Flow Measurements on Single and Merging Spheromaks at SSX

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Spheromaks and Magnetic Reconnection

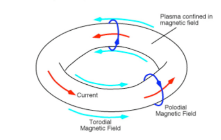

Figure 1. A graphical depiction of a spheromak. The blue arrows represent the poloidal magnetic fields and the green arrows represent the toroidal magnetic fields.

Spheromaks are a stable configuration of plasma in which the motion of charged particles within the plasma create confining magnetic fields. These magnetic fields have both a poloidal component and a toroidal component. The magnetic fields are sustained by a toroidal current within the plasma.

Spheromaks are created in the Swarthmore Spheromak Experiment (SSX) lab by plasma "guns" which achieve voltages high enough to ionize hydrogen into a plasma and then use a stuffing flux to blow out the plasma like a donut-shaped bubble. Two opposing plasma guns flank the cylindrical chamber at SSX.

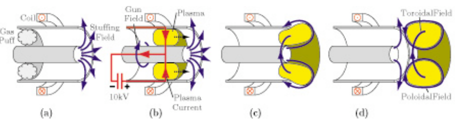

Figure 2. The production of a spheromak in the SSX chamber. (a) Hydrogen gas is released into the gun, (b) the hydrogen gas is ionized, (c) a stuffing flux induces a poloidal magnetic field in the plasma, and (d) the "bubble" is released as a spheromak.

The opposing plasma guns have reversable polarity in order that we can reproduce a phenomenon called magnetic reconnection. Magnetic reconnection occurs when two regions of plasma confined by magnetic fields with opposing polarities collide. In this dynamic process, energy contained in the combining magnetic fields is converted into kinetic energy as plasma is forced outward from the reconnection region in the form of bidirectional plasma jets.

Studying magnetic reconnection provides us with insight into energy transfer in plasmas. It also occurs in astrophysical observations on a regular basis. It is believed to be one of the reasons that the sun's corona is much hotter than the surface of the sun.

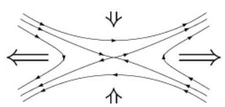

Figure 3. A simplified model of magnetic reconnection. Two regions with opposed magnetic fields move toward each other (arrows up and down), while jets of plasma with recombined magnetic fields are forced out of the sides of the reconnection region.

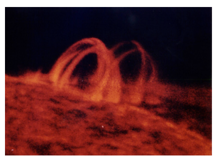

Figure 4. Loops of plasma exhibiting magnetic reconnection above the surface of the sun.

The Mach Probe

A Mach probe is a diagnostic used to measure drift velocity or flow in a plasma. It consists of six tungsten rods surrounding a boron nitride sheath. These materials have been selected for their performance under the stress of high vacuum and high temperature in the SSX chamber. Each tungsten rod is charged negatively with reference to the voltage of the plasma such that it collects free positive ions when it is surrounded by plasma. These collected ions appear as a current. We can gain insight into the local flow of the plasma by comparing the currents in opposite collectors. Clearly, the "upstream" collector will receive more ions than the "downstream" collector. According to analysis of the Mach probe (also referred to as a directional Langmuir probe) first performed by Hudis and Lidsky [1] and later amended by Hutchinson [2], the ratio of the current collected by two ion collectors on either side of a Mach probe is related to the drift velocity across the collectors by the logarithmic function below. In this function, we have used "up" and "down" to signify upstream and downstream, k as a calibration constant that is different for different sizes and geometries of Mach probes, and M as the Mach number, or the drift velocity normalized to the sound speed in plasma.

$$\frac{I_{up}}{I_{down}} = e^{kM}$$

We used two different Mach probes in the chamber this summer. One Mach probe was considered unmagnetized because it had a radius smaller than the Larmor radius, or the average orbit size of a proton in the magnetic field of the plasma. The other was considered magnetized because it had a radius larger than the Larmor radius. These two properties should correspond to two different calibration constants k.

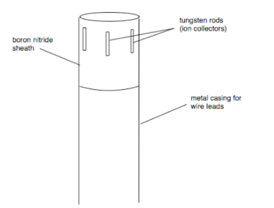

Figure 5. A graphical depiction of the Mach probe. The tungsten rods are exposed through slits in the boron nitride sheath. The metal casing below the sheath contains wire leads to carry collected current. The probe is inserted into the machine such that the casing is in the radial direction. Only axial and azimuthal flows are measurable in this orientation.

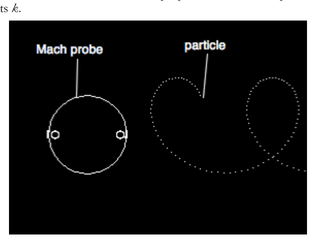

Figure 6. A screen shot from a computer simulation of a particle moving toward a Mach probe, viewing the Mach probe from above. There is a magnetic field out of the page and a downward electric field, resulting in a net velocity in the direction E x B, to the left. In this picture, there are only two ion collectors (an upstream one and a downstream one). The Mach probes we used had six ion collectors evenly spaced, resulting in three upstream and downstream pairs.

Observations and Results

Mach Probe Calibration

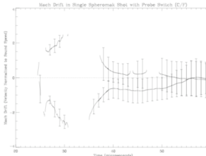

Figure 7. Two measurements of Mach drift during a single spheromak shot. The waveforms are reversed because they are taken with the Mach probe facing opposite directions.

One of the most crucial steps in using a diagnostic like the Mach probe is ensuring that it is working in a way that we can analyze. In order to reassure ourselves that data received by the Mach probe was making sense, we performed an experiment in which we averaged data from twenty single spheromak shots with the Mach probe facing one direction, then turned the Mach probe over and averaged the results of another twenty shots. As expected, the averaged data from the Mach probe facing one direction produced a waveform that was approximately the negative of the waveform produced when the Mach probe was facing the opposite direction.

In order to determine the calibration constant k for each Mach probe, we compared an observed ratio of upstream and downstream currents to the known drift velocity of a single spheromak as it moved across the probe. This known drift velocity was found using an array of four magnetic probes at the edge of the machine. By looking for a sudden jump in the magnetic energy present at each probe, we can have a good estimate of when the plasma is moving by the probe. The magnetic probes were placed a known distance apart in the machine and the Mach probe was directly between them, so it took a simple velocity calculation to determine the actual flow velocity of the plasma in a given single spheromak shot. We found that a single spheromak initially travels across the chamber at approximately 90 $^{km}/_{s}$, or roughly twice the sound speed. With this information, we came to the conclusion that the smaller, unmagnetized Mach probe had a k-value of 1.6 and the larger, magnetized Mach probe had a k-value of 2.3. Both of these values are consistent with theoretical and observed values in these respective realms.

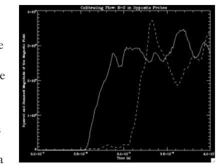

Figure 8. The magnitude of the magnetic field for the magnetic probe at the west side of the chamber (solid line) and the east side of the chamber (dotted line) during a single spheromak shot. The west side of the chamber is the one closer to the gun. The time lapse between the signals was used to determine the drift velocity of the plasma.

Single Spheromak Results

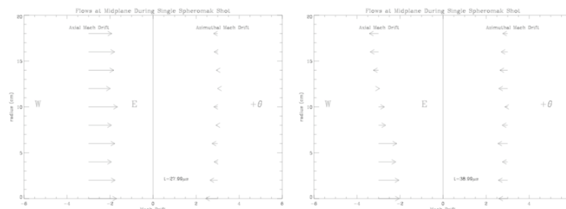

Figure 9. Graphs depicting average results over several single spheromak shots out of the west gun, with the Mach probe placed at different radii. The vectors on the left in each graph correspond to the Mach speed in the axial direction (the direction parallel to the gun) while the vectors on the right of each graph correspond to the Mach speed in the azimuthal direction (rotation). The left graph depicts the flow velocity 28 microseconds after the plasma is released into the chamber. The right graph depicts the flow velocity some time later, at 39 microseconds.

A radial scan with the Mach probe during single spheromak shots had telling results. We found that the axial velocity of the plasma (the velocity parallel to the direction of the gun's output) was radially constant and twice the sound speed shortly after the plasma enters the chamber. After about 10 microseconds, the flow speed at the center of the chamber dies down only slightly while a reversal of flow is clear at the edges of the chamber. This could be explained as a poloidal motion of the single spheromak as it stabilizes and fills the chamber.

The azimuthal drift velocity (the rotational motion of the plasma) is about half of the sound speed and, on average, seemingly independent of radius and time. This implies a constant rotation of the single spheromak throughout the course of the shot.

Counter-Helicity Merging Results

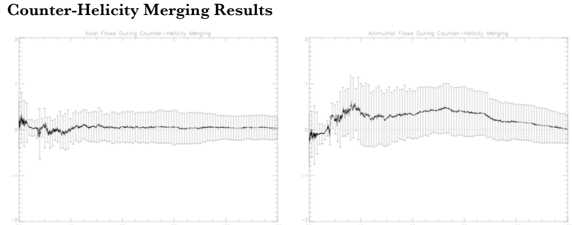

Figure 10. Graphs showing the average axial and azimuthal flows during counter-helicity merging (spheromaks with opposing magnetic polarization merging at the mid-plane).

In the case of counter-helicity merging, we shoot both guns from either side of the chamber such that the spheromaks combining in the center have opposing magnetic fields and sometimes exhibit magnetic reconnection. If the magnetic fields were only poloidal, then we would see bidirectional jets in the radial direction alone. However, since there is a toroidal component to the magnetic fields, we expect to detect an azimuthal component of flow during reconnection as well.

Radial bidirectional jets were observed by J. Hung [3] using Doppler spectroscopy last year. The azimuthal component of the flow is more difficult to observe because it necessitates a local measurement, which can disturb reconnection. Also, we expect a much less significant amount of flow in the azimuthal direction than in the radial direction (on the order of a tenth of the sound speed). Data taken with the Mach probe during counter-helicity merging shows an expected average of zero axial flow with a considerable azimuthal flow. In fact, the azimuthal flow is even greater than originally expected.

Future Work

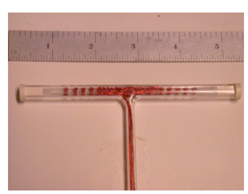

Figure 11. High-resolution magnetic probe. The cluster at the center of the T is actually 16 small coils placed directly next to each other in order to get a more specific reading of the magnetic fields at the reconnection region. The casing is quartz and the plugs on the ends of the T are boron nitride.

A two-dimensional magnetic probe with high spatial resolution (2.3 mm) has been constructed but has not yet been inserted into the chamber. This probe will allow us to determine the magnetic fields with higher spatial and temporal resolution than we have before. It will be placed right at the midplane of the machine, where reconnection occurs. Hopefully, this diagnostic will allow us to understand more about the details of magnetic reconnection.

We are also looking into new ways of lowering both the vacuum in the chamber and the contaminants in the plasma in order to achieve a hotter, more pure plasma state. A project of installing new, cleaner tubing for transporting pure hydrogen is still under way.

References

[1] M. Hudis and L.M. Lidsky, "Directional Langmuir Probe," Journal of Applied Physics 41.12 (1970), 5011.

[2] I.H. Hutchinson, "The Invalidity of a Mach Probe Model," Physics of Plasmas 9.5 (2002), 1832.

[3] Jerome Fung, *High Resolution Flow and Ion Temperature Measurements with Ion Doppler Spectroscopy at SSX*, (Swarthmore, PA: Swarthmore College Department of Physics and Astronomy, 2006).