Self-consistent coronal heating models in an MHD avalanche

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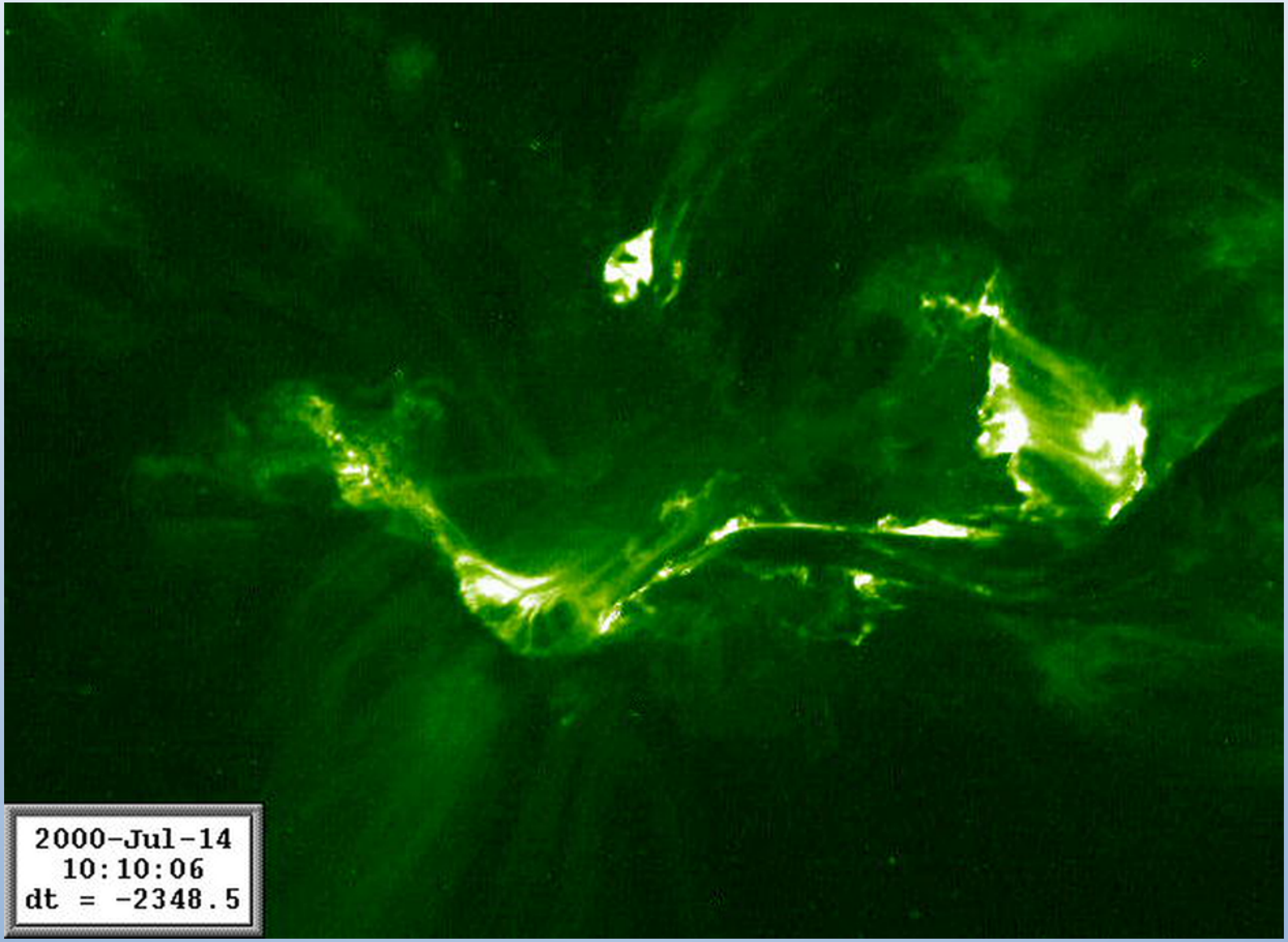
Bastille Day Flare



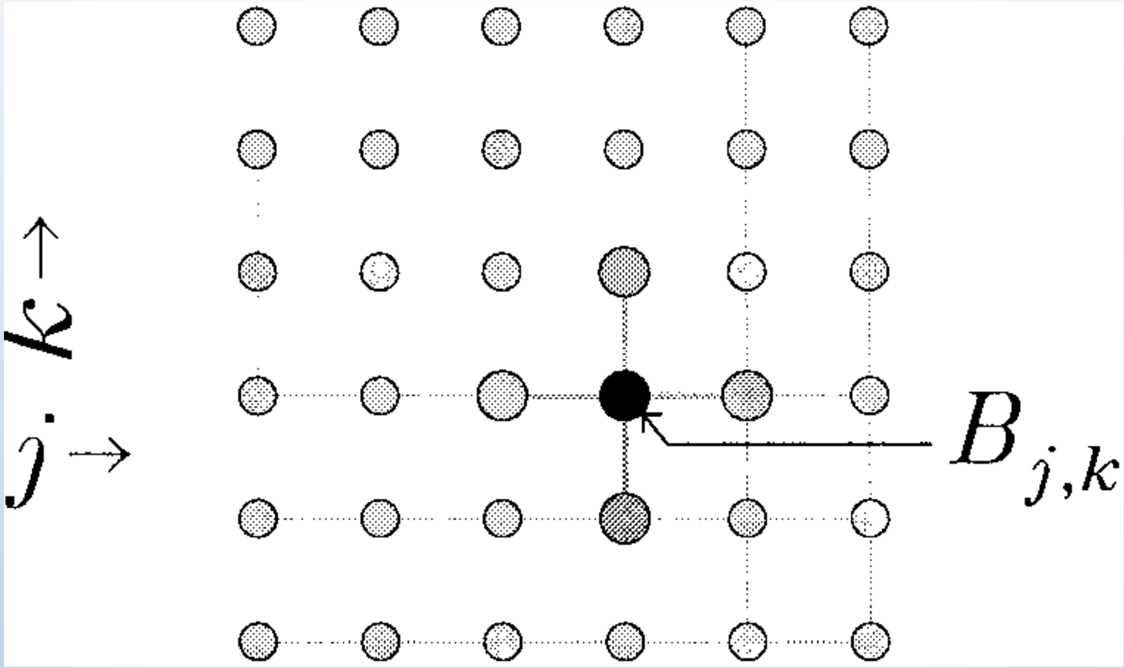
Avalanche models for energy release

- Lu & Hamilton (1991), Aschwanden et al (2016) etc.– trigger an avalanche when critical conditions reached, e.g. critical slope of sand pile, shear in magnetic field. Must be close to marginal stability.

- Cellular Automata (CA) – use rules to determine how avalanche evolves.

Cellullar Automaton Models

Lattice.



Random additions to $B_{j,k}$.

Start avalanche if $$\Delta B = B_k - \frac{1}{4}\sum_{nn=1}^{4} B_{nn} > Z_c$$

Redistribute energy and start again.

Avalanche models for energy release

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- Cellular Automata (CA) – use rules to determine how avalanche evolves.

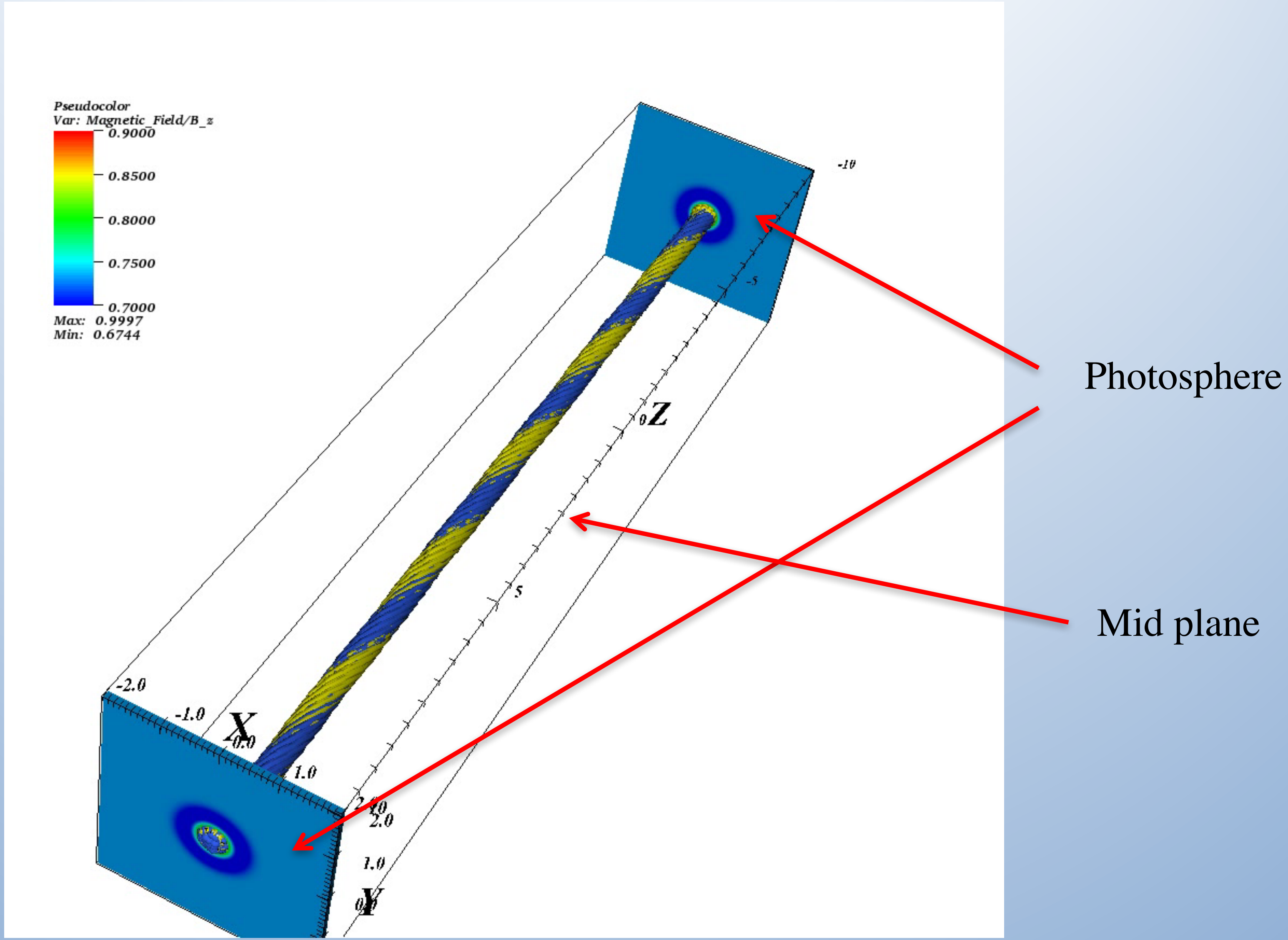
- Advantage: long run-times. "Balance" between driving and dissipation: Self Organised Criticality (SOC).

- Disadvantage: do not use Newton and Maxwell rigorously

- Need to develop ideas in (fully) 3D MHD**

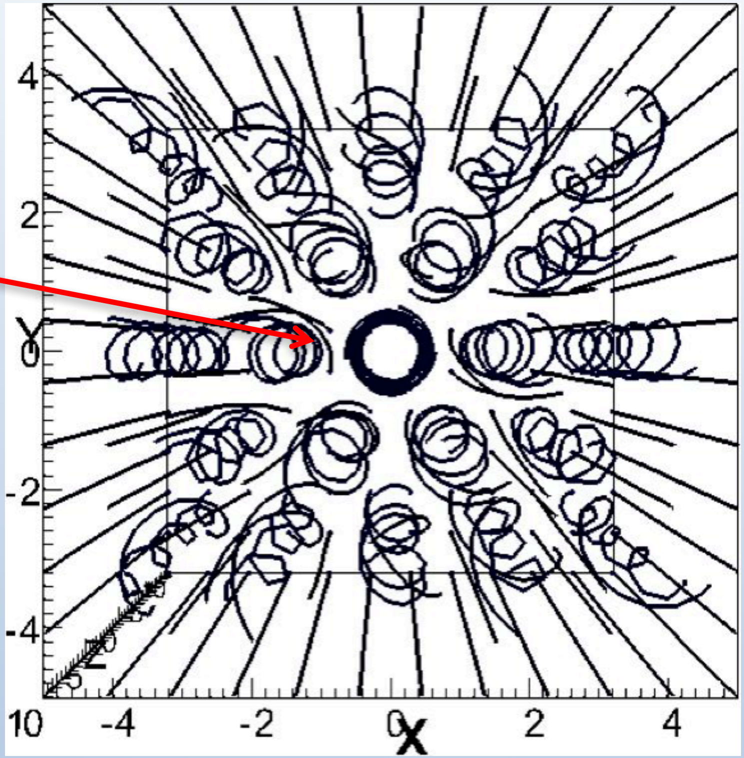
**: NOT Reduced MHD: Problems and limitations

But first!!!
Kink Instability in a single loop – line-tying

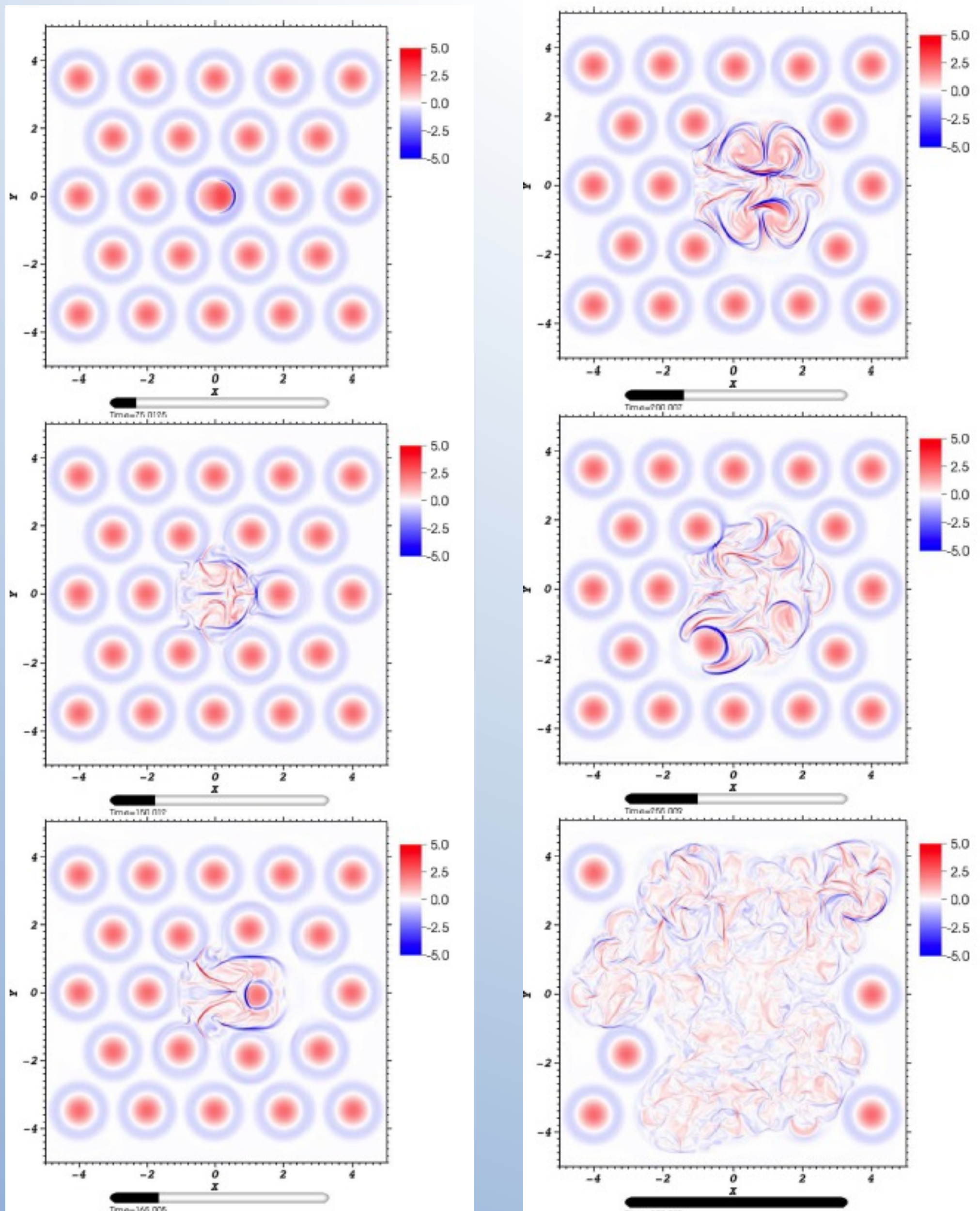


Case 2: 23 (Twenty-three) Loops – only one unstable, same sense of twist (Hood et al, 2015)

Unstable field

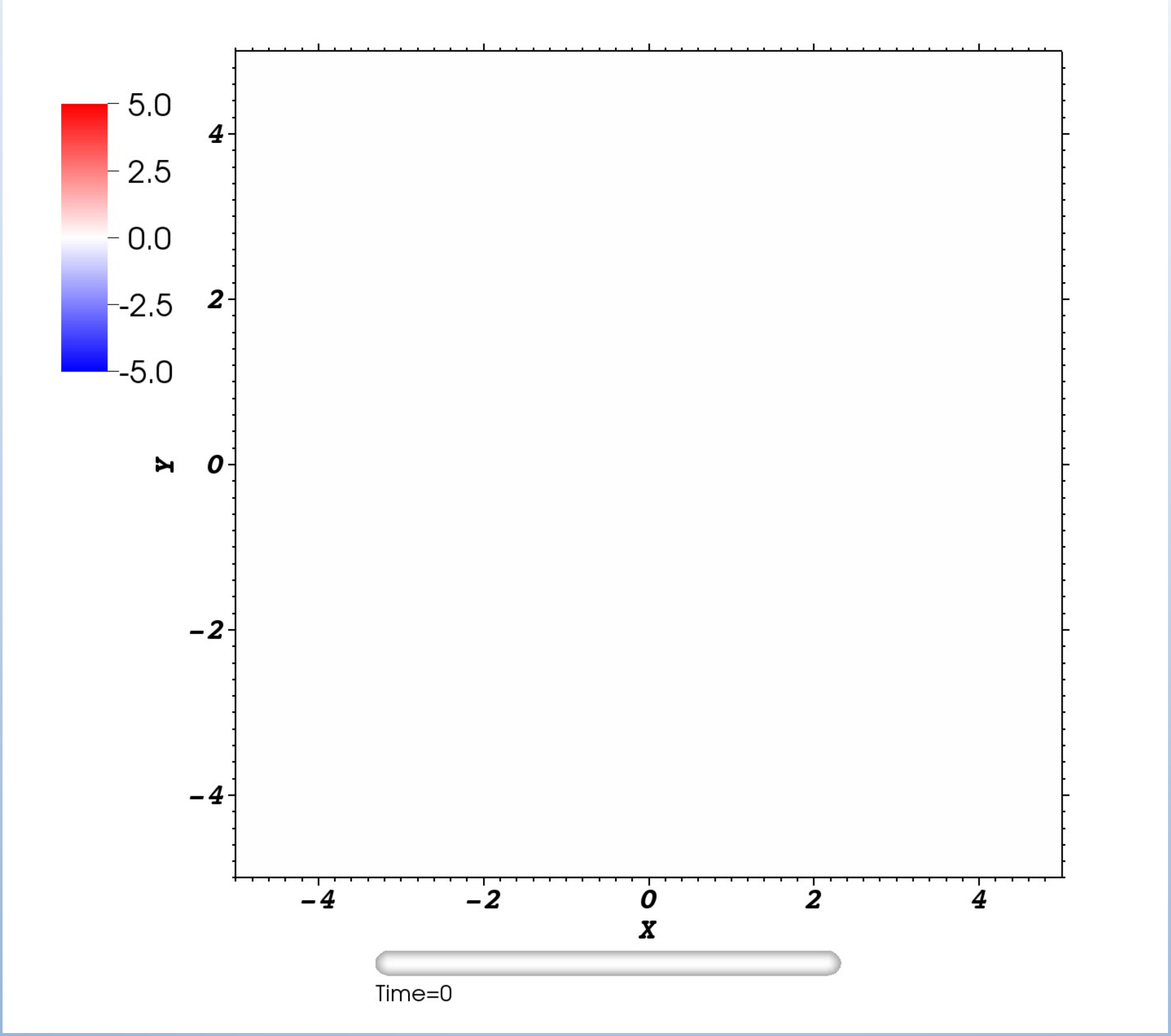


Magnetic field lines of initial setup of 23 loops
3D MHD simulation. Lare3D. 480x480x960 points

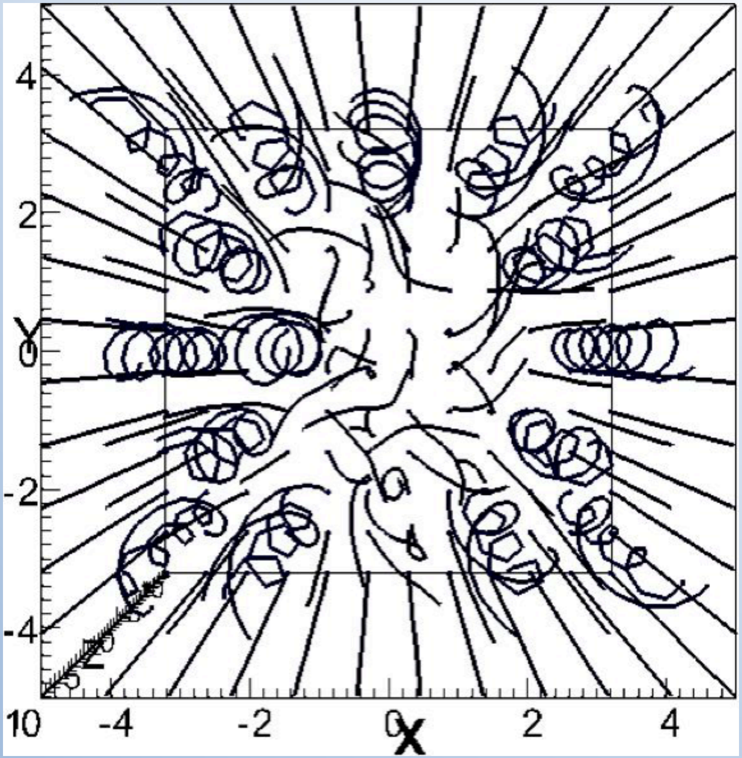


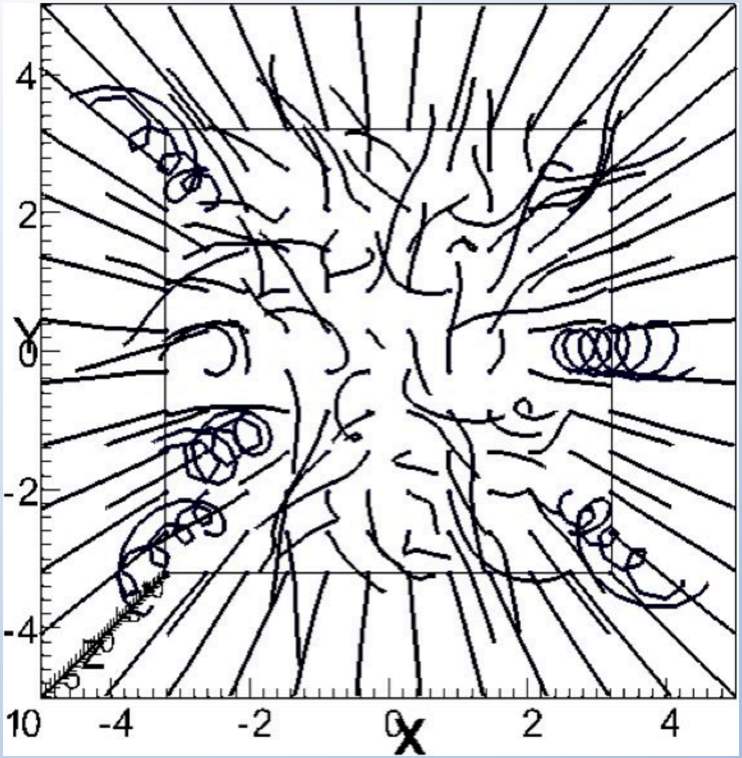
- Unstable flux rope expands
- Interacts with stable one: reconnection then state of non-equilibrium
- Stable twist relaxes, expands.
- Combination then engulfs nearest neighbour(s) etc. etc.
- Process proceeds until almost all flux ropes involved.

Time evolution of current in mid-plane



Magnetic field lines





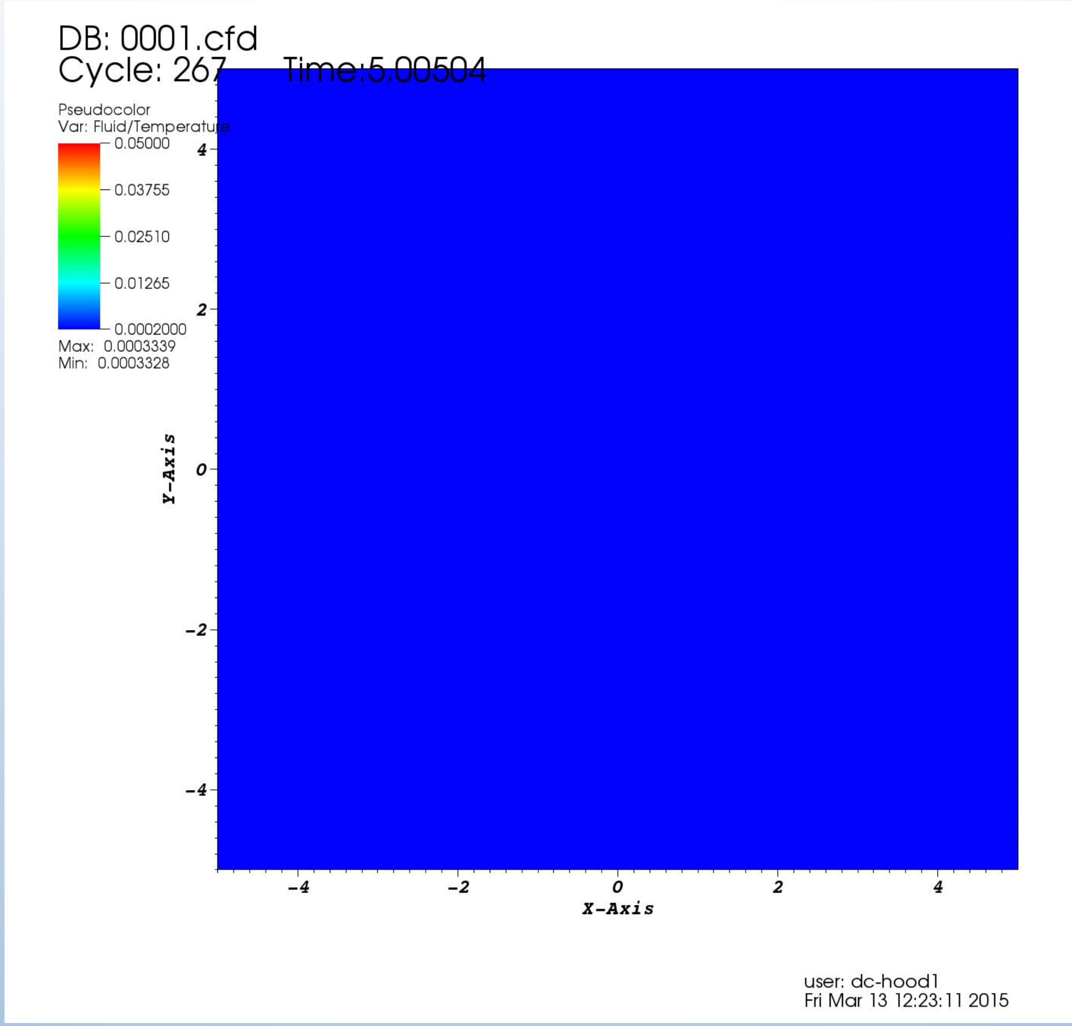
t = 400 t_A

t = 800 t_A

Field is *relaxing*. Less twisted, lower energy.

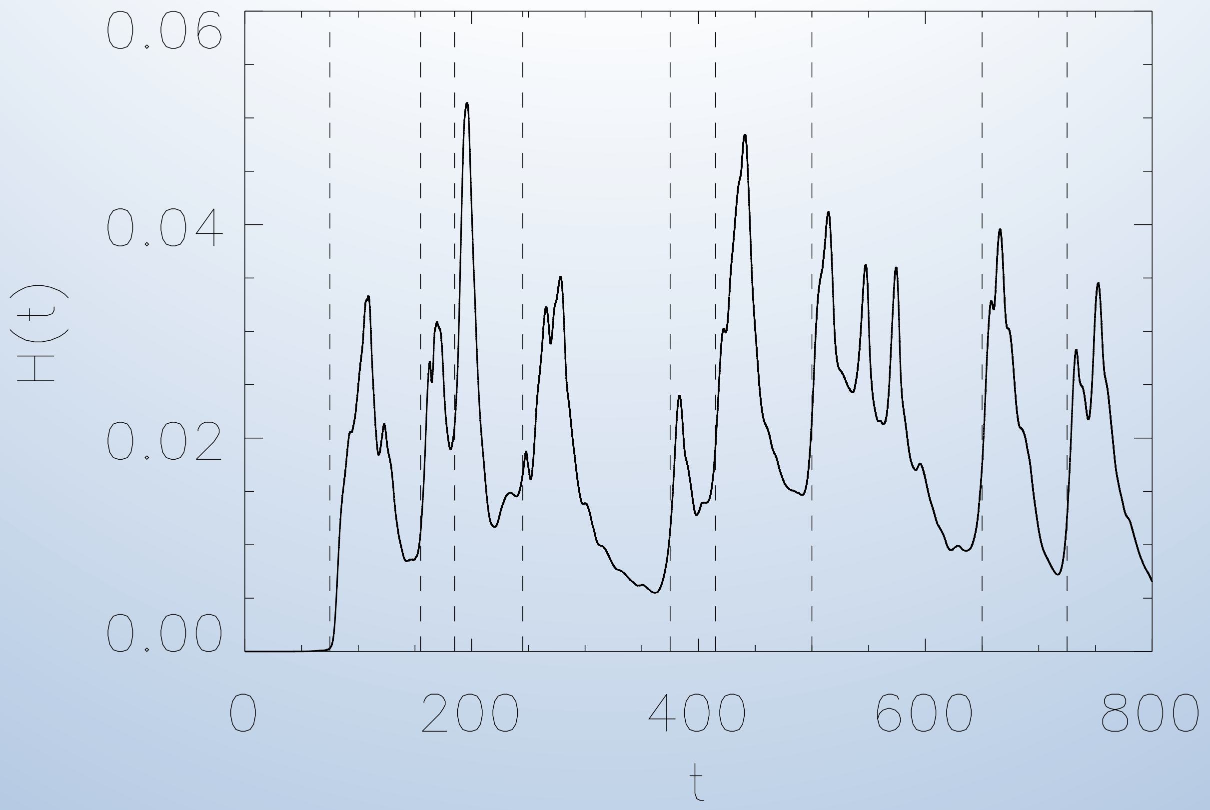
Temperature at mid-plane

Red > 10^8 K
Green >10^7 K
Blue > 10^5 K



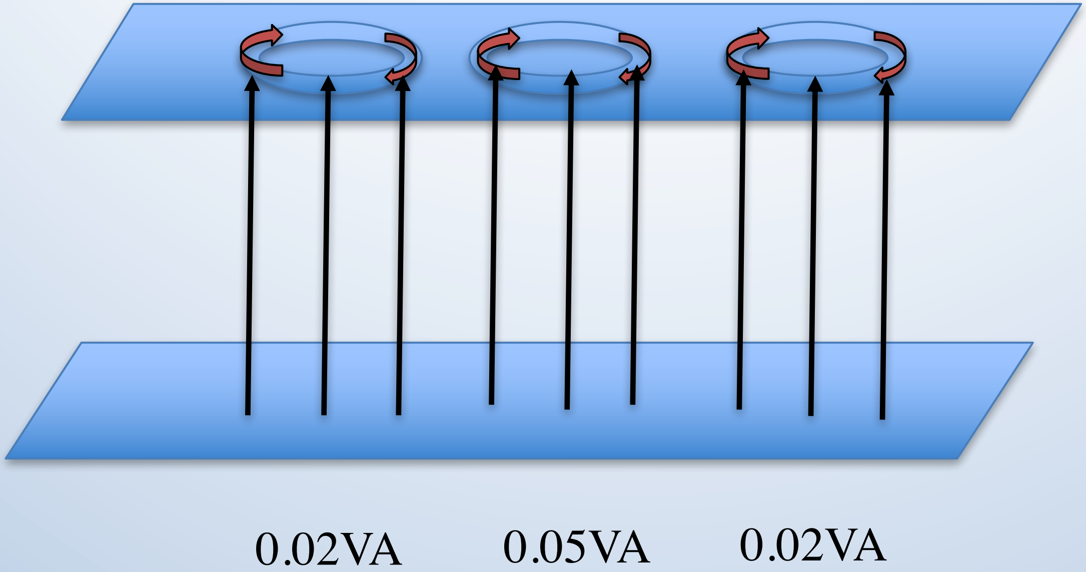
No losses. Shows where energy is actually released (Ohmic/slow shock heating: Bareford & Hood, 2015)

Volume heating

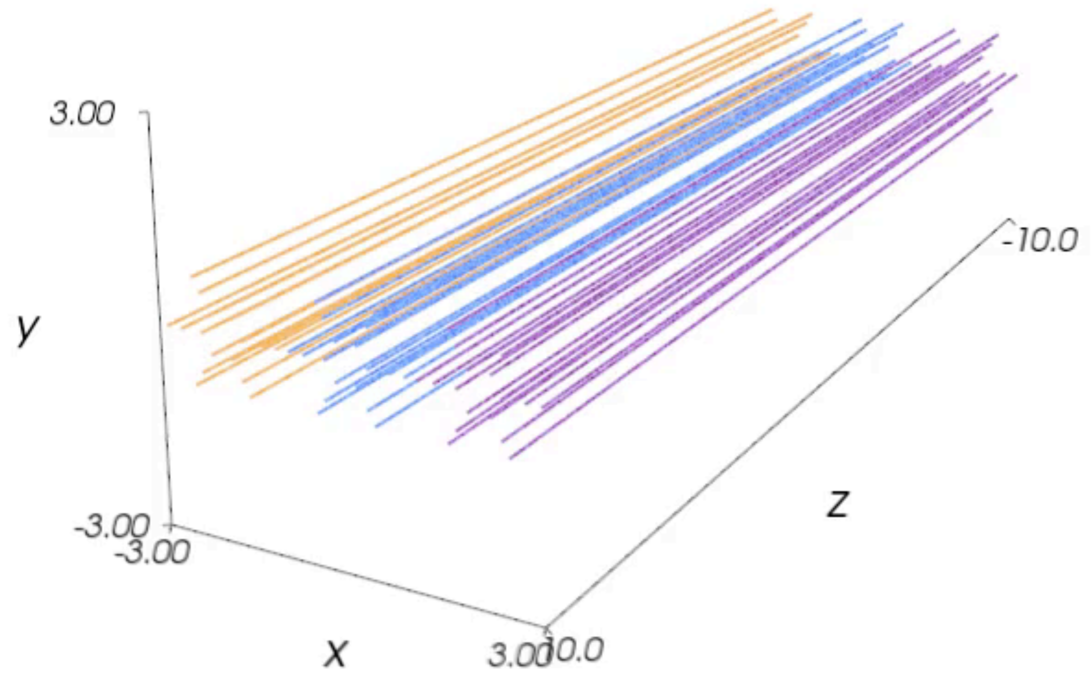


9 energy releases (18 loops disrupted – several at same time).
This is ONE avalanche: no driving.

Footpoint Driving (Jack Reid, PhD)

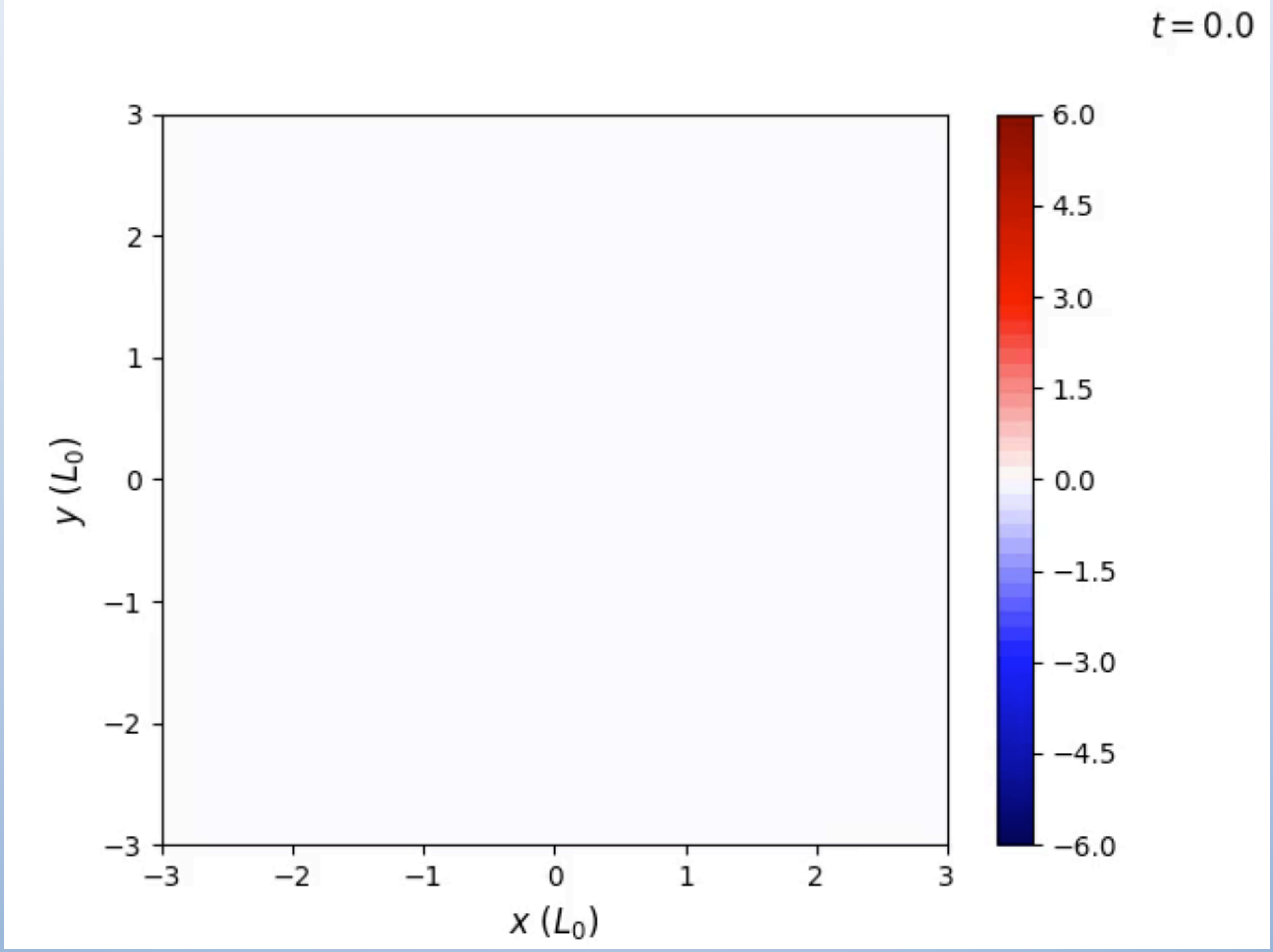


Start from uniform field.
Twist in three patches and keep on twisting!
Opposite rotation on bottom footpoints.



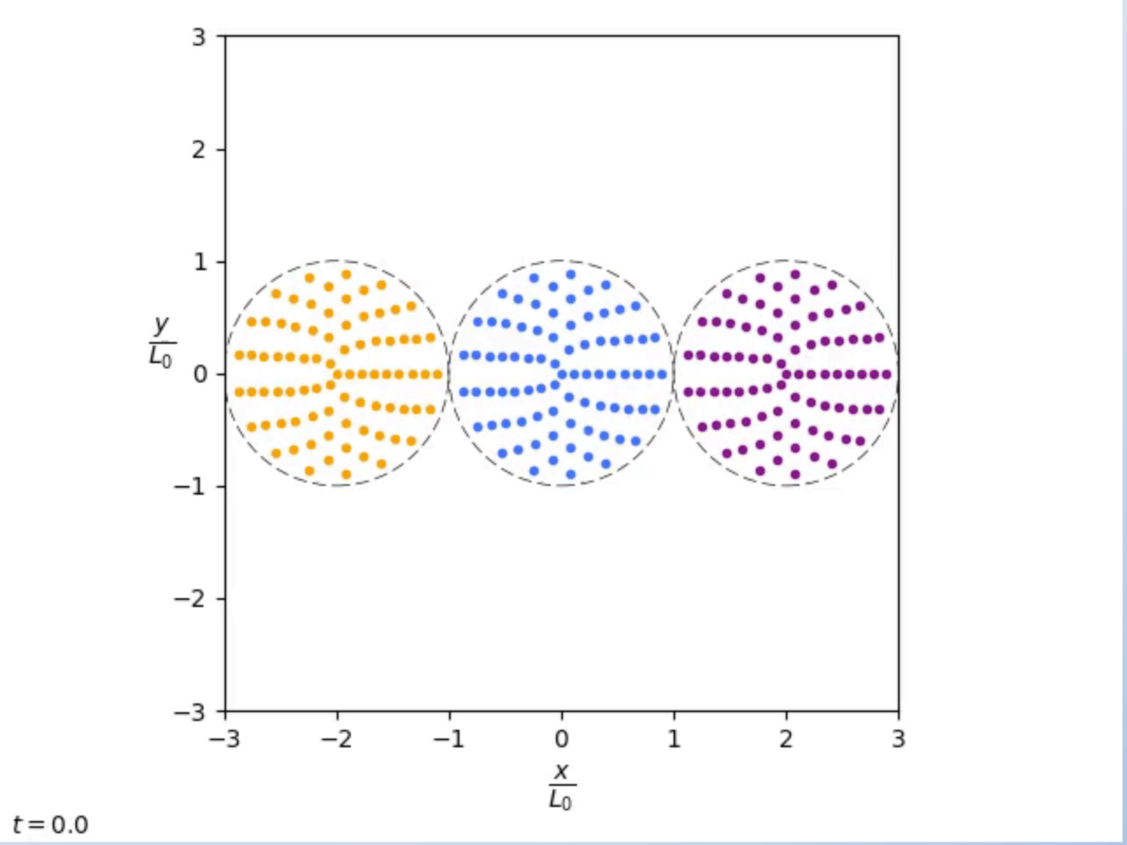
t= 0.0

Axial current jz at mid-plane

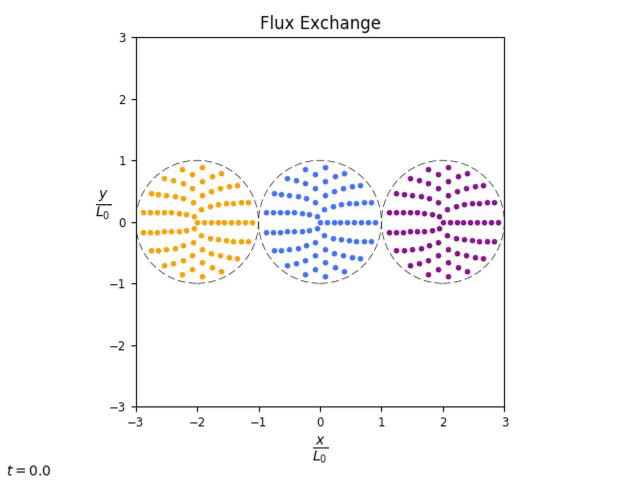


Fieldlines

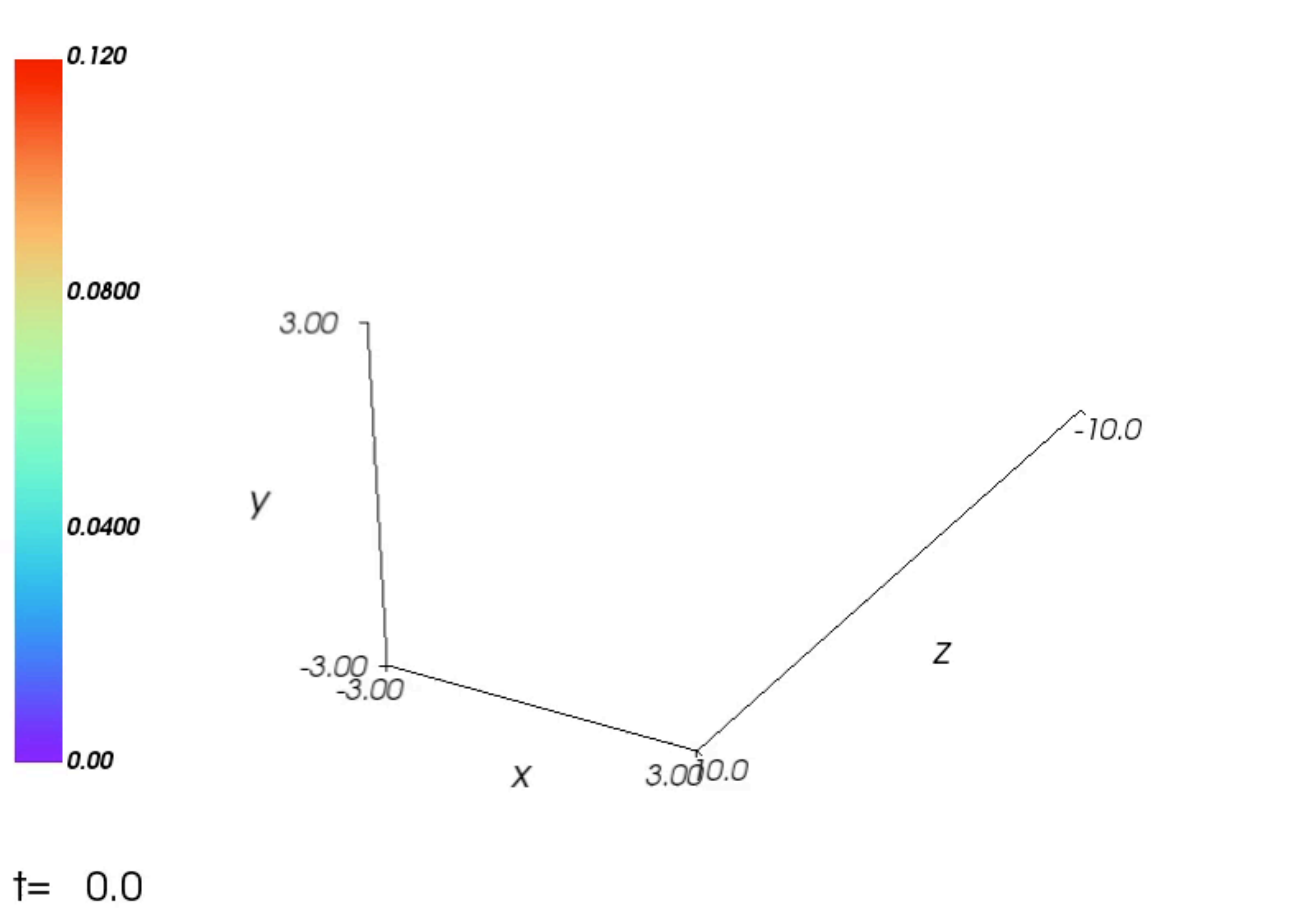
Yellow from left source
Blue middle
Purple right



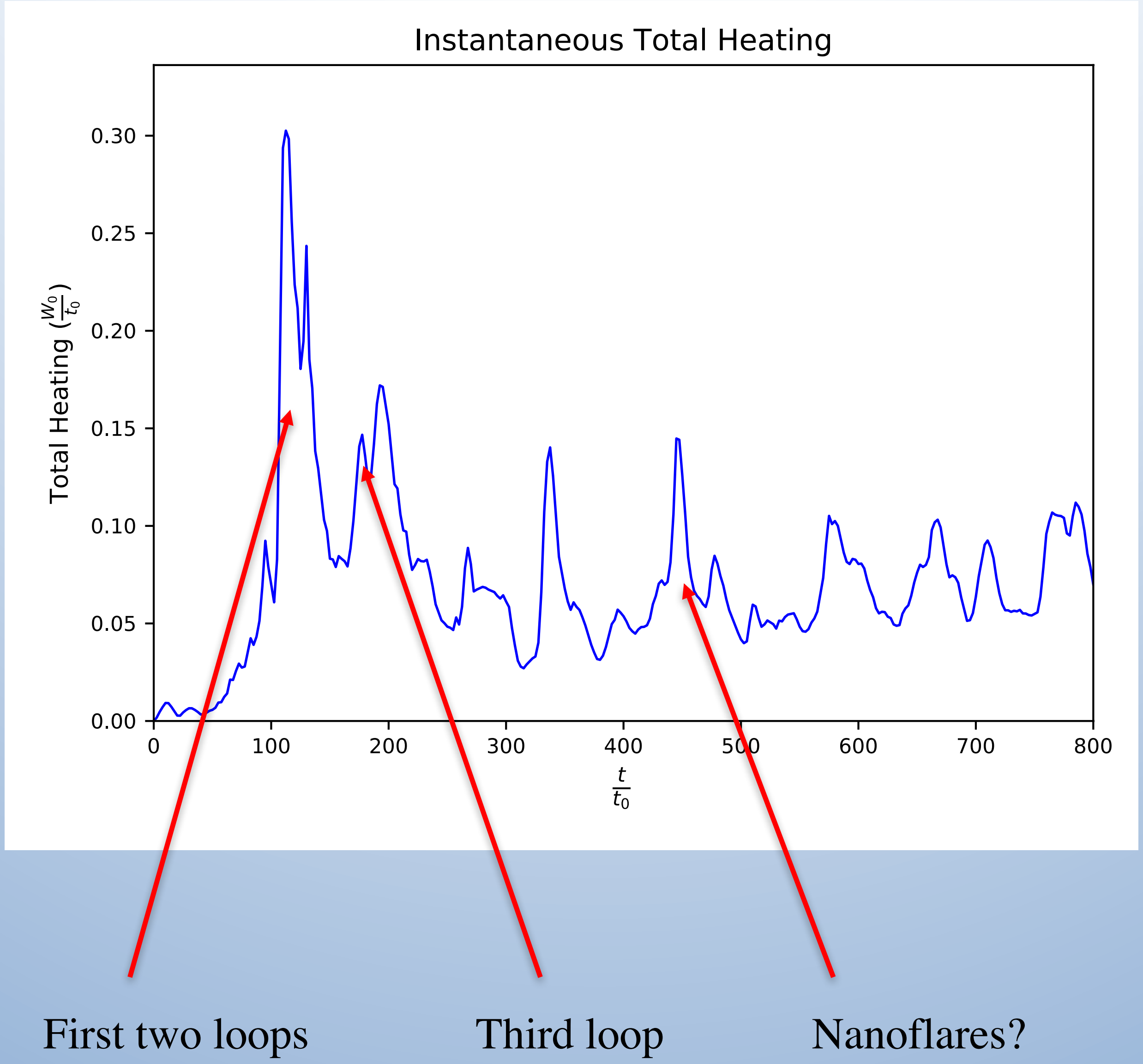
Initial Conditions



Temperature evolution



Heating



Instantaneous Total Heating
Total Heating ($\frac{W_0}{t_0}$)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
100
200
300
400
500
600
700
800
$\frac{t}{t_0}$
First two loops
Third loop
Nanoflares?

Comments

- Demonstration that MHD avalanche can occur in 3D geometry.
- Simple initial state, yet shows energy can be accessed from large volume with single unstable small region.
- Large energy release: relaxation tends towards constant-α field
- Range of avalanche size possible for more complicated fields (e.g. reversed twist): don't want complete avalanche all the time.
- Avalanche creates a complex plasma/field configuration with hierarchy of scales.
- Ideal for acceleration of particles via multiple sites?

Cautionary comments

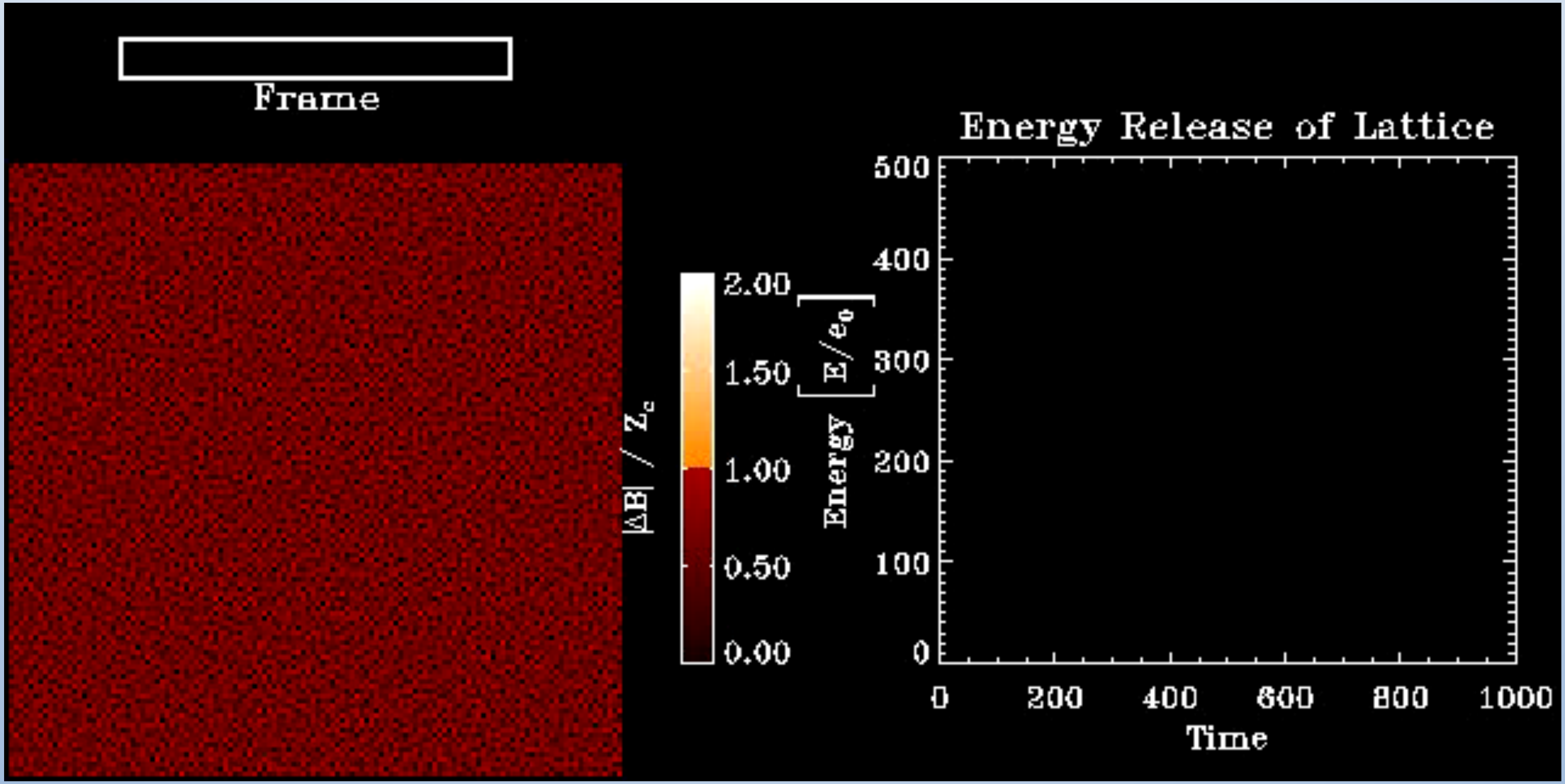
- Simple idealised geometry: “proof of principle”.
- Move onto braiding (see D. Pontin)/ tectonics.

BUT

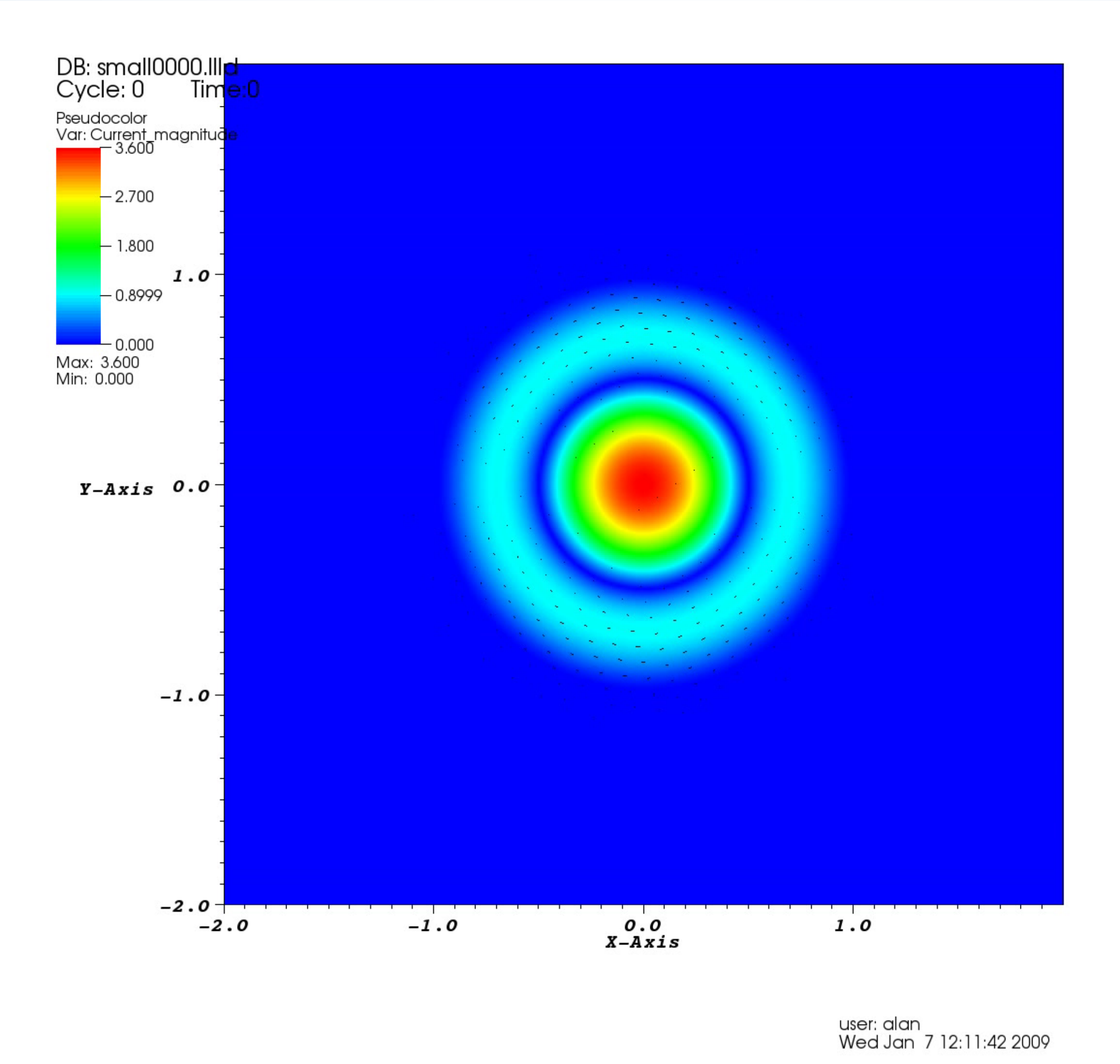
- Fully 3D simulations expensive to run.
- Can’t do drive/dissipate for times required to set up SOC state.
- Approximate MHD models faster, but dubious physics.

Establishment of viability of SOC/avalanche models using 3D MHD a long challenge, but essential for their credibility.

SOC/avalanche models: they probably get things roughly right, but with big surprises as to why.

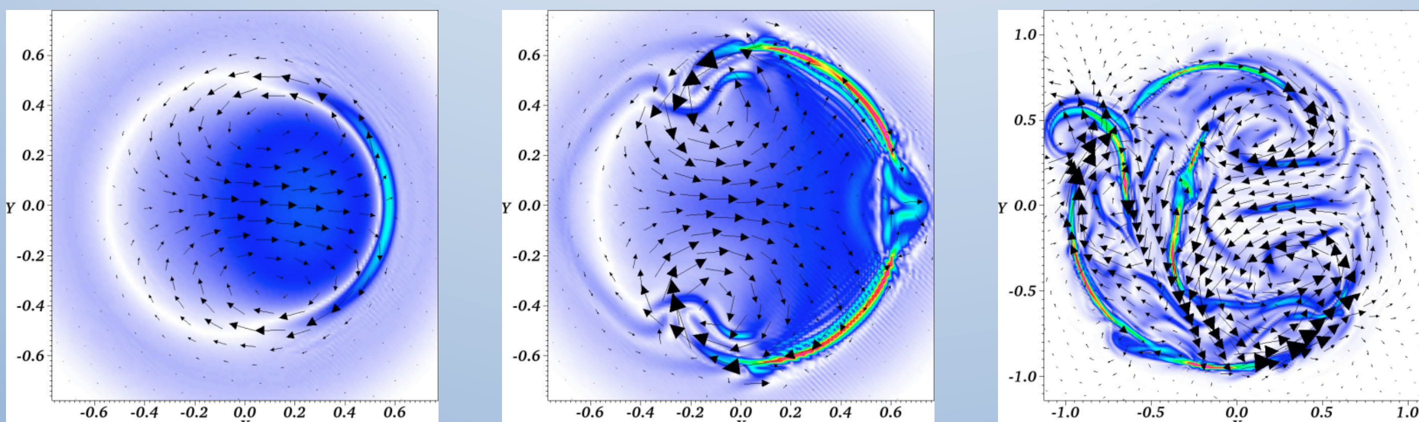

Frame
Energy Release of Lattice
$|\Delta B| / Z_c$
2.00
1.50
1.00
0.50
0.00
Energy $[E/e_0]$
500
400
300
200
100
0
0
200
400
600
800
1000
Time

Axial current at mid-plane



Vehicle for avalanche demonstration: kink instability

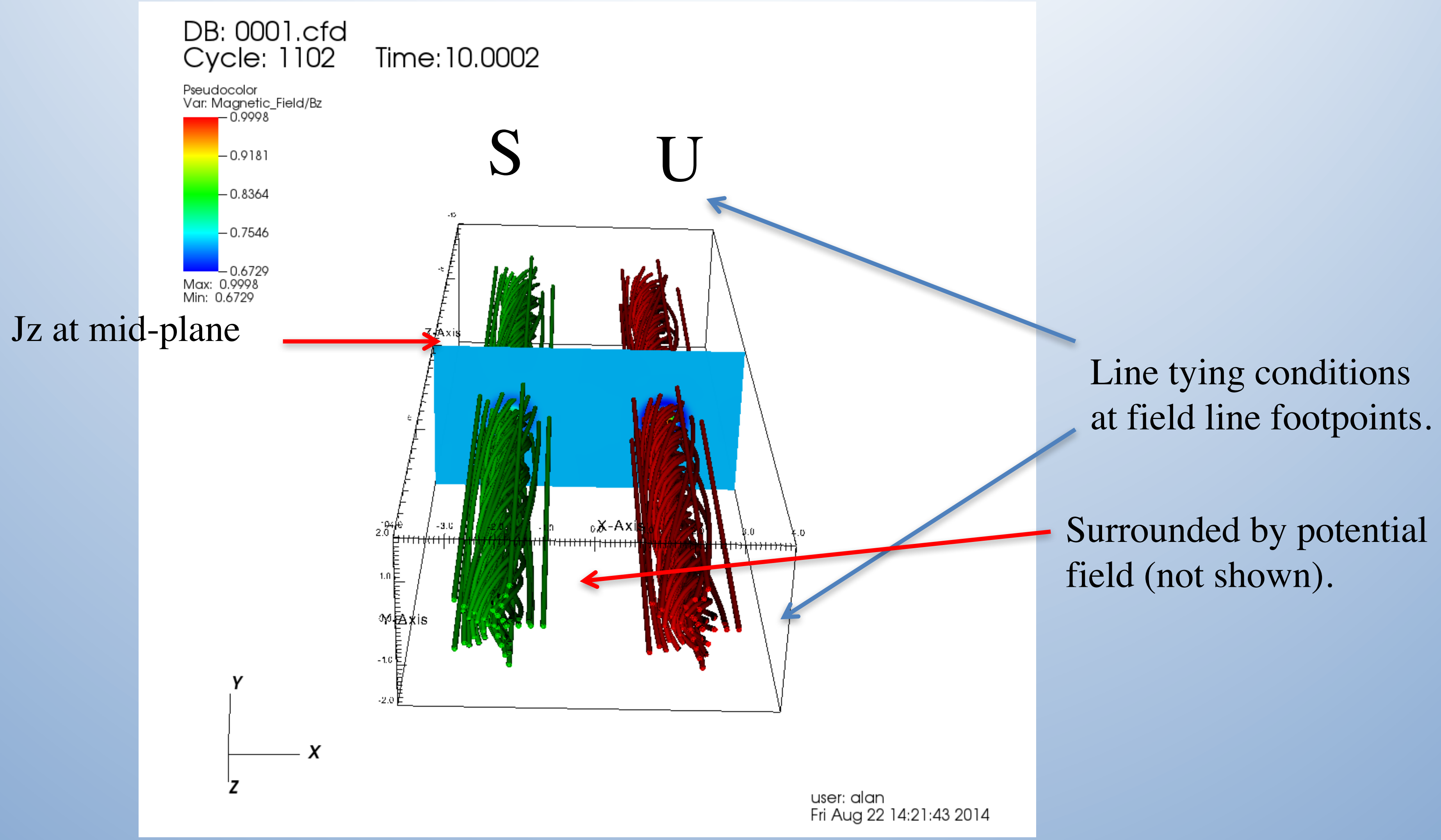
- Twisted magnetic flux rope.
- Unstable if Kruskal-Shafranov condition $\Phi = \frac{2LB_\theta}{rB_z} > 2\pi$ on twist (Φ) violated:
- In presence of line-tying, $\Phi > 3.3\pi$ (Hood & Priest, 1981)
- Instability leads to multi-scale plasma and field (Browning, Hood, Bareford etc.).

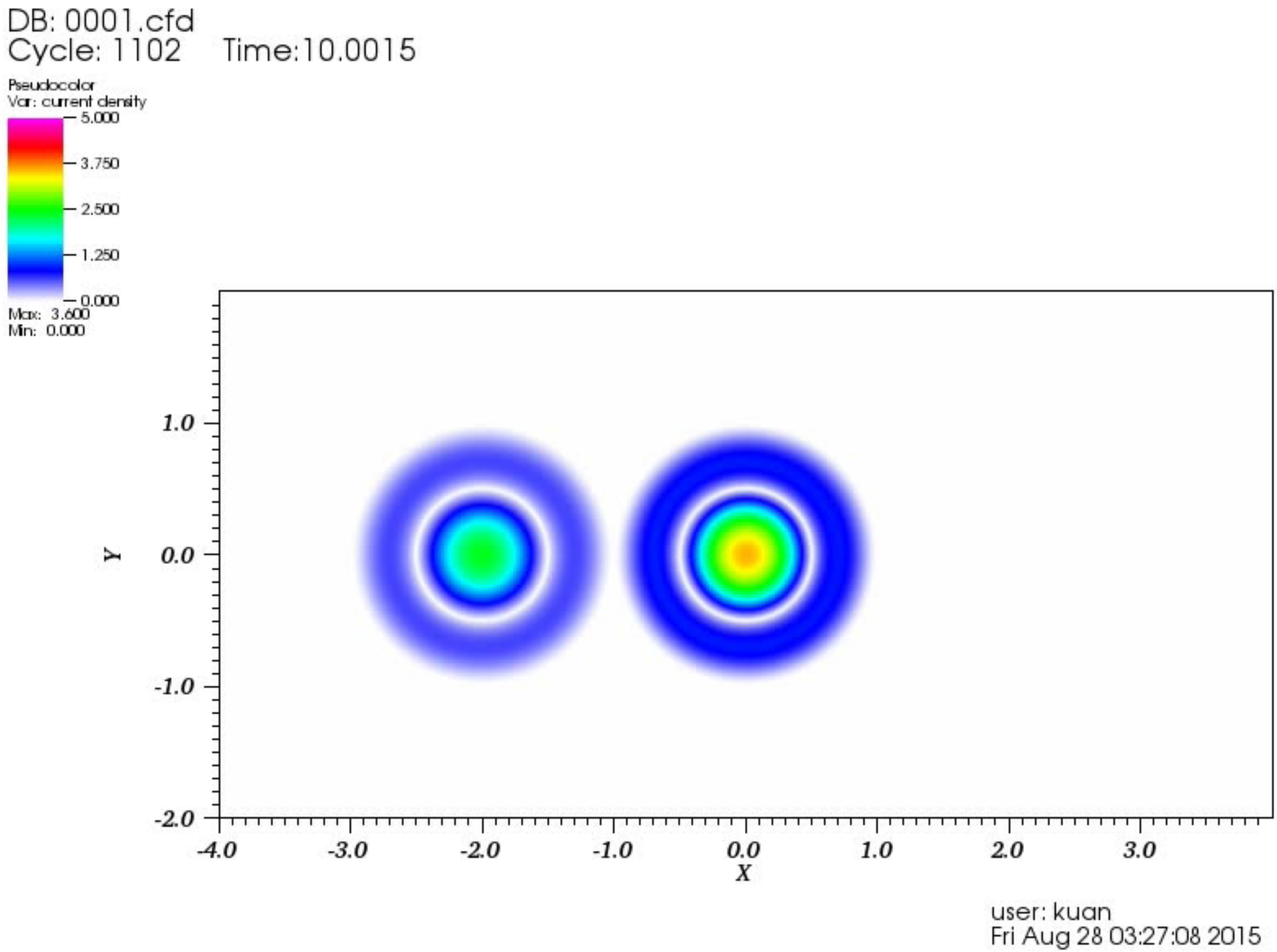


J, V.   t increases to right

Example 1. Can an unstable loop destabilise a stable one? (Tam et al, A&A in press, 2015)

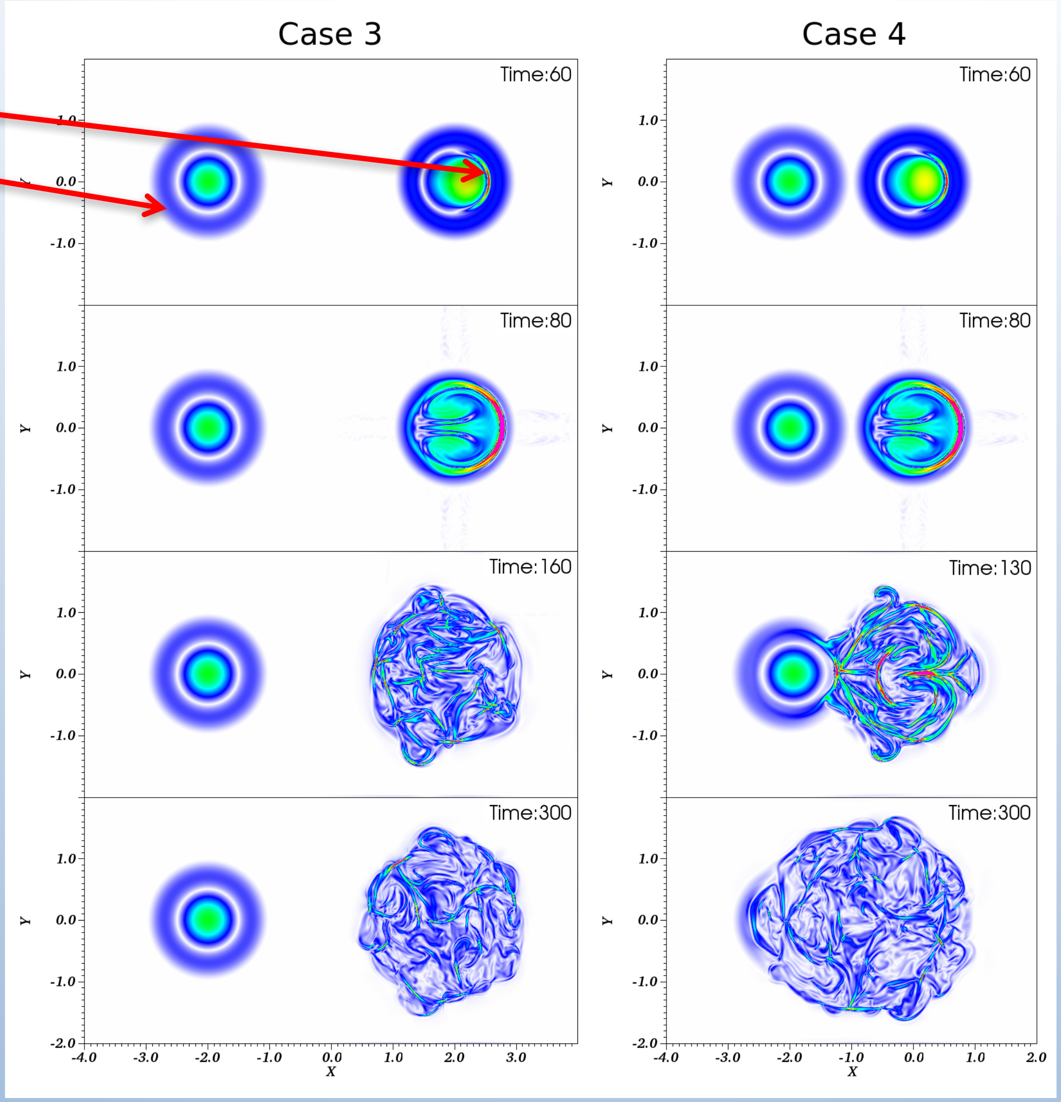
Setup. Two parallel, twisted cylindrical magnetic fields: one stable ($\pi/2$ below marginal state), other unstable. Same sense of twist.




DB: 0001.cfd
Cycle: 1102 Time:10.0015
Pseudocolor
Var: current density
5.000
3.750
2.500
1.250
0.000
Max: 3.600
Min: 0.000
1.0
0.0
-1.0
-2.0
Y
-4.0
-3.0
-2.0
-1.0
0.0
1.0
2.0
3.0
X
user: kuan
Fri Aug 28 03:27:08 2015

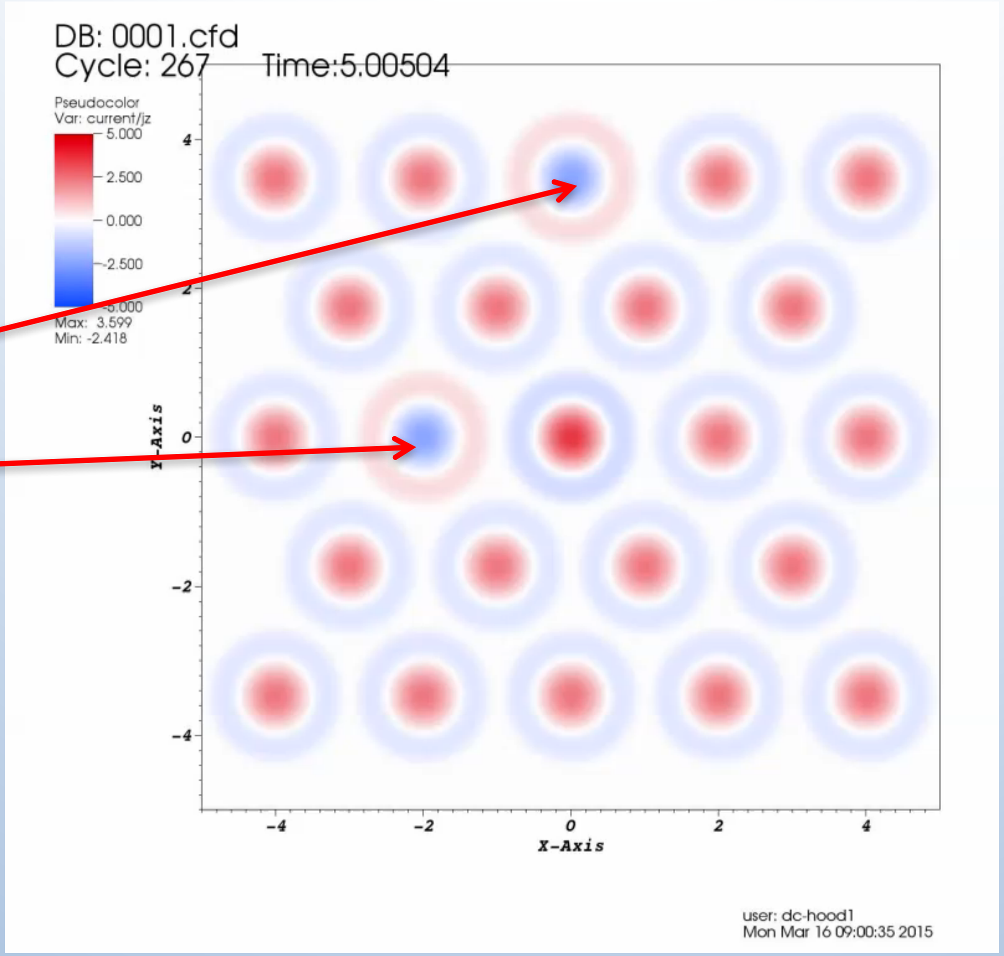
Axial current density –2 cases (at mid-plane)

Unstable B
Stable B



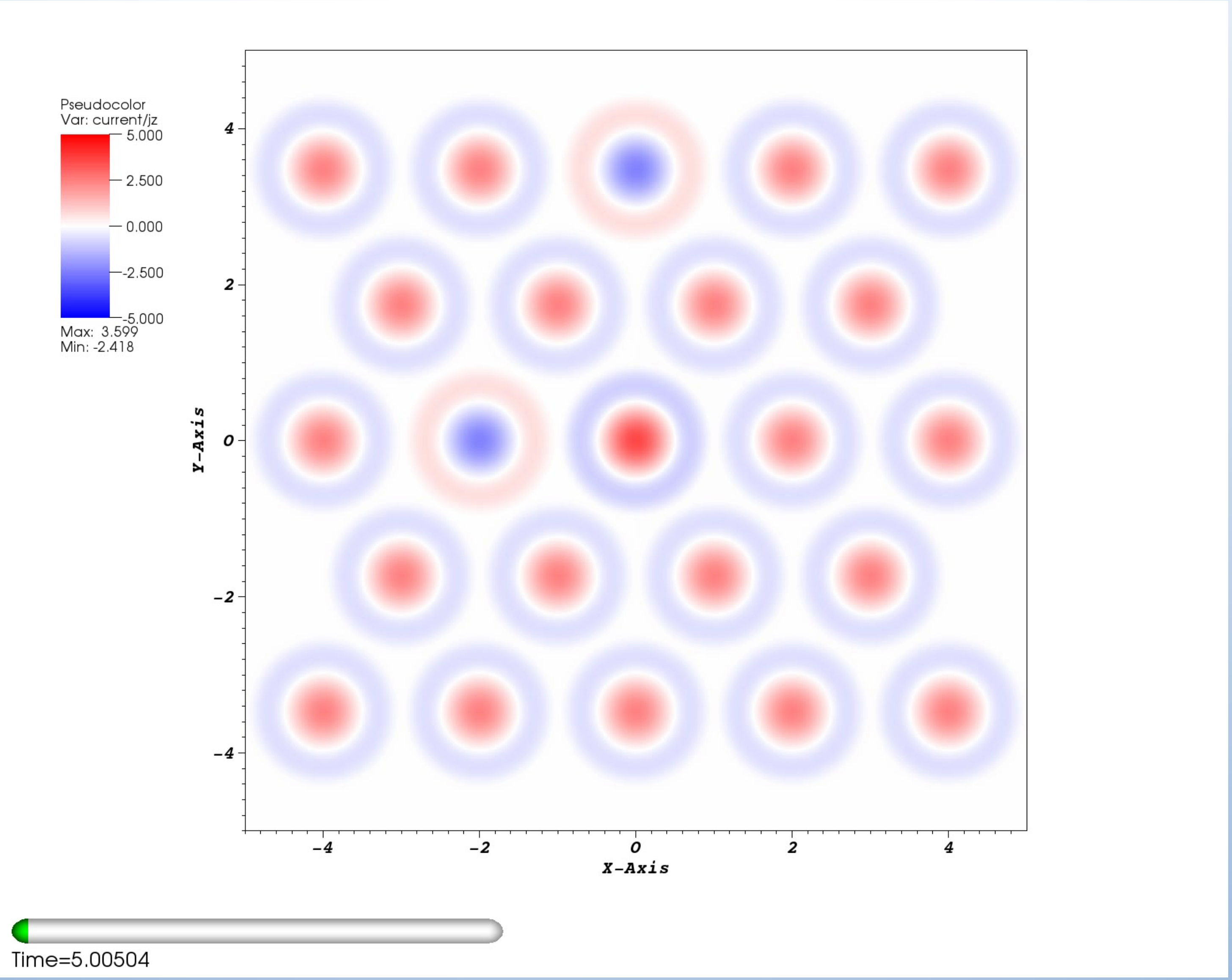
Destabilisation happens if close enough, as expect in the corona. Possible avalanche?

Case 3: 23 Loops –1 unstable, 2 with opposite twist



Opposite twist

Opposite twist loops "block" avalanche (for a while).
Field lines approximately aligned when interact with destabilised loops: no reconnection.



Pseudocolor
Var: current/jz
5.000
2.500
0.000
-2.500
-5.000
Max: 3.599
Min: -2.418
4
2
0
-2
-4
Y-Axis
-4
-2
0
2
4
X-Axis
Time=5.00504