Progress Report from SSX-FRC
ER54604 (renewal, year 2)
"Novel CT's: Equilibrium, Stability, and Dynamics"

Our main efforts in year 2 of this renewal have been the implementation of high spectral and temporal resolution ion doppler spectroscopy (IDS) on SSX-FRC (as we originally proposed in the renewal). The addition of Dr. Elena Belova of PPPL has proven to be very productive (also proposed in the renewal). She has begun to run detailed simulations of our experiment with her HYM code and we have begun to compare her simulations to experiments at SSX-FRC. Our progress and plans for the coming year are outlined below.

Ion Doppler Spectroscopy (IDS): The big result from summer 2005 is some fantastic data from the ion doppler spectrometer. Highlights include routine observation of bi-directional jets (simultaneous measurement of $\pm$ 40 km/s flows) with ion temperatures in the 20 eV range. The attached movie (r26) shows data from a nearly radial chord in the middle of the machine from a C_{III} line (229 nm). The flow is very dynamic and bursty (around 40 μs is the bi-directional burst). These observations are made during our reconnection shots (opposite helicity spheromak merging) and indicate simultaneous flow towards and away from the observer.

IDS measurements on single spheromaks trapped in a simple dipole field at the midplane show heating as they decay (over 20 eV), then slowly cool. We've seen some evidence of rotation from tangential chords (though only 10 km/s or so). Jerome Fung will do his thesis on these results including Abel inversion of the data from many chords. Post-doc Chris Cothran and M. Brown presented these results at the US/Japan workshop in Himeji in September 2005 and the general APS plasma meeting in Denver in October 2005. M. Brown also presented this in July 2005 at IPELS (see below). We've started working on several papers (see below).

The SSX IDS instrument measures with 1 μs or better time resolution the width and doppler shift of the C_{III} impurity (H plasma) 229.7 nm line to determine the temperature and line-averaged flow velocity during spheromak merging events. The instrument design temperature is approximately 15 eV. Velocity resolution is about 7 km/s, corresponding to approximately $0.1 v_A$. The Czerny-Turner spectrometer has 1.33 m focal length, f/9.4, and uses a 316 $groove/mm$ Echelle grating blazed for a 63.5° angle. The C_{III} line is observed at 25th order where the spectrometer achieves a dispersion of 0.03 nm/mm.

In the coming year, we intend to perform complete IDS scans on each of our main configurations: doublet CT formed by counter-helicity merging of two spheromaks, tilted spheromak formed by co-helicity merging of two spheromaks, and single, stable spheromak trapped in a simple dipole magnetic field. Complete scans will yield Abel inversions of flow and ion temperature profiles for each configuration.

Simulations: We've always felt that SSX is a unique experiment to study MHD physics on a "tabletop" setting. The machine is flexible enough that we can easily change boundary conditions (flux conserver size, bias field) or initial conditions (counter- or co-helicity, single or double spheromak, arbitrary delay between east and west). Coupling a flexible MHD experiment with a flexible 3D MHD simulation affords a unique opportunity to test models including non-MHD aspects (eg, two fluid effects and contributions from $\nabla \cdot \mathbf{P}$). Our colleagues Elena Belova at PPPL and Mike Schaffer at GA have performed studies using Dr. Belova's 3D code called HYM (for HYbrid MHD). We have recently obtained results from HYM runs showing (1) flow and magnetic field structures during counter-helicity merging and FRC formation, (2) stability of a dipole-trapped single spheromak in SSX, and (3) dynamics of co-helicity merging and formation of a large tilted spheromak.

As part of our Center for Magnetic Self Organization (CMSO) collaboration (http:// www.cmso.info/), Carl Sovinec's PhD student Nick Murphy has begun to model SSX merging using a code called NIMROD. So far, Nick's simulations are 2D single fluid MHD. See the following website for Nick's recent simulation:

http://www.astro.wisc.edu/m̃urphy/Movies/SSXmovie_try2.avi

As part of our collaboration with the Plasma Science and Innovation Center (see website), we will likely have the benefit of more NIMROD modeling of SSX merging:

http://plasma.aa.washington.edu/psicenter/index.html

In the coming year, we intend to continue our simulation collaborations with an eye towards direct comparison of simulation and experiment.

Glow Discharge Cleaning (GDC): M. Schaffer, C. Cothran, and M. Brown have worked together (during 2 extended visits by M. Schaffer) to prototype, design, and procure a new GDC system for SSX-FRC. We have always been struck by the efficacy of good vacuum techniques on other machines (eg GDC and Ti gettering on SSPX). We are now ready to implement in the coming year a new Helium GDC system featuring (1) clean He delivery

system using bleed valves, (2) small turbo- and scroll pump system isolated with a gate valve for high gas flow, and (3) a 5 $kV, 1$ A dc power supply for the He glow. The parts are procured and in-house. **In the coming year**, this will be our next major experimental campaign.

New space: The $75M Swarthmore College Science Center was completed this summer 2004 (see http://sciencecenter.swarthmore.edu/). We've just completed our first full year in the renovated SSX-FRC lab. Students Jerome Fung, Marc Chang, and Jason Horwitz have completed their summer stints.

Student participation (summer 2005): We supported 3 Swarthmore students this summer 2005 (seniors Jerome Fung and Marc Chang, junior Jason Horwitz, and Wellesley College junior Brie Coellner). Each student participated on a poster which will be presented by Jerome at the APS-DPP meeting in Denver this October 2005. Recent graduate Aongus O Murchadha has begun graduate studies in plasma physics at Wisconsin.

Papers and presentations: A new paper has appeared in Geophysical Research Letters entitled "Generalized Ohm's Law in a 3D Reconnection Experiment" (attached in hard copy):

C. D. Cothran, M. Landreman, **M. R. Brown**, and W. H. Matthaeus, "Generalized Ohm's Law in a 3D Reconnection Experiment", *Geophysical Research Letters* **32**, L03105 (2005).

Two others are in final review with referees:

W. H. Matthaeus, C. D. Cothran, M. Landreman, and **M. R. Brown**, "Fluid and Kinetic Structure of Magnetic Merging in the Swarthmore Spheromak Experiment". *Geophysical Research Letters* (submitted)

E. V. Belova, R. C. Davidson, H. Ji, M. Yamada, C. D. Cothran, **M. R. Brown**, and M. J. Schaffer, "Numerical Study of the Formation, Ion Spin-up, and Nonlinear Stability Properties of Field Reversed Configurations", *Nuclear Fusion* (submitted)

We are also drafting 6 other papers: (1) on the stability and flow in our doublet FRC configuration including experimental data (Brown, Cothran, Schaffer) and numerical simulation (Belova), (2) on the observation of a single stable spheromak supported by our RCC fields (Brown, Cothran, Schaffer), (3) on the observation of a large, tilted, stable spheromak formed with co-helicity merging (Brown, Cothran, Schaffer), (4) observation of bi-directional jets (Brown, Cothran), (5) Physics of Plasma paper based on

invited talk (Brown), (6) Review of Scientific Instruments paper on IDS system (Cothran).

Our group attended the APS-DPP meeting in Savannah this past November 2004 and will attend the October 2005 meeting in Denver (see below for submitted abstracts). We also attended the US/Japan CT workshop in Himeji September 16-18, 2005. Both C. Cothran and M. Brown were selected for invited talks there. M. Brown attended IPELS 2005 in Norway in July and presented an invited talk. Here's the website: http://www.phys.uit.no/IPELS05/. M. Brown gave an invited talk at the MR2005 reconnection meeting in Japan in March 2005: http:// www.kwasan.kyoto-u.ac.jp/mr2005/. We plan to attend the next ICC meeting in Austin in Feb 2006.

Collaborations and informal meetings: We see Dr. Mike Schaffer of GA regularly as part of our collaboration. We had meetings at the APS-DPP conference (in Savannah in 2004) and the CMSO meeting in San Diego (with Wisconsin graduate student Nick Murphy). In addition, Mike visited for 2 days September 27-28, 2004 to design our GDC system and work on IDS with Chris. Mike had an extended (3 week) visit to Swarthmore during the second half of July 2005. We have also met with Dr. Elena Belova at PPPL in September 2005.

Finally, SSX-FRC is part of the new NSF Center on Magnetic Self Organization in Laboratory and Astrophysical Plasmas (CMSO for short). Other CMSO participants include Wisconsin, Chicago, Princeton, and Livermore. Participation in the Center will give us more access and entree into the astrophysical and computational communities (eg the "Flash" computation center at Chicago). We have begun discussions with Wisconsin graduate student Nick Murphy on doing NIMROD simulations of SSX-FRC. Here are the websites for the new NSF Center and for the SSX contribution: http://www.cmso.info/ and http:// plasma.physics.swarthmore.edu/ selforg/ index.html. There have been several meetings of the Center this past year.

APS abstracts (DPP meeting, Oct. 2005):

Two-fluid effects on 3D reconnection in the SSX experiment with comparisons to space data M. R. Brown (Swarthmore College), Invited talk BI1.0003

> We report on several new experimental results from spheromak merging studies at SSX with relevance to three dimensional reconnection in laboratory and space plasmas. First, we report

the measurement of non-ideal terms of the generalized Ohm's law at a reconnection site of a weakly collisional laboratory plasma. Time resolved vector magnetic field measurements on a 3D lattice ($\mathbf{B}(\mathbf{r}, t)$) enables evaluation of the various terms. Results show that the Hall term dominates everywhere ($\mathbf{J} \times \mathbf{B}$); resistive and electron inertia terms are small. We suggest that electron pressure supports the reconnection electric field at the neutral point. Second, we report experimental measurement of the in-plane Lorentz force and out-of-plane magnetic field associated with the Hall electric field near the reconnection zone. Both show a quadrupolar structure at the ion inertial scale. Earlier work at SSX has shown that formation of three-dimensional structure at the ion inertial scale is temporally and spatially correlated with the observation of superthermal, super-Alfvenic ions ions accelerated along the X-line normal to the local 2D plane of reconnection. Anomalous resistivity, while not ruled out, is not required to account for the results. Third, we have performed velocity and temperature measurements of impurity ions using ion doppler spectroscopy (IDS). Bi-directional outflow at nearly the Alfvén speed is clearly observed. Each of these will be related to and compared with similar measurements in a solar or space context.

Spectroscopic measurements of flow and ion temperature at SSX J. Fung, S. C. Chang, J. Horwitz, B. Coellner, C. D. Cothran, M. R. Brown (Swarthmore College), M. J. Schaffer (GA), student poster GP1.00058

Flow measurements in spheromak merging experiments C. D. Cothran, J. Fung, M. R. Brown (Swarthmore College), M. J. Schaffer (GA), E. V. Belova (PPPL), poster GP1.00103

CMSO: We had a general meeting of our Center for Magnetic Self Organization (CMSO) at PPPL Oct 5-7, 2005. M. Brown presented the recent IDL data and showed Elena's latest simulation results. There was an earlier meeting of CMSO experimentalists in Madison.