Happy New Year 2012 from SSX!

Here's a review of 2011 as well as plans for 2012. For 18 years now, we've been interested in merging plasmas together at high velocity but what's new this year is that rather than letting the plasmas expand to collide in a large volume, we've kept them confined in long conducting pipe: a plasma wind tunnel. Think of it like a conventional air wind tunnel but the merging velocity is 100 km/s, the temperature well over 100,000 K, and the fluid is a MHD plasma. Our densities tend to be higher than previous configurations ($n_e \geq 10^{15}\ cm^{-3}$ for most of the shot) 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). Still lots of interesting physics! I'm constantly amazed that two tenuous plasmas don't want to interpenetrate, even if the mean free path is fairly long (10 cm). The fact that they are magnetized helps them maintain their identities and causes reconnection layers to form. Our goal in the coming year will be to see if we can develop and measure shock structures.

Tim Gray is finishing his fourth full year at SSX (as of Feb 2012), so he's an SSX veteran. Slava Lukin (NRL) is our main external collaborator now (part of a DOE grant just starting year 2). We had three students do SSX work in 2011: Ken Flanagan '12, Darren Weinhold '12, and Mike Fisher '14. We all went to the APS-DPP meeting in Salt Lake City (MB, Tim, Ken, Darren, Mike Fisher, as well as lots of SSX alums). Mike could be back next year (maybe with Slava at NRL) but Ken and Darren are graduating in May 2012.

A highlight of 2011 was our re-visiting ideas of MHD turbulence culminating in a proposal submitted to NSF. Bill Matthaeus and Slava Lukin are collaborators on that one for theory and simulation. We will likely hear the outcome of that submission spring 2012. 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.

I would say that another big highlight of 2011 was the appearance of Clayton Myers' Physics of Plasma paper on counter-helicity merging and the emergence of the doublet CT in our prior 0.6 meter long, 0.4 m diameter flux conserver. This was a paper literally in the works for 8 years. This turned out to be a beautiful paper that I think high velocity plasma mergers (Tri-Alpha, General Fusion, U Washington, LANL) will be interested in. The aspect ratio of 3:1 is similar to to the C-2 device at Tri-Alpha (they are about twice the scale of SSX, ie 0.8 m diameter plasma).

We had a pretty light travel year in 2011 (after a busy 2010). Tim Gray was invited to give a talk at the Maryland Physics Department (May 2011). Our main meeting last year was the IPELS 2011 meeting in Whistler, BC, Canada (July 2011). Tim gave an important 25 minute talk on the first day of the conference on his selective decay result ("Turbulence and selective decay in SSX"). We also went to the ICC workshop in Seattle (August 2011)

and Tim gave the SSX invited talk there. On June 23, I did a webinar as part of the CMSO series on Magnetic Relaxation in SSX. An odd experience, but I think several folks dropped in (judging from the sound over the speakers). I also did a Swarthmore alumni talk in Los Angeles in May 2011 (Kevin Setter '02 and Yuhki Tajima '99 were there). Slava gave an excellent colloquium here at Swarthmore in September 2011. MB attended the Fusion Power Associates annual meeting in DC this past December 2011. Very interesting meeting but at a manager/overview level.

Our big trip was the APS-DPP meeting in Salt Lake in November 2011. Once again, we had a mini-Swarthmore reunion at the student poster session on Tuesday. Students Ken Flanagan, Darren Weinhold, and Mike Fisher had posters in that session. Cameron Geddes dropped by, as well as Vernon Chaplin, Tim, Matt Landreman, Dave Schlossberg... thanks to everyone that gave advice and comments to the guys on their posters (and advice for grad school too). We didn't see Mike Schaffer for the first time in years (he is now retired). Matt Landreman gave an excellent invited talk based on his PhD work at MIT. Very esoteric, pure theory stuff about stellarators.

Other stuff coming up in 2012 of interest... The big task for 2012 will be to implement the SSX wind tunnel extension and see what happens to plasmas rolling a few meters down a pipe at 50 km/s. Slava's HiFi simulations will be a big part of 2012 including wind tunnel simulations and particle pushing. I've cycled off of University Fusion Association leadership and will cycle off the NRC chairmanship of the Plasma Science Committee in a few months. Meanwhile, I was elected chair of the so-called ICC's (Innovative Confinement Concepts). ICC chairmanship will take up more of my time during 2012 as we plan the next workshop.

Summary of 2011:

Things are moving along at SSX. We took delivery of a new 4 foot extension to the SSX wind tunnel. We submitted an NSF-DOE proposal in October to put accelerator coils in the extension. We're planning on wrapping up studies (merging and single ended) in the existing 1 meter device, then moving on to the longer one. We plan on doing "grid" turbulence studies by putting a coarse grid in front of one of the guns and see if we drive turbulence that way.

Slava has a lot on his plate but we're planning on adding the capability of pushing test particles to his merging simulations (including collisions and heating... hopefully in the 2:1 geometry), modeling our new plasma wind tunnel configuration (spheromak roaring down a long, evacuated tube with acceleration coils), and wind tunnel merging. If we're funded to do acceleration, Slava will provide simulation help for that too.

MHD wind tunnel and extension (Tim/Ken): 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. During summer 2011, we designed a four-foot

extension to SSX to give us over 2 meters for injected plasma plumes to flow and evolve. This was a group effort involving MB, Tim, and Steve interacting with vacuum engineers at K. Lesker Co. We just took delivery of the extension (from Lesker) in late November 2011. It looks great assembled in the lab and the plan is to mount it to SSX and pump it down in early 2012. We also submitted an NSF-DOE proposal in October 2011 to put accelerator coils in the extension and have Slava and Bill M help with some simulations and theory. Slava's HiFi simulation should help us predict efficiency of a sequence of pulsed magnetic fields to accelerate our plasma plume. Ken built a prototype coil and high voltage pulsed power supply for bench testing. He found that to really do it right, we need super-low inductance switches (spark gaps) and lots of parallel cables. We'll also likely need to work at 10 kV and low capacitance (10 μF), in order to rapidly couple a few 100 joules of kinetic energy into the MHD plume.

Before we install the extension, we plan to do some final runs in the present 1-meter, merging set-up. We have much better calibration of our high resolution probe array (4 mm spacing). Steve built a beautiful single-turn Helmholtz coil system using solid copper rings (0.16 m diameter). It's very sturdy and gives us a calibration field approaching a tesla with a fast rise time. Also Tim cleaned up some noise issues so we should be able to measure fluctuating B fields from about a gauss to a Tesla (14 bits or a factor of 16,000). Our goal will be to wrap up single injection shots, as well as counter- and co-helicity merging in the shorter, 1-meter configuration. The physics is much more complicated than in our prior 3:1 case but still likely involving reconnection, null-points, heating, and relaxation. Our plan is to look at IDS (even with new carbon sources installed) as well as magnetics and line-averaged density. We also plan on doing "grid" turbulence studies by putting a coarse grid in front of one of the guns and see if we drive turbulence that way. 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.

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. We want to do more experiments with co-helicity merging and look at very small fluctuation levels but we're nearly done with this campaign. 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 10:1 helical state with some ion orbits superimposed was the basis for our lab tee shirt design (summer 2011).

Simulations (Mike/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 is slow and ongoing in 2012. 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. 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. In particular, Tim sees characteristic fluctuations at about 2 MHz on the merging shots. If this is high frequency MHD activity, we should see it in the simulations too.

Double Langmuir probe (Darren): Darren built and operated a nice double Langmuir probe (DLP) for his summer 2011 project. We've used triple Langmuir probes in the past with some success but they need to be operated near ion saturation and that causes arcs in our high density wind tunnel geometry. The DLP needs to be scanned in voltage (a little tedious) but information can be gleaned with a few steps at small voltages (less than 20 V) to minimize arcing. We got some useful data from the DLP and are planning a short paper for 2012 (see below).

Papers and manuscripts (2011): Counting Alex's RSI (appearing in 2011 but done in 2010), just two SSX papers appeared in 2011. In addition, Tim and I are each working on papers a few years in the making. Slava has a 2011 simulation paper in the online journal Nonlinear Processes in Geophysics called "3D magnetic reconnection through a moving magnetic null". MB wrote a review of a plasma physics textbook that appeared in Physics Today in 2011.

1. C. E. Myers, E. V. Belova, M. R. Brown, T. Gray, C. D. Cothran, and M. J. Schaffer, "Three-Dimensional MHD Simulations of Counter-Helicity Spheromak Merging in the Swarthmore Spheromak Experiment", *Physics of Plasmas* **18**, 112512 (2011).

2. 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* **82**, 033510 (2011).

3. 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 generated some figures from the new HYM simulations that should really help this project along. This is MB's winter 2012 project now.

4. 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 three excellent students during summer 2011. All three came to Salt Lake for the APS meeting and each presented a poster. I think all of their work will eventually appear in print. Darren and I plan on working on a double Langmuir probe paper this spring of 2012. Ken is applying to grad schools now (several with plasma programs). Darren may end up doing plasma physics as part of a job after graduation.

(1) Ken Flanagan '12 took the lead with Tim Gray to begin analyzing SSX with an eye towards fluctuations. We have typically been interested in large spatial scale magnetic structure in SSX but Ken and Tim have begun to analyze data in Fourier space. First of all, Ken studied the fluctuation power spectra for magnetic fields and density ($E_B(\omega), E_n(\omega)$). We definitely see enhanced fluctuation activity (around ω_{ci}) when we merge in the wind tunnel rather than launch a single plume. We have also studied the spatial spectra as a function of time $E_B(k,t)$. This is how we see the plasma selectively decay to a single mode. Finally, Ken has begun to look at cross-correlations like $\langle B_i(r)B_j(r+\delta)\rangle$. Plots of cross or auto-correlation as a function of time reveal episodic emergence of highly correlated structures. This was Ken's main result presented in his APS-DPP poster: Fluctuation and turbulence studies in the SSX plasma wind tunnel.

(2) Darren Weinhold '12 built a double Langmuir probe on a moveable shaft to compliment our suite of electrostatic probes (Mach, triple, RGEA). The double Langmuir probe stalk diameter measures 6.5 mm and tip spacing is 1.1 mm. Darren's main effort was a long campaign to map out the radial profile of density and temperature for our MHD wind tunnel plasma. He took a lot of data and fit it to the $\tanh(eV/2kT)$ function. The main finding is that the density and temperature profiles are relatively flat (density slightly hollow, temperature slightly peaked on axis). Darren's APS-DPP poster was entitled: Radial Density Profile in the SSX Plasma Wind Tunnel using a Double Langmuir Probe.

(3) Mike Fisher '14 worked closely with Slava Lukin to add the effects of collisions to Slava's particle orbit code (PPC). Mike worked primarily on the binary Coulomb collision code based on the model by Takizuka and Abe. The idea is that when a collision takes place (based on a statistical algorithm), a target particle is drawn from a Maxwellian distribution with the background temperature (typically 20 eV). Collisions are done in the center-of-mass frame so high energy beam ions are eventually slowed to the background energy. Mike's code seems to work so it will become part of the PPC package. His code is described in his APS-DPP poster: Collision Models for Particle Orbit Code on SSX.

Plans for 2012: Our main task for 2012 will be to begin our studies of MHD turbulence in the extended SSX wind tunnel (as we proposed for year 2 of our renewal). On the experimental side, we'll stick with our high resolution magnetic probe arrays, ion Doppler spectroscopy, and He-Ne interferometry. 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. 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 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.

- **Extended MHD wind tunnel (early 2012):** The first order of business will be to get high resolution radial magnetic profiles to compliment older data from the long axial probe. This is happening now (early Jan 2012). Next, 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 (a cross really) of vertical and horizontal copper bars. Steve has already built this. We can compare fluctuations at the midplane between the gridded and non-gridded gun plasmas. Finally, we plan to do turbulence studies in the new 2-meter extension. If the NSF proposal is funded, we can build our four stage plasma accelerator (about $50K).

- **Simulation studies (Slava):** In early 2012, we'll wrap up the collision module of PPC. 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 and papers:** We have a pretty light meeting agenda for 2012. I have one last NRC Plasma Science Committee meeting this spring. That's been an interesting assignment. I've also been invited to a reconnection workshop in Bern, Switzerland in April 2012 (I'll likely go to that one). No IPELS or ICC this year so summer of 2012 looks pretty free. We have the 2012 US-Japan Workshop on Magnetic Reconnection (MR2010) at Princeton University from May 23 to 25 and the 2012 APS-DPP meeting is in Providence, RI in November.

cheers and happy new year for 2012, mb