Happy New Year 2014 from SSX!

Here's a review of 2013 as well as plans for 2014. This marks the 20th year of SSX! We arrived here in Swarthmore in summer 1994 with SSX design drawings, some start-up funds, and some orders placed. Our first plasmas weren't until summer 1995, but SSX as an entity is two decades old. Lots of changes in 2013. Postdoc David Schaffner arrived in February from UCLA with his wife Erin and he's really helped change the direction of the lab. Much less merging and much more turbulence (as I'll outline below). Since I'm on leave (leave number 5 in year 20 at Swarthmore), we've had an opportunity to travel and share our results with the plasma and space communities. David and I spent over a week in Japan for IPELS 2013, a week in SF for AGU, a week in Ft Worth for EPR, and a full week at APS-DPP in Denver in November. There were also visits to Harvard Center for Astrophysics, University of Michigan, even a webinar for CMSO.

Now it's old news, but since Jan 2010 (four years now!), we've kept the plasma confined in a long conducting pipe that we call an MHD plasma wind tunnel. SSX old-timers remember the prior mode of operation of merging two spheromak rings axisymmetrically (side-by-side) in large (0.5 m diameter) cans called flux conservers. Now we launch turbulent plumes up to 100 km/s with temperature well over 100,000 K ($T_i \cong 20\ eV, T_e \cong 10\ eV$). It's a wind tunnel where the wind is a hot MHD plasma (not air). Our densities are running higher than in earlier SSX configurations ($n_e \geq 10^{15}\ cm^{-3}$ for most of the shot), magnetic field much higher (0.5 T when we run with double the capacitor bank), and our lifetimes shorter ($\leq 100\ \mu s$). We have a very robust diagnostic suite featuring magnetics (just 48 channels at the moment, but 14 bits at 65 MHz), HeNe interferometer for density, IDS for flow and T_i, Mach probe for local flow, plus all the bank diagnostics. We have been able to measure fluctuating B fields from about a gauss to a Tesla (14 bits or a factor of 16,000).

David Schaffner has made a big impact in the lab and with the students as the third SSX postdoc. As part of the learning process, we ran SSX a lot last year and tweaked all the diagnostics. David discovered that scanning the stuffing flux (the big green magnetic coil at the gun) had the biggest effect on turbulence parameters. As a result, we have a lot of turbulence data in which many of the metrics change quite a bit. David just published a paper in PPCF (see below) and for the first time in while, we have many more in the pipeline. I'm working on a review paper that will summarize this better but there are 4 main fluctuation metrics we're looking at in the time domain and the same four in the space domain. There are correlation functions in time and space (student Adrian Wan is studying the single-time space correlation functions, see below). There are spectra in time and space, essentially Fourier transforms: $E_B(f), E_B(k)$ (David is putting together the frequency spectrum paper now using "wavelets"). There are things called increments in time and space, e.g. $\langle \mathbf{b}(\mathbf{t}) - \mathbf{b}(\mathbf{t}+\tau) \rangle$ (David has a nice letter

ready to submit on this). Finally there are things called structure functions (basically powers of increments). These have all been studied extensively in the solar wind (and in old-fashioned wind tunnels) but never in a plasma lab.

A highlight of 2013 was the appearance of Tim Gray's selective decay paper in Physical Review Letters, called "Observation of a relaxed plasma state in a quasi-infinite cylinder" in Feb 2013. It was the fluctuations during relaxation in Tim's paper that motivated the work this year. David just had his first SSX paper accepted by Plasma Physics and Controlled Fusion, called "Turbulence analysis of an experimental flux rope plasma" by Schaffner, Lukin, Wan, and Brown. We just got word of the acceptance just before New Years. As I noted above, this should be a productive year and should put us in a good position with the next round of proposals to DOE and NSF. We were successful in getting funding from DOE for 2014 but they asked for just one-year renewals. This spring 2014, we hope to get word on a solicitation for a full three-year proposal that should take us from 2015-2017.

There has been more travel in 2013 (and early 2014) than usual. Things started with the Exploratory Plasma Research meeting (used to be called Innovative Confinement Concepts or ICC) in Fort Worth, TX Feb 11-15, 2013. I was the conference organizer and I'm chair of the EPR group. SSX alum Slava Lukin was on the organizing committee. An interesting meeting featuring all the non-mainstream fusion ideas. Stellarators played a big role, as did merging experiments like C2 at TriAlpha. There were good talks on validated comparisons of simulation and experiment (one of Slava's ideas).

David was introduced to the CMSO group (that's the Center for Magnetic Self Organization, the SSX astro/space connection for about a decade) in 2013. We had a group meeting in Princeton May 13-14 and a "site visit" from NSF in Madison May 21-22. A big trip was to IPELS 2013 in Japan July 1-5. David and I spent time in Tokyo (including an extra day because of the crash at SFO), and the whole week in Hakuba for the conference. We each gave talks, Reconnection and turbulence studies in the SSX plasma wind tunnel for me, and Turbulence scaling studies on the Swarthmore Spheromak Experiment for David.

We had two short but very productive trips in October. One was a visit to the University of Michigan to give a talk (MB) on Oct. 9. There's a big space physics group there and they were very supportive of the wind tunnel turbulence experiments. It was because of that visit that I was invited to write a review article for PSST. The other was a visit to the Harvard Center for Astrophysics (CfA) for another talk (David) as part of a one-day workshop on turbulence. We made a lot of contacts with folks at Harvard and UNH. Slava Lukin also gave a talk at U Delaware (8/29) that featured productive meetings with Bill Matthaeus and Mike Shay.

Our big trip (as it is each year) was the APS-DPP meeting, this time in Denver, CO Nov. 11-15, 2013. Adrian Wan, David, and I flew out together. Adrian's poster abstract is below. His presentation won an APS student prize! David and I also did posters. There's always something of an

SSX/Swarthmore reunion at APS. We saw Ken, Matt, Vernon, Slava, Dave S, Cameron, and Mike Rosenberg (who gave an excellent invited talk on laser plasmas). Many of these folks came by Adrian's poster on Tuesday. Thanks to everyone that dropped by. I had a good chat with Cameron at a reception. We shared a taxi with Matt to the airport on the last day. It was nice to catch up with him.

David and I went to the huge American Geophysical Union meeting in San Francisco Dec. 9-13. AGU is truly mind-boggling with over 24,000 Earth and space scientists from around the world. This was a really important meeting for us and David gave an excellent talk (on the last day) in front of 70 scientists. This was our first introduction to the solar wind turbulence community. There were talks on spectra, increments, correlation functions and we did our homework... David's talk fit right in and he did an excellent job. He even handled a very technical question about the sign of the third order structure function. We hadn't computed the sign but David did have $S_B^3(\tau) = \langle(\mathbf{b}(t+\tau) - \mathbf{b}(t))^3\rangle$ to share. Equally important at AGU were the conversations at lunch, dinner, and coffee breaks with old friends like Bill Matthaeus, and lots of new friends too.

Lots of stuff coming up for 2014... Occupying my time at the moment is the renewal for the CMSO. I'm now a co-PI for the group and in charge (with Ellen Zweibel) of the particle energization piece of the proposal. I organized a CMSO workshop on the subject in Dec 2012. There was a competition with pre-proposals due back in August. We got the word that we were selected to submit a full proposal in Nov and the final full proposal (50 pages or more) is due January 27. We were the only plasma-related Center asked to submit so this is a big deal. The Center is a multi-million dollar enterprise (Swarthmore's piece is about 1% but our influence is larger than that). Cary Forest of Wisconsin is the new director. The other co-PIs are Amitava Bhattacharjee (Princeton), Fausto Cattaneo (Chicago), Ellen Zweibel (Wisconsin), and MB (Swarthmore). If successful, we'll have NSF support from 9/14 to 8/19.

David and I are going to Maryland to give a talk (David) on Jan 24, and to Iowa to give a talk (MB) on Feb 17. I'll also drive up to Hamilton College to give a colloquium there on Feb 6 (Swat alum and former visiting prof Seth Major is there). We have a CMSO General Meeting in Santa Fe March 11-13 (David) and the next EPR workshop will be in Madison Wi Aug 5-8, 2014 (MB is organizing). We're working on getting an invitation to visit UNH based on conversations at CfA. There's a big solar wind group there. I'm also giving a talk at the AAPT meeting in Villanova on March 22.

Summary of 2013:

We focused our work on the original $L = 0.86\ m, D = 0.17\ m$, L:R = 10:1 thick-wall flux conserver. As noted above, we ran SSX quite a bit in 2013 beginning with David's arrival in Feb. We ran with the umbilical probes for a while but in May (running with double caps) we burned a hole in flex 1

and had to vent the machine. David got a good introduction to the inner-workings of SSX and we ended up running with just one linear probe (Ken's) and the Mach probe (Alex Z's). David installed -10 dB pads for attenuation (and to damp a cable resonance Tim discovered). This setup has been the same since June 2013 with many days with over 60 shots (a few over 100). The data we're analyzing now is mostly just a single plume launched down the wind tunnel (i.e. no merging at all). We have lots of merging data too. Thousands of shots in the database.

Increments and Spectra (David): The big question we're asking: "Is the statistical character of MHD turbulence universal?". Conventional turbulence seems to be the same in air and water, but is the MHD turbulence in SSX the same as in the solar wind (statistically)? David found and published in PPCF that at least one statistical measure, probability distribution functions (PDFs) of increments, looks very similar in SSX as it does in the solar wind. Our spectra have some differences and some similarities: velocity and density spectra are similar to solar wind (magnetic field is steeper in SSX). The interesting thing is that the SSX "wind" can be changed with a knob and the solar wind can't. David found that the more helical SSX plumes are more intermittent, though the spectra don't change.

Radial correlation functions (Adrian/David): The other big result from 2013 is the first measurement of the turbulent radial correlation function in SSX, again with a comparison to the solar wind. That was the subject of Adrian's research this summer and a likely paper in 2014. Our correlation function has a shape that's similar to that measured in the solar wind, but what's more, we can extract the Reynolds number of the SSX turbulence from the correlation function and compare to the Reynolds number calculated by other means ($R_m = \mu_0 v L/\eta$). Of course, the SSX Reynolds number is much smaller than the solar wind Reynolds number but that's just because the dimensions of SSX are smaller.

Simulations (Slava/Jeffrey): Slava has been running several SSX MHD wind tunnel cases using his HiFi framework. He ran single plume cases (MHD and Hall) that appeared in David's PPCF paper. The spectra and increments compare favorably with the experiment. Slava also has been running several merging cases that will be useful in studies of the radial correlation function. Jeffrey was very helpful in assembling this simulation data with Slava.

Papers and manuscripts (2013): Officially just Tim's PRL and David's PPCF paper as far as peer-reviewed work in 2013, but as noted above, I think 2014 will be a big year with several papers in the pipeline. I have two review-type papers I'm working on (one for PSST, another for JPP). David is about to submit the increments paper and is well on the way towards a frequency spectrum paper. The angle of the spectrum paper will be a comparison of fluctuations along the local magnetic field vs perpendicular. We're finding more fluctuation power perpendicular to the local magnetic

field. Note that since we don't apply an external field, this mean field changes every few μs. Adrian and David are working on a spatial correlation function paper. So that's five new results well on their way to publication in 2014.

1. D. Schaffner, V. S. Lukin, A. Wan, and M. R. Brown, "Turbulence analysis of an experimental flux rope plasma" (to appear, 2014), *Plasma Physics and Controlled Fusion*, Article reference: PPCF-100012.R1

2. T. Gray, M. R. Brown, and D. Dandurand, "Observation of a Relaxed Plasma State in a Quasi-Infinite Cylinder", *Phys. Rev. Letters* **110**, 085002 (2013).

Students: We had two excellent students during summer 2013 (Adrian Wan and Jeffrey Owusu-Boateng). Adrian came to Denver for the APS meeting and presented a poster. Adrian did a fantastic job at his poster and we were all thrilled to find out that Adrian won one of five APS student presentation awards. Here's the winning abstract:

Adrian Wan '15 with David Schaffner, Jeffrey Owusu-Boateng '16, Michael Brown

Reynolds number measurement from correlation function analysis on the SSX MHD wind tunnel. Plasma turbulence and magnetic reconnection are studied at the Swarthmore Spheromak Experiment through high velocity counter-helicity spheromak merging and single-plume relaxation experiments (typical values $n \geq 10^{20}\ m^{-3}, T \geq 20\ eV, B \cong 0.1\ T$). Fluctuations in magnetic field, velocity field, density, and soft x-ray light are measured in the SSX MHD wind tunnel configuration ($L \cong 1\ m$, $r \cong 10\ cm$). Magnetic structure and fluctuations in SSX plasmas are measured with a 16 channel high-resolution probe array (4 mm spatial resolution, 30 MHz bandwidth), inserted radially at the midplane of the flux conserver. The magnetic Reynolds number of the turbulence can be estimated directly from the radial correlation function between probe channels. The correlation function $R(\mathbf{r}) = \langle \mathbf{b}(\mathbf{x})\mathbf{b}(\mathbf{x}+\mathbf{r})\rangle \cong 1 - r^2/2\lambda_T^2$ yields an estimate for the Taylor microscale λ_T, the scale at which dissipation commences.[1] The correlation scale λ_C is the size of the largest magnetic eddies. The effective magnetic Reynolds number is then $R_M = (\lambda_C/\lambda_T)^2$. Preliminary estimates of R_M measured this way show $R_M \sim 10$.

Jeffrey Owusu-Boateng '16 worked on simulations with Slava and did an excellent job with a new $H\alpha$ detector array for SSX. We hope to use the array in the plasma accelerator to track the trajectory of plasma plumes. The idea is to have a reliable, non-invasive way to detect the leading edge of the plume and it looks like this array will do the trick.

[1] Matthaeus *et al.*, PRL 2005

Plans for 2014: We have some travel plans for the beginning of 2014 (Maryland, Hamilton, Iowa, Santa Fe, maybe New Hampshire). The most important work will be to share David's new discoveries on MHD turbulence from the SSX wind tunnel (probability distribution functions of increments, spectra, correlation functions) both by giving talks and publishing papers. We also have some experimental plans involving the extension and a new camera.

- **Fast camera with extension (early 2013):** At the end of August 2013, we took delivery of a Xybion 750 fast framing camera on extended loan from PPPL. It is capable of taking a single frame at 100 ns shutter speed. Our plasmas move at about 1 cm per μs so the Xybion should freeze the motion pretty well (1 mm of blurring). We bought a large window and we plan to mount the Xybion above SSX and look down. I think this will work best using the wind tunnel extension and let the high velocity plume expand into the main SSX expansion chamber. We haven't worked out the details yet but likely we'll put a probe in the expansion volume and use one of the extended flux conservers Steve and Tim made last year. This should form the basis for new proposals to fund a plasma accelerator for the extension.

- **Simulation studies (Slava):** Slava's simulation studies have evolved away from tracking particle motion (using PPC) to doing high resolution simulations of the wind tunnel with HiFi (both resistive MHD and Hall). The current resolution is about 36 points across a radius, 54 angles, and 540 axial positions (about 2 mm). That's about a million locations within the wind tunnel volume. There are about 1000 time steps in each run (about 0.1 μs per time step). What's interesting is that we can apply the same statistical tools to Slava's simulations that David uses on the wind tunnel (spectra, correlation functions, increments). We plan to pursue those comparisons in 2014, beginning with spatial correlation functions. The long-term goal is to validate Slava's simulations with SSX experiments.

- **Meetings:** Apart from the travel noted above, there's a meeting called SHINE June 23rd- 27th, 2014 in Telluride that looks interesting (the "S" is for solar). The CMSO meeting in March in Santa Fe will be important, especially if our CMSO renewal is successful. The 2014 APS-DPP meeting is October 27-3, 2014 in New Orleans. The 2014 AGU Fall meeting will be Dec. 15-19, 2014 in SF.

cheers and happy new year for 2014, mb