Happy New Year 2017 from SSX!

Here's the annual review from SSX for 2016 as well as plans for 2017. The big news this year is the arrival of Dr. Manjit Kaur as the new SSX postdoc as of May 2016. Manjit comes to us from the Institute for Plasma Research in India (http://www.ipr.res.in/). She has done excellent work picking up the ARPA-E project (Advanced Research Projects Agency, Energy, more below). Her focus has been on the theta pinch accelerator system (also below) and revamping our diagnostics. The ARPA project is one year old. David Schaffner is in his second year at Bryn Mawr and remains a close collaborator.

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 about 1.25 meters in a glass extension before stalling in a stagnation flux conserver (copper lined with tungsten). As of this writing, we have over 400 shots in this configuration.

Our goal in the ARPA project 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 3×10^{19} protons, with a mass of about 50 μg, and fills a volume of about 10 liters. Those parameters correspond to a density of about $3 \times 10^{15}\ cm^{-3}$. By the end of 2016 we have been able to launch the Taylor state into the stagnation flux conserver where it compresses and heats. Our goal for 2017 is to accelerate the plumes magnetically and compress down to perhaps one liter (by a driven stagnation), and to increase the density by a factor of 10.

Turbulence studies: Since Manjit arrived we've been in a building mode. Manjit and Paul Jacobs rebuilt the IDS amplifiers, and Manjit and Steve replaced the SSX gate valve. We installed the new flux conserver. We have a reconfigured Ocean Optics spectrometer, and Manjit went through the entire IDS system. We are in a position to confidently measure important dynamical quantities (B, n_e, T_i, β). On the basic science front, David Schaffner, Jason TenBarge, and I submitted an NSF-DOE proposal in October 2016. The goal of that project would be to complete the work started by Holden Parks in his senior thesis (Magnetic field and ion density correlation analysis of SSX plasma). If funded, Jason will do the modeling and David, Manjit, and I do a series of correlation experiments. We'll hear about that proposal this spring.

ARPA-E ALPHA program: The end of 2016 marks the end of year 1 of our three year ARPA-E project. This has been our primary focus in 2016. The 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.

Technical talks and discussions: Not much traveling in 2016. Manjit, David and I went to the ARPA annual review in Seattle in Aug 2016. Manjit went to Irvine to represent us at the CT workshop in August 22-24, 2016. Her talk was entitled, "Accelerated Taylor State Plumes on SSX". David and I went to our first ARPA summit in DC in Feb 2016.

APS-DPP: Our big trip (as it is each year) was the APS-DPP meeting, this time in San Jose, CA Oct 31-Nov 4, 2016. Jeremy Han, Jaron Shrock, Manjit, David, and I attended the meeting. The abstracts are below. SSX alum Cameron Geddes was named an APS Fellow, and Swarthmore physics alum Mike Rosenberg won the Rosenbluth Prize for top PhD thesis in plasma physics for 2016. Manjit and I gave talks on Monday morning called "Characterization of Taylor plumes on SSX" and "Velocity and magnetic field measurements of Taylor plumes in SSX under different boundary conditions" in a special session of the ALPHA performers. 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 2016:

We've been working with the $L = 1.0\ m, D = 0.15\ m$ glass extension attached to the original chamber (now called the expansion chamber) since early 2016. We recently added a tungsten-lined stagnation flux conserver (Cameron's original SSX small flux conserver) and a new probe array designed and built by Manjit. We ran summer 2016 with a variety of external flux conservers wrapped on the glass. We used stainless and bronze mech liners. In the end, we found the straight glass worked fine.

The next step is to pulse a large magnetic field behind the Taylor plume to give it a push. Right now, the Taylor plume flows into the stagnation flux conserver and stalls. We see a bump in the density and some heating.

Manjit and Jaron completed our 40 kV test stand using components on loan from TriAlpha Energies (TAE). TAE provided high voltage capacitors (100 kV actually), high voltage switches (called pseudo sparkgap switches), and several trigger boxes on a loan agreement. SSX provided the new theta pinch coil, a new TDK Lambda 40 kV charging supply, a new SRS DG535 timing module to provide trigger pulses, and assembly hardware (cable, trigger transformers, high voltage oil, etc). We have also developed a safe charge dump system with the help of TAE engineers. A visit from TAE engineer Ian Allfrey in October was critical to the project's success. We fired the first 40 kV test shots in October and even did a demo for our ARPA friends (Patrick, Colleen, and Ryan). The rise time is under 1 μs and peak current is 60 kA. The system is ready to install on SSX.

Taylor state thermodynamics: Our key science goal in 2016 (and in 2017) has been to generate, accelerate, and compress our twisted Taylor states. If the Taylor state behaves like an ideal gas ($PV = RT$) and we can compress adiabatically ($PV^\gamma = const$), then the temperature should increase like $PVV^{\gamma-1} = TV^{\gamma-1} = const$. The key physics issue is just what is the adiabatic constant in this case. Statistical mechanics says that $\gamma = (f+2)/f$ where is the number of degrees of freedom, If $f = 1$, then $\gamma = 3$ and $TV^2 = const$.This means compression by a factor of 10 yields a temperature increase of a factor of 100.

Papers and manuscripts (2016):

Just one publication in 2016. We've been in a rebuilding phase in 2016. All our papers are on the new ssx-lab website.

1. D. A. Schaffner, M. R. Brown, and A. B. Rock, "Potential signatures of dissipation from time-series analysis techniques using a turbulent laboratory MHD plasma", *Physics of Plasmas* **23**, 055709 (2016).

Students:

Holden Parks '16 and Ariel Rock '16 both graduated. Ariel is at Wisconsin and Holden is applying now to several graduate programs. We had two more excellent students during summer 2016 (Jeremy Han '17 and Jaron Shrock '18). We also collaborated with David's students Hayley Johnson '18 BMC, Codie Fiedler-Kawaguchi '18 BMC, Emmeline Douglas-Mann '18 BMC at Bryn Mawr College. Jeremy, Jaron, Hayley, and Cody came to tha annual APS-DPP meeting (in San Jose, CA for 2016). The total number of SSX alums is now over 50. It looks like Jaron is coming back to SSX for summer 2017. Here are the student APS-DPP abstracts, as well as those for Manjit and me.

J. E. Shrock, J. Han, M. Kaur, M. R. Brown, and D. A. Schaffner, JP10.27
Theta Pinch Coil Design for SSX.

We present the essential physics and design parameters behind a theta pinch coil used on SSX. The coil is used as an accelerator to drive flux behind a Taylor plume traveling about 30 km/sec. Operating between 25 and 40 kV on a time scale

$< 10\ \mu s$, the design focuses on minimizing the quarter cycle rise time ($\frac{\pi}{2}\sqrt{LC}$) of the coil while maintaining the necessary precautions for working at high voltage. Our design works with 1.1 and 3.3 μF capacitors and a maximum stored electrical energy of $U = \frac{1}{2}CV^2 \simeq 880\ J$ (at the lower capacitance). This electrical energy is converted into kinetic energy in the plume. Each plume has a mass greater than 30 μg, giving an initial kinetic energy of at least 14 J. At perfect efficiency, the upper bound of the plume velocity will be 240 km/sec using the lower capacitance circuit.

J. Han, J. E. Shrock, M. Kaur, M. R. Brown, and D. A. Schaffner, JP10.26
Boundary Condition Effects on Taylor States in SSX.

Three different boundary conditions are applied to the SSX 0.15 m diameter plasma wind tunnel and the resultant Taylor states* are characterized. The glass walls of the wind tunnel act as an insulating boundary condition. For the second condition, a flux conserver is wrapped around the tunnel to trap magnetic field lines inside the SSX. For the last condition, the flux conserver is segmented to add theta pinch coils, which will accelerate the plasma. We used resistive stainless steel and copper mesh for the flux conservers, which have soak times of $3\mu s$ and $250\mu s$, respectively. The goal is to increase the speed, temperature, and density of the plasma plume by adding magnetic energy into the system using the coils and compressing the plasma into small volumes by stagnation. The time of flight is measured by using a linear array of magnetic pick-up loops, which track the plasma plume's location as a function of time. The density is measured by precision quadrature He-Ne laser interferometry, and the temperature is measured by ion Doppler spectroscopy. Speed and density without the coils are 30 km/s and $10^{15}\ cm^{-3}$. We will reach a speed of 100 km/s and density of $10^{16}\ cm^{-3}$ by adding the coil. *Gray, et al, PRL **110**, 085002 (2013)

M. Kaur, M. R. Brown, J. Han, J. E. Shrock, and D. A. Schaffner, BO8.6
Velocity and magnetic field measurements of Taylor plumes in SSX under different boundary conditions

The SSX device has been modified by the addition of a 1 m long glass extension for accommodating pulsed theta pinch coils. The Taylor plumes* are launched from a magnetized plasma gun and flow to an expansion volume downstream. The time of flight (TOF) measurements of these plumes are carried out using a linear array of $\dot{B}$ probes (separated by 10 cm). TOF of the plasma plumes from one probe location to the next is determined by direct comparison of the magnetic field structures as well as by carrying out a cross-correlation analysis. With the glass boundary, the typical velocity of the Taylor plumes is found to be $\approx 25\ km/s$, accompanied by a fast plasma ($\geq 50\ km/s$) at the leading edge. Magnetic field embedded in the Taylor plumes is measured in the expansion chamber using a three-dimensional array of $\dot{B}$ probes and is found to be $\approx 700\ G$. Some flux conservation of the Taylor plumes is provided by using a resistive (soak time $\approx 3\ \mu s$) and a mesh (soak time $\approx 170\ \mu s >$ discharge time) liner around the glass tube for improving the downstream Taylor state velocity as well as the magnetic field. The results from these different boundary conditions will be presented. * Gray, et al, PRL **110**, 085002 (2013).

M. R. Brown, M. Kaur, J. Han, J. E. Shrock, and D. A. Schaffner, BO8.5
Characterization of Taylor plumes on SSX

We have added a 1 m glass extension to the SSX plasma wind tunnel device. Initial experiments have been performed to characterize velocity, density, and magnetic field of relaxed helical Taylor states* formed in the glass boundary. We are also experimenting with resistive and mesh liners to provide some flux conservation of the Taylor states. Under construction is a theta pinch coil and pulsed power supply to accelerate the fully relaxed (tilted) Taylor states. Once characterization studies are complete, one or two prototype theta pinch coils will be used to accelerate the Taylor states to over 100 km/s and compressed to small volumes by stagnation. A segmented resistive or mesh flux conserver may also be employed. Preliminary un-accelerated characterizaton studies produce peak proton densities of 10^{15} cm^{-3}. Densities are measured with a precision quadrature He-Ne laser interferometer located in an expansion volume downstream of the glass extension. Temperatures will be measured by an ion Doppler spectrometer. Stagnated plasma parameters will be $n_e \approx 10^{16}$ cm^{-3} with $T_i \geq 20$ $eV, B \geq 0.5$ T with lifetimes over 100 μs. Results from a single prototype acceleration coil will be presented. * Gray, et al, PRL **110**, 085002 (2013).

Plans for 2017:

- **Theta pinch acceleration (early 2017):** In January 2017 we have begun pushing Taylor plumes into a stagnation flux conserver. Manjit and Jaron have assembled a pulsed theta pinch coil system. We had a tremendous amount of help from TriAlpha Energy engineer Ian Allfrey. Ulitmately, we would like to have four independent modules spaced along the glass extension. The goal for 2017 will be to implement that project.

- **Papers:** Manjit is thinking about an RSI paper on the plasma accelerator system. I think there's a paper coming soon on the science of $\beta = 1$ compressed plasmas. We definitely see twisted structure and enhanced density in the stagnation flux conserver. The theta pinch accelerator should increase the compression. There's an old paper that we should pick up again (nearly ready for submission). It's about spatial correlation functions in SSX (work originally done by Adrian Wan '15).

- **ARPA-E:** The next big meeting for the ARPA project is a summit down in DC on Feb 27-28. This is 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.

- **Meetings:** The APS-DPP meeting is in Milwaukee, WI October 23-27, 2017. I'm also going to an NSF workshop in Jan 2017 to celebrate the 20th anniversary of the NSF-DOE partnership (through which we have been funded in the past). I'll be presenting Peter Weck's work on permutation entropy. There's also a nonlinear waves workshop in San Diego in March.

cheers and happy new year for 2017, mb