Preliminary Study of Coronal Jets due to Spheromak Tilt Instability

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Abstract

Activity in the solar corona such as flares, coronal mass ejections, and coronal jets are driven by the release of energy through magnetic reconnection events. Understanding the mechanism(s) behind coronal jets has been long sought-after in solar and space physics. We propose coronal jets could be modeled by embedding a hemispherical spheromak-like closed field structure inside a large scale open field. In the boundary between these structures, current filaments form then undergo a reconnection event linking them to the open field lines, thereby allowing the filaments to become a plasma jet[1]. It is postulated that this reconnection event may be related to the global reconnection which occurs during the spheromak tilt instability. This paper explores the results from a preliminary experiment done on the Magnetic Reconnection Experiment (MRX) in which a spheromak is formed inside of an equilibrium field. Using a magnetic probe array and correlating fast camera data of the C^{II} and C^{III} lines, the stability of this spheromak structure is analyzed and characterized.

Motivation

- Simulations of coronal plasma jets have been successful in showing the interaction between different magnetic field structures in the corona.
- In one such simulation by P.F.Wyper et al.[1] (Figure 1) we can see how jets form by reconnection in the boundary region between open field lines and a closed field structure sitting on the photosphere.
- These structures resemble a spheromak in an equilibrium field undergoing a tilt.

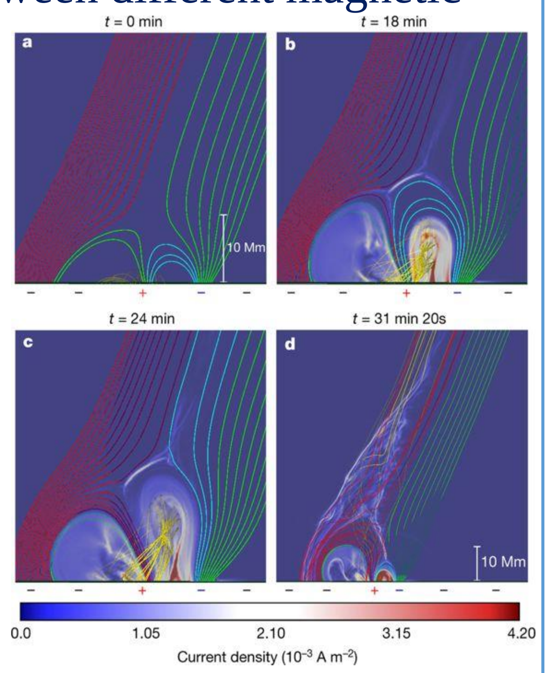

Figure 1: P.F.Wyper et al., **Nature 544**, 452, 2017

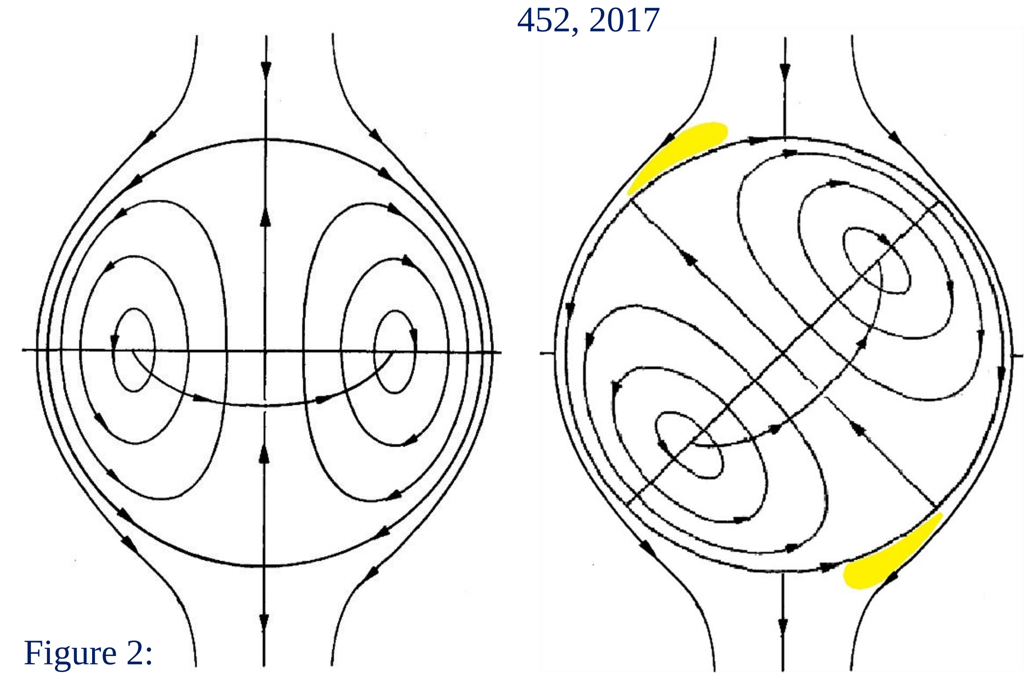

Figure 2:

- In Figure 2 we see the ideal spheromak equilibrium (left) and a spheromak which as undergone a tilt in the equilibrium field (right).
- The yellow regions indicate potential diffusion regions where the magnetic fields oppose each other.
- These regions are similar to the standard Sweet-Parker model seen in Figure 3.

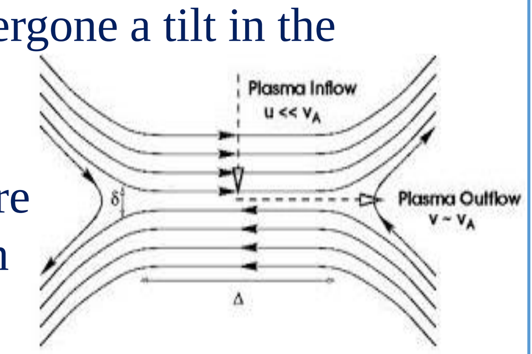

Figure 3: Sweet-Parker model

Methods

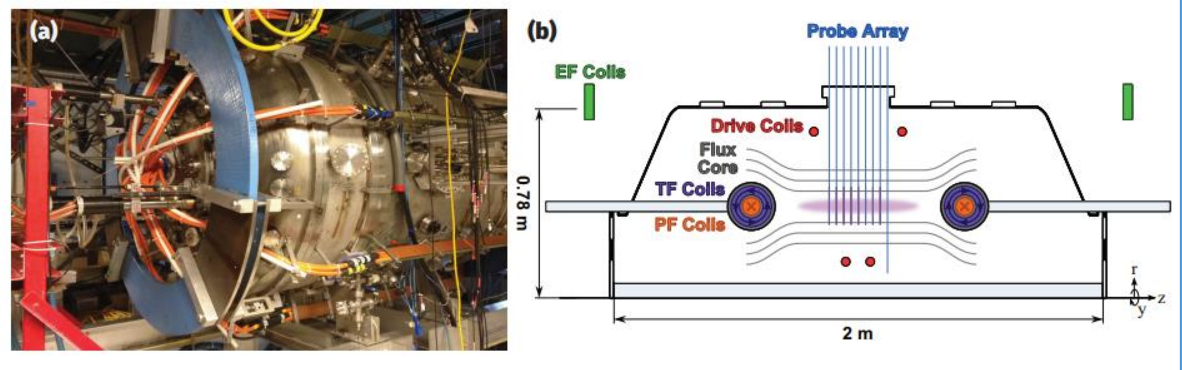

Figure 4: (a) Image of MRX. (b) Cross-section of MRX showing coil geometry, probe array, and typical reconnection region.

- This preliminary experiment was conducted to provide proof of concept that MRX could be used to form a stable spheromak.
- Running the flux cores in co-helicity with a late crowbar, we inductively drive spheromak formation.
- Measurements were used with a magnetic probe array inserted in the 3 o'clock position and a fast camera mounted at the 9 o'clock position.

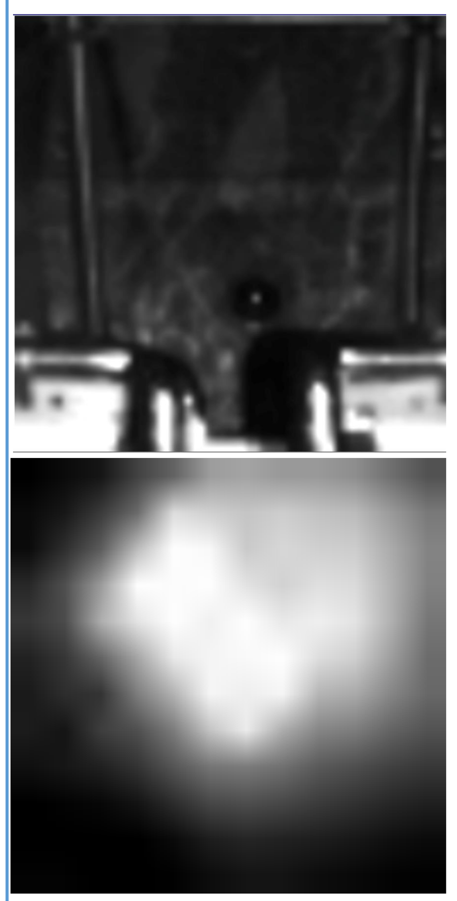

Figure 5: (Upper) A photo from the fast camera while the vessel is backlit. (Lower) An example of an image during shot 184827.

- The fast camera was mounted at the 9 o'clock port with a view down towards 6 o'clock.
- The frames of the probe data and the fast camera were of different locations in MRX, rotated by 90° about the z-axis.
- The purpose of this camera was to qualitatively assess the symmetry of the plasma and look for stability.
- While the magnetics data was sampled every 0.4μs, the camera's frame rate ranged from 7 to 14μs.
- The images represent time integrated views of the plasma.
- C^{II} and C^{III} filters were used on most shots to gain additional information about temperature and structure in the plasma.

- Figure 6, to the right shows the set-up of the camera relative to the magnetic probe array.
- The viewing angle of the camera is approximately 19°.
- During this experiment we also collected data for Ion Doppler tomography.

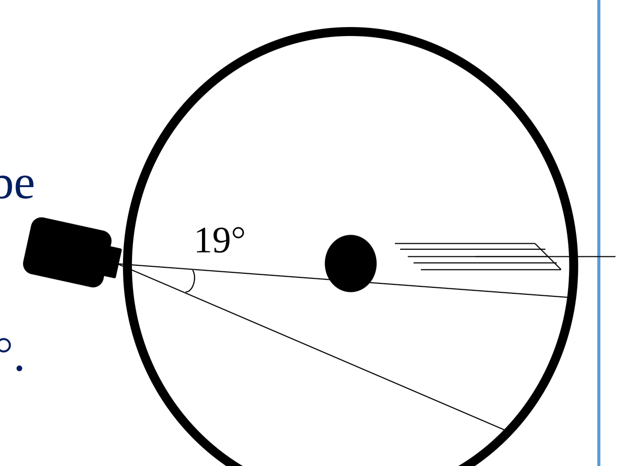

Figure 6:

- The inversion of this data is still being processed but will likely prove to be interesting.
- EF coils were used to form an equilibrium field.
- For a subset of shots the guide field (GF) coils were also used.

Findings

- Over 400 shots were taken for this experiment under a variety of settings.
- The three main categories used to assess these shots were formation mechanics, magnetics/camera correlation, and stability.

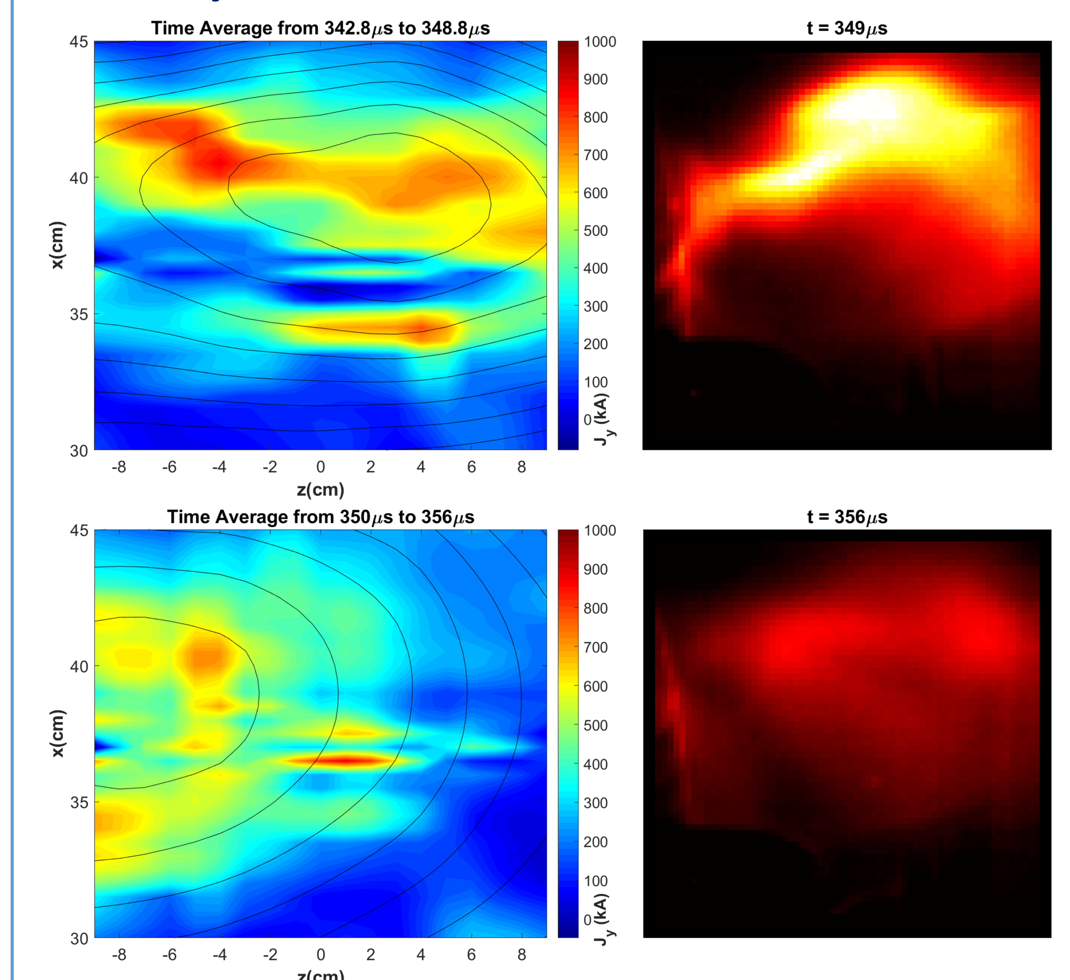

Figure 7: (Upper) Shot 184804 time averaged from 342.8μs to 348.8μs, with corresponding fast camera data. (Lower) Shot 184804 time averaged from 352μs to 356μs. The fast camera images were taken with a C III filter and are presented in false color.

Formation:

- Similar mechanics as the S-1 spheromak [2]. However, there is a different geometry due to the additional flux core.
- 2 common formation events: Detached spheromak from one core and formation of spheromak directly from current sheet.
- Magnetic shifts and reorganization are common just after formation.

Correlation:

- Considering a subset of the shots (~1/4th of total), there is moderate or better correlation between fast camera and magnetics in ~30% of shots.
- In the majority of shots fast camera data was either too dark or did not show any structures corresponding with the magnetics.
- Figure 7, shows fair correlation between camera and magnetics.

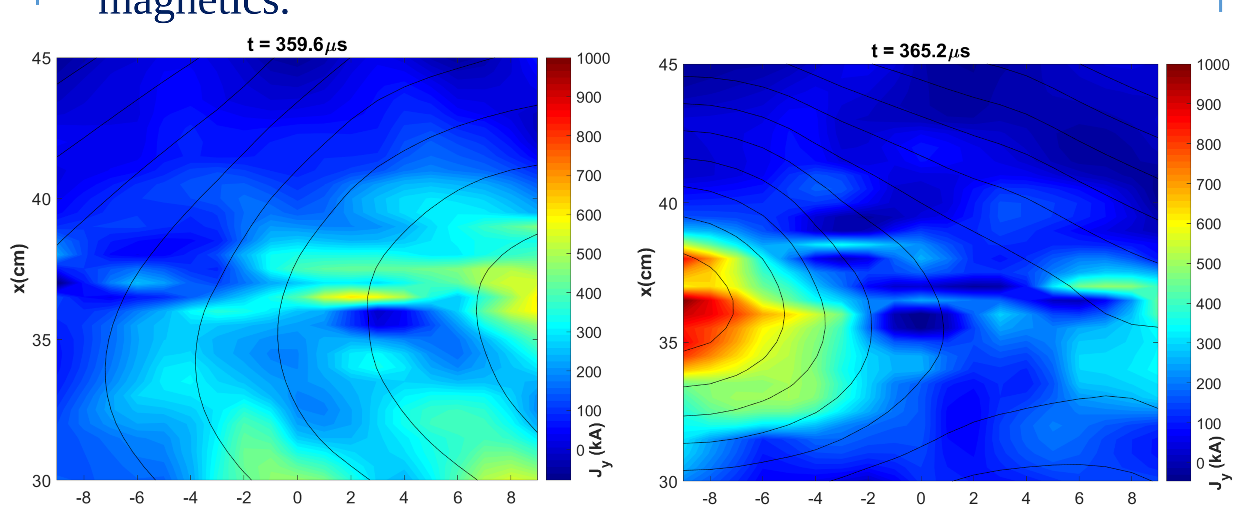

Figure 8: (Left) Plasma at t = 359.2μs, before shift. (Right) Plasma 5.6μs later after a 18cm shift of the magnetic axis. During the shift, the flux lines of intermediate frames show reorganization of the magnetic field rather than a simple translation. About 50% faster than Alfvén speed.

Stability:

- The Alfvén time defined as $\tau_A = \frac{a}{v_A} = 4\mu s$, was used to normalize the time scales of this experiment.
- $v_A = 100 km/s$ [3] is the Alfvén speed and $a = 0.4m$ is a character length in the system chosen to be the major radius of the plasma.

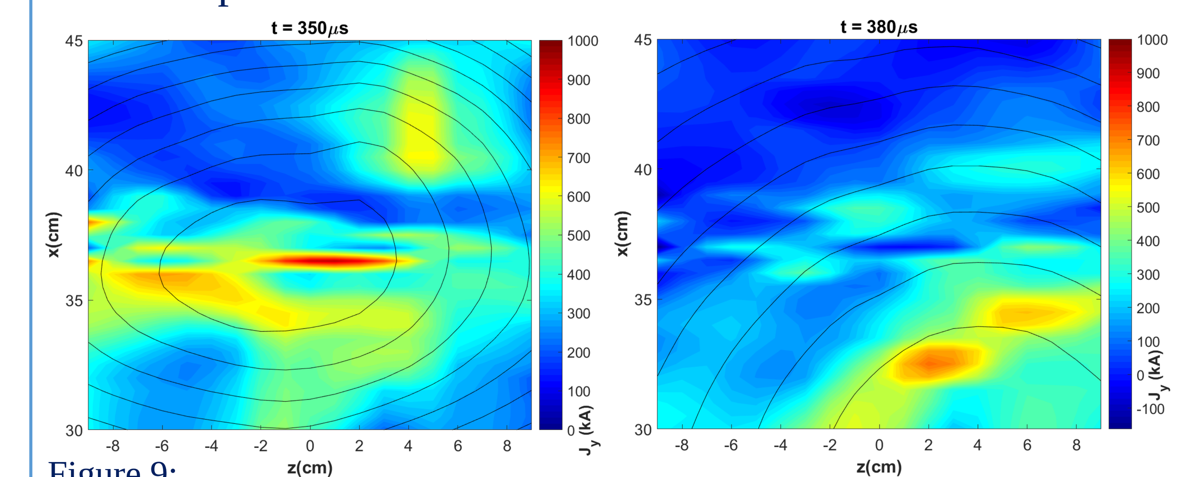

Figure 9:

- Among other fast events, Figure 8 shows reorganization of the magnetic axis on the order of an Alfvén time.
- Longest lasting spheromaks were in frame for ~$10\tau_A$ but would decay to lower r and last for another ~$15\tau_A$.
- Almost all spheromaks eventually relaxed to lower r, thereby moving out of the magnetic probe array frame.
- Figure 9 shows one of the most stable shots. Minimal movement over the 30μs shown.
- From t = 380μs to t = 400μs, little movement is seen but the images drifts further down, out of frame.

Conclusions

- MRX is capable of inductively forming a spheromak using its flux cores.
- This method lacks shot to shot consistency in formation mechanics and stability.
- Concern regarding center-stack linkage and the ability to observe the tilt instability to study jet formation.
- Possible solutions to this problem include removing center-stack and using longer probes, or adding a coil to artificially tilt the equilibrium field rather than tilting the spheromak.

Next Steps:

While the Wyper [1] simulation was a high definition simulation with complex physics, a simpler resistive MHD simulation of the tilting spheromak may lead to similar results. If the reconnection in a resistive MHD simulation leads to the linkage between the spheromak current and the equilibrium field, then there are grounds for a valid model of the plasma jet.

Furthermore, another possibility for continued experimental validation of this model is to use a co-axial Helicity gun. In this case, a configuration more closely resembling the simulation is formed and can be probed.

References

1. Wyper, P.F. et al, **Nature 544**, 452, 2017
2. Yamada, M. et al. *Phys. Rev. Lett.* **46,** 188, 1981
3. Jara-Almonte, J. (2017). *Multiple-Scale Physics During Magnetic Reconnection.* PhD thesis, Princeton University.