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Forward modelling of microwave and other observational signatures of confined flares in twisted loops

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- Modelling energy release in unstable twisted loops
- Observational signatures
  - Thermal emission
  - Hard X-rays
  - Turbulent velocities
  - Radio
- Energy release in interacting twisted loops

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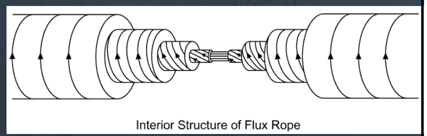
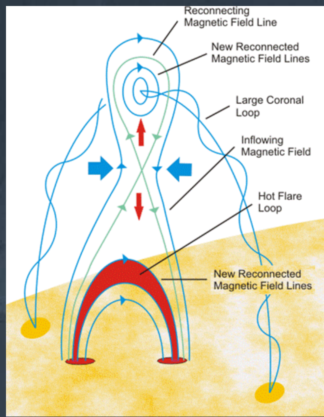
Twisted flux ropes in the solar corona

- Twisted magnetic flux ropes are non-potential fields providing reservoirs of free magnetic energy
- Unstable twisted coronal loops can be a good alternative to the standard model, particularly in smaller flares with isolated loops *(e.g. Aschwanden et al. 2009)*
- In standard model, flux ropes can form due to magnetic island formation in a reconnecting current sheet with guide field *(e.g. Gordovskyy et al. 2010)*
- Twist can be produced by rotation/shear motions at the photosphere *(see e.g. Brown et al. 2003)*. Newly emerging flux is expected to have some twist *(see e.g. simulations by Archontis and Hood)*





Twisted loops in flares

- Twisted magnetic fields often observed/inferred in solar flares (ropes in large flares; twisted loops in smaller flares)

from Shrivastava et al 2010 ApJ

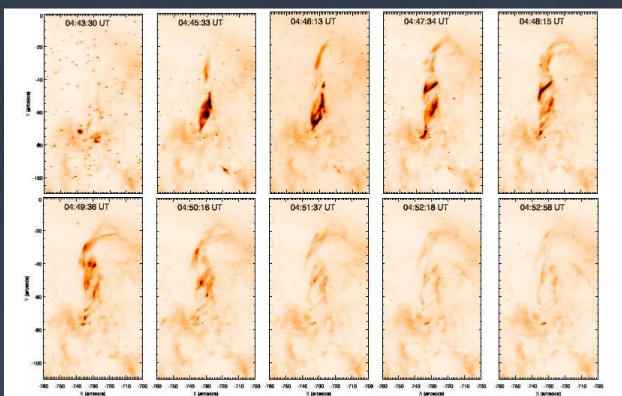
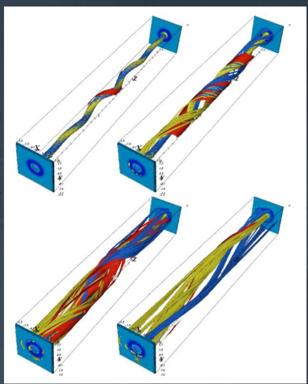


Figure 5. Time sequence of TRACE 171 Å Fe IX images of flaring loop in the AR 10960 during 04:43 UT–04:52 UT on 2007 June 4. The images are in reverse color and show the clear helical twist of the loop during the B5.0 flare. Note the double structure of the coronal loop top between 04:47 UT and 04:51 UT near $(X,Y) = (-720, -20)$.

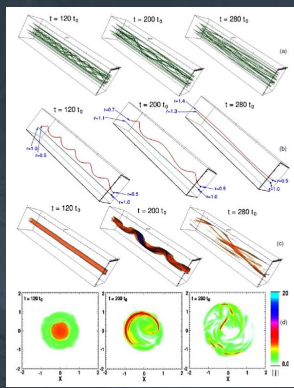
Kink instability theory and modelling

- Ideal kink instability leads to formation of fragmented current sheet in nonlinear phase
- Internal reconnection and reconnection with untwisted ambient field → untwisting of field
- Fast magnetic reconnection dissipates magnetic energy
- Particle aceleration throughout loop volume



Previous works study kink in unstable cylindrical flux ropes

Baty & Heyvaerts 1996; Browning & Van der Linden 2003; Browning et al 2008; Hood et al 2009; Botha et al, 2012; Bareford et al 2013, Bareford & Hood 2015



from Hood et al. 2009 A&A

from Gordovskyy & Browning 2011 ApJ

Observational detection of twisted loops

- Thermal emission (UV & soft X-ray, continuum and spectral lines)?
- Thermal radio?
- Non-thermal Hard X-ray?
- Non-thermal radio?

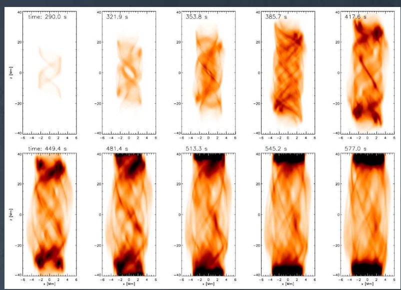
Kink instability modelling and observables

- **Field topology and thermal emission**

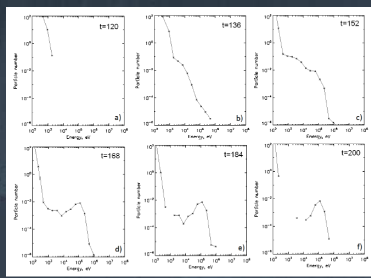
(e.g. Arber et al 1999; Botha et al 2012; Srivastava et al 2014; Pinto et al. 2015; Gordovskyy et al. 2016)

- **Non-thermal particle spectra, HXR**

(Gordovskyy & Browning 2012; Gordovskyy et al 2013, 2014; Pinto et al 2015)



from Botha et al. 2012 ApJ



from Gordovskyy et al 2013 SolPhys

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Towards realistic models – methodology

Potential field in stratified atmosphere → **MHD**: Derivation of twisted loop configuration (ideal phase); Magnetic reconnection triggered by kink (resistive phase) → **Test-particles**: Proton & electron trajectories; Energy spectra, pitch angles, spatial distributions

MHD ↓ Thermal emission, Field topology

Test-particles ↓ Non-thermal emission

- *Gordovskyy, Browning, Kontar & Bian 2014* (loop evolution, non-thermal particles & HXR)
- *Bareford, Gordovskyy, Browning & Hood 2016* (effects of curvature ang expansion)
- *Pinto, Gordovskyy, Browning & Vilmer 2016* (thermal SXR continuum, non-thermal HXR)
- *Gordovskyy, Kontar & Browning 2016* (EUV lines – non-thermal broadening, shifts)
- *Gordovskyy et al 2016 in prep* (thermal and non-thermal microwave)

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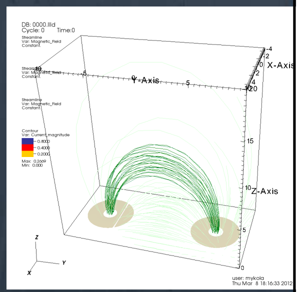
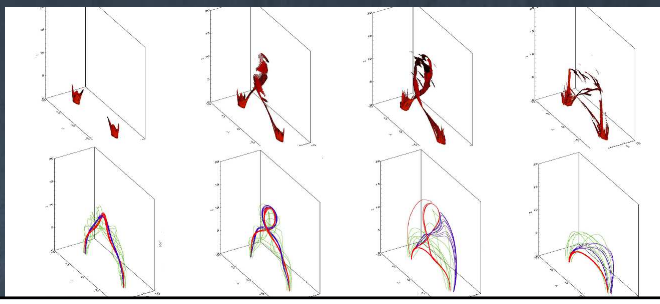
Our model

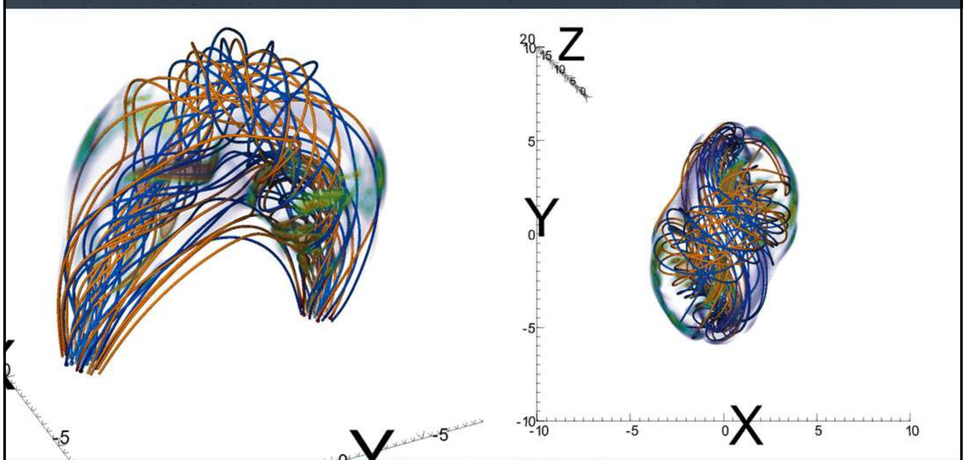
- 3D MHD simulations with LARE3D (Arber et al 2001) with conduction/radiation
- Anomalous resistivity triggered by ion acoustic instability
- Gravitationally-stratified atmosphere
- Bipolar magnetic region – rotational motions in localised region of photosphere → twisted loop
- Onset of kink instability leads to loop expansion, fragmented currents within loop, large-scale currents and reconnection



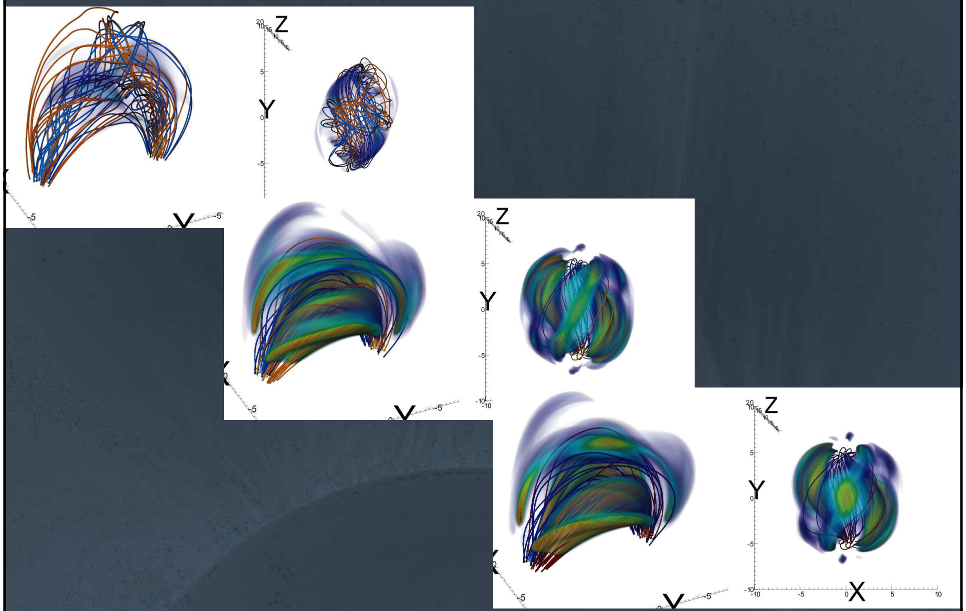


SXR thermal emission

Small loop (model V), 2keV continuum emission



SXR thermal emission



Thermal emission: velocities

- *Doschek et al. 2008 ApJ*
- *Doschek et al. 2013 ApJ*
- *Young et al. 2013 ApJ*

- **Correlation of non-thermal velocity dispersion (line broadening) with temperature: velocity dispersion increases from 20-30 km/s at ~1MK to 100-120km/s at ~15-20MK**

- **Correlation of bulk velocity (line shift) with temperature: it increases from 20-30 km/s to 300-350 km/s in the same interval**

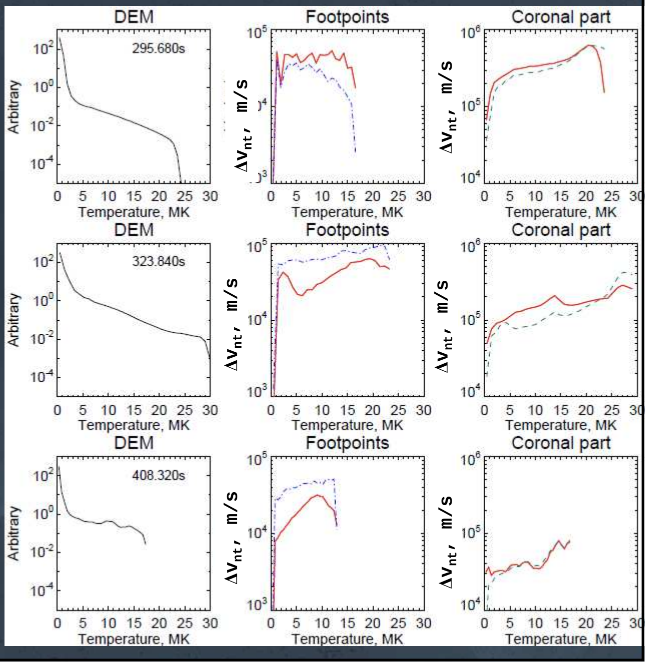
LOS velocity dispersion

Large scale loop
Strong field

Length 80 Mm

Footpoint field 1500 G

Time
↓
↓

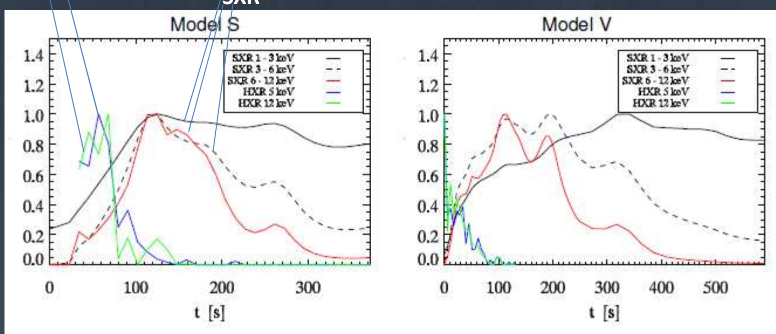


Thermal v. non-thermal emission: Light curves

Neupert effect in small loops

HXR

SXR



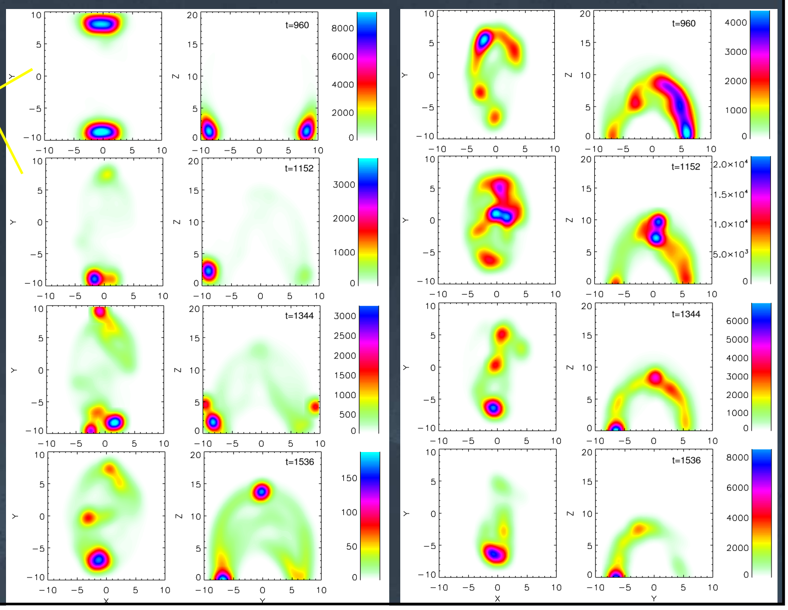
Non-thermal HXR emission

Low-density case, ε=10keV | High-density case, ε=10keV

Onset of magnetic reconnection

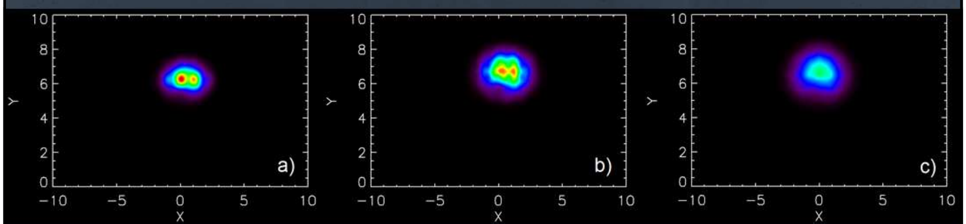
Maximum dE/dt in MHD model

Decay phase



Non-thermal HXR emission

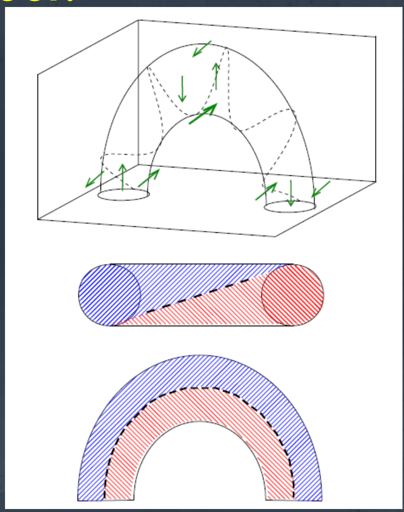
Onset of magnetic reconnection | Maximum dE/dt in MHD model | Decay phase



FWHM=1.9 | FWHM=2.2 | FWHM=2.5

- Loop cross-section increases by 50-100%
- FWHM of HXR sources increases by 20-30% (with RHESSI resolution)
- *Kontar et al 2011 ApJ* – quantitatively and qualitatively similar effect

Circular microwave polarisation pattern as a detection tool?



- *Kuznetsov et al. 2016, Sharykin & Kuznetsov 2016*

Synthetic microwave emission from twisted loops

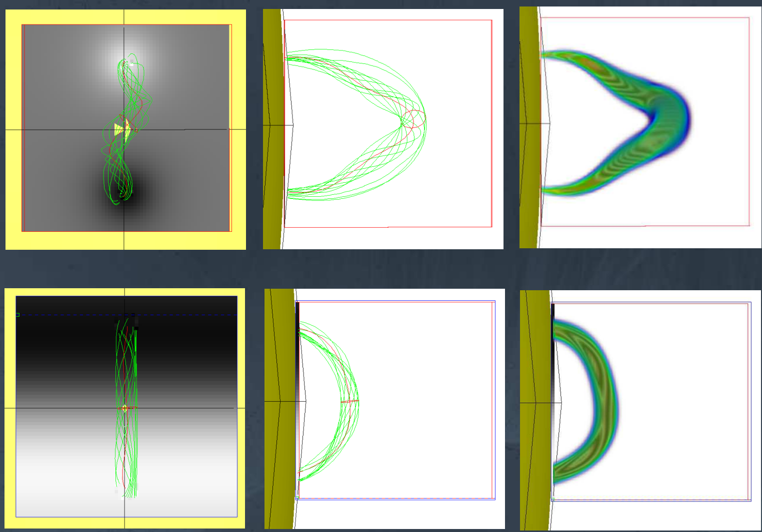
- GX Simulator
  Fleishman & Kuznetsov (2010), Nita et al. (2015)

- Magnetic field and thermal plasma density & temperature can be taken directly from MHD model
  - magnetic field 100-1000 G at foot-points
  - ambient plasma $n \approx 10^9 cm^{-3}$, $T \approx 1MK$
  - hot plasma in the reconnecting loop $n \approx 10^9 cm^{-3}$, $T \approx 10\text{-}30$ MK

- Non-thermal electron population is approximated by a single power law derived from test-particle simulations

  - $n_b \approx 5\ 10^7\ cm^{-3}$, E_{low}= 3keV, E_{up}=3 MeV, γ = 2.0-4.0

Microwaves: magnetic field convergence effect



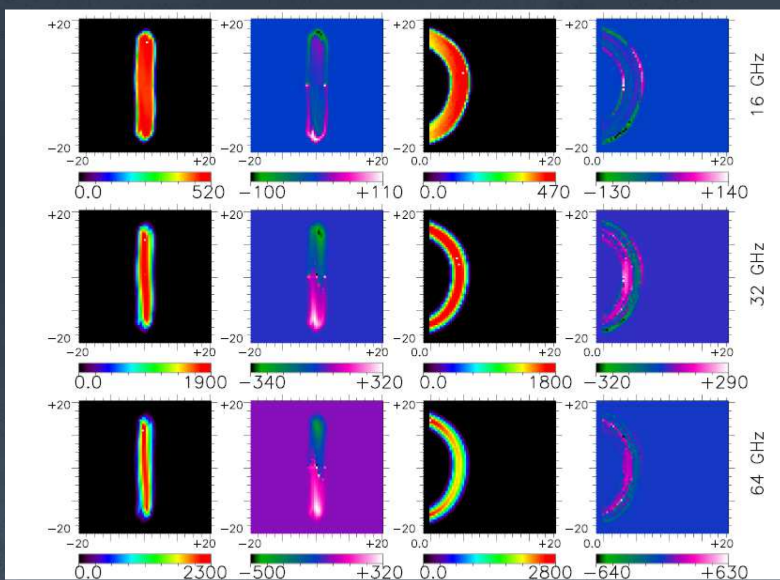
$B_{top}/B_{fp} = 10$

$B_{top}/B_{fp} = 2$

MW polarisation in weakly converging loop

Stokes I Stokes V Stokes I Stokes V

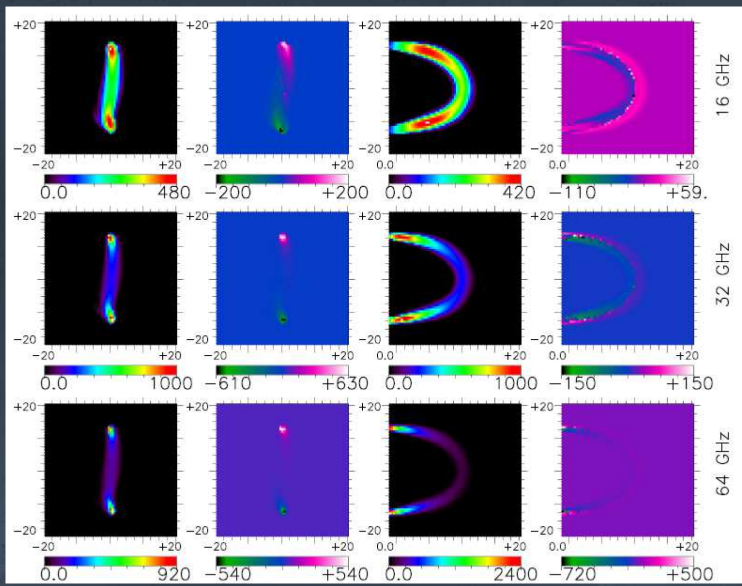
At start of energy release



MW polarisation in strongly converging loop

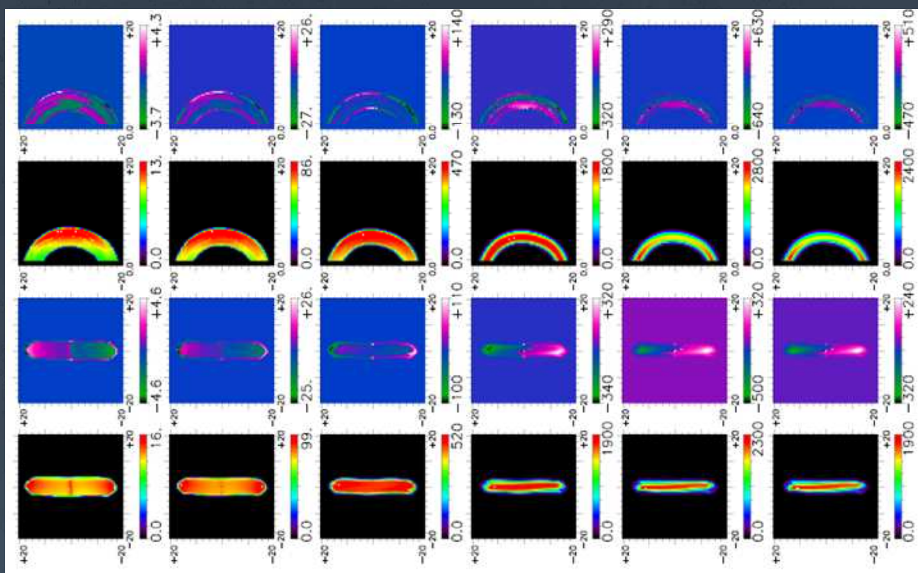
Stokes I | Stokes V | Stokes I | Stokes V

At start of energy release



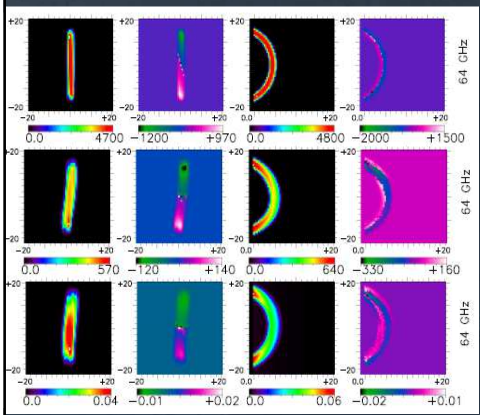
MW polarisation: frequency variation

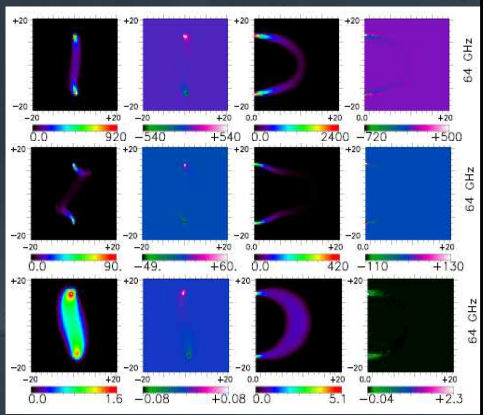
4GHz | 8GHz | 16GHz | 32GHz | 64GHz | 95GHz



MW polarisation: magnetic field convergence

- Just after onset of reconnection
- Peak temperatures (+30s)
- Decay (+60s)

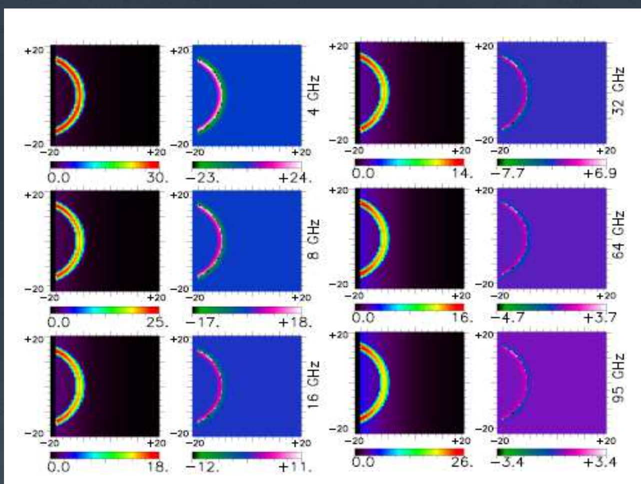




Weakly converging loop, footpoint field 360 G

Strongly converging loop, footpoint field 1180 G

Purely thermal MW emission



Weakly converging loop, footpoint field 360 G, time of peak temperature (about +30s after onset of reconnection)

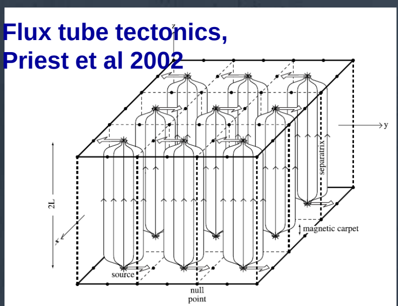
Observational signatures -summary

- Thermal EUV/SXR: in continuum, some twist should be visible, although it may be substantially lower than the critical twist
- Non-thermal HXR: in reconnecting twisted loops, the visible HXR loop cross-section would increase at ~10^4 m/s
- Thermal microwave: circular polarisation gradient across the loop should be visible, especially at the limb, although the intensity should be low
- Non-thermal microwave: circular polarisation gradient across the loop should be visible, however
    - the life-time of that pattern would be ~30-60s
    - visibility of the pattern would depend on loop orientation
    - visibility would depend on the magnetic field convergence

Interacting twisted flux ropes

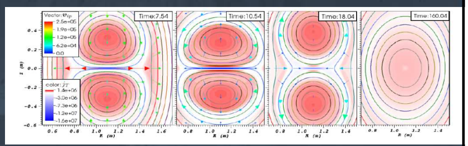
- Multi-thread structures are likely to be common in the corona
- Merger of twisted flux ropes through magnetic reconnection can release stored magnetic energy
- Widely observed and modelled in laboratory plasmas

Flux tube tectonics, Priest et al 2002



- Merging flux ropes observed in some flares

e.g. *Jiang et al 2014, Joshi et al 2014, Joshi et al, 2015*



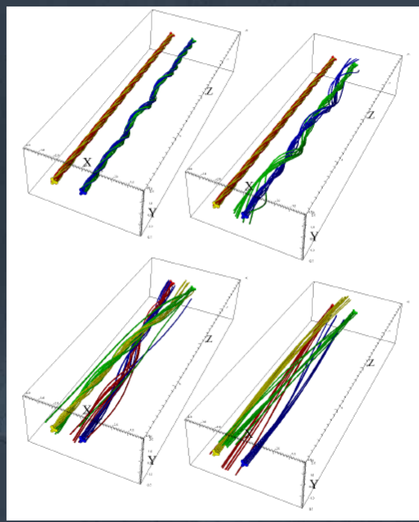
e.g. Merging flux ropes in MAST spherical tokamak
Stanier, Browning et al, 2013

Disruption of neighbouring stable flux rope

Tam, Hood, Browning and Cargill A&A 2015

Consider adjacent zero-net - current loops

- If the loops are sufficiently close, an unstable loop may trigger relaxation in a neighbouring stable loop
- In this case the two loops merge into a single (very weakly twisted) loop
- Releases energy stored in stable loop (as well as unstable loop)



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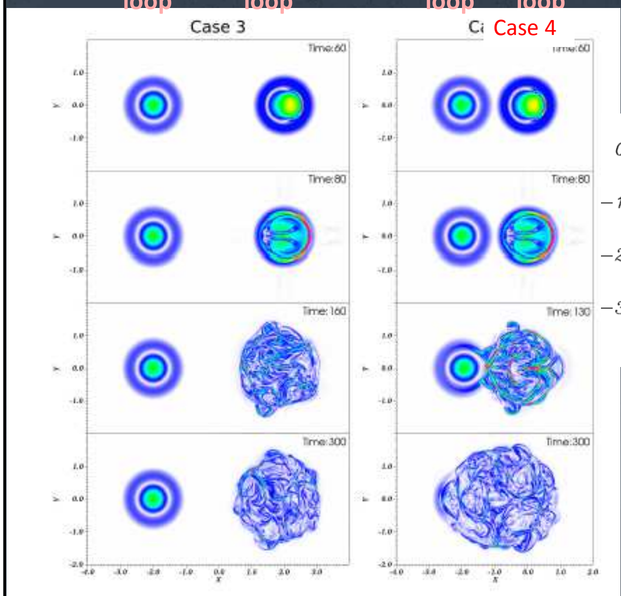
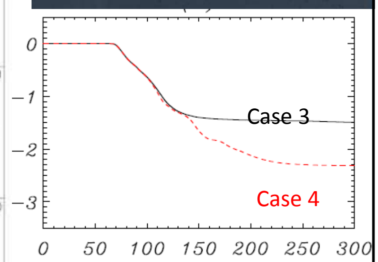
Stable loop | Unstable loop | Stable loop | Unstable loop





Magnetic energy versus time

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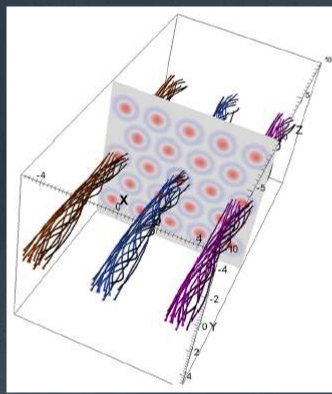
Avalanche triggered by one unstable flux rope

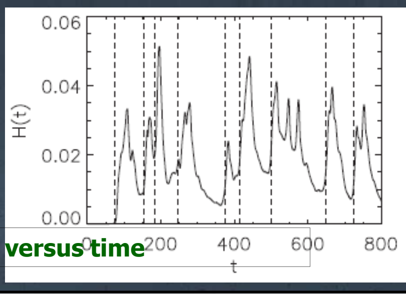
→ Under certain conditions can have an avalanche of heating events

Cf Lu and Hamilton 1881, Charbonneau et al 2001

- First demonstration of avalanche - as in “cellular automaton” models - using 3D magnetohydrodynamics
- One unstable loop, 22 stable loops

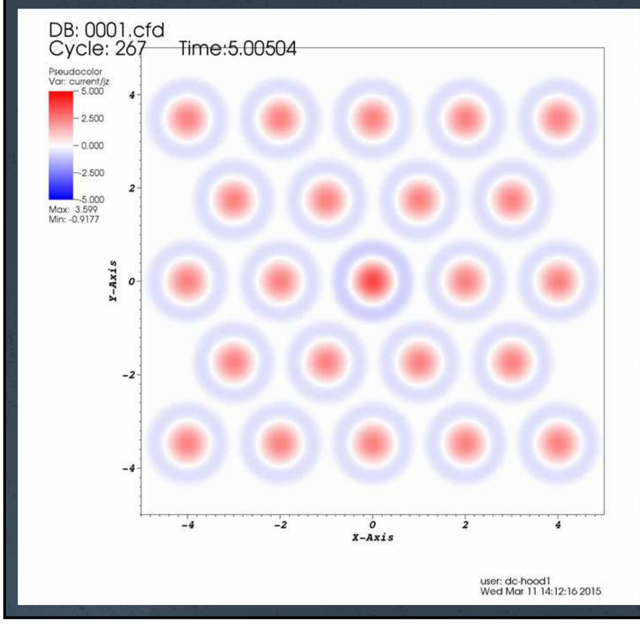
Hood, B et al Ap J 06





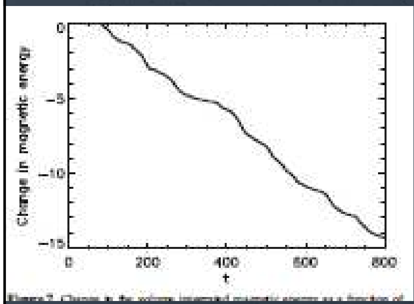
Heat versus time

Multiple Loops (Avalanche)

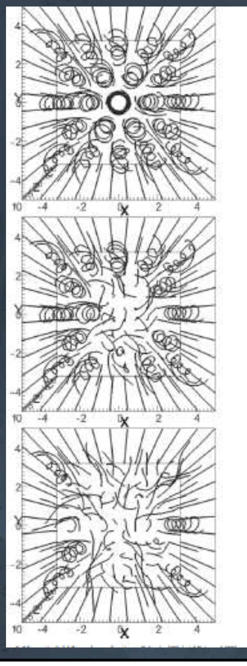


Current in mid plane

Multiple loops (avalanche)



Magnetic energy versus time



Well fitted by multi-loop relaxation model
Hussein, B & H 2016

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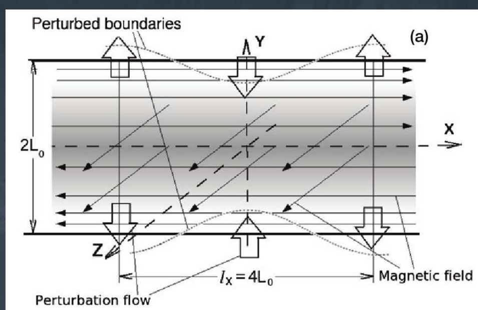
Forced magnetic reconnection

- 2D slab of plasma stable to tearing mode
- Apply transient spatially sinusoidal perturbation to the boundaries
- Current sheet formation then magnetic reconnection leads to chain of magnetic islands/flux ropes

- For solar corona, initial field is a sheared force-free field

Hahm and Kulsrud, 1986; Vekstein and Jain, 1998



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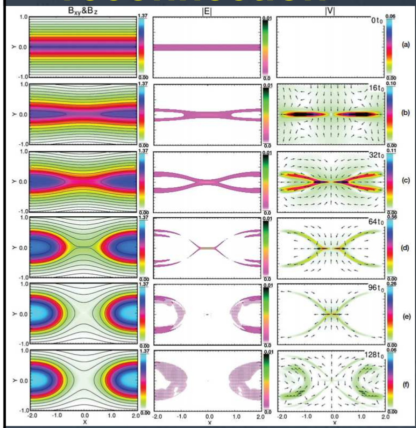
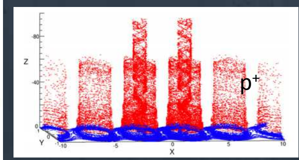
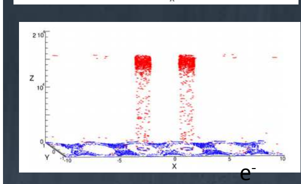
Particle acceleration in forced magnetic reconnection

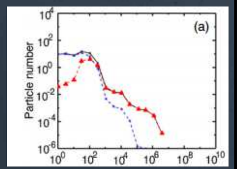


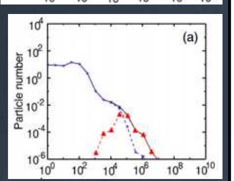
MHD simulation for forced reconnection
With LARE2D (Arber et al 2001)





Test particle final positions



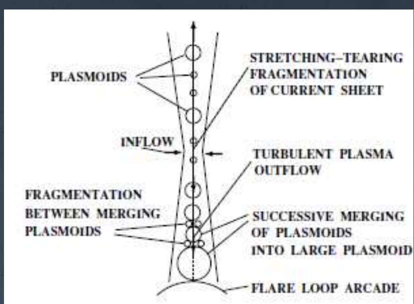


Particle spectra
Red – closed field
Blue – open field

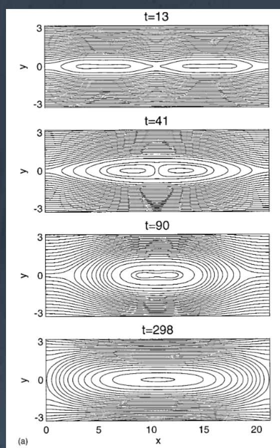
Gordovskyy et al ApJ 2010

Magnetic island (flux rope) coalescence

- Chain of magnetic islands
- Attractive parallel currents at O-points → neighbouring islands coalesce
- Islands (plasmoids) with a guide-field are twisted flux ropes

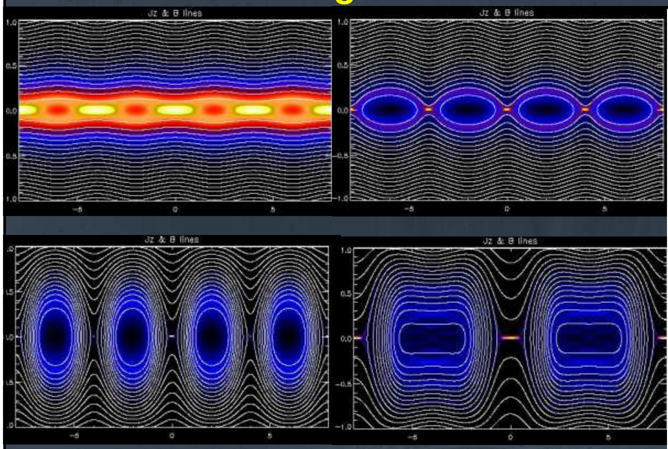


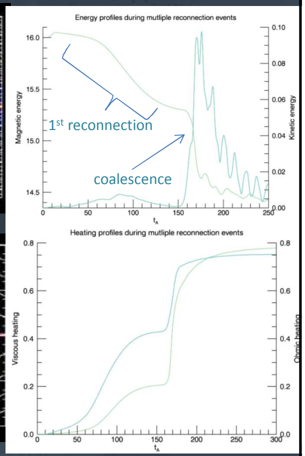
Plasmoids in flare current sheet
Karlicky and Barta 2011



J. Schumacher and B. Kliem 1997

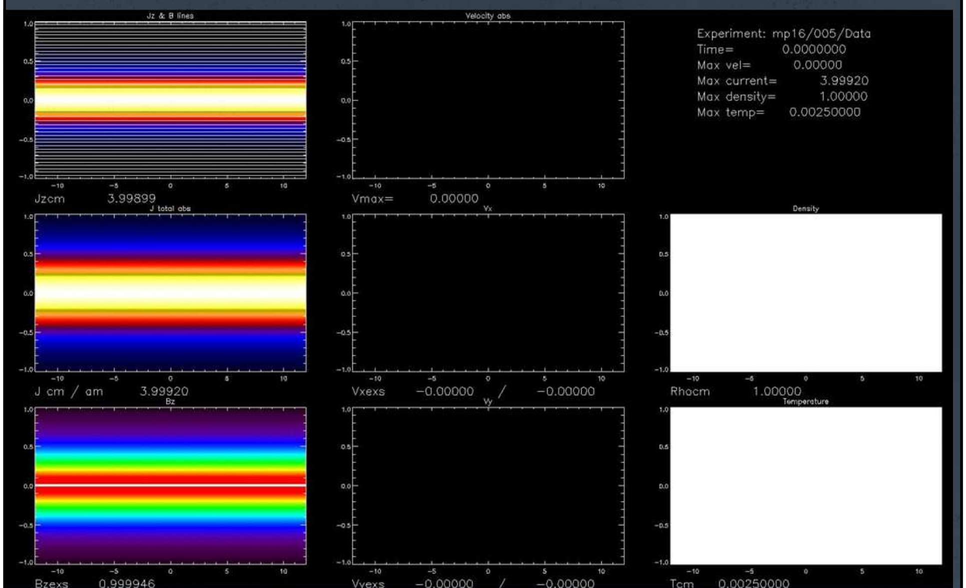
Simulations of forced reconnection with island merger





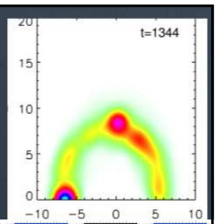
- 2D MHD simulations with LARE2D
- Initial field force-free Harris sheet – transient boundary disturbance
- Long numerical box allows symmetry breaking →coalescence
- Two phase of reconnection
- Potter, B and G 2016

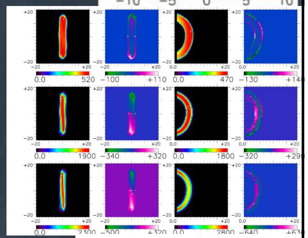
Multiple wavelength perturbation

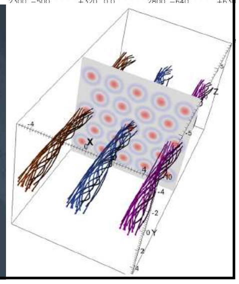


Summary

- Twisted magnetic fields are reservoirs of free magnetic energy which can be released as thermal and particle kinetic energy
- We perform coupled 3D-MHD/test –particle simulations of energy release in unstable twisted loops and predict possible observable signatures in thermal and non-thermal emission
- Spatial distribution of microwave polarisation can provide evidence of twisted fields
- Merging of twisted flux ropes through reconnection can release free energy
  - Avalanches
  - Plasmoid/flux rope merger in large-scale current sheets







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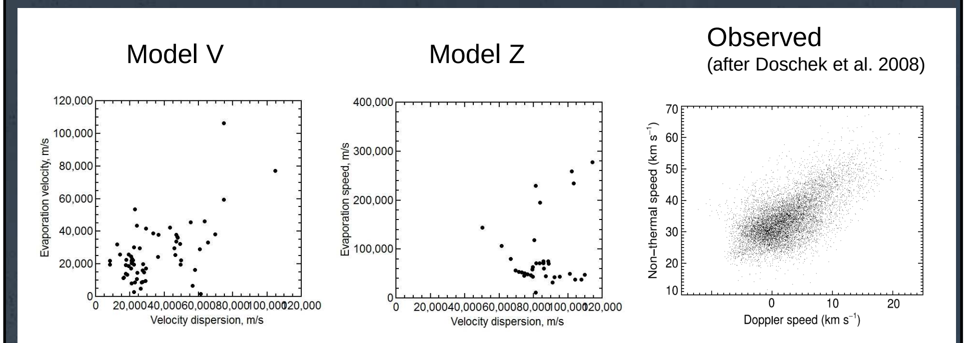
LOS velocity dispersion v. bulk LOS velocity



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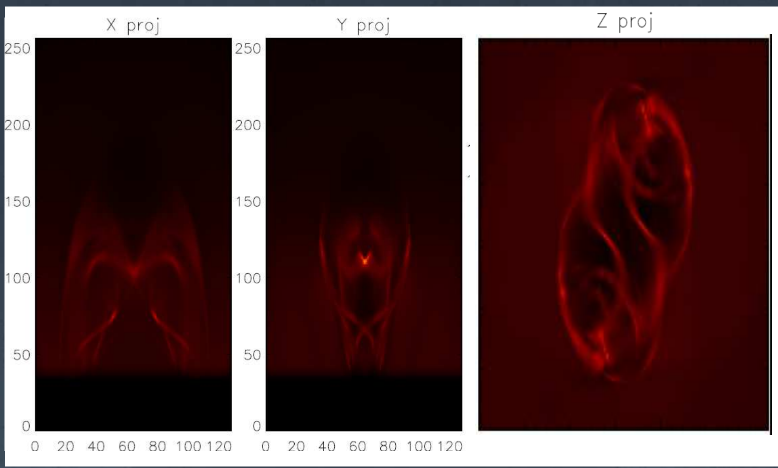
SXR thermal emission (LOS integrated)

2keV emission (near onset, large loop)



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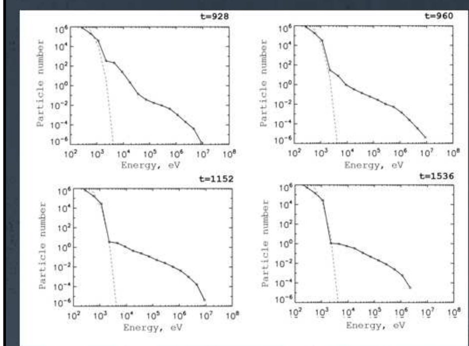
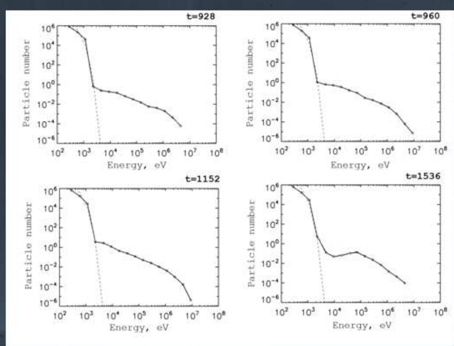
Particle kinetics: electron energy spectra

Low density loop



High density loop



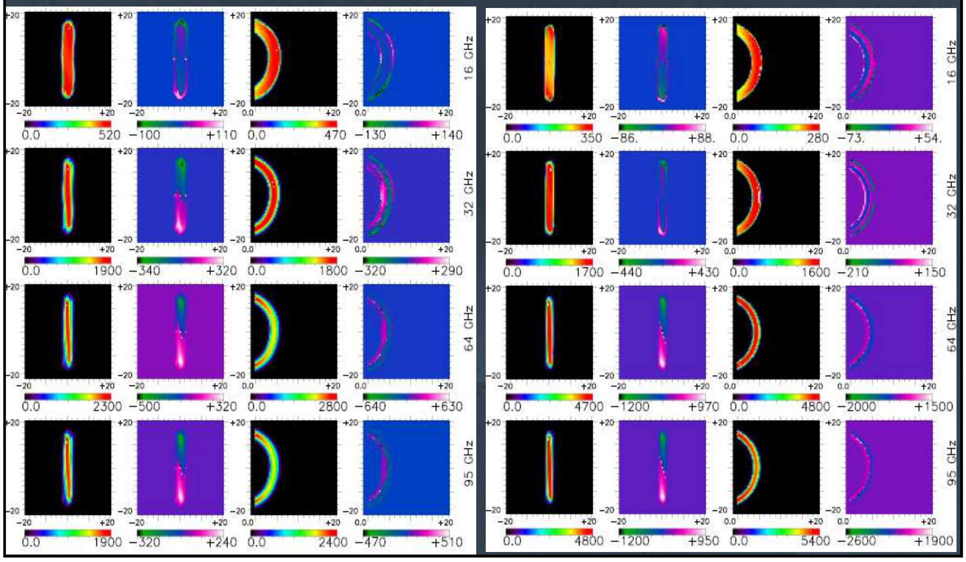
Time evolution of electron energy spectrum

RHESSI Workshop Graz 2016

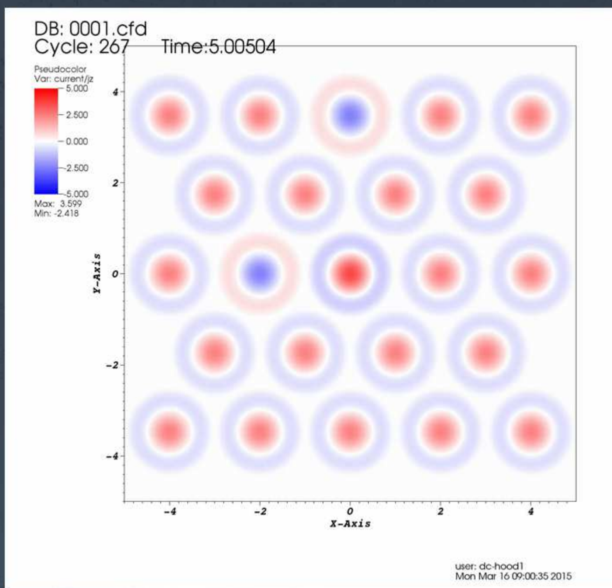
MW polarisation: frequency variation

Footpoint magnetic field

180 G 360 G



Multiple Loops (Avalanche)



Current in mid plane

Two loops with reversed twist

Slows down avalanche