Coronal heating by nanoflares: a reconnection model

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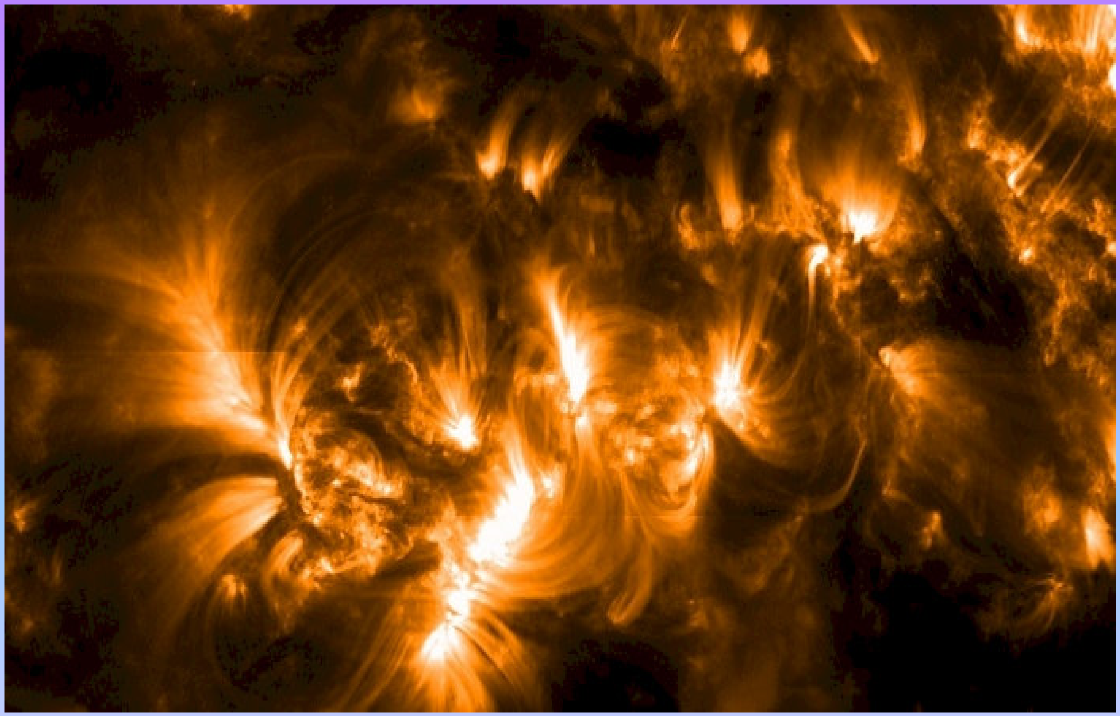
- Predicting coronal heating by nanoflares: using relaxation theory
- Two-dimensional relaxed states
- Nonlinear simulations



Flares and nanoflares

- Large events (flares) are insufficient to heat corona. But coronal heating may be a superposition of many smaller flare-like events down to "nanoflares" or below (10^{17} -10^{20} J) *Parker 1988*
- Space observations suggest that sporadic energy release events are ubiquitous in solar atmosphere
- The primary energy release mechanism in nanoflares is magnetic reconnection
- Are nanoflares sufficiently frequent to heat corona? What is distribution of event sizes?

Magnetic helicity and relaxation

- Global magnetic helicity $K = \int_V \mathbf{A}.\mathbf{B} dV \quad (\nabla \times \mathbf{A} = \mathbf{B})$ conserved during magnetic reconnection - dissipated much more slowly than magnetic energy in highly conducting plasmas
- A disrupted field relaxes to a state with minimum magnetic energy subject to conservation of helicity *(Taylor, 1974)* – a constant-α (linear) force-free field

$$\nabla \times \mathbf{B} = \alpha \mathbf{B}, \quad \alpha = \frac{\mu_0 j}{B}$$

Coronal heating by relaxation

- Coronal field is stressed by slow photospheric footpoint motions into a nonlinear force-free field (variable *α)*

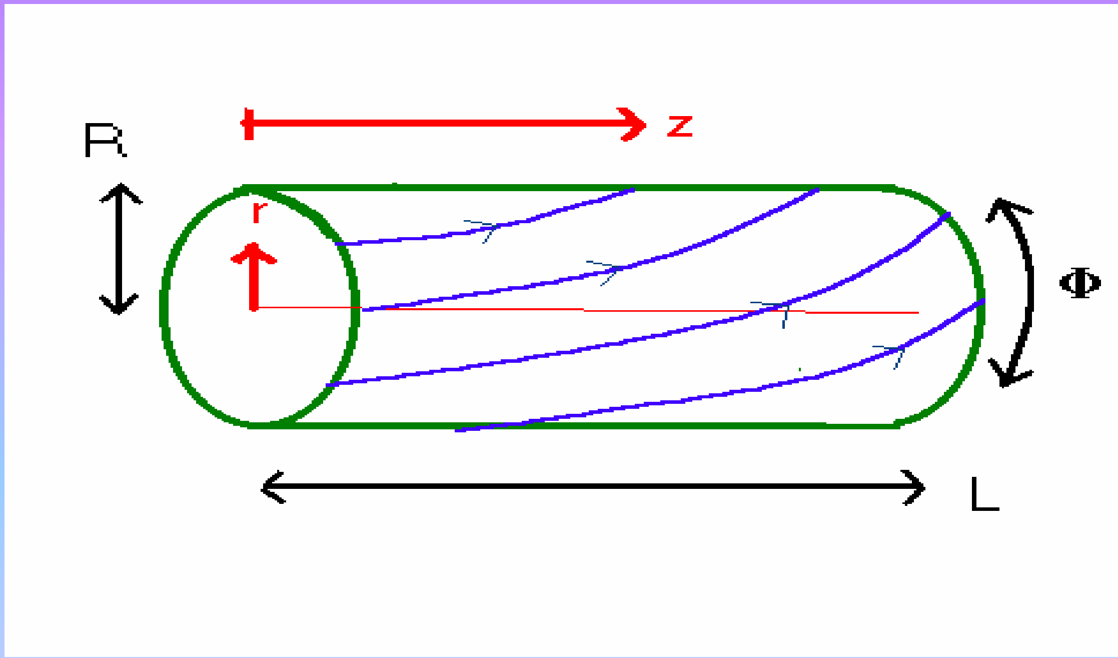
$$\mathbf{j}\times\mathbf{B}=\mathbf{0}\Rightarrow\nabla\times\mathbf{B}=\alpha(\mathbf{r})\mathbf{B}$$

- The stressed field relaxes – releasing free magnetic energy as heat, conserving helicity - to a constant-*α* state *(Heyvaerts and Priest, 1984*)
- **A dynamic episode (heating event) must have a trigger - we propose this is the onset of ideal instability, with dissipation in current sheets due to fast reconnection in the nonlinear phase**

Model problem - cylindrical loop

- A coronal loop evolves through equilibria in response to slow footpoint motions - when it becomes linearly kink unstable, a dynamic heating event is triggered
- Energy dissipation during the nonlinear dynamic phase found from relaxation theory

Length L, radius R - line-tied at photosphere ($z = 0, L$), conducting wall at $r = R$ in stability analysis



Initial (stressed) magnetic fields

- Parametrise profile $\alpha(r)$ by two-layers

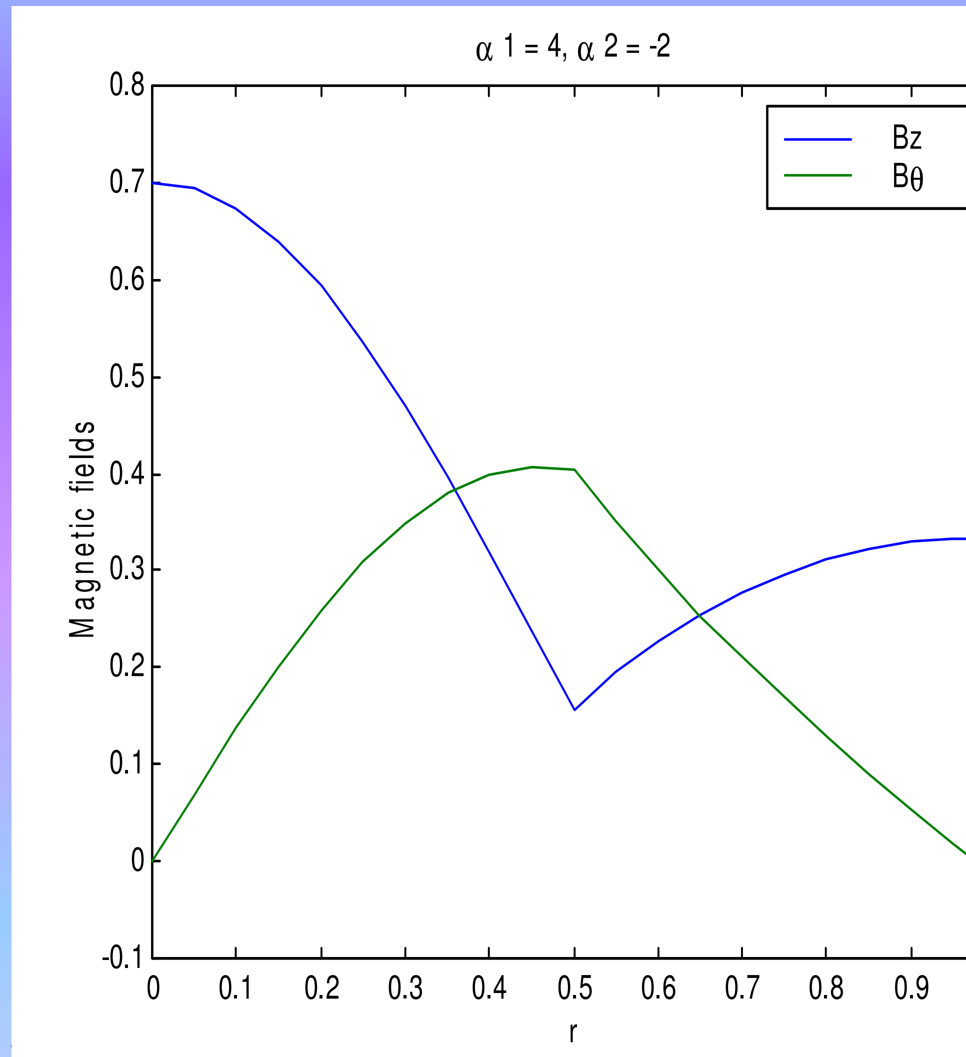
$\alpha = \alpha_1, \quad r < R_c$

$\alpha = \alpha_2, \quad r > R_c$

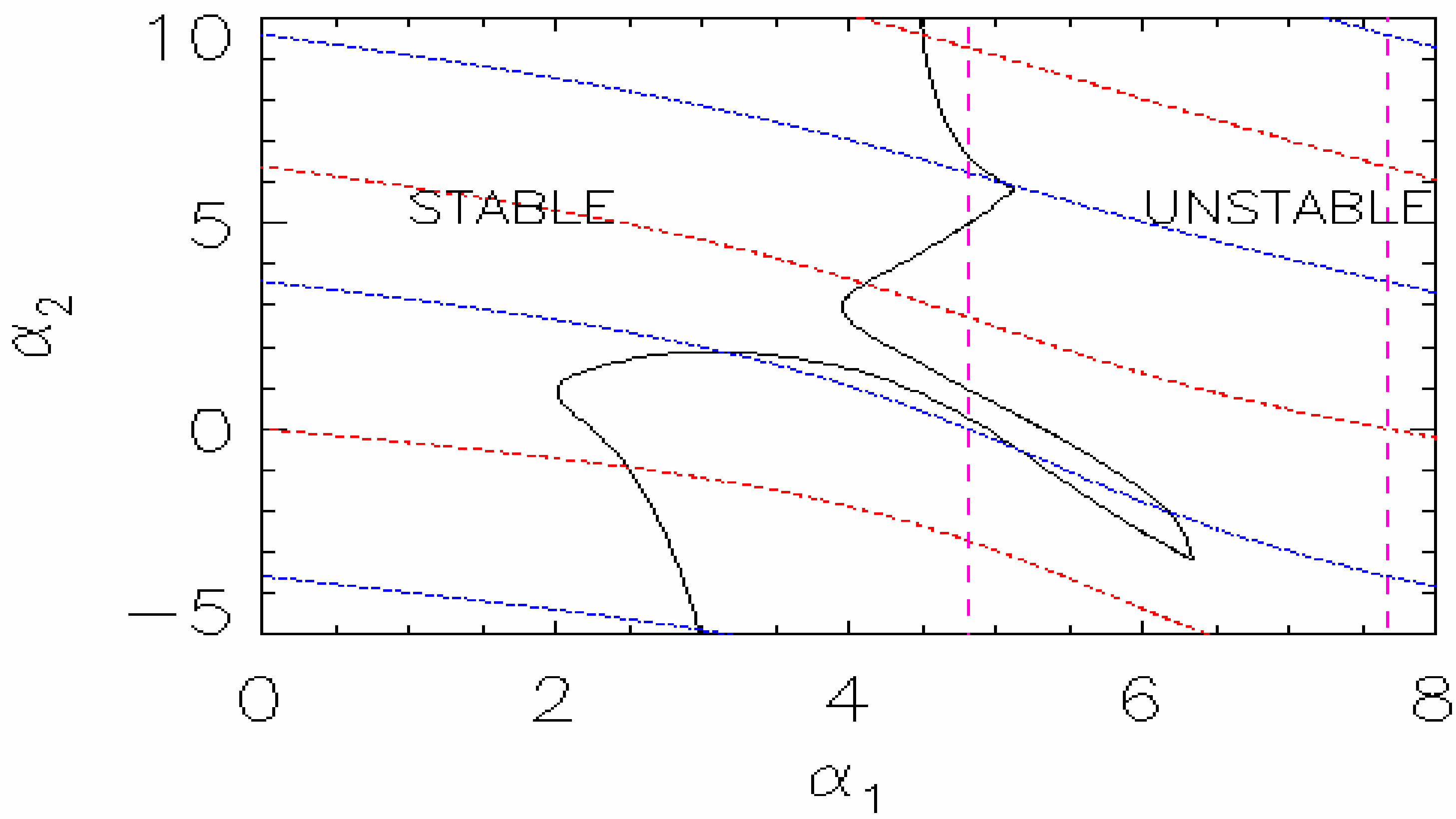
- α_1, α_2 determined by footpoint twist profile

$$B_z = B_1 J_0(\alpha_1 r),$$
$$B_\theta = B_1 J_1(\alpha_1 r), \ r < R_c;$$

$$B_z = B_2 J_0(\alpha_2 r) + C_2 Y_0(\alpha_2 r),$$
$$B_\theta = B_2 J_1(\alpha_2 r) + C_2 Y_1(\alpha_2 r), r \geq R_c$$



Marginal ideal stability threshold
CILTS code, *m* =1 modes (*L*/*R* = 20)



Energy release

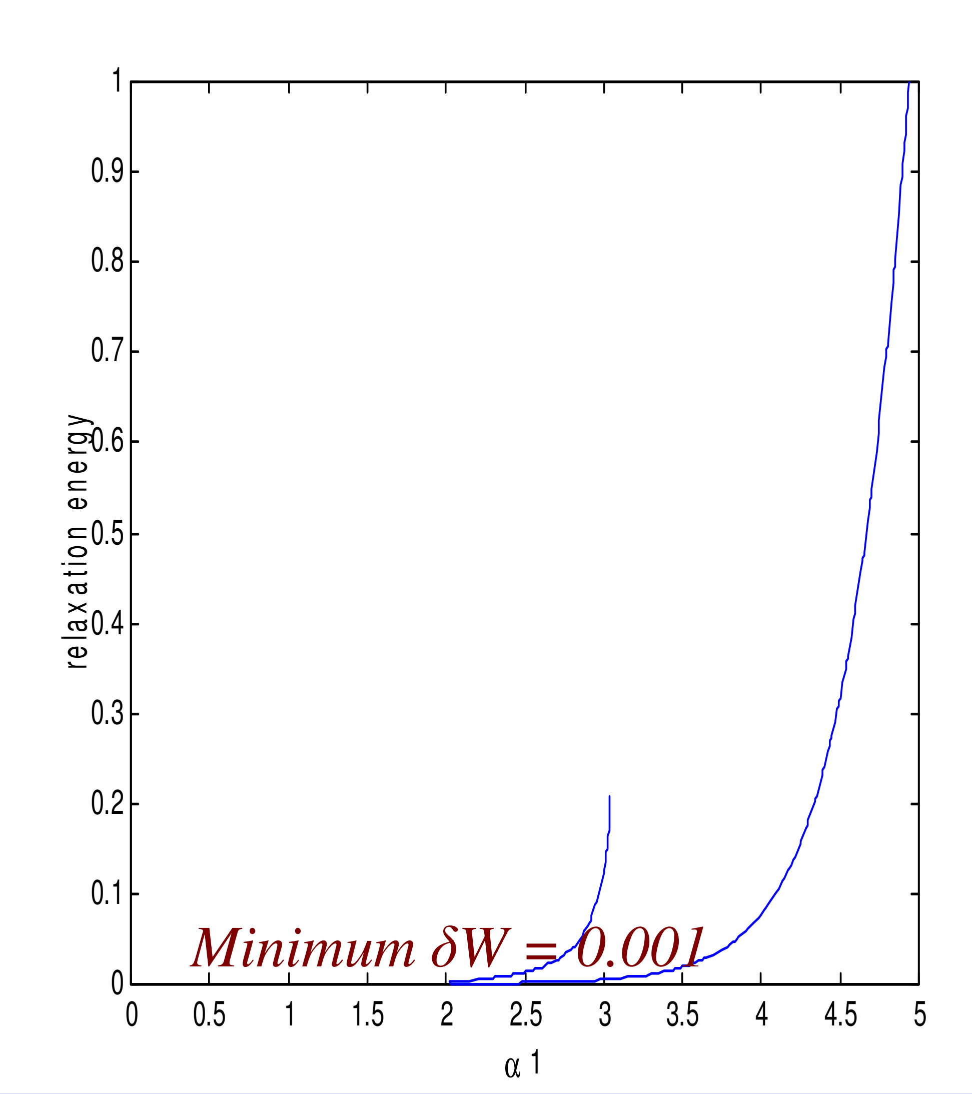
- Initial field with marginally stable current profile α_1,α_2
- Relaxed state with constant α given by

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

(also conserve axial flux)

- Energy released as heat

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



Results of nanoflare model

- For typical small loop L = 20 Mm, R = 1 Mm, B = 0.003 T, heating events in the range 10^{18} J - 3 $\times 10^{20}$ J
- Minimum heating event size for given loop - "elemental nanoflare"
- The process repeats - field evolves, goes unstable, relaxes → heating by a series of transient events of various sizes (about 3 orders of magnitude)
- The distribution of events depends on the spatial/temporal spectrum of driving photospheric motions - small events are more frequent

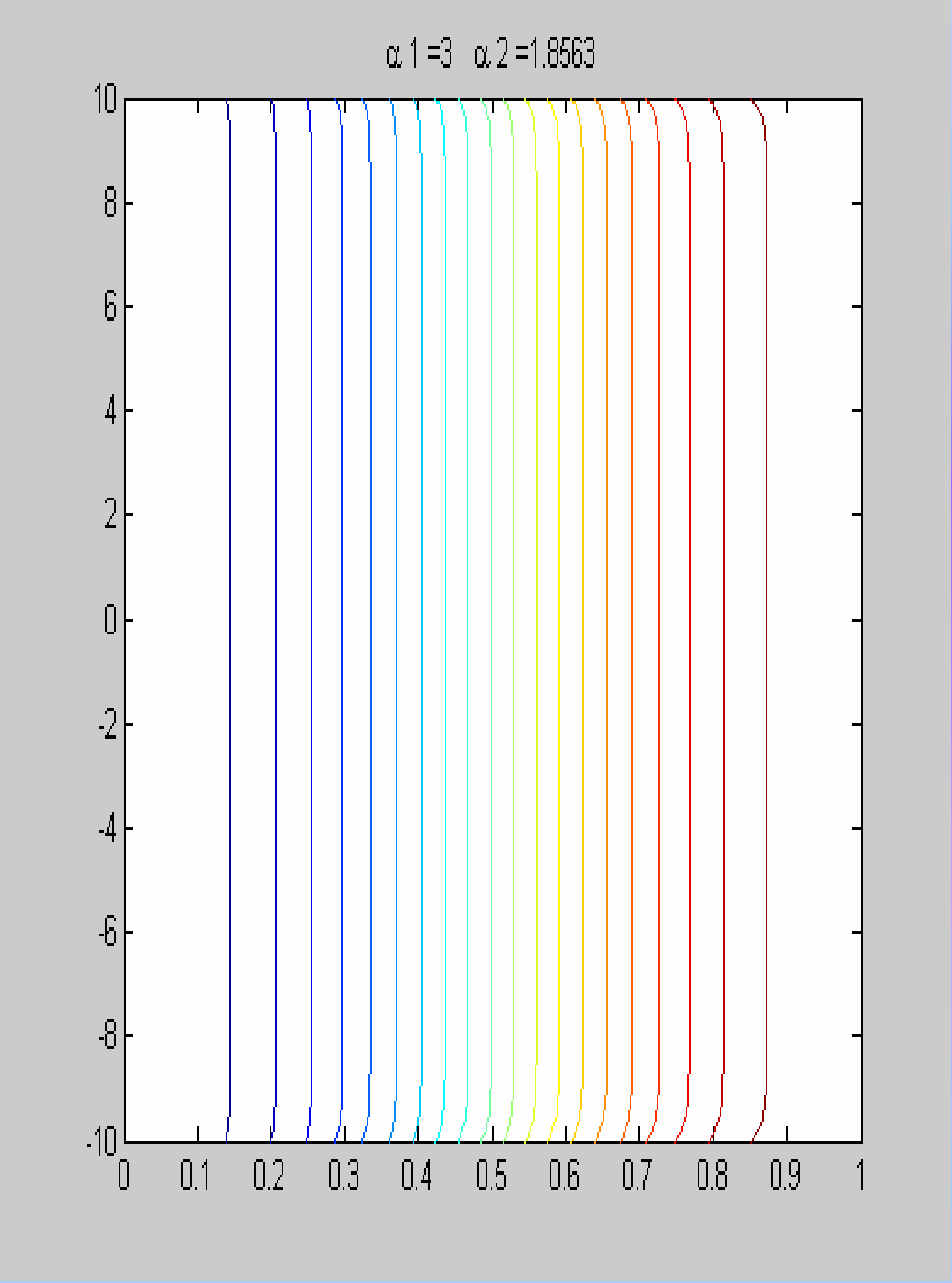
2D relaxed states

- So far, assumed relaxed state (constant- α field) is 1D - but this field has different $B_z(r)$ at ends and hence footpoints are not fixed during relaxation
- Relaxed state with conserved footpoint positions is 2D field $\mathbf{B}(r,z)$

$$\psi = \frac{\psi_0 r J_1(\alpha r)}{R J_1(\alpha R)} + \sum_n c_n r J_1\left(\gamma_n \frac{r}{R}\right)\frac{\cosh(k_n z)}{\cosh(k_n L)}$$

where c_n calculated to match initial (α_1, α_2) field at $z = 0, L$

- For large *L/R*, 2D field is very close to 1D constant-α state except in thin boundary layers near footpoints *(see Browning and Hood, 1988)*
- Magnetic energy and helicity of 2D field also very close to 1D values - hence little effect on energy release except for short fat loops *(Lothian and Browning, 2000)*



Nonlinear numerical simulations

- Solve 3D MHD equations with Lagrangian code Lare3D (*Arber et al, 2001),* 81^3 grid points
- Initial state is unstable 2- α equilibrium
- Loop embedded within potential field in square box ($L_x = L_y = 3R$) - stability threshold re-calculated to include outer potential layer (destabilising)
- Test cases (α_1, α_2) = (2.3,0.01) and (2.3, 1.5)
- Initial numerical growth rate compares well with linear predictions (e.g. numerical $\gamma \approx 0.2$, linear $\gamma \approx$ 0.15 for case 2)

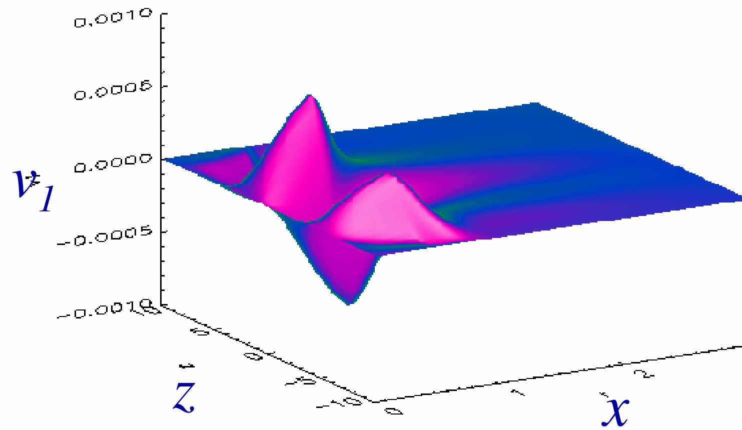
$$\alpha_1 = 2.3, \alpha_2 = 0.01$$

Numerical
- current isosurfaces

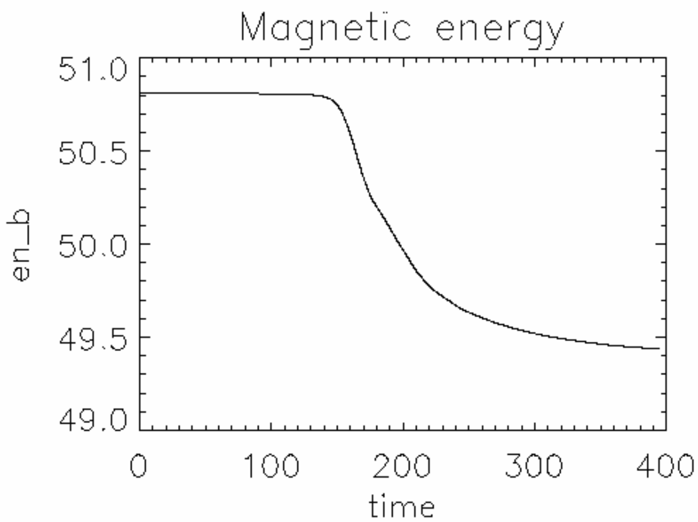
Linear eigenfunctio
vs. *x*, *z*

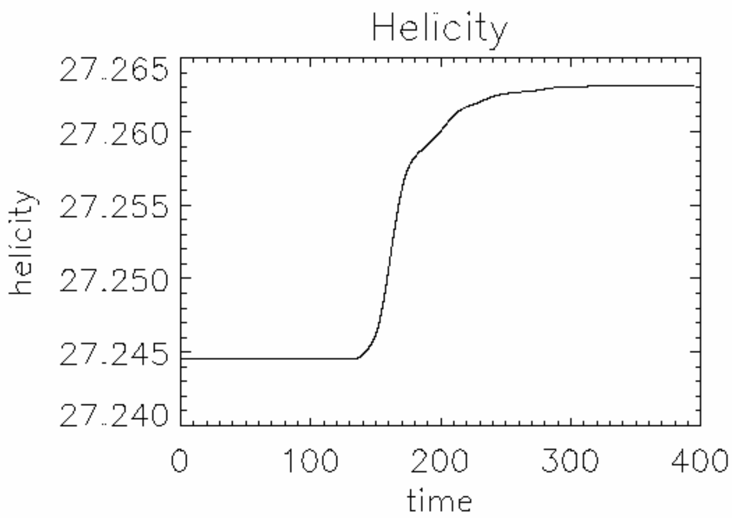
$t = 100 t_A$

$t = 120 t_A$



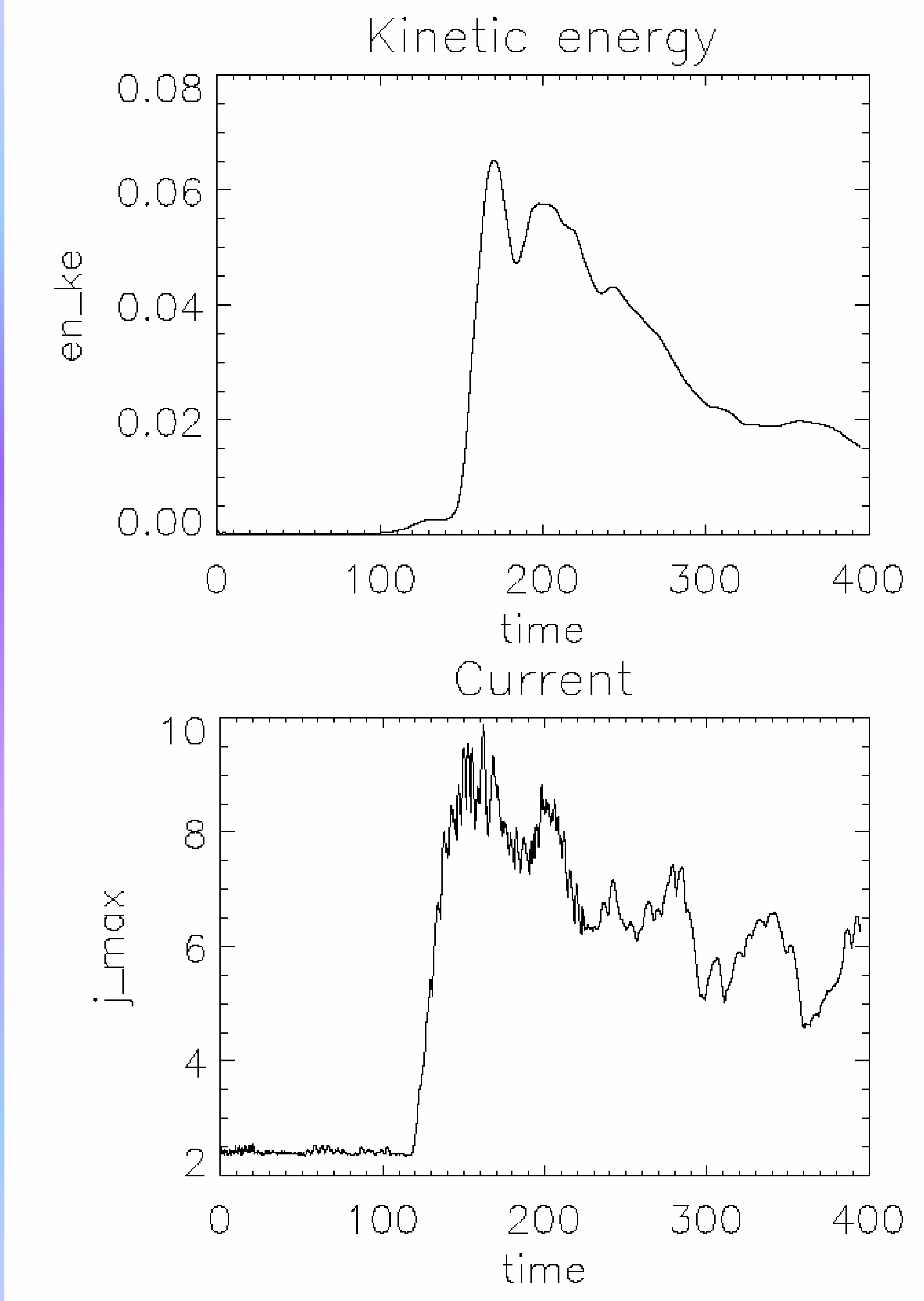
Time evolution of magnetic energy and helicity





$$\frac{\Delta W}{W} \approx .01, \frac{\Delta K}{K} \approx .0003$$

- Helicity is conserved better than energy



- Some evidence of flattening of α profile but “spikes” remain
- Simulation cannot be run long enough for fully relaxed state to be attained current sheets still present, kinetic energy still decaying at end of run

Summary

- A model predicting heating by transient events or "nanoflares" of a wide range of magnitudes has been presented
- Episodic heating is triggered by ideal MHD instabilities, energy dissipated by magnetic reconnection during relaxation to minimum energy state
- 2D relaxed states with line-tying have been calculated - close to 1D fields for long thin loops
- The nonlinear evolution has been explored numerically with a 3D MHD code - agrees well with linear stability analysis - full comparison with relaxation theory not yet achieved