Happy New Year 2010 from SSX!

Here's a review of 2009 as well as plans for 2010... I'll post this one on the SSX website (check out older ones if you like). This makes 15 years of SSX!

We had a big year in 2009. MB is on sabbatical (year 16 is sabbatical #4) so I've been able to focus on SSX stuff full time. Tim Gray is finishing his second full year at SSX. We had two SSX-related invited talks at the APS-DPP meeting in Atlanta in Nov. 2009 (Tim and Chris). We also brought two students with us to Atlanta (Max and Darren). There were 5 SSX-related papers submitted in 2009. Four of them look to be accepted. The biggest news was Chris Cothran's very well received Phys. Rev. Letter appearing in Nov. 2009. More on all this below.

The highlight of a productive summer was a mini-workshop we held for two days at Swarthmore July 23-24. Tim and MB were joined by Chris Cothran, Clayton Myers, Elena Belova, and Slava Lukin (plus students). The goal of the workshop was to make headway on 4 papers and to connect with new SSX simulations by Clayton/Elena (with HYM) and Slava (with HiFi). We have done both co-helicity and counter-helicity merging in both prolate and oblate flux conservers. We have magnetic, IDS, and density data for all those combinations. We also have some simulation data for some of the cases. The first day was about co-helicity merging and Taylor relaxation. Chris and Tim both presented nearly complete papers. The second day was about counter-helicity merging and reconnection. We discussed a simulation/experiment paper on our Doublet CT and Chris' outflow jet result. There are drafts of both of those papers. We're looking at another small, targeted meeting in 2010 to keep the ball rolling.

We had four students do SSX work in 2009, one from every graduating class: Jeff Santner '09, Bevan Gerber-Siff '10, Max Korein '11, Darren Weinhold '12. Details on their work below.

Lots of meetings in 2009! We went to the APS-DPP meeting in Atlanta in November 2009. As usual, there were lots of SSX alums there (Chris, Matt L, Dave S, Dave A, and for the first time Vernon now at Caltech... didn't see Cameron or Amy this year... Slava didn't make it either). As I mentioned, Tim gave a talk called "Evolution to a Minimum-Energy Taylor State in Multiple Flux Conserving Boundaries in SSX" (on Monday of the meeting) and Chris gave a talk called "Observation of a Non-axisymmetric MHD Self-Organized State" (on Friday). Earlier in the year, we went to the CMSO meeting in Santa Fe (April), and I organized an ion heating session for the APS April meeting in Denver (May). We had a great time seeing Bill M, Slava, Steve Cranmer, Steve Spangler, Tim and MB in Denver for that ion heating session at the APS meeting.

Tim and I were in Stockholm for IPELS 2009. I gave a talk called "Mass

dependent ion heating due to magnetic reconnection in the SSX plasma device", June 2009. We were in Japan for the US/Japan CT Workshop on Innovative Confinement Concepts based on Self-Organization and Active Control, Kusatsu, Japan, September 2009. Tim and I both gave talks. Closer to home, there was Magnetic Reconnection 2009, "Mass dependent ion heating due to magnetic reconnection in SSX", Madison, WI, October 2009. Chris also gave a talk. There was also a very small meeting US/Japan Workshop on Magnetic Reconnection 2009, MB's talk was "Ion heating in SSX", Princeton, NJ, March 2009. It was also great to see Clayton's talk at PPPL based on his second year project in October.

Other stuff coming up in 2010 of interest... The big task will be to write our renewal with hopefully some new twists from prior years. Also, I was selected to chair the NRC Plasma Science Committee by the National Academies so I'll be stepping down from the University Fusion Association exec comm. I'll also have to start teaching again in Sept 2010.

Summary of 2009:

2:1 flux conserver: For most of 2009 (since April), we focused on merging in our new 2:1 flux conserver ($L = 0.4\ m, R = 0.2\ m$, L:R = 2:1). Our thinking here was that the oblate flux conserver of 2008 (L:R = 1.2:1) didn't have enough room for the two spheromaks to merge coaxially (see the SSX2009 summary). The previous prolate flux conserver (L:R = 3:1) allowed for a nice coaxial initial merging phase but was ultimately tilt unstable (see Chris' PRL and Clayton's upcoming Doublet CT paper). We thought 2:1 was a good compromise. We studied co- and counter-helicity merging in the 2:1 flux conserver with 4 stainless steel probes at the midplane, or two quartz probes across a diameter (or at 90^o). Early in 2009 we installed all new high vacuum stainless steel gas lines so vacuum conditions in 2009 have been excellent. We can now pump out the lines with a new scroll pump between run days so the whole system stays extremely clean.

Here's a list of experiments we ran with the 2:1 (from my SSX run log): We started with 2 cap vs. 1 cap operation (0.5 mF vs. 1.0 mF at about 5 kV). Our normal 1 cap operation is about 10 kJ of stored energy in the two banks, about 1 kJ in the plasma. We did IDS runs with $He_{II}, C_{III}, Ar_{IV}$. For the argon doped shots, we glowed with argon. During the summer, we ran with the new RGEA and Mach probes (including radial scans, flipping the probe east-to-west, see below). We ran the VUV to measure T_e using Vernon's technique (we saw some mild heating from $10 - 18\ eV$). We installed the 96 channel midplane magnetic probe array (4 stalks of 8 triples) in November. We switched back to He glow operation in December.

After about 8 months with the 2:1 flux conserver (since April 2009), we're ready to move on to the super-prolate. We just finished a solid week of running in December 2009. Vacuum conditions were excellent ($10^{-8}\ torr$)... bak-

ing, glowing before each run day. We have the new 96 channel probe array in the midplane... 4 stalks with 8 triples each, 10 MHz integrators (all channels working). Our thinking was that we needed more coverage to monitor the reconnection process and maybe the metal probes inserted axisymmetrically would slow the tilting down so we might have some axisymmetric merging to start. Very nice data set! We did a full campaign of counter-helicity merging and co-helicity to finish off the 2:1 campaign. Unfortunately, we have not seen an axisymmetric FRC (even transiently). With co-helicity, we now sometimes see a beautiful axisymmetric initial state (ie all probes pointing radially out like a star for left/left for example), but the state quickly evolves to a twisted, non-axisymmetric lowest energy Taylor state. Its been fun to click through the data 0.1 μs at a time.

Super-prolate flux conserver: As of January 2010, we will be installing the super-prolate $L = 0.86\ m$, $D = 0.17\ m$, L:R = 10:1 flux conserver. Steve has started cutting metal. Our initial plan with the 10:1 super-prolate flux conserver (to get some results for the February ICC meeting) is to run with only one gun (east) and introduce a long probe from the west side. We'll likely use the double capacitor to "slowly" drive a double helix down the tube (over a meter!). Tim got some 4 foot quartz tubes and we've got some long lengths of 3/16" Delrin. We think that measuring vertical and horizontal components of **B** right on axis (r=0) will tell us if we have a helical state. In fact, we should see the vector field swirl down the length of the flux conserver with a pitch of $k_z R = 1.23$. Probe separation of 1.9" (about 5 cm) will give us 24 positions each for vertical and horizontal over most of the length of the tube. This is something we're working on right now (around New Years 2010). It looks like we could also use the Colorado probe to study relaxation fluctuations at higher resolution.

I did an estimate of the number of probe coils wound for SSX experiments over the years and we're over 1200. There were big arrays Matt and Andrew did (600 and 480 respectively for the 5x5x8 3D and 3x4x8 distributed arrays). There have been lots of smaller arrays that Cameron and Tom built, the ones Jeff re-did over this summer and the long 48-channel one we're finishing now.

Local probe measurements (Darren/Max): Summer 2009 Darren Weinhold took over the electrostatic probe project from Kevin and Bevan in 2008. He found some evidence of reconnection outflow jets at about $r/R = 0.5$ and at about $30 - 40\ \mu s$ (ie the right place and the right time) in the 2:1 flux conserver. Darren also modified the retarding grid energy analyzer (RGEA) but we still are struggling with tiny signals. Max Korein implemented a particle orbit code from Slava (originally written by Alan Glasser) to study the flow of ions around both the Mach and RGEA probes in realistic SSX fields (about 10^5 ions per run). Max worked on confinement (looking at the fraction of ions that stay inside the flux conserver as a function of ion energy) and probe modeling (looking at the flux of ions to the

RGEA or Mach electrodes). This project is in great shape for a student to pick up in 2010. Next step will be to run orbit calculations in dynamical fields (HiFi) and SSX relaxed states (both 2:1 and 10:1).

Ion heating: We now have a complete set of ion heating experiments in the 2:1 flux conserver, hydrogen plasma doped with helium, carbon, and argon (He^+ 468.9 nm, C^{++} 229.7 nm, Ar^{+++} 219.3 nm), each with the IDS system and a special filter for each line. The helium and argon were doped impurities and we tried various levels (up to 10% with argon). The recent argon measurements proved to be a little tricky. The signal was small and we noticed that there was Ar^{+++} signal very late in the discharge, likely due to recombination. In any case, if we average the data from a bunch of similar shots (counter-helicity), we find that the He^+ is the hottest and the scaling is something like Z/M. We note that a reconnection electric field on for a fixed time would increase velocities of charged particles like Z/M. Another piece of the puzzle is that viscosity scales inversely with ion mass (like $T_i^{5/2} M_i^{-2}$ I think) so energetic, light ions behave viscously. This is a problem that's ripe for a PIC or particle orbit code coupled with an MHD simulation.

Simulations: Computer modeling and simulation has clearly been the difference maker in 2009. We began with George Marklin generating a series of eigenmodes for our four flux conserving boundaries. This helped us understand relaxation in the 3:1 flux conserver and was the springboard for Chris' PRL. The eigenmodes helped us to understand the oblate geometries as well (Tim's letter) and is guiding us in how to probe the new 10:1 flux conserver. In the summer, we had excellent simulations from Elena and Clayton (HYM, co- and counter-helicity, 3:1) and Slava (HiFi, co-helicity only, 3:1 and 2:1). These helped us understand the dynamics of co-helicity merging. Tim's invited talk paper and Slava's letter both discuss the observation of field null where the two spheromaks meet. After the spheromaks tilt slightly, the null evolves and allows the merging to proceed.

Papers and manuscripts (2009): We had 4 papers in 2003 and in 2006 (our previous big years). There are already 7 in the pipeline this year. They could all be published in a 12 month period (the first 4 for sure).

1. C. D. Cothran, M. R. Brown, T. Gray, M. J. Schaffer, and G. Marklin, "Observation of a Helical Self-Organized State in a Compact Toroidal Plasma", *Phys. Rev. Letters* **103**, 215002 (2009). This was Chris' excellent "editor's choice" PRL last November (prolate relaxation).

2. T. Gray, M. R. Brown, M. Schaffer, and G. Marklin, "Stable Spheromak Formation by Merging in an Oblate Flux Conserver", *Physics of Plasmas* (submitted Letter to appear 2010). This is Tim's oblate relaxation paper.

3. C. D. Cothran, M. R. Brown, T. Gray, M. J. Schaffer, and G. Marklin, "Observation of a Non-axisymmetric MHD Self-Organized State", *Physics of Plasmas* (submitted, to appear May 2010). This is Chris' PoP paper based on his APS invited talk.

4. T. Gray, M. R. Brown, C. D. Cothran, V. S. Lukin, G. Marklin, and M. J. Schaffer, "Evolution to a Minimum-Energy Taylor State in Multiple Flux Conserving Boundaries in SSX", *Physics of Plasmas* (submitted, to appear May 2010). This is Tim's PoP paper based on his invited talk.

5. V. S. Lukin, T. Gray, C. D. Cothran, and M. R. Brown, "Computational and Experimental Observation of Null-Point Magnetic Reconnection and Subsequent Dynamical Relaxation". (submitted, under revision)

6. C. Myers, E. Belova, C. D. Cothran, T. Gray, M. R. Brown, "Properties of the Doublet CT configuration". This is a long-standing manuscript greatly enhanced by Clayton's excellent APS poster presentation. Submission on this is immanent. There was a draft after the summer workshop and Clayton has added some excellent graphics from the HYM simulations.

7. "Simultaneous Bi-directional Plasma Jets from a Laboratory Magnetic Reconnection Volume", this is Chris' jets paper. We have a draft from the summer workshop.

Students: We had another big contingent of students this year (4 total) but no theses. Max and Darren came to Atlanta for the APS meeting.

(1) Jeff Santner '09 is off to Princeton for grad school (engineering) and he finished a new 96 channel, 10 MHz magnetic probe array (on 4 stalks), amplifier/integrators, cabling, new digitizers, even needed new power lines into the SSX screen room. Thanks also to Jim for his electronics help on this. We have been able to see the merging process better with 96 probes (at 10 MHz!). Co-helicity at 10 MHz will be interesting too to watch the null line evolve. This experiment was just completed in the 2:1 flux conserver. Jeff also worked on an ion heating/cooling model (MatLab).

(2) Max Korein '11 worked with Slava's particle pushing code PPC to study ion trajectories (and energetic ion loss) in the 2:1 flux conserver. He also has been tracking ion orbits drawn from drifting Maxwellian distributions to understand ion collection on our Mach and RGEA probes (in different magnetic fields). He's tried both single and back-to-back spheromak fields (analytical) and we're set up for even more realistic fields (from HiFi and PSITet). That project has worked out well so far... we'll have a realistic calibration for the Mach probe even for the case of $\rho_i = r_{probe}$.

(3) Darren Weinhold '12 was in charge of electrostatic probes (Mach and RGEA). He has done some rebuilding and re-analysis and took a lot of data. We see evidence of outflow bursts with the Mach probe and energetic electron bursts with the RGEA both at the time of intense reconnection during counter-helicity merging. We also had signs of warm electrons in the 2:1 using Vernon/David's VUV diagnostic. T_e had been pretty cold with the oblate flux conserver (warmer in the 3:1 I think because we had some confinement). Darren also built a pair of graphite carbon sources to be installed in the plasma gun region.

(4) Bevan Gerber-Siff '10 returned to SSX in the fall of 2009. He worked on the final assembly and calibration of Jeff's probe array (with Jim), flanges for the new super-prolate flux conserver (with Steve), and a particle orbit code to supplement what Max is working on. Bevan looks to work part-time on SSX in the spring of 2010.

Plans for 2009: MB will continue his leave until September 2010. The next big event is the Innovative Confinement Concepts meeting (ICC 2010) at Princeton in February. This is our main DOE/Fusion meeting whereas IPELS is our main NSF/reconnection meeting. The ICC should have a big SSX-relevant contingent with MB, Tim, Chris, Slava, Clayton, Elena, Mike Schaffer, and others all there. MB will also visit UT Austin and the famous, "top-secret" TriAlpha private fusion company in Jan 2010. There is also an interesting-looking reconnection workshop in Yosemite in February (with Bill M) as well as a session at the APS meeting in DC in Feb (organized by Slava Lukin). At some point, we expect there to be a call for 3-year proposals in the spring of 2010. Perhaps Slava and Chris will be involved with that. The goal for 2010 will focus on relaxation and the final state in all of our flux conserving shapes. The super-prolate 10:1 will be the main focus at least for the beginning of 2010 but we may return to 3:1. We will be concentrating on three topics for each shape (1) reconnection dynamics perhaps using Beltrami states as a basis (eigenfunctions of $\nabla \times B$), (2) ion heating measurements during relaxation with ions of different mass and charge state (perhaps correlating with fluctuations), (3) outflows and jets. Since reconnection outflows seem to be ubiquitous in everything we do (measured both with IDS and Mach probes), it could be that understanding the velocity field in SSX will be the key to understanding all the important SSX issues: final relaxed states, dynamics, and ion heating.

cheers and happy new year, mb