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On solar coronal heating by forced magnetic reconnection

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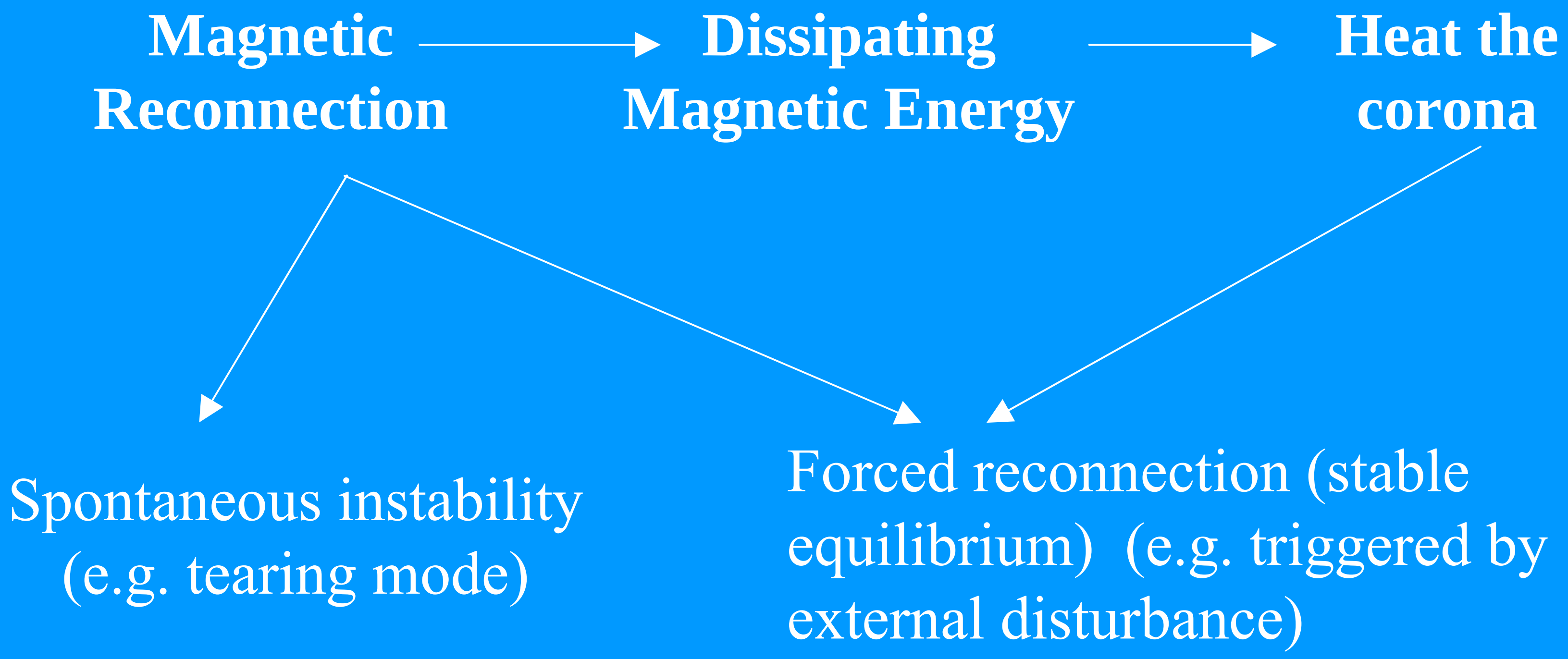
Basic idea



Magnetic Reconnection → **Dissipating Magnetic Energy** → **Heat the corona**

Spontaneous instability (e.g. tearing mode)

Forced reconnection (stable equilibrium) (e.g. triggered by external disturbance)

Brief Background

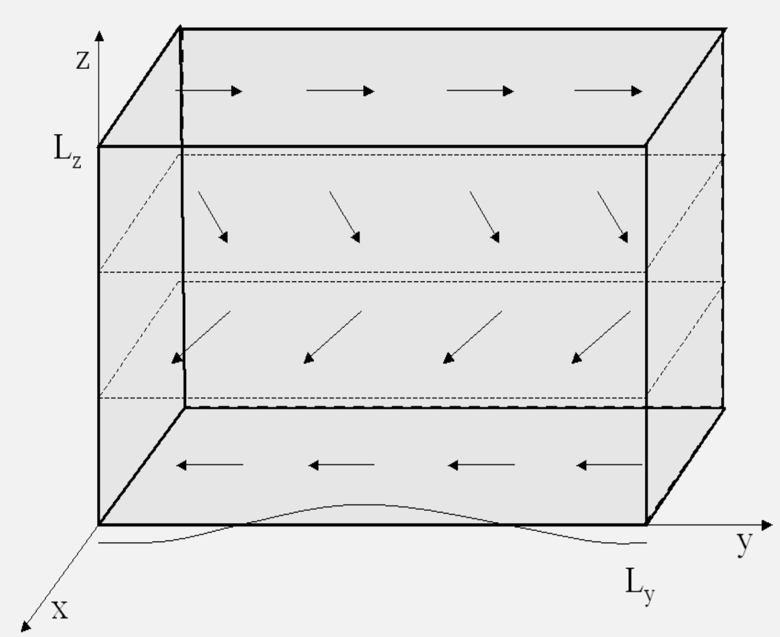
Forced magnetic reconnection can occur in stable equilibrium.
Basic scenario (Hahm & Kulsrud, 1985)

Sine curve
↓
Current sheet
↓
Reconnects

MHD Linear theory for energetics of forced reconnection in a sheared force-free field (Vekstein & Jain, 1998; 1999)

The Model and Results

Simulation Domain



Initial magnetic field

$$\begin{pmatrix} B_x \\ B_y \\ B_z \end{pmatrix}(z,t=0) = B_o \begin{pmatrix} \cos[\alpha(z-L_z/2)] \\ \sin[\alpha(z-L_z/2)] \\ 0 \end{pmatrix}$$

Perturbation at the boundary

$$v(z=0,t) = \begin{cases} -\delta_o(\omega/2\pi)(1-\cos\omega t)\cos ky\,\hat{z} & if\ 0 \le t \le 2\pi/\omega \\ 0 & if\ t > 2\pi/\omega \end{cases}$$

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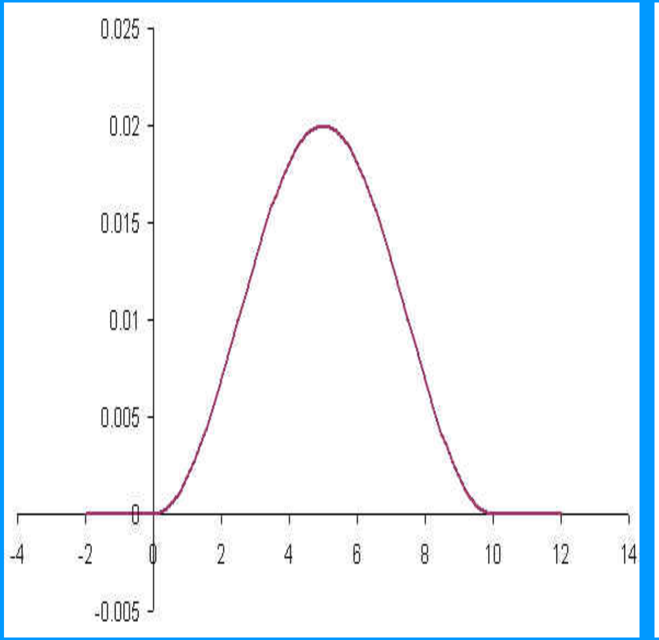
Numerical simulations

(Browning et al. 2001; Jain et al. 2005)

Perturbation at the boundary



MHD Equations

$$
\begin{aligned}
\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v}\cdot\nabla\mathbf{v} &= \rho^{-1}\left[-\nabla p + \mathbf{J}\times\mathbf{B} + \nu\nabla^2\mathbf{v}\right] , \\
\frac{\partial \rho}{\partial t} + \rho\nabla\cdot\mathbf{v} + \mathbf{v}\cdot\nabla\rho &= 0, \\
\frac{\partial p}{\partial t} &= -(\gamma-1)p\,\nabla\cdot\mathbf{v} - \nabla\cdot(\rho\mathbf{v}) , \\
\frac{\partial \mathbf{A}}{\partial t} &= (\mathbf{v}\times\mathbf{B}) - \eta\,(\mathbf{J}-\mathbf{J}_o) , \\
\mathbf{B} &= \nabla\times\mathbf{A} . \\
\mathbf{J} &= \nabla\times\mathbf{B} ,
\end{aligned}
$$

Boundary conditions

$\mathbf{V}(z{=}L_z, t) = 0$

Lateral boundaries ($y = 0$ & L_y): periodic Condition

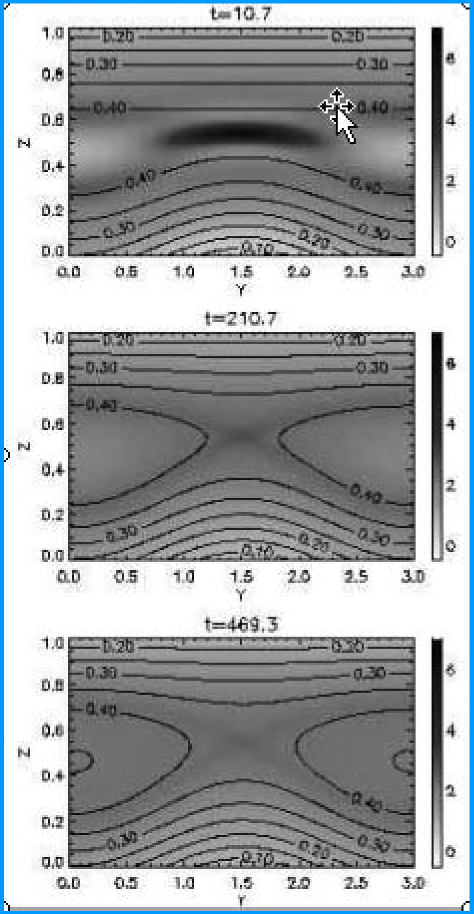
$\mathbf{E} + \mathbf{V} \times \mathbf{B} = 0$ on the boundaries.

Initial conditions

$\rho = 1,\ p = \beta_0$

Numerical code: Two point centred finite difference: Runga-Kutta Gill Method (Kusano, 2001)

Time snapshots for J_x (grey scale) and A_x (contours)



- Current sheet at the resonant surface
- Flux contours follow the boundary perturbation
- Magnetic islands form
- Equilibrium with current sheet is well described by ideal MHD

Estimated transition time

$\tau_\eta S^{-1/2}$

Key findings

$$\Delta E_M \propto \frac{B_o^2}{2\mu}\left(\frac{\delta_o}{L_z}\right)^2 f(\alpha, k, L_z)$$

Boundary displacement → some energy into the field

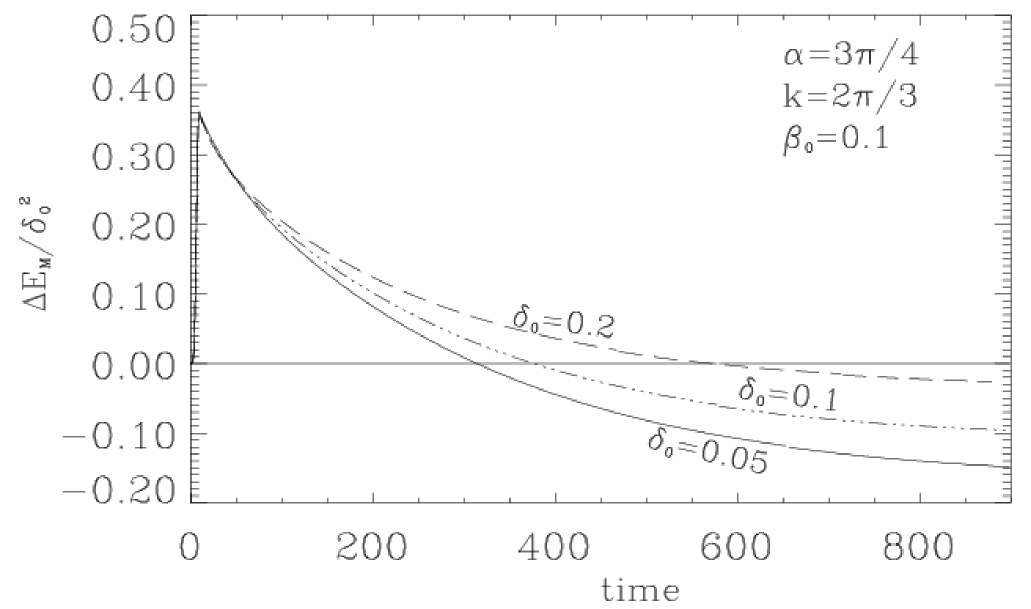
Release energy > poynting flux

Thus, some stored energy of the initial equilibrium is released.

- Boundary displacement is thus a **trigger** for the heating event.
- Forced reconnection dissipates energy even if the initial equilibrium is tearing stable & **more** energy when shear is increased.

Total magnetic energy release $\Delta E_M = E_i - E_r$

$$E = \frac{1}{L_y L_z} \int_0^{L_y} \int_0^{L_z} \frac{B^2}{2}(y,z,t)\, dz\, dy$$



Key findings

The energy release is affected by nonlinearities

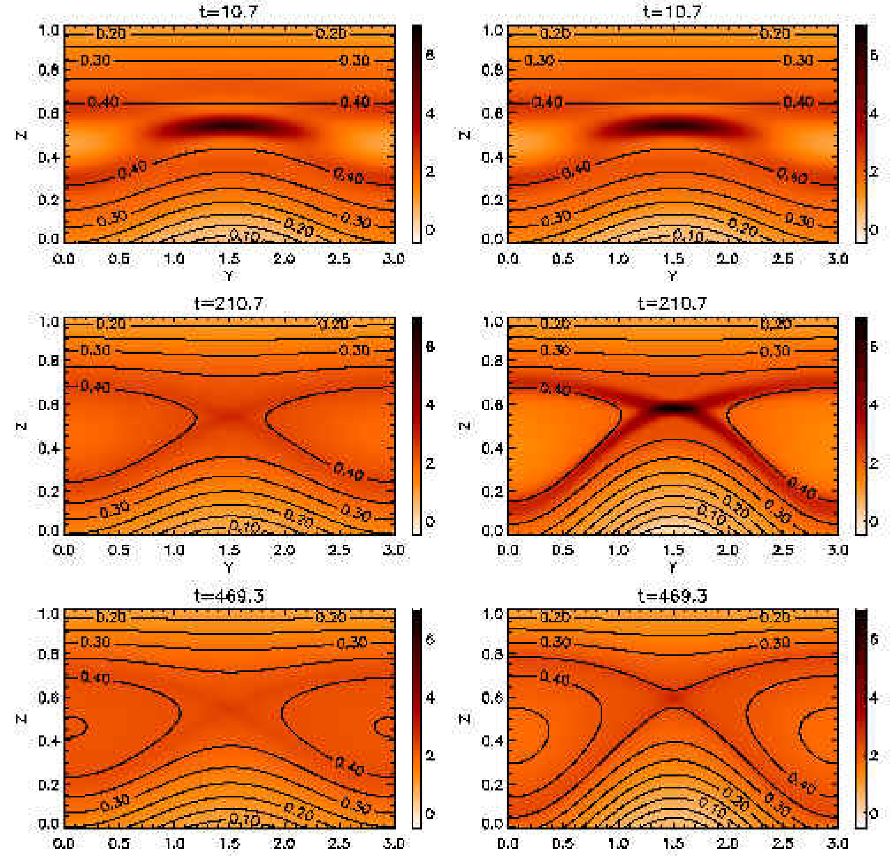
More energy is released for larger shear
(field is tearing unstable if the shear is very large)

Multi-pulse driving

Nanoflare coronal heating scenario suggests that energy release should occur as a sequence of events

Temporal Development
comparison between one pulse and two pulse driving

- First column is for when the boundary displacement is applied between 0 < t < 10
- Second column is for when displacements are applied between 0 < t < 10 and 200 < t < 210



Key finding

Formation of current sheet along the separatrix is a nonlinear effect

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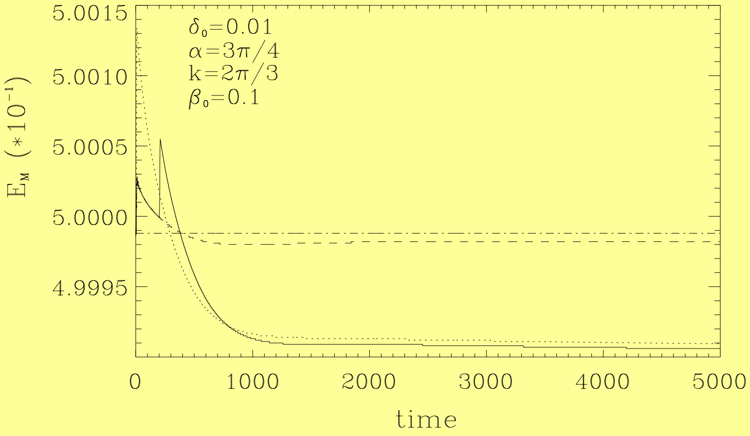

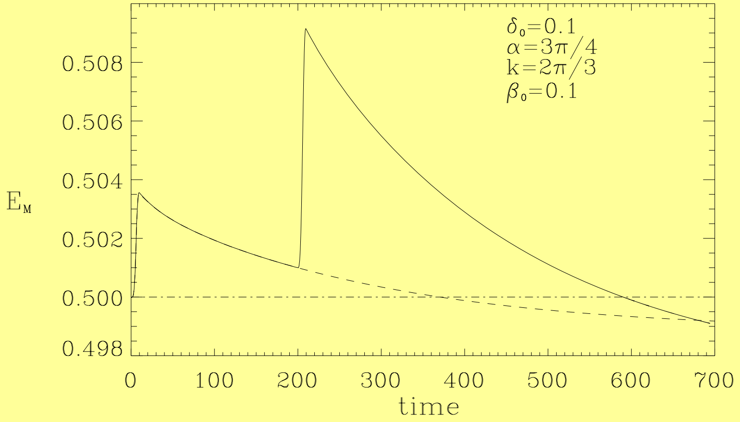

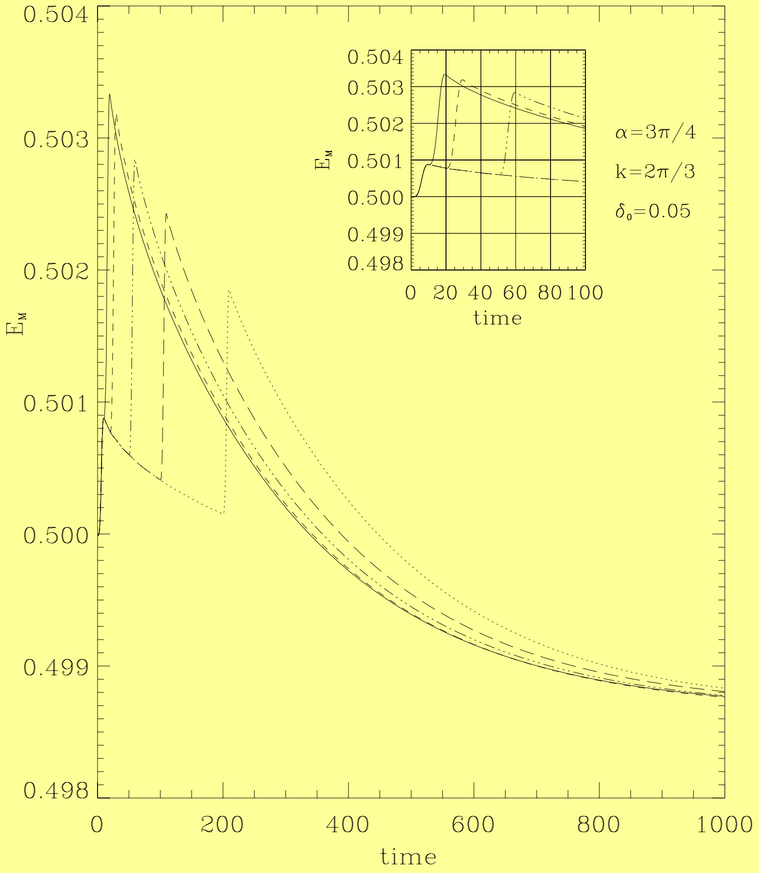

Key findings

- Magnetic energy release depends on the magnitude and the timing of the successive perturbation.
- Two separate pulses of same magnitude & wave no. release slightly less energy than a single combined pulse.

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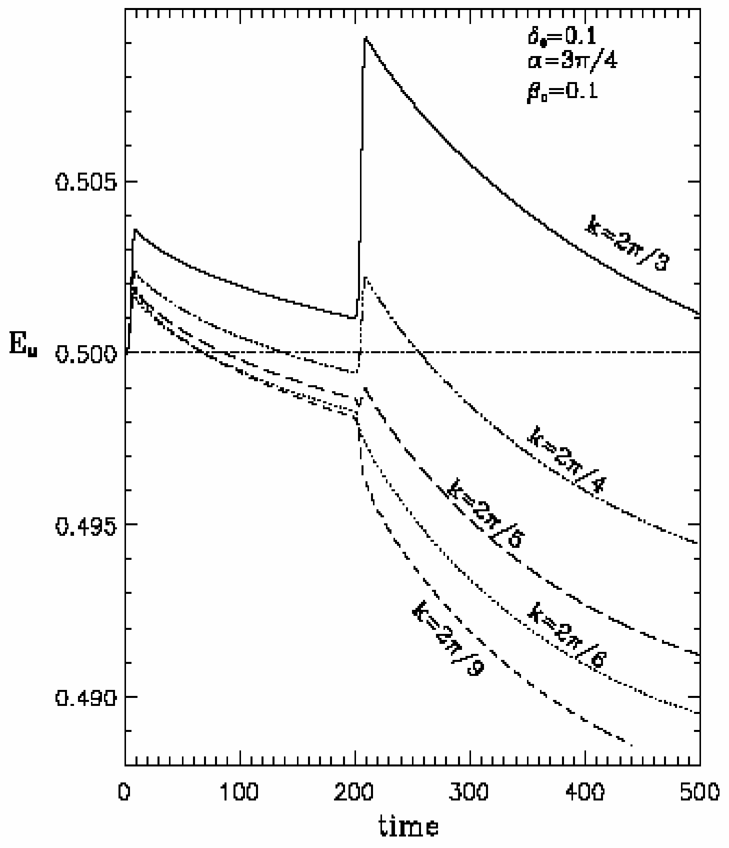
Different Wavelength perturbations

- The **spike** of energy input (due to second boundary displacement) gets smaller as k decreases



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Key findings

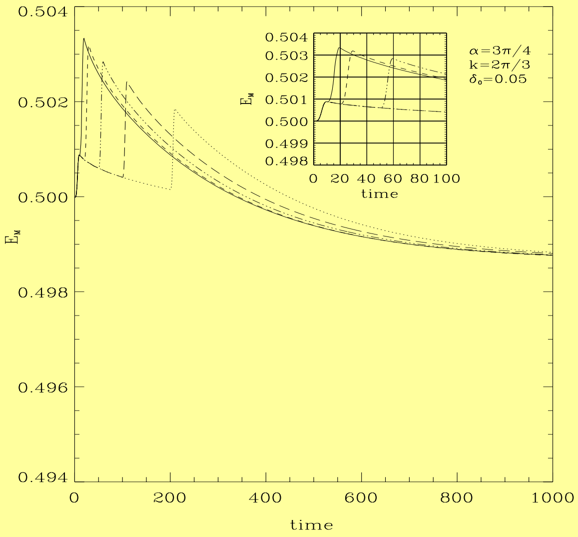
(still under investigation!)

Final state energy is lower as the wavenumber becomes smaller & the energy release is slightly more.

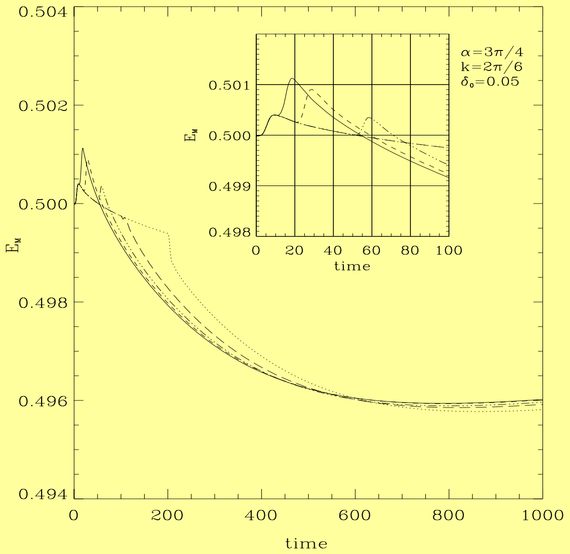
For small wavenumber, close to tearing instability threshold $(\alpha^2 - k^2)^{1/2} \leq \pi$ perturbations are large even for small δ_0 so nonlinear effects are very significant

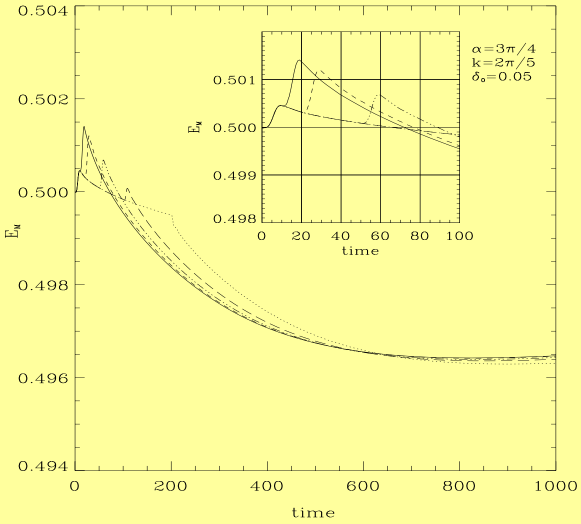
The **spike** of energy input due to second boundary displacement gets smaller as k decreases

K=2 π /3

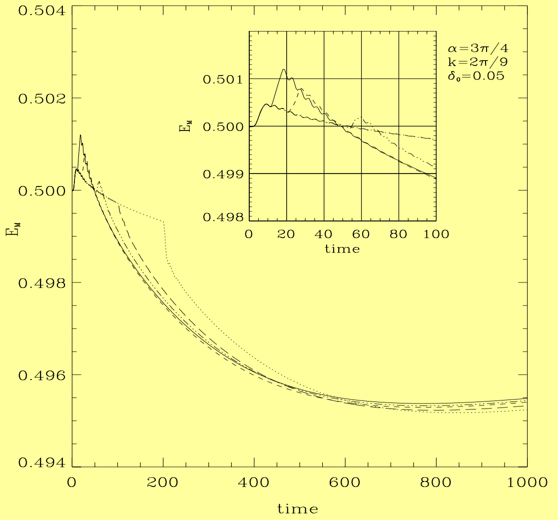


K=2 π /5





K=2 π /6



K=2 π /9

Main Conclusions

- Forced reconnection is a plausible candidate for solar coronal heating
- Energy release is triggered by boundary disturbances and is affected by nonlinearities
- Energy release depends on the timing as well as the magnitude and wavelength of the successive perturbations

Details in Jain, Browning & Kusano (2005), Phys. Plasmas, 1

Main comment

A property of forced reconnection is that each driving pulse releases some stored energy of the initial field (acting more as a catalyst than a primary source of energy). This cannot continue indefinitely as the energy of the initial field will become depleted !

So, to maintain a steady state heating scenario, there must be some energy supply to replenish the background field.

Future Work

Immediate

Consider successive pulses of different magnitudes (interesting because second driving pulse will be out of phase with the pre-existing island chain)

In the corona, footpoint motions are due to exploding granules which are likely to be continuous and quite possibly randomly distributed, so a random distribution for the magnitudes, width and time intervals between the pulses would be good for calculating evolution of the field and distribution of the energy releasing event.

Distant

Include more physics
(e.g. viscosity, proper energy balance, nonuniform sheared field, Hall effect etc.)

3D MHD model

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The end