Laboratory study of the stability of arched, line-tied magnetic flux ropes

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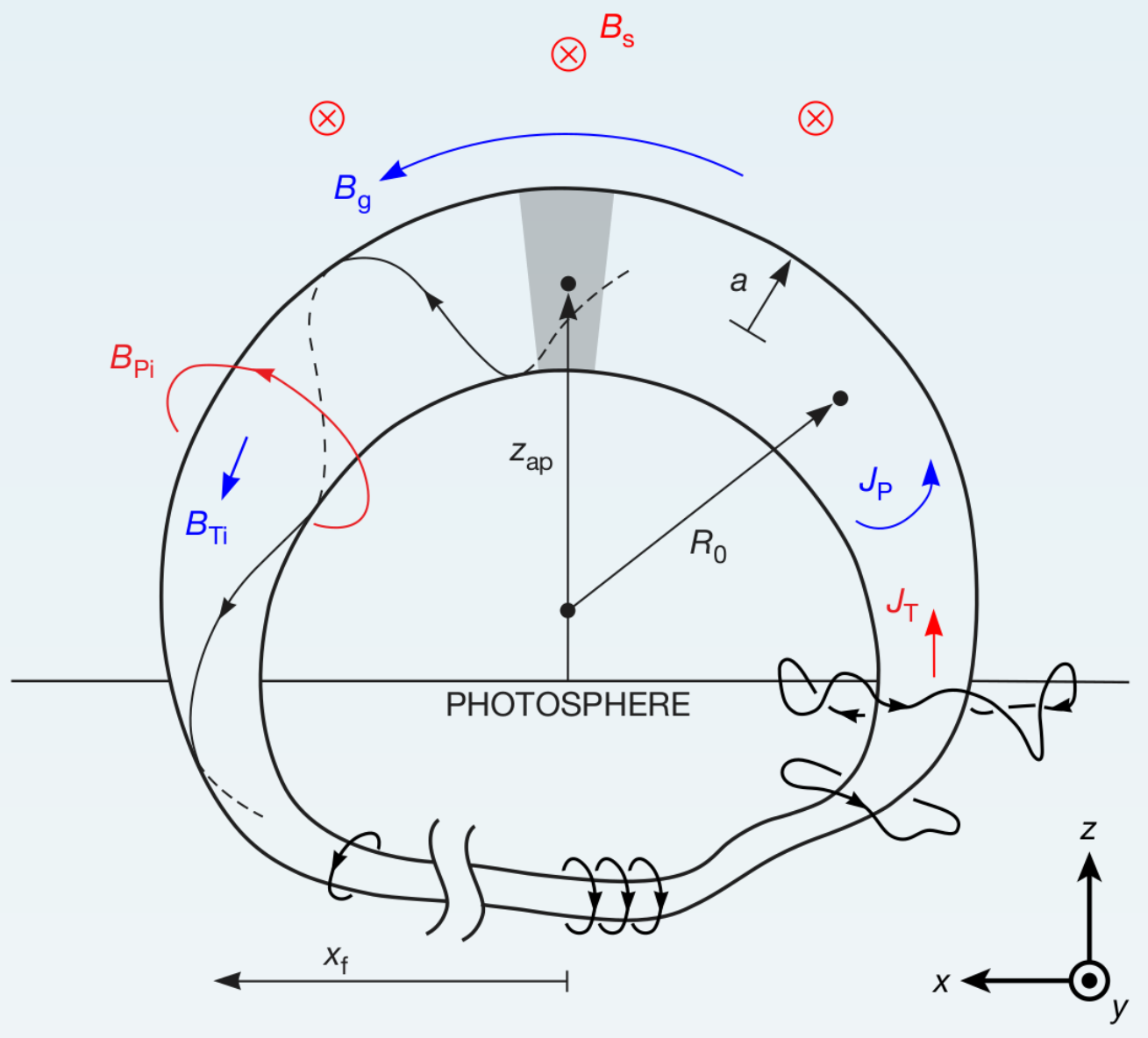
Abstract

Coronal mass ejections (CMEs) occur when long-lived magnetic flux ropes (MFRs) anchored to the solar surface destabilize and erupt away from the Sun. One potential cause for these eruptions is an ideal MHD instability such as the kink or torus instability. These instabilities have long been studied in axisymmetric fusion devices where the instability criteria are given in terms of the edge safety factor and confining magnetic field decay index, respectively. Laboratory experiments have been performed in the Magnetic Reconnection Experiment (MRX), where the stability properties of arched, line-tied MFRs were controlled via the external fields. Previous experiments revealed a class of MFRs that were torus-unstable but kink-stable, which failed to erupt [1]. These "failed-tori" went through a process similar to Taylor relaxation where the toroidal current was redistributed before their eruption ultimately failed. In more recent experiments, we have investigated this behavior through additional diagnostics that measure the current distribution at the foot points and the energy distribution before and after an event. These measurements give further insight into the phenomena responsible for failed torus events. These experiments allow for new physics insights that are required for better understanding and predictions of space weather events but are difficult to obtain otherwise.

Background

- Protrusions of magnetic field and plasma from the solar surface often result in the formation of long, thin magnetic flux ropes (MFR).
- These ropes are long-lived but can violently erupt, causing solar flares and/or coronal mass ejections (CME).
- Understanding the stability of these MFR is necessary to predict CMEs.

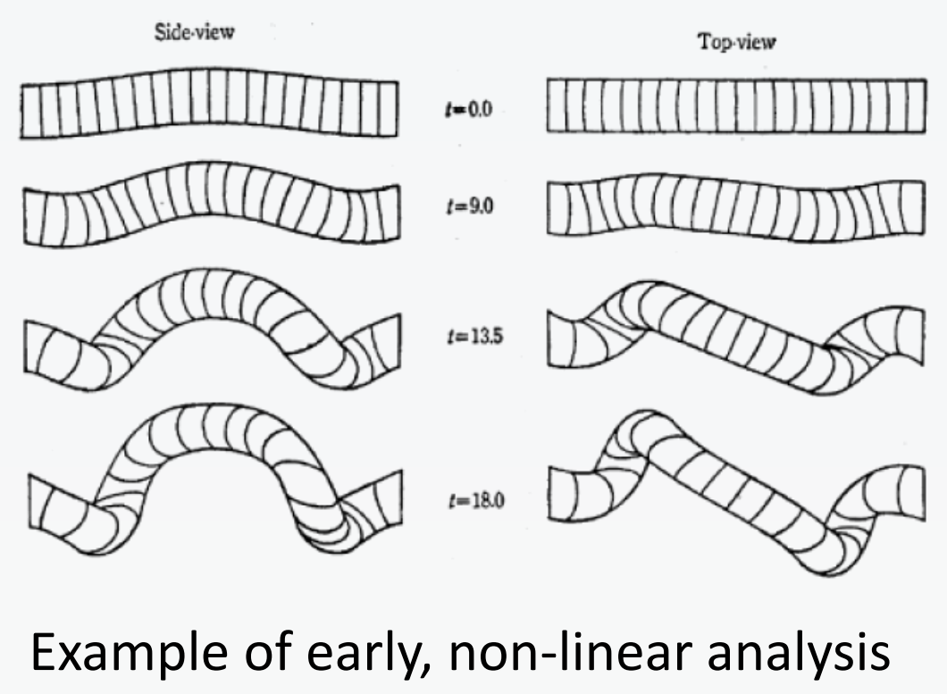


A cartoon depicting the fields and currents associated with a flux rope. Figure reproduced from Ref. [2].

- Foot points of the MFRs are anchored to the conductive Solar surface through line-tying, affecting their stability properties.
- For an eruption to occur, the MFR must be unstable enough to push through the external magnetic fields.
- MFR stability is determined by MHD instabilities such as the kink and torus instabilities.

Kink Instability

- The kink instability is caused when a plasma column has too much axial current.
- This twists the outer field lines so that the entire plasma can kink
- It occurs when the safety factor $q_a \equiv \frac{2\pi a}{L}\frac{B_{Ta}}{B_{Pa}} < 1$

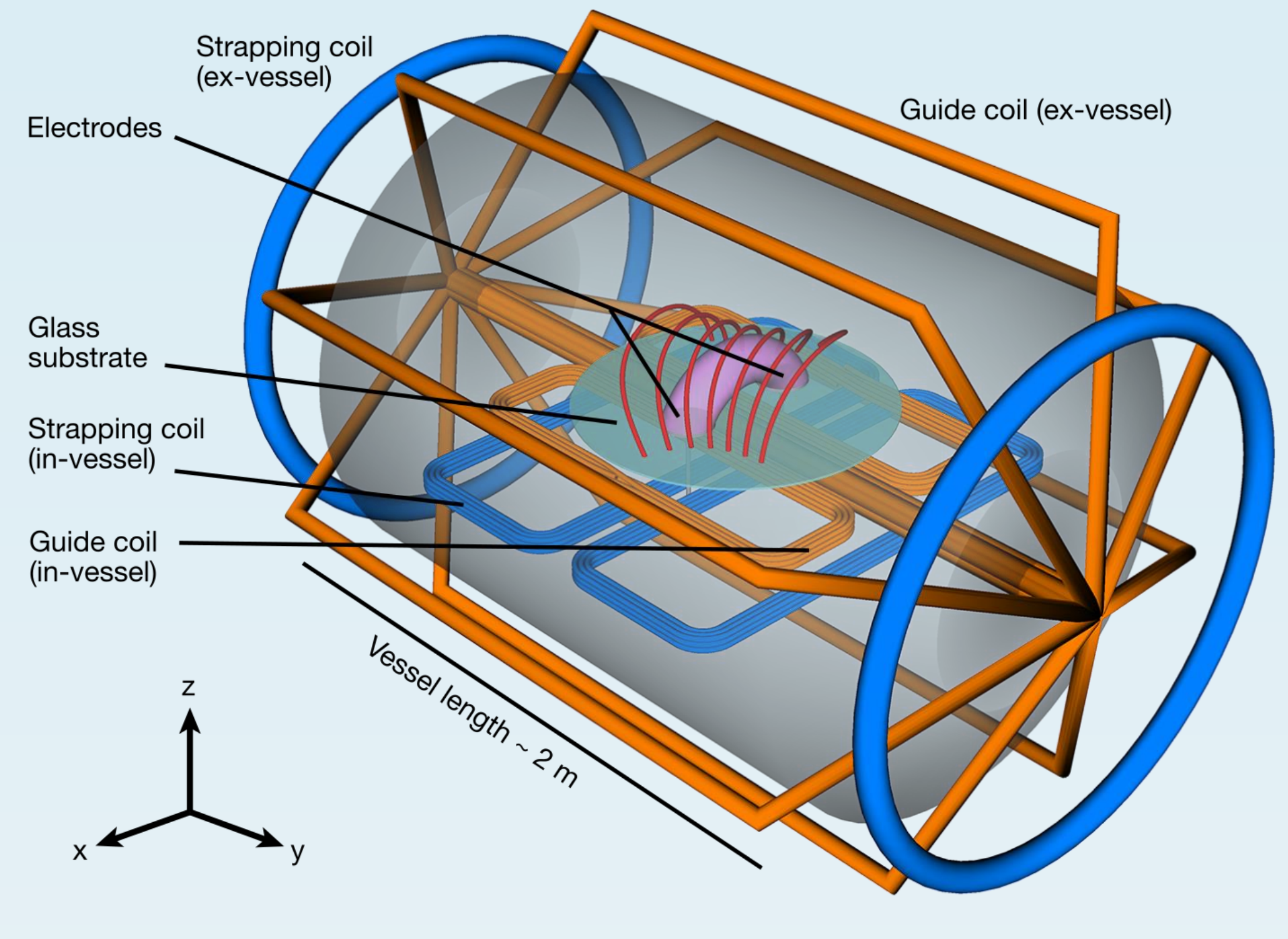


Example of early, non-linear analysis of a kink instability [3].

- The kink is stabilized by reducing the plasma current or increasing the toroidal magnetic field
- The kink instability is relevant to both tokamaks and solar flux ropes.

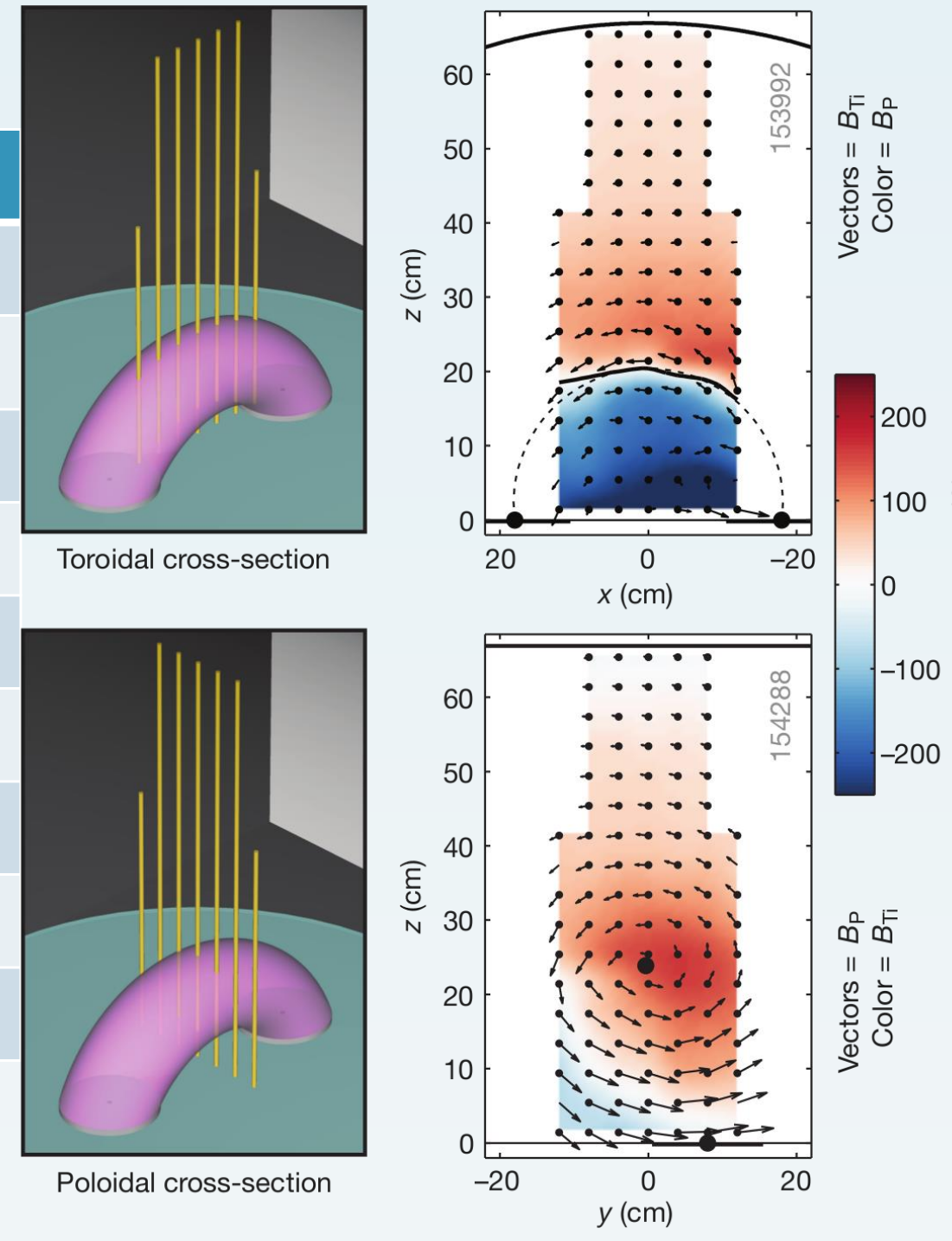
Experiment

- Flux ropes were created in the MRX vessel by creating a discharge between two electrodes. The foot points are line-tied to these conductive electrodes.
- The vacuum fields are controlled by 4 independent coils.
- Plasma current is injected quasi-statically by a capacitor bank.
- A 2D magnetic probe array with limited out-of-plane probes is used to measure the fields in the rope during a discharge. The array can be rotated to measure in different planes of the MFR.



A schematic of the MRX vessel configuration during the flux rope experiments. Figure reproduced from Ref. [4].

Experimental Parameters	
Magnetic field (B)	$300-500$ G
Neutral density (n_n)	$\sim 10^{15}\mathrm{cm}^{-3}$
Electron density (n_e)	$\sim 1\times10^{14}\mathrm{cm}^{-3}$
Electron temperature (T_e)	$3-7$ eV
MFR scale length (L)	50 cm
Alfvén speed (v_A)	$50-150$ km/s
Alfvén time (τ_A)	$3-10\ \mu s$
Driving time (τ_D)	$\sim 150\ \mu s$
Resistive time (τ_R)	~ 1 ms



Example data from 2 shots with the probe array in different orientations. Figure reproduced from Ref. [4].

Torus Instability

Consider a closed flux rope (i.e. a torus) in equilibrium

$$F_\mathrm{h} + F_\mathrm{s} + F_\mathrm{t}\Big|_{z=z_\mathrm{ap}} = 0$$

where the forces are defined below. The torus instability occurs when

$$\frac{\partial F}{\partial R} = \frac{\partial}{\partial R}(F_\mathrm{h} + F_\mathrm{s} + F_\mathrm{t})\Big|_{z=z_\mathrm{ap}} > 0$$

With the equilibrium condition, the MFR is unstable iff

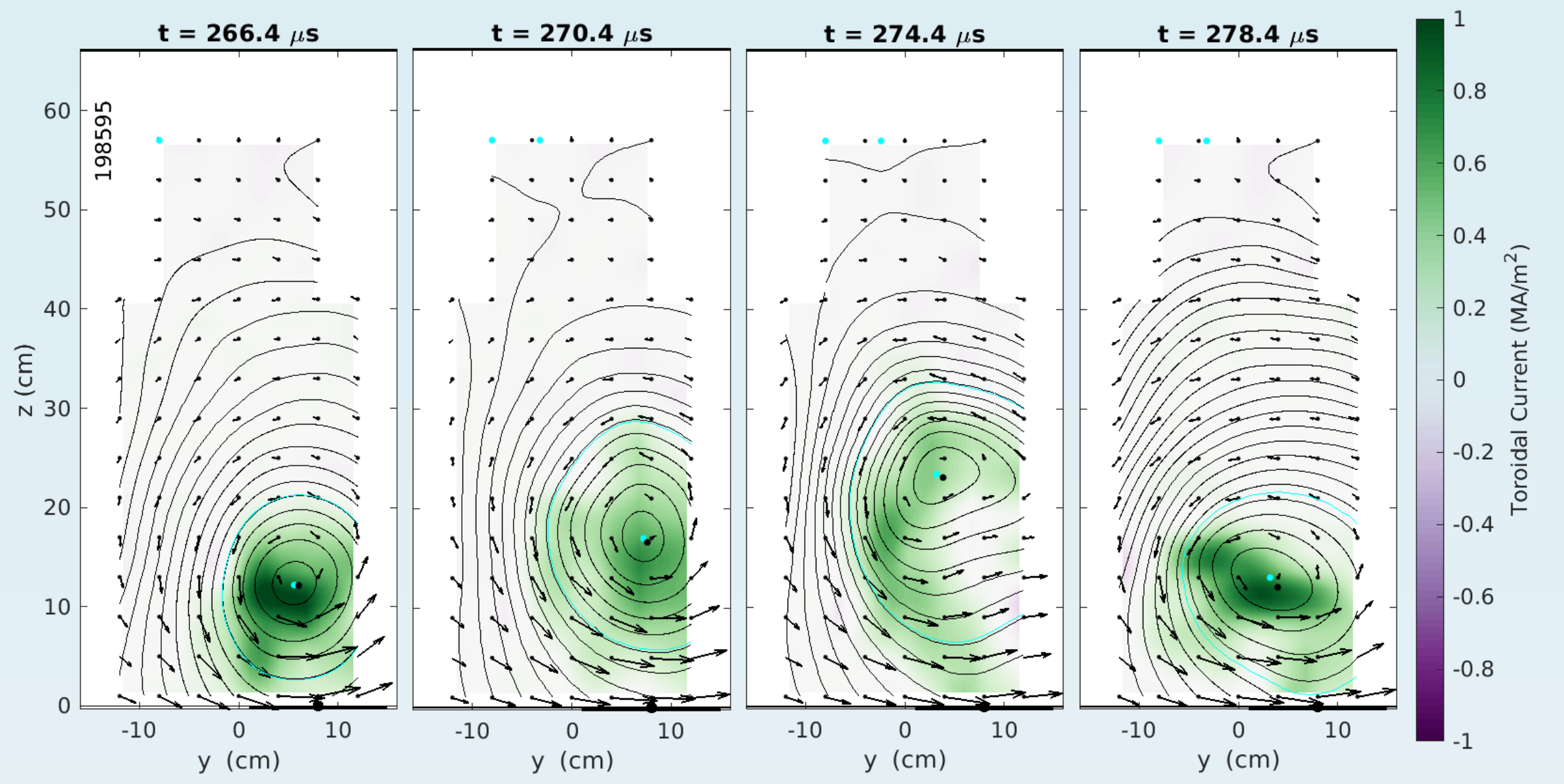
$$n_s > 1 + n_I + \frac{2n_A}{2\ell+1} + \frac{2\ell_i n_{\ell_i}}{2\ell+1} \approx 1.5$$

Where $n_s = -\frac{R}{B_s}\frac{\partial B_s}{\partial R}$ is the decay index of the strapping field and n the decay indices for the current, aspect ratio and internal inductance are similarly defined.

Force	Source	Expression
Hoop (F_h)	$+J_\mathrm{T}B_\mathrm{pi}$	$\frac{\mu_0 I_\mathrm{T}^2}{4\pi R}\left[\ln\left(\frac{8R}{a}\right) - 1 + \frac{\ell_i}{2}\right]$
Strapping (F_s)	$-J_\mathrm{T}B_\mathrm{s}$	$-I_\mathrm{T}B_\mathrm{s}$
Tension (F_t)	$-J_\mathrm{p}(B_\mathrm{g} + B_\mathrm{Ti})$	$-\frac{1}{2}\frac{\mu_0 I_\mathrm{T}^2}{4\pi R}\left[\frac{\langle B_\mathrm{T}^2\rangle - B_\mathrm{g}^2}{B_\mathrm{pa}^2}\right] \approx -\frac{1}{2}\frac{\mu_0 I_\mathrm{T}^2}{4\pi R}$

Toroidal Current Measurements

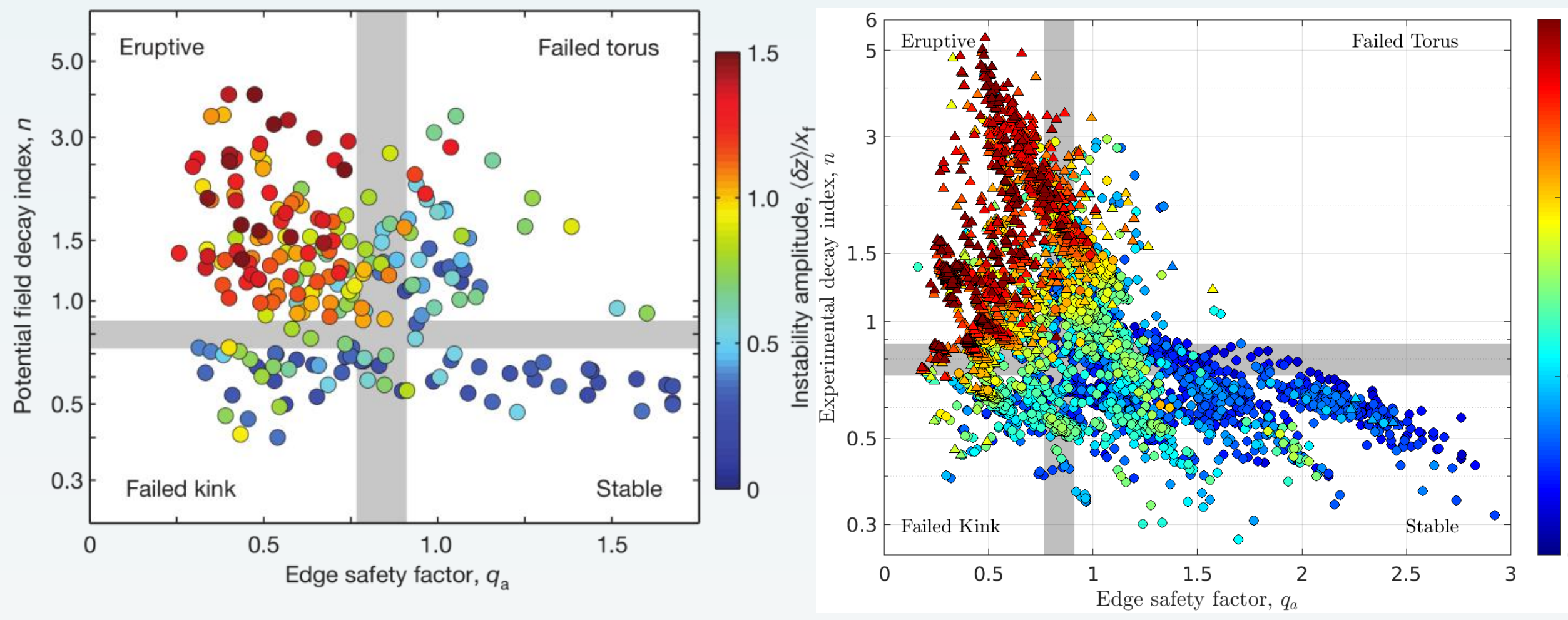
- The 2-D magnetic probe array allows for accurate measurement of the toroidal plasma current within a flux rope.
- In ropes that are unstable to the torus instability, a hollowing of the current profile is often seen while they rise.
- This hollowing is a potential indicator of a form of reorganization such as Taylor relaxation.
- Increase of the toroidal flux is also seen during events.
- The flux increase can increase the tension force, causing the eruption to fail.



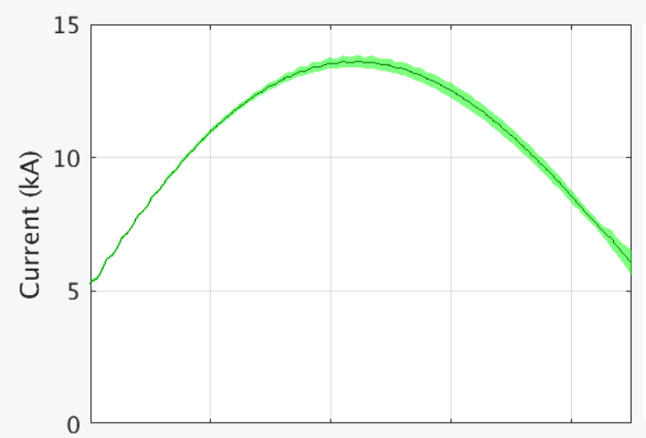
Plots of the toroidal plasma current measured in a flux rope. The locations of the probes and the in-plane magnetic field are also shown. The rise, hollowing, and collapse of the current profile can be clearly seen. See accompanying videos for more detail into this process.

Experimental Parameter Space

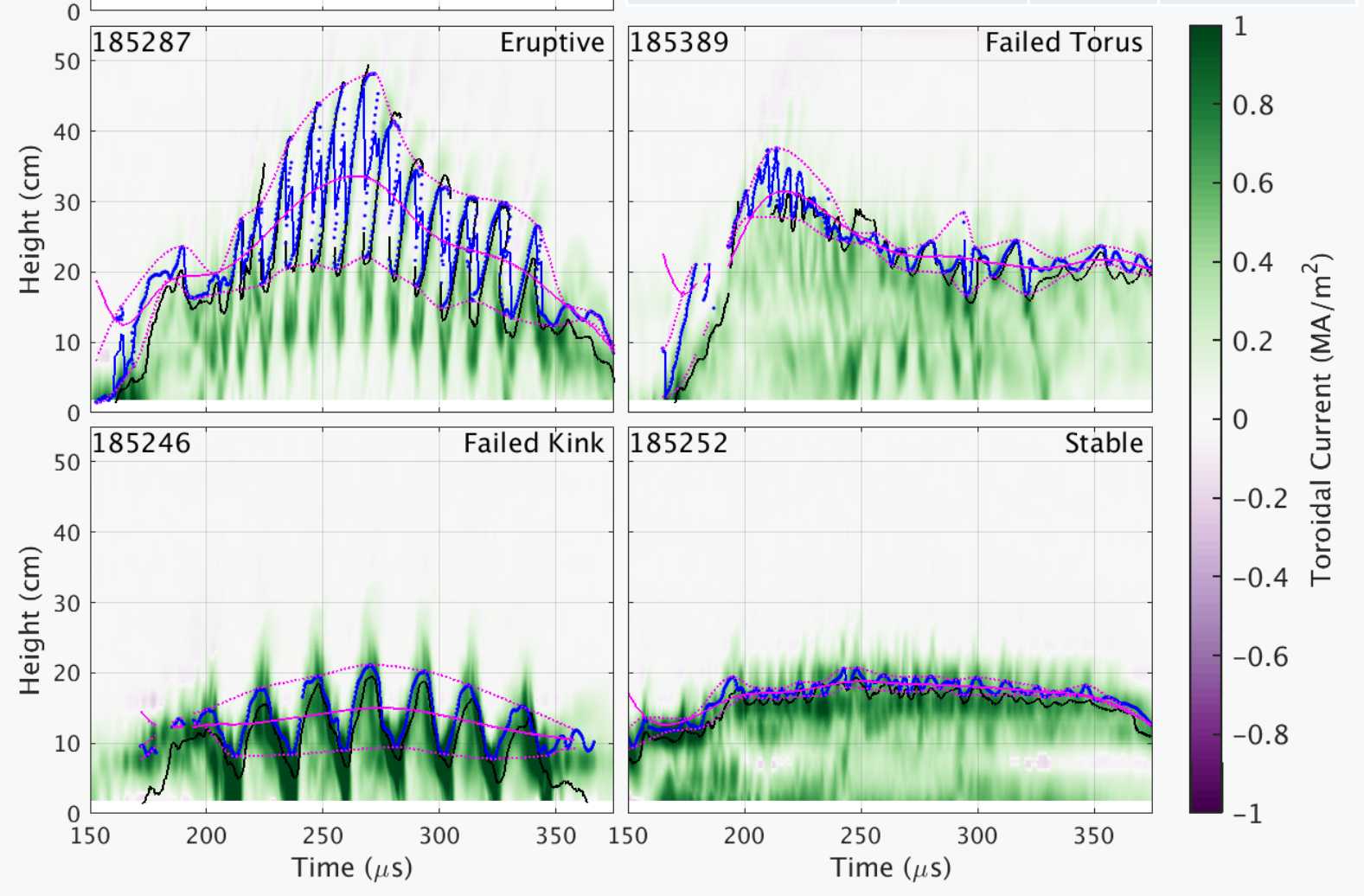
- The governing parameters for MHD instabilities of flux ropes are q_a and n_s, and so they define an experimental parameter space.
- Previous experiments showed 4 distinct regions of stability in relation to these parameters.
- 1 region is stable, 2 have displacements of the ropes but are ultimately confined, and the final region is unstable and eruptive.



Comparison of the experimental parameter space of previous experiments (left, reproduced from Ref. [4]) and the recent experimental campaign (right). The observed thresholds for the torus and kink instabilities are shown by gray bars. The same regions of stability are seen.



	q_a	n_s	$\langle\delta z\rangle/x_f$
Eruptive	0.30	1.47	1.02
Failed Torus	0.90	1.41	0.28
Failed Kink	0.87	0.53	0.57
Stable	1.56	0.73	0.11

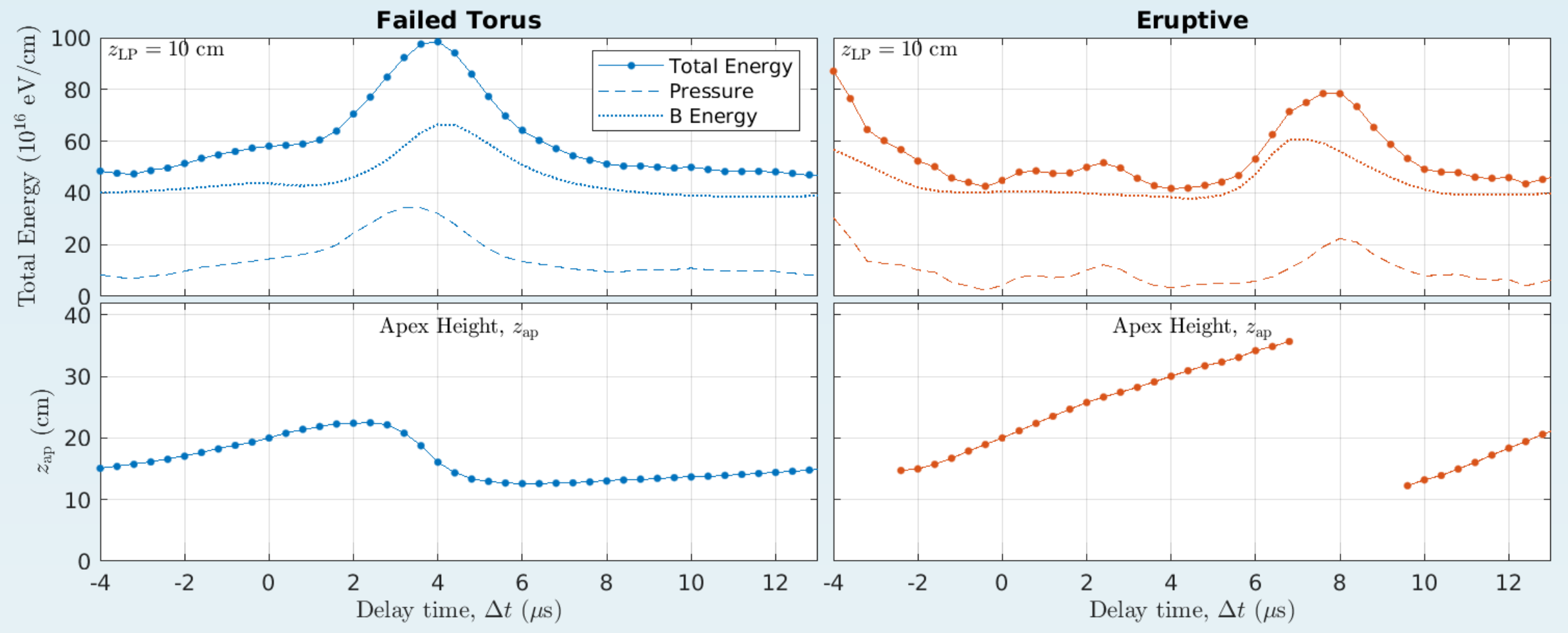


- Examples of the time evolution of flux ropes from each of the 4 quadrants of the parameter space.
- The plasma current vs. time is also shown in the top left plot.
- The blue curves show the apex position defined by the null of the in-plane magnetic field while the magenta line shows an averaged envelope containing the apex.
- The color shows the vertical distribution of the toroidal current within each rope.

Energy Breakdown During Events

- An average event is built up across many shots.
- The energy is measured via triple Langmuir probes and the B-dot probe array.
- The compressive power is based on the cross-section area change while collapsing.
- The total energy change is balanced by the compressive work to within 6%
- The energy can be balanced using only ideal MHD without the need for non-ideal effects such as reconnection.

Work/energy change	Energy $(10^{16}\mathrm{eV/cm})$
Pressure compressive	-8.1
Magnetic compressive	-57
Internal energy	12
Magnetic energy	36
Kinetic energy	13
Total work	**-65**
Total energy change	**62**



The internal energy breakdown in an average failed torus and eruptive event. Thermal energy is measured by a triple Langmuir probe and magnetic energy via the B-dot probe array. Data is averaged over multiple events across many shots.

Conclusions

The stability properties of solar flux ropes are important for understanding the cause and evolution of coronal mass ejections. The torus instability is one MHD instability that can drive MFRs to eruption. While the decay index of the strapping magnetic field has been shown to not be a sufficient condition for eruption [3] it has been shown to strongly correlate with CME activity in solar observations [5]. In previous experiments, certain torus-unstable ropes failed to erupt when the safety factor was large. These ropes went through a self-organization process where the current profile hollowed, and the toroidal magnetic field and tension force were enhanced.

The energy breakdown has been measured before and after a failed torus event via averaging across multiple events and many shots with identical experimental conditions. These measurements show that purely ideal MHD effects can be used to describe the changes in energy and non-ideal effects such as reconnection are not necessary. A potential mechanism of increasing the total flux without violating the line-tied condition at the foot points is currently under investigation.

References

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[2] Myers et al., Phys. Plasmas **23,** 112102 (2016)
[3] T. Sakurai, Pub. Astron. Soc. Japan, **28**, 177 (1976)
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