CORONAL HEATING BY FORCED MAGNETIC RECONNECTION WITH MULTI-PULSE DRIVING

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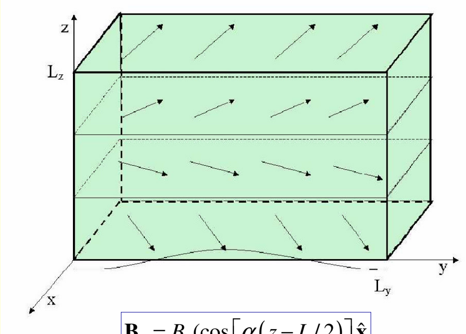
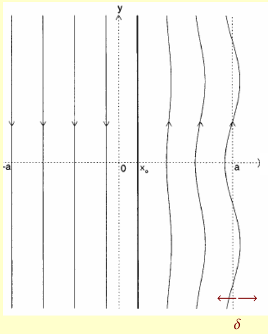
1. Forced reconnection and coronal heating

- Magnetic reconnection is a prime candidate for a solar coronal heating mechanism
- Heating is likely to be due to the combination of many individual "nanoflare" events - the underlying dissipation mechanism being reconnection, as in large solar flares
- In the solar corona, reconnection can be triggered by external disturbances such as photospheric footpoint displacements, emerging flux - this can be modelled as forced magnetic reconnection

- The forced reconnection scenario [1] considers a transient sinusoidal displacement applied to the boundary of an equilibrium field - the disturbance is slow compared with an Alfven time
- A linear theory (small driving displacement) has been developed for solar coronal fields, focusing on the energetics [2]
- A sheared force free field is considered (right) with a driving disturbance applied at one boundary $z = 0$ of the form $\xi_z \sim \delta \cos(ky)$ ($\delta << L$) ($0 < t < 10t_A$)
- Two perturbed equilibria (below)
  - ideal equilibrium with current sheet at the resonant surface $k.B_0 = 0$, $z = L/2$ (flux function $\psi_0 + \psi_1^{(i)}$)
  - reconnected equilibrium with islands ($\psi_1^{(r)}$)

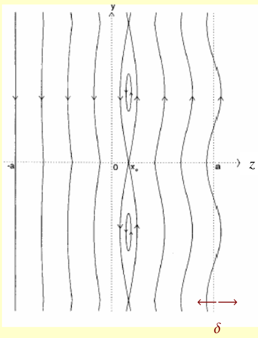


$$\mathbf{B}_0 = B_0(\cos\left[\alpha\left(z - L/2\right)\right]\hat{\mathbf{x}}$$
$$+B_0(\sin\left[\alpha\left(z - L/2\right)\right]\hat{\mathbf{y}}$$



← Current sheet equilibrium forms immediately after driving pulse

→Relaxes to reconnected equilibrium with islands, releasing free energy



- The energy dissipated as heat is the difference between the energy of the initial (ideal) equilibrium and the final (reconnected) equilibrium

$$\Delta W = \frac{B_0^2}{2\mu_0}\left(\frac{\delta}{L}\right)^2 f(\alpha L, kL)$$

- Energy release usually larger than energy input from driving pulse - external displacement is a trigger, allowing stored energy of initial field to be released
- Dissipated energy diverges (in linear theory) as the threshold for tearing instability is reached

- Here we consider the effects on forced reconnection of repeated driving displacements - this is to model the effects of successive heating events (nanoflares) which may interact

2. Nonlinear reconnection: the numerical model

- Solve 2D compressible adiabatic MHD equations numerically using 2 point centred finite differences and Runga-Kutta-Gill time integration; time normalised to Alfven time t_A

- Previous work [3] has used same code to investigate nonlinear effects of a single driving pulse

- Initial state is sheared force-free slab field (above) - perturb boundary $z = 0$ with transient pulses at successive times (here t_{pulse} = 0 and 200)

$$v_z(z=0,t) = \begin{cases} -\delta\frac{\omega}{2\pi}(1-\cos\omega t)\cos ky & \text{if } t_{pulse} < t < t_{pulse} + \frac{2\pi}{\omega} \\ 0 \text{ otherwise} \end{cases}$$

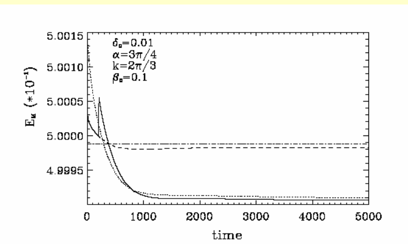
- Here we consider two successive pulses of equal magnitudes δ and wavelengths k. Duration of each pulse is $10t_A$.

- Initially parameters β=0.1, α =3π/4, k =2π/3

3. Multi-pulse driving: predictions of linear theory`

- Naively might expect two pulses to have twice the heating effect of a single pulse but this is not the case!
- For two driving pulses (each magnitude δ_0), the final state will be the reconnected equilibrium ($\psi_0 + \psi_1^{(r)}$) for $2\delta_0$
- Thus, if second pulse were applied immediately after first, this is just like driving with a displacement of $2\delta_0$ - hence energy dissipated is 4 times that of a single pulse of displacement δ_0
- Energy release could depend on timing of the driving pulses since field just before second pulse (and hence energy input) depends on its timing
- Immediately after second pulse, field will be a linear combination of reconnected ($\psi_1^{(r)}$) and ideal equilibria ($\psi_1^{(i)}$) for $2\delta_0$, with reconnected flux equal to that just before the pulse (island width initially unchanged)

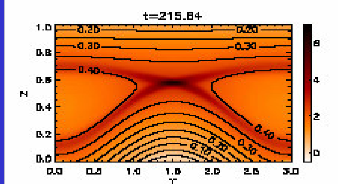
4. Multi-pulse driving: numerical results



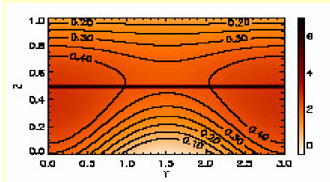
- Energy as a function of time (left) for two pulses (δ_0 = 0.01) - also shows single pulses of magnitude δ_0 and $2\delta_0$

- Note final state for two pulses is very close to that for single pulse $2\delta_0$

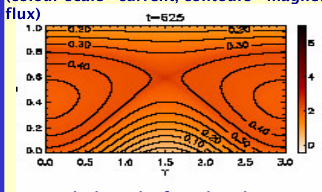
- Total energy release for two pulses is 1.8 × 10^{-4} compared with 2.2 × 10^{-4} single pulse $2\delta_0$ (depends on timing)



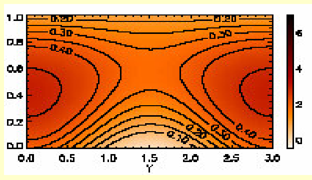
Nonlinear numerical results after second pulse - current sheet forms around separatrix (colour scale - current; contours - magnetic flux)



Linear theory after second pulse



Numerical results for relaxed state

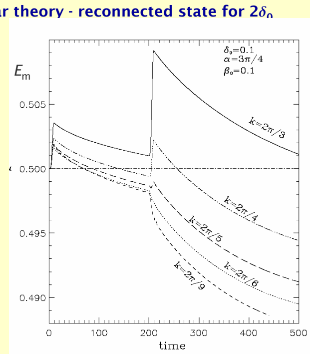


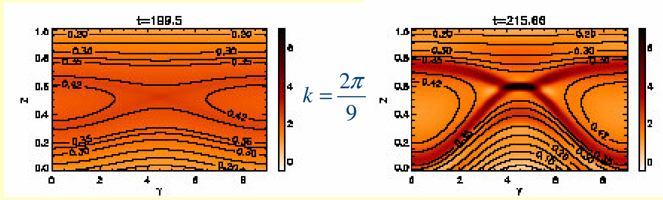
Linear theory - reconnected state for $2\delta_0$

- For smaller k, the "spike" of energy input after the second boundary displacement gets smaller and eventually disappears (right)

- This is associated with strong current sheet formation and very rapid reconnection which appears to be on a similar timescale to the energy input

- This may be a nonlinear effect since perturbations become very large for smaller k even for small boundary displacements - due to proximity to the tearing instability threshold [3]





5. Conclusions and further work

- Even in linear theory, total energy release of multiple heating events depends on the timing of events
- Heating events are not independent of each other; nonlinear effects are stronger for longer wavelength perturbations (closer to tearing instability threshold).
- After the second pulse, a current sheet forms along the pre-existing separatrix, which is not predicted by linear theory
- Future work will investigate: - the long wavelength case in which strong current sheets are formed; driving pulses of different wavelengths and magnitudes; also heating by random distributions of pulses

6. References

1. Hahm,T. and Kulsrud,R.M. Phys. Fluids 28, 2412 (1985)
2. Vekstein,G. and Jain,R. Phys. Plas. 5, 1506 (1998)
3. Browning,P.K. et al, Phys. Plas. 8, 132 (2001)

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