Current associated with a voltage increase over magnetic flux ropes in a helium plasma

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Research suggests that collisions between magnetic flux ropes cause magnetic energy to be converted to heat energy above the surface of the sun. Further studies may lead to more precise explanations of why the corona is 1,000,000°C while the surface of the sun is 8,000°C. This experiment models flux ropes in the solar corona using cylindrical ropes with no radius of curvature. In the laboratory we acquire three-dimensional data over a column of a background, magnetized plasma containing flux ropes in order to examine the interactions of the current channels associated with the ropes. Two adjacent flux ropes are produced in the Large Plasma Device at the University of California, Los Angeles and the magnetic field inside the chamber is measured to determine how the current channels connect. We find that the current channels twist and writhe due to the $\vec{J} x \vec{B}$ forces. Furthermore, we find that they merge approximately halfway down the plasma column. These results will help to judge where energy is transformed and assess the validity of reconnection in magnetic flux ropes as the cause of coronal heating.

I. Introduction

Solar coronal heating has long been a subject of debate; one important candidate for explaining this phenomenon is magnetic reconnection[1]. Magnetic reconnection occurs when two anti-parallel magnetic field lines meet. This can occur in the transverse field during the collision of magnetic flux ropes. Magnetic flux ropes are bundles of braided magnetic flux ropes formed by helical current channels in plasma. They are commonly observed in the solar corona, and are associated with coronal mass ejections[2]. Observations[3] have shown that magnetic reconnection occurs between flux ropes in the quasi-separatrix layer. The quasi-separatix layer is a two-dimensional surface in which magnetic field line reconnection occurs. Magnetic field lines that traverse the quasi-separatrix layer will diverge away from one another due to the changing of the magnetic field topology that occurs within the layer.

This paper focuses on the interactions between current channels associated with two, initially adjacent magnetic flux ropes. We are concerned with investigating the effect of voltage on the current channels associated with the ropes. The results from current channel analysis can be extrapolated to calculate the position of the quasi-separatrix layer.

Previous experiments[4] have analyzed the interactions of magnetic flux ropes within a background plasma and magnetic reconnection[5] in three-dimensions. Others have investigated magnetic reconnection in two dimensions[6]. This experiment examines three-dimensional data across a voltage increase and reports on the change in flux rope behavior when the voltage between the ends of the flux ropes is doubled. This may lead to deeper insights into the behavior of magnetic flux ropes outside of the lab.

An explanation of magnetic reconnection and magnetic flux ropes could enable us to understand the solar corona more explicitly. Furthermore, it may provide us with a greater understanding of coronal mass ejections[7], x-ray bright spots[8], and coronal loops[9].

II. Experimental Setup

This experiment was conducted at the Large Plasma Device[10] (LaPD) at the University of California, Los Angeles (UCLA) (Figure 1). The flux ropes are generated between a Lanthanum Hexaboride (LaB6) cathode and a Molybdenum mesh anode, spaced eleven meters apart in the LaPD chamber. The background Helium plasma column (17m long, 60cm diameter) is produced by a direct current discharge to a second, barium-oxide coated cathode. The machine has 65 ports available through vacuum interlocks that probes can be attached to.

In this experiment the plasma density was 3x10^12 cm^(-3), the background magnetic field was between 330G, the electron temperature of the plasma was 6eV as measured with a swept Langmuir probe.

Data was collected with a three-axis B-dot probe[11] on every other port (dz=64cm) over approximately 10ms and at 10,000 time steps. The B-Dot probe was swept over cross-sections transverse to the background magnetic field in each port by a computer-controlled motor. The probe was moved by hand from port to port to produce fully three-dimensional data. Data was collected at each position in the machine ten times and numerically averaged to smooth out inconsistent data.

The computer data collection system was set to a trigger to eliminate irrelevant data. The experimental sequence was as follows: the data collection system triggered (t=0ms) and began measuring the time rate-of-change of the magnetic field, this was aligned to coincide with the generation of the background plasma as closely as was possible. Next, the flux ropes were generated between a LaB6 cathode,

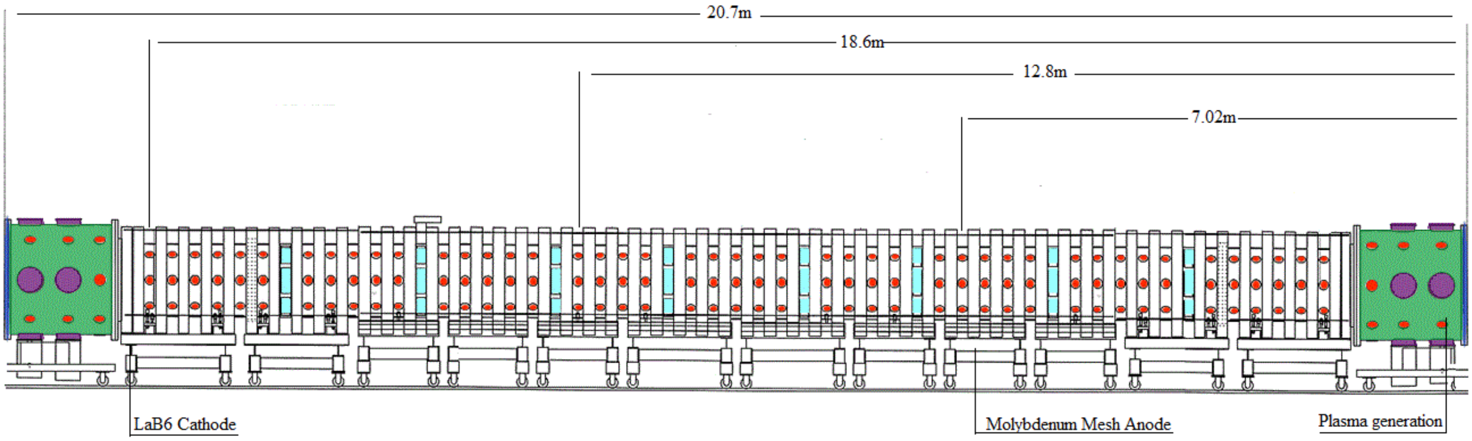

Figure 1: The Large Plasma Device (LaPD) at UCLA. Magnet spacing is 32cm from center-to-center. First 11 magnets on each end are 14.6cm wide, others are 8.4cm. Red circles indicate ports for probes, blue rectangles indicate rectangular valve mounting holes.

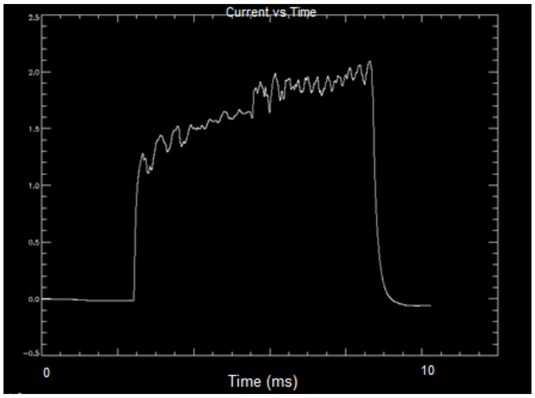

Figure 2: The current versus time plot between the LaB6 cathode and the Molybdenum anode. The voltage increases at t=6ms in this plot.

located on the opposite end of the device from the plasma source, and the Molybdenum anode (V=105V), approximately 2ms after the data collection began (t=2ms). After another 4ms (t=6ms) the voltage over the flux ropes was doubled (V=210V) (Approximately 3ms later (t=9ms) the flux ropes were turned off and 1 ms after that (t=10ms) the data collection terminated.

III. Results

The data collected from the B-dot probe via the data collection system was read in by an Interactive Data Language (IDL) program; we subtracted the mean to center the data at 0 and numerically integrated, averaged to remove inconsistent data, and filtered to remove background noise from the flux ropes. We utilized a digital filter in IDL, with a low-pass frequency of 0Hz and a high-pass frequency of 30Hz with a filter of order 300. The data planes were then each cross-correlated with a B-dot reference probe using Fast Fourier Transforms (FFTs) in IDL.

The curl of the reduced data was taken using an IDL program to find the current flow in the z direction (parallel to the length of the LaPD). The results are best visualized through viewing of a video, as they are three-dimensional and change with time.

Close to the LaB_6 cathode (z=18.6m) the flux ropes form two distinct current channels close together (Figure 2a). In time these flux ropes twist (motion about each other) and writhe (motion about themselves) (Figure 3). As the voltage is increased at t=4ms the magnetic field of the flux ropes increases dramatically, as does the current. The twisting and writhing motions become more dynamic at the voltage switch, as well. The magnetic field around the flux ropes at this point is neatly aligned to the current channels, as they remain wholly distinct.

Halfway down the machine (z=12.8m) the flux ropes interact with each other more heavily and begin to merge and collide (Figure 2b). The twisting and writhing motions continue and are increased at the voltage jump. The motion in the middle of the machine is significantly more clear than it is close to the cathode, the flux ropes move around much more energetically at this

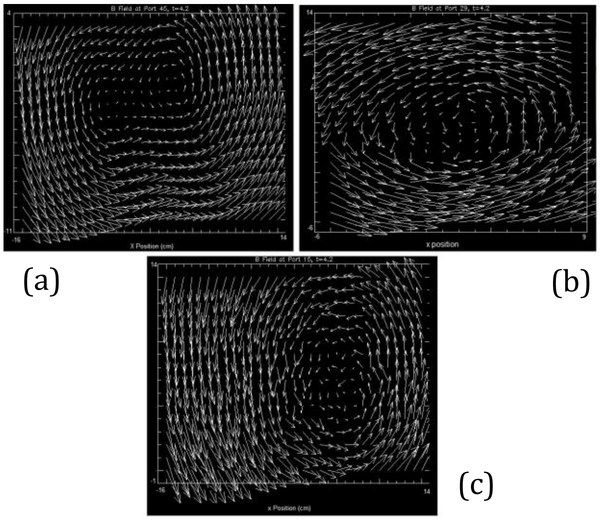

Figure 2: (a) The magnetic vector field at z=18.6m at t=4.2ms shows two distinct current channels with the magnetic field running azimuthally around the channels. (b) The magnetic vector field at the same time at z=12.8m shows the current channels mostly merged. (c) At z=7.02 the channels form one large, oblong channel. The twisting of the ropes in space can also be seen in these diagrams.

position. Here the magnetic field about the flux ropes is much more chaotic as the current channels interact.

Near the anode (z=7m) the flux ropes have merged to form a single, larger current channel, which continues to writhe (Figure 2c). As with the other positions, this motion is more pronounced when the voltage increases. The magnetic field close to the anode is more closely aligned to the current channels than it is in the middle of the machine, but it is still not as smooth as the field close to the cathode.

IV. Discussion

This experiment was designed to test the effect of voltage on the behavior of magnetic flux ropes. We expected the interactions between the flux ropes to become more dynamic when the voltage was increased, due to an increased $\vec{J}\times\vec{B}$ force on them. This is exactly the behavior that we observed in the data collected from our experiment. From this data we might go on to calculate the position of the quasi-separatrix layer and analyze the effect of voltage on magnetic reconnection and the position of the quasi-separatrix.

As expected the flux ropes interact more energetically when the voltage is increased. The increased voltage between the cathode and anode cause an increase in current, which produce a larger $\vec{J}\times\vec{B}$ force on the flux ropes. This force is the cause of the twisting and writhing motions observed in the magnetic flux ropes.

We see the largest change and the most interesting data comes from the mid-way point in the LaPD at z=12.8. When the voltage changes the flux ropes at z=12.8 become significantly more energetic, merging and separating numerous times within a few milliseconds. The fact that the change is most evident in the middle of the machine may be due to the interaction of the currents, and thus, the further increase of the $\vec{J}\times\vec{B}$ due to having two such currents merging, and the subsequent drop of the $\vec{J}\times\vec{B}$ force when they separate again.

The voltage increase produces less of a change in the current channels close to the cathode; this is likely because the flux ropes are line tied to the cathode at this point in the machine and thus, the force change is not as significant, nor as interesting.

Likewise, near the anode at z=7m the change in the flux ropes is not as dynamic as it is in the middle of the chamber. The increase in voltage

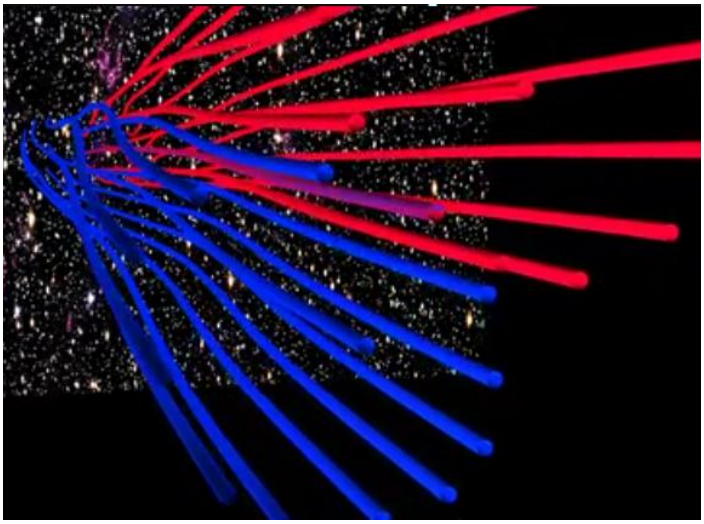

Figure 4: A three-dimensional graphic of the magnetic flux ropes at t=4ms. The field lines from the ropes are colored differently in order to emphasize the separate ropes. The twisting of the ropes in space can be observed as they start out horizontally adjacent and end up vertically adjacent.

makes the current channel more coherent, and it appears to be more distinctly a single, concentrated current channel, rather than a spread-out, diffuse one. The writhing motion of the current channel does increase with the voltage, however, as expected with the increased force.

The current data is the first step in calculation of the quasi-separatrix layer, thus this data can be extrapolated to learn more about the quasi-separatrix layer[11]. Further analysis of this data may lead to further understanding of the connections between flux ropes and energy outflows in the corona and near-earth space[12].

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