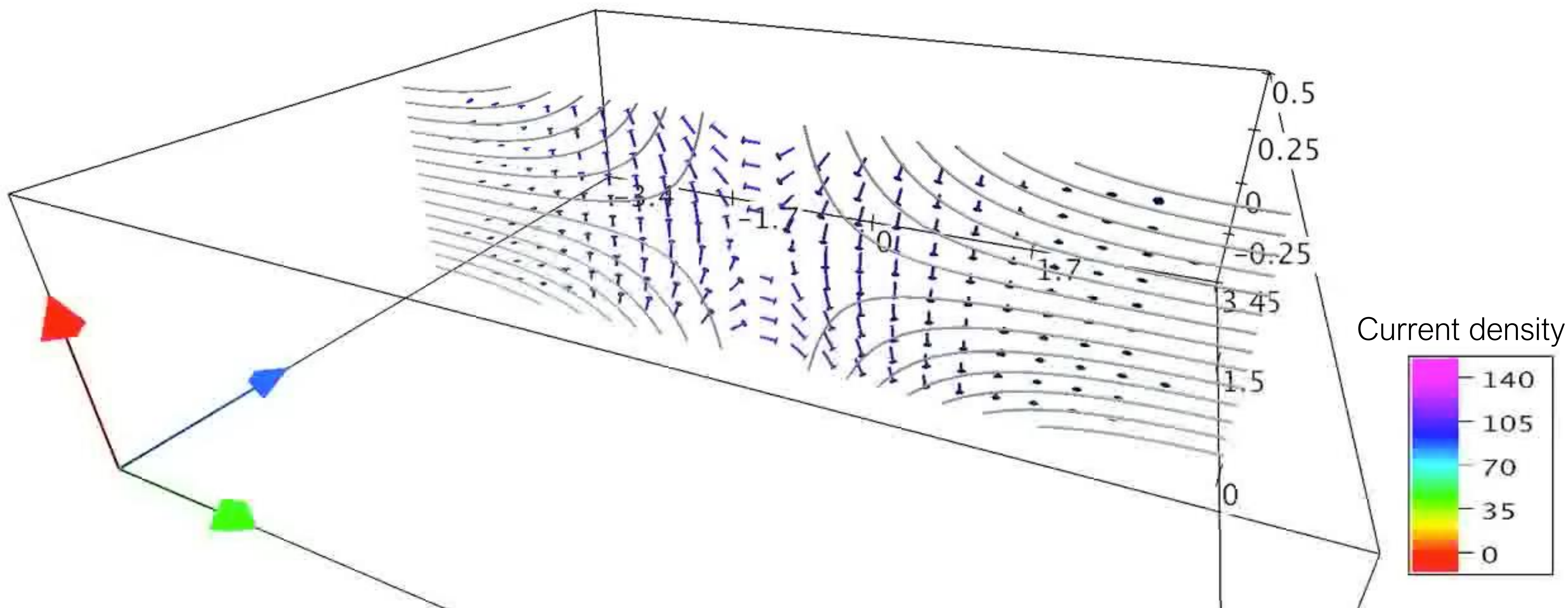


Opposite driving forces shear magnetic null point, causing formation and subsequent tearing of current sheet.

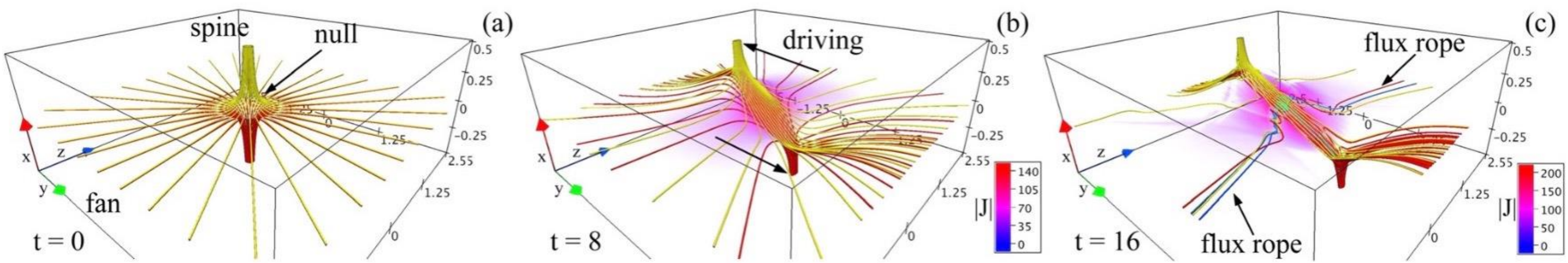
Acceleration profile

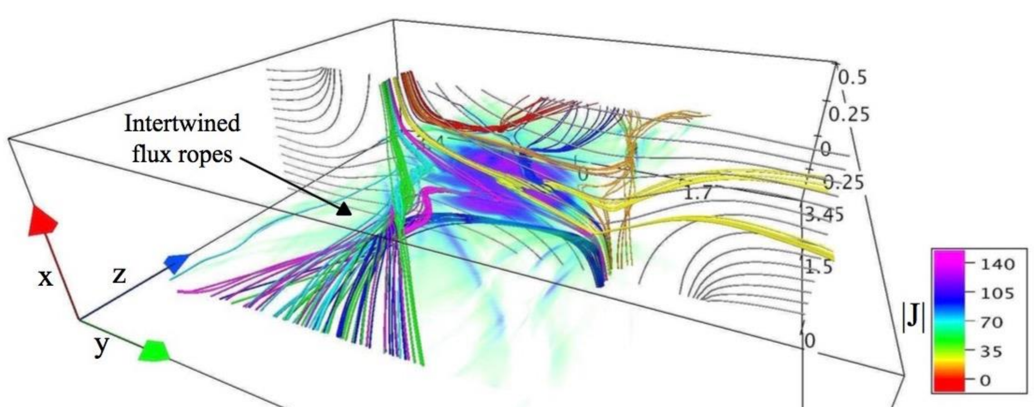
1. From where are the particles accelerated?
2. Where are the particles accelerated to?
3. How much are they accelerated by?

Run test particle simulations at various stages of tearing along z=0 plane. Take snapshots of geometries at key points of sheet evolution:

- Quasi-steady intact sheet (t=8).
- Onset of sheet tearing (t=16).
- Some time after tearing (t=21).

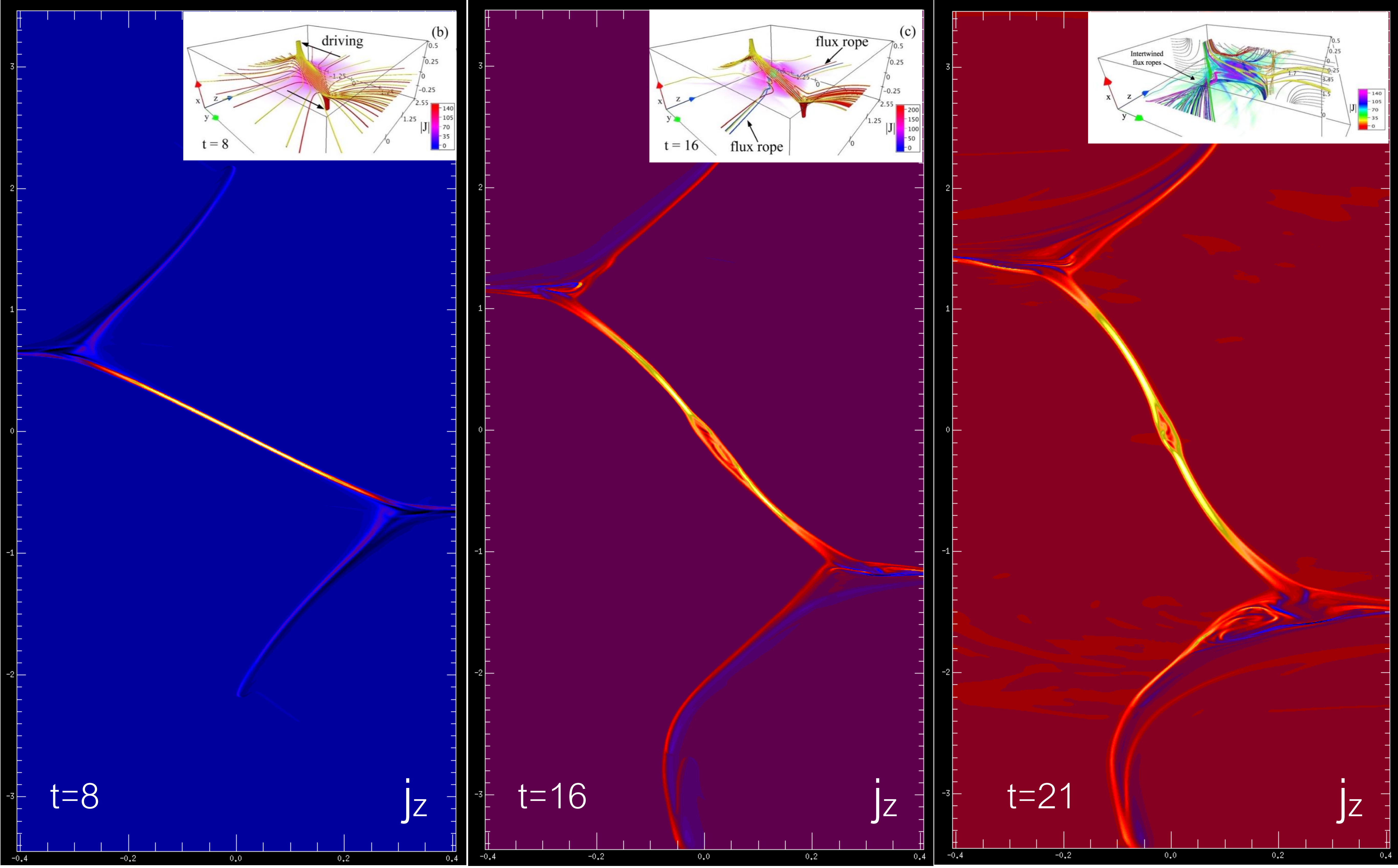
Each snapshot is composed of a regular grid with varying cell size. We get non-dimensional field values at each grid point and use linear interpolation to find field values in between grid points.





t=21

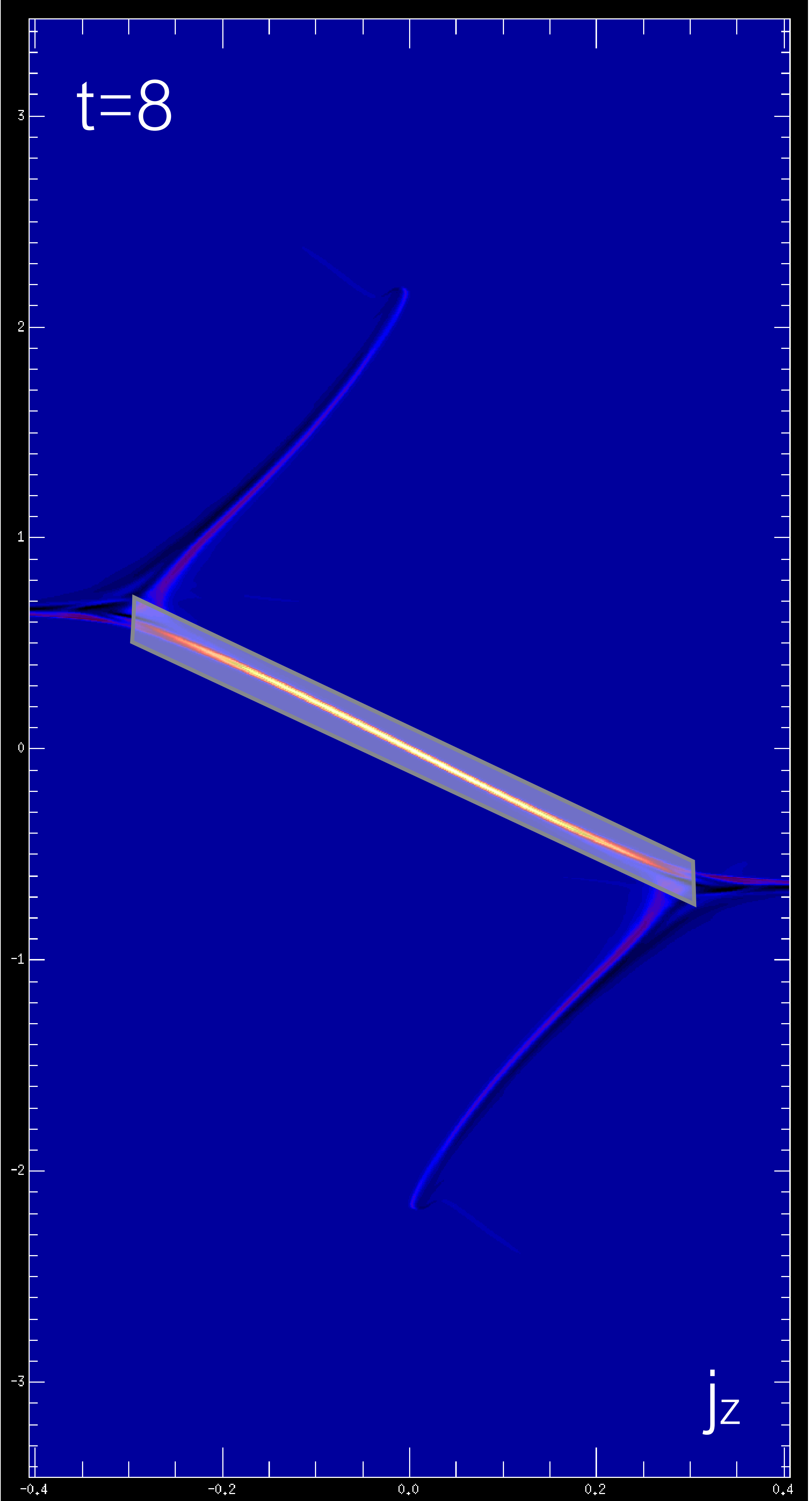
(Wyper & Pontin, 2014a,b)



Relative current density distributions (j_z) at z=0 plane across entire x-y domain.

Scaling factors

- Grid from MHD simulation in non-dimensional units - need to apply scaling factors.
- Temperature $T_0 = 10^6$ K
- Length $l_0 = 10^6$ m
- Magnetic field strength $B_0 = 10^{-4}$ T = 1 Gauss
- Electric field strength $E_0 = 10^2$ Vm^{-1}



- Create initial parallelogram distribution of 10^4 protons across current sheet (100x100). Ignore Coulomb interactions.

- Give protons initial Maxwellian distributed thermal energies. Applied temperature scale T_0 with negligible overall drift.

- Set simulation length to be shorter than output timestep of MHD simulation Δt (we chose $0.3\Delta t$).

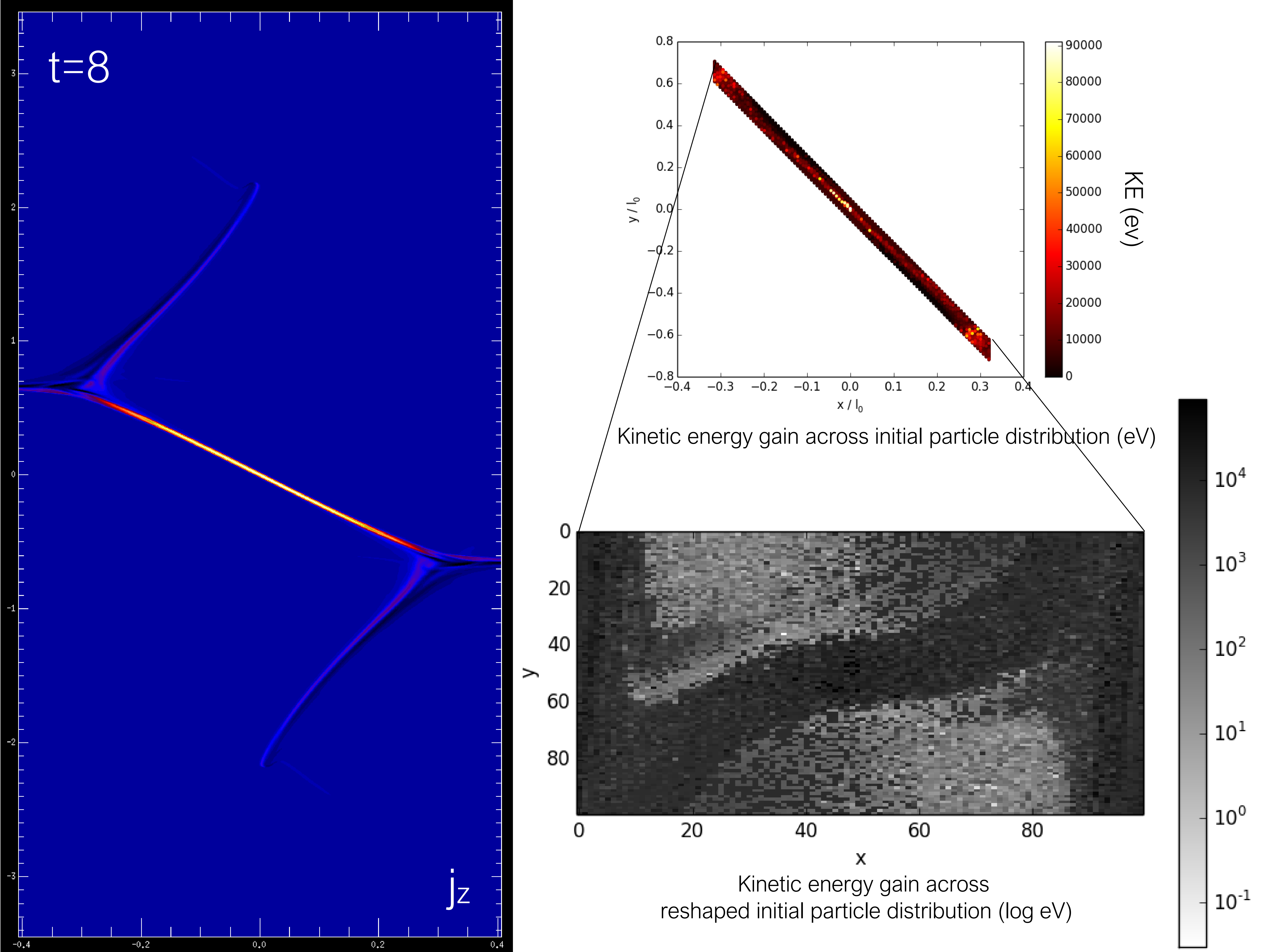
- Model full motion of particles → solve relativistic Lorentz equation.

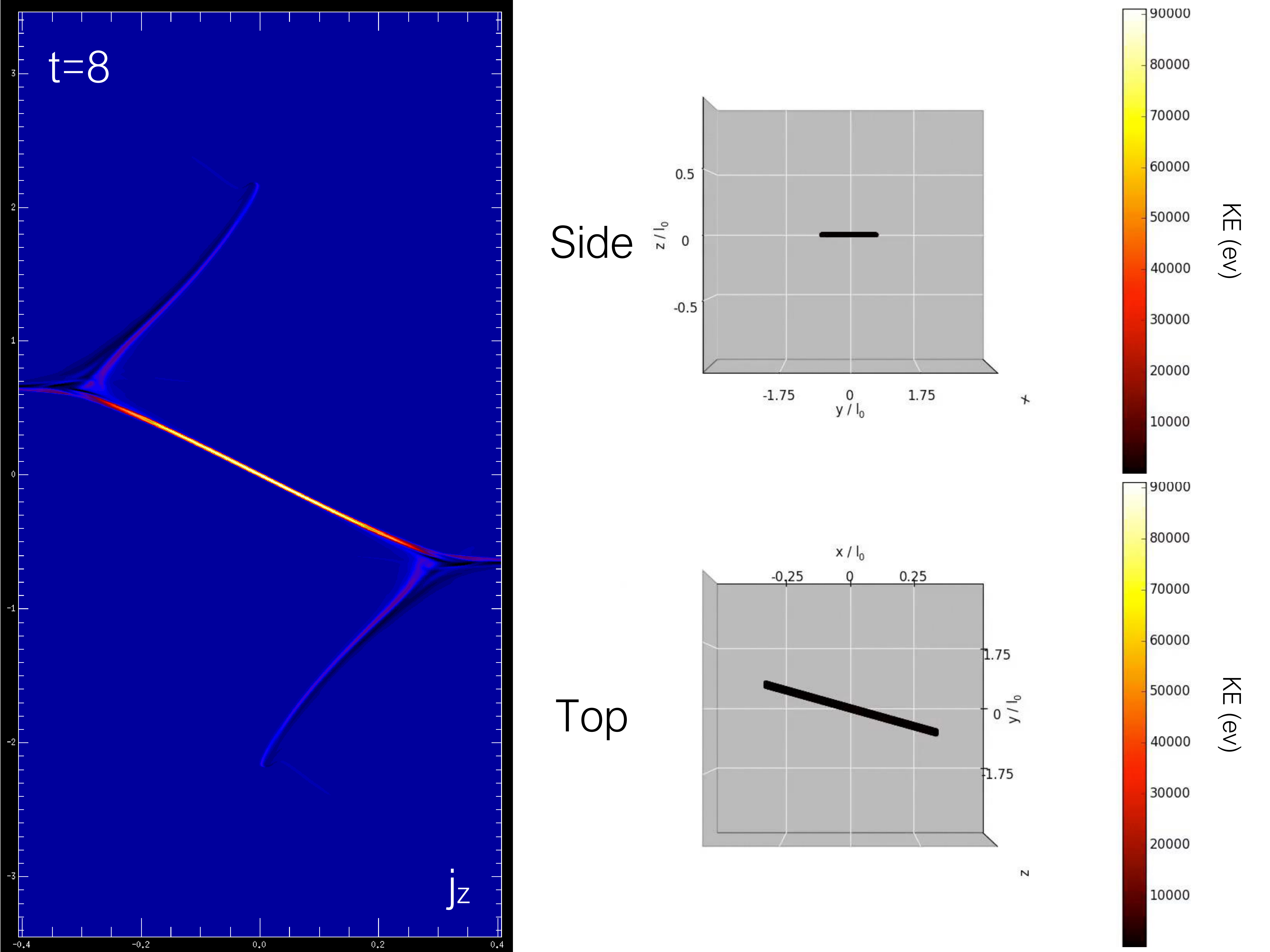
$$\frac{d\mathbf{p}}{dt} = q\left(\mathbf{E}(\mathbf{r}) + \frac{\mathbf{p}}{\gamma m_0} \times \mathbf{B}(\mathbf{r})\right)$$

$$\frac{d\mathbf{r}}{dt} = \frac{\mathbf{p}}{\gamma m_0}$$

- Solved using variable step-size 4$^{\text{th}}$ order Adams-Bashforth predictor and Adams-Moulton corrector.

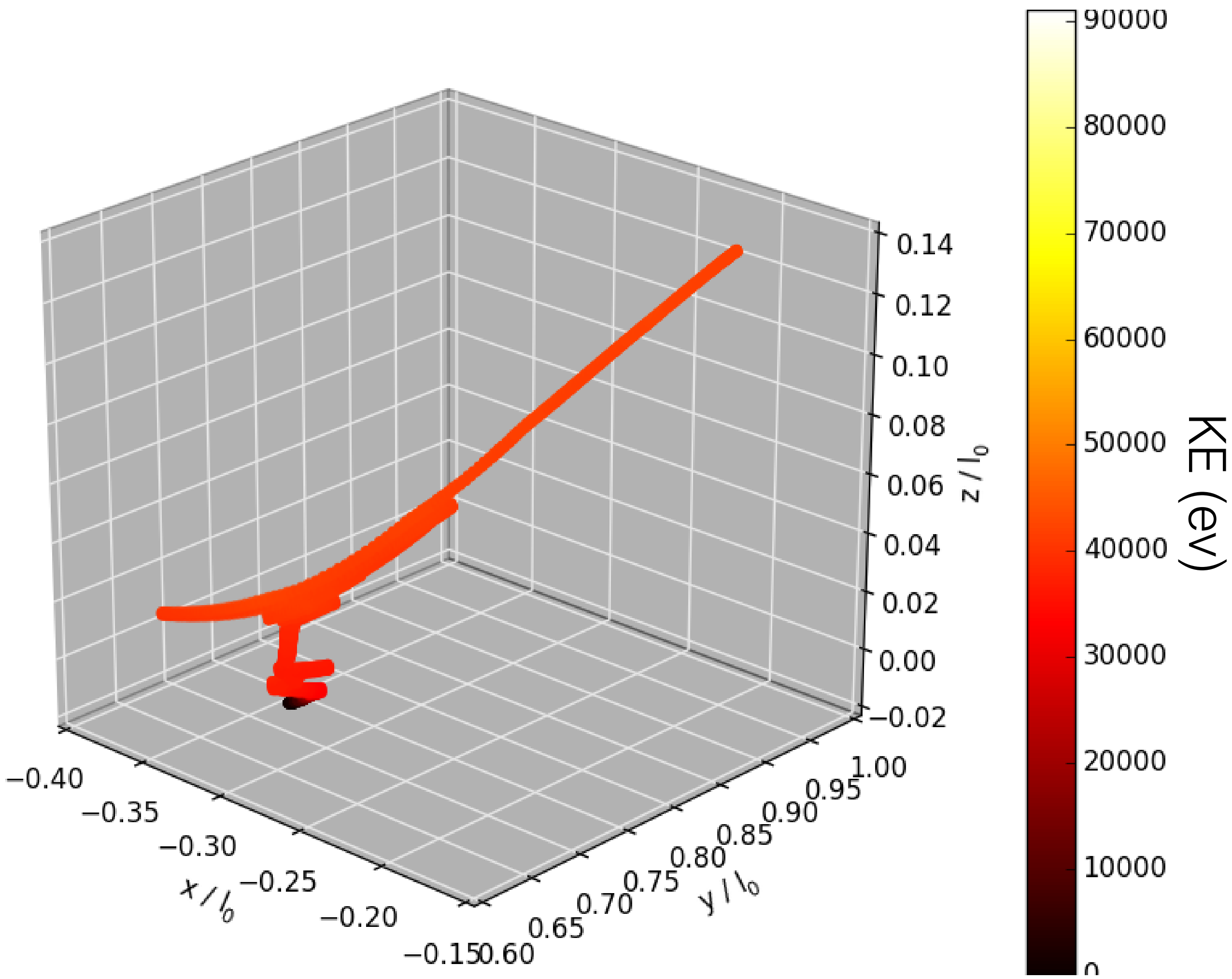
- Individual particle time-steps selected using difference between predicted and corrected values compared with user selected relative error.
- Time-steps doubled or halved to minimise interpolation/extrapolation of past data.
- Tested with analytical solutions of a uniform current sheet derived by Speiser (1965).


t=8
jz
KE (ev)
y / l0
x / l0
Kinetic energy gain across initial particle distribution (eV)
y
x
Kinetic energy gain across
reshaped initial particle distribution (log eV)

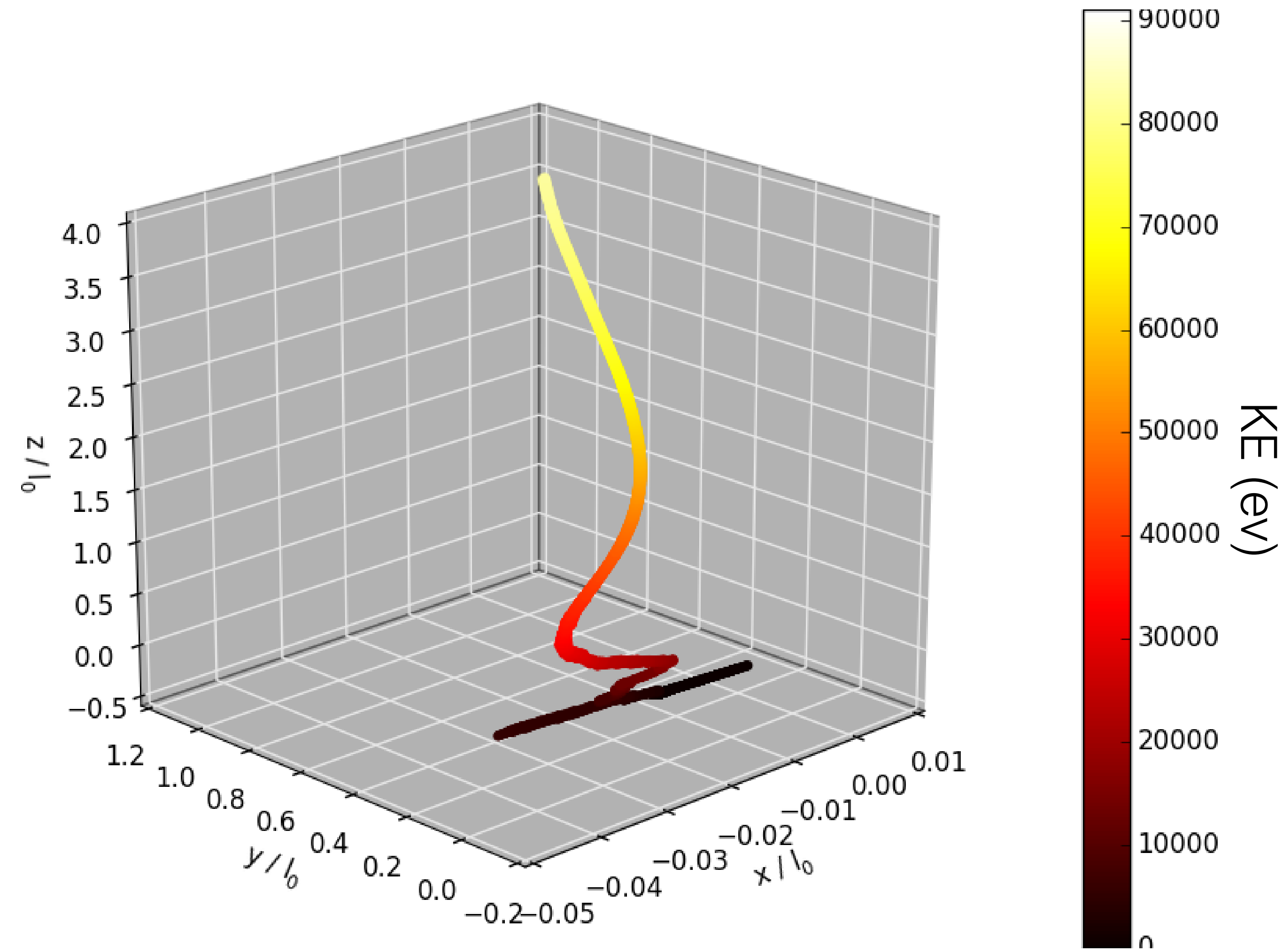


t=8
jz
Side
Top
z / l0
y / l0
x / l0
0.5
0
-0.5
-1.75
1.75
-0.25
0.25
x
z
KE (ev)
90000
80000
70000
60000
50000
40000
30000
20000
10000

Example trajectories

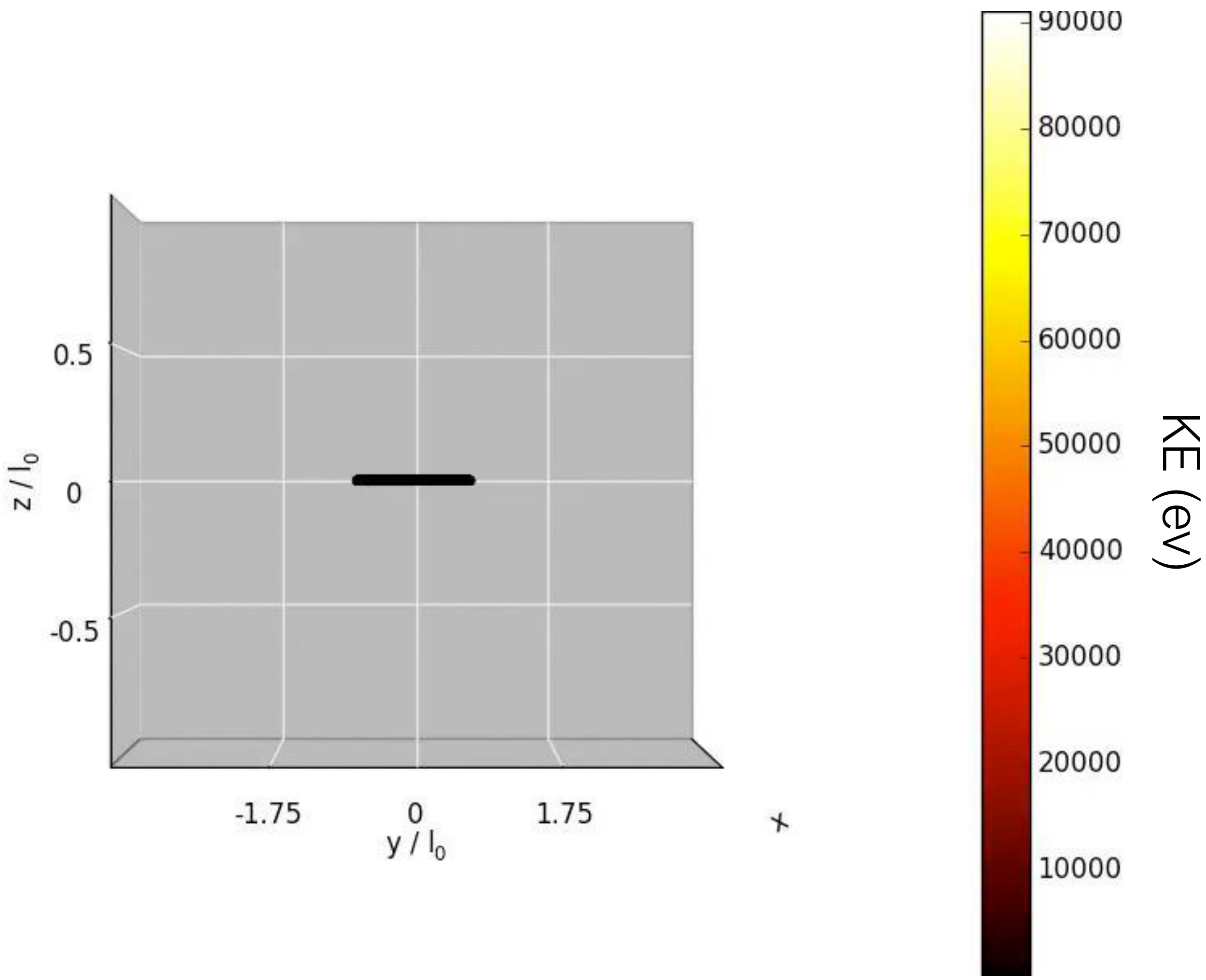


Outflow region

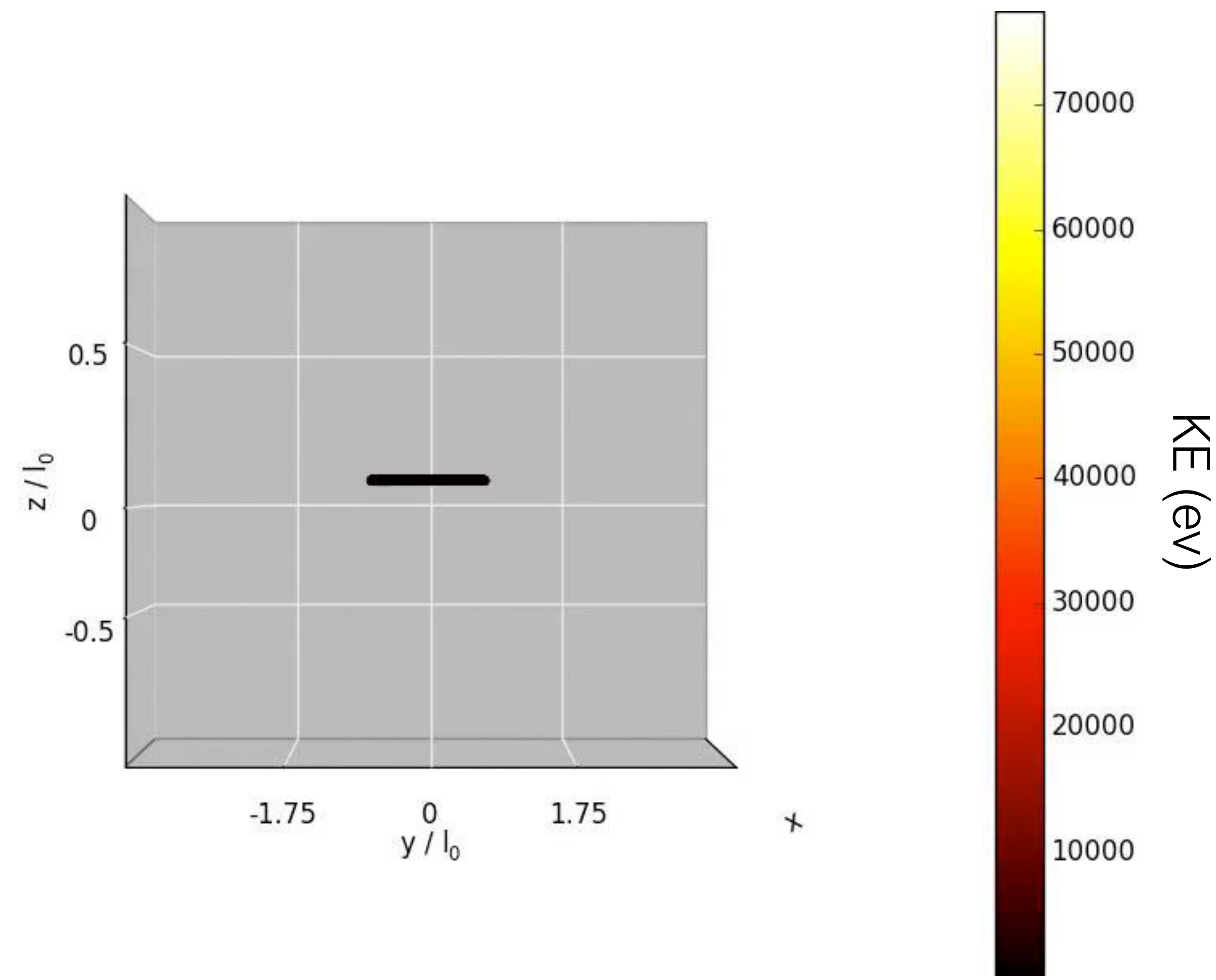


Mid-current sheet

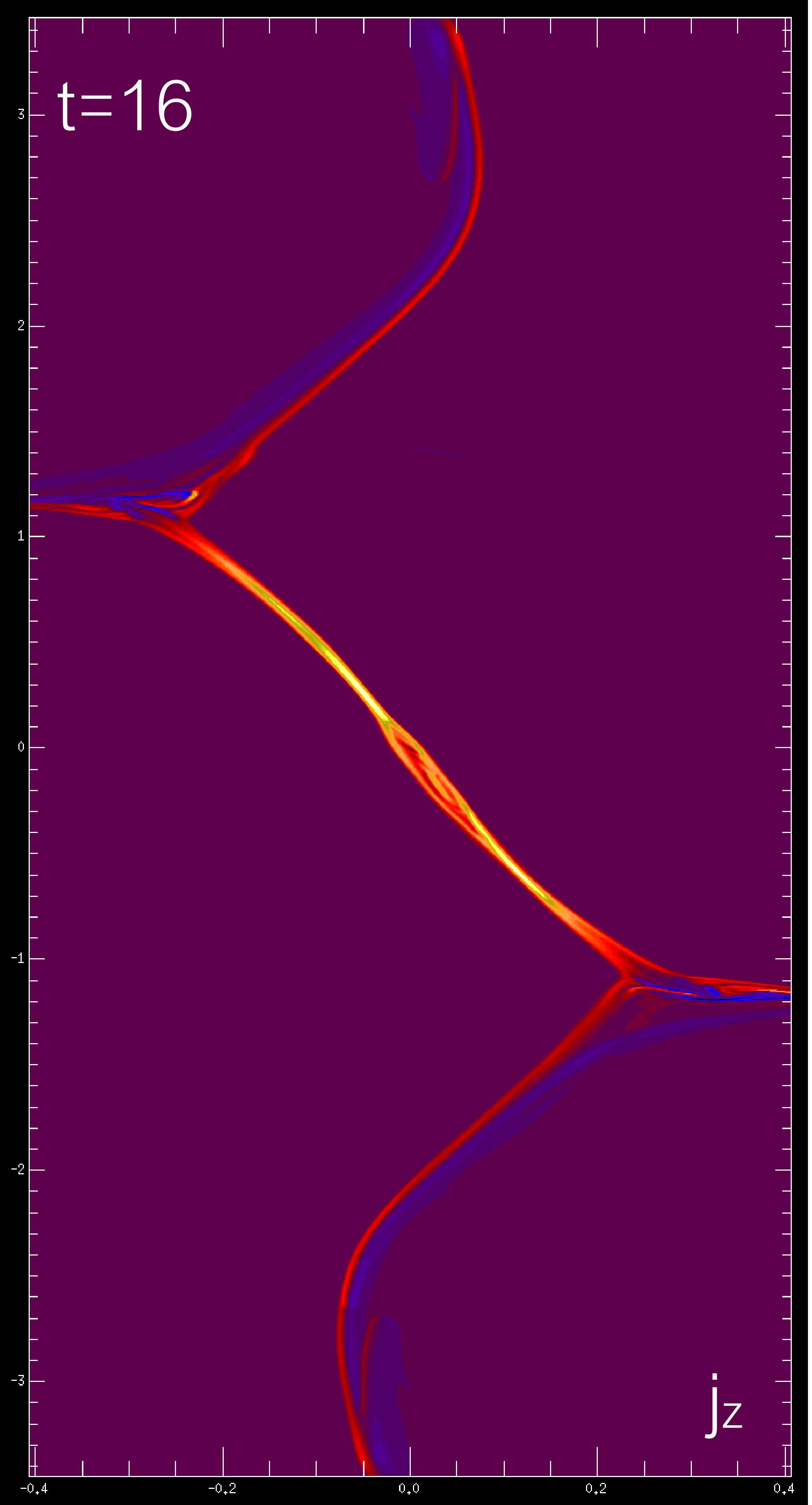
z=+0.1 out of centre

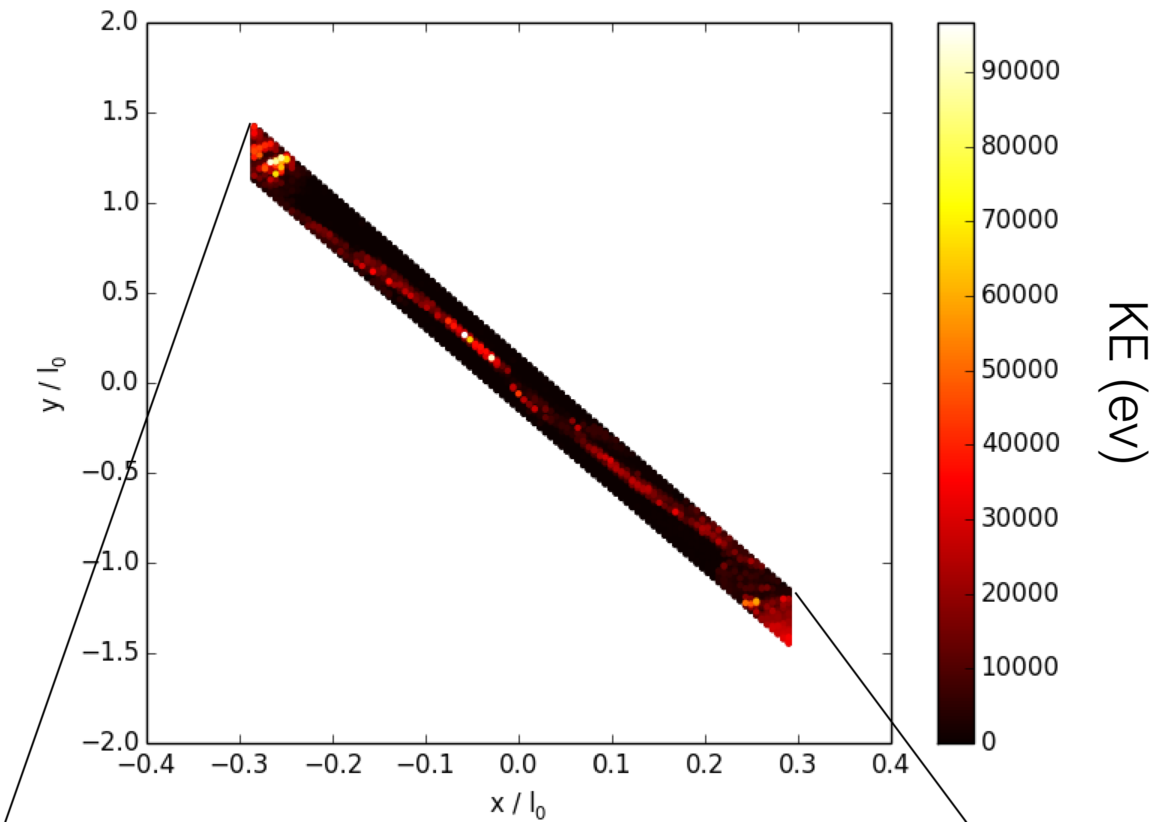


z=0

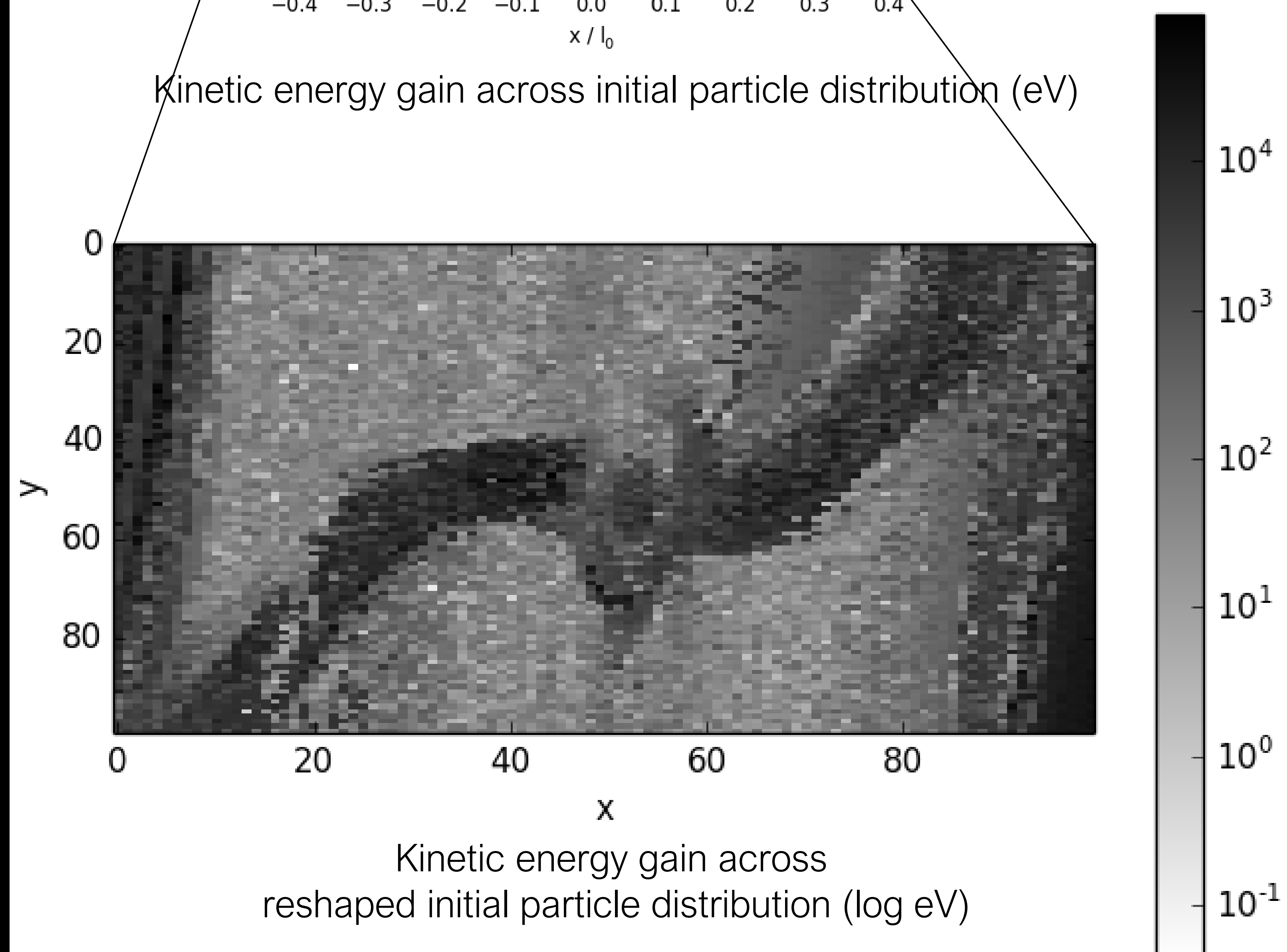


z=+0.1

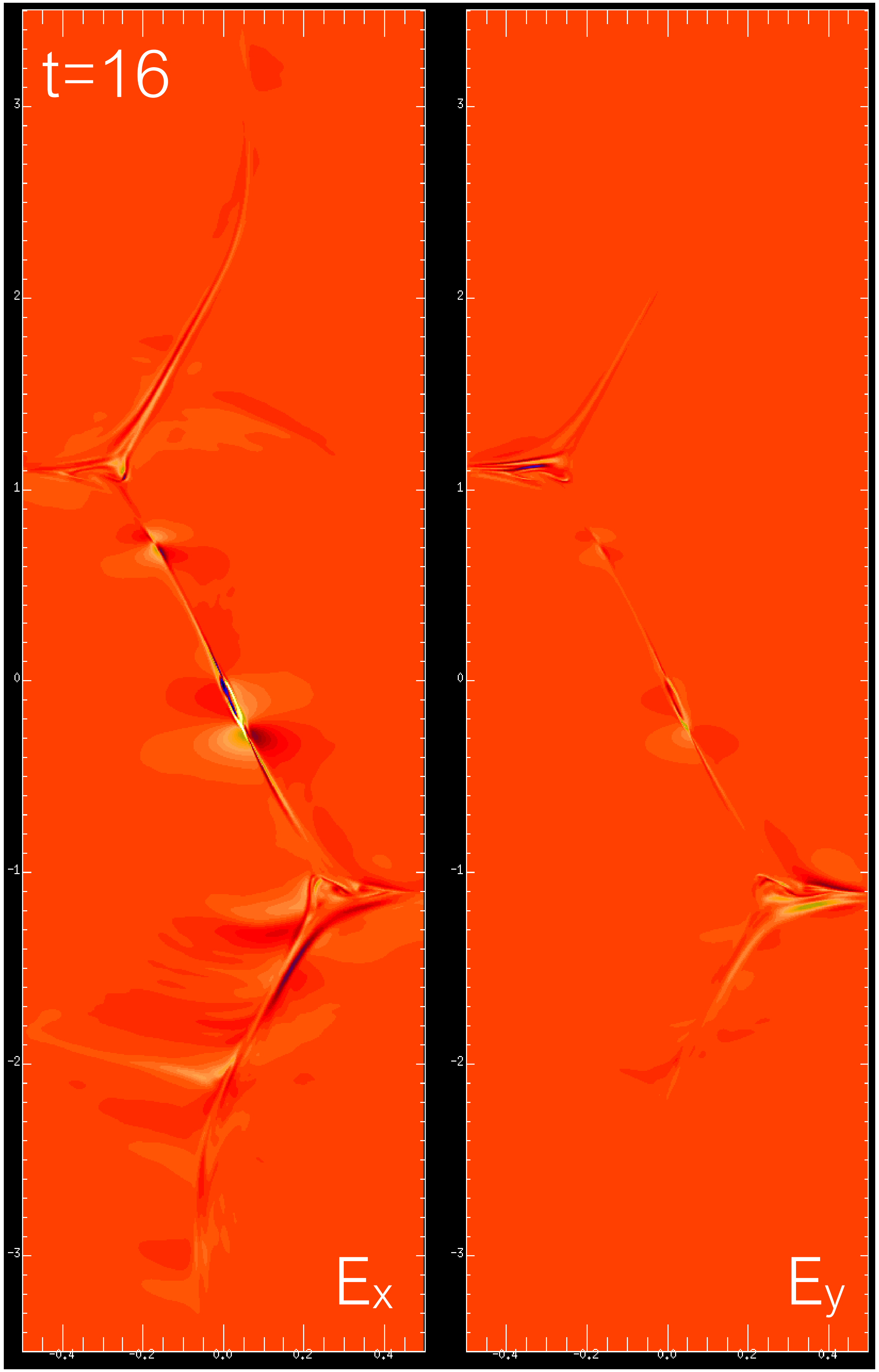




Kinetic energy gain across initial particle distribution (eV)

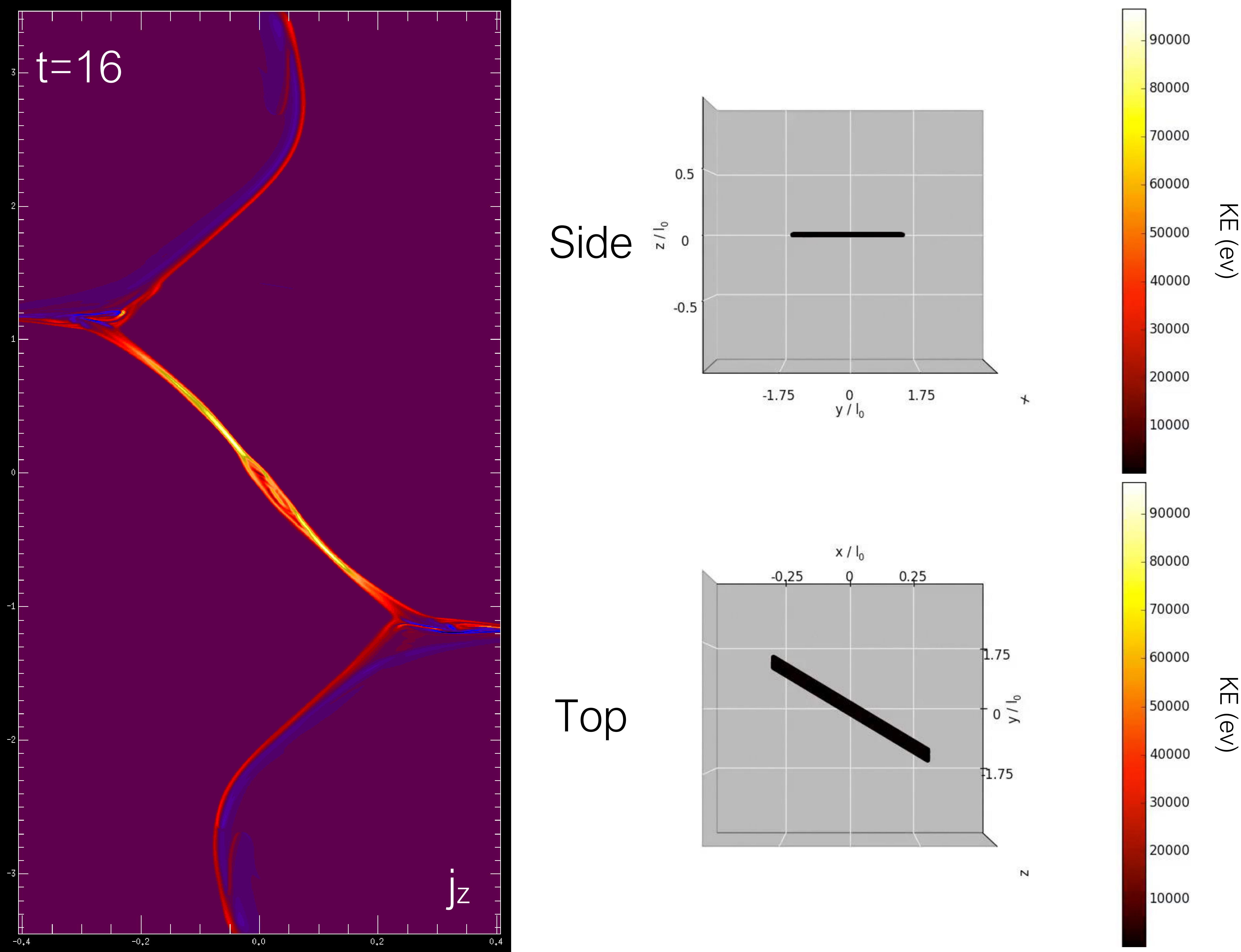


Kinetic energy gain across
reshaped initial particle distribution (log eV)

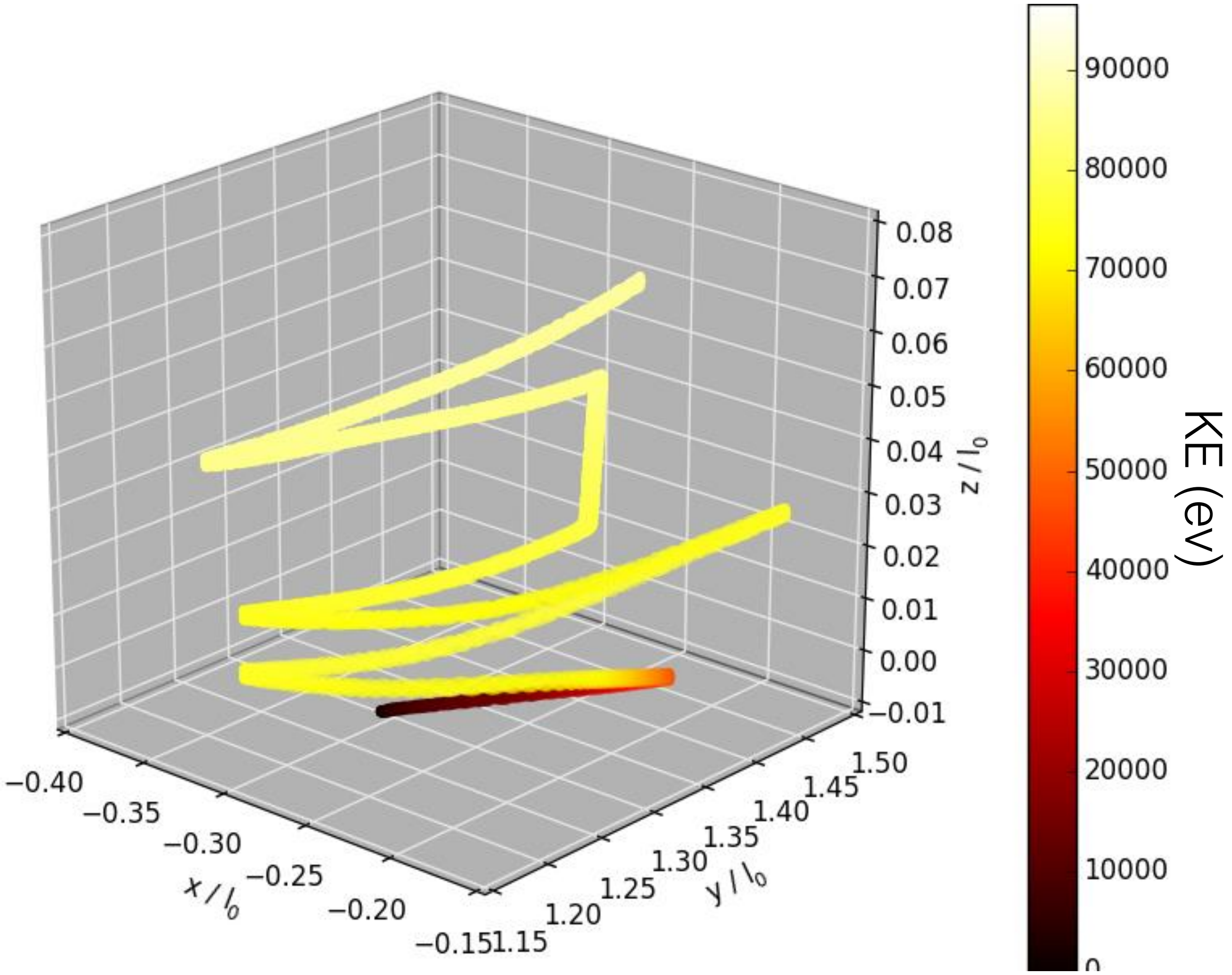


Acceleration profile disruption in centre corresponds to large flux rope.

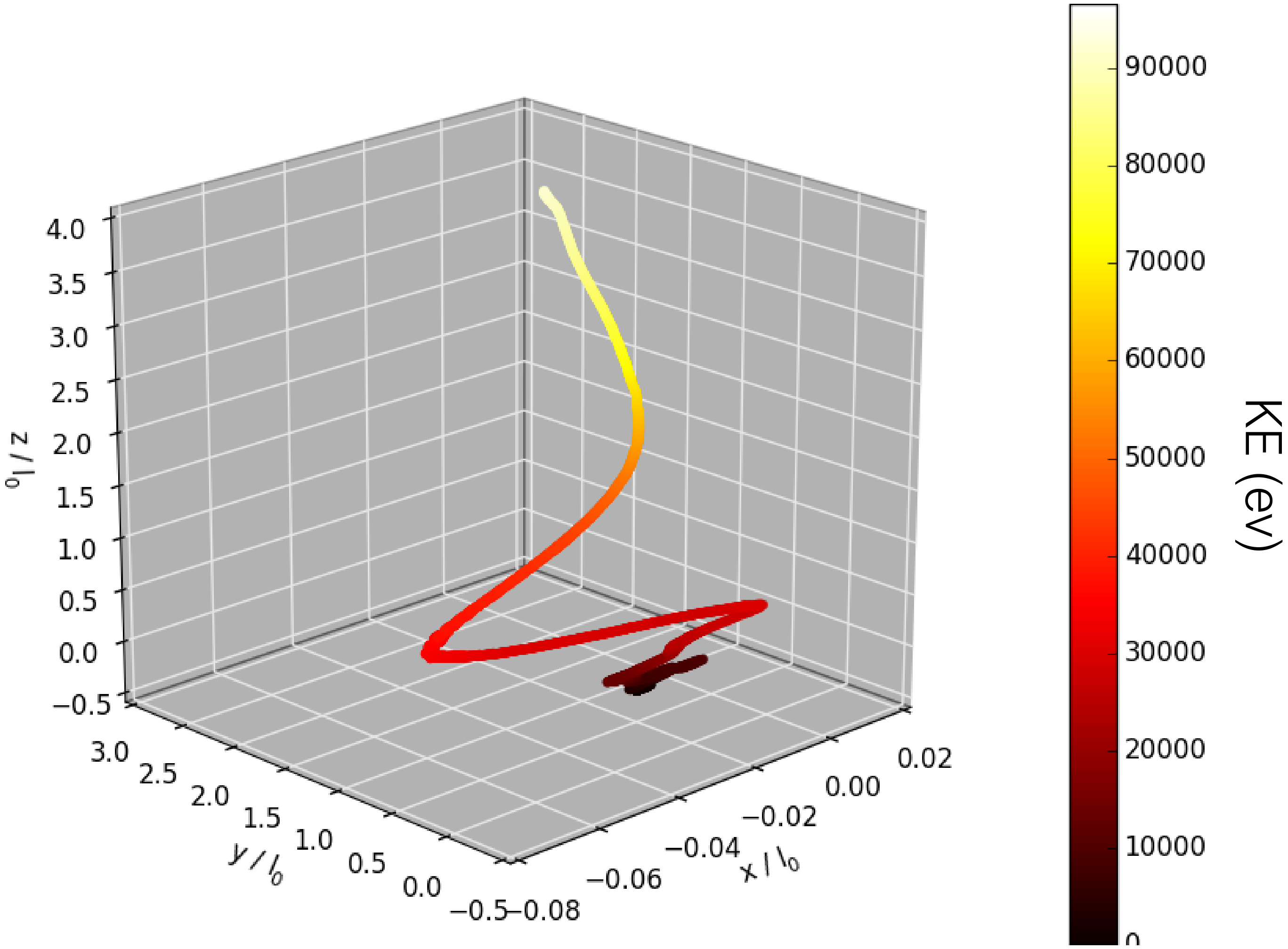
Profile disruption along +y section of sheet seems to correspond with small quadripolar plasmoid structure.


t=16
jz
Side
z / l0
0.5
0
-0.5
-1.75
0
1.75
y / l0
x
Top
x / l0
-0.25
0
0.25
1.75
0
-1.75
y / l0
z
90000
80000
70000
60000
50000
40000
30000
20000
10000
KE (ev)

Example trajectories

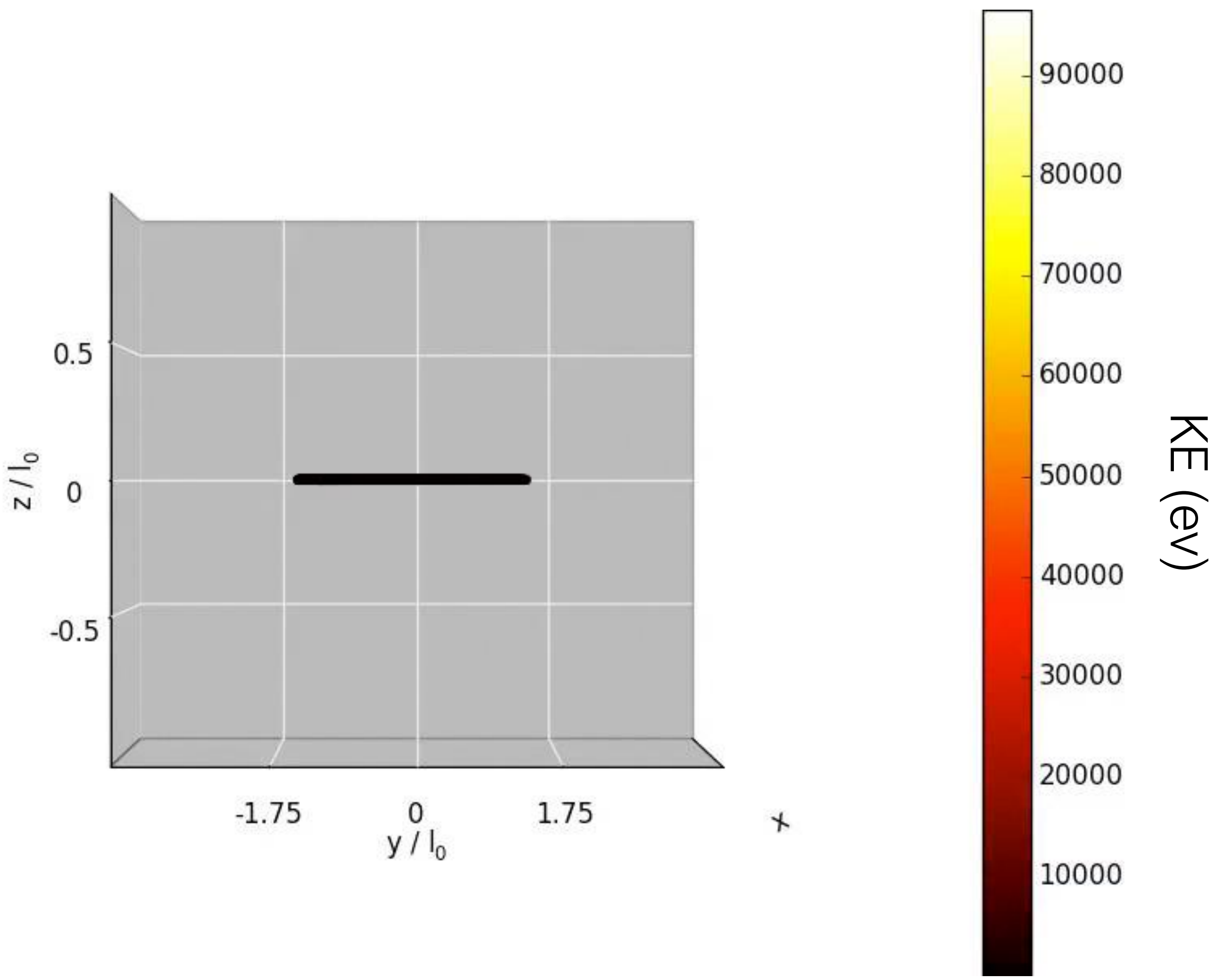


Outflow region

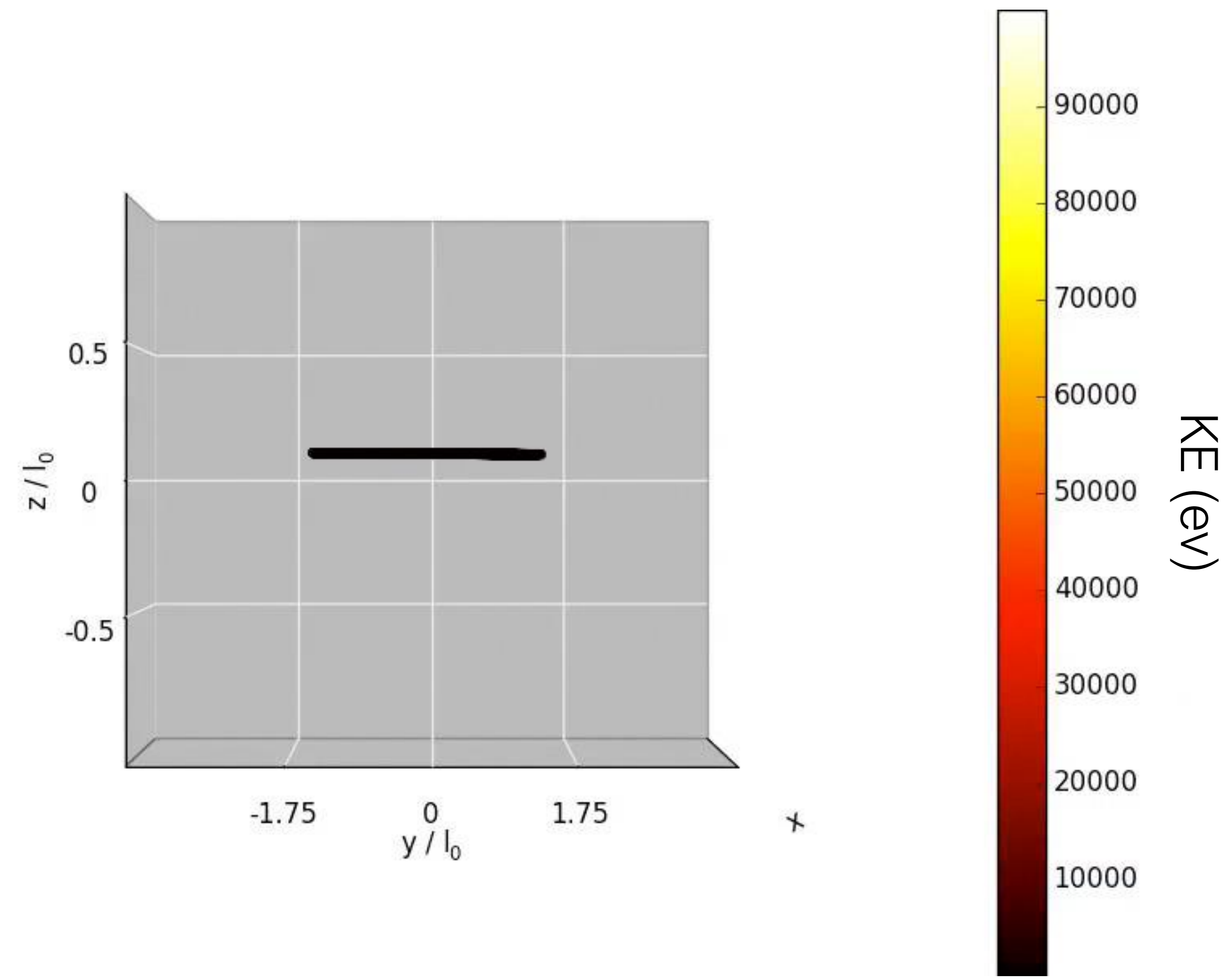


Mid-current sheet

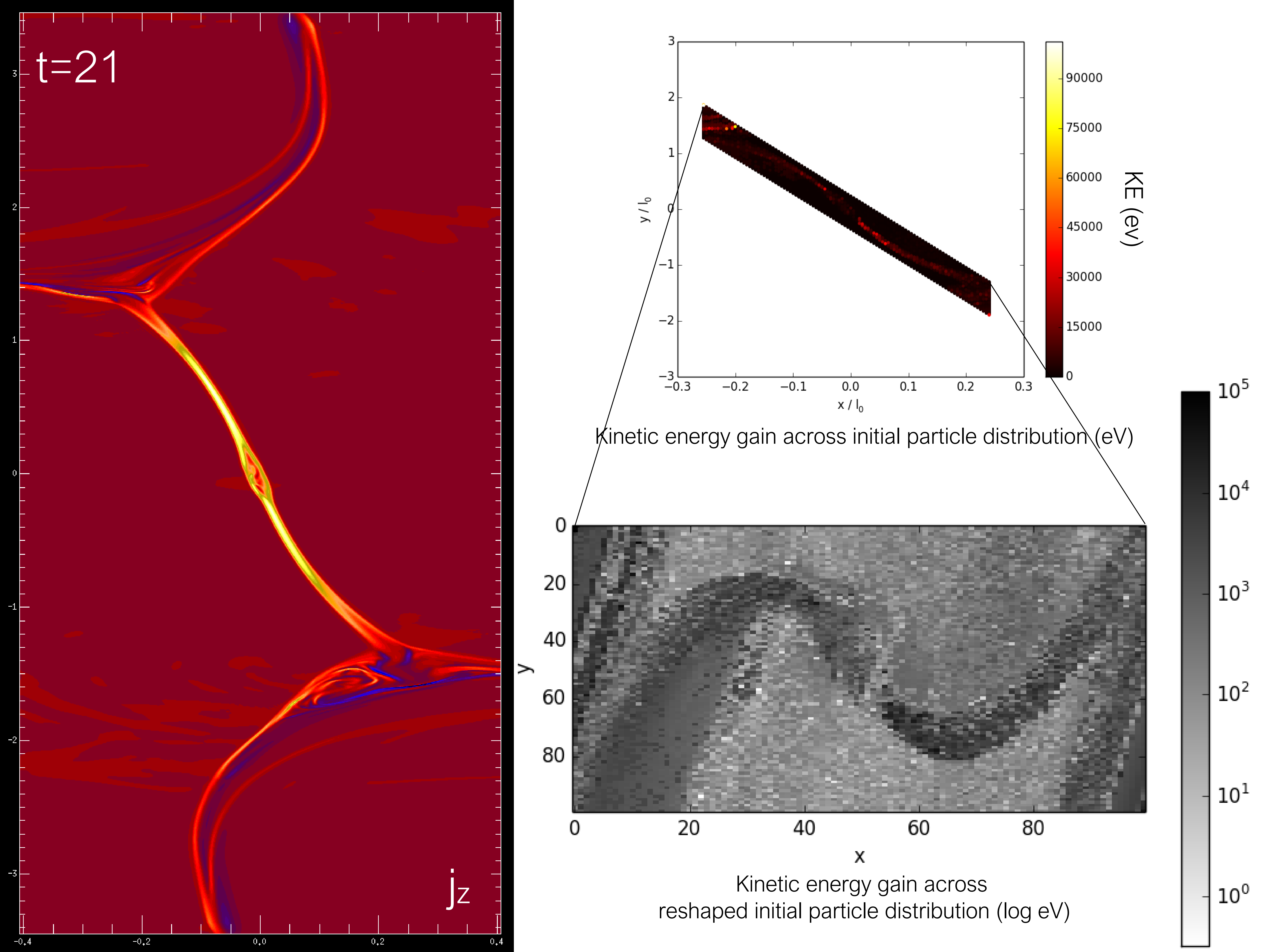
z=+0.1 out of centre

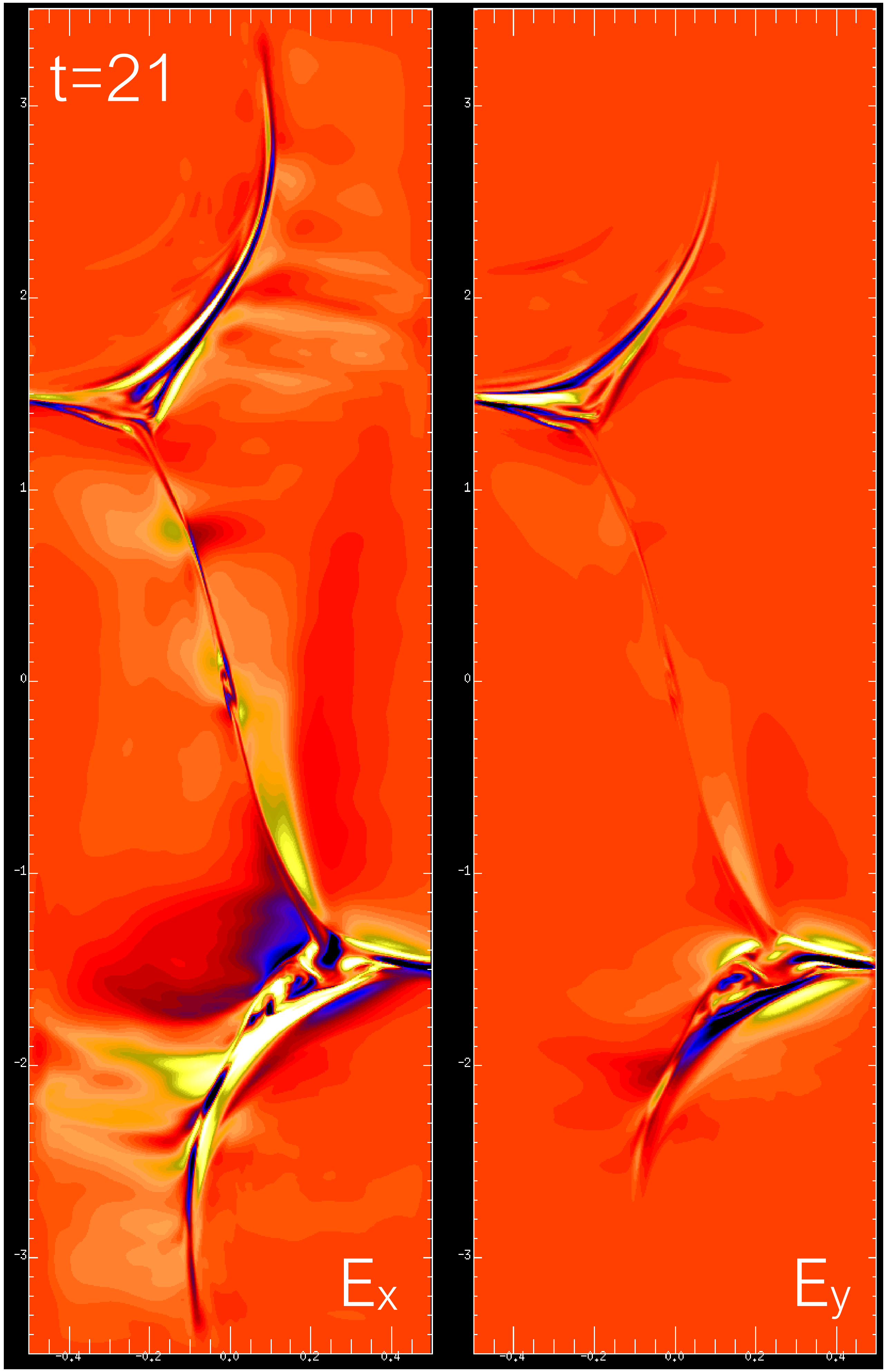


z=0



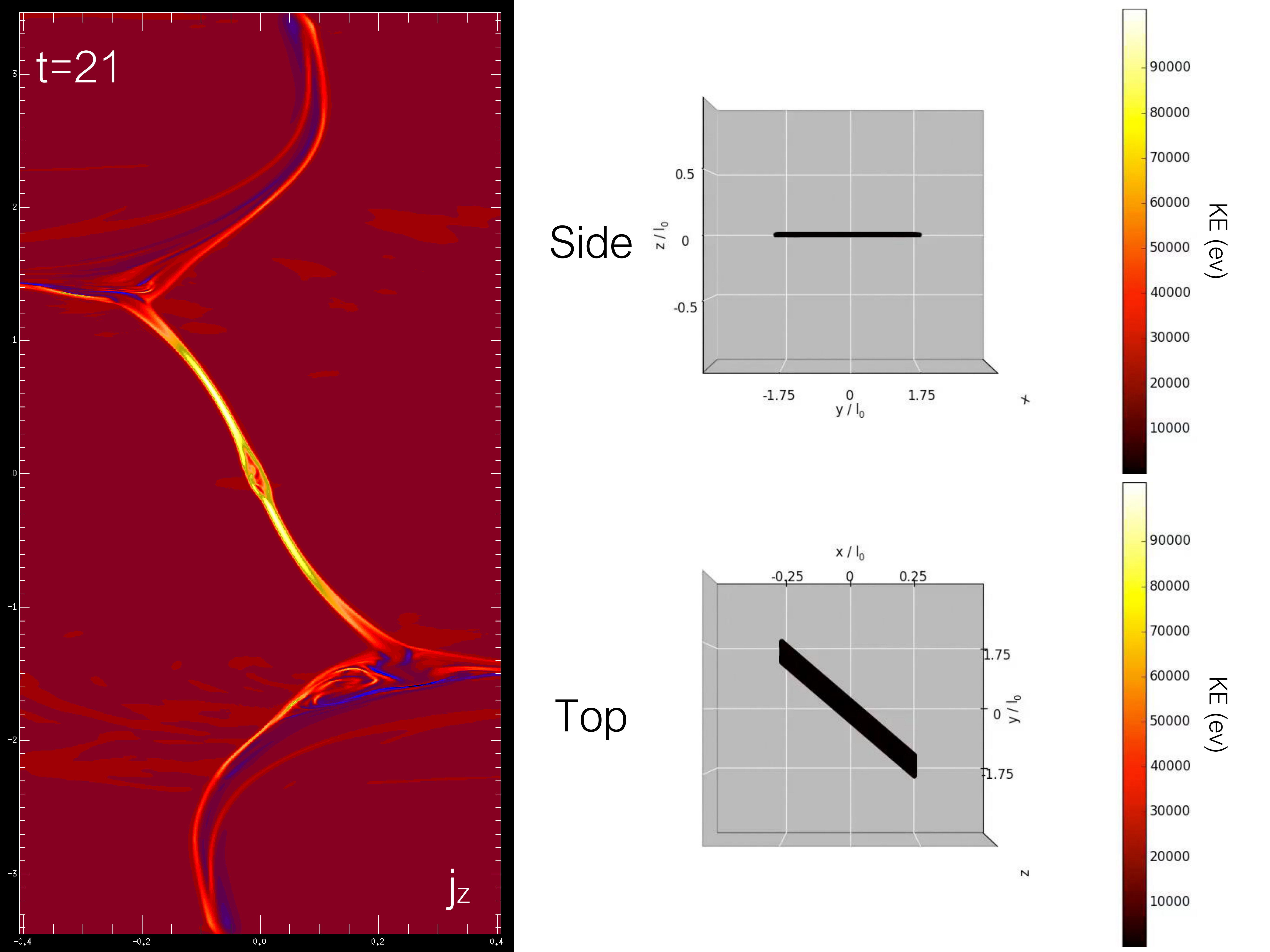
z=+0.1


t=21
jz
KE (ev)
y / l0
x / l0
Kinetic energy gain across initial particle distribution (eV)
y
x
Kinetic energy gain across
reshaped initial particle distribution (log eV)



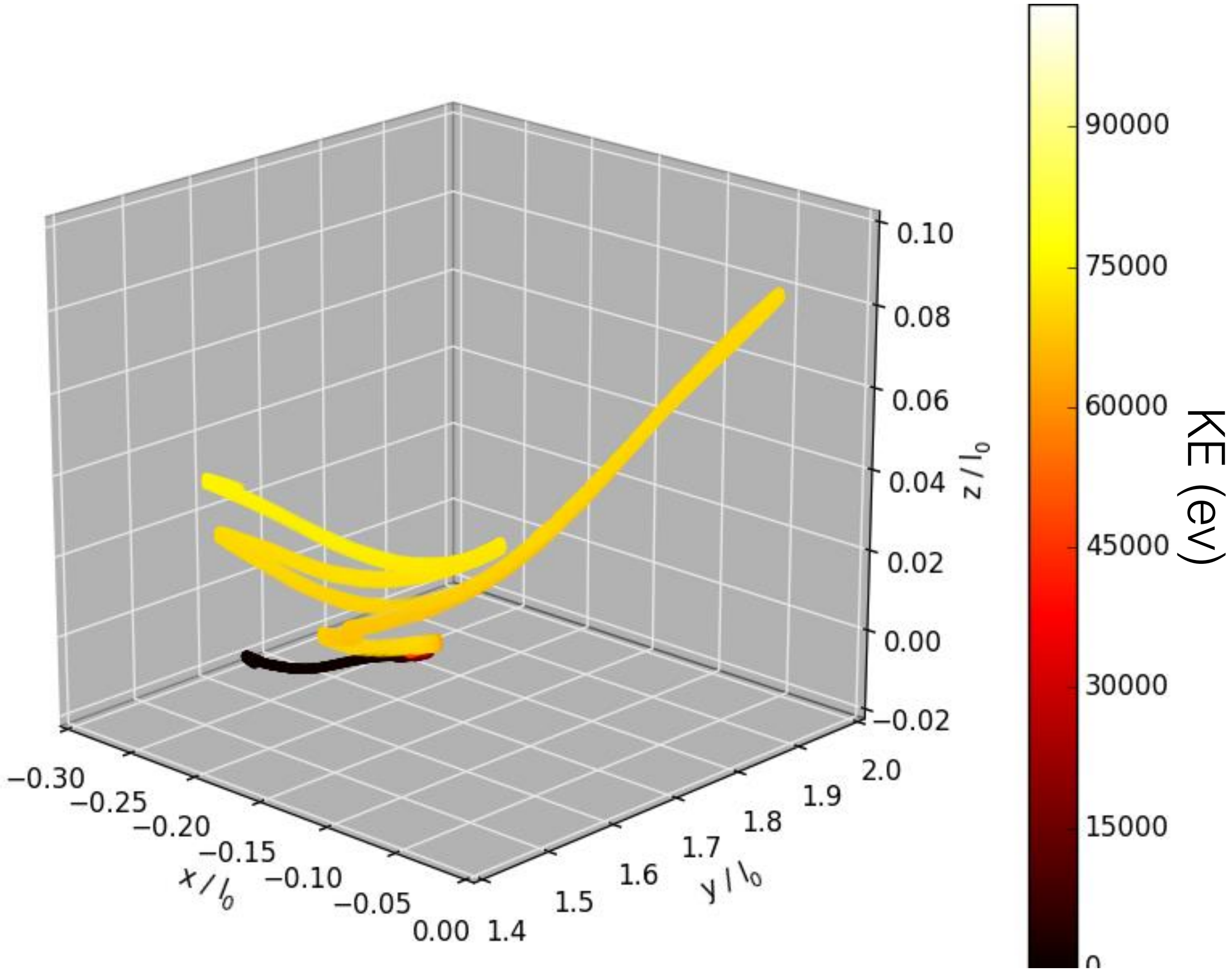
Acceleration profile disrupted in centre corresponds to flux rope.

Dipolar plasmoid structure close to that in t=16 sheet, but no noticeable corresponding disruption in acceleration profile.

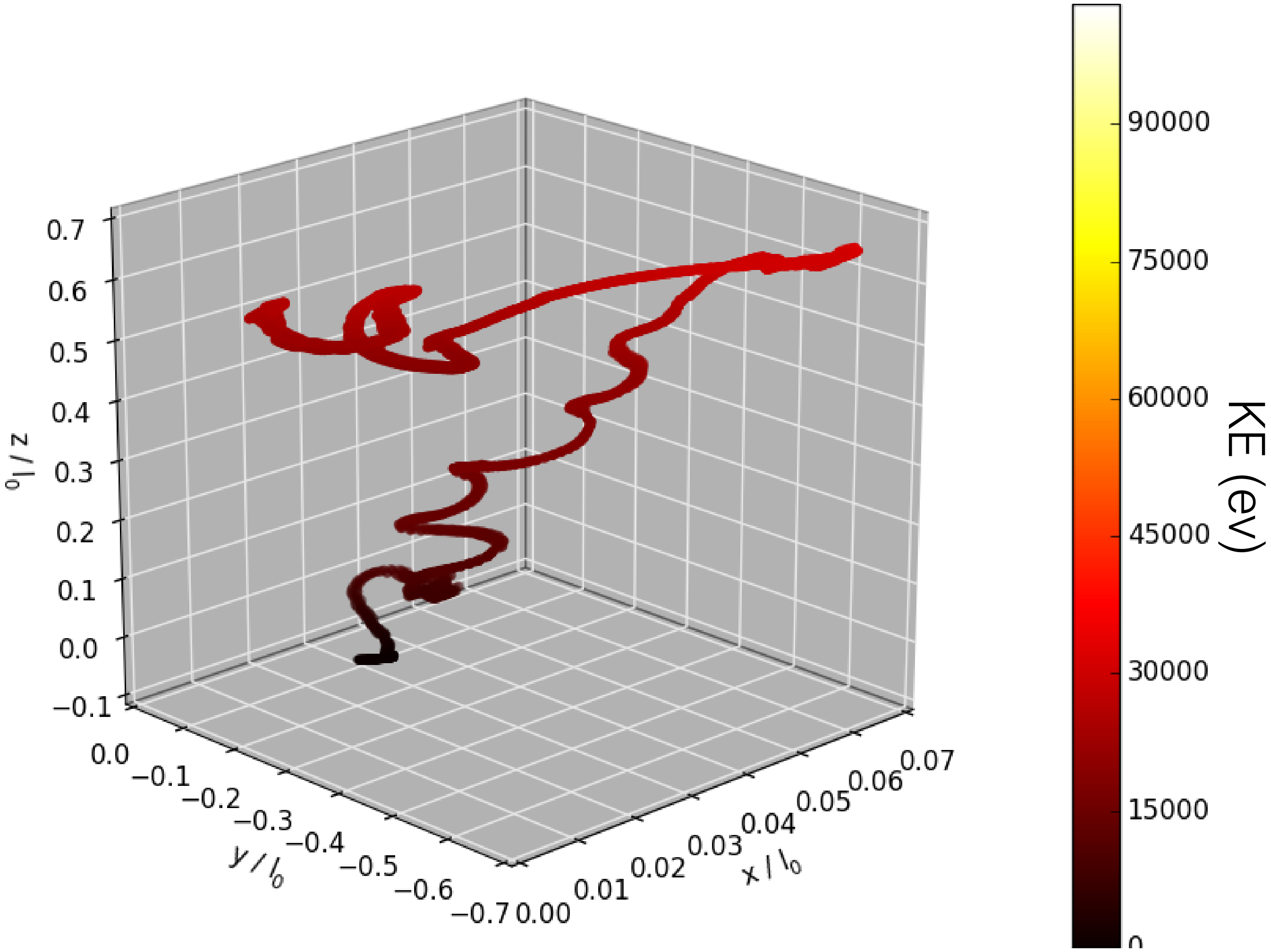


t=21
jz
Side
Top
KE (ev)
KE (ev)

Example trajectories

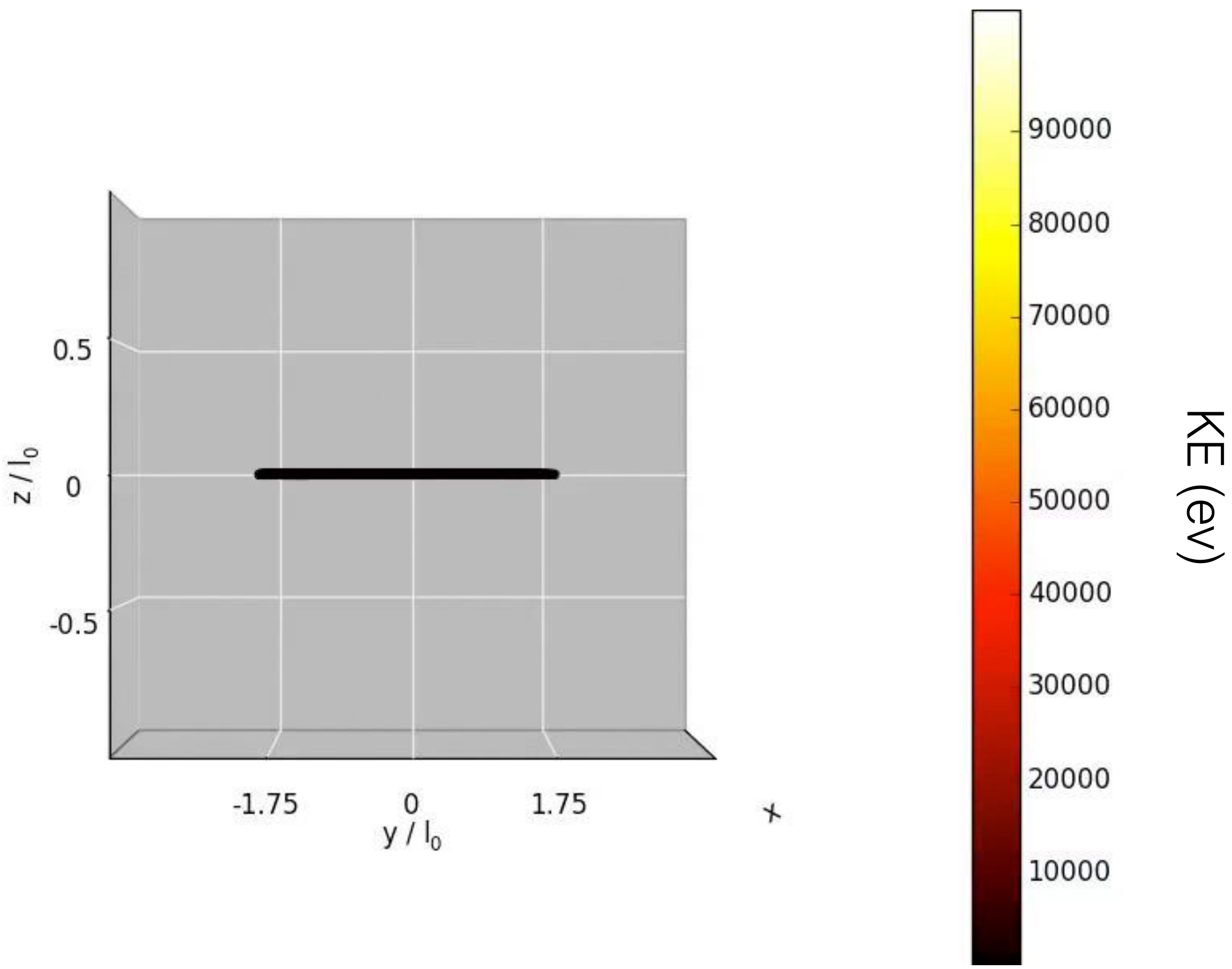


Outflow region

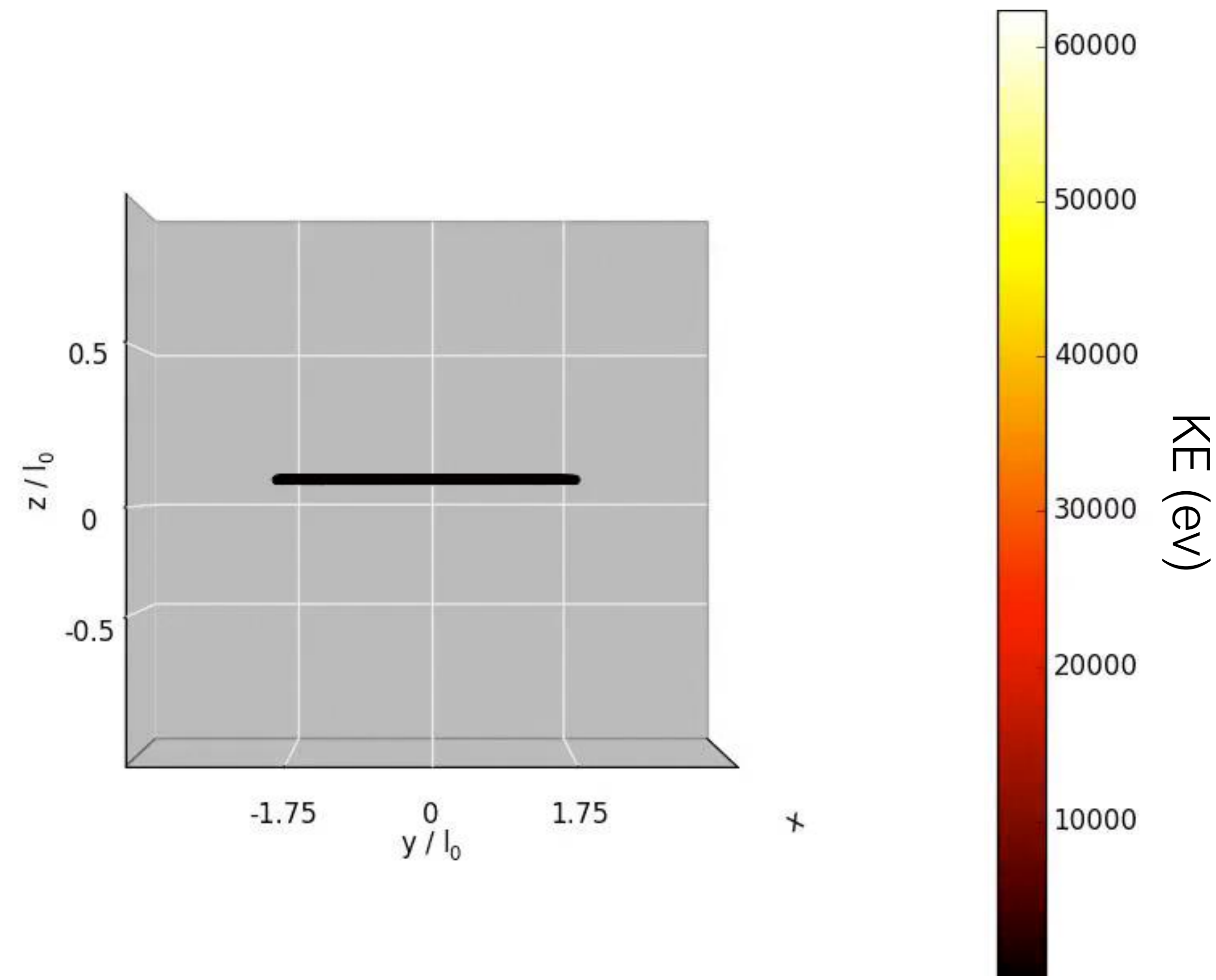


Mid-current sheet

z=+0.1 out of centre



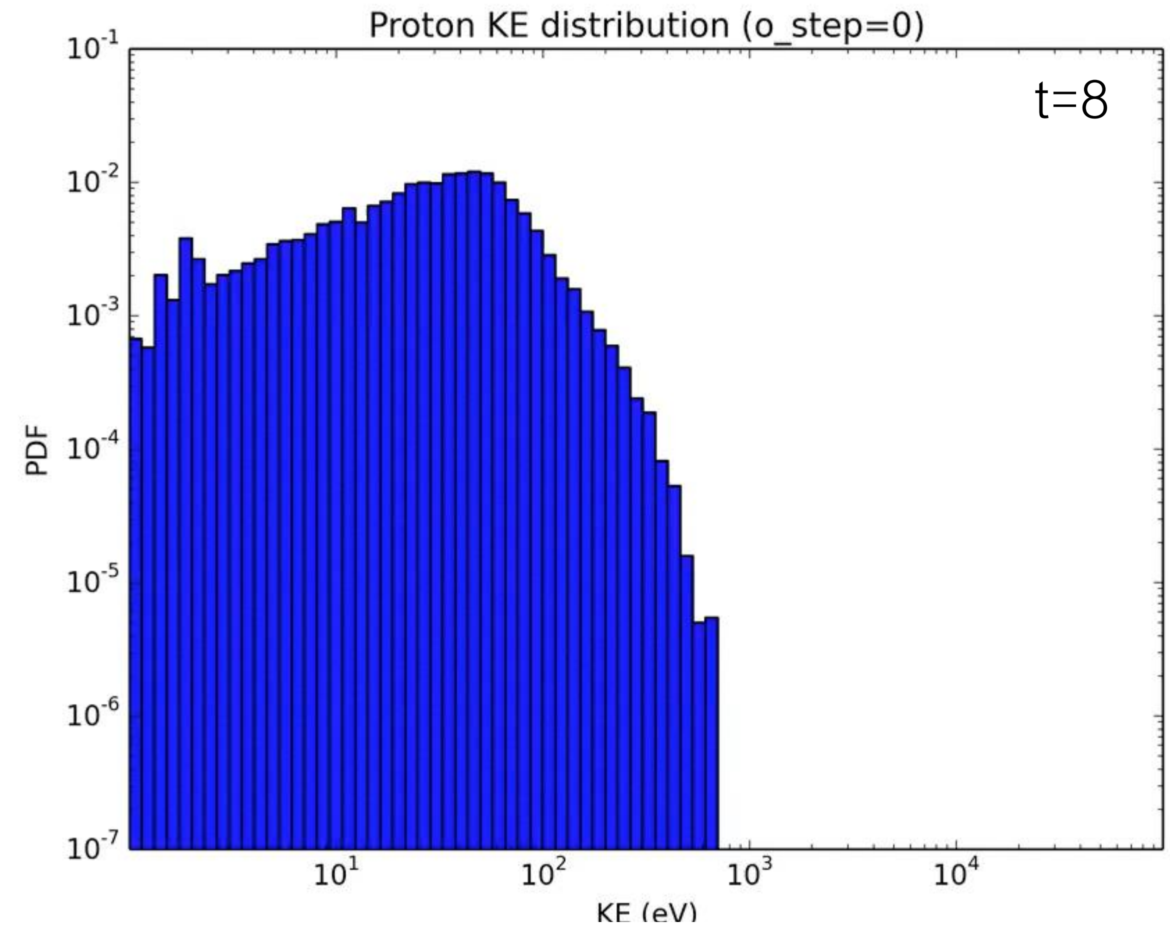
z=0

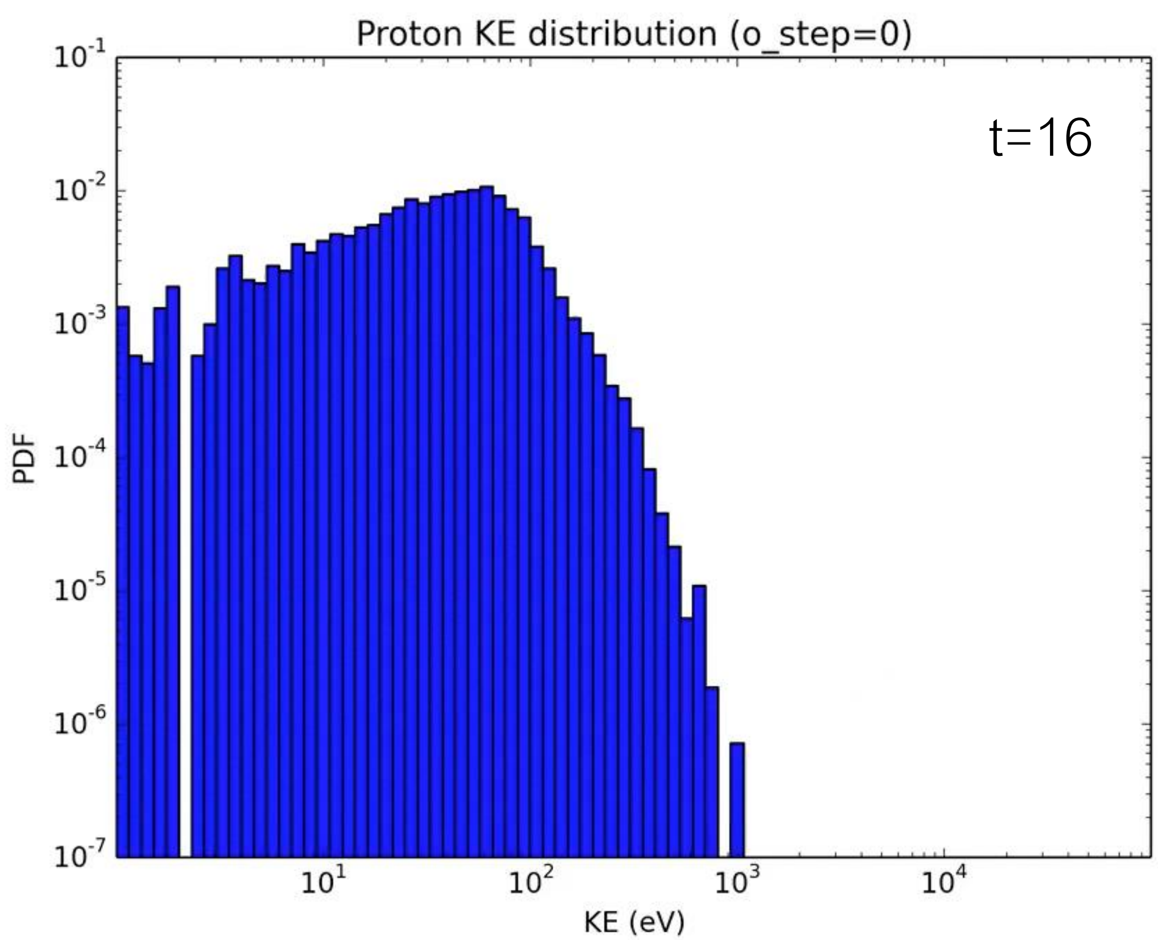


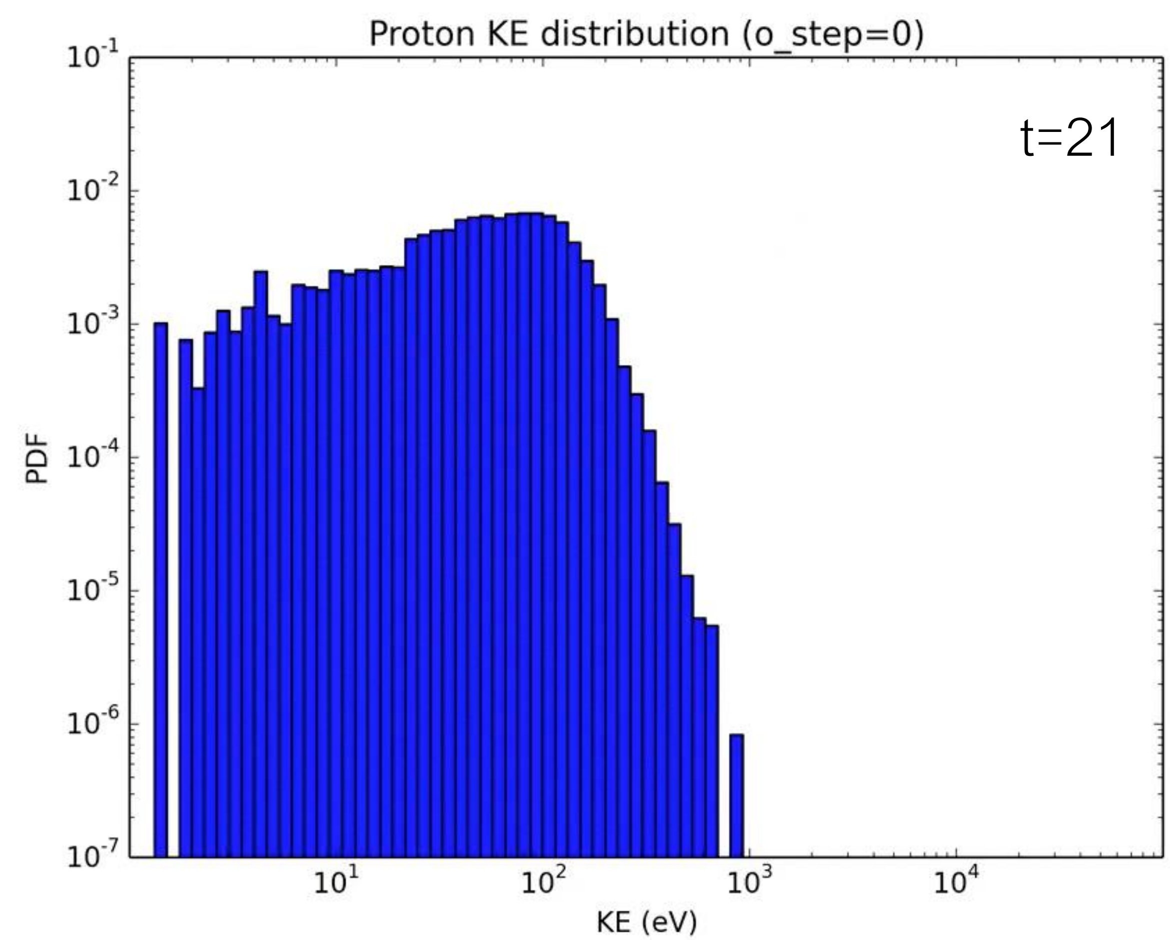
z=+0.1

Kinetic Energy Distributions

Initial flattening of Maxwellian distribution, tail becoming slightly less pronounced as sheet develops.







Summary

- Acceleration in the plane of the current sheet greatly disrupted by sheet tearing.

- Outflow regions become main source of acceleration after sheet tears. Highest energy protons are the result of multiple reflections in outflow regions.

- Plasmoid structures and flux ropes in sheet hinder acceleration.

- Areas of relatively uniform acceleration can appear near spines after sheet tears. The cause and result of these is worth exploring.

- High kinetic energy tail appears to become less prominent over time.

Further code development

- Develop and integrate system to dynamically switch between full motion and guiding centre approximation.
- Model electron trajectories.
- Develop variable-order component.

References

Wyper, P.F. and Pontin, D.I. (2014a) Non-linear tearing of 3D null point current sheets, *Physics of Plasmas,* **21**

Wyper, P.F. and Pontin, D.I. (2014b) Dynamic Topology and Flux Rope Evolution During Non-linear Tearing of 3D Null Point Current Sheets, *Physics of Plasmas*, **21**

Speiser, T.W. (1965) Particle Trajectories in Model Current Sheets, *Journal of Geophysical Research,* **70**, 4219-4226