The University of Manchester

Particle acceleration in solar flares: merging magnetic islands in forced reconnection

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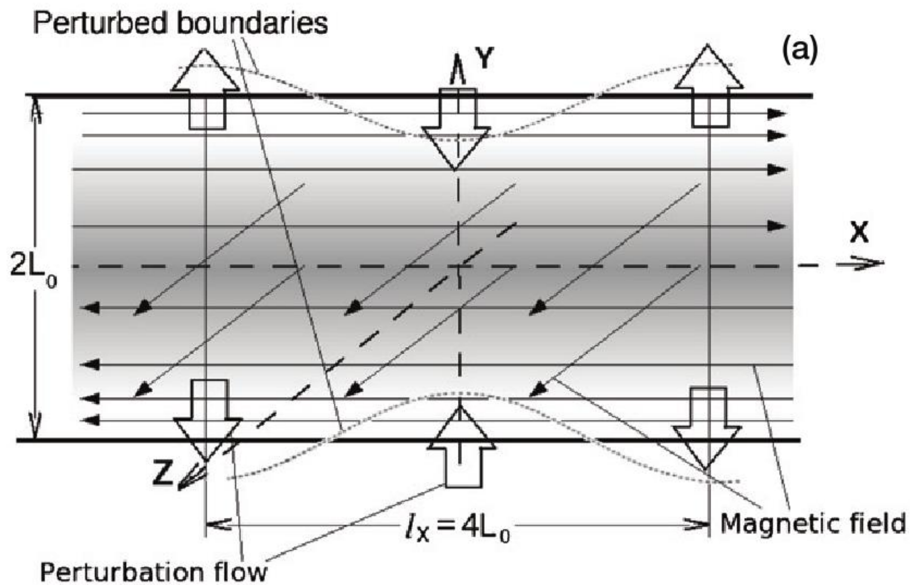
Image: Anthony Holloway

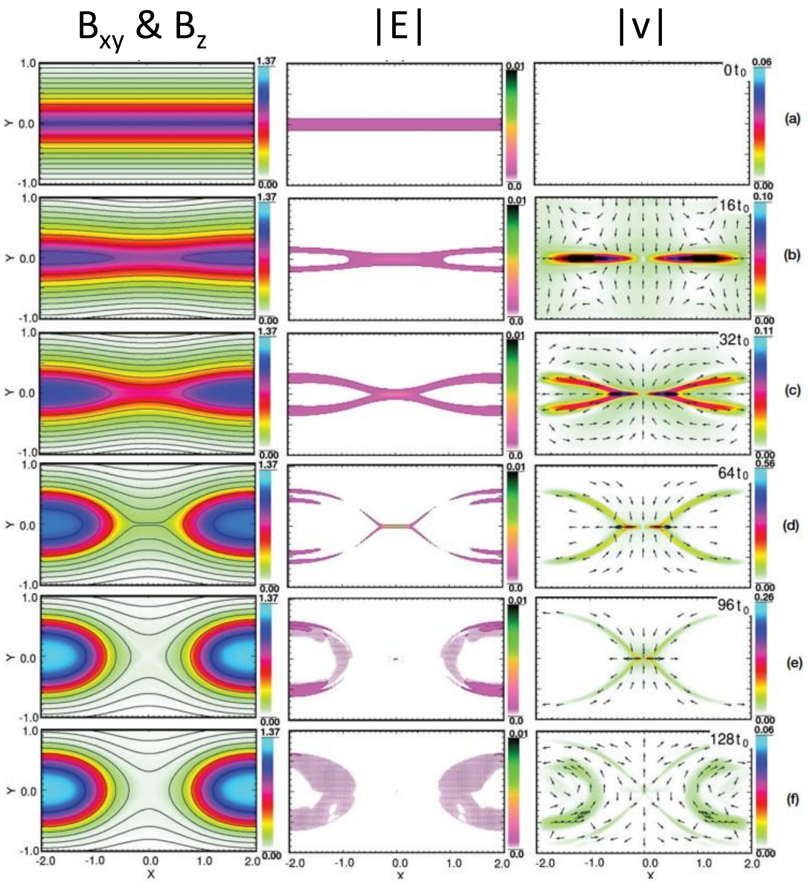
Forced magnetic reconnection

- 2D slab of plasma with sheared force-free field stable to tearing mode
  - *Hahm & Kulsrud 1985, Vekstein & Jain 1998*
- Apply transient perturbation to the boundaries
  - Analytic models: directly perturb the boundary of the plasma
  - Numerical models: normal flows at boundary
- Magnetic reconnection forms a chain of magnetic islands

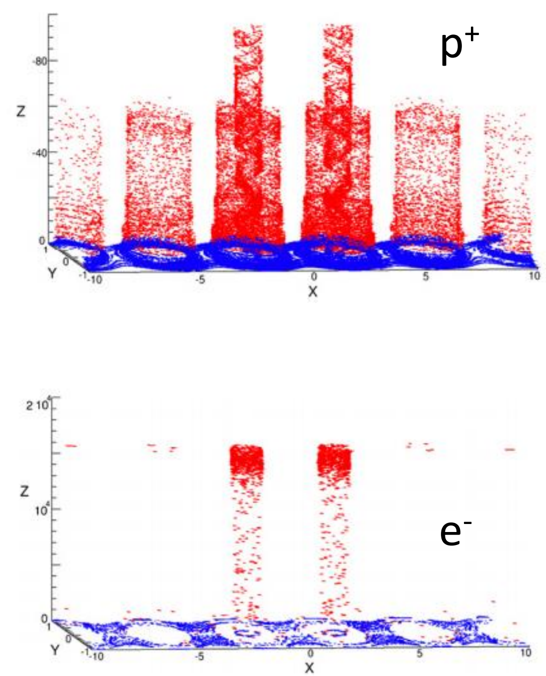


Forced reconnection diagram – *Gordovskyy et al 2010*

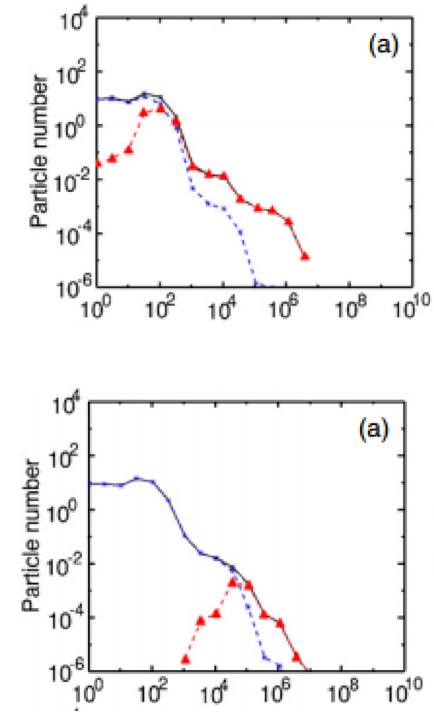
Particle acceleration in forced reconnection: 2D MHD + test particles



MHD simulation for forced reconnection



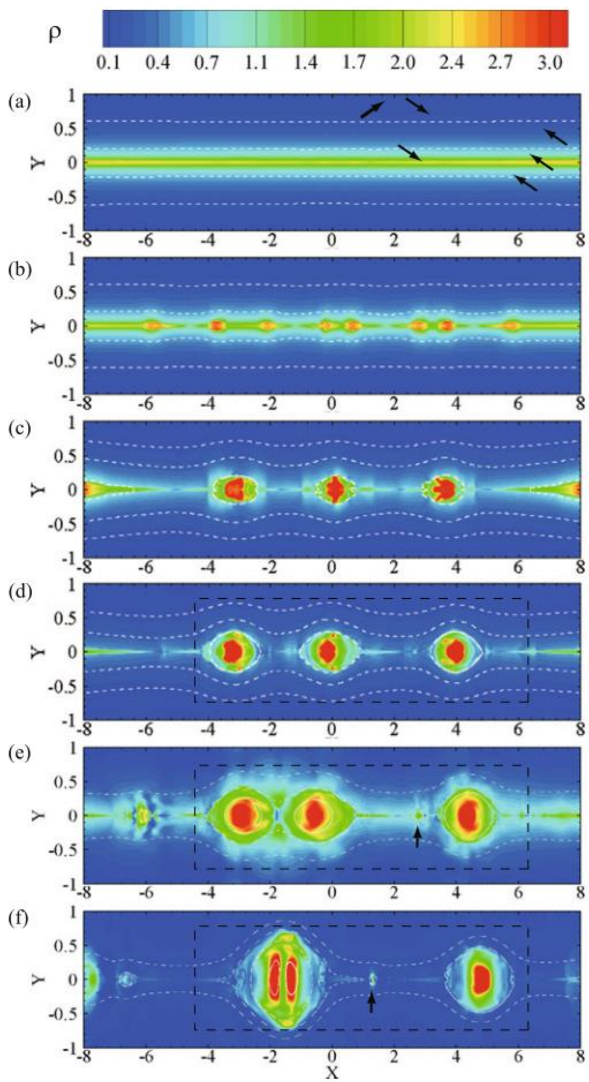
Test particle final positions



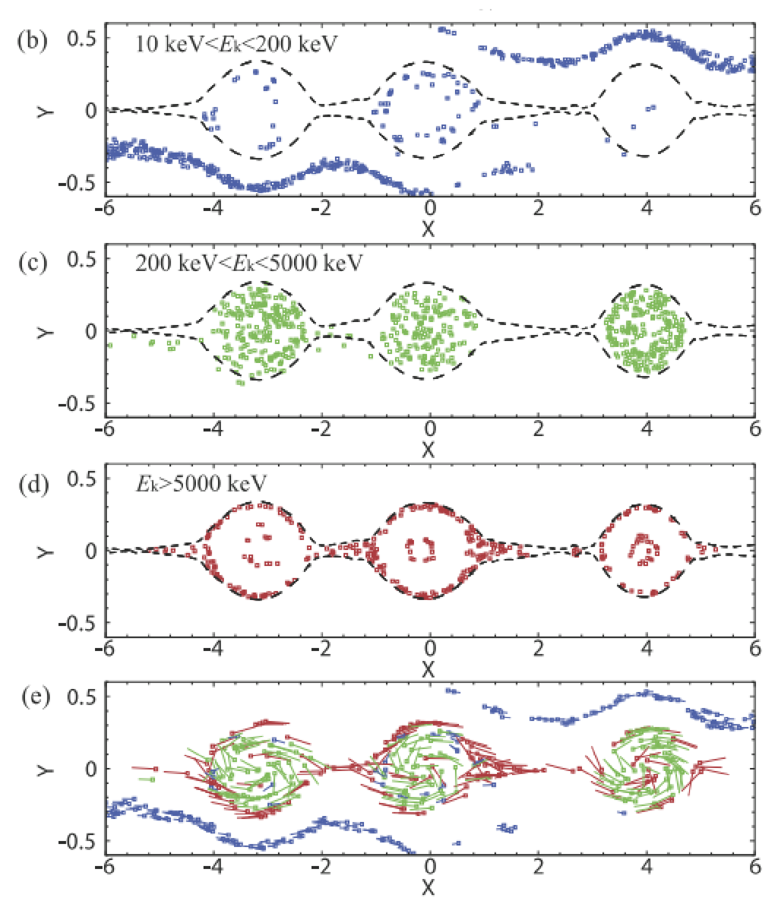
Particle spectra

'PARTICLE ACCELERATION IN FRAGMENTING PERIODIC RECONNECTING CURRENT SHEETS IN SOLAR FLARES' – *Gordovskyy et al. 2010*

Merging islands in tearing unstable current sheet MHD + Test Particle approach



MHD simulation for tearing unstable CS – *Zhang 2015*

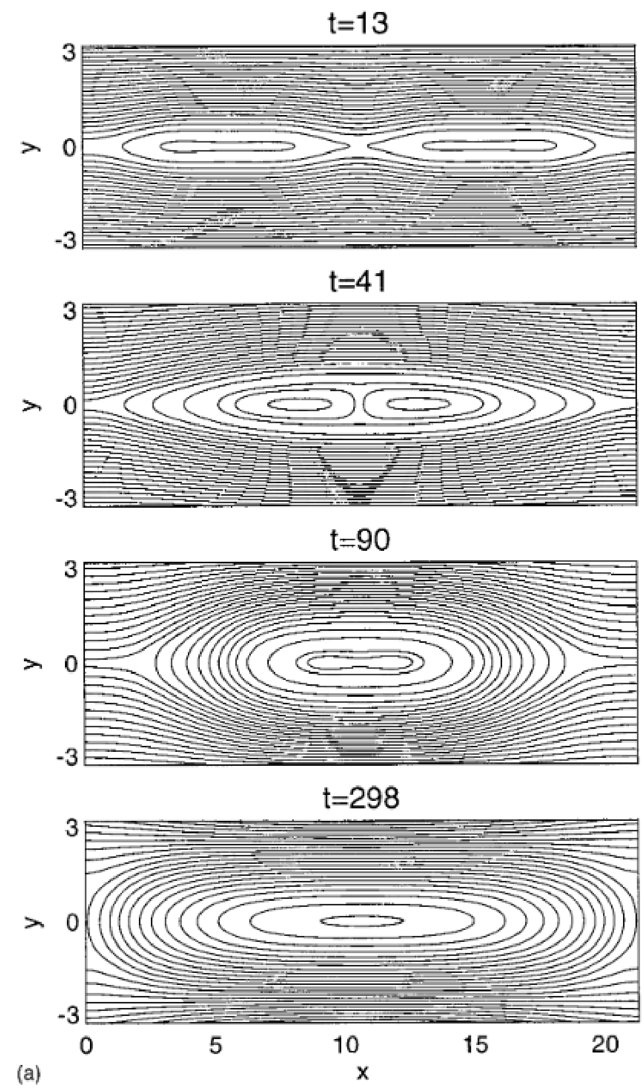


Test particles in stationary field snapshots – *Zhang 2015*

Coalescence

- Chain of magnetic islands (O-points)
- Attractive parallel currents
- Neighbouring islands coalesce

- To simulate this:
  - Capture multiple islands and allow symmetry-breaking with a long numerical box
  - Simulate large period of time (> 150 Alfvén times)

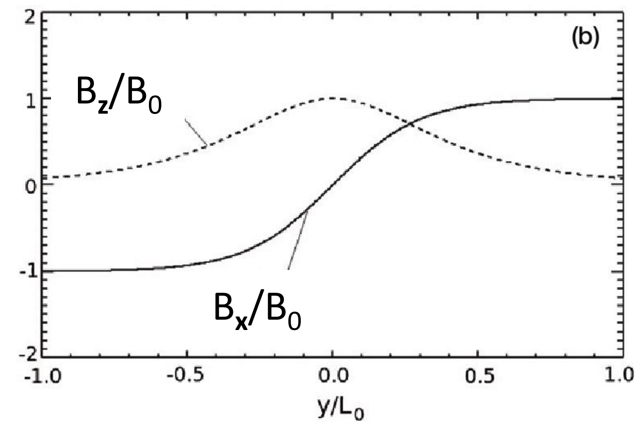


J. Schumacher and B. Kliem 1997

Aims of current study

- To investigate effect of different spatial driving disturbances on forced reconnection – field evolution and energetic particles
  - In general,driving disturbance is superposition of many wavelengths
  - How do islands develop and evolve for multi-wavelength perturbations?
  - Does forced reconnection “work” for more realistic driving disturbances e.g. localised perturbation?
- To investigate reconnection, energy release and particle acceleration during island formation and island coalescence
  - How does distribution of energetic particles evolve through different phases?
  - How does merger of islands affect particle energy spectra and spatial distributions?

Simulation set up



- Initial 1D force-free field:

$$\mathbf{B}_i = \left\{ B_0 \tanh\left(\frac{y}{y_0}\right), 0, B_0 \cosh^{-1}\left(\frac{y}{y_0}\right) \right\}$$

- Boundary conditions:
  - Conducting walls in *y*
  - Periodic in *x*

$$y = \pm a: \qquad v = B_z = \frac{\partial B_x}{\partial y} = 0 \quad , \quad \frac{\partial B_x}{\partial y} = \frac{\partial B_y}{\partial x}$$

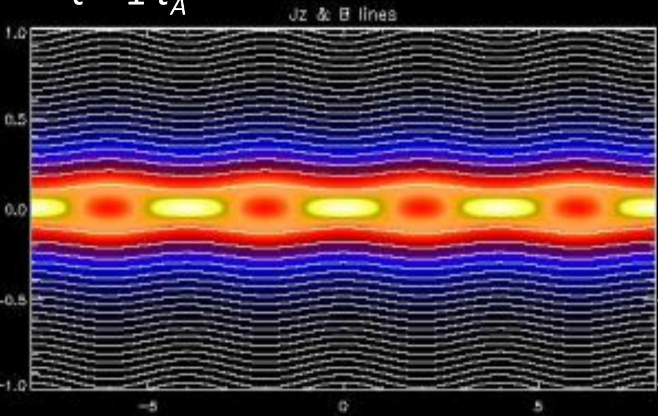
- Transient spatially-sinusoidal boundary perturbation:

$$t < \tau_p : \qquad v_y = \frac{\Delta}{\tau_p}\left[1 - \cos\left(\frac{2\pi t}{\tau_p}\right)\right]\cos\left(\frac{2\pi x}{L}\right)$$

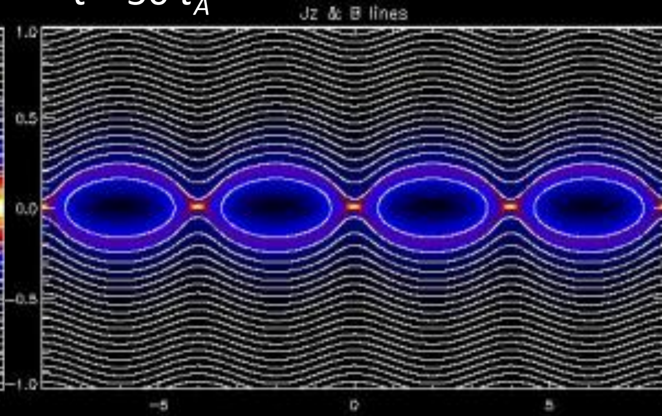
- Simulations were performed using **Lare2D** (*Arber et al. 2001*)
  - **Anomalous resistivity** was used: resistivity is enhanced in regions of strong current.

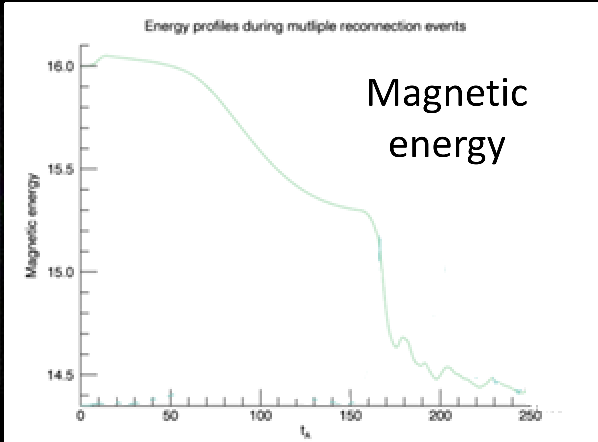
Long cell simulations

t = 1 t_A

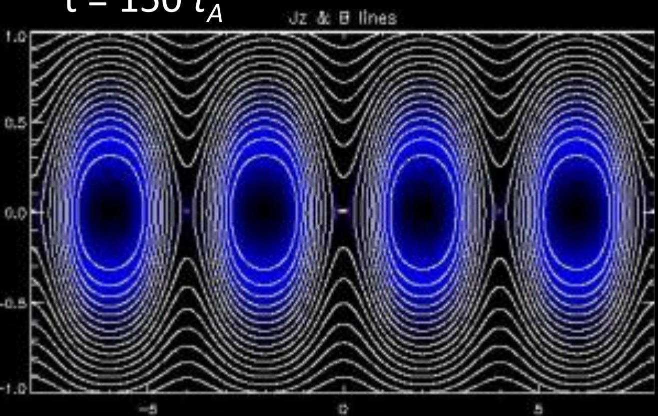


t = 50 t_A





t = 150 t_A



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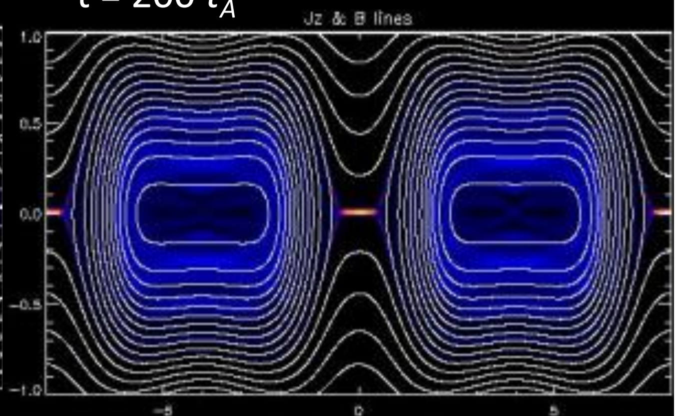

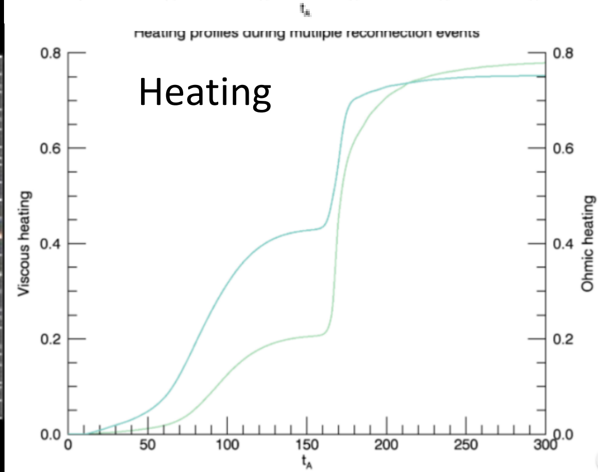

- 16 by 2 length grid with 2048 by 256 grid points
- **Resistivity:** $\boldsymbol{\eta} = 10^{-4}$ when **J** > 6, else $\boldsymbol{\eta} = 10^{-7}$
- **Perturbation**: amplitude $\Delta = 0.05$, wavelength $L = 4$, duration $t_p = 16\ t_A$

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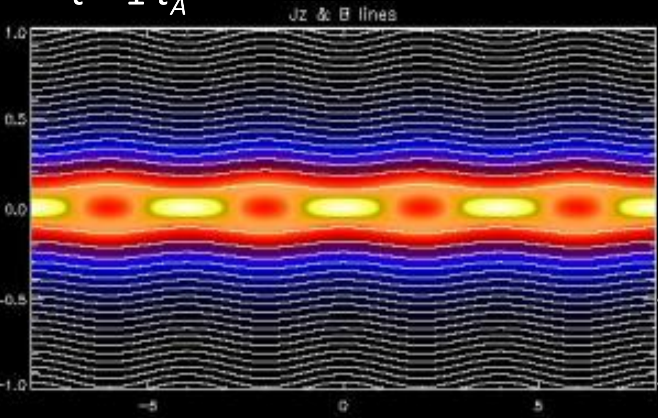

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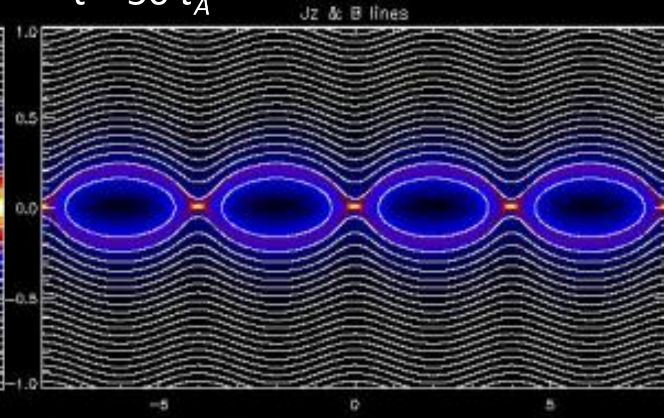

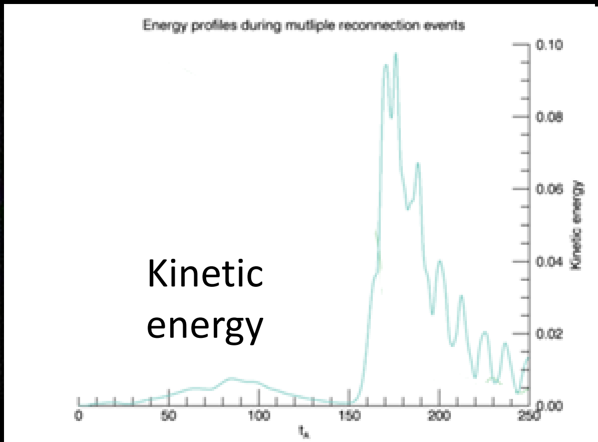

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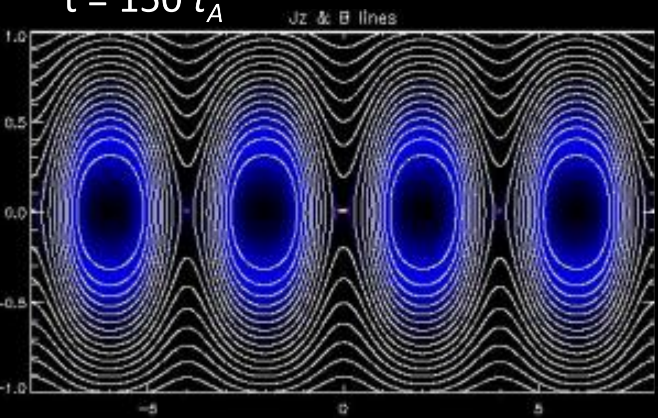

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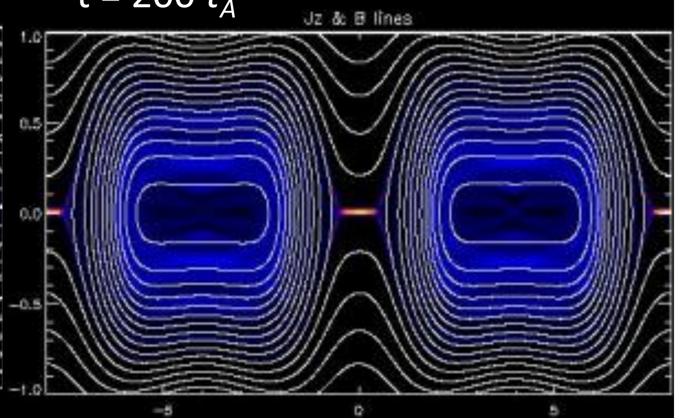

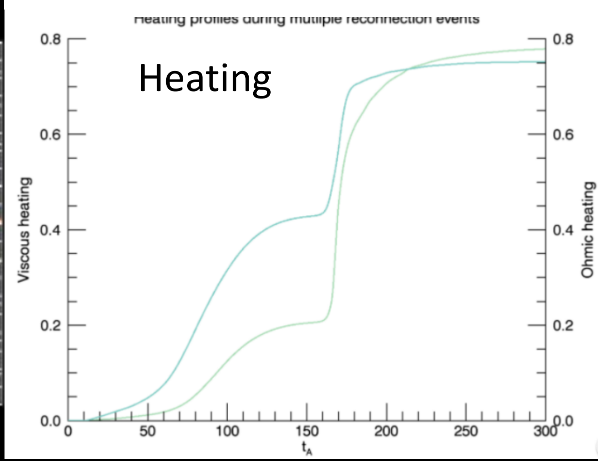

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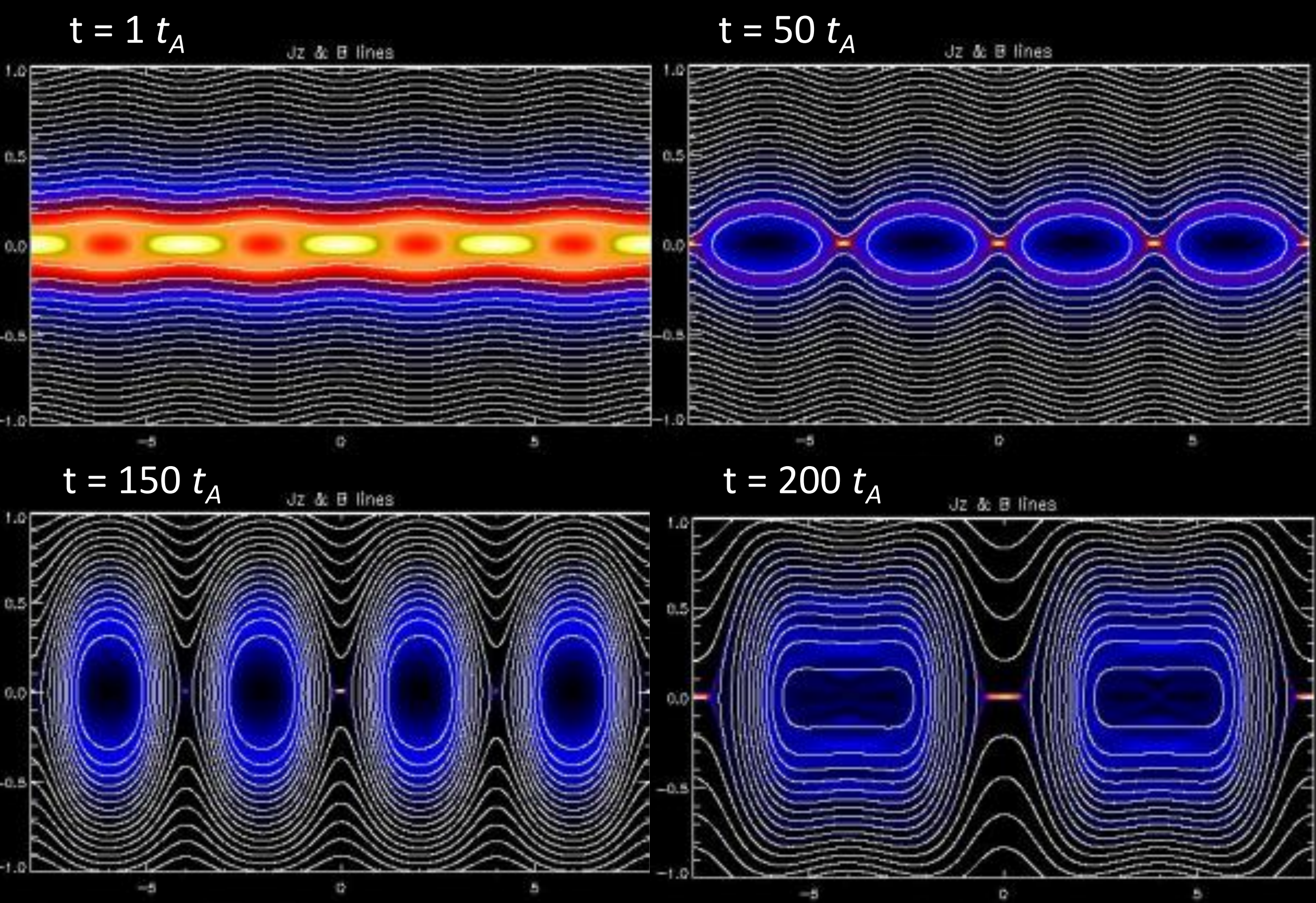

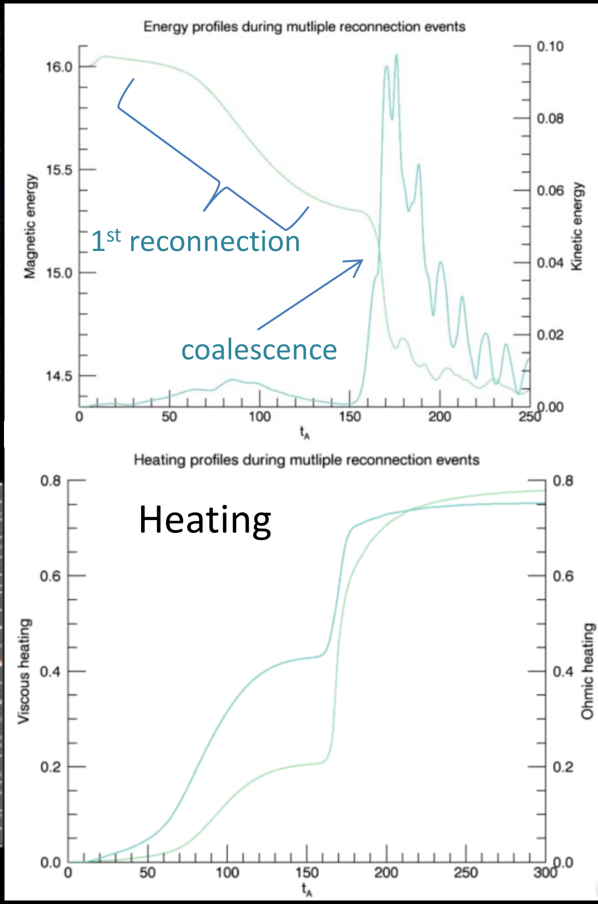

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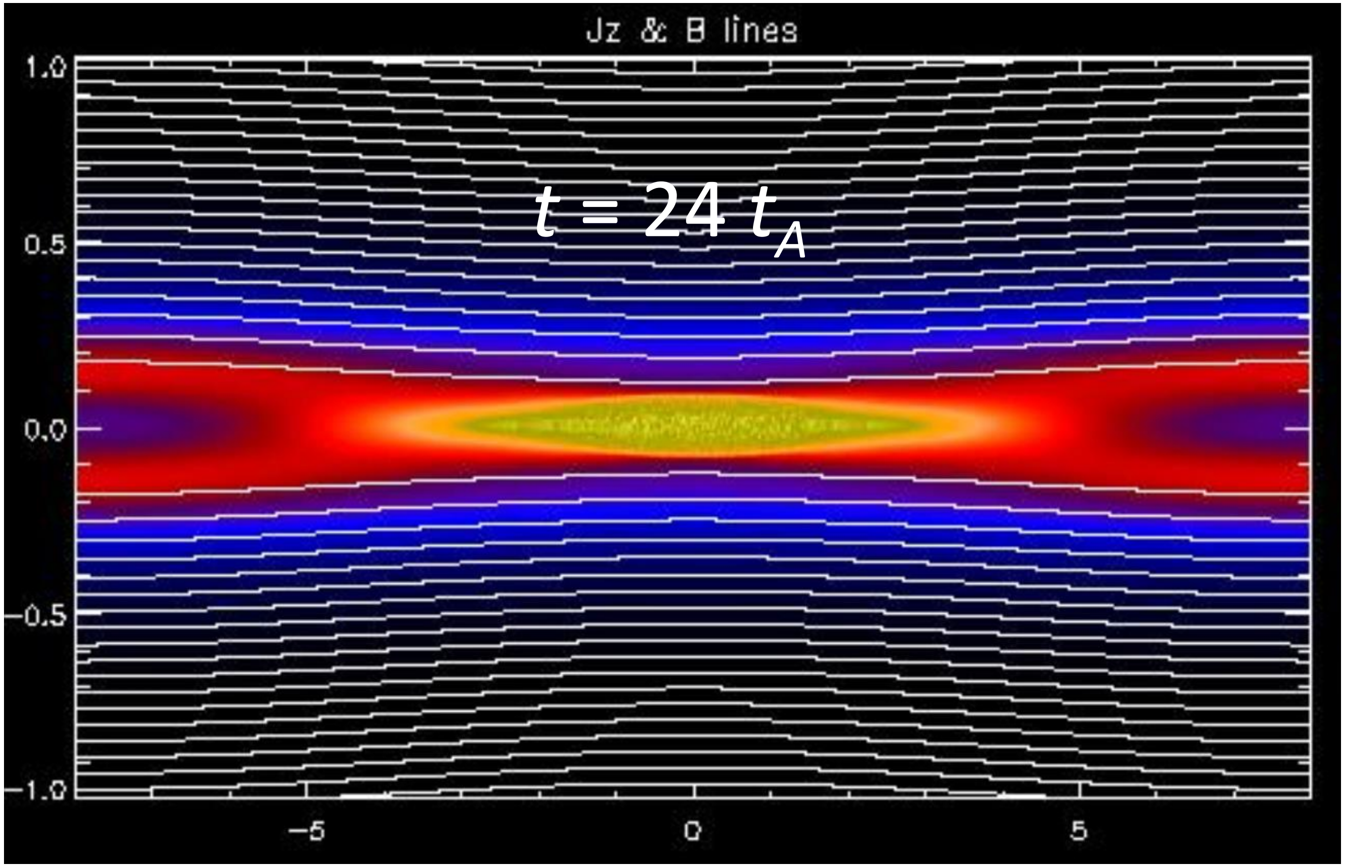
Single long-wavelength driving disturbance



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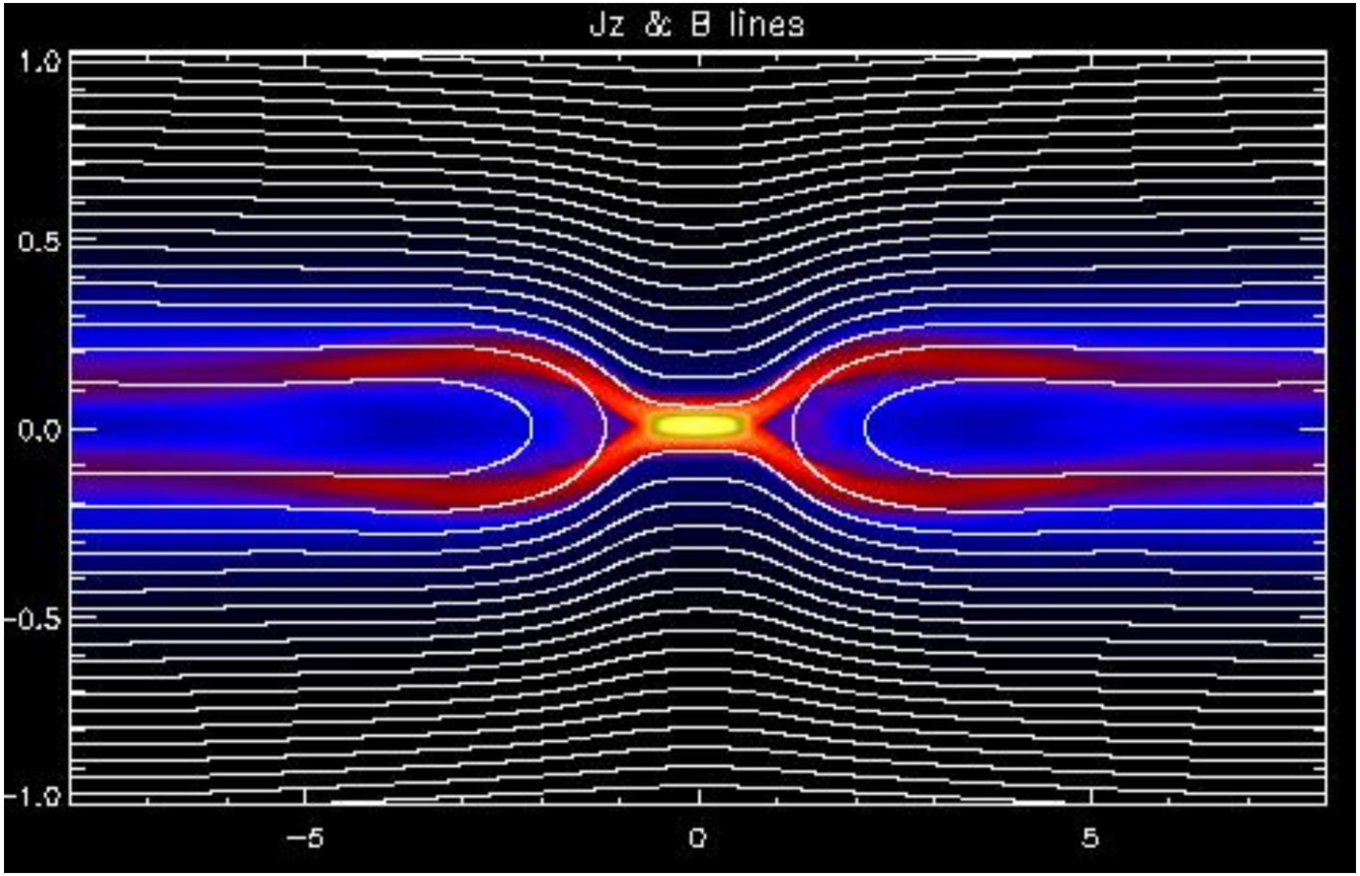

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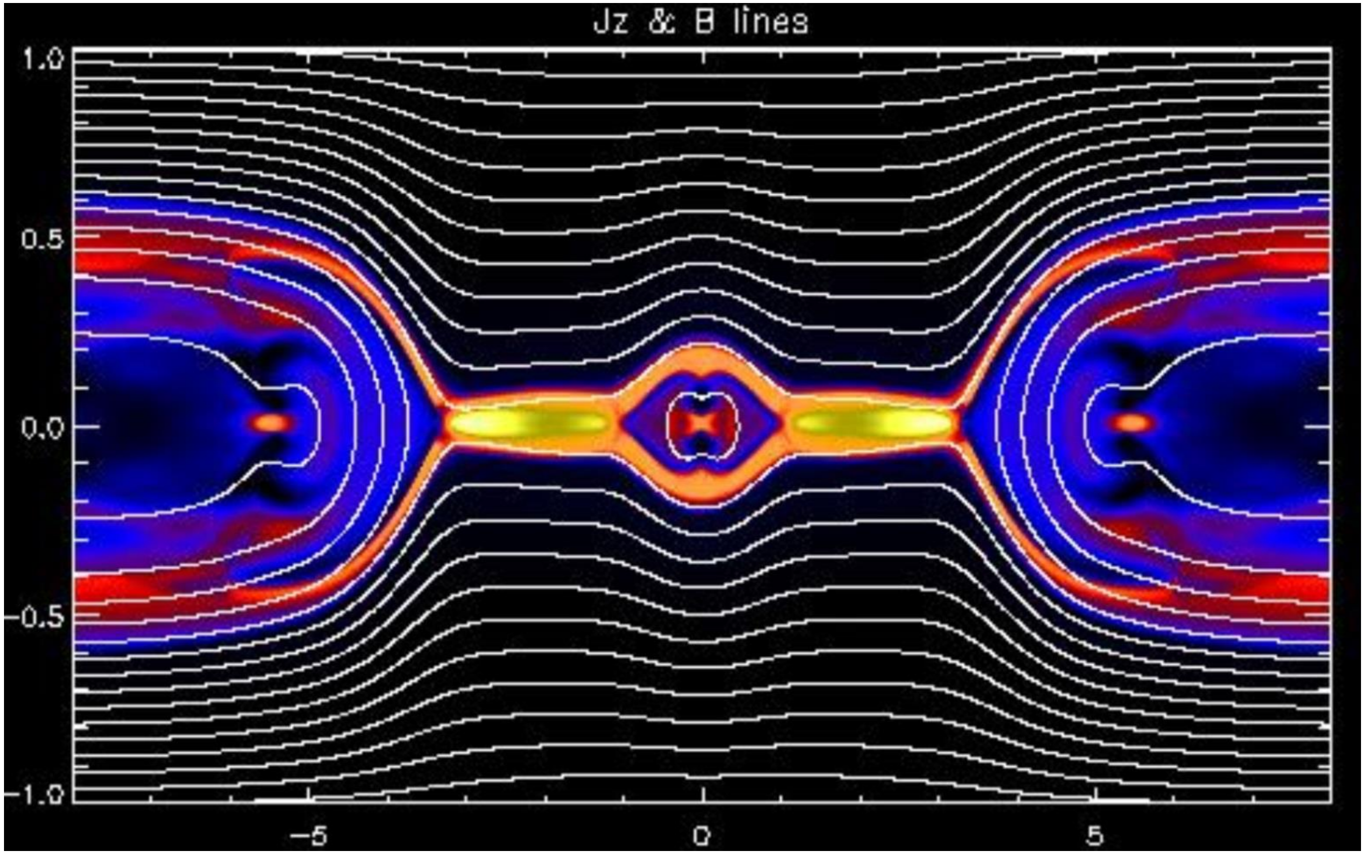

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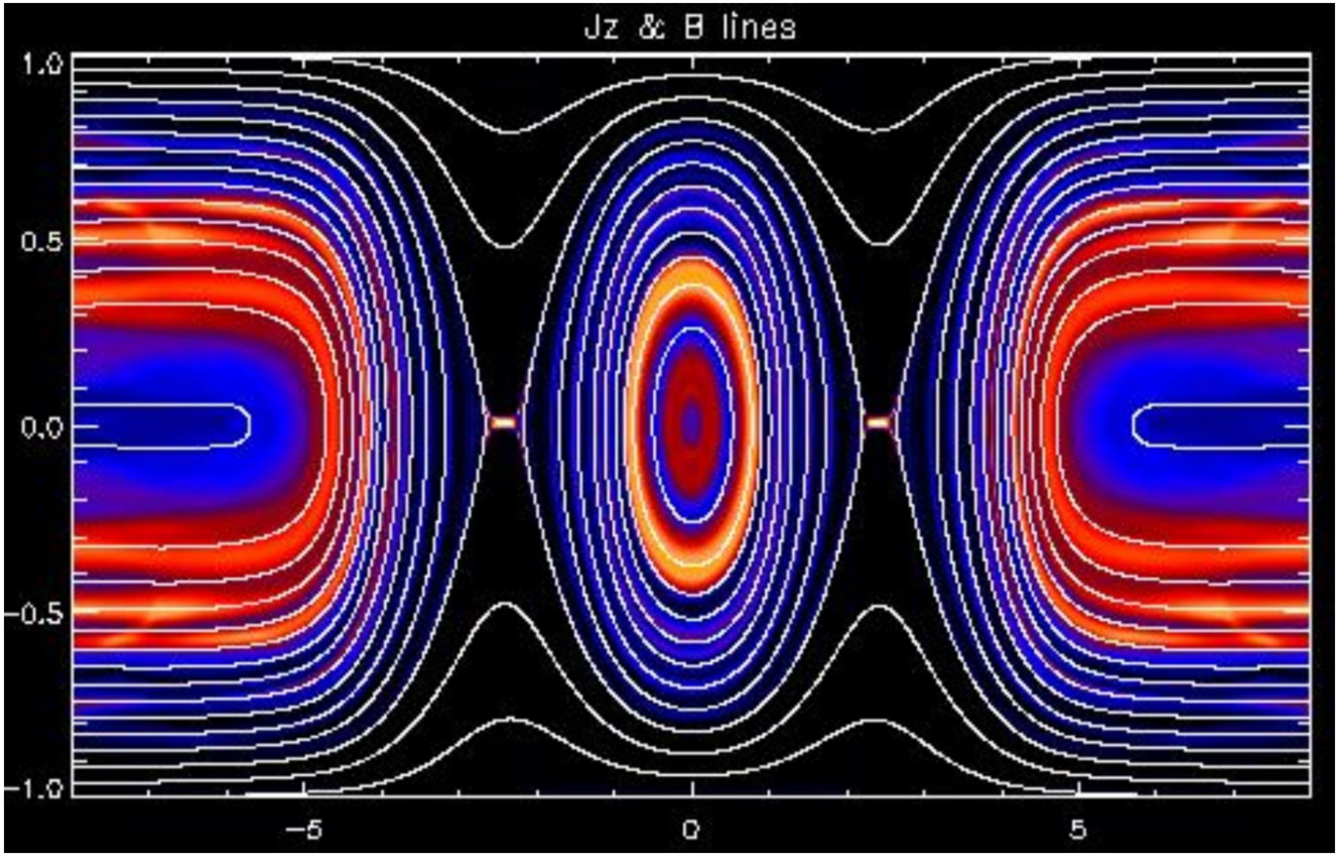

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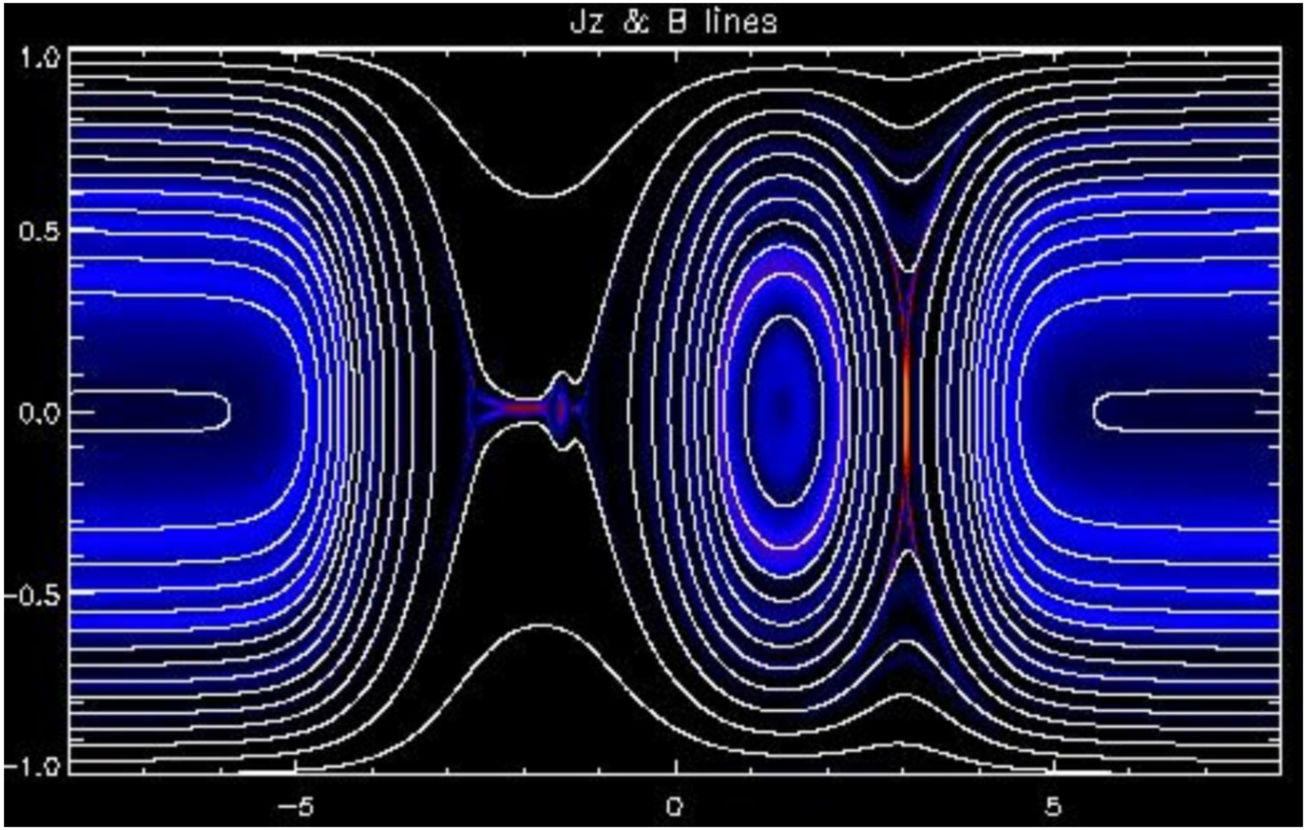

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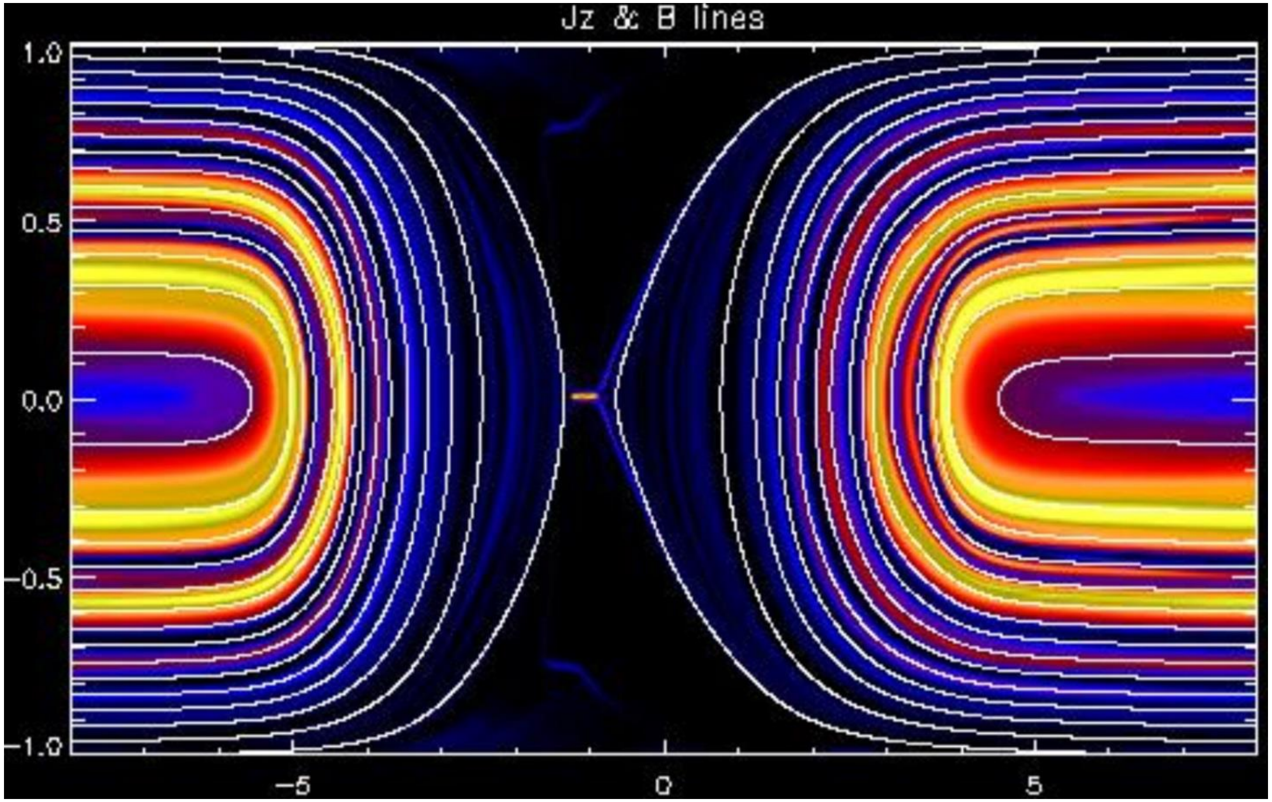
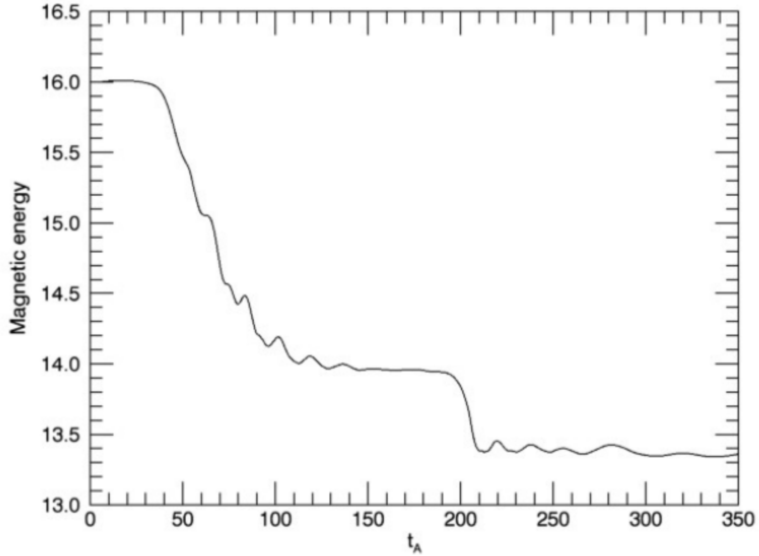


Energetics with merging islands

Magnetic energy



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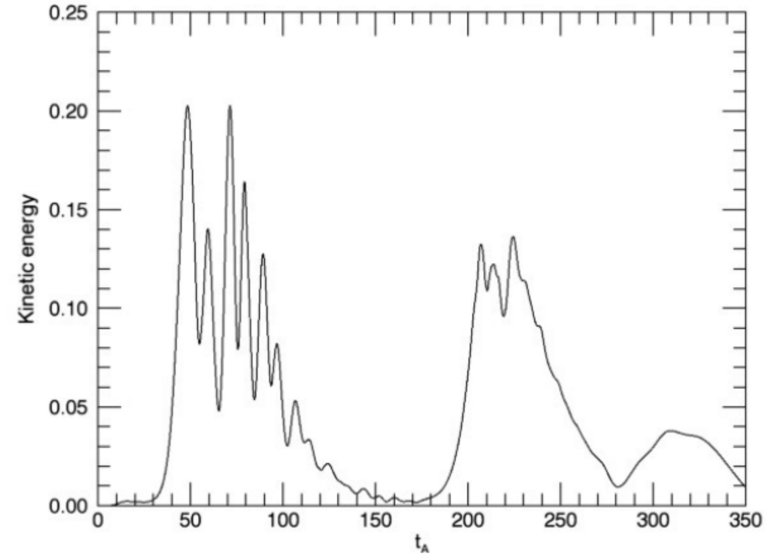
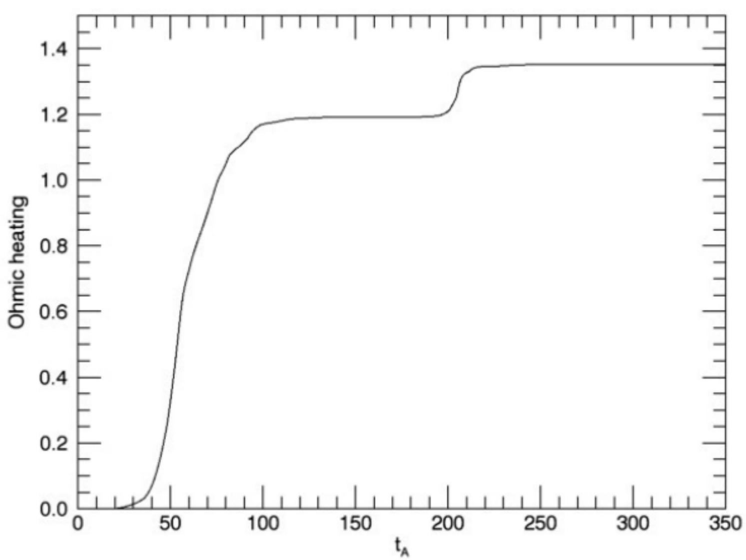
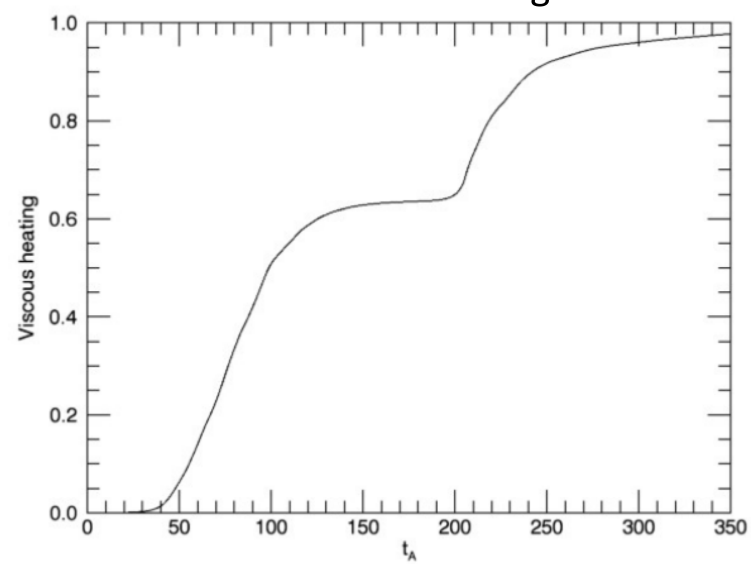


Ohmic heating



Viscous heating



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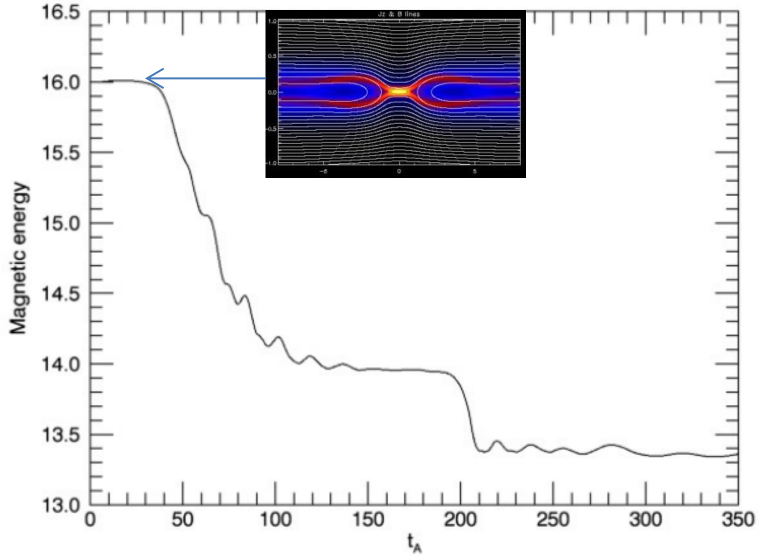

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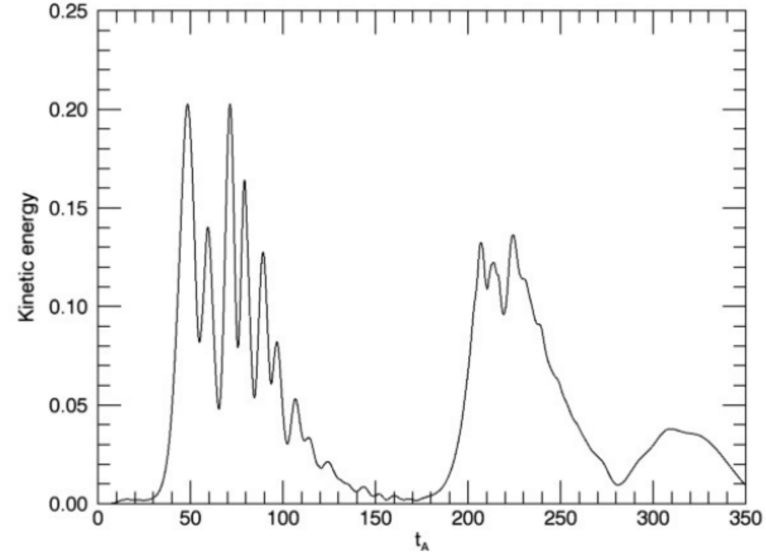

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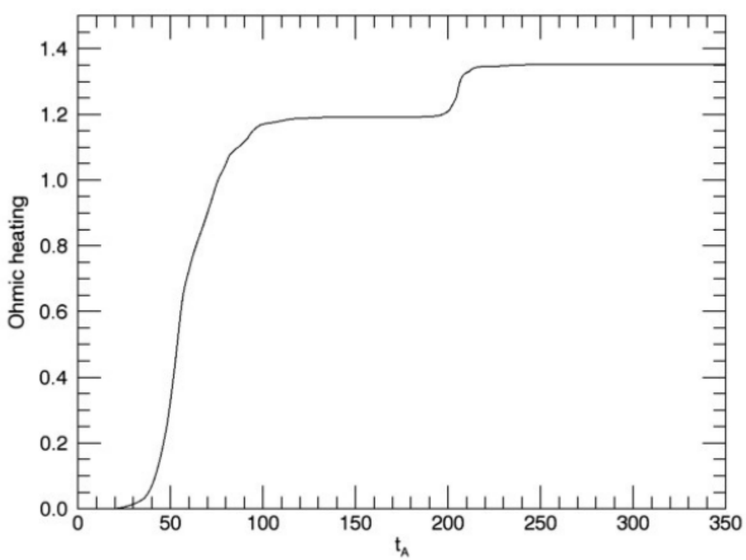

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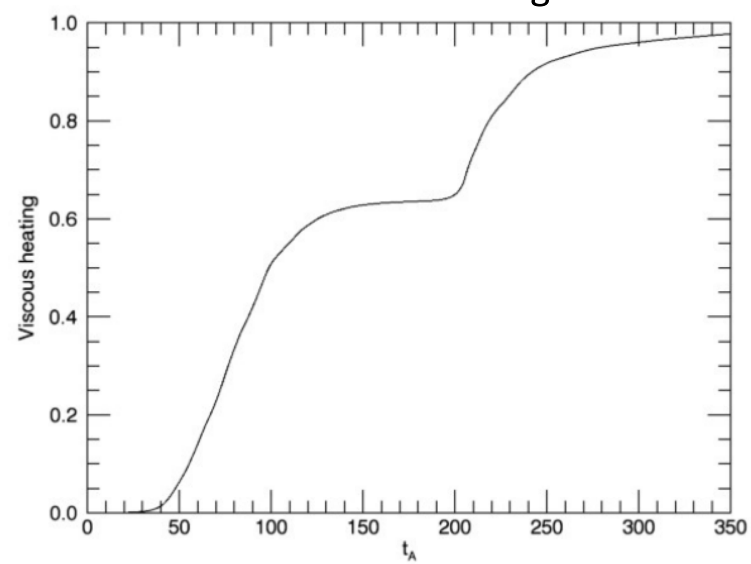

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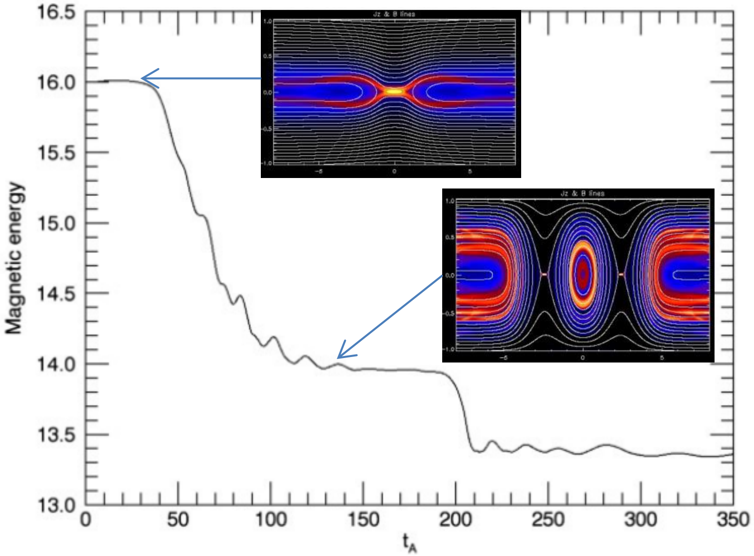

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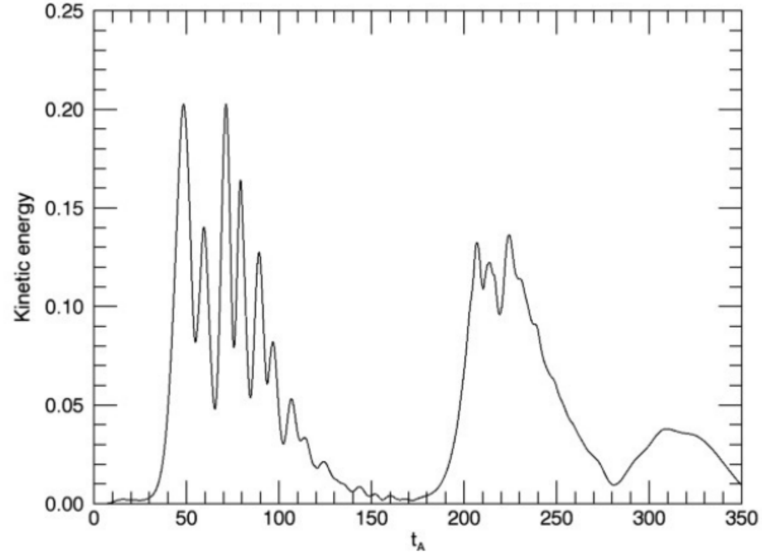

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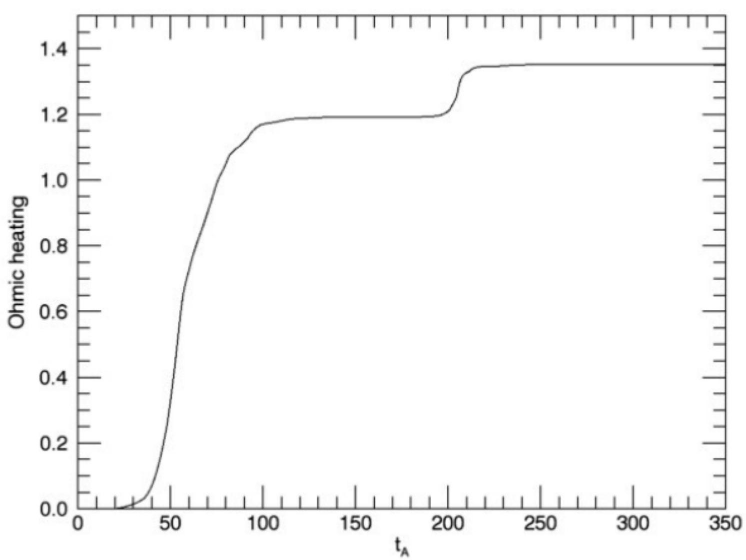

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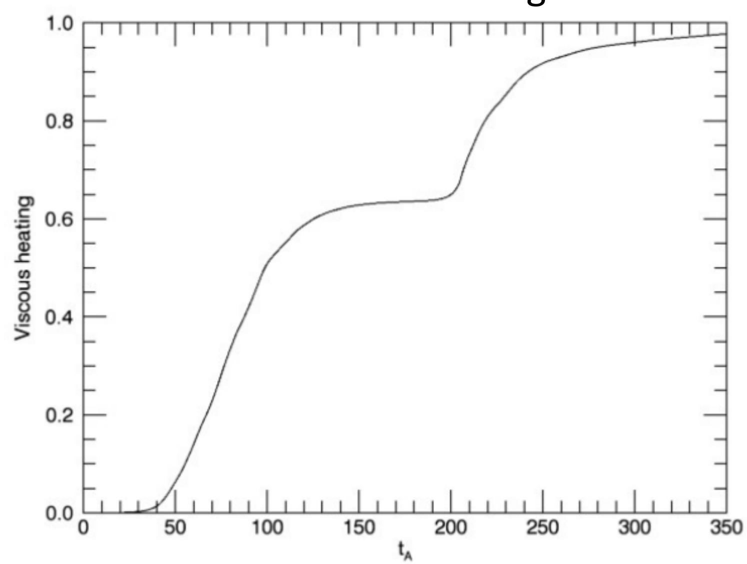

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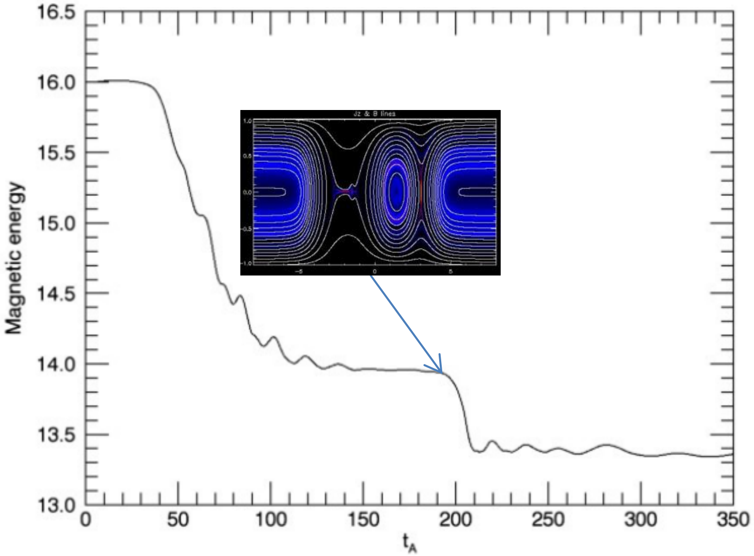

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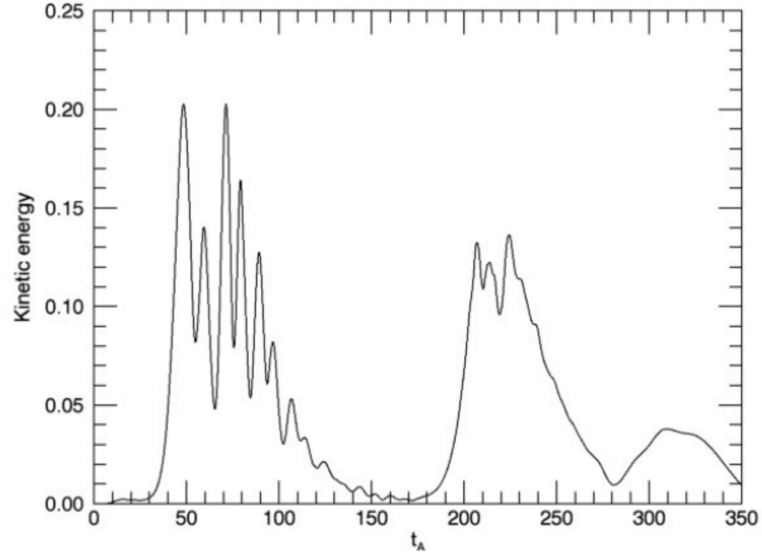

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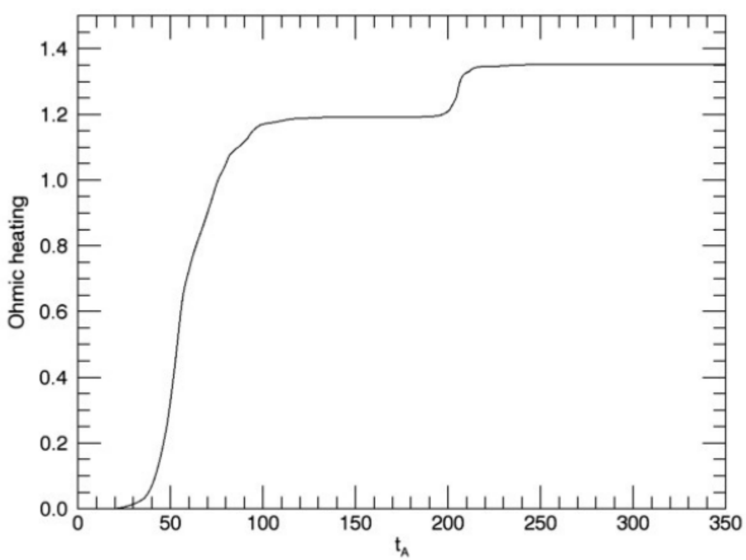

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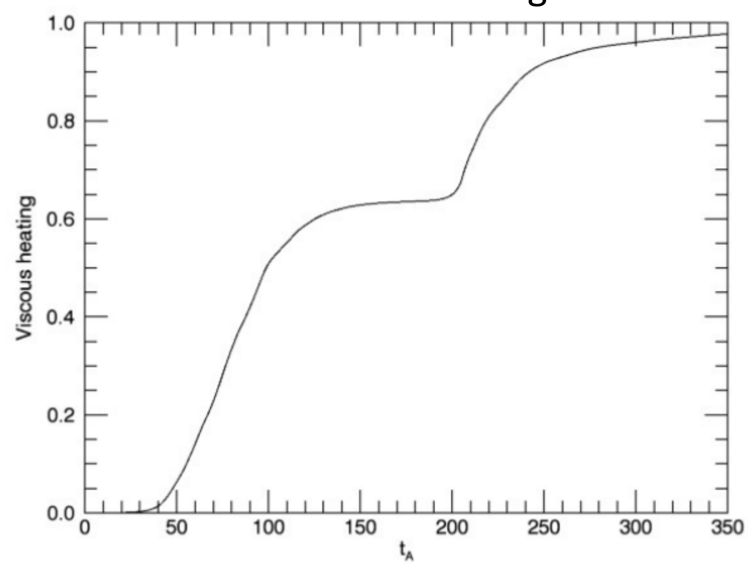

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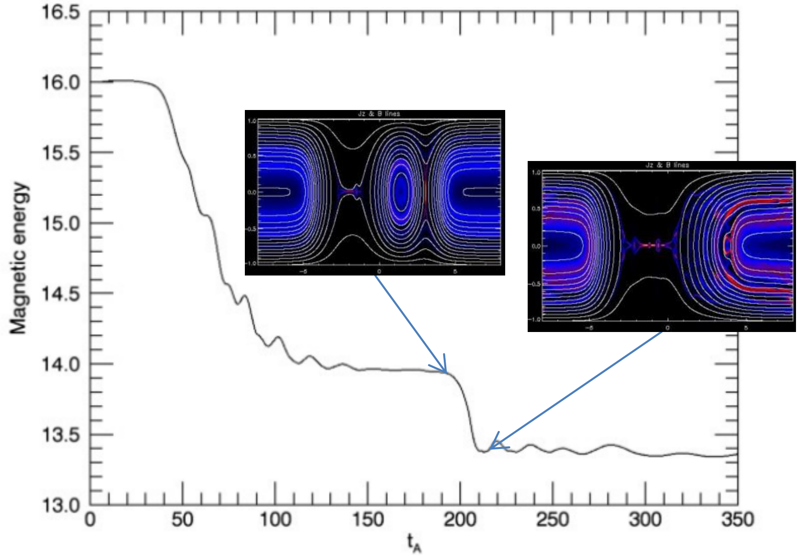

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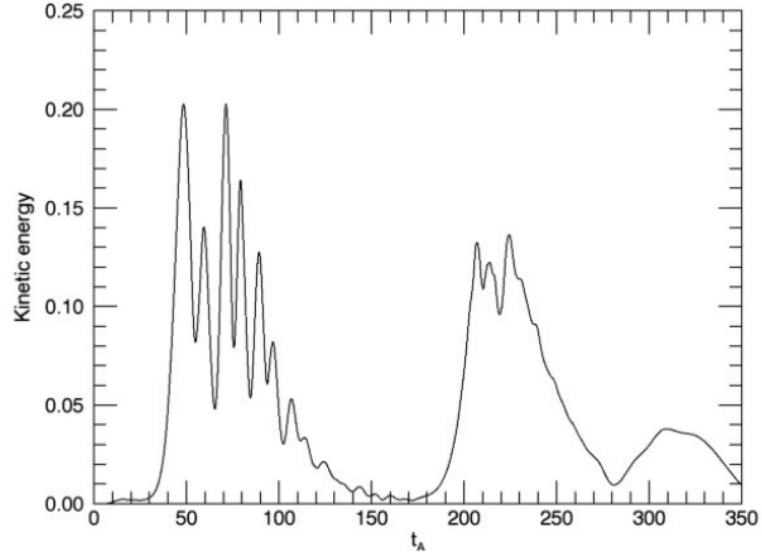

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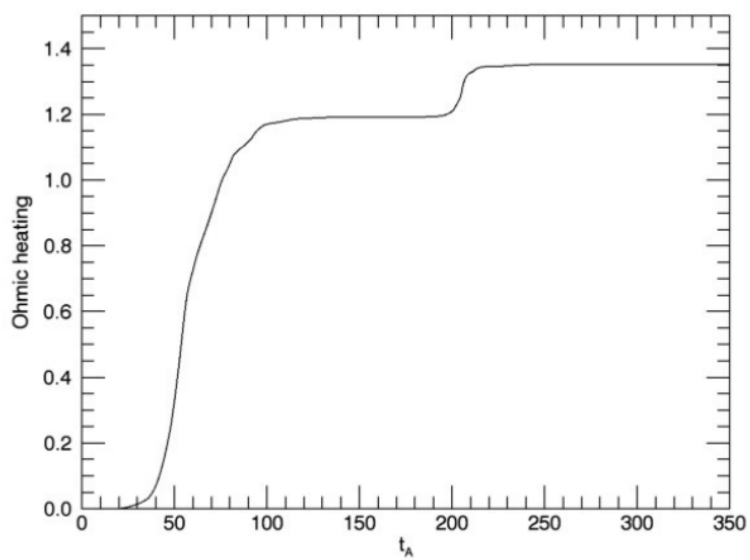

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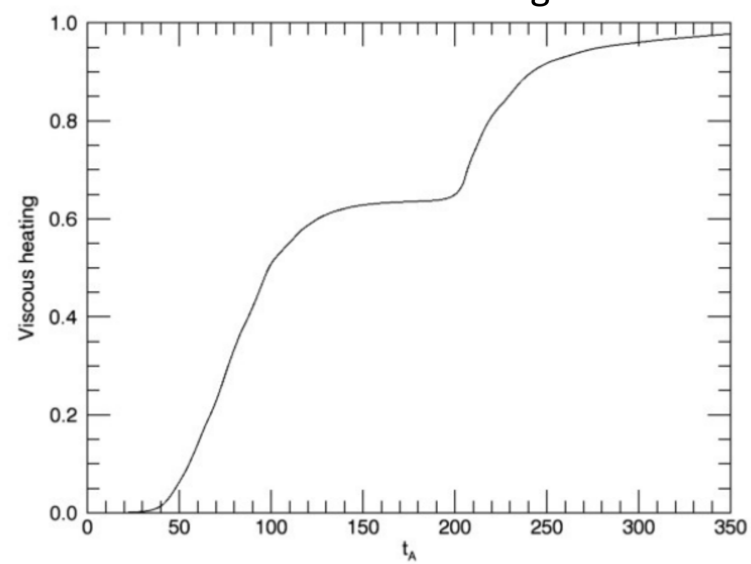
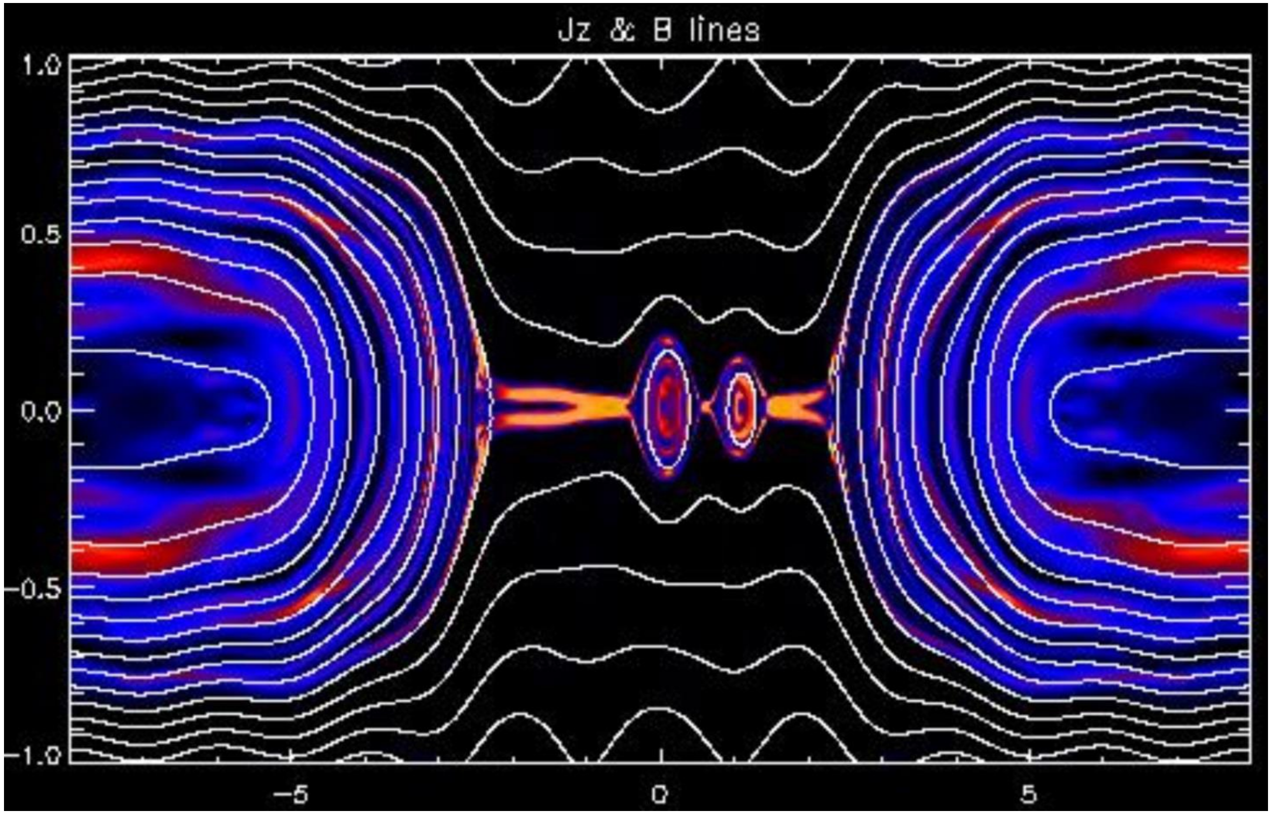
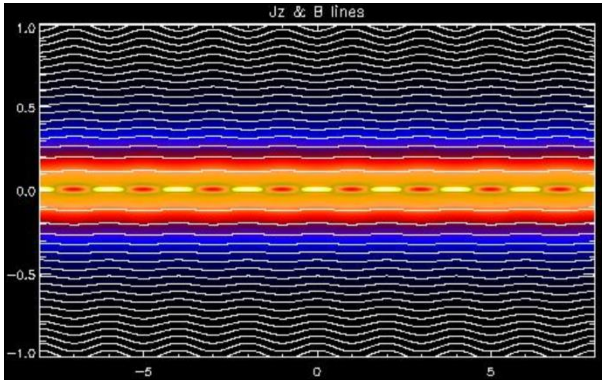
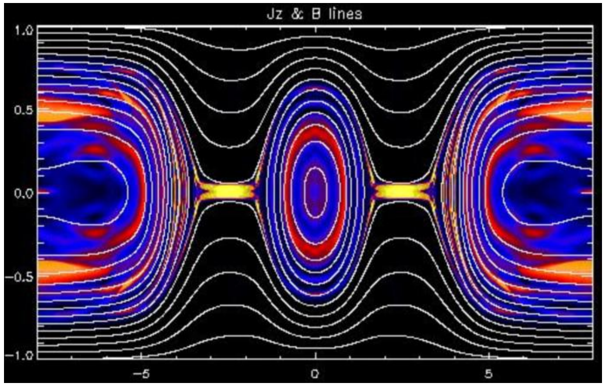


Mixed wavelength perturbation







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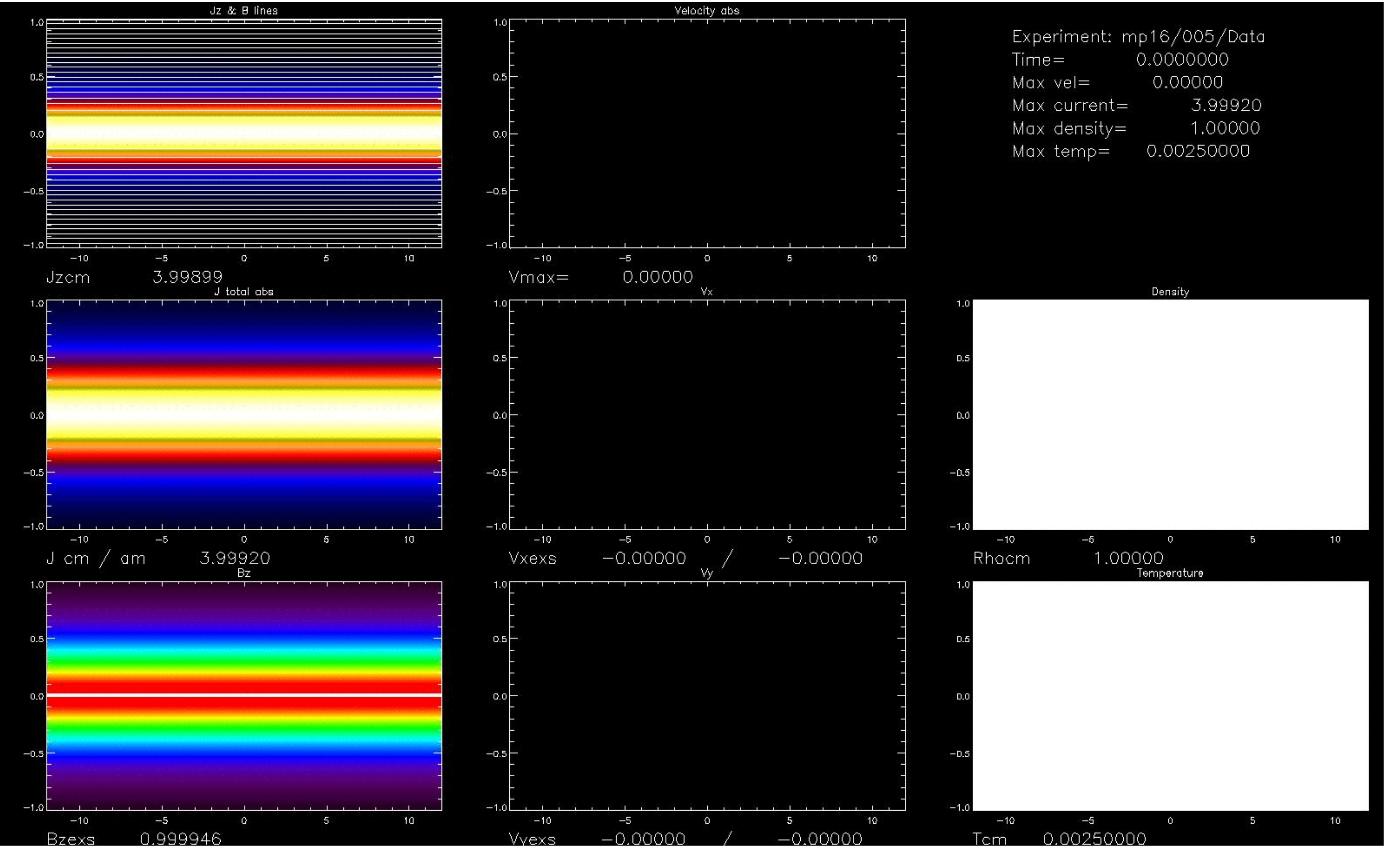
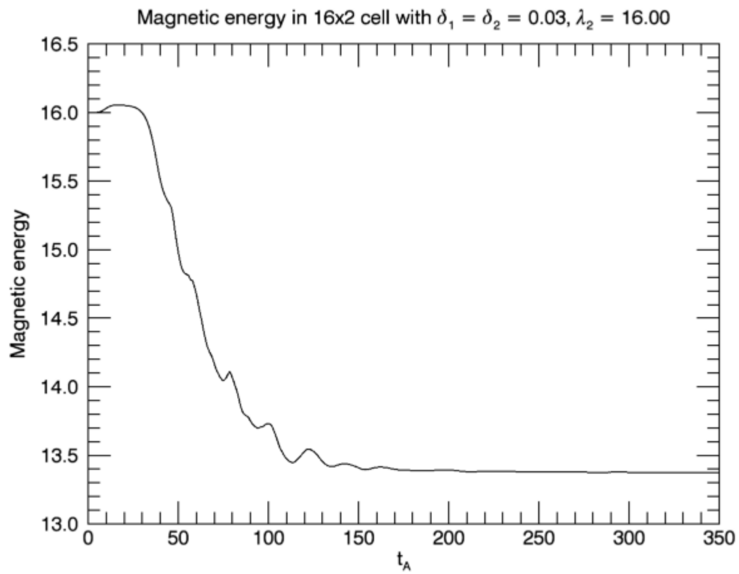
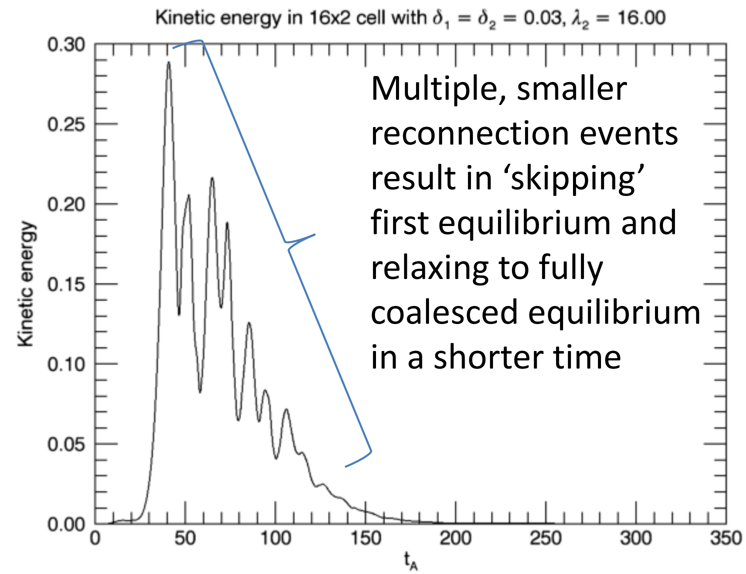
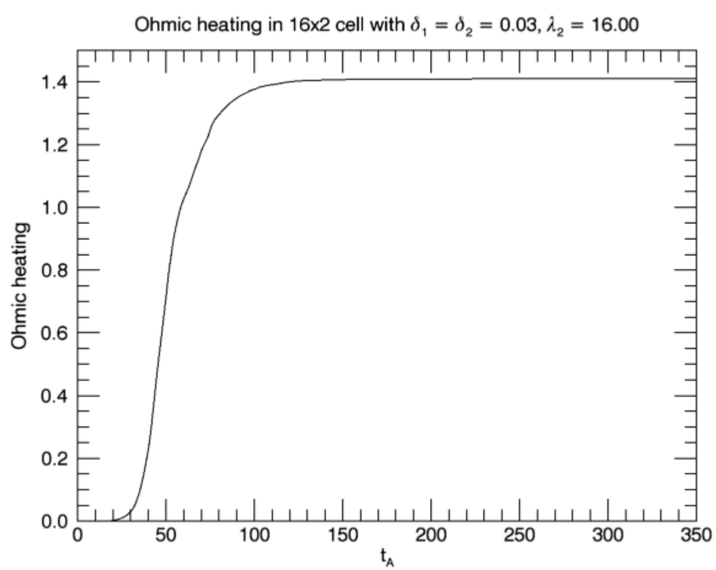
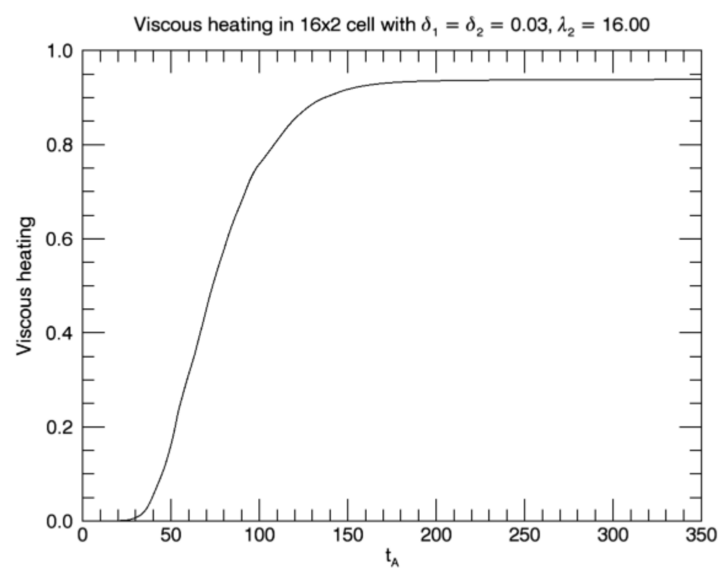


Energetics for multiple wavelength perturbation: $L_1 = 16, L_2 = 2$

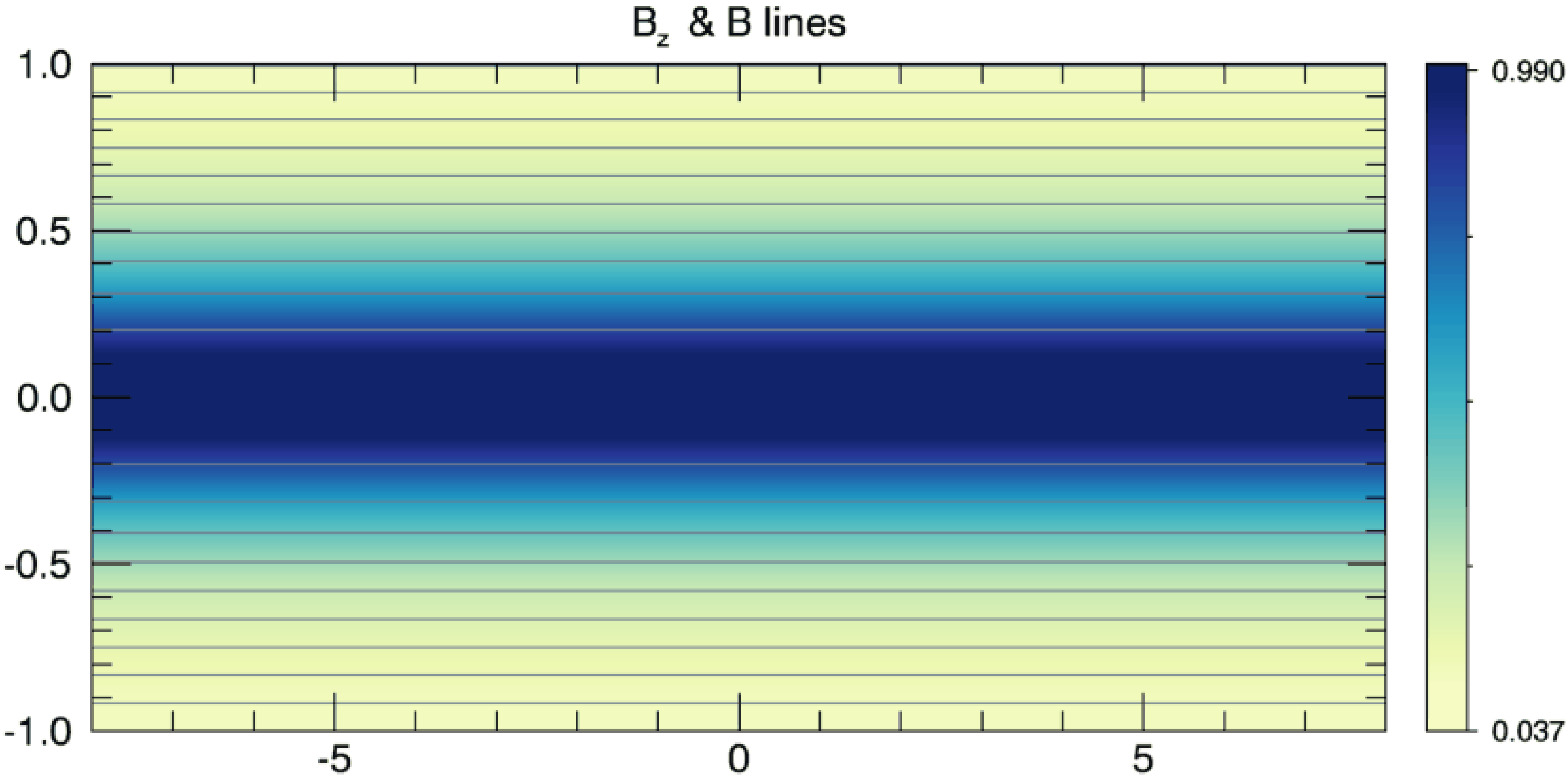




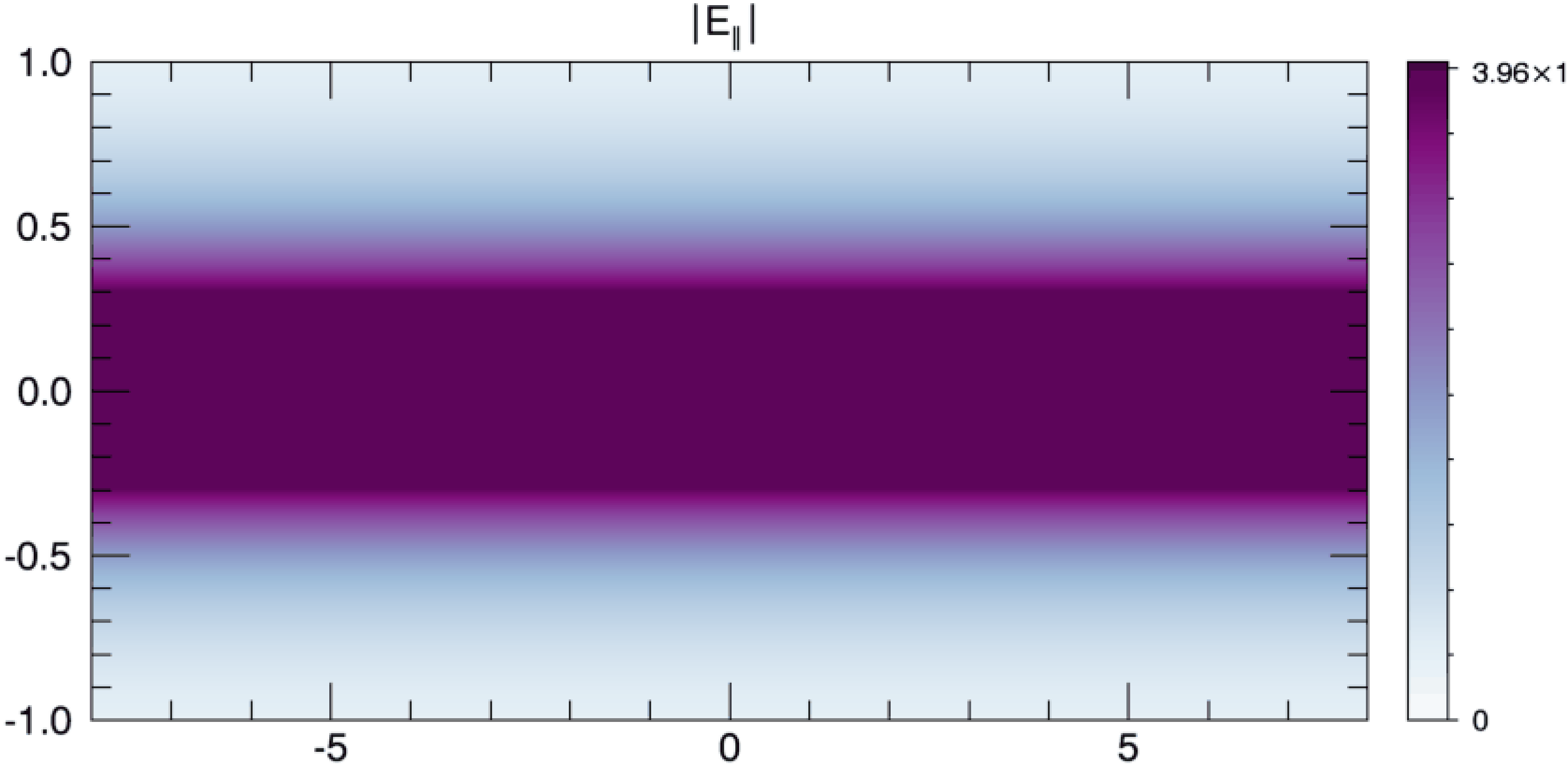




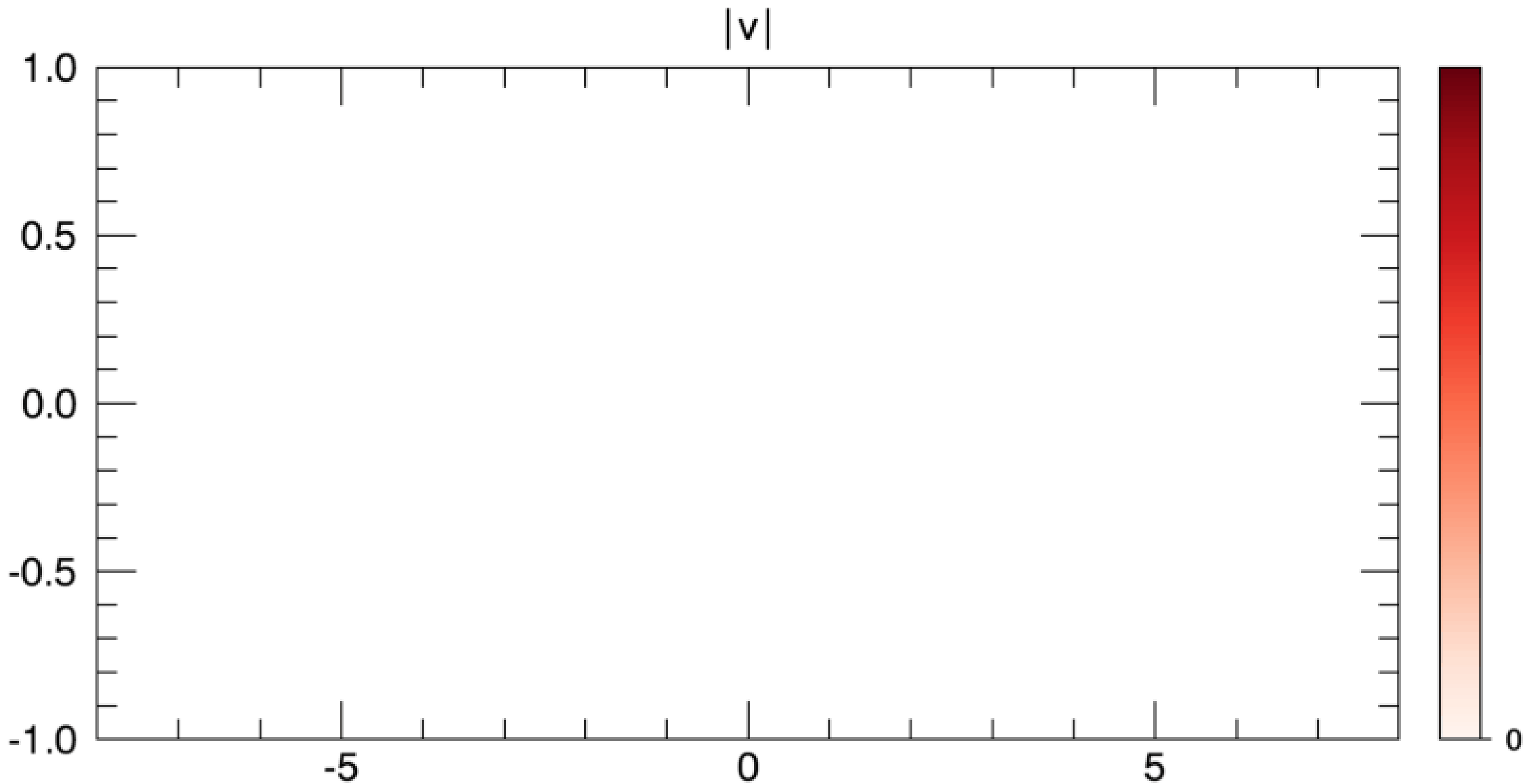
Localised driving perturbation
(Gaussian) – Magnetic field



Localised driving perturbation
(Gaussian) – Electric field



Localised driving perturbation
(Gaussian) – velocity field



Test particles

- Test particle trajectories were calculated using GCA (Guiding Centre Approximation) code[1]

- Takes time-dependent MHD fields, interpolates fields in time and space.

- Scale parameters:

  $L_0 = 10^4$ m $B_0 = 3\times10^{-3}$ T $\rho = 2.4\times10^9$ cm^{-3}

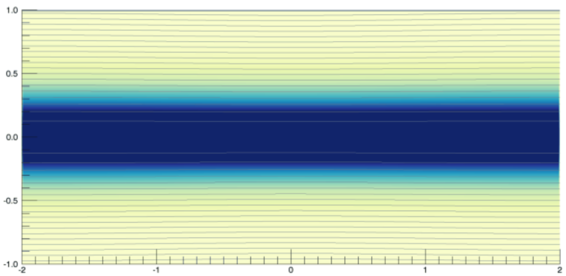
- Boundary conditions: periodic in x, free in y & z.

[1] Gordovskyy et al., ApJ 2010
[2] Northrop, 1963

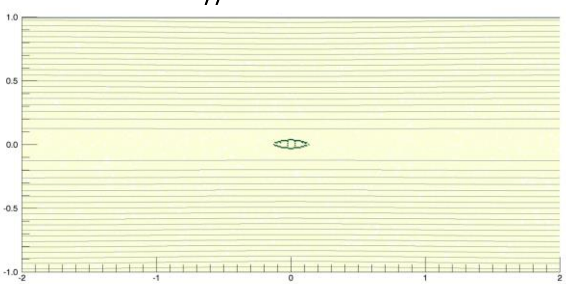
Short domain trajectories

No coalescence

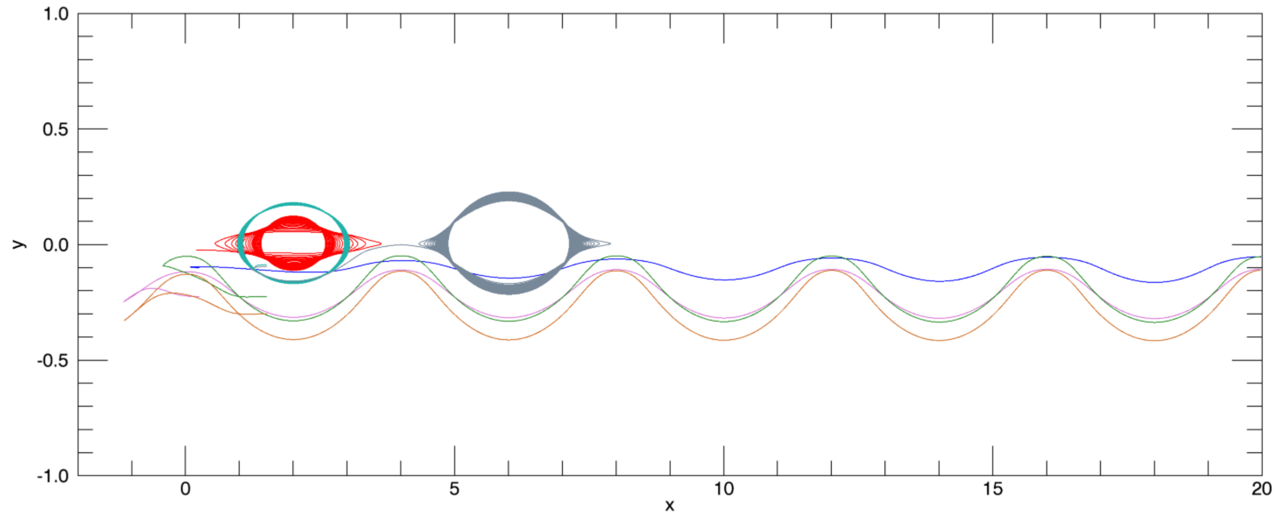
|J_z| & B lines



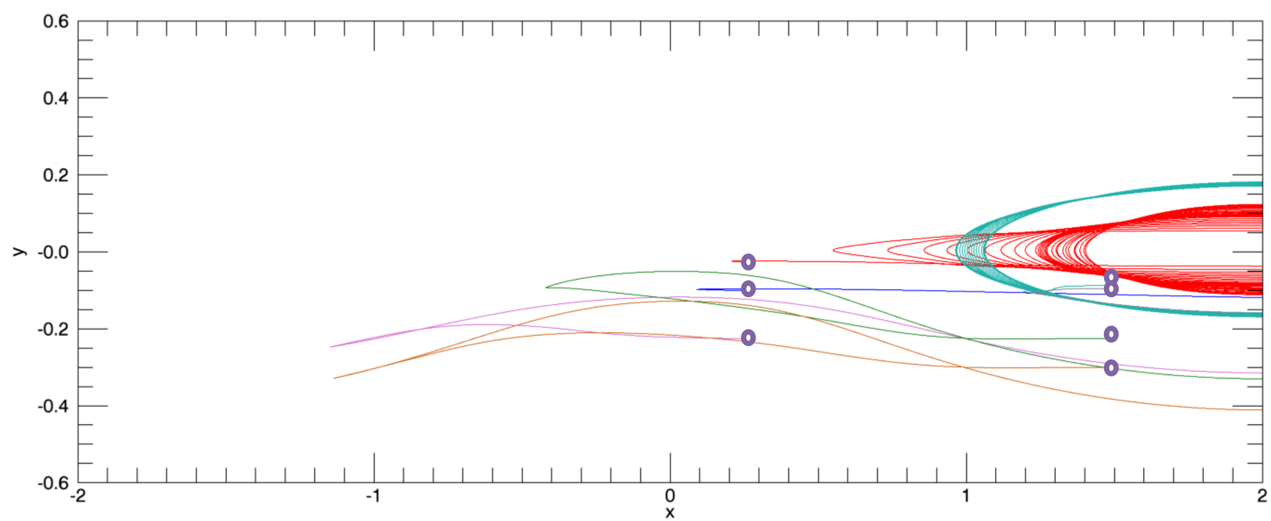
|$E_{//}$| & B lines



Typical trajectories: **x-y** plane



Typical trajectories: **x-z** plane



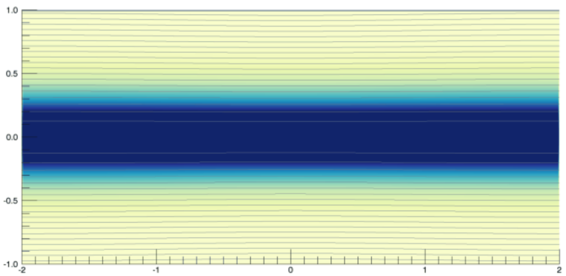
MHD parameters:

- Initial current sheet thickness $y_0 = 0.25$
- $\eta = 3.2 \times 10^{-4}$ when **J** > 4.1, else $\eta = 0$

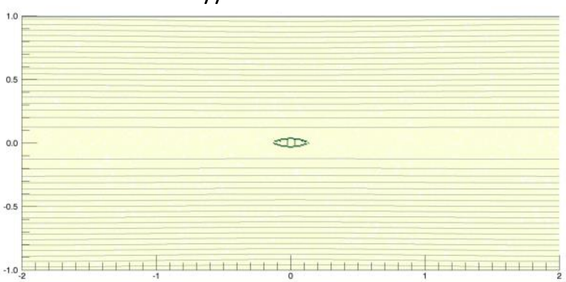
Right: Bottom plot is a zoomed in section of top. Initial particle positions highlighted by dots.

Short domain trajectories

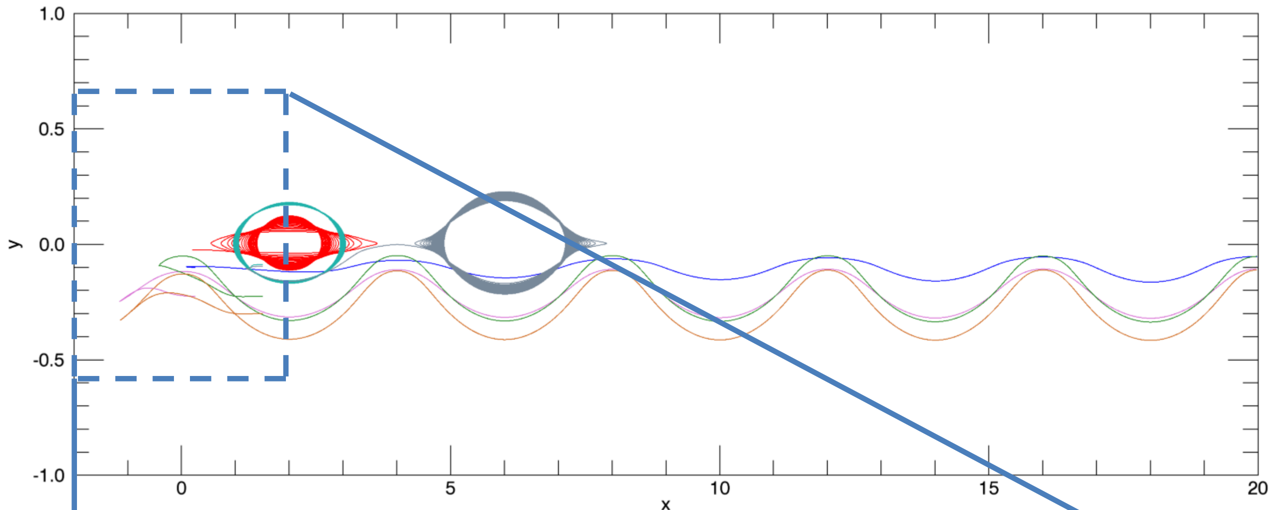
|J$_z$| & B lines



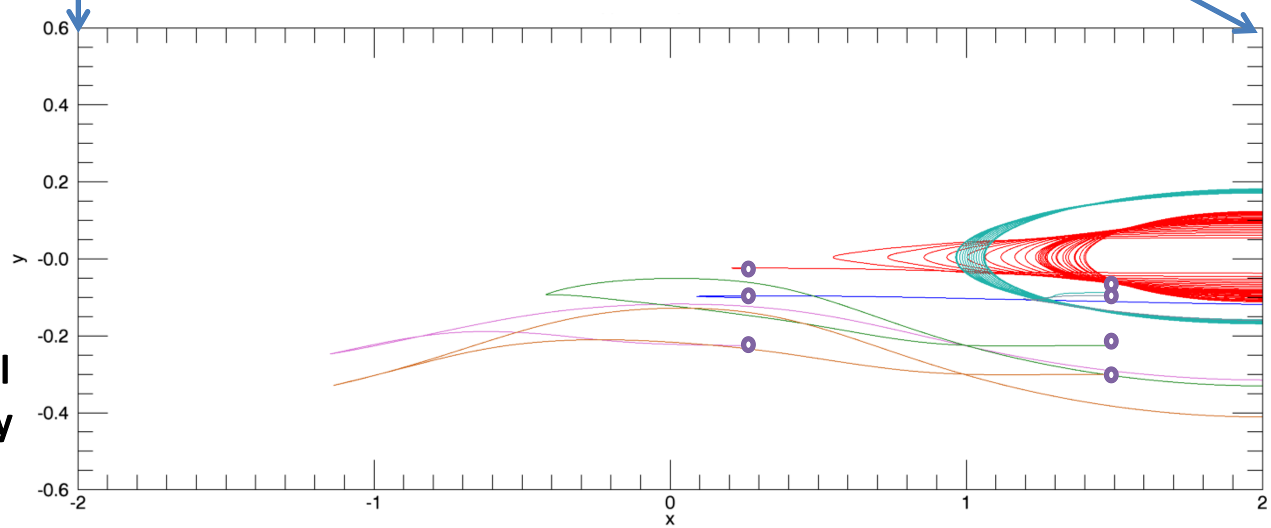
|E$_{//}$| & B lines



Typical trajectories: **x-y** plane



Typical trajectories: **x-y** plane



MHD parameters:

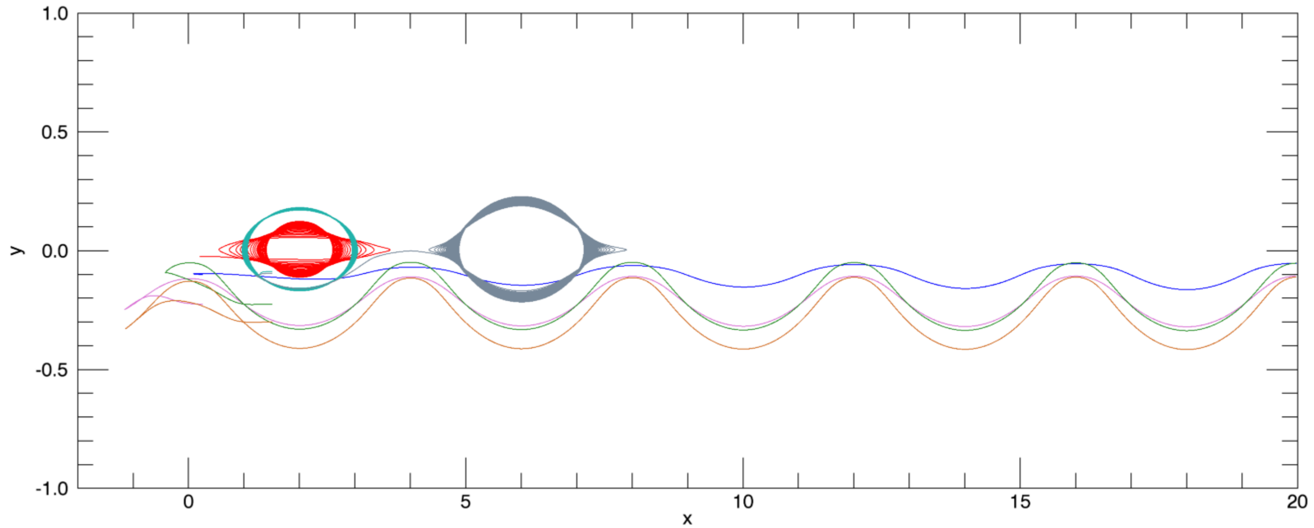
- **Initial current sheet thickness y_0 = 0.25**
- **η = 3.2×10^{-4} when J > 4.1, else η = 0**

Zoomed in section of top. Initial particle positions highlighted by dots.

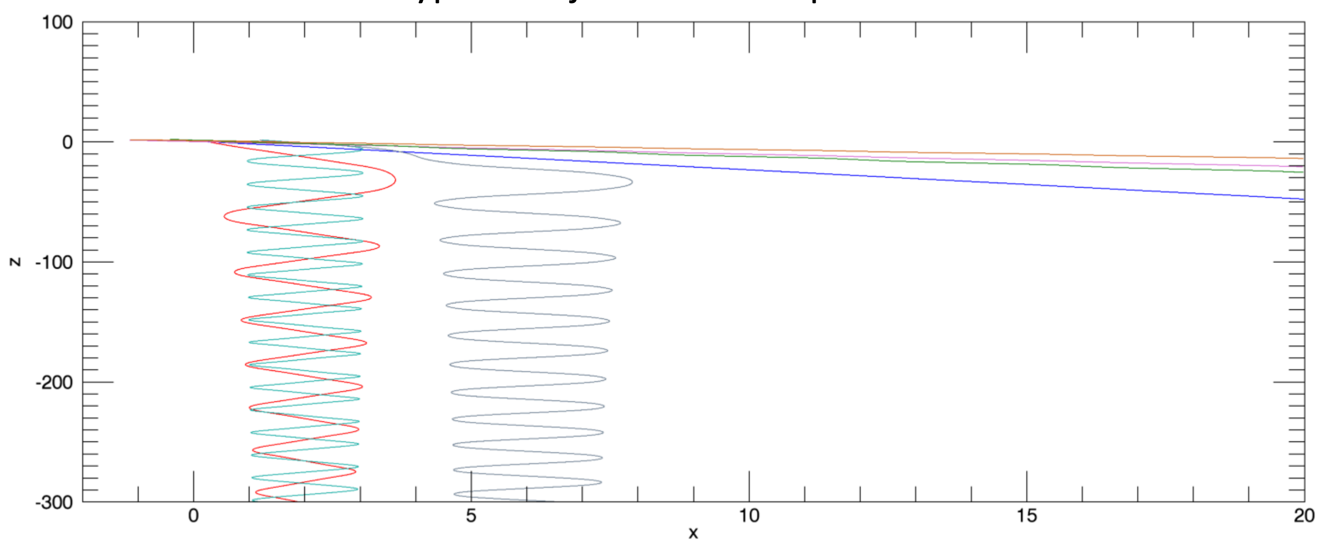
Short domain trajectories

Particles on closed field lines travel further in z direction, indicating greater acceleration due to concentrated electric field at island separatrices.

Typical trajectories: **x-y** plane



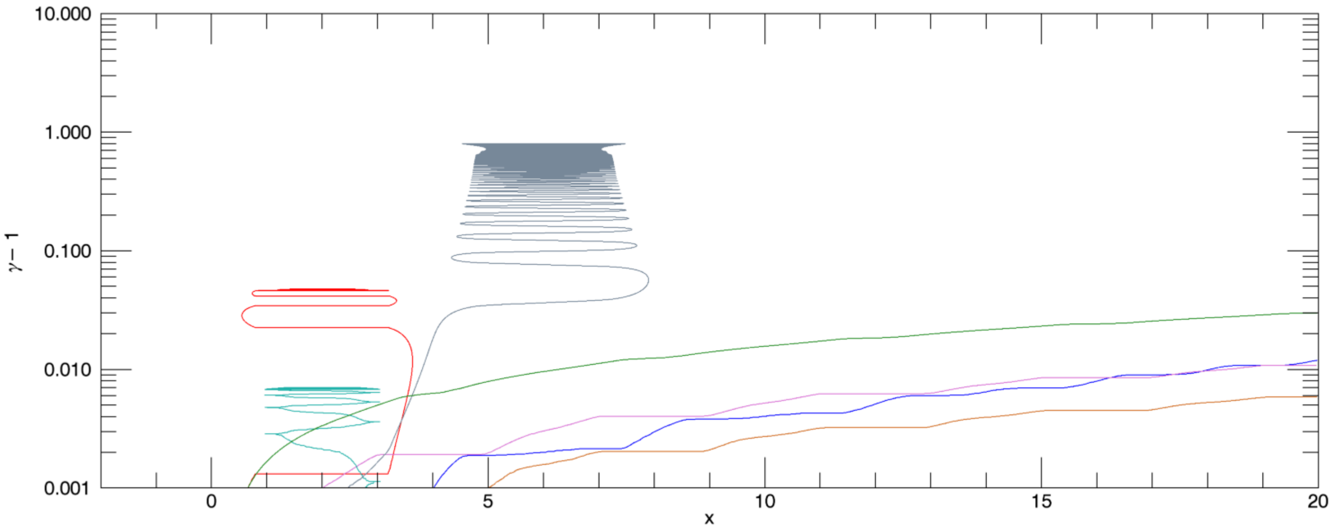
Typical trajectories: **x-z** plane



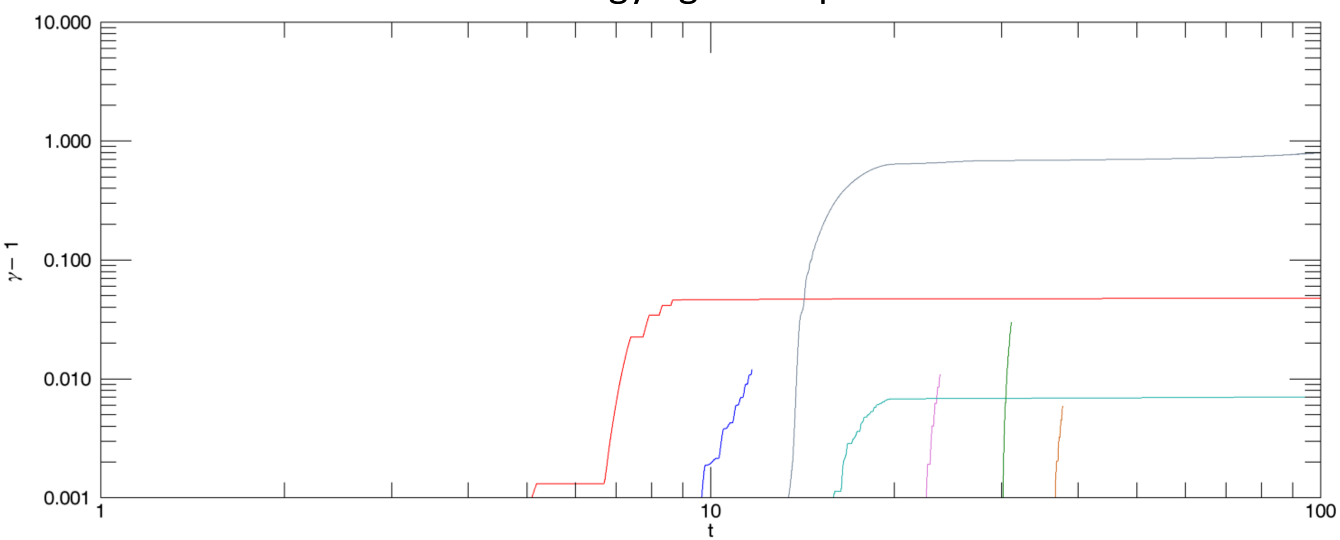
x-z plane

Short domain trajectories

Particle energy against x position

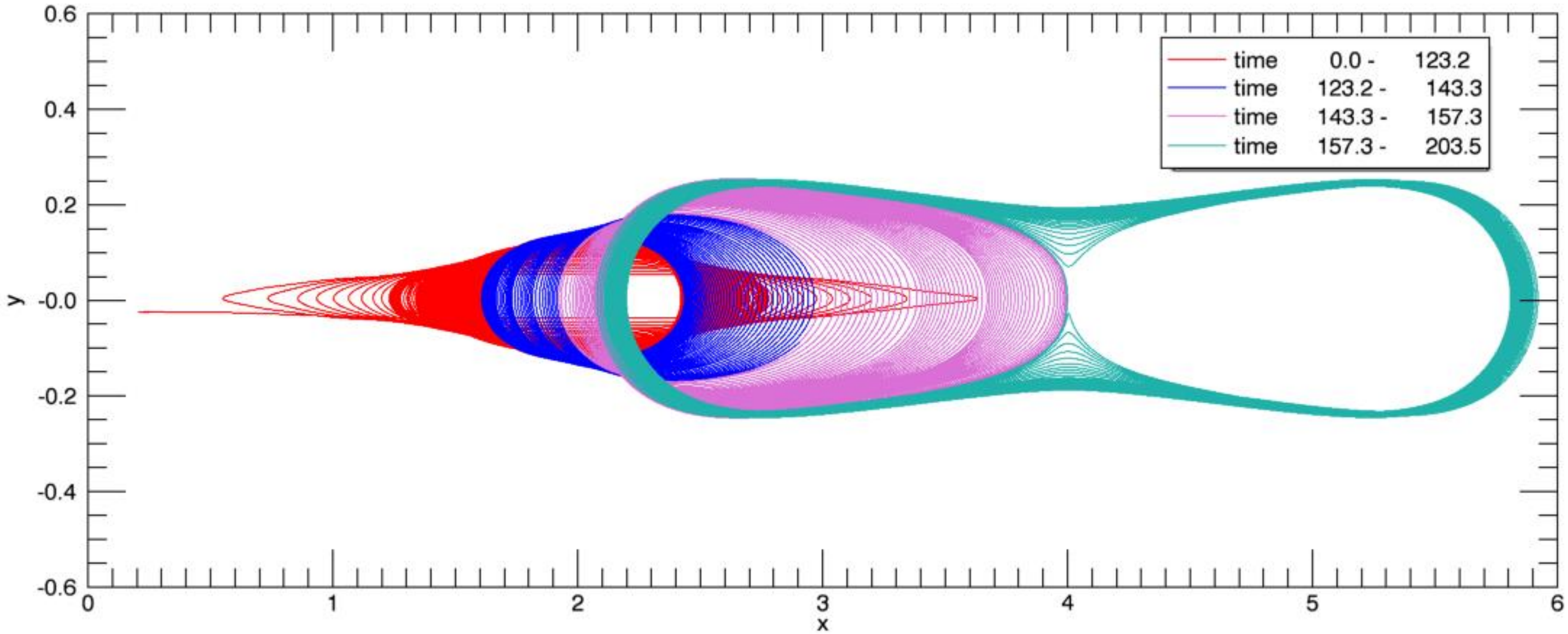


Particle energy against x position

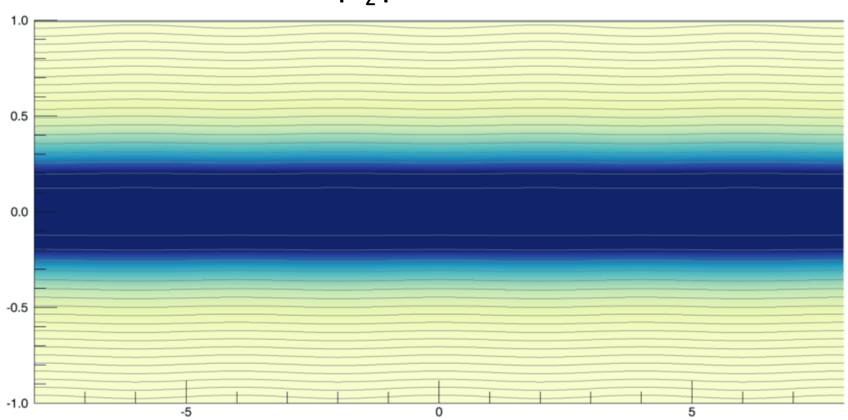


Long domain with island coalescence - trajectories

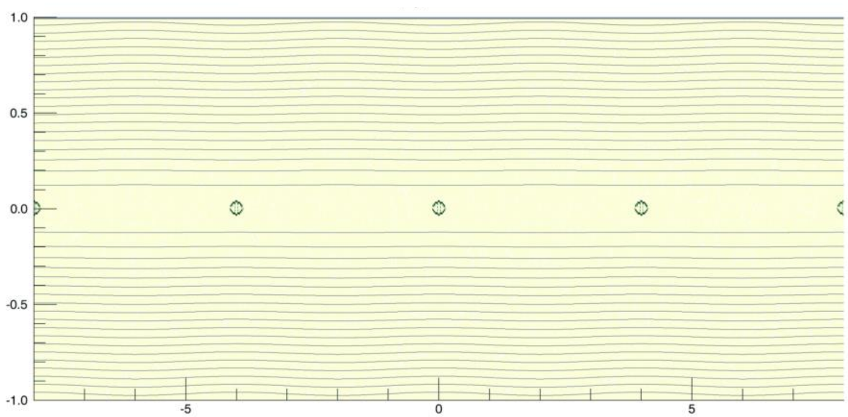
Position in **x-y** plane



$|J_z|$ & B lines

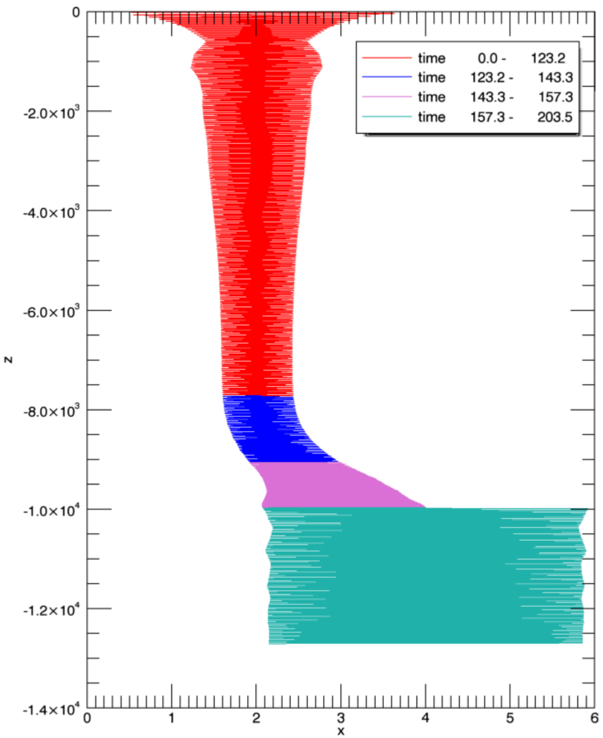


$|E_{//}|$ & B lines

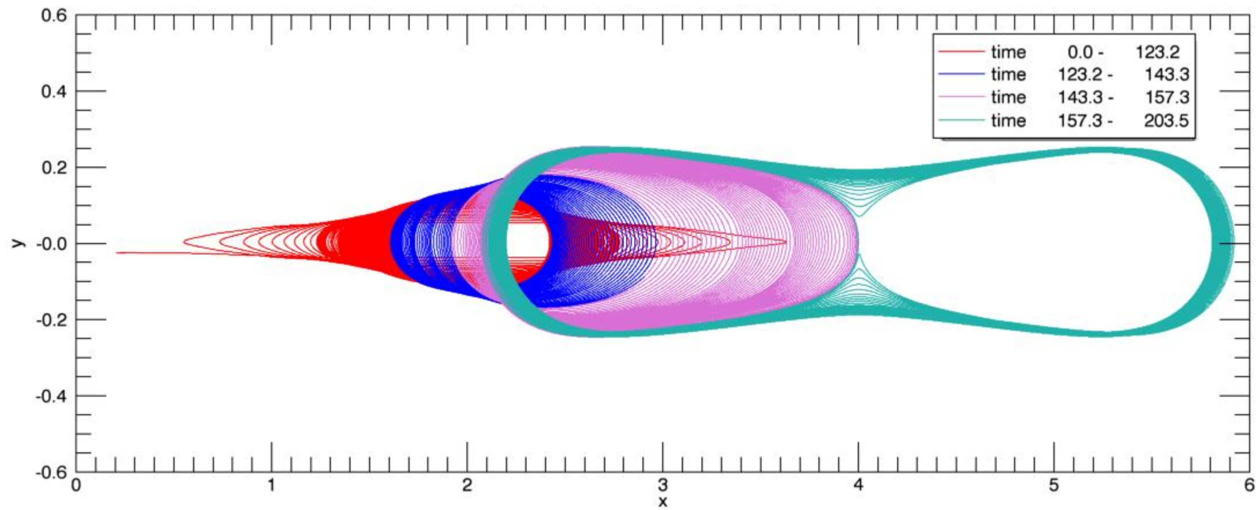


Long domain with island coalescence - trajectories

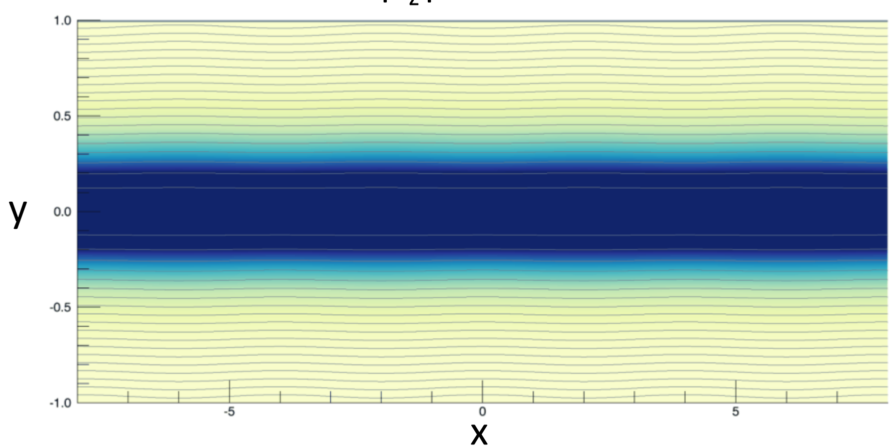
Position in **x-z** plane



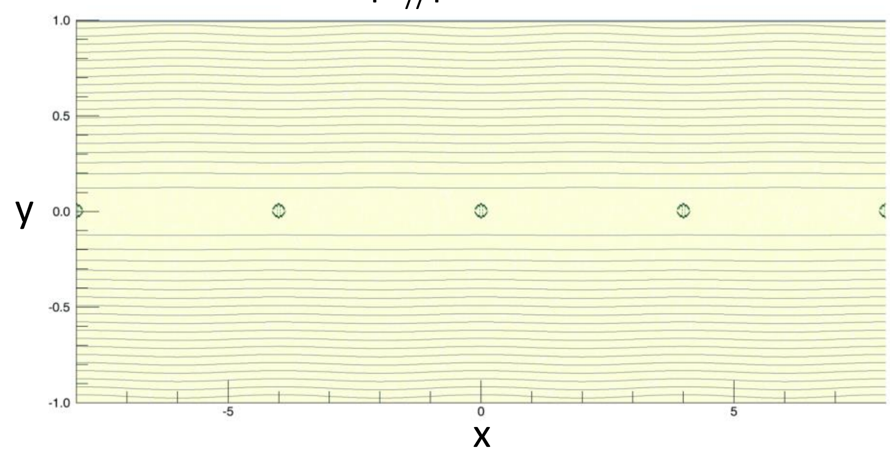
Position in **x-y** plane



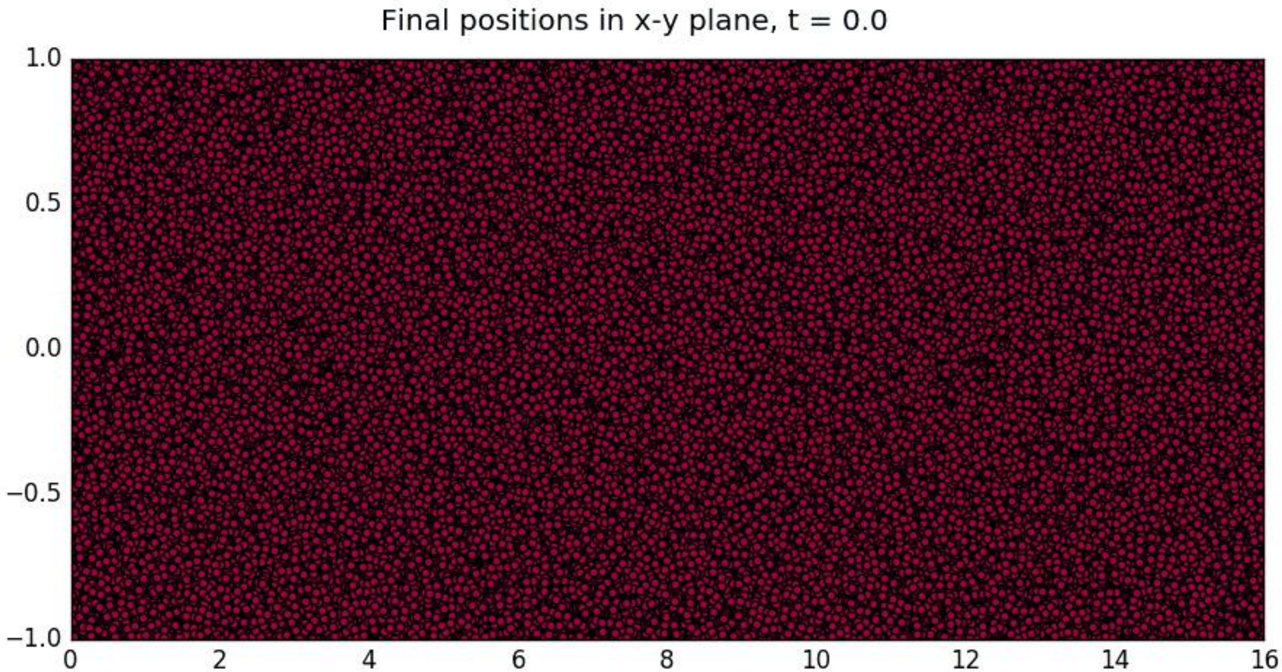
$|J_z|$ & B lines

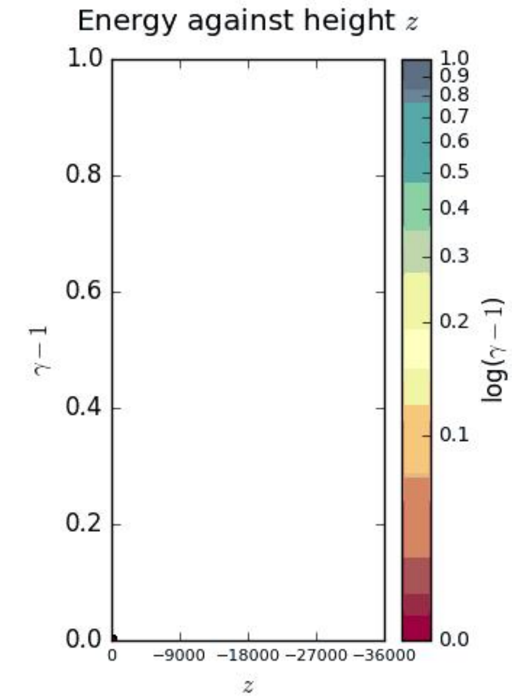


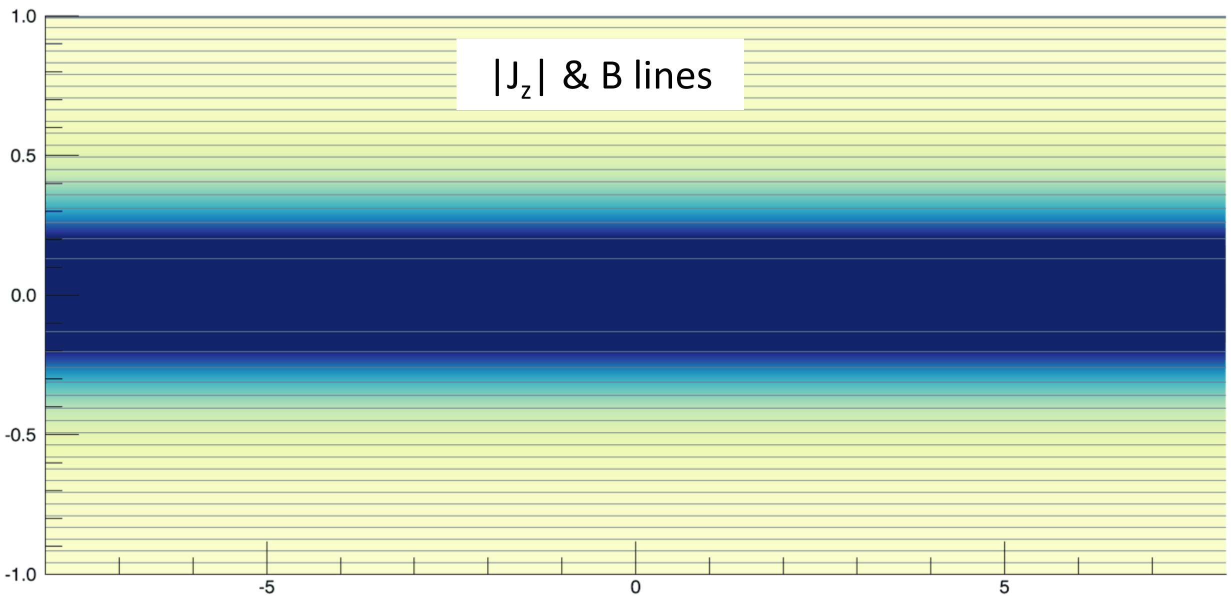
$|E_{//}|$ & B lines

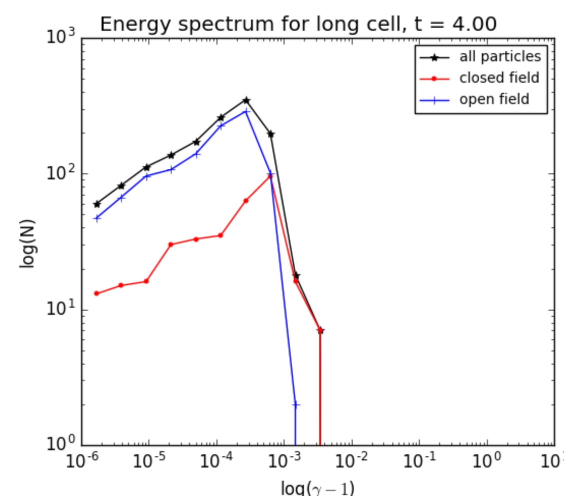


Long domain with island coalescence –ion distribution









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Summary & future work

- Particles on closed field (magnetic islands) are preferentially accelerated due to concentration of electric field about separatrices
- Island coalesence second step of magnetic reconnection & particle acceleration.
- Electric fields in coalesence are very localised and in reverse direction
- Forced reconnection and island coalescence could play a role in multi-stage acceleration in solar flares

- Further analysis of particle energisation in 2D fields
- 3D geometries
    - Islands → twisted flux ropes (kink instability?)
    - Reconnection on different resonant surfaces → island overlap (stochastic fields?)