Final Scientific Report: *Experimental Investigation of Reconnection in a Line-tied Plasma*

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Executive Summary and Abstract

This grant used funding from the NSF/DoE Partnership on Plasma Science to investigate magnetic reconnection phenomena in a line-tied pinch experiment. The experiment was upgraded from a previous device intended to study fusion plasma related instabilities to a new configuration capable of studying a number of new, previously unstudied configurations. A high spatial and time resolution arrray of magnetic probes was constructed to measure time evolving structures present as instability and turbulence developed. The most important new equilibrium made possible by this grant was was a Zero-Net-Current equilibrium that models the footpoint twisting of solar flux tubes that occurs prior to solar eruptions (flares and coronal mass ejections). This new equilibrium was successfully created in the lab, and it exhibited a host of instabilities. In particular, at low current when the equilibrium was not overly stressed, a saturated internal kink mode oscillation was observed. At high current, 2 D magnetic turbulence developed which we attribute to the lack of a equilibrium brought about by a subcritical transition to turbulence. A second set of experiments involved the turbulent interactions of a collection of flux tubes all being twisted independently, a problem known as the Parker Problem. Current profiles consisting of 2, 3 and 4 guns were used to impose a fine scale drive and resulted in a new experimental platform in which the injection scale of the magnetic turbulence could be controlled. First experiments in this configuration support the conclusion that an inverse cascade of magnetic energy occured which self-organized the plasma into a nearly axisymmetric current distribution.

Background. Magnetohydrodynamic (MHD) instability of current carrying plasmas is a topic of importance to astrophysical and laboratory plasmas. In the Sun, current driven MHD instability is believed responsible for solar flares. The twisting of solar coronal loops caused by photospheric shear flow and vortices results in current flow parallel to the magnetic fields. When the current exceeds a critical value dependent upon the background magnetic field, instability can occur, resulting in a flare or mass ejection; similar phenomena may occur in accretion disks. Considerable theoretical effort has been made to understand the instability onset by modeling these plasmas as line-tied cylindrical plasmas [1, 2, 3, 4]. Current driven instabilities may also be responsible for the sinusoidal form of some astrophysical jets [5]. Laboratory plasmas, such as the tokamak, reversed field pinch and spheromak, are all susceptible to kink instabilities from the same excessive twisting in field lines. When the current in the plasma exceeds a critical value, the plasma deforms into a helical structure which grows exponentially on a time scale similar to the time it takes an Alfvén wave to propagate across the plasma.

In numerical studies of solar flares, it has been pointed out that the vortical twisting of a flux tube footpoint may very well have the effect of generating an equilibrium which has zero net current [6, 7, 4]. The cylindrical equilibrium can be thought of as being generated by a vortex characterized by $V_\theta(r)$ which goes to zero at some finite distance from the center of the column. At that point, the field lines remain straight (the poloidal field remains zero). The equilibrium current density profile must, by definition, be coaxial in nature such that there if there is a positive current in the center, there must be a corresponding negative, return current in the edge.

A related class of screw pinch equilibria are those where plasma current density on the axis of the device is smaller than current at the edge. These screw-pinch equilibria may be related the recently observed phenomena of "current holes" in toroidal (tokamak) plasmas [8, 9, 10]. Current hole plasmas exhibit internal transport barriers, increasing interest from the fusion community [11], but are also suspect to a variety of MHD instabilites such as tearing modes. [12] Researchers attempted to create current profiles with negative current in the core and positive current in the periphery of toroidal devices by controlling the inductive programming of the current profile evolution together with non-inductive sources of off-axis current. Interestingly, negative current was never observed in the core, rather the central current density was clamped at "zero". It is speculated that MHD instability is responsible for maintaining the strange equilibrium. It is interesting to consider how the line tying may effect the stability of these equilibria.

The primary goal was to investigate the stability of Zero-Net-Current equilibria in a device a the University of Wisconsin known as the Line-Tied Reconnection Experiment (see Fig. reffig:LTRXminimal). It is a linear screw pinch plasma device consisting a linear solenoidal magnet and plasma that carries current along the column. The device used an electrostatic plasma gun array for producing a current carrying column with a programmable current profile. 19 Discrete current injecting guns injected current at different locations to control the current profile of the resulting screw pinch. The original experiment was built to study how rotating metal walls could be used to stabilize MHD instabilities in fusion experiments and these guns were used to create a nearly uniform current density plasma column that would exhibit and external kink instability—arguably one of the most fundamental MHD instabilites, as first described by Kruskal and Shafranov. Very early in the life of this experiment, observations showed that internal fluctuations, driving by tearing, occurred and that reconnection was a playing a critical role in the plasma behavior. This allowed the experiment to evolve into a facility dedicated to understanding MHD instability and resulting turbulence in line-tied rather than periodic systems.

Major Hardware Activities.

During the duration of this grant, a number of device upgrades and diagnostic additions were made to the device, transforming the Rotating Wall machine[13, 14, 15, 16, 17],in a dedicated line-tied reconnection experiment. These activities were led by graduate student Matthew Brookhart, undergraduate Aaron Stemo and our engineering team Mike Clark and John Wallace.

The first hardware upgrade was to the vacuum vessel and magnets, which were intended to lead to higher temperature (high Lundquist number) plasmas. Four new high field magnets (acquired as surplus from LANL) were repaired and retrofitted to work on the LTRX experiment (Figure **??**) increasing the length of the experimental volume from 1.2m to 2.1m. The longer experiment allows current driven instabilities to be observed at nearly twice applied field for the same amount of axial current (limited by the guns to 1kA/gun). The stronger guide field, together with a mild magnetic mirror, should allow for larger the plasma temperature. Measurements from a triple-tip Langmuir probe indicated a temperature increase from 3-4 eV to 6-8 eV. Optical diagnostics and a sweeping probe are under construction to confirm this measurement.

The second set of hardware upgrades include provisions for additional higher resolution diagnostics. The new vacuum vessel in the longer configuration required only an additional pyrex tube and a new, insulating box port installed at the equator of the experiment (Figure 2). This new box port drastically improves both probe and optical diagnostic access to the center of the plasma. A variety of new diagnostics were under construction in the first months of 2013. First, a 1.5m Czerny-Turner Monochrometer has been refitted to measure line shapes of emitted light. Spectroscopic measurements of H_β radiation have been used to measure the plasma density via Stark broadening and an Intensified CCD Camera has been purchased which will allow multi-cord density measurements, helium ion temperature measurements (via Doppler broadening) with 0.25 eV resolution, and helium ion flow (via doppler shifts) with 250 m/s resolution. The new camera will be installed and used for these measurements by July 1, 2013. Second, a visible light heterodyne interferometer [18] was been constructed. This interferometer was mounted underneath the vacuum vessel on a scanable linear stage with a beam that passes through the box port.

Third, a 288-coil B-dot probe array (Figure 2 iwas constructed to simultaneously measure all three components of magnetic field at 96 locations on the 2D midplane of the experiment, allowing for 2D data sets to be taking at the 1MHz time resolution of the digitizers. The array was mounted in the box port and integrated by a set of custom analog integration circuits. The array is installed in a plastic box port at the axial midplane of the experiment, providing detailed and complete information of the 2D, time resolved structure of the plasma equilibrium and instabilities without relying on shot-to-shot reproducibility. The box port and probe array can be seen in Figure 2. Custom analog integration and amplification circuits were constructed for the array. The integrators use a "spoiled" design that allows for low-cost construction but also introduces a sag in the integrated signal. Fortunately, this sag is deterministically derived from the output signal and can be removed in post processing for precise equilibrium and instability measurements. The array was built in incremental stages: the first 96 coils were installed in October 2013 and initial data was presented at the APS-DPP meeting. The second set of 96 coils (for a total of 192) was installed in February 2014 and a more complete set of data was presented at the CMSO general meeting. The final set of coils was installed in May 2014 and data collection is currently underway.

Fourth, the plasma gun array was modified to allow for Zero-Net-Current equilibria to be created. The central gun of the main plasma gun array was replaced by an anode and the central anode at the opposite end of the device was replaced by a plasma gun cathode.

Findings. To create a zero-net current equilibrium, six guns produce a ring of negative plasma current at $r \approx 3.6cm$ while one gun, located on the other end of the experiment, provides positive current at the center of the device. A pulse width modulation system controls the currents on each gun to create a constant current discharge. Fig. 4 displays current and magnetic time traces from the experiment. Currents from the central gun balance currents from the outer six guns for much of the discharge. Internal measurements of this equilibrium are charted in Fig. 3. The internal probe array measures $B_\theta = 0$ at the edge of the plasma, slight diamagnetism, and the reversed current profile. For this equilibrium, the safety factor q is minimal on axis and $q \to \infty$ at large radius.

The internal magnetic data reveals bursty events; fast magnetic fluctuations appear on the time trace in Fig. 4 (b). Fig. **??** (a) details one of these events. An $m = 1$ internal kink mode grows exponentially with $\gamma = 127 \pm 15$ kHz. While large mode activity occurs in the center of the plasma, the external magnetic array exhibits no m=1 activity above the noise floor. This indicates a purely internal kink instability. The growth rate $\gamma\tau_A = \gamma a/v_A = .027 \pm .006$ is consistent with calculations of the internal kink mode in ideal MHD [7, 19, 20].

When the kink mode reaches its peak amplitude, the safety factor at the center of the plasma begins to rise, as shown in Fig. **??** (b). This is consistent with the redistribution of current expected in a magnetic reconnection event. Fig. 5 graphs the current profile measured by (a) the internal array, and (b) the segmented anode, 20 μs before and after the peak of the kink mode. There is a large drop in plasma current at the axis of the machine but very little change at the boundary of the experiment. The localized magnetic fluctuations and current redistribution illustrate a fully 3D internal magnetic reconnection event. The slight dip in the edge current appears as the plasma experiences a two-fold increase in effective resistivity; the biasing power supply struggles to maintain current drive.

The $m = 1$ eigenstructure of the kink mode is clearly visible in Fig. 6. Additionally, a strong current spike occurs at $(x, y) = (-1, 4)$ cm. This spike in the current density, lasting for $\approx 6\mu s$, is approximately 1 cm thick and 5 cm long. While this is suggestive of current sheet formation, the limited time resolution ($2\mu s$) and spatial resolution ($1.1cm$ in y, $2.5cm$ in x) of the probe array prevent detailed comparisons. These data are qualitatively similar to the non-linear calculations by Velli et al. [21] and Lionello et al. [4], but the low experimental resolution prevents quantitative comparisons. Utilizing measured plasma density, temperature, and B_θ, a Sweet-Parker [22, 23] current sheet of $L = 5cm$ would have thickness $d = 2.5 \pm 1cm$ and $\tau_{SP} = 12 \pm 4\mu s$. Given the high error bars on these measurements we concluded that this reconnection event is consistent with the Sweet-Parker model.

Fig. 7 explores the non-resonant nature of reconnection in the line tied geometry. A total of 2074 reconnection events were found in 78 shots of various current and guide field. The critical safety factor q_{crit} varies considerably from event to event. The strength of the events, as measured by the drop in current density, increases as guide field is decreased, but shows no correlation with the critical safety factor. The large range of safety factors and event strengths illustrate non-resonant nature of the ideal internal kink mode with line-tied boundary conditions. Instead of a resonant phenomenon as is seen in toroidal devices, the stability of the mode depends critically on the equilibrium profile which changes from event to event.

The data in Fig. 7 show critical safety factors $q_{crit} \approx 1.3 - 3.5$, while ideal MHD simulations and models calculate critical safety factors $q_{crit} \approx 0.5 - 0.6$ [7, 19, 24, 20]. Plasma resistivity and flow decrease the critical safety factor of the line-tied kink [25, 26], but the complicated current and flow geometry of the experiment have not been directly studied.

We do not currently understand the observed spread in critical safety factor. The fast, bursty nature of the events offer one possible explanation. Since many events in the data set are separated by $< 50\mu s$, we think that the plasma may not be reaching full equilibrium between events and some non-linear drive creating the large spread in q_{crit}.

The data presented here build upon two previous results from the experiment. Bergerson et al. [27] presented evidence for the internal kink mode in a line-tied screw pinch with a monotonic current profile. Sawtooth-like events that redistributed the current profile where observed in highly kink-unstable discharges. The authors interpreted these results as reconnection, but no internal diagnostics were available. Alternatively, other authors have argued that these data can also be explained as an external kink mode in a plasma that is line-tied on only one end [28]. In contrast, the experiments presented in this Letter show unambiguous evidence for the internal kink mode and reconnection with no external behavior.

More recently, Paz-Soldan et al. [29] used a scanning probe and shot-to shot reproducibility to show the 3D equilibrium structure of a saturated external kink. In these experiments, no reconnection events were observed. The data presented in this Letter improve upon those results by measuring the full magnetic behavior simultaneously, removing the need for shot-to-shot correlations and allowing the direct capture of transient events.

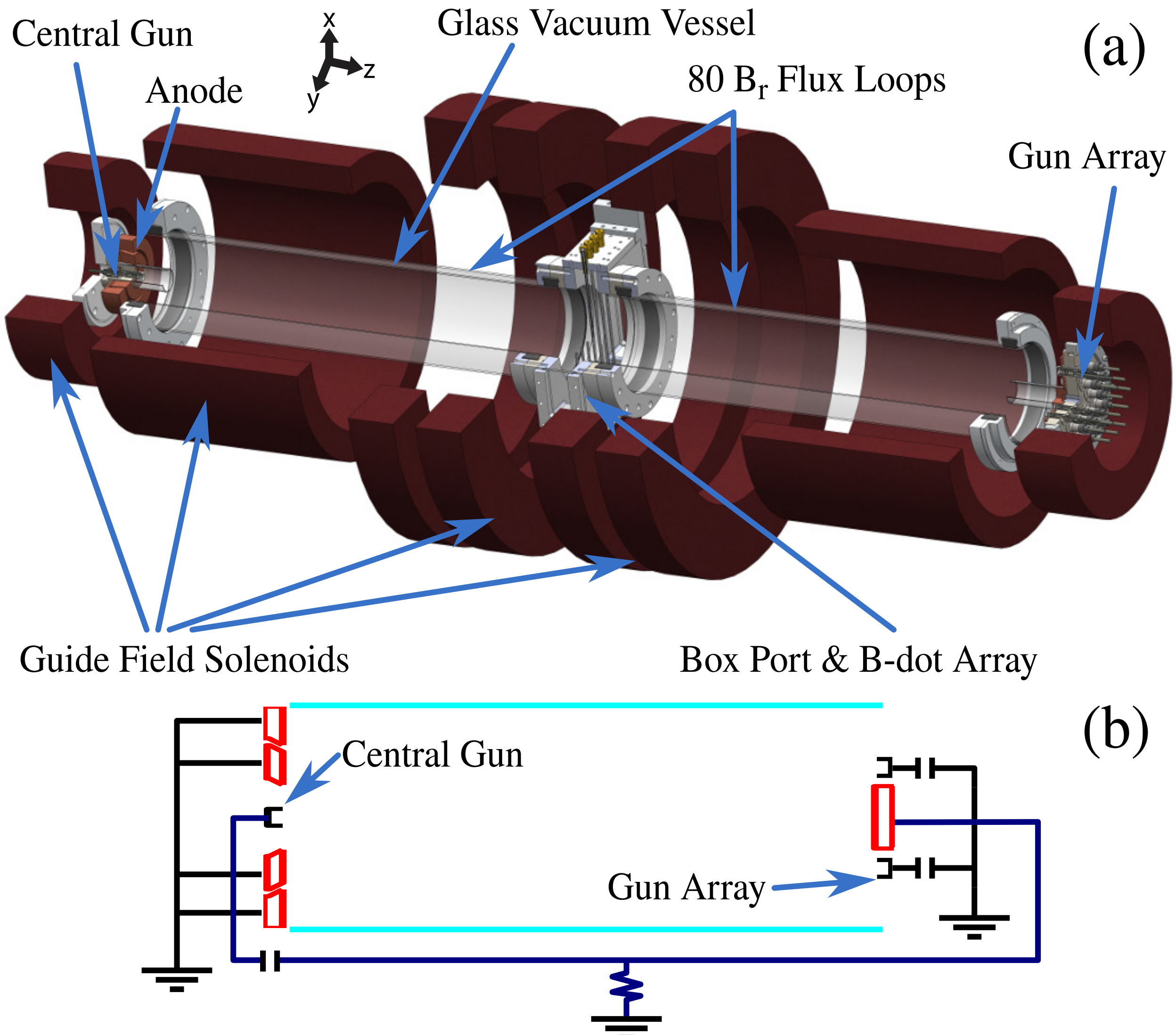
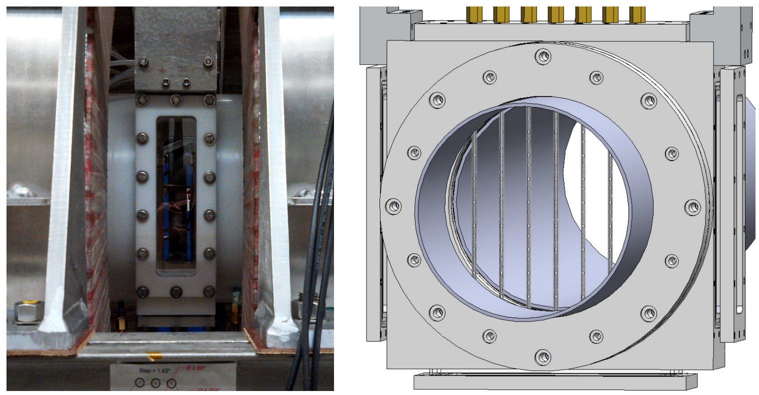


Figure 1: (Color online) The Line-tied Reconnection Experiment geometry. (a) A 3D CAD model of the experiment with components highlighted. (b) A representation of the biasing circuit showing the independent supplies for each gun. The central gun is floating with respect to laboratory ground, this prevents stray arc currents.



(a) (b)

Figure 2: (a) An acetal copolymer box port was constructed and added to the center of the vacuum vessel. The open nature of the new magnets and box port allows for much greater probe and optical diagnostic access while the plastic construction maintains overall insulating boundary conditions. (b) A CAD drawing of the B-dot Array mounted in the Box Port.

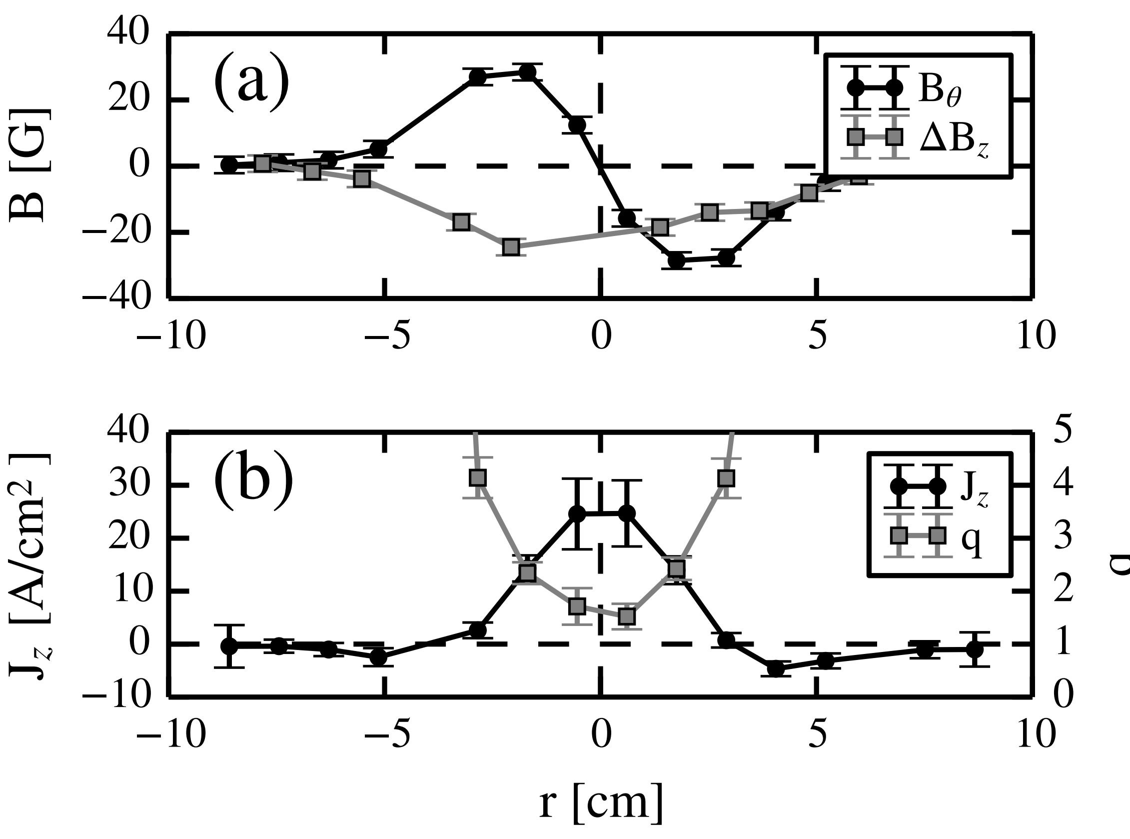


Figure 3: An example zero-net Current equilibrium. (a) The measured ΔB_z and B_θ profiles and the accompanying pressure profile. Note that $B_\theta = 0$ at the edge of the vessel. (b) The current density with the reversal at 3 cm and the steep q profile.

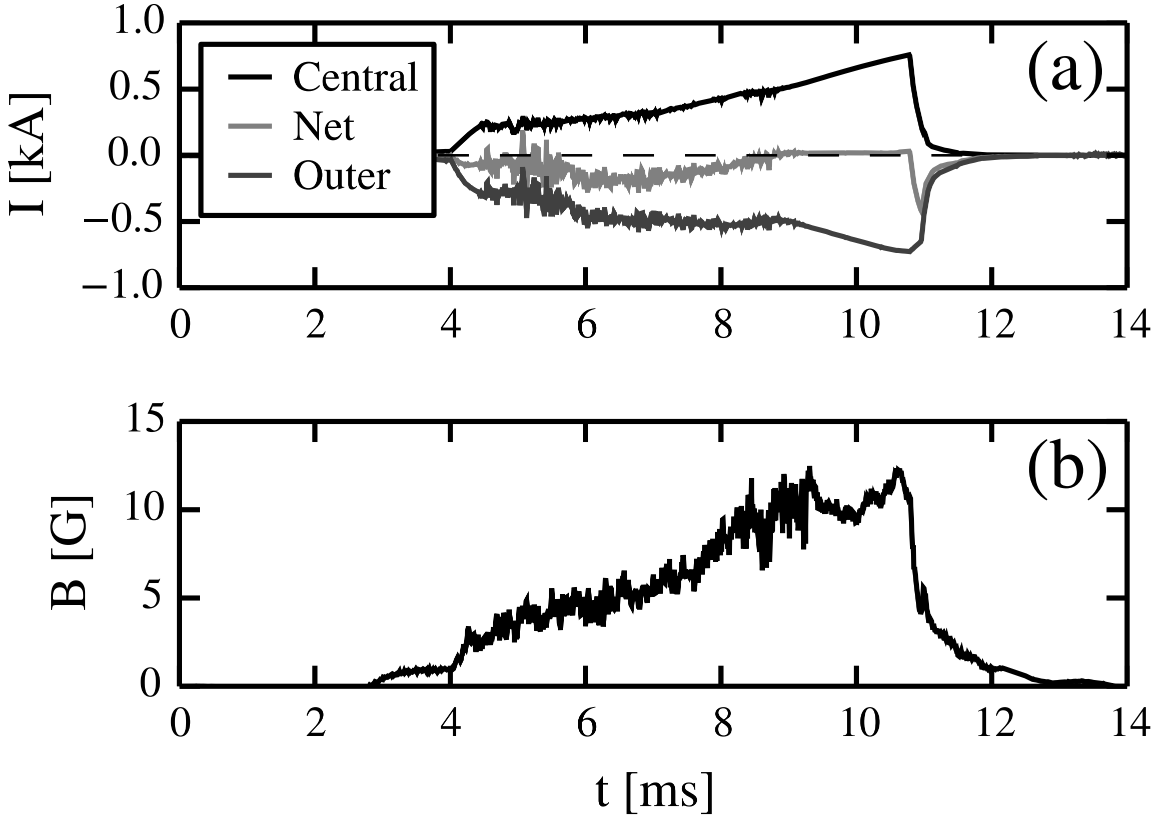


Figure 4: An example discharge. (a) The currents on the center gun, the current from the outer guns, and the total plasma current. (b) An example magnetic probe trace, the fast fluctuations are due to plasma instabilities.

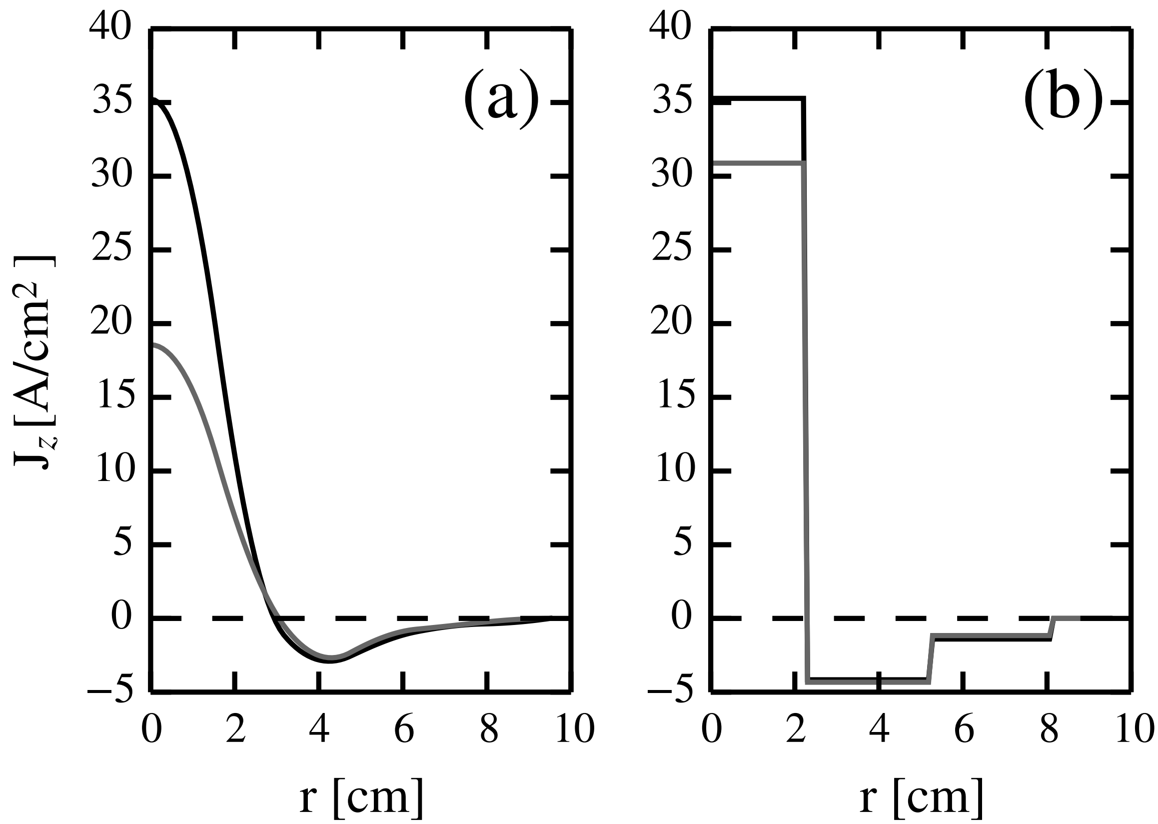


Figure 5: The current profile 10 μs before (black) and after (grey) the crash shown in Fig. **??**. (a) shows a fit to the internal magnetic data measured at 1.04 m from the guns. Notice how the central current density decreases by a factor of 2. Error on the fit is +/-2 A/cm^2. (b) shows the current profile measured at the anode (2.08 m from the guns) of the experiment. The drop in central current is much lower.

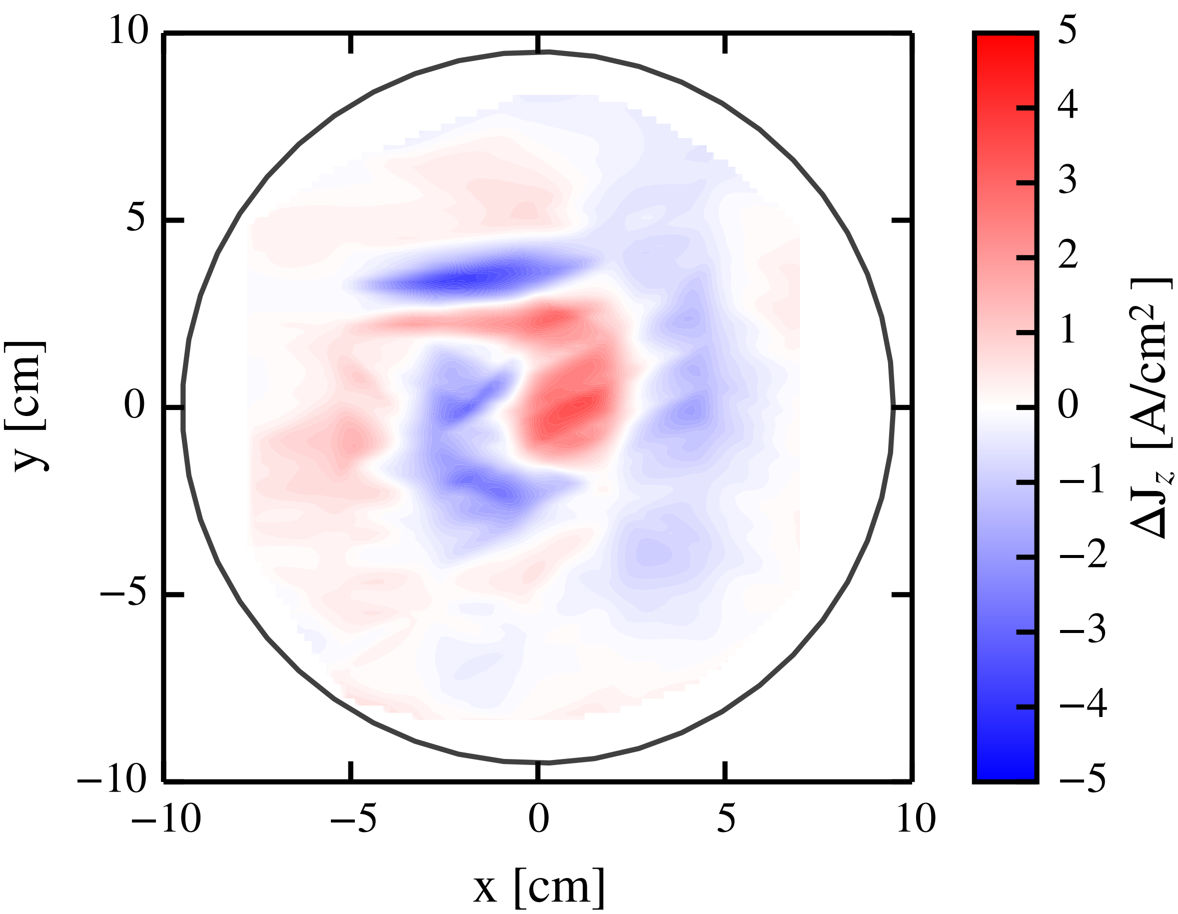


Figure 6: (Color online) The current perturbation at the peak of the $m = 1$ activity. There is clear $m = 1$ perturbation along with a large spike in current at $(x, y) = (-1, 4)$. While this feature suggestive is of a current sheet, low resolution on the probe array prohibits definitive identification.

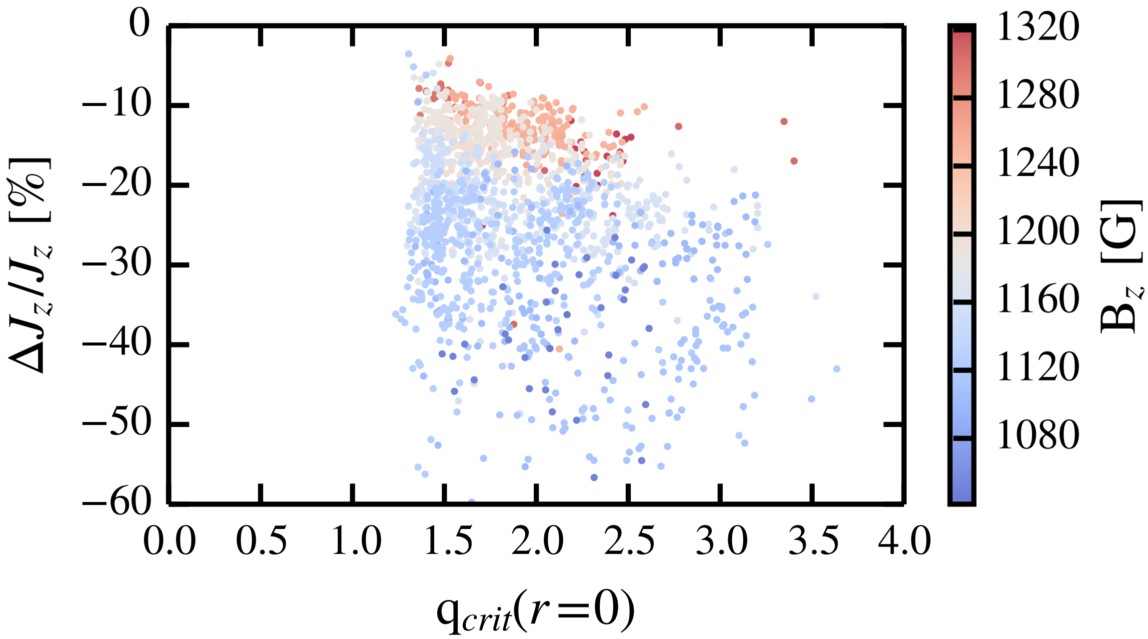


Figure 7: (Color online) A scatter plot of the change in safety factor and critical safety factor for 2074 measured events. Darker colors indicate stronger magnetic fields. The large spread in q_{crit} indicates no critical safety factor/resonant phenomenon, while the large in Δq shows the highly variable nature of the phenomenon. Interestingly, there are equilibrium conditions in the data set with lower safety factor but no reconnection events.

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