

# Fast Camera Images of Flux Ropes During Plasma Relaxation

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**Abstract**—Images of visible light emission from flux ropes during plasma relaxation are presented. Multiple images are used to gain insight into the dynamics of driven/dissipative plasma relaxation processes in finite- $\beta$  plasmas. A fast-gated (40–200 ns) intensified charge coupled device (ICCD) camera generates time-resolved images of 1–3 flux ropes in the reconnection scaling experiment (RSX) device. During relaxation, flux ropes are observed to evolve toward states characterized by the presence of single and multiple helical mode structures.

**Index Terms**—Cylindrical, dissipation, flux ropes, helicity, instability, mode structures, relaxation.

PLASMA relaxation, the tendency of plasmas to evolve toward a preferred equilibrium state determined by global constraints, is a topic of interest in both laboratory and astrophysical plasmas. The Taylor relaxation paradigm [1], while successful in predicting equilibrium plasma states such as spheromaks and reversed field pinches, can be rigorously applied only to zero  $\beta$ , nondriven plasmas in the absence of flows. Such stringent limitations can be overcome by different approaches such as the minimum dissipation rate theory [2], which has yet to be tested experimentally. Our research is geared toward providing dedicated experiments to investigate the effects of nonnegligible plasma flow, finite/high  $\beta$ , and external drive on plasma relaxation.

In the reconnection scaling experiment (RSX), plasma relaxation is studied using single and multiple current carrying plasma columns, i.e., flux ropes [3]. Fig. 1 depicts a cutaway of the cylindrical vacuum vessel (4 m length, 0.20 m radius) with a view of two radially inserted plasma guns ( $z_{\text{guns}} = 0$ ). Inside each gun, a miniature plasma source creates hydrogen or argon plasma by means of an arc discharge ( $V_{\text{arc}} = 700$  V, duration  $\leq 10$  ms). Plasma is ejected through a circular nozzle aperture ( $r = 0.79$  cm) and forms cylindrically shaped columns in the constant, uniform, axial magnetic field ( $B_z = 0$ –1000 G) generated by 12 external coils. One millisecond later, current ( $I_{\text{ext}}$ ) is driven through the plasma by an external bias ( $V_{\text{bias}} \leq 320$  V) from the gun anodes to a large stainless steel anode positioned at  $z_{\text{anode}} = 0.3$ –3 m down the axis of the chamber. The applied bias voltage and the inductance of the total circuit (including the plasma) determine the slope of the applied current ramp (typically  $dI_{\text{ext}}/dt \sim 5$ –30 A  $\mu\text{s}^{-1}$ ). During current

drive, the flux ropes are inductively tied to the gun cathode, but are free to wander around the large anode. Plasma  $\beta$  can be adjusted by varying the axial magnetic field, from  $\beta \ll 1$  up to  $\beta \sim 1$ . For the research presented herein, operating parameters are as follows:  $V_{\text{bias}} = 300$  V,  $B_z = 200$  G,  $z_{\text{anode}} = 1$  m,  $T_e \sim T_i \sim 8$ –15 eV,  $n_e \sim 0.5$ –5  $\times 10^{19}$  m $^{-3}$ ,  $\beta \sim 10\%$ .

Images of flux ropes during relaxation are taken with a Cooke DiCam Pro intensified charge coupled device (ICCD) camera [4] over multiple repeatable RSX discharges. The viewing perspective is end-on to the chamber as indicated in Fig. 1. In the present setup, Alfvén times are estimated to be somewhat long ( $\tau_{\text{Alfvén}} = 0.7$ –1  $\mu\text{s}$ ) as compared to gate times (40–200 ns), so the images are likely to accurately resolve the plasma dynamics. This is supported by the agreement between images and data collected from *in situ* probes that measure temperature, density, and magnetic field structure. The camera provides two 12-bit images, each with  $1280 \times 1024$  pixel resolution. Unfiltered visible light from the plasma (mostly  $H_\alpha$  here) is collected with an AF Nikkor 70–210 mm Nikon zoom lens and a 1.6 $\times$  AF TC-16A teleconverter mounted onto the camera. Fiber optic communication to a PCI card enables digital control of triggering, gate, and interframe times. The camera is housed inside a custom steel enclosure for shielding against pulsed electromagnetic fields.

Fig. 2 shows false color images of one, two, and three flux ropes as they evolve through a variety of mode structures. Images of hydrogen plasma are collected at different times during the current ramp up. The time values are given from the start of the bias and do not necessarily represent the onset of a particular mode, but rather periods where such distinct structures are clearly visible. At early times, (left column) straight flux ropes are visible. Later, the ropes begin to twist into small helical structures (center column). As current continues to increase, larger structures also develop as the ropes collectively twist (right column). The upper right image illustrates that small-scale modes can persist and a superposition of coexisting mode structures is observed. In the case of multiple plasma guns, the flux ropes are also observed to partially coalesce. This, combined with magnetic probe data, suggests that magnetic reconnection plays an important role in the dynamics of the relaxation.

It is interesting to note that the onset of the mode activity leads to an increase in the overall inductance of the plasma/external circuit as seen from the total current measured at the external anode. This is in qualitative agreement with principles of relaxation in that plasmas tend to maximize their inductance as they evolve toward relaxation. It also follows intuitively that a finite inductance is introduced when the conducting plasma is wound

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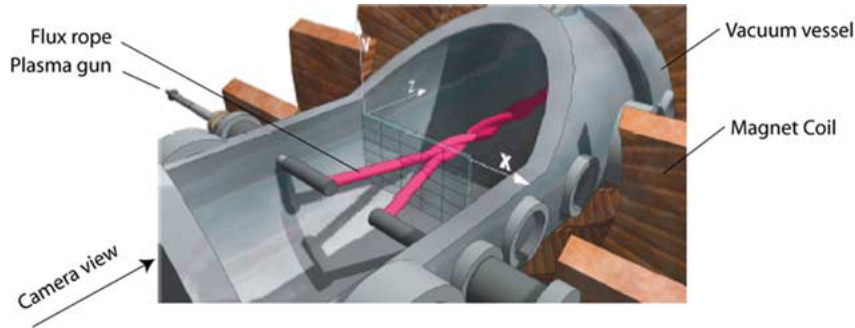


Fig. 1. Diagram of the RSX device.

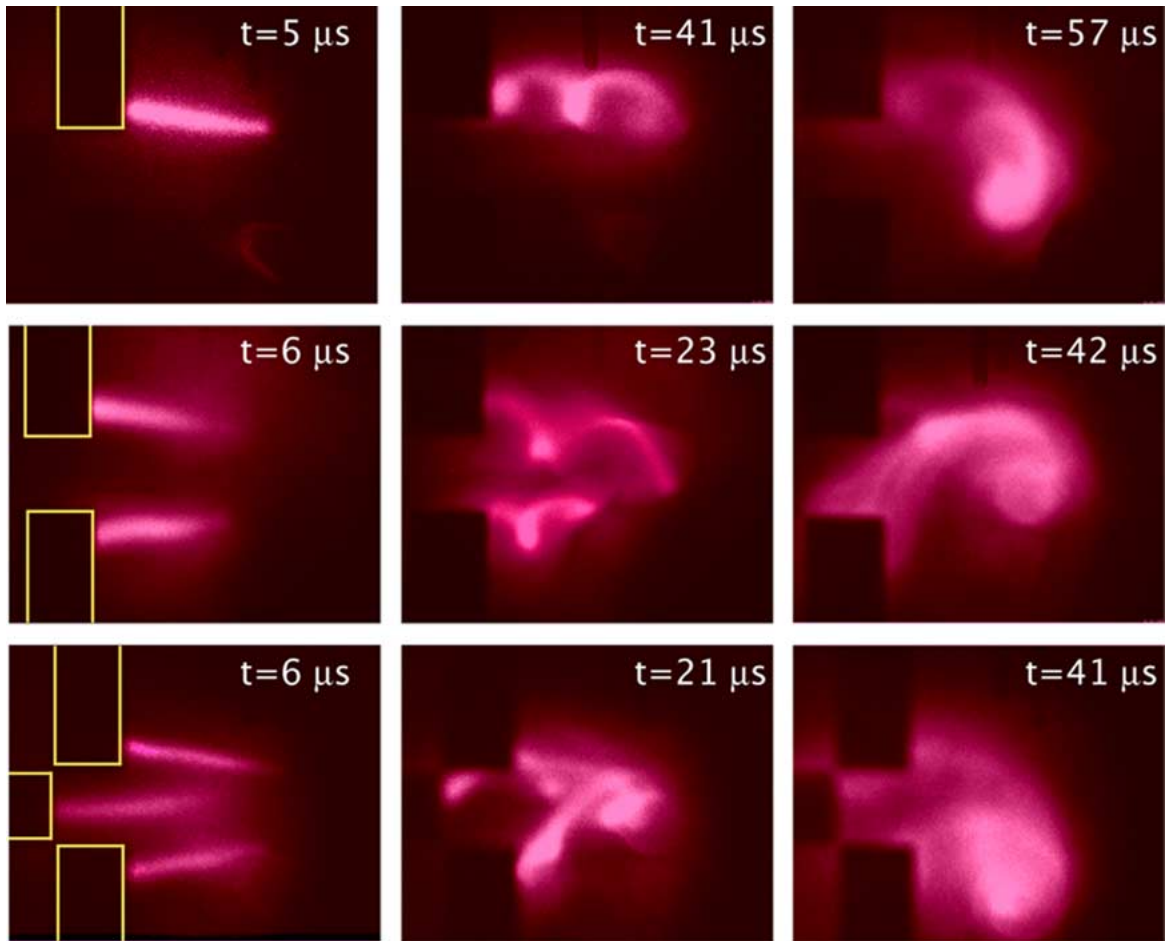


Fig. 2. False color images of single and multiple flux ropes in hydrogen plasma reveal helically twisted structures. Times are given from the start of the applied current drive ( $t = 0$ ). Silhouetted plasma guns in the foreground are outlined for early times.

into a helix. Preliminary analysis of images yields estimates for the change in inductance of the plasma that agree with the observed change in  $dI_{\text{ext}}/dt$ .

For this work, the images provide a useful tool for describing the dynamics of relaxing plasma in a driven/dissipative system. Presently, efforts are focused on characterization of distinct mode structures. This involves the development and implementation of small, three-dimensional magnetic probes and multiple cameras from which we can extract information on the changes in magnetic field topology, magnetic helicity,  $q$ -profile and helical pitch angles.

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