Energy release and particle acceleration in reconnection – and a bit of waves….

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Alan Hood, St Andrews;

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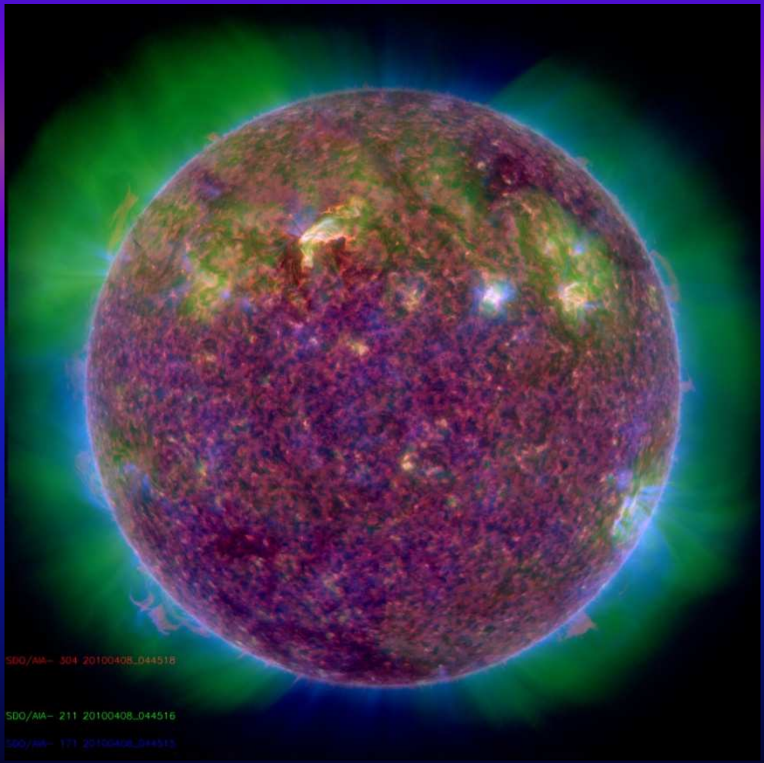
Royal Observatory of Belgium

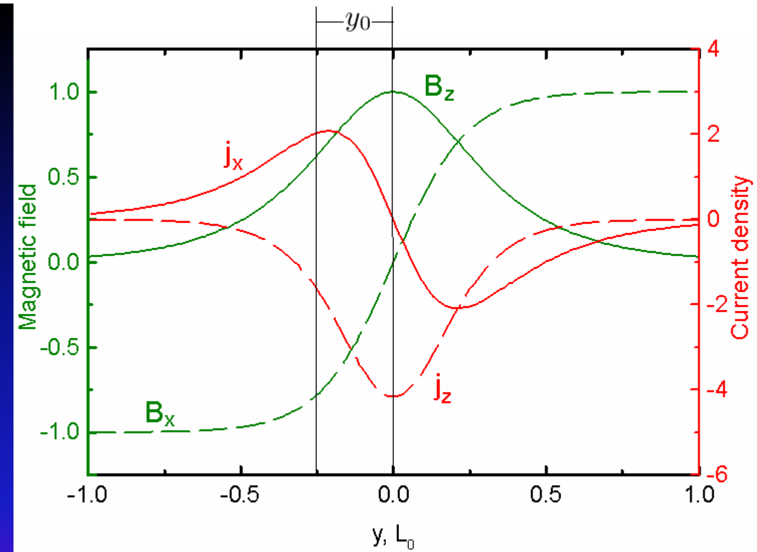
- Reconnection and particle acceleration in 2D time—dependent fields
- Reconnection, energy release and nanoflare distributions in 3D twisted loops
- Particle acceleration in twisted loops
- Some thoughts on waves and reconnection

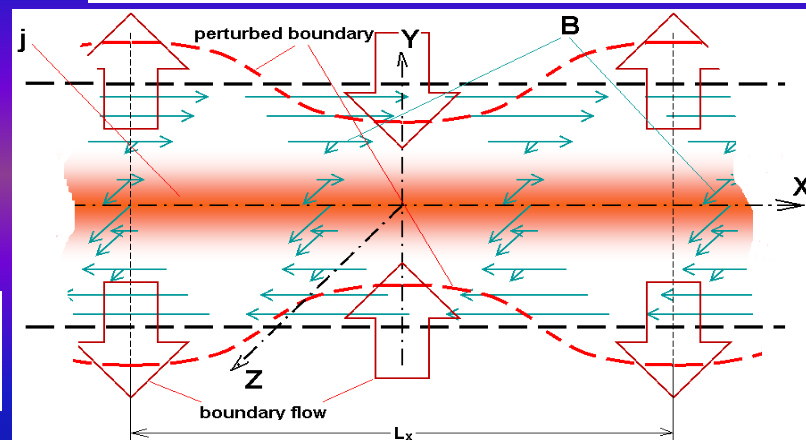


Forced reconnection in 2D current sheet

•Initial force-free Harris current sheet
•Slow, transient sinusoidal boundary disturbance
•Strong current sheet created which subsequently reconnects

Hahm and Kulsrud 1985
Gordovskyy and Browning 2010 a,b



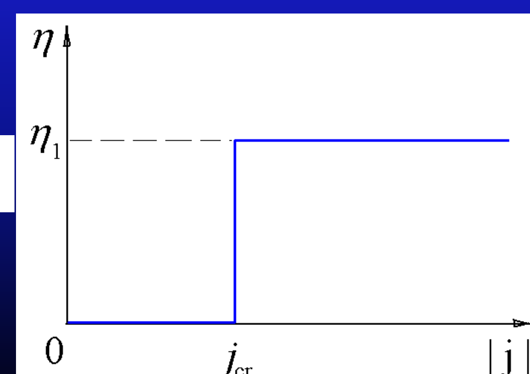


$$\mathbf{B}_{ini} = B_0\left[\tanh\frac{y}{y_0}; 0; \mathrm{sech}\frac{y}{y_0}\right]$$

$$\boldsymbol{j}_{ini} = -\frac{B_0}{\mu_0 y_0}\left[\tanh\frac{y}{y_0}\,\mathrm{sech}\,\frac{y}{y_0}; 0; \mathrm{sech}^2\frac{y}{y_0}\right]$$

$$p_{ini} = 0.01\frac{B_0^2}{2\mu_0}$$

$$\rho_{ini} = \rho_0$$



- Boundary driver

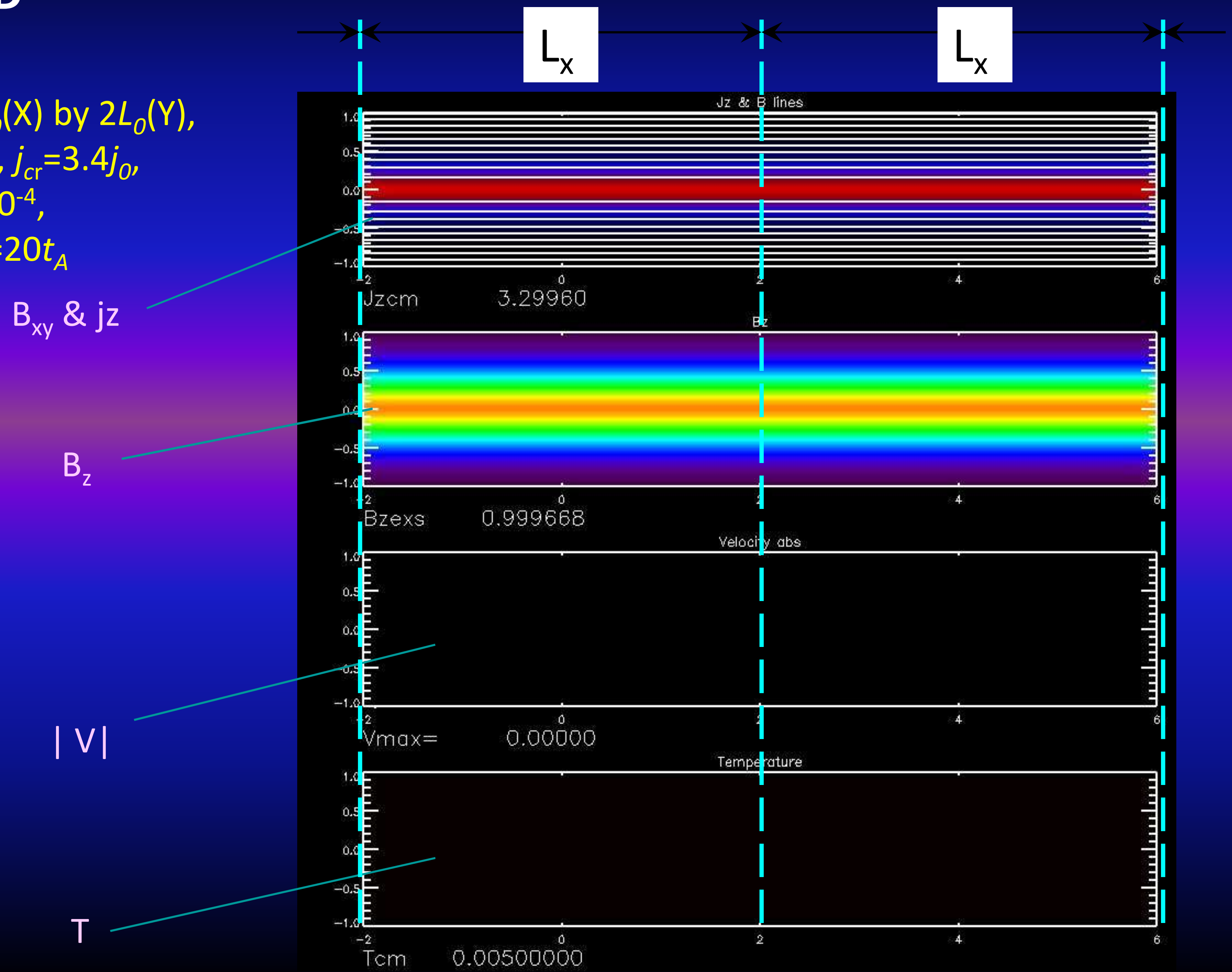
$$v_x = 0$$

$$v_y = \begin{cases} \pm\frac{\Delta}{t_{imp}}\cos\left(\frac{2\pi}{l_x}x\right)\left[1-\cos\left(\frac{2\pi}{t_{imp}}t\right)\right], & (t<t_{imp}) \\ 0, & (t>t_{imp}) \end{cases}$$

$$v_z = 0$$

Numerical MHD model of forced reconnection LARE2D

- **Case:** $4L_0$(X) by $2L_0$(Y), $y_0 = 0.30L_0$, $j_{cr}=3.4j_0$, $S_1^{-1} = 3.2\ 10^{-4}$, $\Delta=0.1L_0$, $\tau=20t_A$



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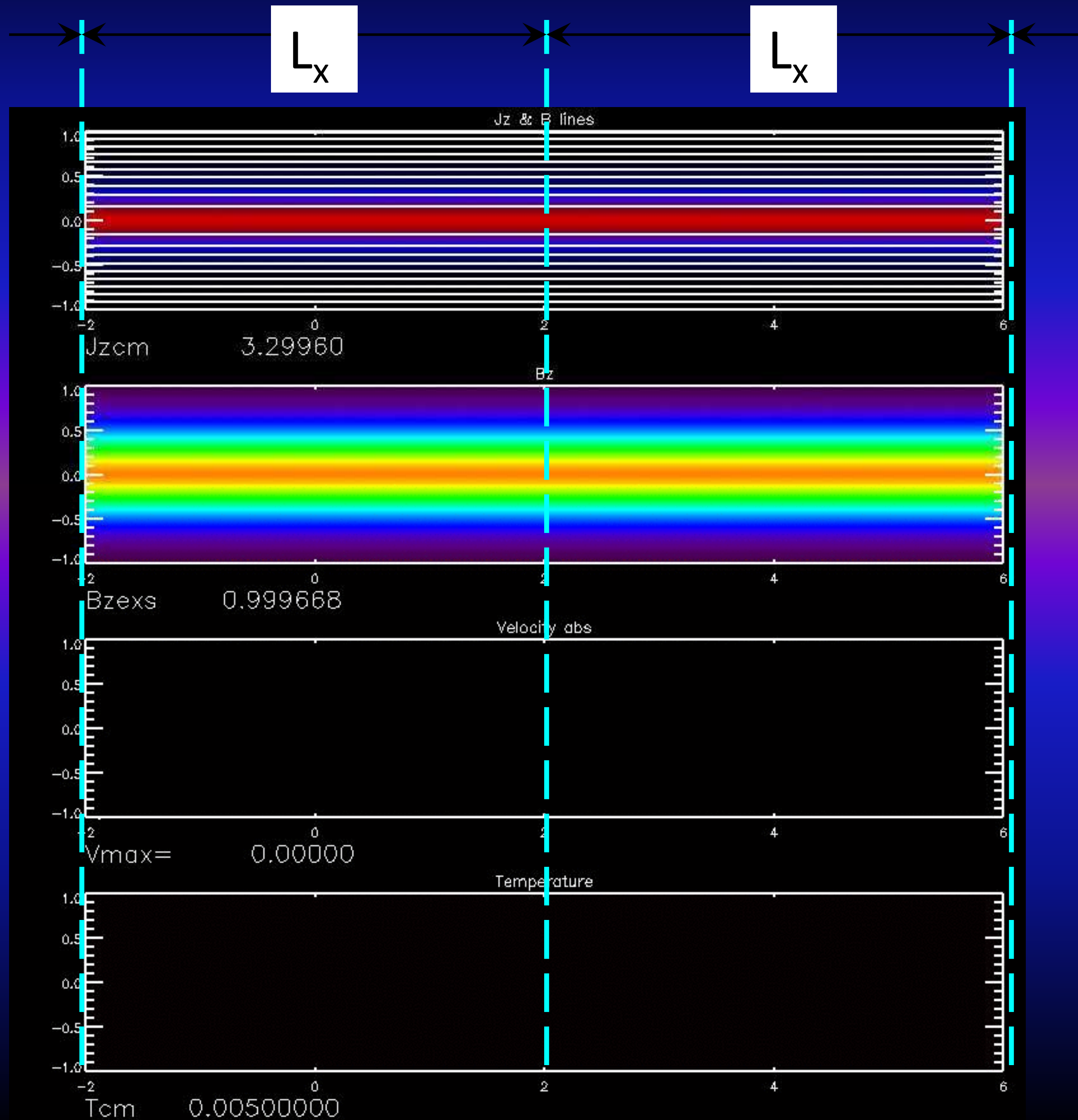

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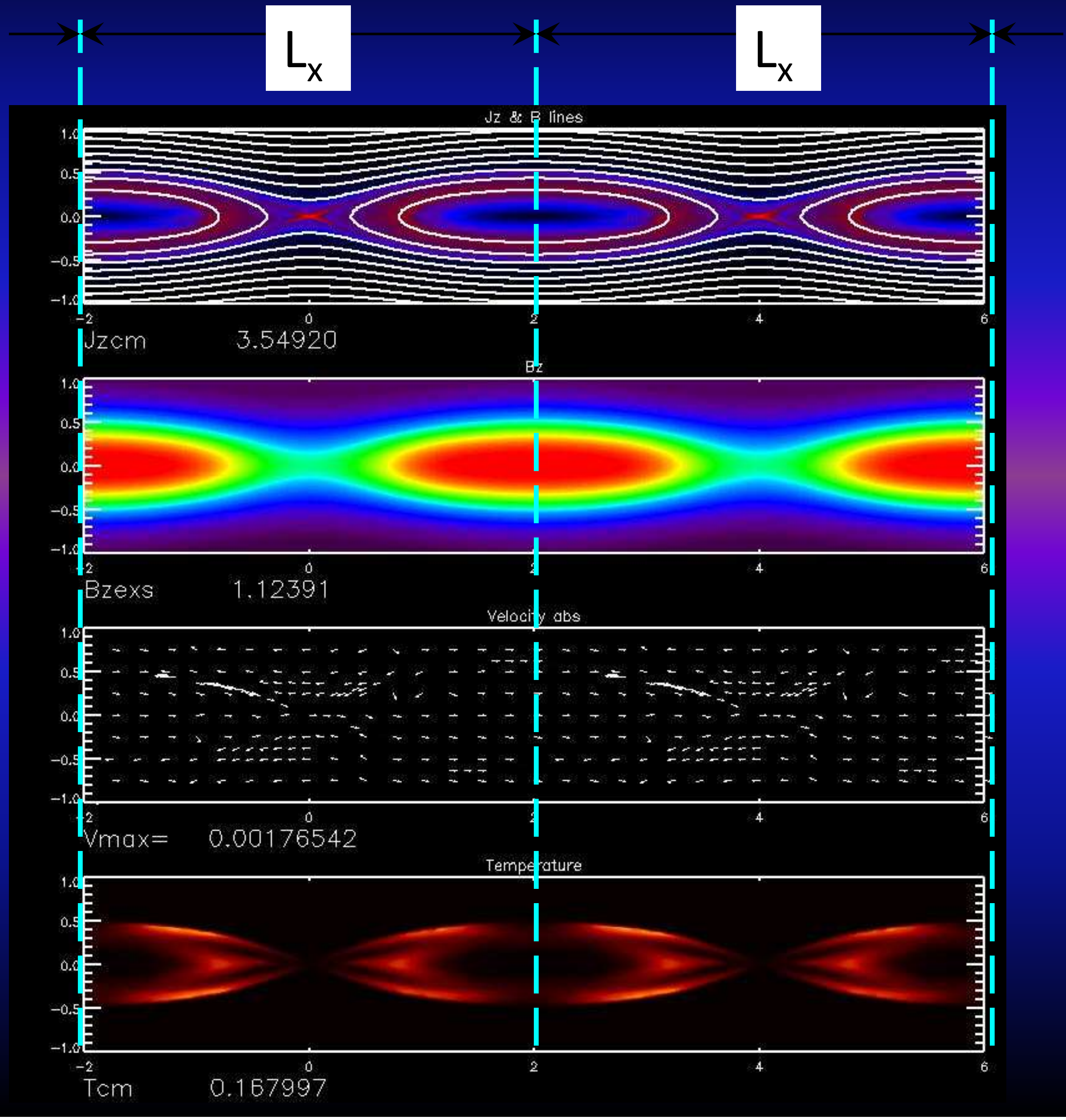
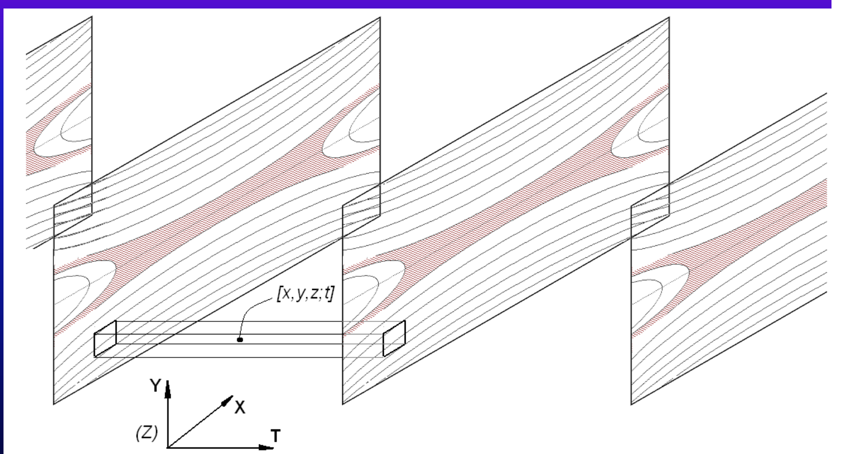


Time-dependent test particle models in 2D reconnecting current sheet

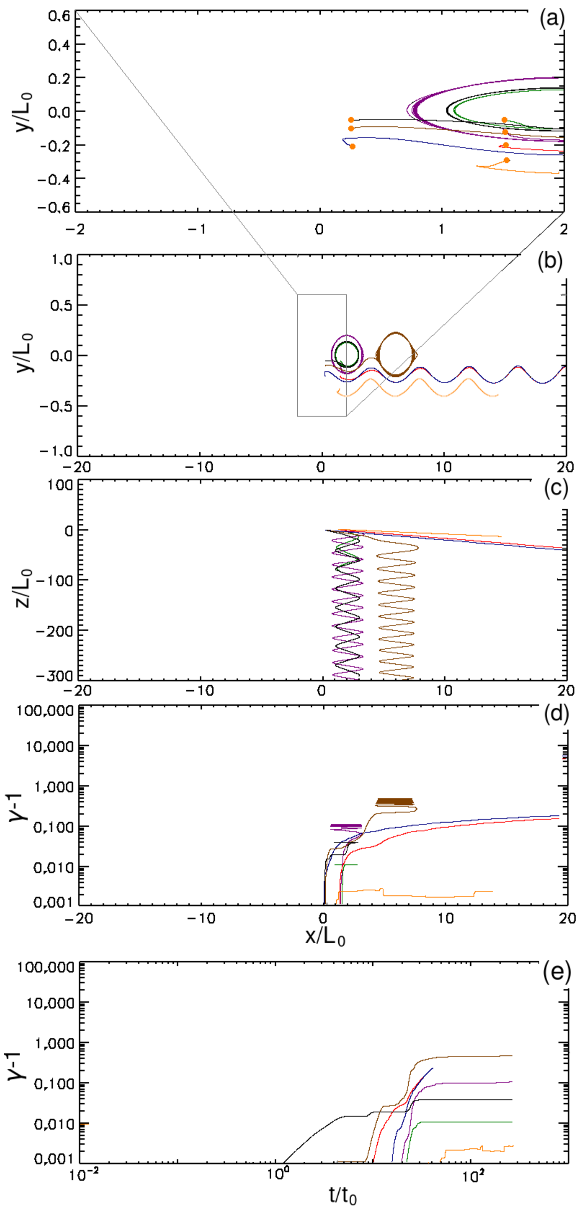
- Inject 10^6 test particles into fields from MHD simulations
- Relativistic guiding-centre equations
- Interpolate E and B from space/time grid to particle positions

$$
\begin{aligned}
\frac{d\mathbf{r}}{dt} &= \mathbf{u} + \frac{\gamma(v_{||})}{\gamma}\mathbf{b} \\
\mathbf{u} &= \mathbf{u}_E + \frac{m}{q}\frac{(\gamma v_{||})^2}{\gamma\kappa^2 B}[\mathbf{b}\times(\mathbf{b}\cdot\nabla)\mathbf{b}] + \frac{m}{q}\frac{\mu}{\gamma\kappa^2 B}[\mathbf{b}\times(\nabla(\kappa B))] \\
&\quad \frac{m}{q}\frac{(\gamma v_{||})}{\kappa^2 B}[\mathbf{b}\times(\mathbf{b}\cdot\nabla)\mathbf{u}_E] + \frac{m}{q}\frac{(\gamma v_{||})}{\kappa^2 B}[\mathbf{b}\times(\mathbf{u}_E\cdot\nabla)\mathbf{b}] + \\
&\quad \frac{m}{q}\frac{\gamma}{\kappa^2 B}[\mathbf{b}\times(\mathbf{u}_E\cdot\nabla)\mathbf{u}_E] + \frac{1}{\gamma c^2}\frac{E_{||}}{\kappa^2 B}(\gamma v_{||})[\mathbf{b}\times\mathbf{u}_E] \\
\frac{d(\gamma v_{||})}{dt} &= \frac{q}{m}\mathbf{E}\cdot\mathbf{b} - \frac{\mu}{\gamma}(\mathbf{b}\cdot\nabla(\kappa B)) + (\gamma v_{||})\mathbf{u}_E\cdot((\mathbf{b}\cdot\nabla)\mathbf{b}) + \\
&\quad \gamma\mathbf{u}_E\cdot((\mathbf{u}_E\cdot\nabla)\mathbf{b}) \\
\gamma &= \sqrt{\frac{c^2 + (\gamma v_{||})^2 + 2\mu B}{c^2 - u^2}} \\
\frac{d\mu}{dt} &= 0 \qquad \left(\mu = \frac{u_g^2}{2B}\right)
\end{aligned}
$$

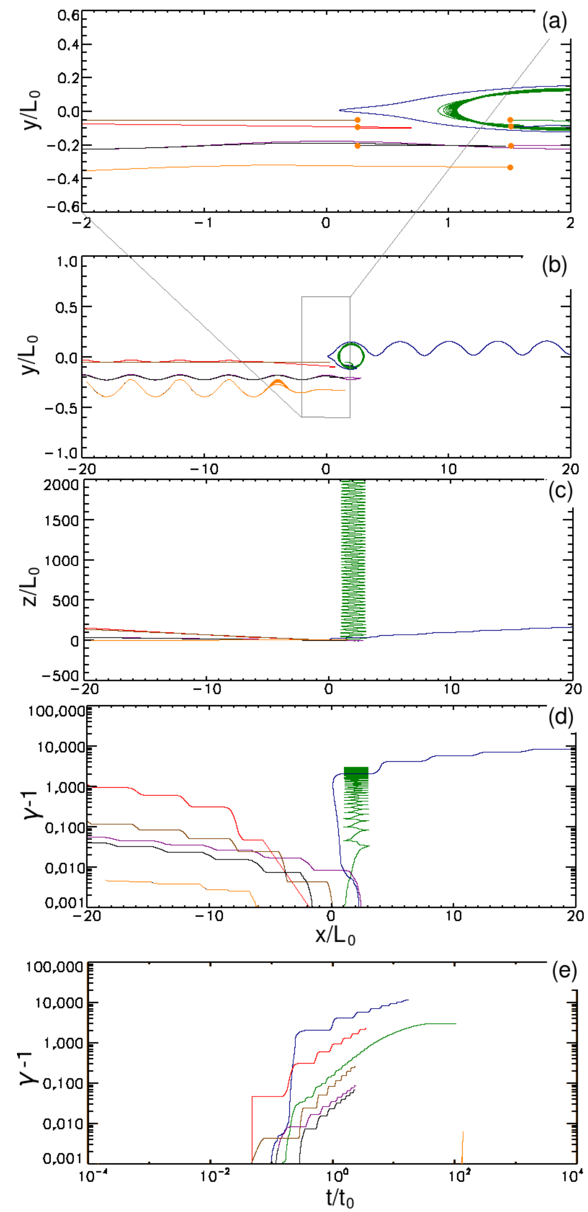


- **Case:** $4L_0$(X) by $2L_0$(Y), $y_0 = 0.30L_0$, $j_{cr}=3.4j_0$, $S_1^{-1} = 3.2\ 10^{-4}$, $\Delta=0.1L_0$, $\tau=20t_A$

Protons



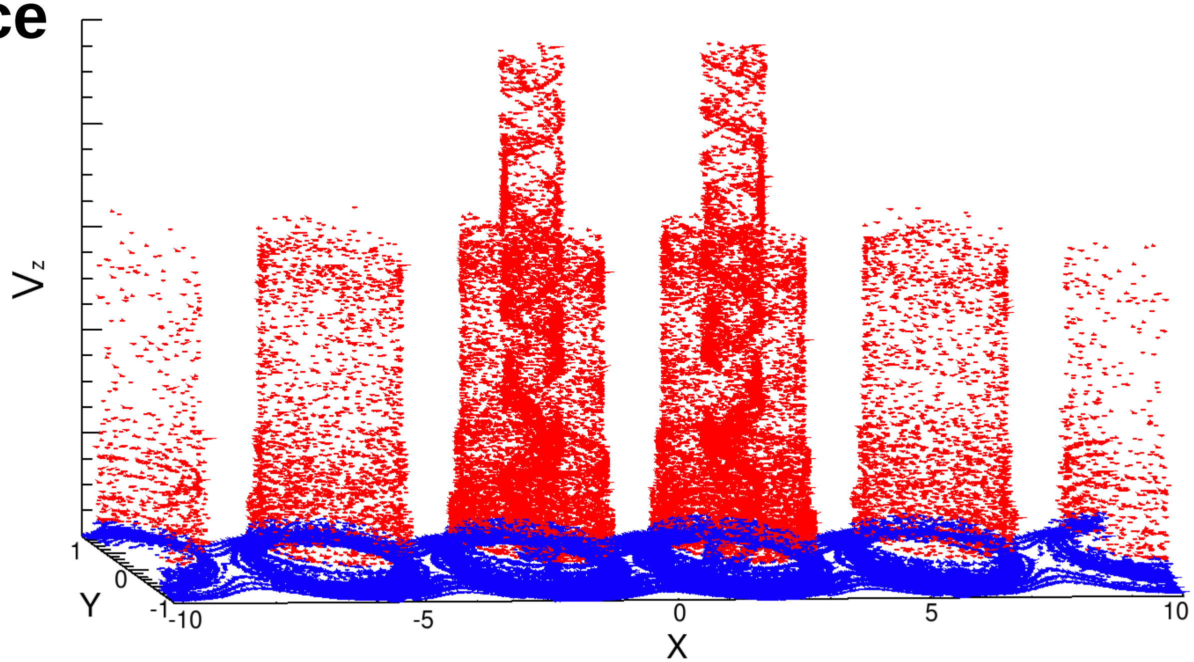
Electrons



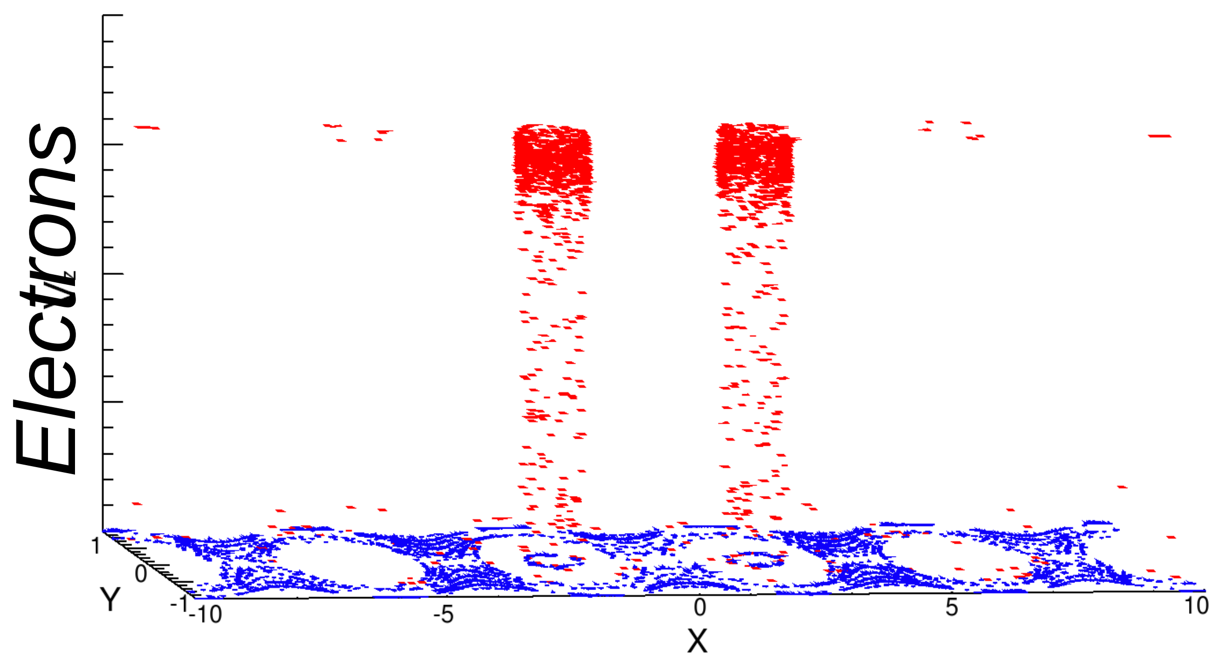
Particle velocity/space distribution

Population A: protons and electrons in open magnetic field moving in X-Y, small z-velocities

Protons



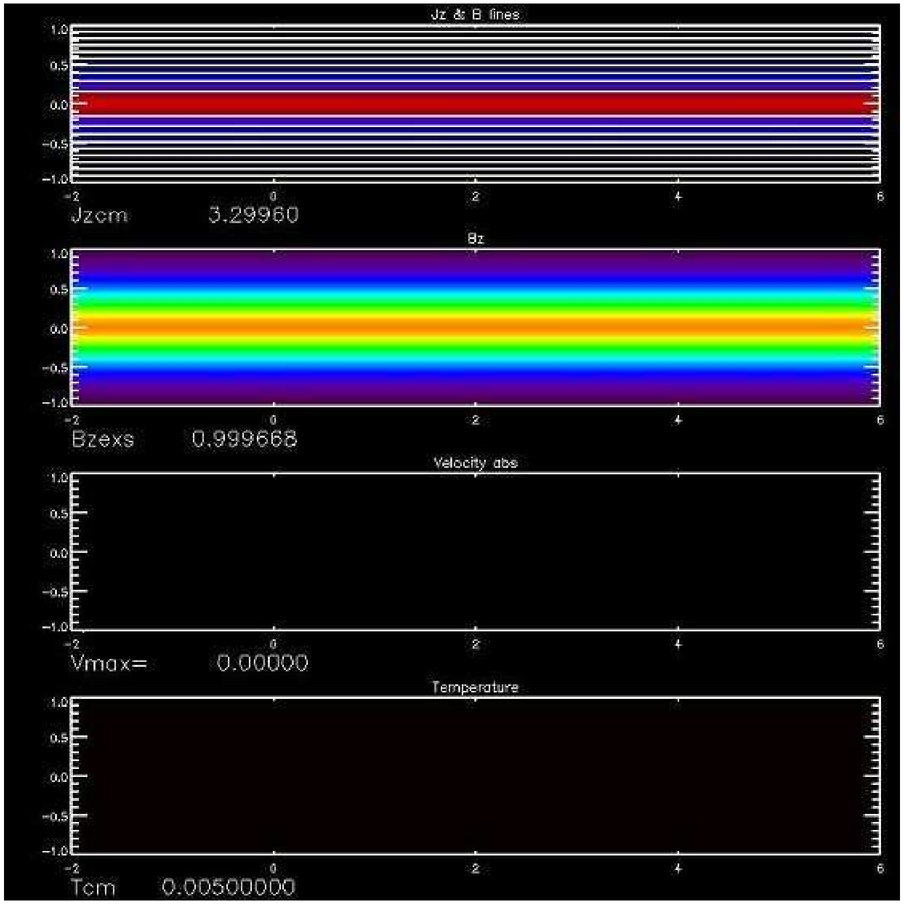
Population B: protons and electrons trapped in closed field of magnetic islands moving predominantly in z direction

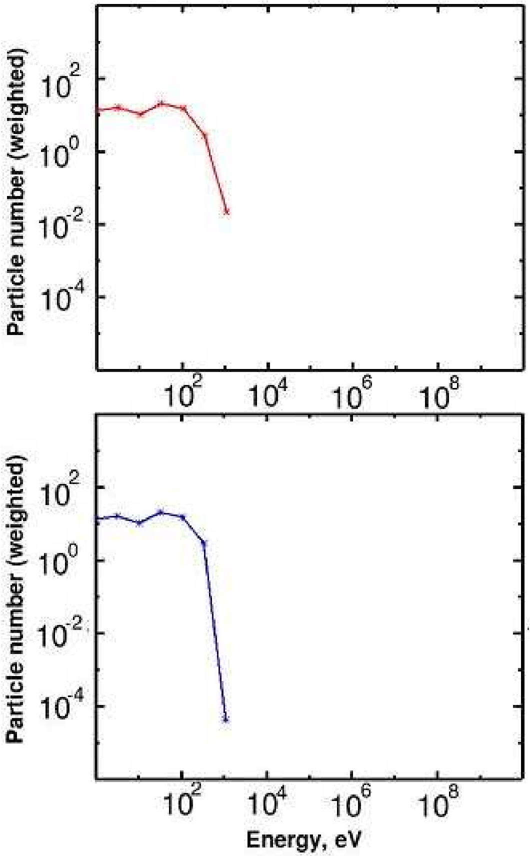


- **Case:** $4L_0$(X) by $2L_0$(Y), $y_0 = 0.30L_0$, $j_{cr}=3.4j_0$, $S_1^{-1} = 3.2\ 10^{-4}$, $\Delta=0.1L_0$, $\tau=20t_A$

Energy spectra: evolution

t=0





p^+

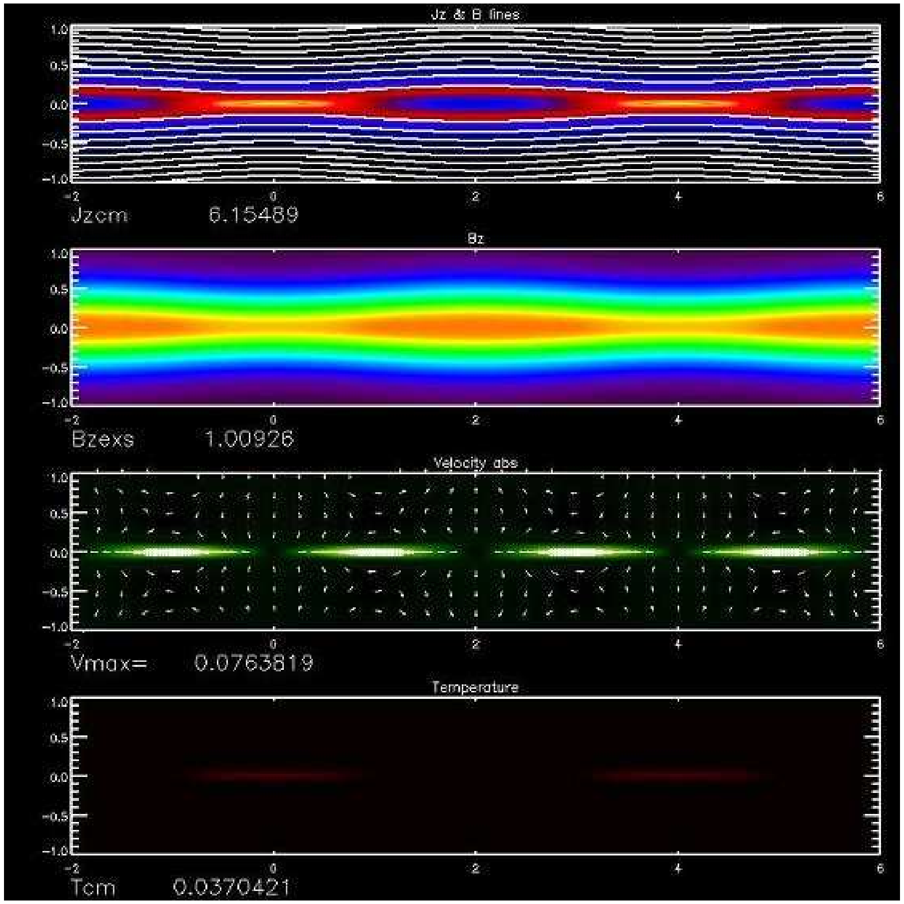
e^-

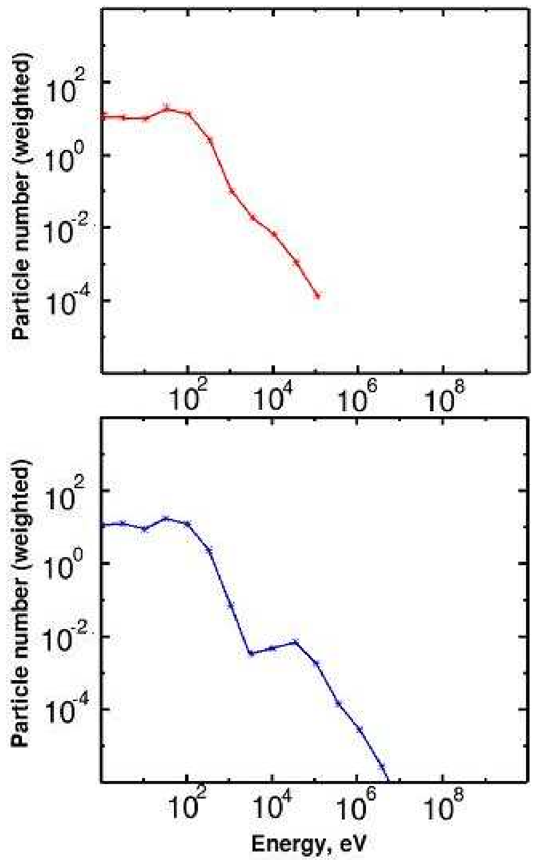
• **Case:** $4L_0$(X) by $2L_0$(Y), $y_0 = 0.30L_0$, $j_{cr}=3.4j_0$, $S_1^{-1} = 3.2\ 10^{-4}$, $\Delta=0.1L_0$, $\tau=20t_A$

Energy spectra: evolution

$t=16t_0$

(≈0.13s)





p^+

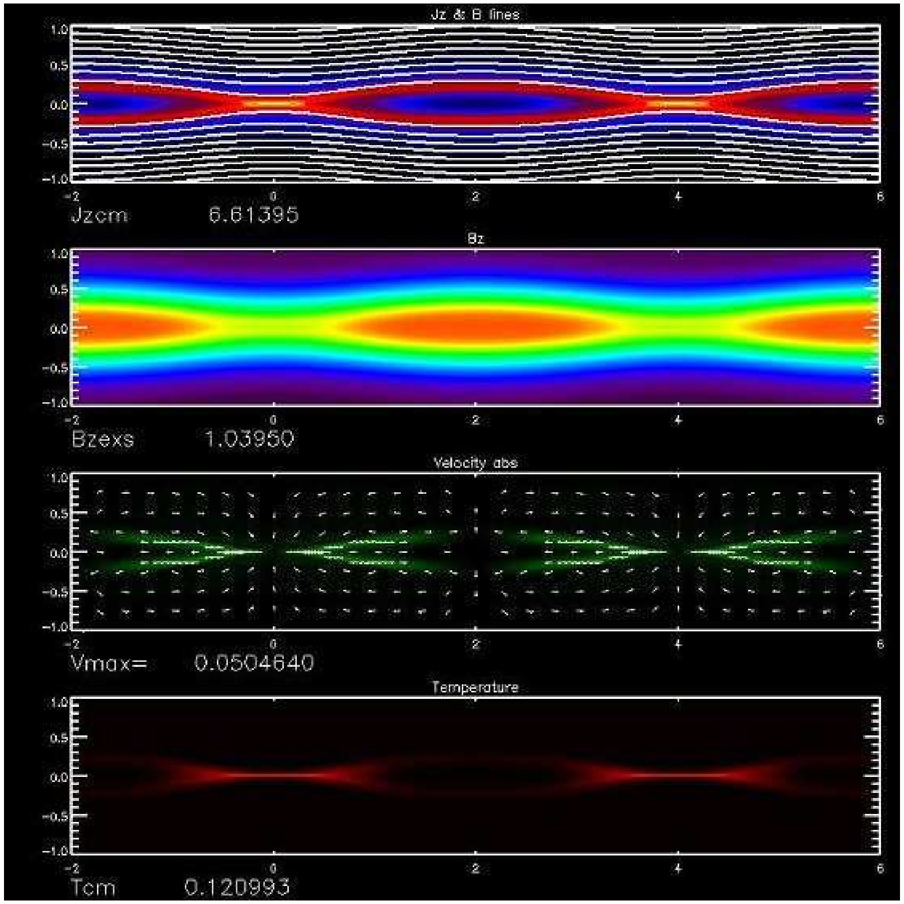
e^-

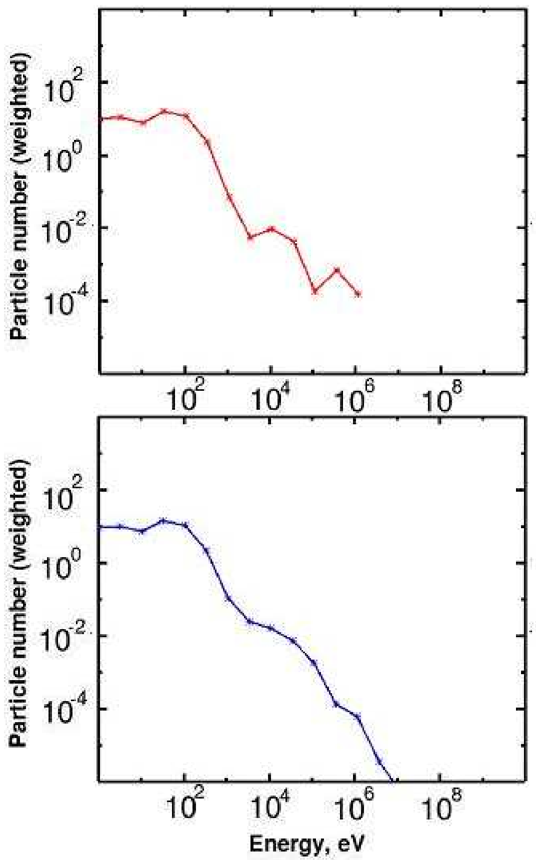
• **Case:** $4L_0$(X) by $2L_0$(Y), $y_0 = 0.30L_0$, j_{cr}=3.4j_0, S_1^{-1} = 3.2 10^{-4}, Δ=0.1L_0, τ=20t_A

Energy spectra: evolution

t=32t_0

(≈0.26s)





p^+

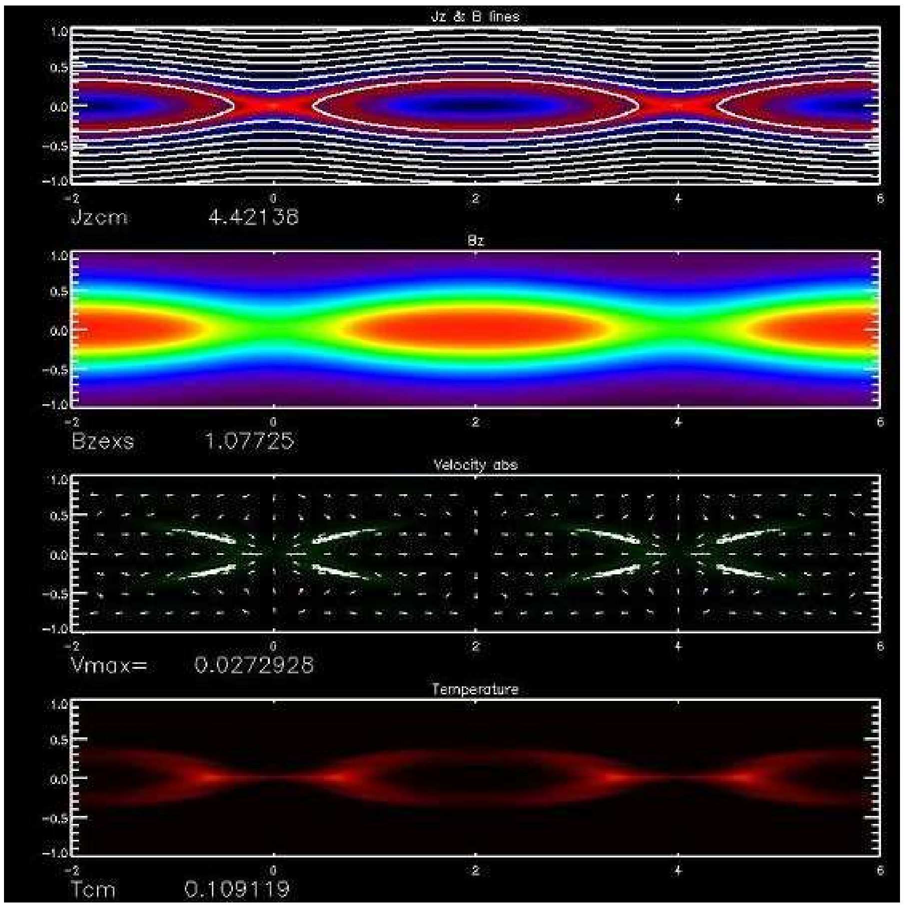
e^-

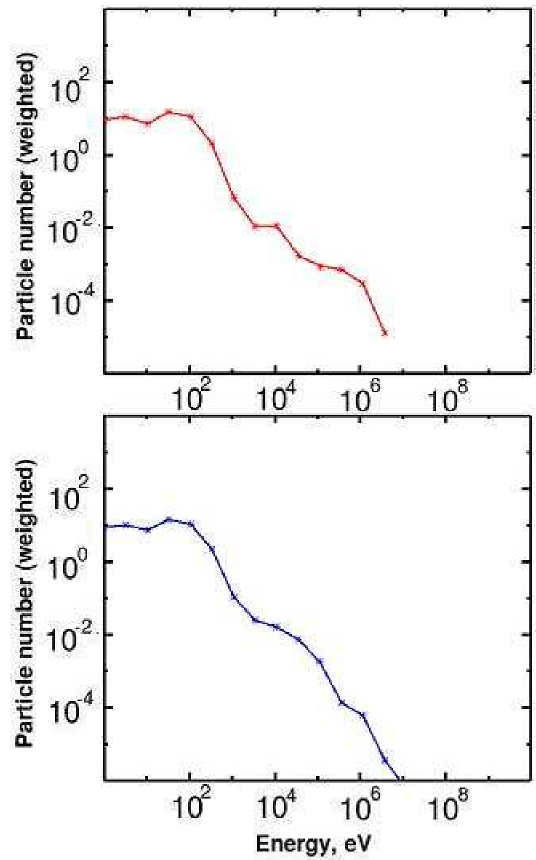
- **Case:** $4L_0$(X) by $2L_0$(Y), $y_0 = 0.30L_0$, $j_{cr}=3.4j_0$, $S_1^{-1} = 3.2\ 10^{-4}$, $\Delta=0.1L_0$, $\tau=20t_A$

Energy spectra: evolution

$t=64t_0$

($\approx$0.52s)





p^+

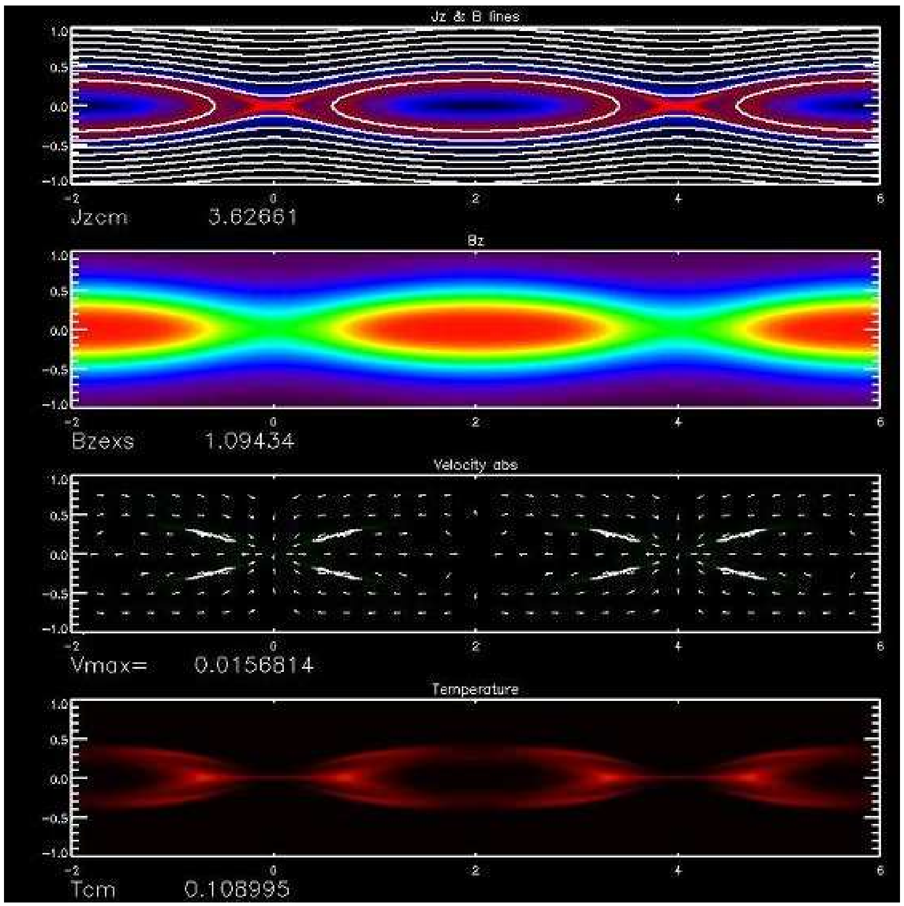
e^-

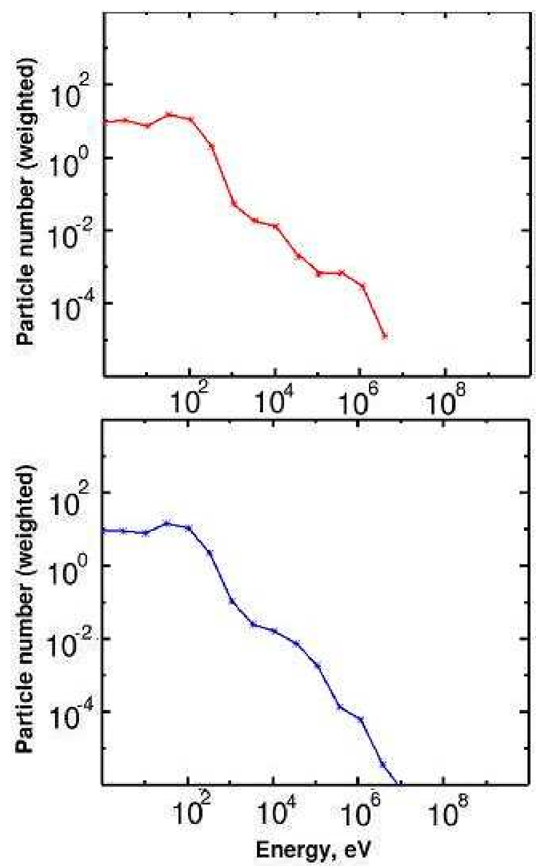
- **Case:** $4L_0$(X) by $2L_0$(Y), $y_0 = 0.30L_0$, $j_{cr}=3.4j_0$, $S_1^{-1} = 3.2\ 10^{-4}$, $\Delta=0.1L_0$, $\tau=20t_A$

Energy spectra: evolution

$t=128t_0$

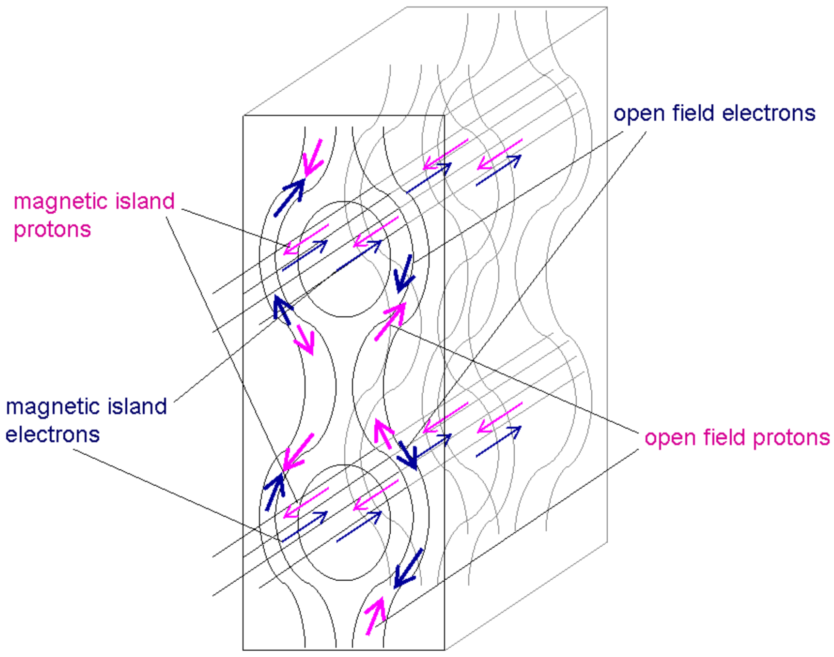
(≈1.04s)

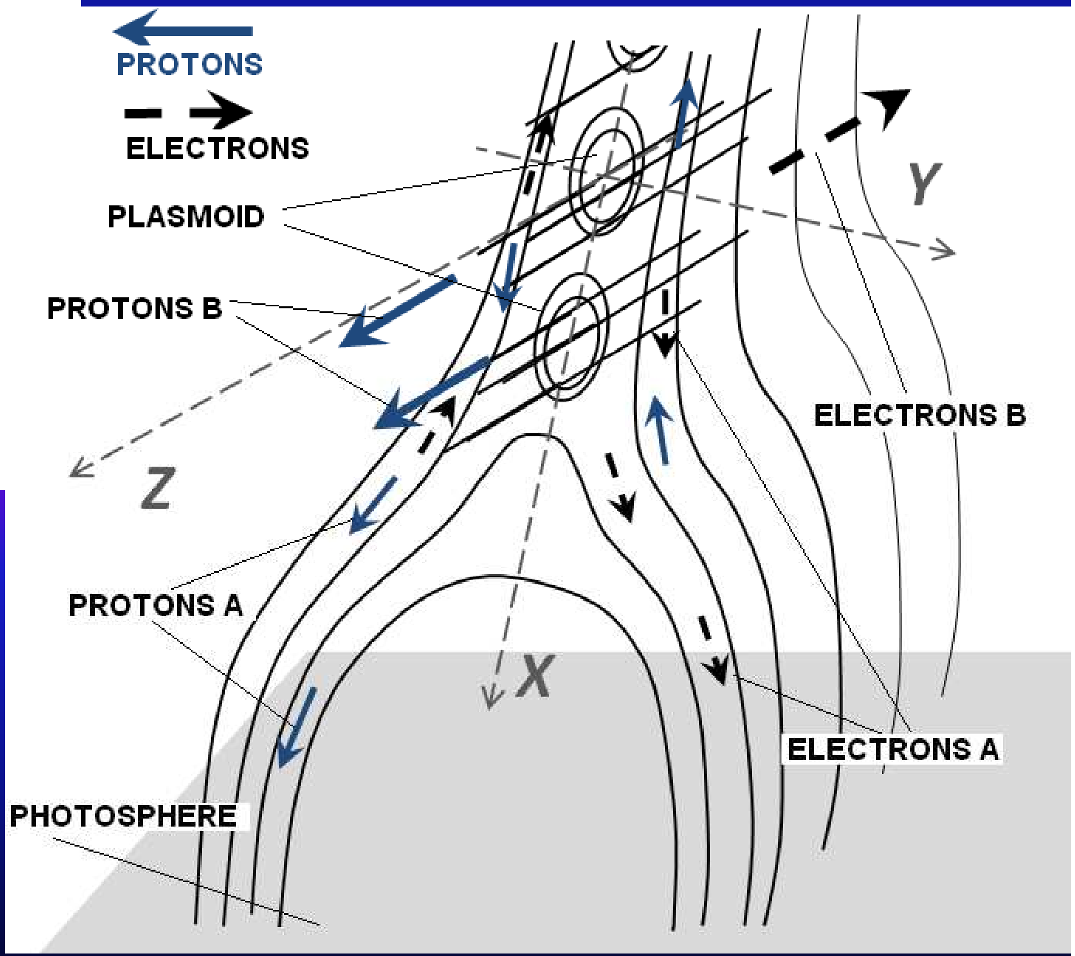




p⁺

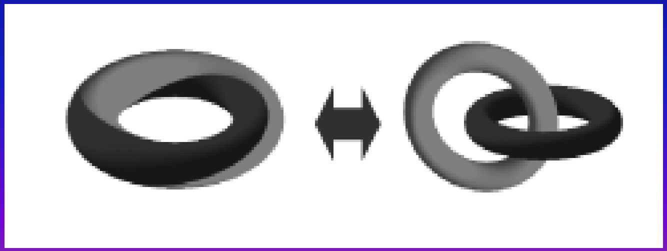
e⁻





➢ *Gordovskyy, Browning & Vekstein 2010 A&A; 2010 ApJ*

Coronal heating by relaxation



•A disrupted field with many reconnections relaxes to a state with minimum magnetic energy - subject to the constraint that total magnetic helicity is conserved *(Taylor, 1974)*

•Coronal field is stressed by slow photospheric footpoint motions into nonlinear force-free field

$$\mathbf{j}\times\mathbf{B}=\mathbf{0}\Rightarrow\nabla\times\mathbf{B}=\alpha(\mathbf{r})\mathbf{B}$$

$$\alpha=\mu_0 j_{//}/B$$

- Energy is released as heat when the stressed field relaxes, conserving helicity to constant-α force-free field *(Heyvaerts and Priest, 1984)*
- Requires energy storage prior to relaxation – heating by a transient series of energy-release events

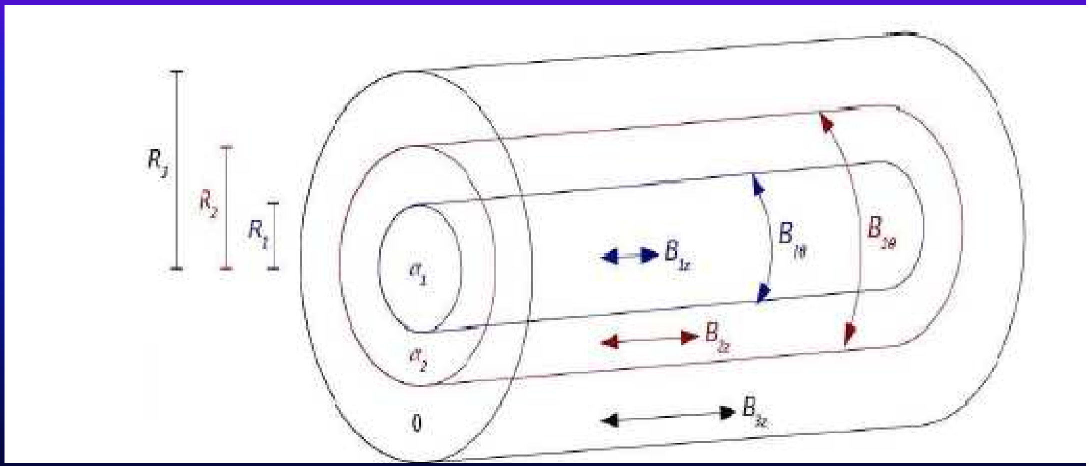
A simple model in a cylindrical twisted loop

- **Field evolves quasi-statically through equilibria (variable *α)* due to photospheric driving**
- **Heating event triggered when ideal kink instability occurs**
- **Energy dissipated by reconnection in nonlinear phase of instability - relaxation to minimum energy constant-α state (*Browning and Van der Linden 2003*)**

Cylindrical loop, length L, radius R with initial nonlinear force-free field modelled by a step α profile:

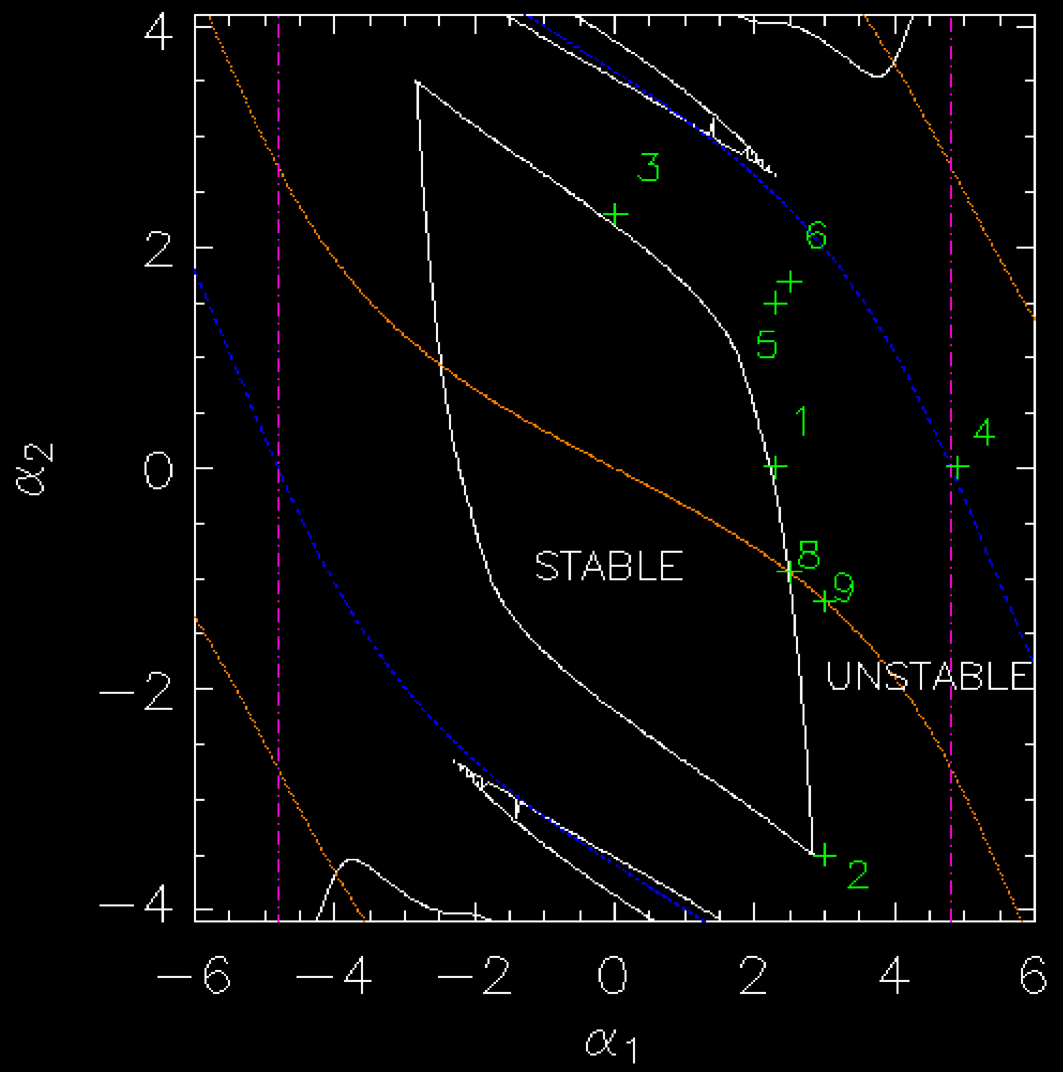
$\alpha = \alpha_1 , \quad r < R_1;$
$\alpha = \alpha_2 , \quad r > R_1$
Optional potential layer (α = 0) outside R_2

Fields expressed in terms of Bessel functions



Marginal ideal stability map

Conducting wall at R_W = 3, potential field layer between ***R*** =1 and R_W



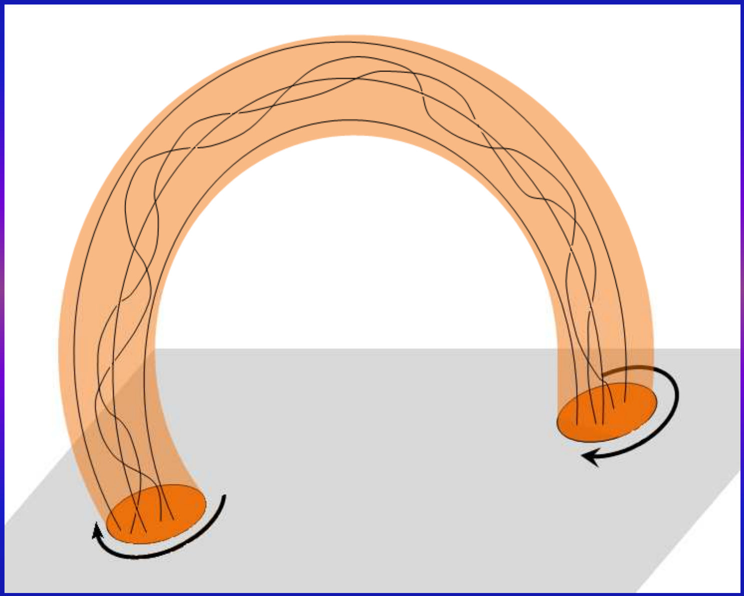
Browning et al, 2008)

- Two parameter family of force-free equilibria (α_1, α_2)
- Ideal linear stability threshold using CILTS code
- Line-tying at *z* = 0, *L*

How does the relaxation work?

Browning et al, 2008; Hood et al, 2009

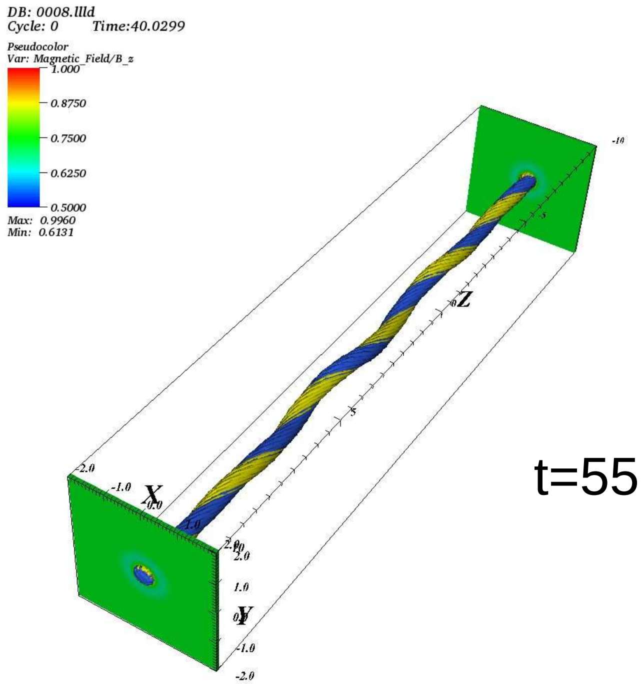
- Solve 3D MHD equations with Lagrangian-Remap code LARE3D
- Loop embedded within potential field in square box, line-tying at "photosphere" z =0, *L*
- Recent focus on **zero net current – twisting is radially localised**



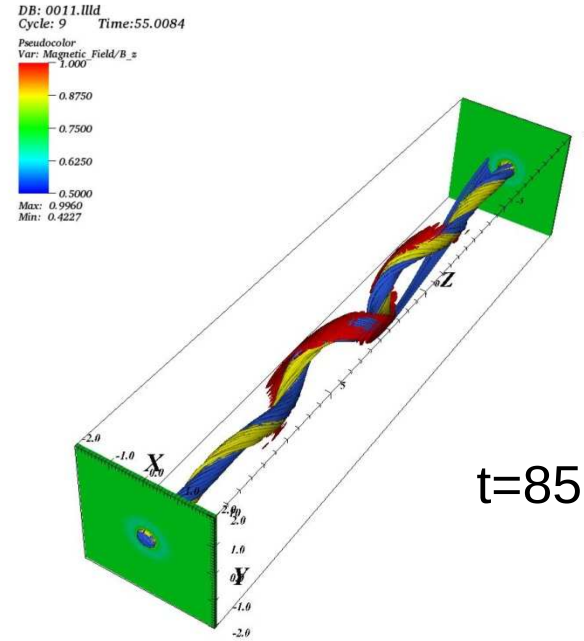
- Initial state – unstable two-α equilibrium

α profile → $B_\theta = 0$ at loop edge

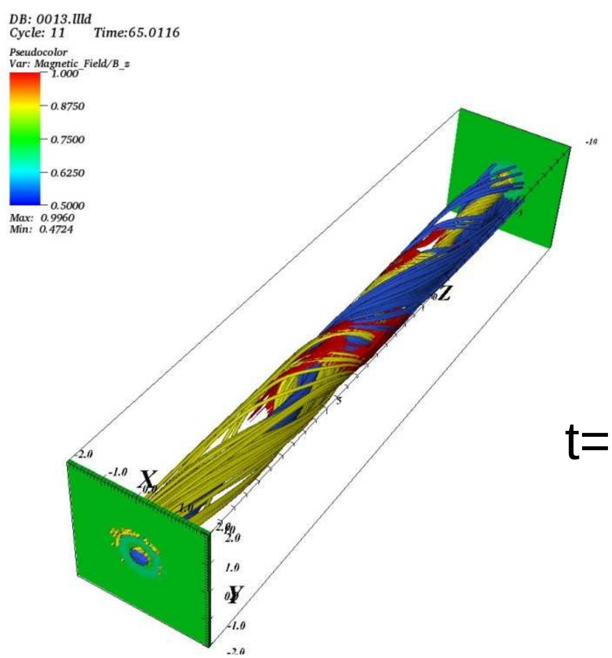
- Initially loop develops helical kink due to ideal instability → formation of helical current sheet and fast reconnection



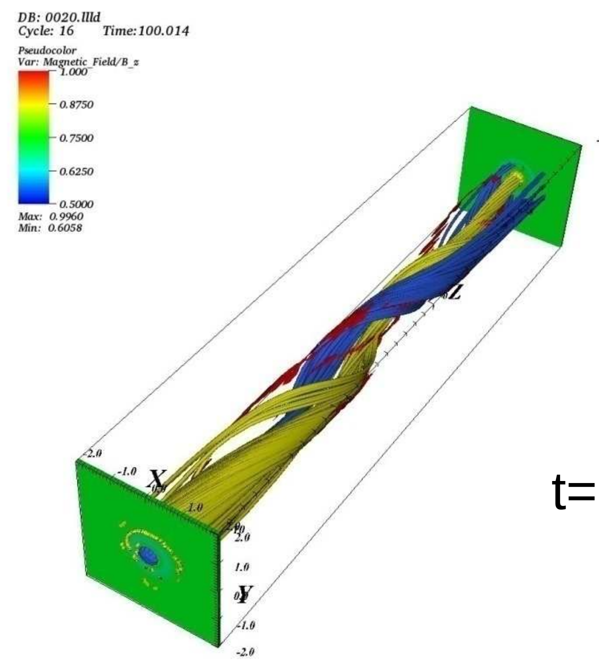
t=55



t=85

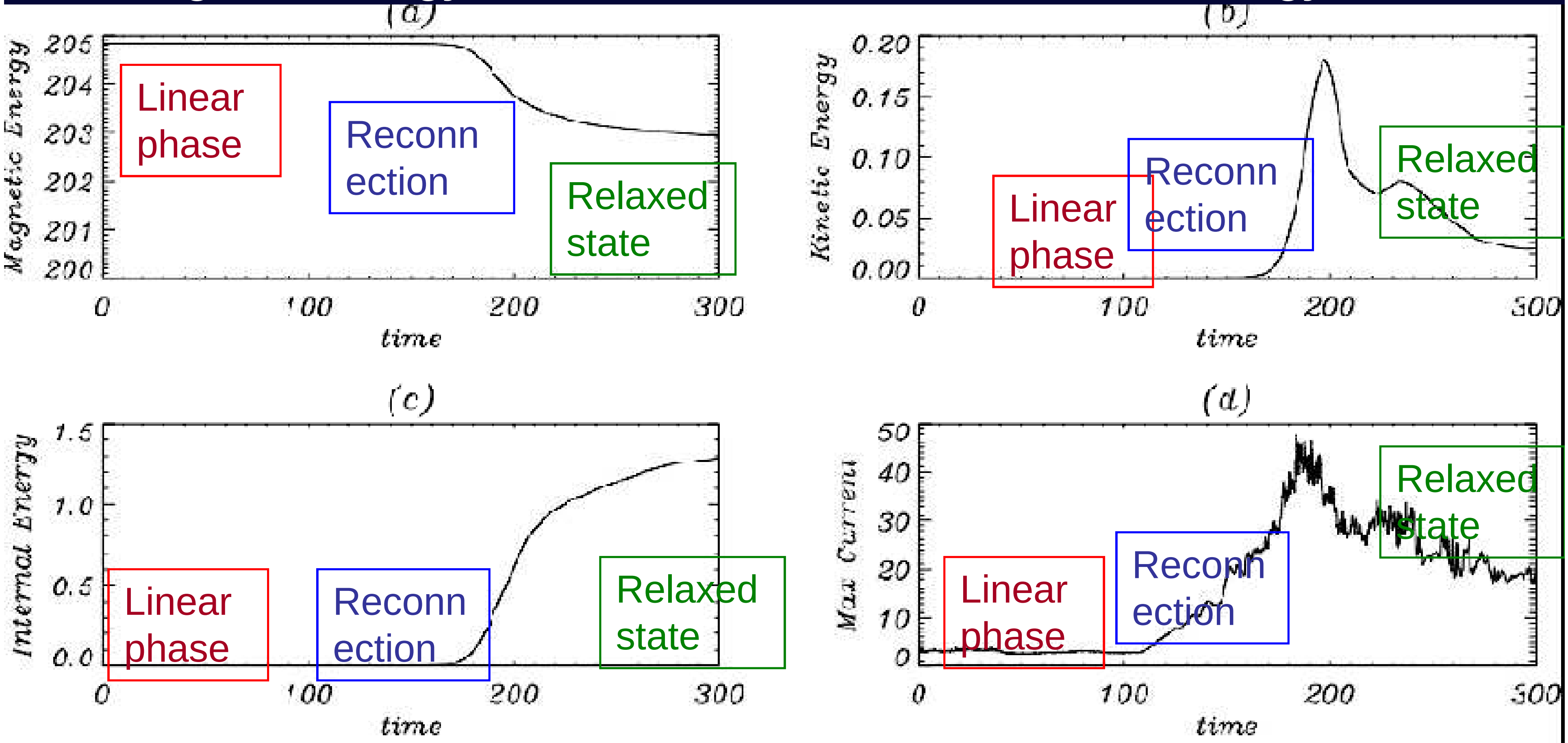


t=150



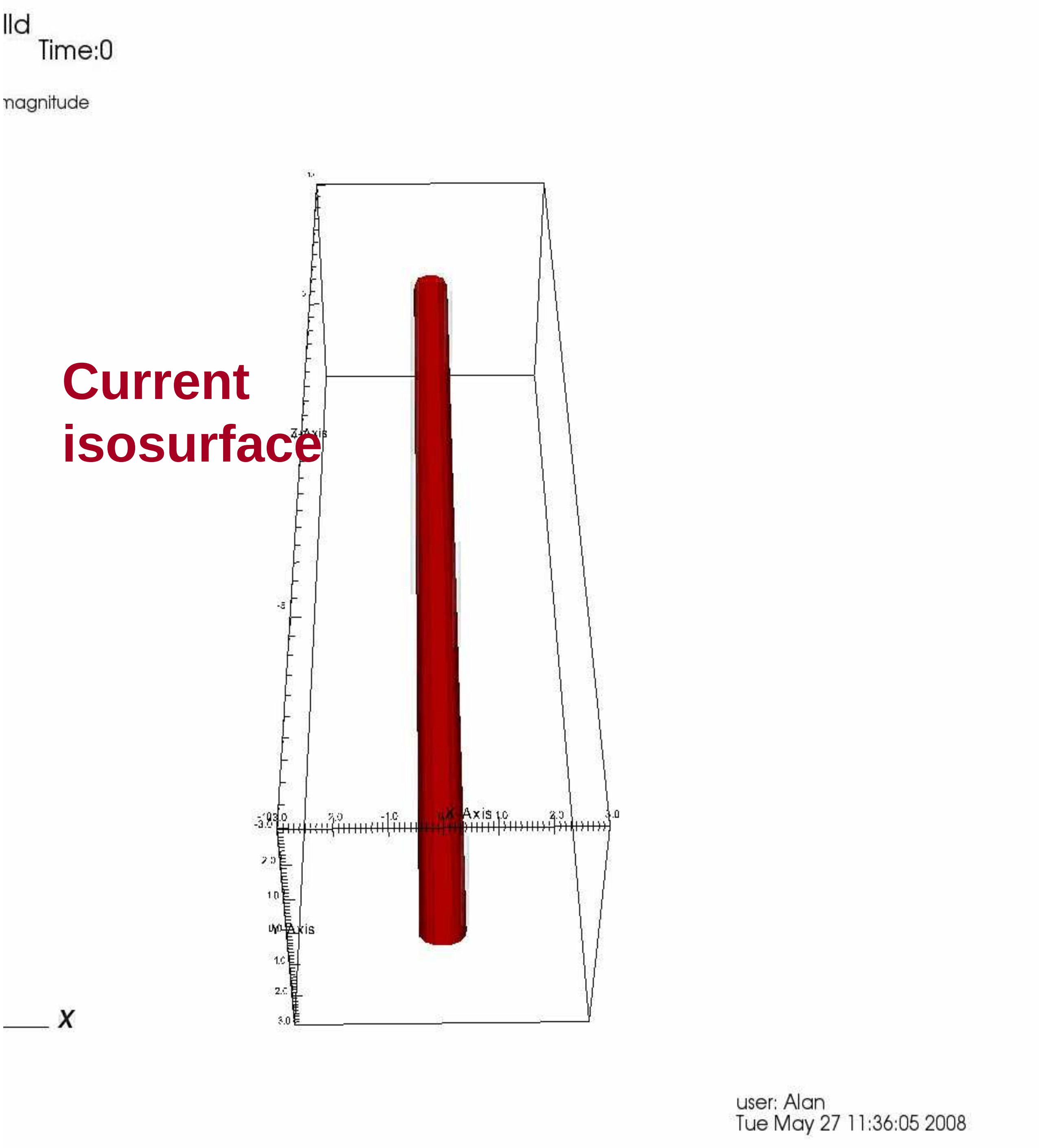
t=295

Magnetic energy | **Kinetic energy**

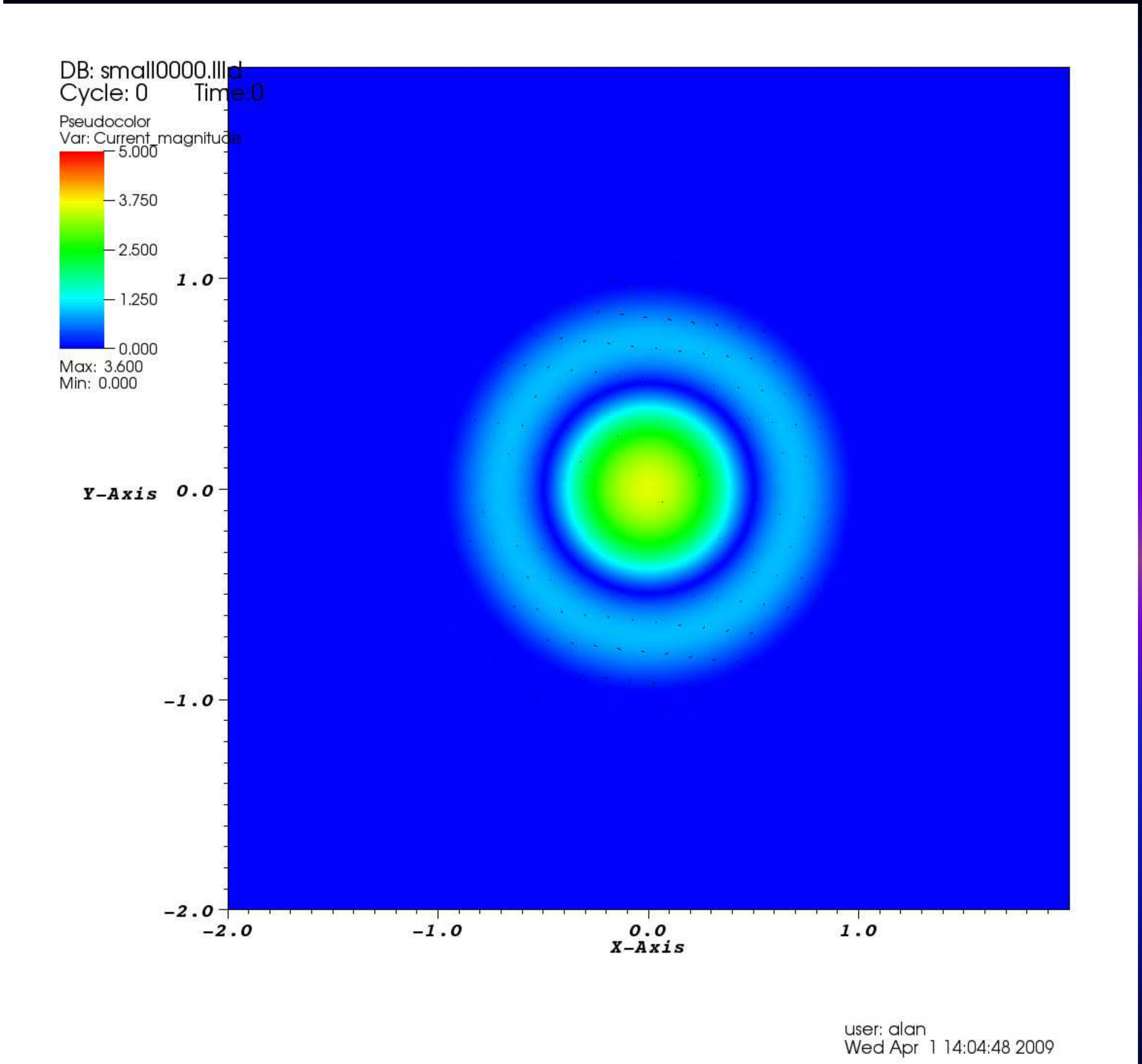


Internal energy | **Peak current**

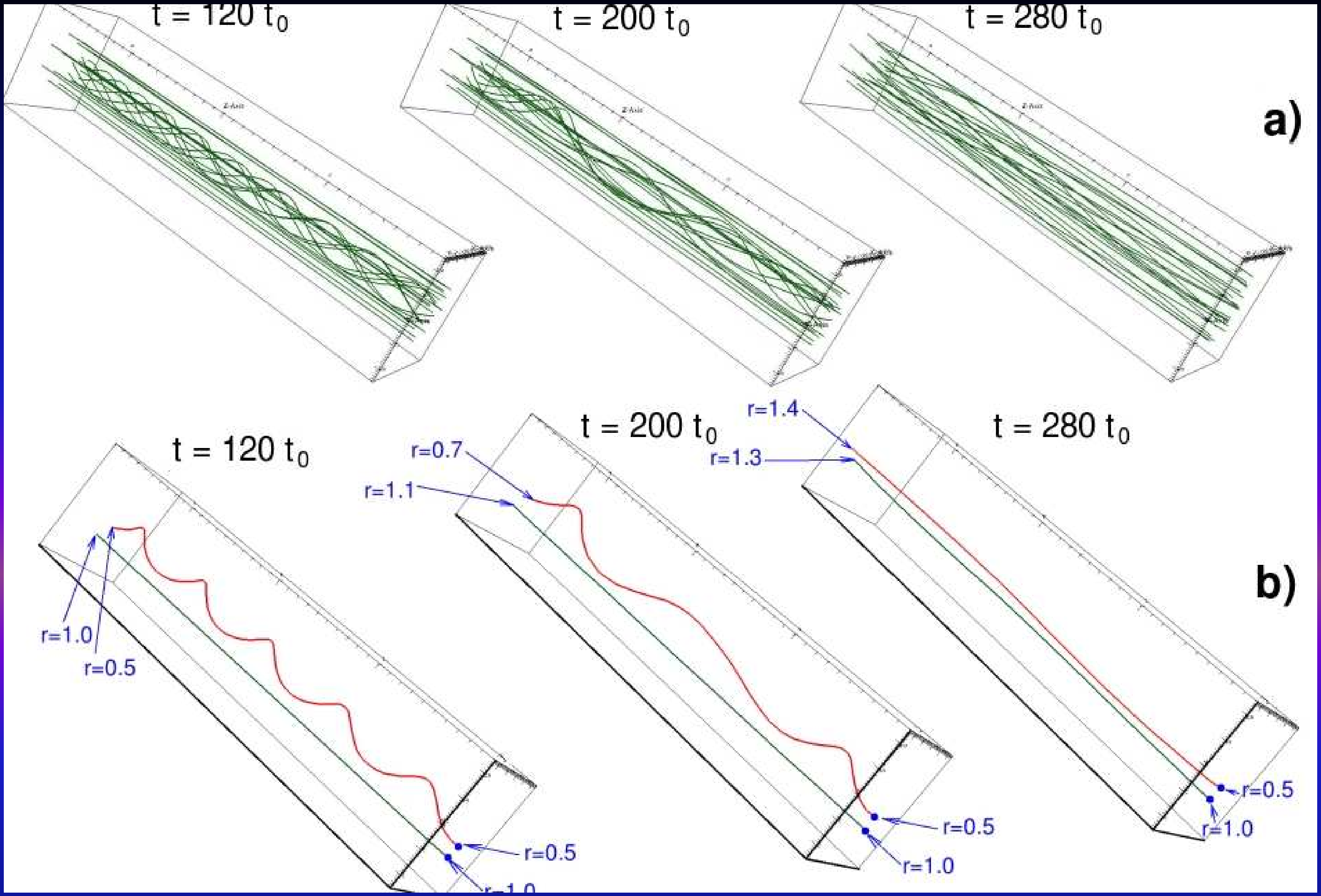
- **Magnetic field in final state is close to constant-α relaxed state**
- **Energy dissipated agrees with relaxation theory**



- In nonlinear phase, helical current sheet develops at quasi-resonant surface
- Fast reconnection in current sheet dissipates magnetic energy – kinetic energy peaks
- Current sheet then fragments →strong dissipation of magnetic energy and flattening of α profile



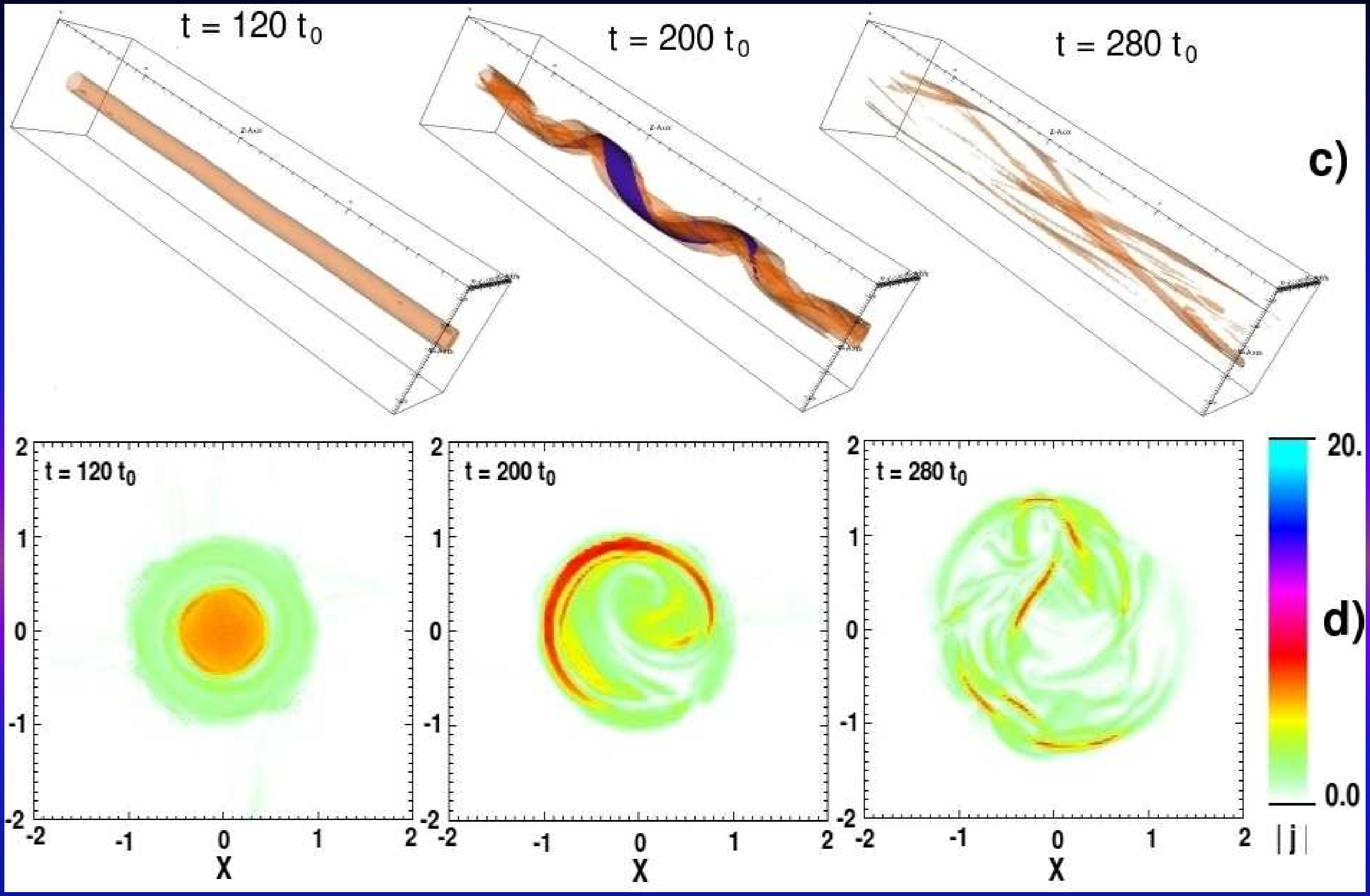
Current density and velocity at midplane



- Reconnection within twisted loop and with outer (untwisted) field lines

Gordovskyy and Browning 2010c

- Relaxes to very weakly twisted field



- Twisted loop expands due to reconnection with outer field
- Modelled by localised relaxation

Bareford and Browning 2010

Energy release – back to relaxation theory

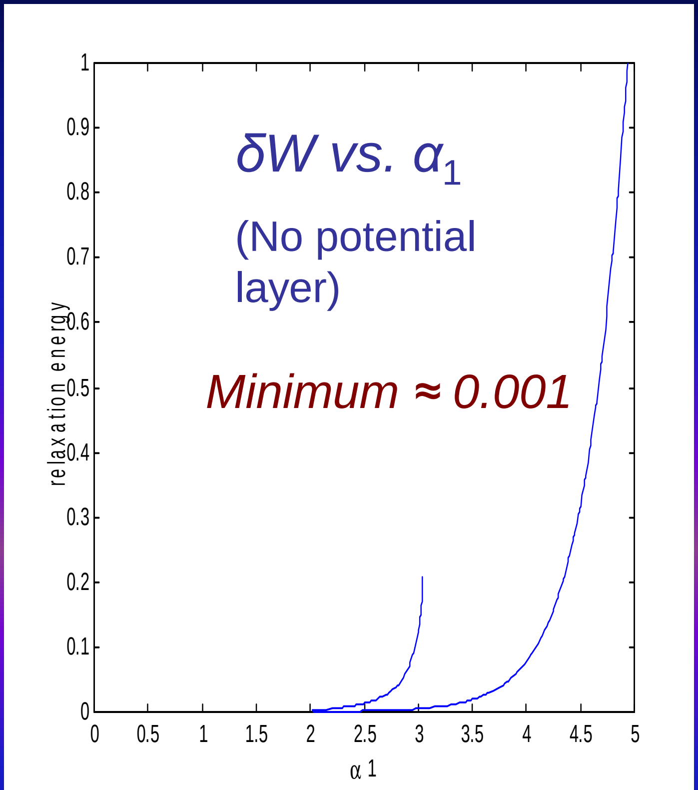
- Relaxed state (constant *α*) given by

  $K_{relax}(\alpha) - K(\alpha_1,\alpha_2) = 0$

- Energy released as heat:

  $\delta W = W(\alpha_1,\alpha_2) - W_{relax}(\alpha)$

- Energy release δW depends on where stability boundary is crossed



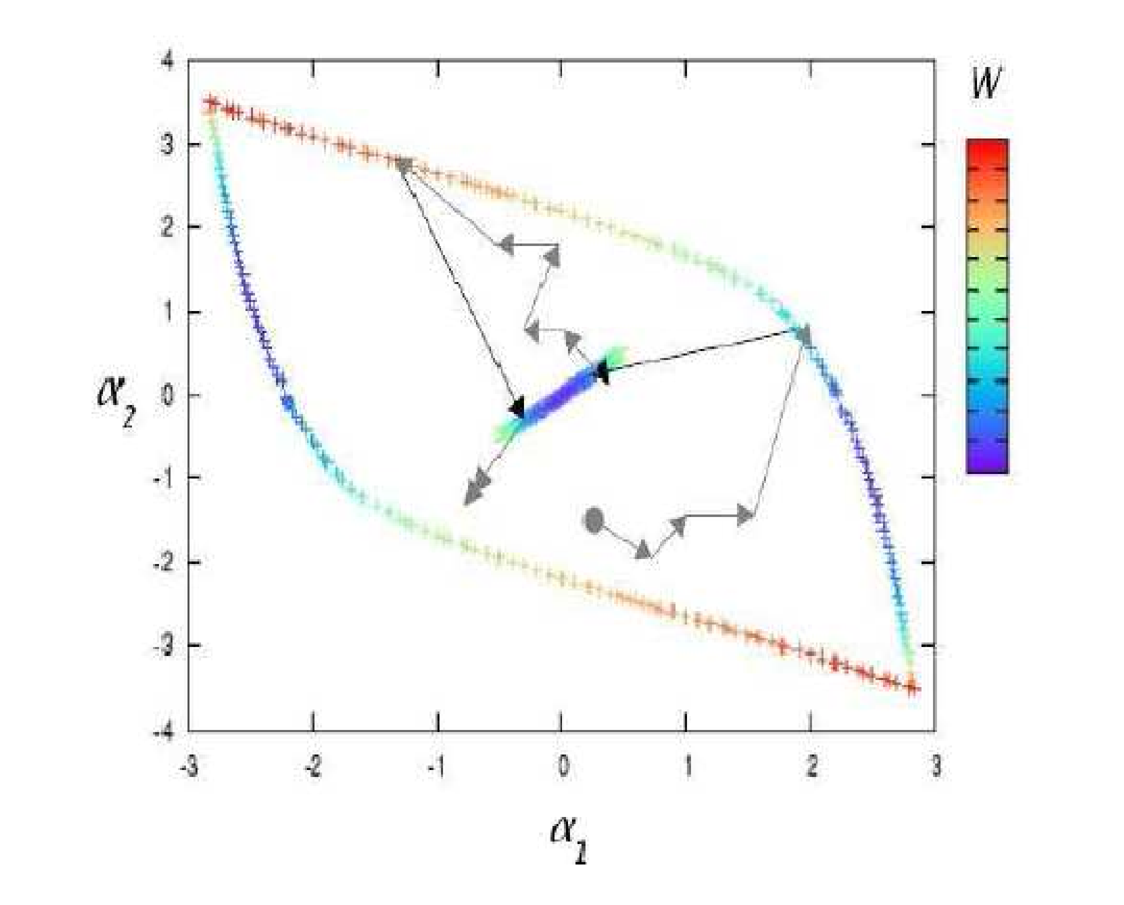
•The process repeats - field evolves due to photospheric driving, goes unstable, relaxes

→ episodic heating by multiple transient events of various sizes

Generation of "nanoflare" distribution

Bareford et al A&A 2010a

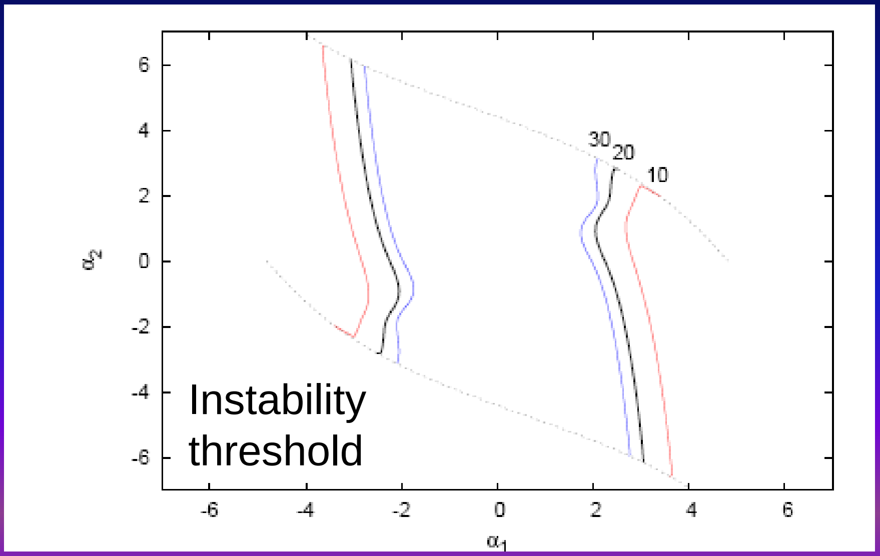
- Photospheric motions generate random walk through equilibria (*α* space)
- Every time random walk crosses stability threshold, calculate energy release due to relaxation to constant- *α*
- Re-start random walk from relaxed state
- Build up distribution of heating events

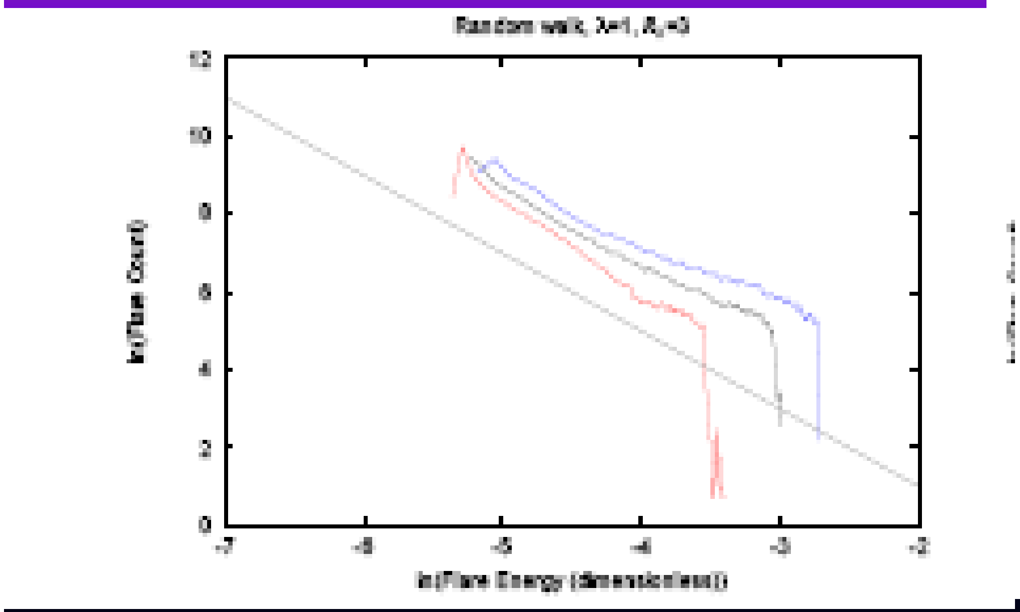


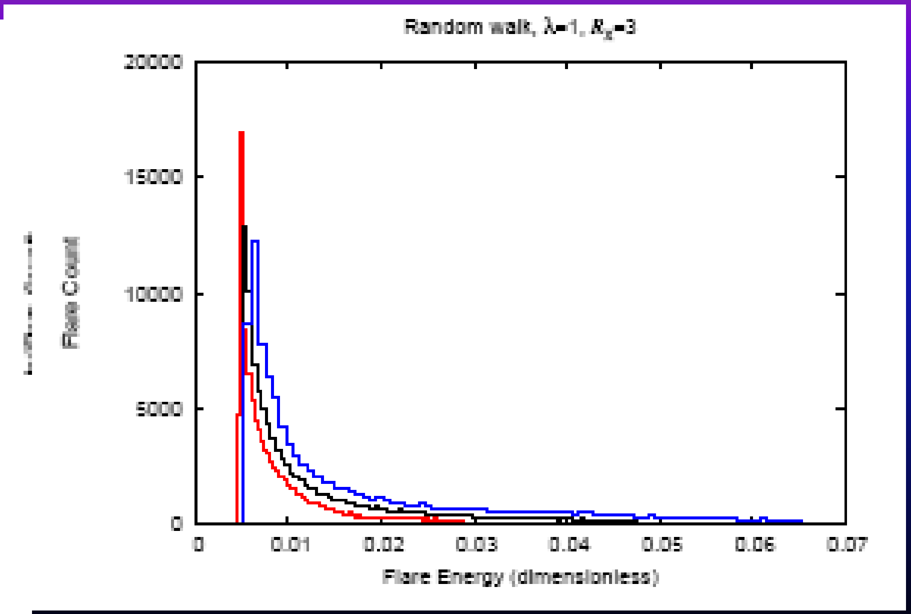
Loop with zero net current

Bareford et al 2010b

- Consider loop with zero net axial current – localised footpoint twisting
- Vary aspect ratio L/R = 10 - 30
- Current neutralisation layer (α_3) at loop edge so that $B_\theta = 0$ at edge
- Gives power-law distribution of heating events – “nanoflares”



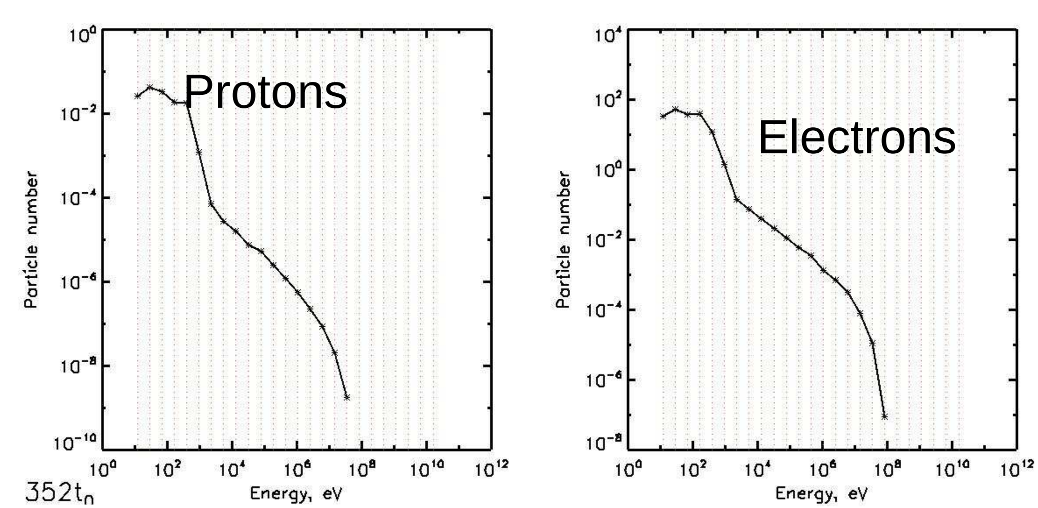


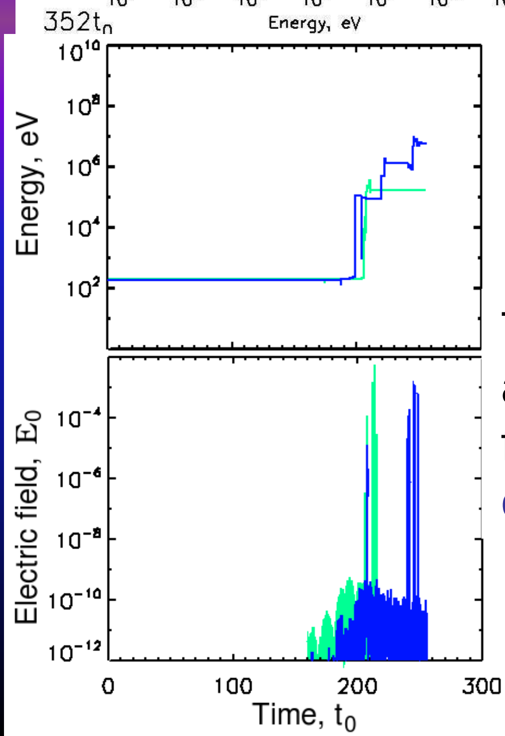


Particle acceleration in twisted loop

- Investigate particle acceleration in unstable twisted loop e.g small solar flare
- We inject test particles into time-dependent MHD fields arising from simulations of nonlinear kink instability
- Both protons and electrons accelerated – repeated jumps in energy as current sheets encountered
- Accelerated particles fill loop volume in later stages

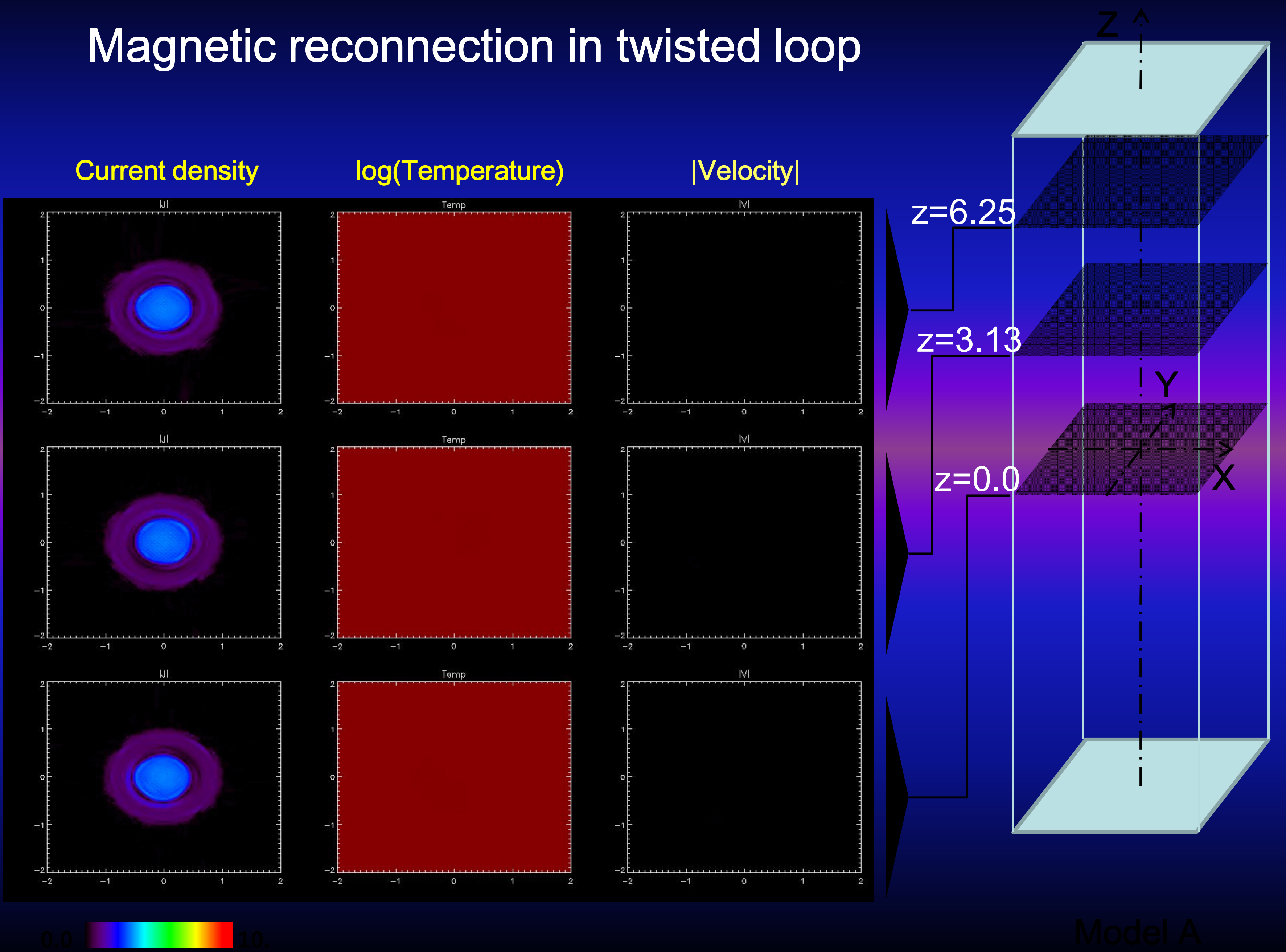
Final energy spectra



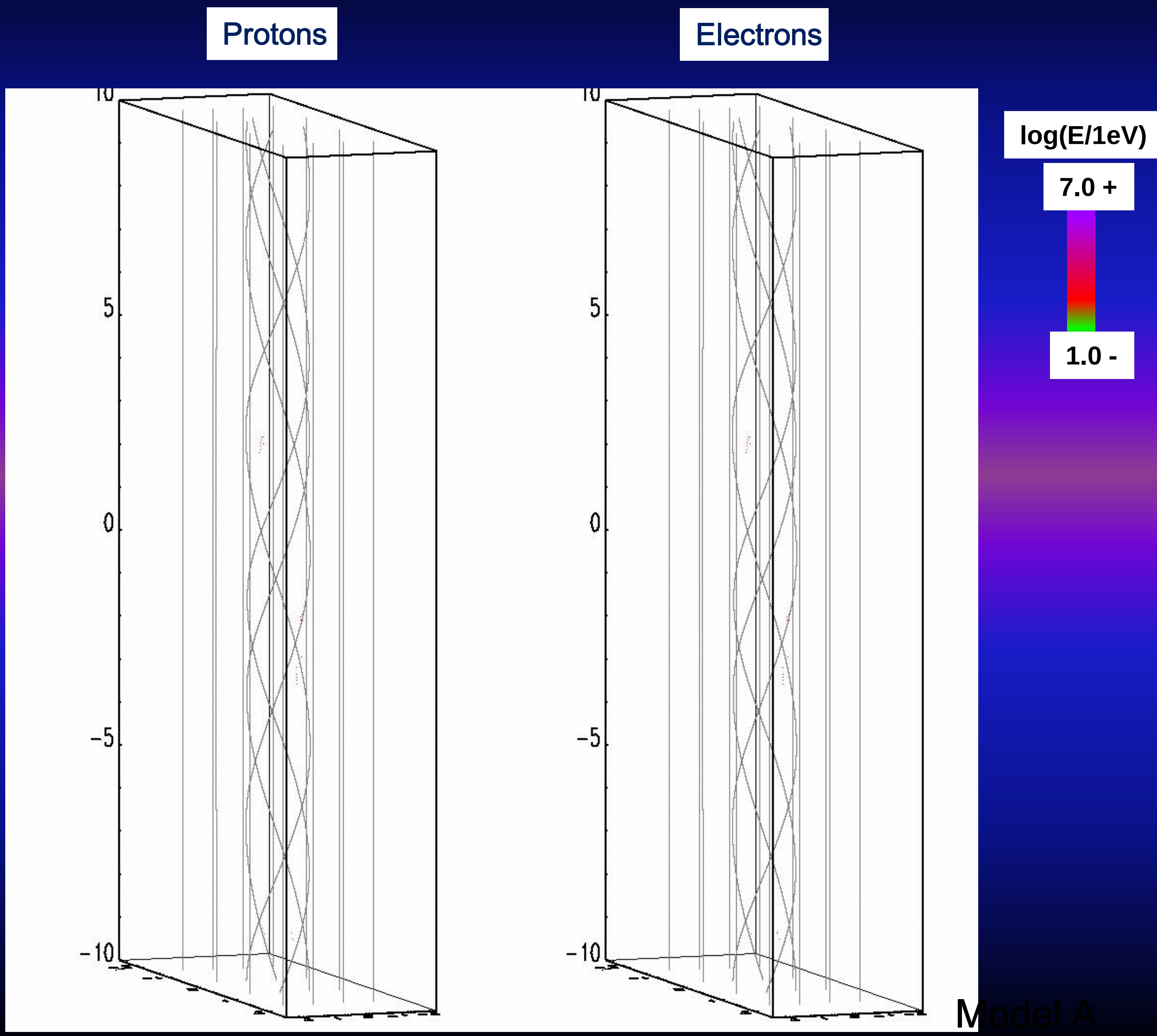


Typical energy gains and parallel electric field for proton and electron

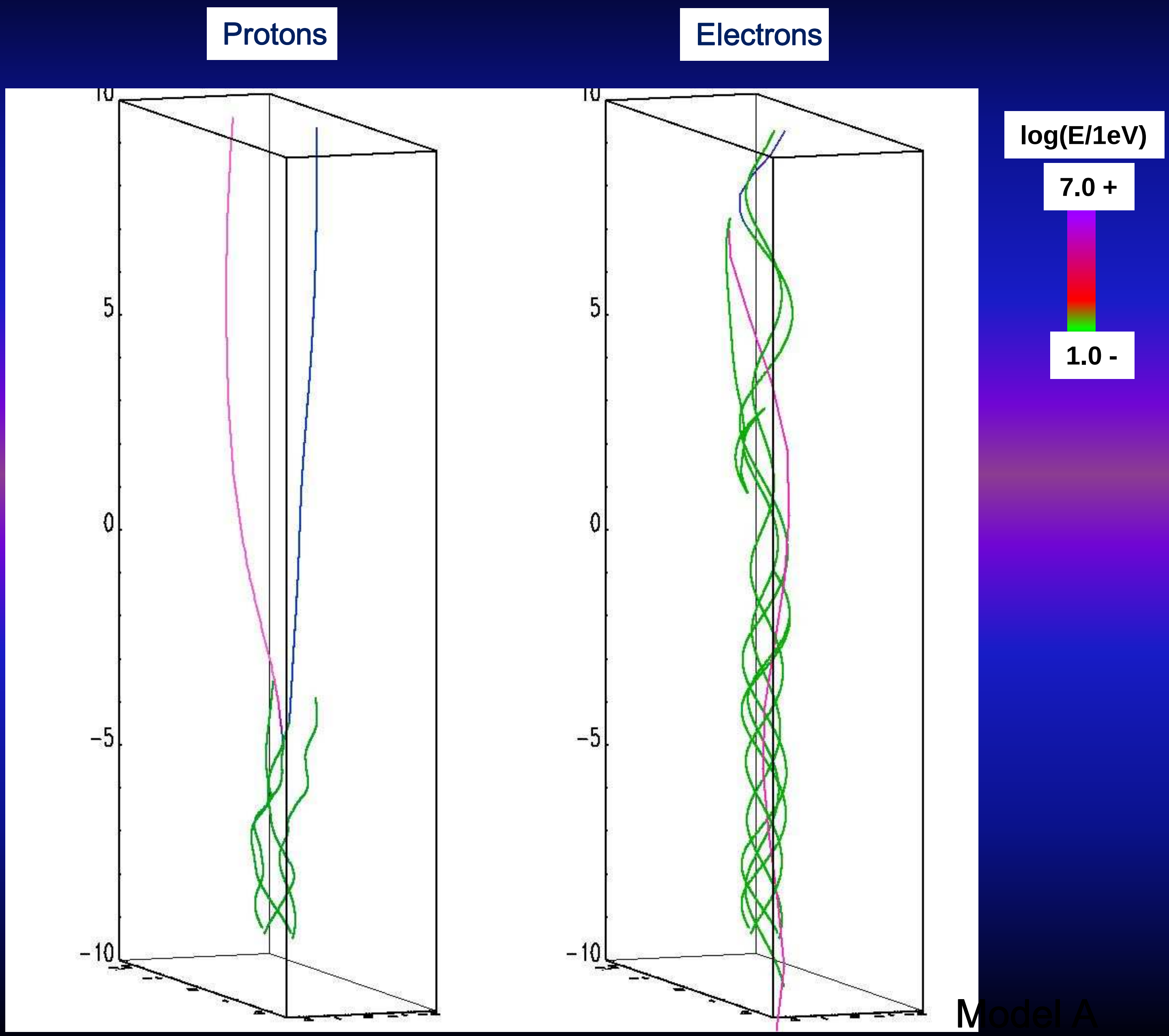
Magnetic reconnection in twisted loop



Particle trajectories

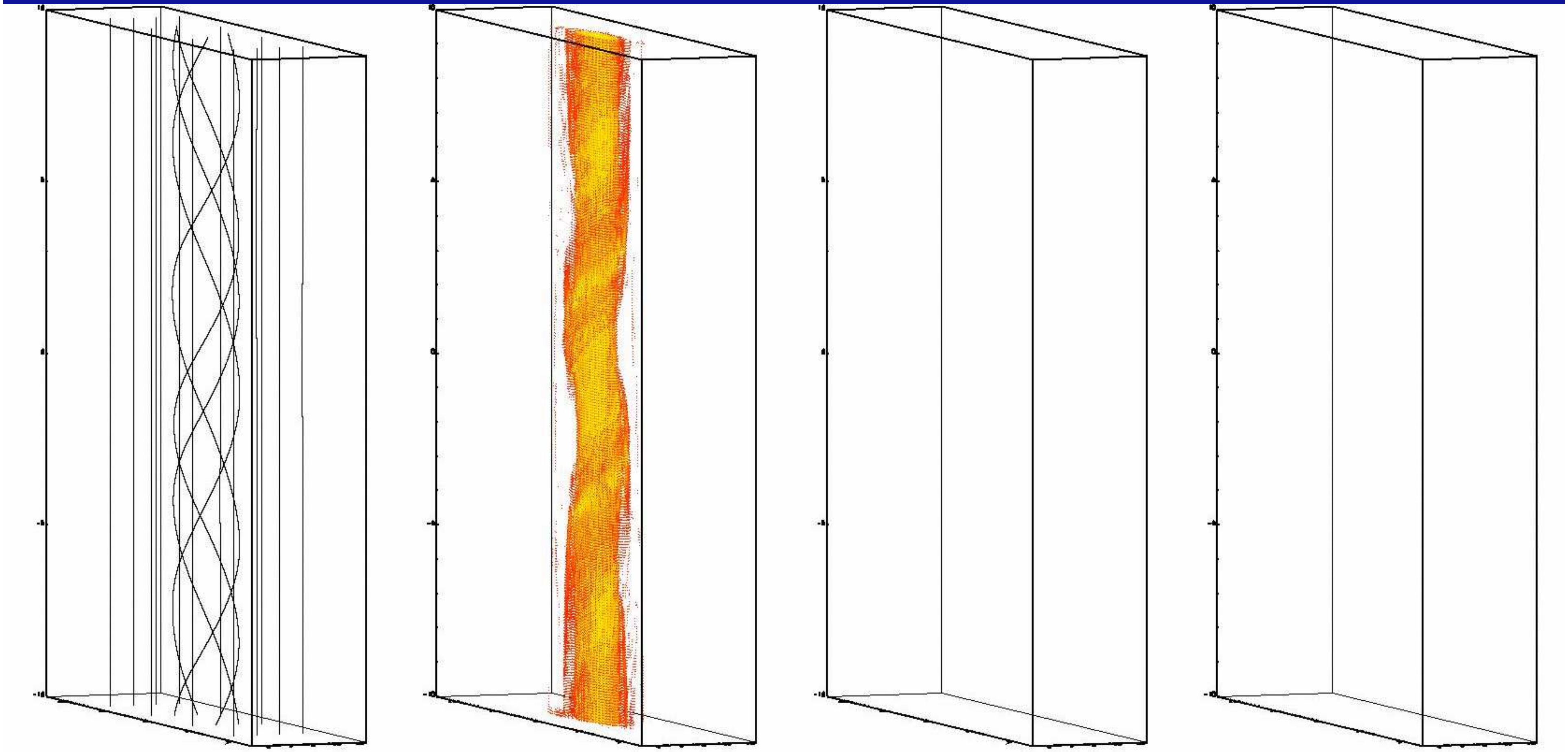


Particle trajectories



Particle distribution in space

Magnetic field | Current density | Protons | Electrons

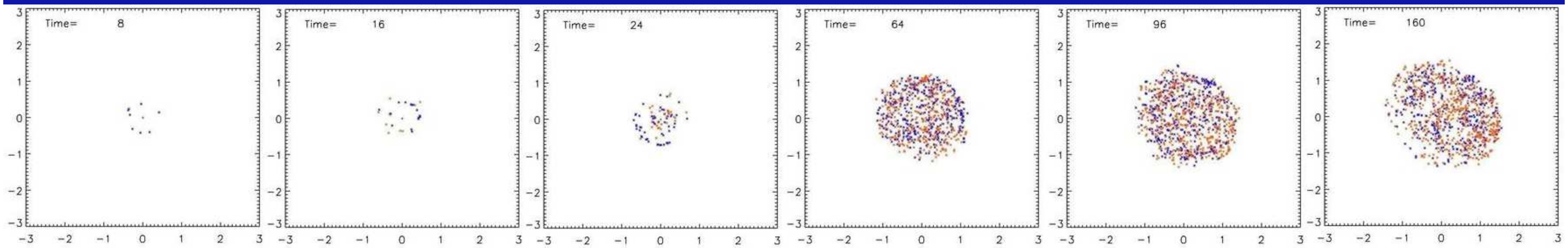


E = 100keV...1MeV
E > 1MeV

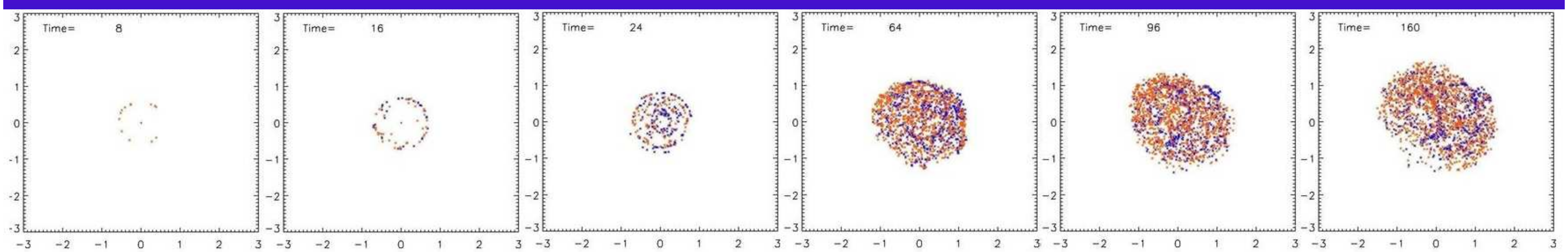
Particle distribution in space

- Proton and electron distribution near "footpoints" ($|z| > 9.6$)
- Agreement with observations? *(e.g. Kontar et al. 2010 ApJ)*

Protons



Electrons



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Model A

Some thoughts about waves/reconnection

Competition?

- **Coronal heating – AC or DC? Fast ($t < t_A$) or slow ($t \gg t_A$) footpoint motions?**

- What about intermediate regime?
- Waves on complex fields?

- **Particle acceleration in flares – by DC electric fields in current sheet or by waves/shocks generated by reconnection?**

- How do waves originate?
- Fragmented reconnection has elements of both
- Test particles models of more global field configurations?

Waves driving reconnection

- Forced reconnection – could be driven by waves?
- Allows reconnection in fields with simple topology
- Observations of forced reconnection in photosphere (Jess et al 2010)
- But requires slow time-scales compared with local Alfven speed

- Waves may trigger reconnection at X-points, loop close to instability threshold etc?

Reconnection driving waves

- Time-dependent reconnection must generate waves

- Analyse waves in reconnection simulations
- Role of waves in energy balance?
- Waves as diagnostic of reconnection?