Happy New Year 2011 from SSX!

Here's a review of 2010 as well as plans for 2011... I'll post this one on the SSX website (check out older ones if you like). Since we were just renewed by DOE, I'll summarize plans in some detail at the bottom of the document. For those new to SSX, these annual summaries have come out every January for a decade or so. I find them very useful for report writing and planning throughout the year.

We had a good year in 2010. MB finished his sabbatical in September 2010 (year 16 was sabbatical #4) and this fall introduced a new freshman seminar on energy (including a bit on fusion). Tim Gray is finishing his third full year at SSX (as of Feb 2011). We all went to the APS-DPP meeting in Chicago (MB, Tim, Dan, Alex, as well as lots of SSX alums).

A highlight of a summer 2010 was the General Meeting of the Center for Magnetic Self-Organization (CMSO) held at Swarthmore June 8-11, 2010. About 50 scientists from around the world stayed on campus at the new Kemp dorm including 5 from Japan and 2 from Germany. Tim Gray gave a nice talk about our selective decay result. There were other excellent talks including one by Mike Shay (stepping in for Bill Matthaeus). I think the banquet on the evening of June 10 went especially well. This was the first time a major international scientific meeting was held on campus.

Another major highlight was submitting our DOE renewal in April and hearing of our successful funding in September. We changed directions a bit emphasizing a computational effort with Slava Lukin. Long-time collaborator Mike Schaffer got busy with ITER planning and is now heading towards retirement. Thanks to Mike for all his contributions over the years. We also decided to emphasize turbulent relaxation processes in SSX (involving reconnection as always). Turbulence (or intense, broad-band fluctuations) seems to play a role in the approach to relaxation in SSX, ion heating, and the intense, bursty flows we see.

Another interesting thing that happened is we were awarded an ARRA grant for $46k (stimulus money). We bought a bunch of modern digitizers from DTAQ (96 total channels at 2 MHz, 14 bit, 20Vpp). What's really useful about these is that they have a burst mode at 65 MHz for half the channels (48 total) for an 8K record (about 120 μs). Our plan is to dedicate a system of high frequency magnetic probes for statistical turbulence studies. Note that 65 MHz will resolve proton cyclotron fluctuations even at a few kG. Importantly, we also bought cabling and connectors to go with it so we have a significantly upgraded data acquisition capability.

We had two students do SSX work in 2010: Alex Zhang '12 and Dan Dandurand '11. We always have very good students at Swarthmore but I thought the combination of Alex and Dan (junior/senior) doing experiment/simulation coupled with the help of Tim and Slava all worked synergistically in 2010. The upshot is an excellent paper that has been accepted by Review of Scientific Instruments **while Alex and Dan are still undergrads!** Details on their work below.

Since I was on leave last year, we did more traveling than usual. We had the ICC meeting in Princeton Feb 16-19. Tim gave a talk summarizing our aspect ratio scan (several different flux conserver shapes) while Chris gave a talk on the 3:1 helical state. I visited UT Austin and Tri-Alpha in January (Tri-Alpha was pretty impressive). Slava organized a session at the APS April meeting and I gave a talk there in DC. I gave a talk at the Yosemite 2010 Magnetic Reconnection workshop called "Reconnection-driven ion heating and plasma relaxation in SSX". That was an interesting meeting in a great setting (in Yosemite National Park). Bill Matthaeus was there along with lots of other space and solar reconnection types. I gave a talk at Oberlin College too. We gave talks here at Swarthmore (Tim did the Physics Colloquium and MB did the Wednesday Faculty Lecture). Finally, Tim just got back from a trip to Nara, Japan for the 2010 Magnetic Reconnection workshop (MR2010). He gave a talk called "Three-dimensional reconnection and relaxation of merging spheromak plasmas" in a session with Paul Bellan and John Sarff. This is the main reconnection meeting with all the main players (Yamada, Ono, Egedal, Ji, Kusano, Shibata, Shimizu, etc). We had some useful interactions with a theorist from England named David Pontin.

We went to the APS-DPP meeting in Chicago in November 2010. As usual, there were lots of SSX alums there (Chris, Matt L, Dave S, Dave A, Vernon, Cameron, Slava, Tim...). Cameron Geddes '97 was part of a group that won the APS-DPP Excellence in Plasma Physics prize for 2010. Dave Auerbach '01 gave an invited talk on his PhD work at UCLA. Work on LAPD seemed to be one of the star attractions at the meeting. Big congratulations to both Cameron and Dave on their success in 2010! We had a mini-Swarthmore reunion at the student poster session on Tuesday (with students Alex and Dan)... Cameron dropped by, as well as Vernon, Slava, Tim, Matt Landreman, Dave Schlossberg... thanks to everyone that gave advice and comments to Alex and Dan on their posters (and advice for grad school too).

On a sad note, many of you remember our dog Feynman from the SSX summer BBQs. Feynman passed away over the summer (he was 14). We now have two young basset hounds (Mocha and Daisy).

Other stuff coming up in 2011 of interest... The big task for 2011 will be to do the work proposed in our successful DOE grant (see below). This will include a significant modification to the MHD wind tunnel as well as integrating Slava's simulations. I continue to chair the NRC Plasma Science Committee by the National Academies.

Summary of 2010:

MHD wind tunnel in the super-prolate flux conserver: As of January 2010, we've been operating the super-prolate $L = 0.86\ m, D = 0.17\ m$, L:R = 10:1 flux conserver. So far we've only run with only one gun (east) and used a long axial magnetic probe array introduced from the west side. We've launched both right-handed and left-handed plumes down the wind tunnel. We've measured T_e, T_i, and flow with VUV and IDS. Tim got some nice results early in 2010 that formed the basis for several talks and posters this year. In particular, this will form the basis of Tim's selective decay paper. Tim's key observation is the turbulent evolution towards a long, twisted helical state. The process begins with broadband fluctuations with wavenumbers spanning a decade but evolving towards a single state with $k_z = 2.2\ m^{-1}$. We're couching the emergence of this state in the language of selective decay (coined by our friend Bill Matthaeus). The data are really nice (both the final helical magnetics and the turbulent spectrum $E_B(k,t)$). The rendering of the final 10:1 helical state was the logo for our CMSO workshop here last summer. I've asked Dan to do a rendering of the 10:1 helical state maybe with some ion orbits superimposed for the next lab tee shirt design.

Mach probe (Alex/Dan): The main effort during summer 2010 was a long campaign of running with the six-sided Mach probe. Alex developed a careful protocol for baking and discharge cleaning both the wind tunnel and the Mach probe. He was also careful about discarding any shot with evidence of arcing on any of the six faces. In the end, we used an ensemble of 40 clean shots under identical conditions (both Mach data and magnetic data). We used the mean arrival times of $|\mathbf{B}|$ at each magnetic probe in the linear array for 40 discharges to get the time-of-flight.

From Alex and Dan's paper... The SSX Mach probe has a cylindrical Gundestrup geometry in which six evenly-spaced tungsten electrodes are encased in a boron nitride turret. The ceramic turret is 2.54 cm in length and 1.3 cm in diameter. The electrode collector faces are recessed into the ceramic housing by 2.0 mm. Each rectangular opening has length 4.0 mm, width 1.6 mm, and area $A = 6.0 \pm 0.1\ mm^2$. Individual electrode collectors effectively provide independent current measurements when biased with respect to the central pin, which protrudes from the end of the turret 1.6 mm. The exposed electrode collector areas are the same within 2%. The probe is mounted at the midplane of the SSX vessel, and inserted 5.5 cm from the center of the flux conserver for these calibration studies. The probe is otherwise moveable in the radial direction.

From time-of-flight measurements in the SSX wind tunnel, with flow speeds of about 50 km/s, absolute calibration of the probe to the functional form $\frac{J_{up}}{J_{down}} = e^{KM}$ gives $K = 2.0 \pm 0.5$. The SSX regime is neither in the un-magnetized nor fully-magnetized limit so we employed a particle simulation to corroborate our measurement. Using 50 million particles drawn from a Maxwellian distribution of $T = 20\ eV$ at a variety of drift speeds relative to the thermal speed gives a calibration constant of $K = 2.61 \pm 0.01$ with a uniform 1 kG magnetic field.

Simulations: Clayton Myers and Elena Belova (PPPL) continue to work on MHD simulations of SSX (both counter- and co-helicity) using HYM.

Clayton's last two APS posters have been SSX-related and he's working on the long-standing doublet-CT paper. We now have an official funded collaboration with Slava Lukin (NRL). Slava has been instrumental in our particle simulations with Max and Dan. His simulation work with Dan was a key part of the RSI Mach probe paper. Slava's co-helicity simulation was a key part of Tim's recent PoP.

Slava has a lot on his plate but we're planning on adding the capability of pushing test particles in his particle code PPC to his HiFi MHD merging simulations. In the near term, this will include the addition of collisions to the PPC model with static fields. In the longer term, we will integrate PPC and HiFi so we can study ion heating in merging simulations. We also will be modeling our new plasma wind tunnel configuration (spheromak roaring down a long, evacuated tube), and maybe modeling our oblate merging attempts from last year (Mike S is interested in that one... we still don't know why it didn't work).

There are three direct experimental observations that are ripe for a simulation comparison (or even an analytical explanation). **(1) Ion heating:** We have a sequence of experiments in the 2:1 flux conserver with counter-helicity merging (reconnection scenario) that definitely shows more heating of helium (He^+) than carbon (C^{++}). The scaling is Z/M. We have additional data with Ar^{+++} corroborating this scaling. Once we have the particle orbit code coupled with the dynamical HiFi MHD code, we should be able to sort this out. **(2) Aspect ratio and jets:** A direct comparison of the structure of the reconnection zone in the 3:1 flux conserver is coming. Clayton has the new HYM simulations ready to address this and the side-by-side comparisons look very good. The structure comparison will be a part of his doublet paper and a comparison of the outflows with IDS data could be part of the jets paper. **(3) MHD wind tunnel flow:** Once we have a full MHD simulation of flow down the wind tunnel (initiated by gun formation), flow data near the wall can be compared with Alex's Mach probe data. Alex sees a very specific time signature. I guess a fourth one is a study of counter-helicity merging in the oblate flux conservers and a comparison to the unusual non-axisymmetric states we observed in 2009.

Papers and manuscripts (2010): Counting Chris' PRL in Nov. 2009, four SSX-related papers appeared this year. In addition, Alex's RSI paper was just accepted and will appear in 2011 sometime. Tim, Clayton, and MB are each working on papers that have been in the works for a long while. The Gray/Lukin 2010 paper was a Physics of Plasmas editor's choice (it was on the cover sheet of the PoP web page).

1. X. Zhang, D. Dandurand, T. Gray, M. R. Brown, and V. S. Lukin, "Calibrated Cylindrical Mach Probe in a Plasma Wind Tunnel", *Review of Scientific Instruments* (to appear 2011).

2. T. Gray, V. S. Lukin, M. R. Brown, and C. D. Cothran, "Three-dimensional Reconnection and Relaxation of Merging Spheromak Plasmas", *Physics of Plasmas* **17**, 102106 (2010).

3. T. Gray, M. R. Brown, C. D. Cothran, M. Schaffer, and G. Marklin, "Stable Spheromak Formation by Merging in an Oblate Flux Conserver", *Physics of Plasmas* **17**, 032510 (2010).

4. 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* **17**, 055705 (2010).

5. 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).

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 presentations in 2009 and 2010. Submission on this is immanent. The draft has been steadily growing and improving since 2009. Clayton has added some excellent VisIt rendered graphics from the HYM simulations.

7. M. R. Brown, C. D. Cothran, T. Gray, E. Belova, C. Myers, "Spectroscopic observation of bi-directional reconnection outflows in a laboratory plasma", this is the draft of the jets paper kicking around for a long time. Clayton has recently analyzed aspect ratios of reconnection layers in the new HYM simulations that should really help this project along.

8. T. Gray, M. R. Brown, "Selective decay in a quasi-infinite cylinder", this is Tim's paper showing the evolution to a final, long helical state.

Students: We had two excellent students during summer 2010. Their work resulted in a recently accepted Review of Scientific Instruments paper (with Alex as lead author). Both Alex and Dan came to Chicago for the APS meeting and each presented a poster. I was particularly impressed with the way Alex and Dan picked up threads established by Bevan, Kevin, Darren, Max, even going back to Abram and Slava. Kevin and Max along with Dan are all applying to graduate schools right now (Jan 2011). We'll know more about where they end up in the spring.

(1) Xingyu (Alex) Zhang '12 picked up the work started with Bevan, Kevin, and Darren in prior summers. His focus was on the six-sided Mach probe in our new MHD wind tunnel configuration. Alex was relentless in getting the best possible data taking several weeks of SSX run time. We've always had problems with arcing with the Mach probe (even going back to the thesis work of Jason and Abram). Alex worked out a protocol including baking and glow cleaning both the chamber and the probe. He was meticulous about weeding out any shots with any hint of arcing. In the end, we had a very comprehensive data set that formed the basis of Alex's successful RSI paper.

(2) Dan Dandurand '11 picked up the work Max started last summer. He worked with Slava's particle pushing code PPC to study ion trajectories (and energetic ion loss) in the MHD wind tunnel configuration. 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 repeated both single and back-to-back spheromak fields (analytical) and we're gearing up for even more realistic dynamical fields (from HiFi). His main effort was to study confinement in the new 10:1 helical state. It will be interesting to study the confinement properties of this object. There might be some identifiable flux surfaces or drift surfaces. On the Mach probe front, Dan's work was an integral part of the RSI paper. Perhaps with more realistic fields and drifts, we'll have an even better simulation calibration for the Mach probe for the case of $\rho_i \approx r_{probe}$. Dan has navigated the TeraGrid computation system well and now has an excellent introduction to computational physics. We have 10's of thousands of hours of computational time at our disposal in the coming year. Thanks to Andrew Ruether at ITS here at Swarthmore for setting that up. Finally, Dan used his appreciable math skills early in the summer to help with analytical models of our static fields.

Plans for 2011: Our main task for 2011 will be to begin the work we proposed for our renewal. On the experimental side, we plan to extend the SSX wind tunnel by 1 meter and use the main chamber as an exhaust volume. We will also instrument an array of 48 fast-magnetic probes (quartz) dedicated to fluctuation studies across a radius (65 MHz). On the simulation side, we'll start with particle studies in static fields but ultimately we want to study ion heating in dynamical, merging SSX simulated plasmas.

- **MHD wind tunnel (early 2011):** The first order of business will be to get high resolution radial magnetic profiles. We have been studying turbulent evolution and relaxation with our long axial probe array. We are using the Colorado probe at the moment which has high spatial resolution but is too sensitive for our digitizers. We will try it with our new 20V DTAQ digitizers when they arrive. We will also try to attenuate the signal with some older integrator boxes. Ultimately we'll want to study the raw, unintegrated signal with a new fast radial array with tiny 1-2 turn loops. Once we have a reliable radial array, we'll add the east gun and do merging in the existing one-meter geometry. Finally, our plan is to do the analog of grid turbulence but in an MHD wind tunnel. In front of one gun, we'll put a coarse grid of perhaps two vertical and two horizontal wires. We can compare fluctuations at the midplane between the gridded and non-gridded gun plasmas.

- **Extended wind tunnel (summer 2011):** We proposed to extend the SSX vessel by about a meter (about 2 meters total) and use part of the existing chamber as an exhaust vessel. We will need to finalize the design of the vacuum chamber extension and support structure. We will also need to move the gas valves and stuffing flux coil on the west side. We've started discussions with Steve but the design isn't finalized.

- **Simulation studies (Slava):** In the near-term, Dan will be working with Slava on adding collisions to the PPC simulations. They will continue large-scale statistical studies using TeraGrid in static SSX fields (but including $E \times B$ drifts). The next steps will be to simulate the plasma gun injection process into HiFi, then to merge the particle pushing capability to the dynamical, time-dependent fields of HiFi. These simulations could help us figure out how flows, reconnection, and fluctuations heat the ions.

- **Meetings and papers:** After a busy 2010, we have a pretty light meeting agenda for 2011. Tim and I will be going to Whistler, Canada for IPELS 2011 in July 10-15. The week of March 5 is our Spring break and MB is slated to give an alumni talk about SSX in Los Angeles. We will spend the beginning of 2011 on finishing papers. Clayton has the doublet paper. Tim has the selective decay paper. MB is tinkering with the jets paper. Dan/Slava have a possible ion orbit paper.

Big picture: Flows seem to be the big physics driver in SSX. Maybe it's obvious in retrospect but we've always had large inflow/merging speeds driving reconnection and relaxation. Alex has measured 50 km/s with the calibrated Mach probe. Reconnection and relaxation generate large outflows (40 km/s) that likely play a role in ion heating. An outstanding mystery is the Z/M scaling of ion heating during merging and reconnection. This might be an SSX-specific phenomena or something more interesting. It seems that flow and ion physics will be our focus in the coming year.

We remain interested in three main topics in the reconnection/relaxation realm (1) reconnection dynamics perhaps using Beltrami states as a basis (eigenfunctions of $\nabla \times B$), (2) ion heating measurements and simulations during relaxation with ions of different mass and charge state (perhaps correlating with fluctuations... Slava's simulations will be a big help here), (3) measurements and simulations of 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