Controlled Laboratory Experiments on Expanding Magnetic Flux Ropes

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The experimental setup necessary to generate a toroidal magnetic flux rope configuration is discussed. The experiment is executed successfully in that the flux rope configuration is created and maintained in a repeatable system. High speed CCD images suggest complex flux rope formation and evolution in time. Known problems and future experimental possibilities are discussed.

I. INTRODUCTION

Since the dawn of our civilization for many individuals it has been a natural curiosity to study the physical world. Historical records date back as far as 2000 B.C. documenting observed Sun-Earth phenomena like the aurora. It was not until the 17$^{\text{th}}$ century that scientific theories began to try and explain the happenings of such phenomena and to this day our inquiries persist and continue to grow in sophistication(3).

It is now understood that the many physical phenomena (auorae, the Van Allen Radiation Belt, the Interplanetary Magnetic Field, geomagnetic storms, etc.) are correlated with solar activity. Plasma physics has become an important element in trying to understand Sun-Earth interactions. With the discovery of solar flares and coronal mass ejections (CME's) a particular interest in understanding the origin of what are now known as magnetic flux ropes has developed.

The physics of eruption at the Sun and propagation of the ejecta is of major importance, spanning several active scientific disciplines. One of the most important questions is what mechanisms are responsible for the eruption and propagation. One of the many theories, proposed by Chen(2), is that a toroidal flux rope connected to the photosphere by two footpoints is driven by the Lorentz force. This theory has been found to be in reasonable agreement with observation.(1)

Found at the surface of the sun are complex plasma flows with twisted magnetic fields which give rise to numerous instabilities such as solar flares. In the current experiment we simplify many of the complicating features of the Sun and isolate the magnetic flux rope configuration. Apart from making controlled measurements of flux rope velocities, full spatial data of the fields and currents can be gathered, contributing information to the flux rope topology and evolution not obtainable from the traditional 2D coronagraphs and satellite observation.

In this paper the experimental setup and the parameters from the first trial are discussed, followed by initial results and discussion.

II. EXPERIMENTAL SETUP AND PROCEDURE

To simulate the flux rope topology found on the sun we needed to create a toroidal magnetic field and have two stationary footpoints for the plasma source. The toroidal magnetic field was generated by two adjacent solenoids with opposite direction current so that the net field was directed from one coil to the next (see Fig. 3). The cathode was placed inside one coil and in the other coil we placed the anode. The nickel cathode was coated with BaO to reduce the work function of the metal so electron emission could be attained by heating the metal to 900 °C. The cathode was connected to a heater and in addition both the bias voltage applied across the cathode-anode and the coils were connected to a pulsar circuit. A schematic of the setup is shown below in Fig. 1.

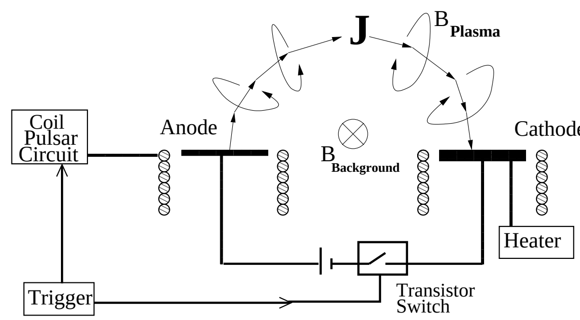

FIG. 1 **Experimental Setup**

The laboratory dimensions of the setup are shown in Fig. 2.

Using a computer program we calculated(4) the magnetic field generated by the two solenoids, shown in Fig. 3. The electrons are restricted to move along magnetic field lines and the ions are dragged along by space charge effects.

The important parameters of our experiment are summarized in the table below. Note that the magnetic field generated by the coils varies spatially and that the maximum value at the center of the coils is listed. The current in the coils used to generate the background magnetic field varied from 0 to 0.5 amps (going into the page in

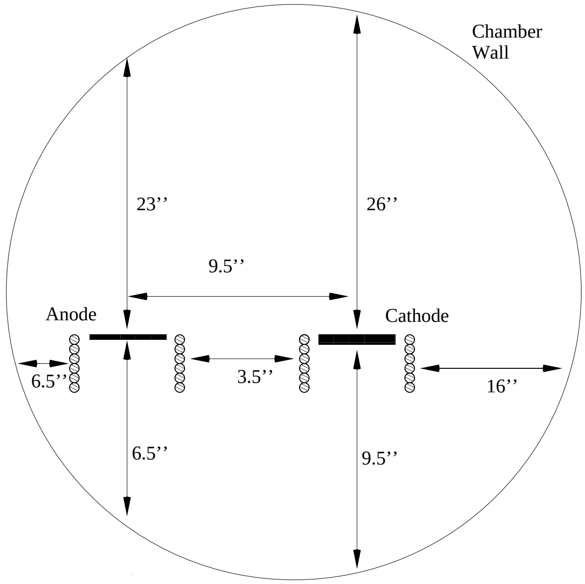

FIG. 2 **Dimensions of Solar Flare Apparatus**

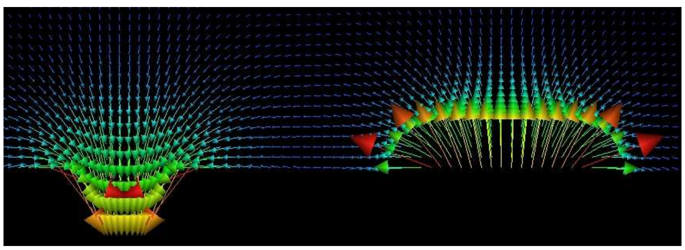

FIG. 3 **Simulated B-Field due to Coils. The largest arrows correspond to approximately 200 gauss.**

Fig. 2) and we assumed a value of about 1 gauss/amp. The discharge magnetic field is the field created by the toroidal discharge current and is poloidal about the discharge current.

The experiment was pulsed at 3Hz. Each Experimental shot took place over the course of 20ms. The coils would be triggered first, 3ms later, after B_{coils} was near maximum strength, the bias voltage across the cathode-anode system was pulsed for 15ms.

Experimental Parameters	
$B_{coils,max}$	200 g
$B_{background}$	0-0.5 g
$B_{discharge}$	5 g
Bias Voltage	120 V
Pressure	$2-4\times10^{-3}$ torr
Cathode Temp	900-1000 °C
Max Current	200A
$R_{ci}, T_i = 0.5eV$	7.2 cm
$R_{ce}, T_e = 2eV$	0.3 cm
Gas	H_2

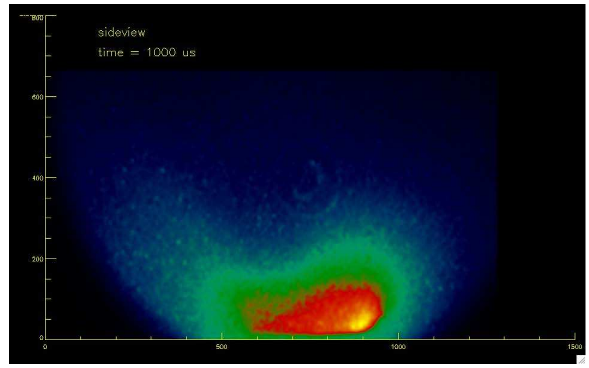

FIG. 4 **Side view image showing a slight drift to the right, $t = 1000\mu s$, color enhanced. $t = 0$ is time at which discharge is initiated.**

III. FINDINGS

The cathode in our experiment emitted less than half of the expected discharge current. Vacuum leaks early in the experiment are thought to have poisoned the coating, thus resulting in the low discharge current of 200A instead of the expected 400A. However, the flux rope configuration described in theory and observed on the surface of the sun was successfully created. As the Lorentz force is proportional to $\mathbf{J}$ it is expected that a more dramatic time-evolution of the flux rope will be observed when the proper amperage is obtained from a non-poisoned cathode. During the lifetime of the cathode we were able to acquire visual data from the front and side perspectives. Using a high speed CCD camera (70 ns/exposure) and digital processing we were able to reconstruct the formation of the prominence starting at $t = 0$, imaging at 5μs intervals. Despite the limitation of these images definite signs of complex formation are evident. Hints of plasma instabilities are made evident by movies constructed from the data in which the plasma reaches a connected arch shape and breaks apart only to reform multiple times. From the side perspective it can be seen that the prominence has a slant to one side indicative of a $\mathbf{B}\times\nabla\mathbf{B}$ [1] drift, as in Fig. 4.

The movies suggest the occurance of the MHD sausage instability, which is a complicated occurance with a relatively simple physical explanation. As current is flowing it may have small constrictive disturbances in its path. If one of these happens to be a radial squeeze then the poloidal magnetic field about the current will be concentrated. This increase in the magnetic field causes the

[1] *Schmidt* gives the drift velocity to be

$$\overrightarrow{W} = \frac{m}{eB^4}\left(v_{||}^2 + \frac{v_\perp^2}{2}\right)\left(\overrightarrow{B}\times\frac{\nabla B^2}{2}\right),$$

where $v_{||}$ and $v_\perp$ are the parallel and perpendicular particle velocities relative to the magnetic field.

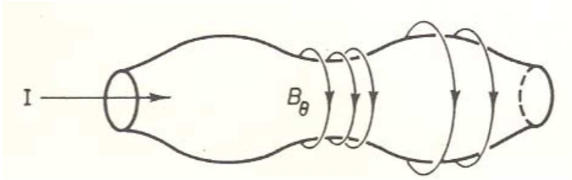

FIG. 5 **Current flow being contracted by the magnetic field, known as the sausage instability.**

squeeze to tighten and eventually breaks the plasma flow. Further evidence for this instability is the time scale on which they occur happens to be on the order of one ion gyroperiod. With an approximate total magnetic field of 10 gauss we obtain a gyroperiod $\tau = 66\mu s$, which is about the timescale at which the instabilities in the movie occur.

This experiment was the first attempt at what will undoubtedly bloom into many more attempts to understand the dynamics of magnetic flux ropes. With the ability to create the flux rope prominence in a highly repeatable fashion it will be possible to explore with the aid of full 3D data on magnetic fields and currents the physics of multiple footpoints, or perhaps moving footpoints, to better simulate the complex solar surface.

IV. ACKNOWLEDGEMENTS

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[7] Schmidt, G., Physics of High Temperature Plasmas, Academic Press, 1966.

APPENDIX A: Frames Illustrating Plasma Growth and Instability

The following frames were taken from our front perspective movie. The frames are at different times and they illustrate the initial growth of the plasma, full connection, instability which fits the description of the sausage effect, and finally a stable state. All instabilities occured within the first 1500 μs, after which the stable state remains for the duration of the pulse.

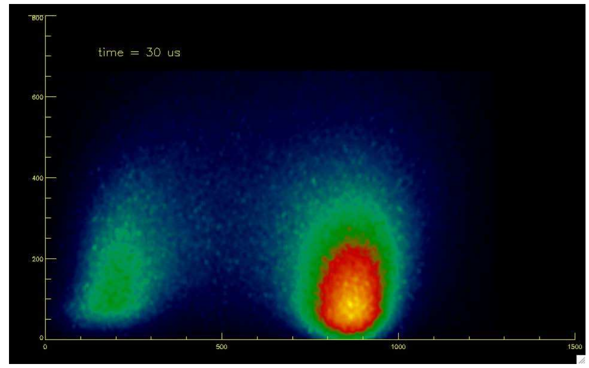

FIG. 6 $t = 30\mu s$

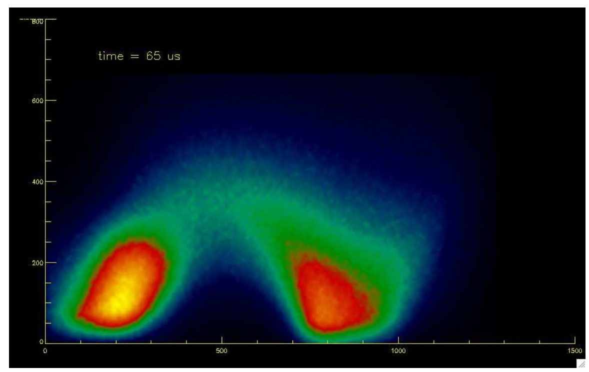

FIG. 7 $t = 65\mu s$

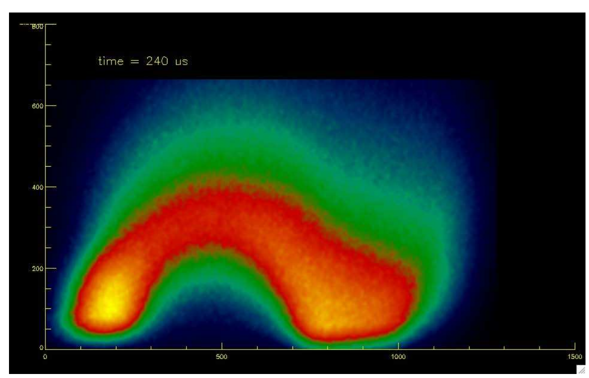

FIG. 8 $t = 240\mu s$

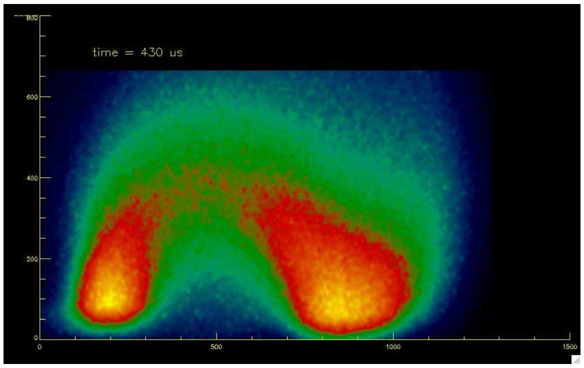

FIG. 9 $t = 430\mu s$

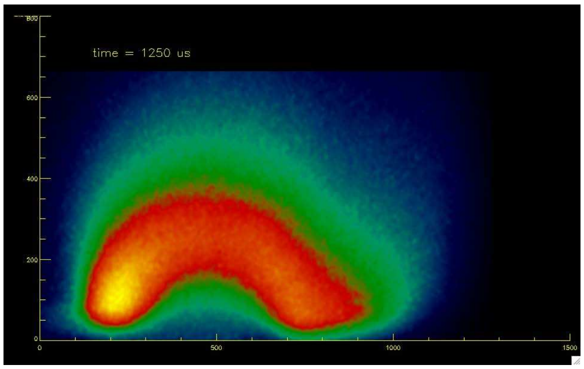

FIG. 10 $t = 1250\mu s$

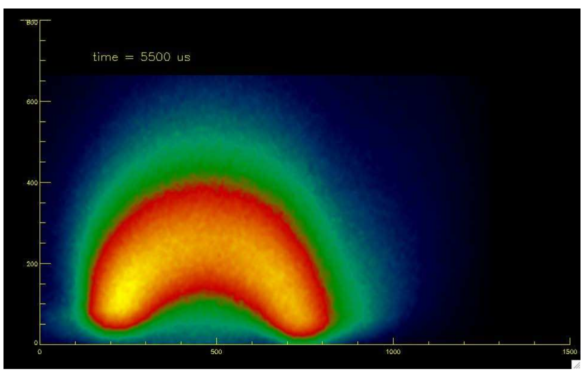

FIG. 11 $t = 5500\mu s$