# High resolution ion doppler spectroscopy at SSX

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## Abstract

*The Swarthmore Spheromak Experiment (SSX) studies magnetic reconnection by co- and counter-helicity spheromak merging. We recently installed a new high-resolution ion doppler spectroscopy (IDS) system to enhance our ability to diagnose flows and ion temperatures. Our IDS system features a 1.33 m Czerny-Turner monochromator with a 316 grooves/mm echelle grating, and a 32 channel photomultiplier tube array. On any given shot, we can observe any of 10 chords through the plasma with submicrosecond time resolution and an instrument temperature ∼6 eV. We observed the dynamics of the C III 229.7 nm line at $25^{th}$ order with dispersion 0.008 mm/nm during counter-helicity, co-helicity, and single spheromak shots. We have begun to perform Abel inversions to determine radial velocity and ion temperature profiles. During counter-helicity shots, we have observed near-Alfvènic bi-directional flows due to reconnection.*

## 1. Introduction

Plasmas are ionized gases consisting of electrons, ions, and neutral gas molecules. They make up the majority of the visible matter in the universe. Because plasmas are electrically conducting, they carry electric and magnetic fields. Consequently, their behavior is both much richer and difficult to understand than that of ordinary gases; for this reason, plasmas are often referred to as the fourth state of matter.

- Plasma behavior often described using fluid model called **magnetohydrodynamics (MHD)**
- Ideal MHD postulates that plasma resistivity is zero, such that Ohm's Law for the plasma is

$$\mathbf{E} + \mathbf{u} \times \mathbf{B} = 0$$

- Ideal MHD predicts that magnetic field lines should be "frozen in" to the plasma
- Magnetic reconnection occurs when a large field gradient results in a breakdown of ideal MHD

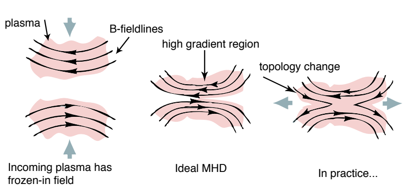


**Figure 1:** *Canonical picture of magnetic reconnection.*

- $\mathbf{B}$ consumed during reconnection; energy density $B^2/2\mu_0$ of reconnected field converted to flow and heating
- Magnetic reconnection thought to be involved in numerous astrophysical phenomena, including the heating of the solar corona

## 2. The Swarthmore Spheromak Experiment

- The Swarthmore Spheromak Experiment (SSX) studies magnetic reconnection by merging co- and counter-helicity spheromaks
- Spheromaks are toroidal plasma configurations with both poloidal and toroidal magnetic fields, with a pressure balance between kinetic and magnetic pressure
- Typical plasma parameters include electron density $n_e \sim 10^{15}$ cm$^{-3}$, temperature $T_i + T_e \sim 30$ eV, and magnetic fields $|B| \sim 0.1$ T

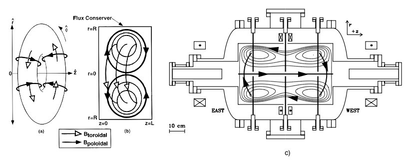


**Figure 2:** *a) & b): Two views of the geometry and fields of a spheromak. c): Overview of SSX chamber*

- Newly constructed high-resolution ion doppler spectroscopy (IDS) system allows better measurements of chord-integrated flows and ion temperatures
- IDS system observes spectral light emitted by impurity ions in the SSX hydrogen plasma
- The wavelength of light coming from plasma that is moving towards or away from the observer at speed $v$ is Doppler shifted by $\Delta\lambda$, where

$$\Delta\lambda = \lambda_0 \frac{v}{c}$$

and $\lambda_0$ is the nominal wavelength of the light

- Assuming a Maxwellian velocity distribution, the lineshape is Gaussian with half-width

$$\Delta\lambda_{\mathrm{FWHM}} = \frac{2\lambda_0}{c}\sqrt{\frac{2kT_i \ln 2}{m}}$$

where $m$ is the mass of the emitting ions

## 3. The IDS System

- Light can be collected from any of 10 chords through the plasma
- System features 1.33 m Czerny-Turner monochromator with 316 grooves/mm echelle grating
- Light travels from plasma at midplane to monochromator via collection optics and a fiber optic
- Magnifying exit optics increase the size of the image at the exit plane of the spectrometer ∼ 4x.
- 32-channel photomultiplier tube (PMT) array detector gives submicrosecond time response
- PMT array has disadvantage of large (1 mm) pixel width; this is compensated for by use of exit optics and by observing at high order, where the dispersion is as large as possible

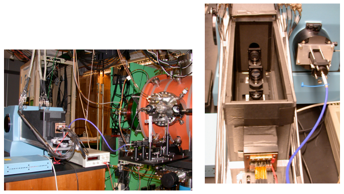

**Figure 3:** *Left: Photograph of SSX lab showing vacuum chamber, monochromator, and associated IDS optics. Right: Overhead view of spectrometer exit slit, magnifying optics, and PMT array. The fiber optic carrying light to the entrance slit of the spectrometer is visible at right.*

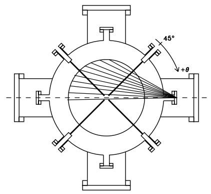


**Figure 4:** *Axial view of the SSX chamber. The solid lines are the approximate lines of sight of the 10 chords from which the IDS system can detect light.*

## 4. Results and Discussion

We observed the 227.9 nm C III line at $25^{\text{th}}$ order, with dispersion 0.008 nm/mm. Our instrument temperature is approximately 6 eV. In our setup, only Doppler broadening is significant; other effects such as pressure broadening are negligible.

For counter-helicity merging, we observed double-peaked line indicative of bi-directional flow:

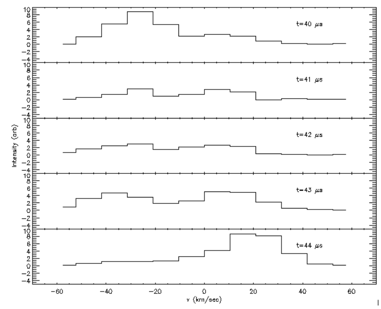


**Figure 5:** *227.9 nm CIII line during counter-helicity merging. Velocities shown correspond to the Doppler shift of the emitting plasma.*

The double-peaked lineshape shown above is seen consistently but only during counter-helicity merging, during which the toroidal fields of the spheromaks reconnect. Thus it is likely that reconnection is causing the bi-directional flows that we have observed. Bi-directional flows have been measured by spacecraft observing the sun, but most prior laboratory experiments studying reconnection with IDS have not reported the observation of such a structure [1]. Some of these other experiments have observed broadened spectral lines and interpreted them as high ion temperatures [2]. It is possible that the broadened lines were due to transient bi-directional flow activity that was averaged out due to insufficient time resolution.

Currently, we are performing Abel inversions to determine radial profiles of velocity and ion temperature. Measurements of any plasma parameter from the IDS system are averaged along the line of sight of the system. Assuming cylindrical symmetry, it may be shown that, given some parameter $f(r)$ that depends on radius, the quantity $F(y)$ that is measured along a chord of height $y$ from the center is given by

$$F(y) = 2\int_y^R \frac{f(r)r\,dr}{\sqrt{r^2 - y^2}}$$

We are using a cubic spline interpolation to perform a curve fit before numerically inverting the above integral equation.

## References

[1] D.E. Innes et al. Bi-directional plasma jets produced by magnetic reconnection on the Sun. *Nature*, 386 (1993), 811.

[2] Y. Ono et al. Experimental investigation of three-component magnetic reconnection by use of merging spheromaks and tokamaks. *Phys. Plasmas*, 4 (1997), 1953.