Happy New Year 2008 from SSX!

Here's a quick review of 2007 as well as plans for 2008... For new folks, I've been doing these little summaries for SSX alums and friends for a while now (10 years or so)... I hope folks don't mind receiving them (I get good responses from the alums). In any case, I end up using summaries like this for reports and proposals throughout the coming year.

We're looking forward to having Tim Gray '01 here at Swarthmore full time (soon). Tim was down at SSX from Princeton several times in 2007 in the new postdoc position. Chris Cothran is now finishing his second year teaching at Haverford and will be elsewhere by this summer. No senior thesis students this year but Lake Bookman '08 and Anna Phillips '10 were a huge help this summer and fall as we changed out the SSX machine.

Each year, we make progress on SSX (every year something different). Big news this year is the end of the prolate SSX-FRC flux conserver (0.4 m diameter, 0.6 m long) and the beginning of the SSX oblate configuration (first results were presented in Orlando at the APS-DPP meeting). There were several talks in 2007 including IPELS 2007, "Plasma heating and flow dynamics during 3D reconnection events in the SSX experiment", Cairns, Australia, August 2007; Magnetic Reconnection 2007, "Plasma heating and flow dynamics during 3D reconnection events in SSX", St. Michaels, MD, Mar. 2007; Current Trends in International Fusion Research, "3D reconnection and flow dynamics in the SSX experiment", Washington, DC, Mar. 2007; and Innovative Confinement Concepts, "Flow dynamics and heating of spheromaks in SSX", College Park, MD, Feb. 2007. There are several more talks planned for 2008 including American Association of Physics Teachers, "Flow and heating dynamics of merging spheromaks in SSX", Award Winning Research at Undergraduate Institutions, January 2008, an APS April meeting talk (in April 2008) and an MR2008 talk in Okinawa in March 2008. The ICC meeting will be in June in Reno, NV.

Other stuff coming up in 2008 of interest... we have a renewal of the NSF Center for Magnetic Self Organization (CMSO) coming up. 2008 will be year 5 of that grant believe it or not. SSX gets a small amount of money each year for that. I'm on the program committee for the 50th APS-DPP meeting (in Dallas in Nov 2008). I'll also continue with the NRC Plasma Science Committee as well as the review committee for our journal Physics of Plasmas. There's also an awards ceremony at the St. Louis APS April

meeting where I'll pick up a check for the APS Award for Research at an Undergraduate Institution. Drinks are on me next time!

Our main results in 2007 will appear in the paper Vernon Chaplin and David Cohen are completing. There are also some nice new results in a paper from Yu Lin at Auburn. Both papers focus on the initial merging physics (ie the $30 - 40$ μs reconnection timeframe).

Summary of 2007:

Oblate flux conservers: With the invaluable assistance of Mike Schaffer of GA, we have designed and constructed a new oblate flux conserver for SSX. The oblate flux conserver consists of two identical copper cones (0.5 m in diameter, each half 0.2 m long) with cylindrical outer electrodes welded. The flux conservers were spun out of single sheets of $1/4''$ copper by C. Schillinger Co in Bensalem, PA. The spinning copper disk is pressed onto a mandril of our specifications. The flux conservers are completed and installed. Once we're satisfied with experiments on bare copper, the entire inner surface will be coated with tungsten.

Tiny mag probes: We have recently tested a small high resolution array of magnetic probes (Anna Phillip's summer 2007 project). The probes are 1 mm scale with 2 mm separation and are housed in tiny quartz tubes. This is below the ion inertial scale ($c/\omega_{pi} \sim 20$ mm) in SSX and approaching the electron scale ($c/\omega_{pe} \sim 0.5$ mm). We have observed some structures that vary across a probe stalk (mm scale) spatially and up to 10 MHz (our digitization rate) temporally. Most structures we see with these tiny probes are smooth on the 10 mm scale. Each array only probes a few cubic mm of plasma so we have to mine the data for interesting events. Based on results of these prototypes, we'll build another array and put it in the reconnection zone (summer 2008). There is interest among space scientists and other laboratories in small scale, high frequency structure. Our participation in CMSO helps coordinate this interest.

External optical studies (soft x-ray and VUV): Former student Vernon Chaplin '07 worked on analyzing optical data from SSX with David Cohen. The non-LTE excitation kinematics code PrismSPECT is used to simulate emission spectra for a variety of plasma conditions. These model spectra are compared to experimental data from two main diagnostics: a vacuum ultraviolet (VUV) monochromator and a low-resolution soft x-ray detector (SXR). Measured UV line strength ratios depend primarily on the electron temperature in the plasma, so we are able to use observations of

carbon impurity emission lines in conjunction with SXR measurements as a temperature diagnostic. In particular, the CIII 97.7 nm / CIV 155 nm line intensity ratio proves to be extremely useful, while the CIII 229.7 nm line appears anomalously strong in experimental measurements. The key result from Vernon's thesis is the observation of transient electron heating ($T_e = 20 - 40\ eV$) inferred from bursts on a 4-channel soft x-ray array as well as from vacuum ultraviolet spectroscopy. Such heating is not observed in our dipole trapped spheromak. Vernon's thesis was selected among the finalists for the APS Apker award for 2007. We are presently completing a manuscript based on his work for submission to Physics of Plasmas.

IDS amplifiers: Chris built a set of new fast transimpedance amps (a matching set of 16 for now). These are based on the LM7171 chip and are all built ("dead bug" style) onto grounded boards. Chris designed them to tune out cable capacitance so they have very good time response (10 MHz or better). All 16 channels worked flawlessly with no ground loops, noise, or other electronic mishaps. The amps give us a large dynamic range (peak burst signals were 5 V while photon "buzz" in the wings at late times was down in the 50 mV range). Chris was pleased with the results!

Doping experiments: For the first time, we're running SSX with doped impurity... mostly helium for now. We've done two kinds of experiments with IDS (magnetics, SXR, and VUV have been operating too). One was to fire normal hydrogen spheromaks (counter helicity for reconnection) into a low density Helium background (10^{-5} to 10^{-4} torr range... a few %). For this we had to run with the turbo pump only (too much He flow for the cryo). The second was to dope the gas delivery lines with a few % He. This was tricky since we needed to pump the lines out and re-fill with H and He. In both cases, we see heating in the He_{II} 468.6 nm line (4-3 transition I think) up to 40 eV then a long cooling down to 10 eV or so. A few shots show jets/bursts. The He_{II} light seems to persist much longer than the C_{III} light did. This was the topic of Chris' APS 2007 poster and we'll pursue this in 2008.

Colorado collaboration: Tobin Munsat and his student Jeremy Nuger have been working on some high resolution magnetic probes and amplifiers for us. It turns out that the Colorado FRC is very similar to SSX (spheromak merging in a prolate FC, bigger than SSX). Their probe arrays have about 5 mm resolution (16 locations in x, y, z... 48 channels total wound on a Macor stalk) in a 10×10 mm rectangular quartz enclosure (100 mm long). The amplifiers use LMH6703 op amps with a 10 MHz bandwidth and a gain of 5 with all SMA connectors. Jeremy has prepared some useful reports on

the probes and amplifiers. The SSX prototype of a probe array/amplifier should be ready soon.

Simulations: Yu Lin at Auburn did a simulation for us and submitted a paper to PPCF (see below). Her code treats ions kinetically (0.5×10^9 ions for now!) and electrons as a fluid. This might be a good model for us since SSX ion mean free paths can approach the machine size $0.4\ m$ while electron mean free paths tend to be less than $0.1\ m$. Her simulation shows a population of heated ions accumulating near the machine axis. The mechanism is reconnection outflow (radially inward actually) and viscosity. We hope to do more work in 2008. Elena Belova of PPPL and Nick Murphy of Wisconsin (CMSO) are continuing to provide computational support with HYM and NIMROD respectively. Chris has been analyzing the output of Elena's 2D code with an eye towards representing data the same way we measure it (for example line-averaged and density-weighted flow measurements from IDS).

Lab updates: We had our first run day with the new oblate flux conservers just before the APS meeting. Things went very well I think. We've since had a multi day campaign of He glowing ($\geq 50\ hr, 300\ V, 0.1\ A, 30\ \mu m$) and baking ($\geq 100\ C$). Base pressure is 1.5e-7 so I think the system is pretty clean. Next up is to re-learn how to un-stuff the gun (different parameters since the outer electrode is longer). We want to verify stability to the tilt but also look at $n = 2, 3, 4$ (that will mean more probes). At some point (soon), we'll pull the flux conservers and have them tungsten coated. We've used Flame Spray in MI in the past... we might want to try a new, closer place (Steve is looking into that).

Papers and manuscripts (2007): We had some manuscripts appear in print in 2007 (others are still being reviewed). We're also working on several more that should be submitted soon (see below).

1. **M. R. Brown**, C. D. Cothran, D. Cohen, J. Horwitz, V. Chaplin, "Flow Dynamics and Plasma Heating of Spheromaks in SSX", *Journal of Fusion Energy* (to appear 2008).

2. **M. R. Brown**, C. D. Cothran, J. Fung, M. J. Schaffer, E. V. Belova, "Novel Dipole Trapped Spheromak Configuration", *Journal of Fusion Energy* **26**, 31 (2007).

3. C. D. Cothran, J. Fung, **M. R. Brown**, M. J. Schaffer, E. V. Belova, "Spectroscopic Flow and Ion Temperature Studies of a Large s FRC", *Journal of Fusion Energy* **26**, 37 (2007).

4. Y. Lin, X. Y. Wang, **M. R. Brown**, M. J. Schaffer, and C. D. Cothran, "Modeling Swarthmore Spheromak Reconnection Experiment using a Hybrid Code", *Plasma Physics and Controlled Fusion* (submitted 2007).

Manuscripts in progress (2008): We have been working on at least four possible manuscripts that should be ready for submission soon. I think Tim Gray could jump in and help organize/write on a few of these.

C. D. Cothran, T. Gray, M. J. Schaffer, E. Belova, and M. R. Brown, "Observation of Doublet CT Structure in SSX". First observation of an FRC-like object with persistent toroidal flux at the ends formed via counter-helicity merging in SSX. It is studied in the prolate (tilt unstable) 0.4 m diameter, $L = 0.6\ m$ length, 3 mm wall copper flux conserver in SSX formed by counter helicity merging of spheromaks. We have high n mode analysis, IDS, and MHD simulations for this.

C. D. Cothran, T. Gray, M. J. Schaffer, E. Belova, and M. R. Brown, "Self Organization from Co-helicity Merging in SSX" or "Non-axisymmetric relaxed state in a prolate flux conserver". Observation of stable, tilted spheromak structure formed via co-helicity merging also studied in the prolate (tilt unstable) 0.4 m diameter, $L = 0.6\ m$ length, 3 mm wall copper flux conserver in SSX. We have some IDS and a nice MHD simulation for this.

C. D. Cothran, J. Fung, E. Belova, and M. R. Brown, "Simultaneous Bi-directional Plasma Jets from a Laboratory Magnetic Reconnection Volume". Observation of bi-directional jets and ion heating in the reconnection zone of SSX. The ratio of inflow speed to outflow speed is the normalized reconnection rate. A rapid reconnection rate is corroborated with a separate measurement of reconnecting magnetic flux. Chris has some new analysis based on Elena's simulation for this. This will be submitted to PRL.

V. H. Chaplin, J. Horwitz, M. R. Brown, D. H. Cohen, and C. D. Cothran, "Temperature and flow measurements during magnetic reconnection at SSX". This manuscript is nearly complete. We should be submitting to Physics of Plasmas soon.

Students: Vernon and Jason have both moved on (Vernon will be at Caltech fall 2008 after returning from Vietnam). We haven't lined up anyone for summer 2008 but we have some possibilities (stay tuned). I saw many SSX alums at the APS-DPP 2007 meeting in Orlando. I was extremely proud of everyone's success! Cameron and Amy are well into their new post-PhD careers... Slava and Tim are just finishing at Princeton. Matt is now at MIT, Dave A is working on the big LAPD machine at UCLA, and Dave S is doing

BES on the big DIII tokamak (while at U Wisconsin). I've also been in touch with Jerome, Marc, Zach, and Abram in 2007.

Plans for 2008: We'll certainly push on the baking and glowing to make the bare copper as clean as possible. The next science campaign is to re-build the gas delivery system (all stainless steel) and meter in known cocktails of gases in the gas feed (H, D, He, methane, Xe). In Orlando, Chris presented some interesting (but puzzling) results with He, C, and Si. T_{He} was hot, T_C was cooler (about 30 eV), but T_{Si} was hot again for the same conditions. As we make SSX cleaner with new polished stainless steel gas lines, new valves, beefier bakeout, tungsten coating, etc, we may find less and less impurity radiation signal so having a controlled way to dope will be important.

We have plans to build yet another mach probe (Mach III) to replace Jason's nice Mach II probe (now at WIsconsin). We also are planning a new moveable ion energy analyzer (like the ones Dave S built but on a sliding fitting to get near the reconnection zone). Both of these projects are ready for Tim and the next round of students to begin.

David Cohen is on leave in 2007-8, so he is planning to help us continue the work Vernon has started. In particular, David will modify the PrismSpect analysis of SSX spectra. We hope to calculate the effect of non-Maxwellian electron distributions on model spectra. Perhaps we can resolve the anomalous intensity of the carbon line C_{III} at 229.7 nm.

cheers and happy new year, mb