# Happy New Year 2016 from SSX!

Here's the annual review from SSX for 2015 as well as plans for 2016. This has been a transitional year for SSX. SSX postdoc David Schaffner left after two-and-a-half extraordinary years here at Swarthmore to accept a tenure-track job as a professor at Bryn Mawr College (beginning Sept 2015). We are interviewing postdoc candidates now to begin as soon as possible. There are 40 in the pool from all over the world. David and I have collaborative funding from a new outfit called APRA-E (Advanced Research Projects Agency, Energy), plus some carry-over funding from DOE-OFES.

Recall that we now launch turbulent plumes up to 100 km/s with temperature well over 100,000 K ($T_i \cong 20\ eV, T_e \cong 10\ eV$). Our densities are running higher than in earlier SSX configurations ($n_e \geq 10^{15}\ cm^{-3}$ for most of the shot, with peak densities over $5 \times 10^{15}\ cm^{-3}$), magnetic field much higher (0.5 $T$ when we run with double the capacitor bank), and our lifetimes shorter ($\leq 100\ \mu s$). In the current set up, the plasma plume flows the entire 2.5 meter length of the experiment. Soon, we'll see if we can form plumes in a glass extension.

On the more applied side (funded by ARPA-E), our goal is to form a hot, dense plasma configuration that might serve as a "target" for fusion energy. The plasma plumes noted above, relax to an interesting configuration called a Taylor state (originally studied by Tim Gray). The Taylor state has about $3 \times 10^{19}$ protons, with a mass of about 50 $\mu g$, and fills a volume of about 10 liters. Those parameters correspond to a density of about $3 \times 10^{15}\ cm^{-3}$. Our plan in the coming year is to compress the Taylor state down to perhaps one liter (either by stagnation or merging), to increase the density by a factor of 10, after accelerating the plumes magnetically.

**Turbulence studies:** SSX is still a turbulence lab with growing connections to space physics. We've published (and/or submitted) **five** papers in 2015, all were on the topic of turbulence, with a particular emphasis on dissipation mechanisms in MHD turbulence. David Schaffner in just 2.5 years really made a name for himself in this field, and helped changed the direction of the lab. Our main scientific mission (funded by DOE and NSF) is the study of MHD turbulence in the MHD wind tunnel configuration of SSX. The scientific highlight for 2015 was David's invited talk at the APS-DPP meeting in Savannah (his abstract is below).

The projects of our SSX student researchers highlight the scientific direction of the lab in 2015. Holden Parks studied the correlation of density and magnetic fluctuations in SSX turbulence. Ariel Rock continued the project begun by Peter Weck, studying the permutation entropy and complexity of SSX turbulence with comparisons to both solar wind turbulence and turbulence in a conventional (air) wind tunnel. Student abstracts are reproduced below, along with more scientific discussion.

**ARPA-E ALPHA program:** The big news for 2015, and likely for the next three years, is new funding through the ARPA-E branch of DOE.

This began in Oct. 2015 and will mean a somewhat different direction for the lab for three years. ARPA stands for Advanced Research Projects Agency, and our program is called ALPHA (for Accelerating Low-cost Plasma Heating and Assembly). "Accelerating" here refers to getting these experiments done in three years (although we're planning on accelerating our plasmas too). While we remain committed to fundamental science (plasma turbulence, reconnection, MHD relaxation), the ALPHA program is a three-year, milestone-driven enterprise focused on fusion energy.

The very short story is that there is a growing movement of start-ups and small-scale fusion projects operating outside the usual Department of Energy framework. The DOE Office of Fusion Energy Sciences is a $500M per year operation that supports mostly mainline fusion projects at national labs (so-called tokamaks like ITER and DIII-D), and to a much lesser extent, projects like SSX. The ALPHA project is a $30M three-year program (also DOE but a different division) to focus on a new scheme called magneto-inertial fusion.

The idea of magneto-inertial fusion is to create a hot magnetized plasma target (think SSX spheromak), then rapidly implode it (somehow). The parameter space for magneto-inertial fusion is between conventional magnetic confinement and inertial confinement, in particular, higher densities ($n \geq 10^{16}\ cm^{-3}$). Our target is the elongated, relaxed Taylor-state structure we've been studying for years. Our scheme is to accelerate one of these objects and stagnate it in a small volume so it heats up. We will also merge two Taylor states together to form a single hot "target". It will then be up to some other group to figure out a way to compress or implode our target.

Along with the nine ALPHA "performers" (including us, folks at LANL, Washington, Caltech, Helion, etc), there are start-ups like Tri-Alpha and General Fusion that have sprung up. These were featured in a Time magazine cover article in November 2015. TAE and GF are privately funded companies in the $100M+ range. We had a very productive "kick-off" meeting for the ALPHA project in Santa Fe, NM in Oct 14-15.

**CMSO:** Funding for NSF-funded CMSO wrapped up in Oct 2015 after a very successful 10 year run.

**Technical talks and discussions:** David gave an invited technical talk at West Virginia University on April 20, 2015, as well as talk at Bryn Mawr College (now his home institution). David also gave an invited talk at AGU in San Francisco on December 18, 2015. 2015 also featured scientific visits to SSX from collaborators Slava (6/15-16), Bill Matthaeus and Sergio Servidio and the UD team on July 21, and Rob Wicks on Feb 6. MB gave a talk at Maryland Mar 10, 2015 with some technical content but it was geared towards grad student career opportunities at small colleges. We also participated in some policy workshops one on Frontiers in Plasma Science in DC 6/30-7/1, and another sponsored by UFA in Maryland Dec 14-15.

**SHINE:** David went to the SHINE meeting in Stowe, VT July 6-10. This is David's second time there so he's becoming a regular at this meeting of experts. Virtually the whole solar wind community was there.

**APS-DPP:** Our big trip (as it is each year) was the APS-DPP meeting, this time in Savannah, GA Nov. 16-20, 2015. Holden Parks, Ariel Rock, David, and I attended the meeting. The student poster abstracts are below. David gave an excellent invited talk on Monday entitled, "The End of the Turbulent Cascade?: Exploring possible signatures of MHD turbulent dissipation beyond spectra in a magnetically-dynamic laboratory plasma". We had a great celebratory dinner at a place called Circa 1875 with David, Ariel, Holden, and also Slava, our new collaborator Obi Ohia, and Chris Cooper. I gave a talk on Wednesday morning called "Accelerated Taylor plumes for MIF targets" in a special session of the ALPHA performers, with David, Ariel, and Holden as co- authors. There's always something of an SSX/Swarthmore reunion at APS. We saw Ken F, Matt L, Slava, Cameron, and Dave Schlossberg. Lots of folks visited the student posters on Tuesday. Thanks to everyone that dropped by.

## Summary of 2015:

We've been working with the $L = 2.5\ m, D = 0.17\ m$ flux conserver and extension attached to the original chamber (now called the expansion chamber) since early 2015. We ran this summer with a co-located magnetic probe and double Langmuir probe for the most part. The focus was on correlations of magnetic field and density (Holden's project) and more on complexity and entropy (Ariel's project). A lot of the data this summer was taken on a very nice 4-channel PicoScope.

**Correlations and Entropy (David/Holden/Ariel):** The core science projects from 2015 were turbulence analysis of data from the SSX wind tunnel. David and I have been thinking about how energy is dissipated in MHD turbulence. This is a particular problem in the solar wind where collisions are infrequent. The mean free path in the solar wind can be the entire Sun-Earth distance, so it's possible for a parcel of wind to have suffered no collisions by the time we see it at one AU. Even what dissipation means under such conditions is subtle. "Heating" means proton orbits get larger, and the phases of the motion are more randomized than they would be in, say, a coherent wave or reconnection structure. Something David has been studying is the role structures (like tiny reconnection sites) might play in dissipation.

Plasma physicists typically study waves by launching a single mode and measuring the frequency and wavelength that results (the so-called dispersion relation). In a turbulent plasma, there are a whole sea of waves and structures. Holden's project is to study the correlation between magnetic fluctuations and density fluctuations in SSX. If the magnetic field and density wiggle together (positive correlation coefficient), then that suggests the MHD turbulence consists of more so-called "fast waves". If the magnetic field goes up when the density goes down (negative correlation coefficient), then "slow waves", or pressure-balanced structures might be at play. No correlation suggests Alfven waves. Stay tuned as Holden works on his thesis, but we're seeing more negative correlation, especially at lower frequencies.

Ariel picked up the project begun by Peter Weck about permutation entropy and complexity. The idea here is that in turbulent signals (SSX, solar wind, even conventional wind tunnels) sometimes certain signatures can be buried in the fluctuations. Evidence of these signatures revealed by lower permutation entropy, and higher complexity, can tell us whether the turbulence is deterministic (chaotic) or if all possible signatures are equally likely, then the turbulence is truly stochastic. Ariel has done a careful comparison of fluctuations in SSX with solar wind data (from the four-spacecraft flotilla called CLUSTER) and actual air wind tunnel data (from the Corsin Wind Tunnel at Johns Hopkins). Stay tuned here as well as Ariel completes his thesis in the coming semester.

**Papers and manuscripts (2015):** Five publications in 2015, one was just submitted in Dec, some were submitted in 2014 but appeared in 2015. These are all on the new ssx-lab website.

1. D. A. Schaffner, M. R. Brown, and A. Rock, "Potential signatures of dissipation from time-series analysis techniques using a turbulent laboratory MHD plasma", (submitted to *Physics of Plasmas*, Dec. 2015).

2. D. A. Schaffner and M. R. Brown, "Multifractal and Monofractal Scaling in a Laboratory Magnetohydrodynamic Turbulence Experiment", *Astrophysical Journal*, 811:61 (2015).

3. M. R. Brown, D. A. Schaffner, and P. J. Weck, "Magnetohydrodynamic Turbulence: Observation and Experiment", *Physics of Plasmas* **22**, 055601 (2015).

4. P. Weck, D. A. Schaffner, R. Wicks, and M. R. Brown, "Permutation Entropy and Statistical Complexity Analysis of Turbulence in Laboratory Plasmas and the Solar Wind", *Phys. Rev. E* **91**, 023101 (2015).

5. M. R. Brown and D. A. Schaffner, "SSX MHD plasma wind tunnel", *J. Plasma Physics* **81**, 345810302 (2015).

**Students:** As noted above, we had two excellent students during summer 2015 (Holden Parks '16 and Ariel Rock '16). Both are honors students and both are writing theses. Both Holden and Ariel came to the annual APS-DPP meeting (in Savannah, GA for 2015). The total number of SSX alums is now over 50 (counting the two students starting this summer). It looks like the two students working this summer (2016) at SSX will be Jeremy Han '17 and Jaron Shrock '18. Here are the student APS-DPP abstracts, as well as those for David and me.

**H. Parks**, A. Rock, D. A. Schaffner, and M. R. Brown

**Correlation analysis of magnetic field and density fluctuations in SSX.**

The cross correlation and cross spectrum of magnetic field and density fluctuations of plasmas created by the Swarthmore Spheromak Experiment (SSX) MHD wind tunnel are examined. The SSX MHD wind tunnel produces dynamic magnetized plasma plumes with typical values $B \approx 0.2$ T, $n \geq 10^{21}$ m$^{-3}$, and $T_i \geq 20$ eV. Magnetic field fluctuations of these plasmas are measured with a $\dot{B}$ probe and local density fluctuations are measured with a double Langmuir probe inserted radially within 1 mm of the $\dot{B}$ probe. The axial distance of both probes from the plasma source is varied to examine plasmas of different "turbulent ages." Linearized MHD theory admits three types of waves - slow, fast, and Alfvén - each with different correlation values between magnetic field and density. By taking the Fourier transforms of $B(t)$ and $n(t)$ time series data, the cross spectrum $\widetilde{B}^*(f)\widetilde{n}(f)$ is calculated, and the correlation between magnetic field and density can be determined as a function of frequency. Preliminary results of SSX data analysis indicate a pressure balanced structure present at 100 kHz, likely in the form of a flux tube, as well as predominately positive correlations in the frequency range 100 kHz to 10 MHz.

**A. Rock**, H. Parks, D. A. Schaffner, and M. R. Brown

**Physical interpretations of permutation entropy scaling analyses of turbulent space and laboratory fluids.**

Statistical properties of various turbulent laboratory and natural (magneto)fluids are investigated using both complexity measures of ordinal pattern distribution[1] and temporal increments. The systems analyzed are solar wind $|B|$ time series from the Cluster satellites, streamwise velocity time series from the Johns Hopkins University Corsin Wind Tunnel, and $|\dot{B}|$ time series from the Swarthmore Spheromak Experiment (SSX) MHD wind tunnel. Plasma in the SSX wind tunnel has parameters $B \approx .2$T, $n \geq 10^{21}$ m$^{-3}$, and $T_i \geq 20$ eV. By comparing the permutation entropy and Jensen-Shannon complexity with the behavior of the structure functions derived from the intermittency analysis, the connections between the complexity measures and dissipation mechanisms can be determined. The Corsin Wind Tunnel velocity data is used to compare the statistical signatures of dissipation in conventional hydrofluids with that seen in magnetofluids.

M. R. Brown, D. A. Schaffner, H. L. Parks, A. B. Rock

**Accelerated Taylor plumes for MIF targets**

The SSX plasma device has been converted to a 2.5 $m$ merging plasma wind tunnel configuration. Experiments are underway to study merging and stagnation of high density, helical Taylor states to employ as a potential target for magneto-inertial fusion. Eventually, SSX Taylor states will be accelerated to over 100 $km/s$ and compressed to small volumes either by stagnation or merging. Initial un-accelerated merging studies produce peak proton densities of $5 \times 10^{15}$ $cm^{-3}$. Densities are measured with a precision quadrature He-Ne laser interferometer. Typical merged plasma parameters are $T_i = 20\ eV, T_e = 10\ eV, B = 0.4\ T$ with lifetimes of 100 $\mu s$. Results from a single prototype acceleration coil will be presented, as

[1] Rosso *et al.*, PRL **99**, 154102 (2007).

well as initial simulation studies of Taylor state plasma acceleration using multiple staged, pulsed theta-pinch coils.

D. A. Schaffner

**The End of the Turbulent Cascade?: Exploring possible signatures of MHD turbulent dissipation beyond spectra in a magnetically-dynamic laboratory plasma**

A typical signature of dissipation in conventional fluid turbulence is the steepening power spectrum of velocity fluctuations, signaling the transition from the inertial range to the dissipation range where scales become small enough for fluid viscosity effects to be dominant and convert flow energy into thermal energy. In MHD fluids, resistivity can play an analogous role to viscosity for magnetic field fluctuations, where collisional scales determine the onset of dissipation. However, turbulent plasmas can exhibit other mechanisms for converting magnetic energy into thermal energy such as through the generation of current sheets and magnetic reconnection or through coupling to kinetic scale fluctuations such as Kinetic Alfven waves or Whistler waves. In collisionless plasmas such as the solar wind, only these alternative dissipation mechanisms are likely active. Recent experiments with MHD turbulence generated in the wind-tunnel configuration of the Swarthmore Spheromak Experiment (SSX) provide an environment in which various potential non-resistive signatures of magnetic turbulent energy dissipation can be studied. SSX plasma is magnetically dynamic with no background field. Previous work has demonstrated that a steepening in the magnetic fluctuation spectrum is observed which can be roughly interpreted as a transition from inertial range to a dissipation range magnetic turbulence. The frequency range at which this steepening occurs can be correlated to the ion inertial scale of the plasma, a length which is characteristic of the size of current sheets in MHD plasmas. Detailed intermittency and structure function analysis presented here coupled with appeals to fractal scaling models support the hypothesis that the observed turbulence is being affected by a global dissipation mechanism such as the generation of current sheets. Information theory based analysis techniques using permutation entropy and statistical complexity are also applied to seek dissipation signatures.

## Plans for 2016:

- **Glass extension on SSX wind tunnel (early 2016):** We have a new glass extension to replace the stainless steel extension we had all of 2015. The idea will be to mount our plasma gun on one end and launch a plume into the expansion chamber. The new postdoc will be in charge of mounting new accelerator coils around the glass to push the plume to high velocity. We have begun to do some simulation work on this with Simon Woodruff and his associates at WSI. The simulation is important in the design, placement, and timing of the coils. Demonstration of this idea of magnetically pushing twisted plumes will be the main goal of 2016.

- **Papers:** There's at least one paper in the works, very close to submission. It's about spatial correlation functions in SSX (work originally done by Adrian Wan '15). The thesis work of Ariel and Holden looks very interesting but we're a ways from a paper.

- **ARPA-E:** The next big meeting for the ARPA project is a summit down in DC. This will be a big affair featuring all ARPA performers (not just the nine ALPHA teams), over 2000 attendees. The setting is a fancy hotel (the Gaylord National Resort) and the theme is the energy marketplace. A few fusion folk will be mixed in with researchers studying renewable energy, solar cells, the grid, biotech, etc. DOE Secretary Ernest Moniz is scheduled to speak, as well as Senator Lisa Murkowski.

- **Meetings:** The APS-DPP meeting is in San Jose, CA Oct 3–Nov 4, 2016. MB will also go to the Exploratory Plasma Research workshop in February in Auburn. I remain on the executive committee of the EPR group. We'll be organizing that program soon.

cheers and happy new year for 2016, mb