Happy New Year 2020 from SSX!

Here's the annual review from SSX for 2019 as well as plans for 2020. We have passed the 25^{th} anniversary of SSX (we started in 1994), and even had a nice 25^{th} anniversary event at the Inn for 12 faculty members that have been at the College since then (thanks to Sarah and Val for attending!). We are also now well over 60 students trained at SSX. Dr. Manjit Kaur left SSX in May 2019 for TAE Technologies in CA, and our ARPA-E grant terminated in October 2019. I am now APS-DPP vice-chair, so I'm working on the DPP meeting in Memphis for November 9-13, 2020. Turns out I'm writing a Math Methods book based on the old P50 and the new P17 that many former students took here at Swarthmore. Prof. Tristan Smith is a co-author. I'm teaching math methods again in the Spring 2020, so I'll be beta-testing it there. I'm also teaching stat mech and intro electrodynamics (P8) so I'll be busy.

Our main effort the past three years has been on the ARPA-E funded Taylor state fusion project. We have now written 8 papers on the project (see below). Our project for summer 2019 was to merge two Taylor states. Katie Gelber, Mati Mebratu, and I submitted a paper about this at the end of the year.

For the past several years now, 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. In 2019, we set up a new experiment to study the merger of two Taylor states at high velocity. Our goal was to study the merged object and reconnection at high density ($n_e \cong 10^{16}\ cm^{-3}$), with a strong magnetic field ($\sim 0.4\ T$). The idea of the ARPA project has been to form a hot, dense plasma configuration that might serve as a "target" for fusion energy. Our merged state could be an interesting configuration. These experiments also give us an opportunity to study reconnection in a new regime: high density, high β (near unity), and with significant turbulence. Our earlier reconnection work (with Chris and Tim) was very quiescent by comparison.

ARPA-E ALPHA and BETHE programs: The end of 2019 marks the end of our ARPA-E project. The short story is that there has been 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 $400M 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 was a $30M three-year program (also DOE but a different division) to focus on a new scheme called magneto-inertial fusion. There is a new program called BETHE (Breakthroughs Enabling THermonuclear-fusion Energy). SSX is a very small part of a proposal by Sett You, founder of a company called HelicitySpace. That proposal will be submitted January 2020.

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 a decade (since January 2010). Our scheme for the past three years was to accelerate one of these objects and stagnate it in a small volume so it heats up. In summer 2019 we started to stagnate two high-velocity Taylor states against each other with promising results.

NSF-DOE turbulence studies: David Schaffner, Jason TenBarge (now at Princeton), and I have been funded by NSF-DOE since the end of 2017 (over two years now). The project is called: "Analysis of wave mode content in fully turbulent, moderately collisional plasma through laboratory experiment and kinetic simulation". It's about density/magnetic field field correlations in SSX and the solar wind. We are designing small Langmuir/$\dot{\mathbf{B}}$ probes that have been fielded at SSX and David's BMX device at Bryn Mawr. Jason has done kinetic simulations relevant to our parameters using codes called Gkeyll and Eurus. We have been allocated 4×10^6 hours on NERSC. These experiments and simulations will be helpful for future space missions such as Parker Solar Probe launched summer 2018. PSP has now made three passes with perihelia at 30 solar radii (Earth at 1 AU is 200 solar radii away). Perihelion #4 will be on January 29, 2020. Ultimately PSP will get to 10 solar radii.

XSEDE simulations with Dedalus: Big news is that we had a successful proposal to run magnetohydrodynamic (MHD) and particle simulations of the SSX plasma experiment at Swarthmore College using the Pittsburgh Supercomputing Center (PSC) Bridges Regular Memory machine, and implementing the Dedalus computing environment (http://dedalus-project.org). Our research allocation on PSC/ Bridges was for 500,000 core-hours (SUs), and 5000 GB storage units. Mati has done a great job getting some initial results using about 100,000 SU's so far.

Technical talks and discussions: I went to SHINE in Boulder in August 5-9, 2019 (met with Adam Light and Tobin Munsat), and an excellent NSF-sponsored workshop on Basic Plasma Science User Facilities in May 20-21 at UMd (Bill M was there). We had a very successful plasma astrophysics summer school here at Swarthmore sponsored by NSF and APS-DPP GPAP. About 30 students attended from all over the US (mostly astronomy grad and undergrad students), and stayed in Parrish dorm rooms.

APS-DPP 2019: APS-DPP was in Fort Lauderdale, FL, October 21-25, 2019. We brought the whole SSX team (see abstracts below): Katie Gelber, Lucas Dyke, and Mati Mebratu. We had a great dinner with the SSX group, Adam Light (Colorado College), Carlos Cartagena (Bryn Mawr), and David's group: Leah Baker, Maise Shepard, Cat Slanski, Fariha Tamboli. It was great to see SSX alums too. On a related note, we're back in touch with Tim Gray (now at NASA) about possible summer internship opportunities at NASA Glenn in Cleveland.

Summary of 2019: We can merge Taylor states with the same helicity (twist), or with opposite helicity, and with precise delays. It turns out that we have to run **many** shots since the merging fields from the left object and the right object can have any orientation at the midplane. The most conducive orientation for magnetic reconnection is anti-aligned, but we have little control over the rotation angle at the midplane. In addition, we have found that, even with identical initial conditions, Taylor state flow speeds can vary up to $\pm 10\ km/s = \pm 1\ cm/\mu s$, so with a 20 μs time-of-flight, merging can occur as much as 20 cm off the midplane. We have opened a 15 cm gap and have installed a 2D array of magnetic probes at the midplane (built by Manjit), using a special new flange for the 2D array. We have also put our HeNe interferometer and IDS system at the midplane.

We used the 4×4 magnetic probe array at the midplane to measure magnetic field structure. The probe resolution is coarse; 3.8 cm separation radially, and 3.7 cm separation axially. Vector $\mathbf{B}$ is measured at the 16 locations at a cadence of up to 65 MHz. The probe array was calibrated with a pulsed Helmholtz coil and tested with pulsed line currents. Data from the 2D probe array indicates whether magnetic reconnection on a given shot is likely or not. Unlike prior experiments, we have little control over the eventual orientation of the magnetic flux at the midplane in the present experiment.

We studied 2D magnetic field movies for over 120 selected shots and found evidence of magnetic field reversal and reconnection in most of them. Non-axisymmetric merging of Taylor states is significantly more complex than has been observed in typical axisymmetric reconnection experiments conducted at SSX. Reconnection can occur anywhere on our 4×4 array, indeed reconnection could occur somewhere other than where we measure. The two plasmas merge at the midplane, indicated by a large peak in line-averaged midplane density of up to $8 \times 10^{15}\ cm^{-3}$. This is followed after a significant heating delay by a peak proton temperature of $T_p = 75\ eV$. We plan to continue these studies in 2020.

Papers and manuscripts (2018-20): There are a total of eight papers in the ARPA-E era of SSX. All either appeared or were submitted in

2018.

1. M. R. Brown, K. D. Gelber, M. Mebratu, "Taylor state merging at SSX: experiment and simulation", *Plasma*, to appear 2020.

2. M. R. Brown and M. Kaur, "Magnetothermodynamics in SSX: Measuring the Equations of State of a Compressible Magnetized Plasma", *Fusion Science and Technology*, **75:4**, 275-282, DOI: 10.1080/15361055.2019.1579622 (2019).

3. M. Kaur, A. D. Light, and M. R. Brown, "Magnetothermodynamics: An experimental study of the equations of state applicable to a magnetized plasma", *Physics of Plasmas* **26**, 052506 (2019).

4. M. Kaur and M. R. Brown, "Propagation of a non-linear wave packet driven in a relaxed magnetohydrodynamic plasma", *Journal of Plasma Physics*, **84**, 1 (2018).

5. M. Kaur, K. D. Gelber, A. D. Light, and M. R. Brown, "Temperature and Lifetime Measurements in the SSX Wind Tunnel", *Plasma* **1**, 229 (2018).

6. 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).

7. 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* **84**, 905840114 (2018).

8. M. R. Brown, "Literal Sun Jars: Shrinking Stars for Energy Production", *Scientia*, doi.org/10.26320/SCIENTIA57 (2017)

Students: Our excellent cohort of summer undergraduate researchers ran experiments with me for summer 2019 and each presented a poster at the APS-DPP meeting in October in Fort Lauderdale, FL (abstracts below). Posters were also used for our senior comps (Katie, Lucas, Nick). The student cohort was Katie Gelber '20 who worked on magnetics and density measurements for a second summer. She ran the HeNe interferometer, and the 2D magnetic probe array. Matiwos Mebratu '21 has been working on learning the MHD simulation Dedalus, and ran merging simulations on the supercomputer Bridges at the University of Pittsburgh. Lucas Dyke '20 performed particle confinement calculations based on work started by Hari and Adam.

We have a new cohort for summer 2020 pretty much lined up. Ercong (Tony) Luo '21 will be taking over the Dedalus simulations from Mati. Miriam Moore '22 and Shouzhuo (Gary) Yang '23 will be taking over the experimental duties in SSX, with some assistance from Katie.

Plans for 2020:

- **Taylor state merging and reconnection:** We will continue studies with the Taylor state merging configuration with the new SSX team. I think first, we will re-calibrate our 4×4 $r - z$ array of vector $\mathbf{B}$ at the midplane (48 channels). We want to be sure of what we measure. Once re-calibrated, Mariam and Gary will help take and analyze merging data.

- **Paddle probe materials studies:** We are starting a project with Prof. Ben Maruca at U Delaware to study the properties of different coatings on electrostatic probe electrodes (gold, graphene, copper). Rhys Manley '20 did a great job building the prototype for a Fall 2019 research project. We will do some preliminary studies on SSX (in the He glow) and hopefully fly a diagnostic on the International Space Station. The ISS supports small projects like this, and our goal is to identify coatings that will survive well in space and have good (ie low) photoemission and secondary emission properties.

- **XSEDE Dedalus MHD studies:** Mati did a great job with preliminary simulation results in 2019 that we will continue in 2020. The key point is that the SSX normalized magnetic diffusivity $\eta = 0.001$ (ie magnetic Reynolds number $R_m = 1000$), is well within the capabilities of a full 3D MHD simulation. The first model we implemented with Nick Anderson was a MHD simulation of the general evolution of the SSX plasma, from formation through turbulent evolution and relaxation to a final structure. Mati has some good results of Taylor state merging. Fluctuations of magnetic fields necessarily generate electric fields that can accelerate and heat charged particles, so at some point we want to study proton heating. We will also continue to study the statistics of charged particle (proton) orbits in static SSX magnetic fields with Adam Light's help at Colorado College. Ultimately, we hope to merge these studies into a comprehensive model with evolving magnetic and electric fields, and associated proton acceleration and heating during merging.

- **Correlation studies:** We have done perhaps 1000 shots focusing on correlations of fluctuations of density and magnetic field. We've tried a few different probes, separated by a few mm. We have good results from a tantalum double Langmuir probe about 5 mm from a small magnetic probe. We calculated $C_{nB} = \langle \tilde{n}\tilde{B_{\|}}\rangle / \langle \tilde{n}\rangle\langle \tilde{B_{\|}}\rangle$ for short epochs ($1-5\ \mu s$) and found periods of strong negative correlation $C_{nB} \approx -1$ during the turbulent phase of the discharge (around 50 μs). This is part of a paper in progress.

- **Particle orbits:** We had very good success working with Lucas and Adam on a particle orbit code for our Taylor state equilibrium. The idea is that we know the magnetic structure of the Taylor state is robust, but we're beginning to understand 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 has done this in a Taylor state. Hari ran $2\pi \times 10^5$ protons in static Taylor state fields Adam generated with PSI-TET. Lucas continued this work in 2019. We are working on a paper about this too.

- **NSF-DOE project:** We are in year 3 of support under the NSF-DOE partnership with a grant entitled "Collaborative Research: Analysis of wave mode content in fully turbulent, moderately collisional plasma through laboratory experiment and kinetic simulation" (DE-SC0017909), with MB, David Schaffner, and Jason TenBarge PIs (Swarthmore, Bryn Mawr, Princeton). This project aims to explore and understand the turbulent characteristics of hot, magnetically-dynamic, moderately collisional laboratory plasma generated by a plasma gun launched into a flux-conserving plasma wind tunnel. Experiments of this nature will be conducted on SSX and a new experiment at Bryn Mawr College (BMX). These measurements will then be compared to kinetic simulations of the experiments using Gkeyll and Eurus developed at the University of Maryland and University of Iowa, respectively, and performed at Princeton University.

- **Science meetings:** The APS-DPP meeting is November 9-13, 2020 in Memphis, TN. This is "my" meeting as DPP Program Chair. The very interesting SHINE conference is in Honolulu, HI in July 13-17, 2020. It would be great to go, but will be expensive. There will be a lot of discussion of the Parker Solar Probe results there. Perihelion #5 will be June 7, 2020.

cheers and happy new year for 2020, mb

APS-DPP student abstracts
2019 meeting, Fort Lauderdale, FL
Student Session, Tuesday, Oct. 22, 2019

Abstract: JP10.00012 : Taylor State Merging Experiments at SSX*

Kaitlin Gelber, Adam Light, Michael Brown (Swarthmore College)

We are studying magnetic reconnection that occurs with the high-velocity (40 km/s) merging of two Taylor state plasmas in SSX. We are using the merging configuration previously used by Gray, *et al* ($L = 0.86\ m, R = 0.17\ m$). We record the ion temperature with ion Doppler spectroscopy, and electron density with a Helium-Neon interferometer. Magnetic field vectors $\mathbf{B}$(t) are measured with a 2D probe array at the mid-plane. We time the Taylor states so that both arrive at the center of the probe array within a microsecond. We have examined both co-helicity and counter-helicity merging of the Taylor states. Preliminary results show an increase in the magnetic field strength and electron density at the mid-plane, followed by an increase in ion temperature. We find the density to be $\geq 0.5 \times 10^{16}\ cm^{-3}$ proton temperature $\geq 20\ eV$, and magnetic field 0.3 T of relaxed helical Taylor states.

Gray *et. al.*, Phys. Rev. Lett. 110, 085002 (2013).

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Abstract: JP10.00013 : MHD simulation of Taylor state merging at SSX*

Matiwos Mebratu, Michael Brown, Adam Light (Swarthmore College)

We present results of a resistive MHD simulation of the evolution and merging of two Taylor state plasmas. The simulation models merging experiments at SSX, where we have characterized the magnetic structure, velocity (40 km/s), density ($0.5 \times 10^{16}\ cm^{-3}$), proton temperature (20 eV), and magnetic field (0.4 T) of relaxed helical Taylor states (see K. Gelber, *et al*, this session). We simulated the merging of both co- and counter-helicity Taylor states. We are using the Dedalus framework, and run simulations on the Bridges Supercomputer. Dedalus solves differential equations using spectral methods, written with a Python wrapper in an open-source, MPI-parallelized environment (http://dedalus-project.org/). Simulations are run on a rectangular grid ($N \times M \times P = 28 \times 24 \times 180$). Initially we have a $2 \times 2 \times 10$ rectangular box with two spheromaks and dense plasma regions at each end and low density regions in the middle. Perturbation is added to the structure of the spheromaks to break axisymmetry. At the boundaries we have free slip and perfectly conducting walls. The code has been verified by solving the Hartmann problem (vertical magnetic field, uniform pressure gradient) on a rectangular grid of same size with no-slip and perfectly conducting boundary conditions.

*Work supported by DOE ARPA-E ALPHA, XSEDE, and NSF-DOE programs.

Abstract: JP10.00014 : Proton Orbit Calculations in Relaxed Taylor States at SSX*

Lucas Dyke, Adam Light, Michael Brown (Swarthmore College) Christopher Hansen (University of Washington)

We aim to analyze the dynamical properties of plasma particles within the cylindrical, helical “Taylor state” magnetic field structure. We also wish to study the potential confinement properties of the Taylor state to assess if it is a viable fusion energy configuration. We simulate the motions of particles in the Taylor state through of a total of $2\pi \times 10^5$ orbits of particles with a set distribution of initial positions and velocities. The field structure itself is calculated by first solving the eigenvalue equation $\nabla \times B = \lambda B$ using the program PSI-Tet. Then, the Boris algorithm is implemented to solve the equations of motion for the particle orbits. The results of the simulation show that the majority of escaped particles escape either at the ends of the Taylor state or at points along the surface of the cylinder containing the state that have a weak field. In addition, we found that the particles that remain confined within the state for an extended period of time exhibit general trends for the distribution both radially and along the z-axis. The data also shows that particles initialized with greater initial velocities were generally more likely to escape the Taylor state, and approximately 55% of particles stayed confined.

*Work supported by DOE ARPA-E ALPHA, and NSF-DOE programs.