Investigating the Role of Magnetic Shear in the Onset of Magnetic Reconnection in the Corona

Work Package Meeting

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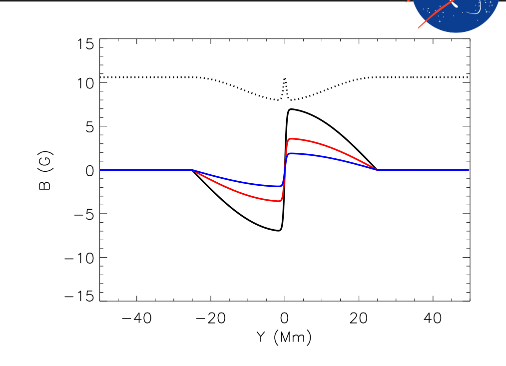
Magnetic Shear as a Criteria for 'Switch-On Nature'

- Model for sporadic coronal heating requires gradual build-up and rapid release
- Magnetic reconnection (plasmoid/tearing instability)
- Magnetic reconnection - how can this achieve rapid onset of large free energy release?
  - Magnetic shear - secondary (kink) instability of 3D version of plasmsoids
    - Dahlburg, Klimchuk, Antiochos
  - "Ideal tearing" - Current sheets become unstable to tearing on Alfven scales well before they get to S-P scaling width and below
    - Velli et al.
- We are going to investigate both in realistic coronal conditions, but start with magnetic shear

A Simple Coronal Experiment to Investigate Shear

- 3D sheared, force-free, modified Harris current sheet
  - $B_x(y) = B_{x,0} \tanh(y/a) \cos(\pi y/(L_y/2)$
  - $B_z(y) = \sqrt{(B_{z,0}^2 - B_x(y)^2)}$
- Coronal density ($10^{14} m^{-3}$) and temperature (1 MK)
- Lundquist number (based on L) of 10^6
- Initial velocity is random summation of various allowed 3D tearing modes
- Triply-periodic in all 3 dimensions
- Parameter study of magnetic shear ($B_{x,0}$) and current sheet length (L_x)



Name	L_x (Mm)	$B_{x,0}$ (G)	$B_{z,0}$ (G)	θ
1	100	7.0	10	80
2	100	3.6	10	40
3	100	1.9	10	20
4	20	7.0	10	80
5	20	3.6	10	40
6	20	1.9	10	20

Table: Pertinent simulations

Numerical MHD Model

Visco-resistive 3D MHD code, solved using a Lagrangian-Remap approach on a staggered grid

$$\frac{D\rho}{Dt} = -\rho\nabla.\mathbf{v} \quad (1)$$

$$\frac{D\mathbf{v}}{Dt} = -\frac{1}{\rho}\left[\nabla P + \mathbf{j}\wedge\mathbf{B} + \rho\mathbf{g} + \mathbf{F}_{visc}\right] \quad (2)$$

$$\frac{D\mathbf{B}}{Dt} = (\mathbf{B}.\nabla)\mathbf{v} - \mathbf{B}(\nabla.\mathbf{v}) - \nabla\wedge(\eta_{\parallel}\mathbf{j}) - \nabla\wedge(\eta_{\perp}-\eta_{\parallel})\mathbf{j}_{\perp} \quad (3)$$

$$\frac{D\epsilon}{Dt} = \frac{1}{\rho}\left[-P\nabla.\mathbf{v} + H_{visc} + \eta j^2 + H_c + \nabla\cdot q_{th} - n^2\Lambda(T)\right] \quad (4)$$

Shock viscosity capture transfer of energy from bulk to thermal at small scales

Ohmic (Joule) heating is removed from system but not put into thermal energy

Only heating mechanism is viscous heating at small scales, flows driven by magnetic reconnection

Parameter Study

- Domain $(L_x, L_y, L_z) = (L_x, 100, 50)$ Mm
- Current sheet width $a = 0.5$ Mm
- Magnetic Reynolds number $R_m = \mu_0 a.V_a/\eta \sim 10^4$
- Diffusivity of 10^8 m^2/s
- Numerical diffusivity less than 10^8.
- Timescales
  - Diffusive 2500 s >> Tearing growth time
- Background diffusion of current sheet is small but non-negligible (not removed as in previous studies)
- Vary $B_{x,0} = [1.9, 3.6, 7.0]$ G, and $L_x = [100, 20]$ Mm

Name	L_x (Mm)	$B_{x,0}$ (G)	$B_{z,0}$ (G)	θ
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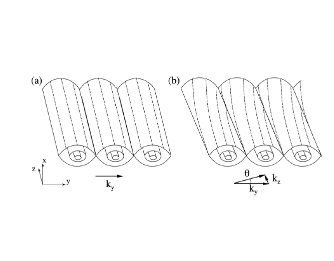
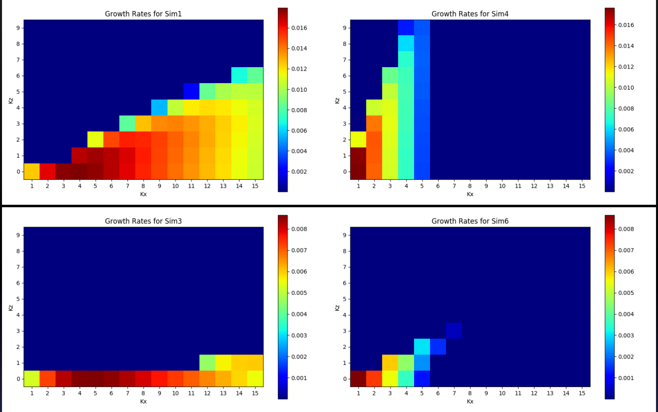
Table: Pertinent simulations

3D Oblique Tearing Instability

- Plasmoid instabilities arise at $\mathbf{k} \cdot \mathbf{B} = 0$
- Modes of $[k_x, k_z] = [1 : nk_x, 0 : nk_z]$
- In 2D plasmoid studies, either $B_z = 0$, or $k_z = 0$, so single resonant surface at center of current sheet ($y = 0$)
- In our 3D setup, expect growth at various distances from the center of CS
- Baalrud (2012) showed that oblique modes ($|k_z| > 0$) can be as unstable as parallel modes ($k_z = 0$)

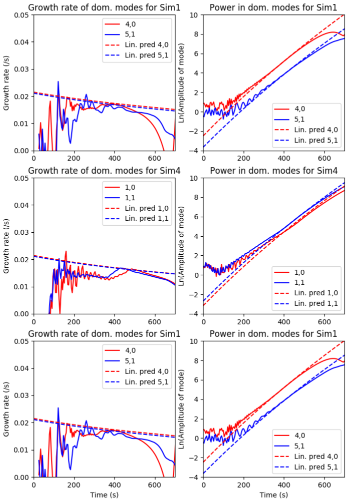


Linear Evolution and Code Validation

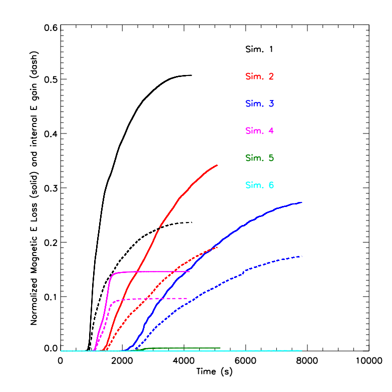


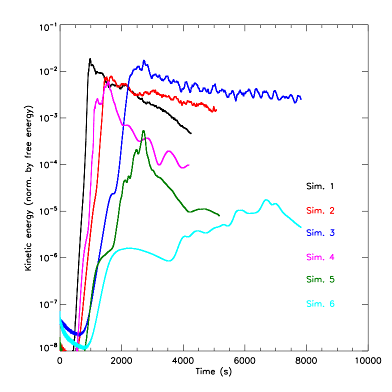
- Two regimes
  - Sim 1-3 (left) $\lambda_{par,max} < L_x, (k_{x,max} = 4)$ Sub-harmonics ($k_x < k_{x,max}$) can be almost as strong as dominant parallel and oblique modes, non-linear evolution dominated by coalescence to smaller k_x
  - Sim 4-6 (right) $\lambda_{par,max} \sim L_x, (k_{x,max} = 1)$ Oblique modes can be as strong as parallel modes - no subharmonics - non-linearity of oblique modes can be important at high shear

Linear Evolution and Code Validation



Non-linear Results: Energy Release

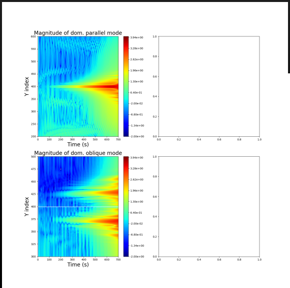


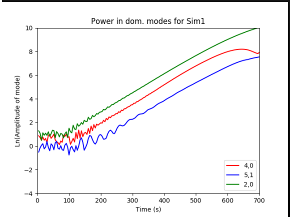


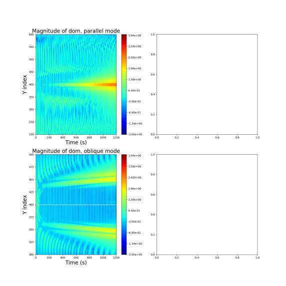
Regime 1: (1-3) $\lambda_{x,max} < L_x$ evolution for all three simulations is similar, with gradual dependence on shear.

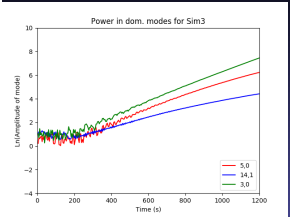
Regime 2: (4-6) $\lambda_{x,max} \; L_x$ evolution critically dependent on magnetic shear

Regime 1: $\lambda_{par,max} <\sim L_x$ - Sim. 1 (2,3)



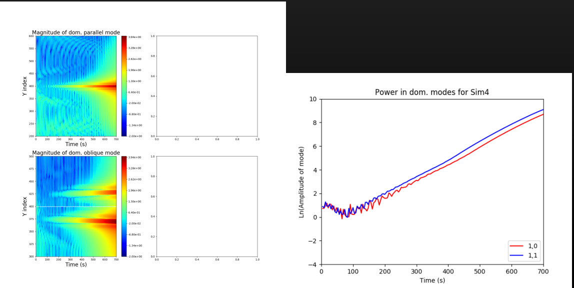


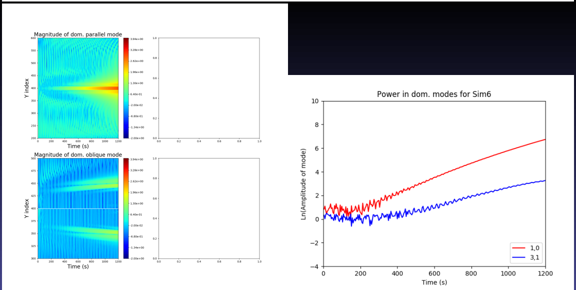




MOVIES OF SIM 1

Regime 2: $\lambda_{par,max} \sim L_x$ (Sims. 4-6)





MOVIES OF SIM 4 and 6

Summary

- When $\lambda_{par,max} < L_x$:
  - Even if oblique modes are as unstable as parallel modes, presence of strong sub-harmonics leads to coalescence into one large island formed, this process dominates energy release
  - Weak dependence on magnetic shear
- When $\lambda_{par,max} \sim L_x$:
  - Parallel mode saturates, no sub-harmonics, no coalescence
  - For strong shear, the oblique modes can go non-linear and release large amount of free energy
  - For weak shear, the oblique modes are not as unstable and so release very little energy
  - Strong dependence of energy release on magnetic shear
- Q: How is this related to the 'kinking' of 3D plasmoids reported in earlier incompressible MHD studies of reconnection?
- Q: Which regime is appropriate for coronal heating?
  - flare currnet sheets - large L_x - multiple plasmoids - coalescence dominates - shear not a critical parameter for onset
  - Braided, sheared field, locally small L_x - oblique modes dominate - shear is critical parameter