Happy New Year 2013 from SSX!

Here's a review of 2012 as well as plans for 2013. It's hard to believe, but we've been at it for nearly 20 years now (and I've been doing these summaries since 2001). Our very first vacuum and plasmas were down in the "research wing" (kind of where the chemistry building sits now). The SSX mode of operation has been the same all along: we merge high temperature, magnetized plasmas together at high velocity. Interesting stuff has always happened. We can look locally at small-scale reconnection events (a few cm), or we can study the evolution and relaxation of large-scale structures (up to a meter). Lately, we've been studying the statistical aspects of these dynamic events using the tools of fluid turbulence (fluctuation spectra like $E_B(\omega, k)$ and correlations after dynamic merging events).

For the last few years, we've kept the plasma confined in a long conducting pipe called a plasma wind tunnel. Think of it like a conventional air wind tunnel (maybe smaller than the ones they use for aircraft wings) but the merging velocity is 100 km/s (as opposed to 100 m/s, or just 220 mph used in regular wind tunnels), the temperature well over 100,000 K (instead of room temperature, 300 K), and the fluid is a MHD plasma (not just air). Our densities tend to be higher than earlier SSX configurations ($n_e \geq 10^{15}\ cm^{-3}$ for most of the shot), magnetic field higher ($0.25\,T$), and our lifetimes shorter. We have also backed off on the number of magnetic probes (now fewer than 100 in two small quartz shafts, rather than many 100's in 4 or 12 or 25 stainless steel tubes). In the machine at the moment, we have 4 sets of 48 probes (two are Alexandra's, one is Ken's, one is Tim's).

I guess the big news from 2012 is the departure of Tim Gray after about 4 years at SSX, and the recent hiring of David Schaffner from UCLA. David will be arriving in a few weeks with his wife Erin. Tim has relocated to Cleveland, OH. We wish him well! Since Tim left in August, not much has happened in the SSX lab except preparations for the APS-DPP meeting in Providence (me, Alexandra Werth '14, and Ezra Day-Roberts '13... more on that below).

The new SSX postdoc David Schaffner is just now defending his PhD thesis at UCLA. His area of expertise is experimental analysis of plasma turbulence. He recently had an important paper appear in Physical Review Letters called "Modification of Turbulent Transport with Continuous Variation of Flow Shear in the Large Plasma Device". The idea is that he is able to turn turbulence (and turbulent transport) on and off by modifying how much the azimuthal flow is sheared. Lots of shear (i.e. different layers moving a different velocities) tended to diminish the turbulence. The tools that David developed at UCLA will have an immediate impact here at SSX.

A scientific highlight of 2012 was the appearance of our "jets" paper in Physics of Plasmas, and more exciting is the likely acceptance of Tim's selective decay paper in Physical Review Letters, called "Observation of a relaxed plasma state in a quasi-infinite cylinder". Tim just responded to

some very favorable referee reports so I predict his paper will appear in early 2013. Alex and Ezra did a great job during summer 2012, including a nice measurement by Alex of the local velocity of the leading edge of our plasma plumes using her high resolution linear probe array. We will be writing our DOE renewal sometime during Spring 2013 with the help of David Schaffner and Slava Lukin. Slava has always been connected to SSX as an alum but he's been a funded collaborator the past 3 years. We're looking forward to many more years of collaboration with Slava.

We had our share of meetings in 2012. There may be more than usual in 2013-14 since I'll be on leave and David S will want to meet the plasma/astro and reconnection crowd. I went to an interesting, small workshop on "Microphysics of cosmic plasmas" in Bern, Switzerland at the International Space Science Institute (ISSI), April 16-20, 2012. I learned quite a bit about MHD shocks and turbulence. The talk Tim and I prepared went well. Tim and I went to the main magnetic reconnection workshop (called MR2012) in Princeton in May 23-25, 2012 and gave back-to-back SSX reconnection talks. Tim's was called "Turbulence, selective decay, and merging in the SSX plasma wind tunnel". MB gave a talk at MIT/PFSC in March 2012 (the same day Jan Egedal's tenure denial was announced!). Tim and I visited Delaware and Bill Matthaeus in June 2012.

There were/are two meetings that I helped plan, one connected to space physics, the other connected to fusion. One just happened Dec. 17-19, 2012 in Madison. It was a 2.5 day meeting on particle energization addressing the question how do ions/electrons get accelerated/heated in space/solar/lab plasmas? A very big meta-question but I think the meeting was pretty successful. In a shocking development, our keynote speaker, Bob Lin from UC Berkeley suddenly passed away just weeks before the meeting. We decided to dedicate the proceedings to his memory and it turned out well. Many of Bob's friends were there to remember him. We had speakers from Bob's Berkeley group on electron heating in solar flares (Krücker). We had several lab talks (Heidbrink, Yamada, Egedal, Sarff), and several computational talks (Matthaeus, Daughton, Li). Slava Lukin and Bill Matthaeus were both there (as well as Ken Flanagan for my talk). The links to all the talks and relevant papers are here: http://www.cmso.info/enerparttalks.

Another conference I'm working on now is related to the fusion energy sciences side of things. I'm chair of the program committee for EPR 2013 (Exploratory Plasma Research). This is the group of non-tokamak, non-laser fusion schemes. It includes small scale experiments (like SSX) and also plasma simulations (esp validation and verification of codes). Slava is heavily involved in this group as well. This meeting is still a month away but planning is still active. We'll be in Fort Worth, TX in Feb 2013. Here's the link: http://www.iccworkshops.org/conferences.php. I think the only SSX'ers at this meeting will be me and Slava (David will have just arrived at Swarthmore, and we're in-between student researchers).

Our big trip (as it is each year) was the APS-DPP meeting, this time in

Providence, RI in October 2012. Alexandra Werth, Ezra Day-Roberts, and I took the train up and barely beat hurricane Sandy moving up the eastern seaboard. We missed most of the devastation, power loss, flooding etc. but had to drive back to Swarthmore when Amtrak cancelled all the trains back through NYC. It was at DPP that we met and spent some time with David Schaffner. He and Erin drove down to Swarthmore for an extended visit the following week. David made a great impression on all of us. It's always fun to have a mini-SSX reunion at the Tuesday afternoon student session. We saw Vernon Chaplin, Slava, Matt Landreman, and Dave Schlossberg.

Other stuff coming up in 2013 of interest... The big task for 2013 will be to write the renewal for our DOE grant sometime this spring. Slava Lukin has been the co-I for the last 3 years, receiving some funding for his HiFi MHD/Hall simulations of SSX plasmas. For the next round, we will likely focus on turbulence studies, perhaps with a plasma accelerator to push SSX plasma plumes to over 100 km/s.

Summary of 2012:

There were several experiments in early 2012 that were interesting but didn't bear any scientific fruit (as least not immediately). One was an experiment in "grid" turbulence where we put a coarse grid (a simple copper cross that Steve built from 1/2" square stock) about 0.2 m in front of the west gun. Our plan was to see if we could drive turbulence downstream of the cross with 50 km/s flows. It turned out that our simple grid acted more like a barrier! Less than 10% of the plasma and magnetic field (so less than 1% of the magnetic energy) came out the other side. For sure, no one had ever done an experiment like that before so I'm glad we did it but it would have been hard to predict the outcome. We might try something along these lines later. Another thing we tried was to inject an SSX plasma plume into the 4 foot extension to the SSX wind tunnel. The idea there was a proof-of-principle and it worked fine (vacuum and alignment were excellent). We are able to inject plasma over 2 meters. We had hoped to begin work on our plasma acceleration system in this configuration but our NSF-DOE proposal for the project was unfunded (got the bad news in April 2012).

Axial probe array in the MHD wind tunnel (Alex/Tim): For three years now (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. We have done both single-ended flow (like a conventional wind tunnel) and merging. As mentioned above, we've demonstrated that we can push plasma down a $L = 2.5$ m extension. Preliminary results indicate that the plume maintains it's integrity with a length of about 1 meter as it moves into the extension. Steve has prepared some new flux conservers with a variety of lengths so we can pursue this more in 2013.

During the summer of 2012, Alexandra Werth designed and built 4 flexible (literally and figuratively) magnetic probe arrays (see her abstract below). Steve and Paul provided excellent technical support. We have fielded 2 of

them to study axial flow down the wind tunnel. Since Tim cleaned up some noise issues we have been able to measure fluctuating B fields from about a gauss to a Tesla (14 bits or a factor of 16,000). The key was cross-talk inside the screen room, so now we use a plastic (Delrin) patch panel for isolation. We have been running almost exclusively with a bunch of modern digitizers from DTAQ (96 total channels at 2 MHz, 14 bit, 5Vpp). 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). That's the mode we're running now.

At this point, we've launched both right-handed and left-handed plumes down the wind tunnel, and done all the merging combinations. We've measured T_e, T_i, and flow with VUV and IDS. Tim's key observation is the turbulent evolution towards a long, twisted helical state (the topic of his paper below). The process begins with broadband fluctuations with wave-numbers 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 $E_B(k,t)$).

Simulations (Ezra/Slava): The top science priority for simulations is to couple the particle orbit code (PPC) with the dynamical fields Slava creates with HiFi. That work made some headway in 2012 with Ezra's successful collision model (see his abstract below). We'll try to pick up a new simulation student for summer 2013 to continue the effort. In the meantime, Slava has some beautiful simulations of plasma flow down our 1 meter wind tunnel from 2011. Slava has been tweaking the boundary conditions and now sees a structure very similar to what we see in the experiment. He's working on a paper now. We will want to compare the simulation results with the experimental results we have in hand. Also, it will be interesting to compare fluctuation results from merging experiments in the wind tunnel to merging simulations.

Papers and manuscripts (2012): Counting the jets paper and Tim's PRL (which is all but accepted, I think), just two SSX papers to report in 2012. There are a few possible papers in the pipeline including Darren's work on double-Langmuir probe mapping of the radial density and temperature structure in the wind tunnel plumes. Slava is working on a simulation paper as well. Otherwise, the slate is clean for me, David, and Slava in 2013.

1. M. R. Brown, C. D. Cothran, T. Gray, C. Myers, E. Belova, "Spectroscopic observation of bi-directional reconnection outflows in a laboratory plasma", Physics of Plasmas **19**, 080704 (2012);

2. T. Gray, M. R. Brown, D. Dandurand, "Observation of a relaxed plasma state in a quasi-infinite cylinder", Phys. Rev. Lett (submitted, 2012).

Students: We had two excellent students during summer 2012. Both came to Providence for the APS meeting and each presented a poster.

(1) Alexandra Werth '14 took over probe development and designed four new umbilical probes. Here's her DPP abstract:

High frequency umbilical magnetic probe array for SSX wind tunnel fluctuation studies: A. Werth, T. Gray, M.R. Brown, Swarthmore College. The Swarthmore Spheromak Experiment (SSX) wind tunnel consists of a high velocity plume of magnetized plasma injected into a copper flux conserver with dimensions $L = 1\ m$ and $R = 0.08\ m$ (aspect ratio 10:1). The plasma spheromaks in this wind tunnel typically have densities on the order of $1 - 5 \times 10^{15}\ cm^{-3}$ and flow speeds of 50 km/s. In the past, fluctuations and turbulence in the SSX plasma wind tunnel during magnetic reconnection have been examined by means of two high resolution (16 positions at 0.46 cm spacing) radial magnetic probes. Results from the radial probes show high frequency magnetic fluctuations at the site of reconnection. Four more probes have been designed to help detect magnetic fluctuations and reconnection activity along the axial direction of the wind tunnel. The four new probes have 8 positions at 0.95 cm spacing and have a part bellow, part quartz exterior. The bellows act as an umbilical giving the probe excellent flexibility and versatility. The flexibility allows the probe to be bent so it lies along the axis of the flux conserver.

(2) Ezra Day-Roberts '13 worked closely with Slava Lukin to study the effects of collisions in Slava's particle orbit code (PPC). Here's his DPP abstract:

Comparison of Monte Carlo simulations with Braginskii analytic collision model: E. Day-Roberts, T. Gray, M.R. Brown, Swarthmore College, V.S. Lukin, Naval Research Laboratory. We test a Monte Carlo simulation of particle collisions based on a model by Takizuka and Abe [JCP 25, 205, (1977)]. This was included in the Hamiltonian particle pushing code (PPC) for simulating particles in the Swarthmore Spheromak eXperiment (SSX) MHD wind tunnel. The simulated dynamics, with collisions, are compared with analytical transport equations for slowing down, diffusion, and energy loss. Preliminary results show general agreement with the analytic model. The Takizuka model performs binary collisions between the test particle and a particle drawn from a stationary background Maxwellian distribution of ions. The time difference between collisions is dependent on the current plasma parameters. Realistic particle dynamics in simulated SSX wind tunnel fields will be presented if available.

Plans for 2013: Our main task for early 2013 will be to introduce David Schaffner to Swarthmore and SSX operations, and begin to focus in on turbulence studies. At some point in the Spring of 2013, we will hear the details of the DOE OFES call for renewals. At that point, Slava, David, and I will pull together a renewal for 2014-17. I suspect our emphasis will be a connection between experiment and simulation. We measure certain

fluctuation spectra, and measure certain flows/heating. Are these also seen in simulations? As far as the experiment goes, we'll stick with our high resolution magnetic probe arrays, ion Doppler spectroscopy, and He-Ne interferometry. We now have a nice suite of calibrated, fast, high-resolution magnetic probe arrays and lots of channels of digitizers. I'm looking into a telecom 1.55 μm diode laser system that could be implemented at up to four chords so that we could look for shock steepening as the plume is accelerated down the tunnel (maybe our new electronics technician Paul Jacobs can help with that). On the simulation side, our goal will be to track particle orbits in dynamical HiFi fields (Slava and Alan Glasser are working on that). Ultimately, we want to study ion heating and flows in dynamical, merging SSX simulated plasmas for different ion charge and mass. Slava already has a great wind tunnel simulation which tracks evolution from formation to final relaxed state.

- **Turbulence studies (early 2013):** The first order of business will be to reproduce our high resolution magnetic fluctuation studies with David at the helm. We'll also do some network analysis of our probe/ cable/ connector system to look for resonances. We have all the hardware in place to launch plasma down a long drift tube and have it emerge into either a vacuum expansion volume, a target plasma, or cold neutral gas. Any of those experiments could be interesting and imminently accessible to simulation with Slava's HiFi code.

- **Simulation studies (Slava):** Slava and Ezra were able wrap up the collision module of PPC in 2012. Slava and Alan Glasser are working on folding the particle orbit code (PPC) into the dynamical MHD fluid code (HiFi). This is tricky since the two codes have different demands for spatial and temporal resolution. We should be able to do direct comparisons of dynamical HiFi simulations with SSX experiments (both single-ended and merging in the wind tunnel geometry). I would really like to figure out the Z/M dependence of ion heating in SSX (best data was in the 2:1 flux conserver). It will also be interesting to follow ions in the wind tunnel geometry.

- **Meetings:** We have a full meeting agenda for 2013. First up is our EPR 2013 meeting in Fort Worth in February. Then the 12th International Workshop on the Interrelationship between Plasma Experiments in the Laboratory and in Space, IPELS 2013, will be at Hakuba Tokyu Hotel, Hakuba City, Nagano, Japan from July 1-5. Here's the link for that: http://tanuki.t.u-tokyo.ac.jp/IPELS2013/?p=1. The 2013 APS-DPP meeting is November 11-15, 2013 in Denver, Colorado.

cheers and happy new year for 2013, mb