Happy New Year 2018 from SSX!

Here's the annual review from SSX for 2017 as well as plans for 2018. This marks the 24^{th} year of SSX. Our main effort the past two years has been on the ARPA-E funded Taylor state fusion project. Postdoc Dr. Manjit Kaur has now been here about a year and a half. Manjit has been the prime mover on the project. She has two papers accepted as of the turn of the New Year! One has appeared in PRE Rapid Communications, the other longer paper will appear in JPP (see below). I've also done a general science piece for an online publisher called Scientia (also see below).

For the past few years, we have launched turbulent plumes at up to 100 km/s with temperature well over 100,000 K ($T_i \cong 20\ eV, T_e \cong 10\ eV$), and stalled them in a small flux conserver. As we begin 2018, we are in the mode of accelerating our plumes to higher velocities using theta pinch coils. 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 approaching $10^{16}\ cm^{-3}$), magnetic field higher ($\leq 0.3\ T$), 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 2500 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 2017 we have been able to accelerate a pulse of plasma magnetically with the pinch coils. The velocities are high (greater than the Alfvén speed). The pulses could be a shock, or they could be a non-linear whistler disturbance.

ARPA-E ALPHA program: The end of 2017 marks the end of year 2 of our three year ARPA-E project. This has been our primary focus in 2017. 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 small 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 than a tokamak ($n \geq 10^{16}\ cm^{-3}$). 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.

It will then be up to some other group to figure out a way to compress or implode our target.

In 2017, we have developed a new area of study that we call magnetothermodynamics. We have been able to compress our Taylor states a bit (30%) and measure density, temperature, magnetic field, and volume. This is what you would do to measure the equation of state (EOS) of any substance ($PV = NRT$ for an ideal gas, say). We have identified an EOS that seems to fit our compression experiments. Have a look at the papers (when they appear) and the Scientia article for more details.

NSF-DOE turbulence studies: David Schaffner, Jason TenBarge (now at Princeton), and I are now funded through NSF-DOE! We got the good news in June 2017, and the funding turned on towards the end of the year. The project has the cumbersome title: "Analysis of wave mode content in fully turbulent, moderately collisional plasma through laboratory experiment and kinetic simulation", but it's about density/magnetic field field correlations in SSX and the solar wind. The goal of that project would be to complete the work started by Holden Parks and Emma Lewis in their senior theses (Magnetic field and ion density correlation analysis of SSX plasma). We are designing small Langmuir/$\dot{\mathbf{B}}$ probes that will be fielded at SSX and David's BMX device at Bryn Mawr. Jason will be doing kinetic simulations relevant to our parameters using codes called Gkeyll and Eurus. We have just been allocated 4×10^6 hours on NERSC. These experiments and simulations will be helpful for future space missions such as Parker Solar Probe to be launched summer 2018. Parker Solar Probe will be heading within 10 solar radii of the solar surface (Earth at 1 AU is 200 solar radii).

Technical talks and discussions: We did quite a bit of traveling in 2017. MB was on leave, so I was able to get away more (looks like about 10 trips last year). First, I went to a really interesting symposium hosted by Slava at NSF, celebrating the 20th anniversary of the NSF-DOE partnership (through which we have been funded in the past, and have recently garnered funds, see above). We went to the ARPA summit at the Gaylord on Feb 27-Mar 1, 2017 (Manjit, David, MB). I went to another interesting workshop on the beach in La Jolla, called Nonlinear Waves and Chaos Mar 20-24. I spoke about permutation entropy but there were excellent talks from Jason TenBarge, Cary Forest, Lynn Wilson, and Annick Pouquet. It was a good mix of lab, space, and astro talks (only about 30 people).

Manjit, David, and I went to IPELS in San Diego June 19-23, the EPR in Vancouver Aug 1-4, then to the ARPA ALPHA meeting in San Francisco Aug. 28-31 (just me and Manjit). Manjit's IPELS talk was entitled "Magnetothermodynamics: Measuring the equation of state of a MHD plasma", and was very well received. At the ALPHA meeting, we met with some private investors for the first time including a guy named Malcolm Handley from StrongAtomics.

Manjit went to the CT workshop in Yokohama, Japan (CT2017) Nov

7-9, while MB went to a 2017 JSI Workshop on Cosmic Accelerators: Understanding Nature's High-energy Particles and Radiation Nov 6-9. For that one, I revisited some earlier work on energetic particles in SSX. I learned about the Fermi bubbles (gamma ray sources above and below our galaxy), gamma ray pulsars (like Geminga), and new results from high energy observatories like HAWC and AMS. AMS is particularly amazing. It sits on the Space Station and has precisely recorded 10^{11} high energy particle events. These can be sorted by mass and charge (A and Z), and angular direction, and has a range up to 100 GeV. HAWC has a range up to 500 TeV and does TeV cosmic ray astronomy using an array of 300 Cerenkov water detectors in 7-m diameter tanks.

Finally, I just returned from a fusion workshop in Austin called "Strategic directions for US magnetic fusion research", Dec 11-15, 2017. This was a community exercise to provide input to the National Academy of Sciences NAS committee to develop a compelling strategic plan for fusion in the US, whether or not we participate in ITER. There were multiple presentations on various strategic approaches in the mornings, then we broke into discussion groups in the afternoons. I was a group leader for one of six groups. We are working on our report to be forwarded to NAS.

APS-DPP 2017: We had record attendance from Tri-Co the APS-DPP meeting, this time in Milwaukee, WI Oct. 23-27, 2017. Jaron Shrock, Emma Lewis, Luke Barbano, Manjit, and I came from SSX. Adam Light and Dan Green attended the meeting too. David Schaffner brought grad student Carlos Cartagena, and four undergrads: Hayley Johnson, Codie Fiedler-Kawaguchi, Emmeline Douglas-Mann, Leila Fahim. Slava Lukin joined us for an epic dinner for 13 at Alem Ethiopian Village. The abstracts are below. Manjit and I gave talks on Thursday morning called "Magnetothermodynamics: Measuring the equations of state in a relaxed MHD plasma for magneto-inertial fusion" and "Acceleration of Taylor plumes on SSX for magneto-inertial fusion" in a special session of the ALPHA performers. Lots of folks visited the student posters on Tuesday. Thanks to everyone that dropped by.

Summary of 2017:

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 added a tungsten-lined stagnation flux conserver (Cameron's original SSX small flux conserver) and a probe array designed and built by Manjit. In 2017, we began to pulse a large magnetic field behind the Taylor plume to give it a push.

Taylor state thermodynamics: Our key technical goal in 2017 was to generate, accelerate, and compress our twisted Taylor states. Our main result is the experimental confirmation of a candidate equation of state (see papers below). The MHD EOS does not fit our data (somewhat to our surprise) but the so-called CGL EOS (in particular, the one associated with parallel ion flow) seems to hold.

Single pinch coil acceleration studies: We spent a lot of time at the end of 2017 trying to accelerate our Taylor state with a single theta pinch coil. We tried various locations (upstream by the gun and downstream by the flux conserver). We tried various timings (waiting for full evolution vs pulsing early in the discharge), and voltages (up to 35 kV). What we see is a distinct density pulse (and associated magnetic enhancement) moving at about twice the Alfvén speed. Unfortunately, we don't see a bodily acceleration of the entire Taylor state structure. This pulse could be an MHD shock, or it could be a whistler disturbance. We will be doing more analysis in 2018.

Papers and manuscripts (2017): As noted above, Manjit published a short letter (just appeared in PRE) and a longer JPP paper.

1. M. Kaur, L. J. Barbano, E. M. Suen-Lewis, J. E. Shrock, A. D. Light, M. R. Brown, and D. A. Schaffner, "Measuring equations of state in a relaxed MHD plasma", *Physical Review E* **97**, 011202 (2018).

2. M. Kaur, L. J. Barbano, E. M. Suen-Lewis, J. E. Shrock, A. D. Light, D. A. Schaffner, M. R. Brown, S. Woodruff, and T. Meyer, "Magnetothermodynamics: Measurements of thermodynamic properties in a relaxed magnetohydrodynamic plasma", *Journal of Plasma Physics* (to appear 2018).

Scientia piece for general audiences: This was a non-peer-reviewed piece but with excellent editorial assistance and beautiful graphics. There's a nice picture with Manjit, David, Jaron, and Jeremy too. I think we explained pretty clearly where the ARPA project fits into the whole fusion enterprise. This should be required reading for all SSX students. The article is available in the Scientia digital library in both HTML and pdf format, please see the links below, as well as the hypertext within the article.
HTML: http://www.scientia.global/professor-michael-brown-literal-sun-jars-shrinking-stars-energy-production/
PDF: http://www.scientia.global/wp-content/uploads/2017/11/Mike-Brown.pdf
And here is the DOI for citing the article: https://doi.org/10.26320/SCIENTIA57

Students: We had all seniors this year at SSX, and all will be graduating in May. Each could be doing plasma physics in the future. Jaron and Emma have several applications in to various plasma places. Emily Hudson (SSX alum graduated last year) is also applying to plasma schools. Luke is looking for internships (one is possible at GA). Recent SSX alums are settling into grad programs around the US (Peter at JHU, Holden at CMU, Ariel at UW). We also collaborated again with some of David's excellent students Hayley Johnson '18 BMC, Codie Fiedler-Kawaguchi '18 BMC, Emmeline Douglas-Mann '18 BMC, Leila Fahim '18 BMC, and Carlos Cartagena (graduate student) all at Bryn Mawr College. The total number of SSX alums is now close to 60. We will be adding two more during the summer of 2018. Here are the student APS-DPP abstracts, as well as those for Manjit and me.

J. E. Shrock, E. M. Suen-Lewis, L. J. Barbano, M. Kaur, D. A. Schaffner, and M. R. Brown, JP11.37

Compression of an Accelerated Taylor State in SSX.

In the Swarthmore Spheromak Experiment (SSX), compact toroidal plasmas are launched from a plasma gun and evolve into minimum energy twisted Taylor states. The plumes initially have a velocity 40 km/s, density $0.4 \times 10^{16} cm^{-3}$, and proton temperature 20 eV. After formation, the plumes are accelerated by pulsed pinch coils with rise times less than 1 μs and currents I_{peak} on the order of 10^4 A. The accelerated Taylor States are abruptly stagnated in a copper flux conserver, and over the course of ≤ 10 μs, adiabatic compression is observed. The magnetothermodynamics of this compression do not appear to be dictated by the MHD equation of state $d/dt(P/n^{\gamma}) = 0$. Rather, the compression appears to evolve according to the Chew-Goldberger-Low (CGL) double adiabatic model. CGL theory presents two equations of state, one corresponding with particle motion perpendicular to magnetic field in a plasma, the other to particle motion parallel to the field. We observe Taylor state compression most in agreement with the parallel equation of state.

E. M. Suen-Lewis, L. J. Barbano, J. E. Shrock, M. Kaur, D. A. Schaffner, and M. R. Brown, JP11.40

Precision Electron Density Measurements in the SSX MHD Wind Tunnel.

We characterize fluctuations of the line averaged electron density of Taylor states produced by the magnetized coaxial plasma gun of the SSX device using a 632.8 nm HeNe laser interferometer. The analysis method uses the electron density dependence of the refractive index of the plasma to determine the electron density of the Taylor states. Typical magnetic field and density values in the SSX device approach about $B = 0.3T$ and $n = 0.4 \times 10^{16} cm^{-3}$. Analysis is improved from previous density measurement methods by developing a post-processing method to remove relative phase error between interferometer outputs and to account for approximately linear phase drift due to low-frequency mechanical vibrations of the interferometer. Precision density measurements coupled with local measurements of the magnetic field will allow us to characterize the wave composition of SSX plasma via density vs. magnetic field correlation analysis, and compare the wave composition of SSX plasma with that of the solar wind *. Preliminary results indicate that density and magnetic field appear negatively correlated. * G. G Howes et al., *The Astrophysical Journal Letters*, vol. 753, July 2012.

L. J. Barbano, E. M. Suen-Lewis, J. E. Shrock, M. Kaur, D. A. Schaffner, and M. R. Brown, JP11.44

Characterizing the volume of a compressed Taylor state object in the SSX plasma.

A cookbook of numerical techniques (namely wavelet transforms, smoothing filters, and spline interpolations) is applied to characterize the length of a stagnating Taylor state object in SSX. This length analysis uses magnetic field data from a linear array of 20 evenly spaced 2-D B-dot probes positioned along the compression can axis. A 3-D animation of the Taylor state object's magnetic field in the compression volume reveals the object's wavelet-like magnetic structure in space. In order to localize the object in space and characterize its length, a continuous wavelet transform is performed. The most dominant spatial frequency given by the resulting frequency-space spectrogram is taken to be the length of the object in the compression volume. This analysis is performed at every time in the B-dot time series to give some measure of the Taylor state object's length as a function of time. This length, in conjunction with the cross-sectional area of the compression can, gives the object's volume. Information about the object's volume as a function of time allows us to identify instances of compressive heating and investigate the magnetothermodynamic (MTD) properties of the SSX plasma.

M. Kaur, L. J. Barbano, E. M. Suen-Lewis, J. E. Shrock, A. D. Light, D. A. Schaffner, and M. R. Brown, TO7.6

Magnetothermodynamics: Measuring the equations of state in a relaxed MHD plasma for magneto-inertial fusion

The estimation of the equations of state (isothermal or adiabatic) for any set-up is necessary to envisage its behavior as the theoretical models and numerical simulations rely on them. In this talk, we will present compression experiments in which we generate parcels of magnetized, relaxed plasma (called Taylor states*) and compress them in a closed volume. We call these experiments magnetothermodynamics. The compressed plasma parameters are measured in a compression volume and a PV diagram is produced which shows ion heating during plasma compression. The magnetohydrodynamic and the double adiabatic (i.e., Chew, Goldberger and Low) equations of state are tested under several experimental conditions. The results from these experiments show that the parallel component of double adiabatic equation of state fit our data best. The compression of this magnetized, relaxed plasma is being investigated as an eventual target for magneto-inertial fusion reactors. * Gray, et al, PRL **110**, 085002 (2013).

M. R. Brown, M. Kaur, J. E. Shrock, E. M. Suen-Lewis, L. J. Barbano, S. Nambiar, D. A. Schaffner, TO7.7

Acceleration of Taylor plumes on SSX for magneto-inertial fusion.

We have added two pinch coils to the glass extension of the SSX plasma wind tunnel device in order to accelerate Taylor plumes to over 100 km/s. We have characterized velocity (40 km/s), density (0.4×10^{16} cm^{-3}), proton temperature (20 eV), and magnetic field (0.2 T) of relaxed, unaccelerated helical Taylor states*. Our goal is to accelerate the Taylor states to over 100 km/s and compress to small volumes by stagnation. Compression by a factor of ten to increase both density and temperature will put the Taylor state in a suitable parameter regime as a magneto-inertial fusion target. One prototype pinch coil operates at 1 kJ ($1.3\ \mu F, 40\ kV$) and the other operates at 2 kJ ($3\ \mu F, 40\ kV$). Both have quarter-cycle rise times of less than 1 μs. Results from both prototype units will be presented. * Gray, et al, PRL **110**, 085002 (2013).

Plans for 2018:

- **Dual theta pinch acceleration (early 2018):** In January 2018 we have begun the setup for a sequential pinch experiment. We have tested two pinch coils, the 1– and 2–kJ units discussed in the abstracts above. Our plan is to fire one module upstream and the second further downstream from the gun.

- **Paper 3:** We are working on what we call paper 3 on our single pinch acceleration results. As I mentioned above, we observe a rapid burst of plasma (and associated magnetic field) but not a bodily acceleration of the entire structure, and also no ion heating. If it's an MHD shock, we'd expect the Rankine-Hugoniot jump conditions to apply. In particular, the normal component of $\mathbf{B}$ shouldn't change across the shock (it does for us). It could be a whistler disturbance (which would explain the super-Alfvénic velocity) but we need to carefully compare the pulse velocity to the whistler group velocity.

- **Paper 4:** I have in mind working with a student (and Adam) on a particle orbit code for our Taylor state equilibrium. This is a near-certain publication if we can get the code to work. The idea is that we know the magnetic structure of the Taylor state is robust, but we don't know how good a magnetic bottle it is for ions and electrons. Confined orbits and so-called flux surfaces are well-known in tokamaks, stellarators, spheromaks, and FRCs but no one knows what ions do in a Taylor state. We have some experience with this (Slava was involved). We also have some experience calculating the equilibrium magnetic fields (Tim and Dan D were involved).

- **New NSF-DOE project:** As noted above, we were pleased to hear that our NSF-DOE proposal to study correlations between density and magnetic field fluctuations in our turbulent MHD wind tunnel was funded for 2018-20. This is a collaboration with David Schaffner at Bryn Mawr and Jason TenBarge at Princeton. Our plan for 2018 is to do identical experiments on SSX and BMX supported by kinetic simulations done by Jason.

- **ARPA-E:** The next big meeting for the ARPA project is our final summit down in DC on March 13-15, 2018. We have been to the previous two. 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.

- **Theses and plasma seminar:** Associated with the curriculum/honors, we have two students doing theses this spring: Jaron and Emma. That makes 20 SSX theses so far. Jaron's (currently entitled "Thesis") will be about the acceleration and compression of our Taylor states, and will have a decidedly fusion feel. His thesis will be part of his honors prep for May 2018. Emma's (currently entitled "Non-perturbative electron density measurements and density-magnetic field correlations of Taylor states under compression") will be about her non-invasive measurements of density fluctuations on SSX correlated with magnetic field fluctuations. Our plan is to do some associated experiments at the "Big Red Ball" BRB at UW Madison (see below). Also, Adam Light will be offering a plasma seminar in the spring and many of the Tri-Co plasma group will be taking it and/or sitting in. Manjit and I will be there, along with about 15 others (including Luke, Emma, Jaron, Sahir, Hayley from BMC). Associated with the plasma seminar, we will be showing the excellent fusion film "Let there be light" here on campus in the spring.

- **Research on shared facilities:** I am looking to do some research on machines other than SSX. Emma and I have an opportunity to do some n/B correlation experiments on the BRB in Madison with Cary Forest. We have a mini-proposal already submitted. In addition, we're looking at an opportunity to bring a very nice facility from UW Seattle to nearby UMBC (about 1.5 hours away). The machine is called MoCHI and is a large spherical version of SSX, built by Sett You. Prof. Carlos Romeo-Talamás would be in charge of the experiment at UMBC. I would be a co-I.

- **Science meetings:** The APS-DPP meeting is in Portland, OR, November 5-9, 2018. There are not many formal science meetings scheduled during 2018 (no IPELS or EPR or CT planned). Perhaps we will go to SHINE in Florida July 30-Aug 3, 2018. I will be going to more meetings about community governance. I'm involved in leadership for DPP GPAP (the astro-plasma community) as well as APS DPP leadership. More on this in 2018.

cheers and happy new year for 2018, mb