Happy New Year 2019 from SSX!

Here's the annual review from SSX for 2018 as well as plans for 2019. This marks the 25^{th} year of SSX (we started in 1994), and I'm anticipating a lot of changes this year. Manjit is wrapping up her 3^{rd} year as SSX postdoc, and our ARPA-E grant will be wrapping up too. I was just elected to the DPP chair succession, so I'll be busy with that the next four years. I've cycled off being chair of the department, so I'm back to teaching. I'm doing an Energy seminar, stat mech seminar (P114), and intro E&M (P8) in the spring, so I'll be busy with that.

Our main effort the past three years has been on the ARPA-E funded Taylor state fusion project. We have now written 6 papers on the project (see below). We have a small extension from ARPA to continue the work into summer 2019. Our plan is to resurrect plasma merging and reconnection, this time with two Taylor states.

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

ARPA-E ALPHA program: The end of 2018 marks the end of year 3 of our three year 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.

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 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. Our next step in 2019 will be to stagnate two high-velocity Taylor states against each other.

NSF-DOE turbulence studies: David Schaffner, Jason TenBarge (now at Princeton), and I have been funded by NSF-DOE since the end of 2017 (about a year 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 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 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. Parker Solar Probe is heading within 10 solar radii of the solar surface (Earth at 1 AU is 200 solar radii away). We just missed seeing the launch of PSP in Florida at SHINE.

XSEDE simulations with Dedalus: We are about to submit a 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 request on PSC/ Bridges is for 800,000 core-hours (SUs), and 5000 GB storage units.

Technical talks and discussions: I gave talks at at Bates College April 5, and Carleton on May 2, 2018. Paul Bellan had his 70^{th} Bellanniversary in Pasadena on Mar 16, that I spoke at and helped organize. We also went to SHINE in Florida July 30, and to TOFE in Florida Nov 11. Manjit gave a talk at the CT workshop just before the DPP meeting in Portland.

APS-DPP 2018: APS-DPP was in Portland, OR November 5-9, 2018. Manjit gave an invited talk on the Friday morning that went very well, and was well attended. Her talk was entitled, "Magnetothermodynamics: An experimental study of the equations of state applicable to a magnetized plasma". It was great to see all the SSX alums. Cameron Geddes and I had a very nice dinner together. Matt Landreman, Dave Schlossberg, Vernon Chaplin, Ken Flanigan, Emma Lewis, and Slava Lukin were all there.

Summary of 2018: We've been working with the $L = 1.5\ m, D = 0.16\ m$ extension attached to the original chamber (now called the expansion chamber) since early 2018. Inside is a copper flux conserver with a copper end-cap at the far end. We tried a tungsten-coated version over the summer of 2018, but switched to a solid copper one in fall 2018. We performed compression studies near the end-cap, and turbulence studies upstream near the gun. The quartz extension has been removed in early 2018. For these studies, the cylinder is operated at $120^o\ C$ (a thermocouple is mounted inside). We find that a hot plasma-facing surface tends to reduce accumulation of cold gas, which is very difficult to model. The volume is bounded by a highly conducting copper shell ($r = 0.08\ m$, thickness 3 mm), which can be easily modeled as a perfectly conducting boundary.

The main results are that we continue to study compression due to stagnation at the far end of the flux conserver. This was the topic of Manjit's invited talk at DPP. The work of Emma Lewis and Katie Gelber have made the HeNe interferometer a very accurate, very stable diagnostic. We also wrote up the results of our studies of non-linear waves using the pinch coils in the quartz chamber (see below).

Papers and manuscripts (2018-19): There are a total of six papers in the ARPA-E era of SSX. All either appeared or were submitted in 2018.

1. M. R. Brown and M. Kaur, "Magnetothermodynamics in SSX: Measuring the Equations of State of a Compressible Magnetized Plasma", *Journal of Fusion Energy*, (to appear 2019).

2. 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*, (to appear 2019).

3. 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).

4. 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).

5. 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).

6. 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).

Pieces for general audiences: One was a non-peer-reviewed piece in Scientia with excellent editorial assistance and beautiful graphics. 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

I also wrote a piece in APS News for GPAP.
HTML: https://www.aps.org/publications/apsnews/201807/gpap.cfm

Students: We had all younger students this year at SSX (first and second-years). All could be back in future summers. Nick Anderson '20 and

Hari Srinivasulu '21 worked on simulations. Nick ran MHD simulations with Dedalus on PSC Bridges using XSEDE. Hari ran particle orbit simulations also on Bridges with our own code. Katie Gelber '20 and Kat Lima '20 worked in the lab. Katie was instrumental in setting up and running the VUV spectrometer to measure T_e. The total number of SSX alums is now over 60. We will be adding two or three more during the summer of 2019, including Matiwos Mebratu '21 who will help with the simulations.

Plans for 2019:

- **Taylor state merging and reconnection (early 2019):** As noted above, we are in the process of converting back to the 2010 Taylor state merging configuration. This time, we will open more space at the midplane for the merging, perhaps 15 cm. We are designing a new 2D magnetic probe array to map reconnection structures. It looks like it will be a 4×4 $r - z$ array of vector $\mathbf{B}$ at the midplane (48 channels).

- **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. At the moment, we have a tantalum double Langmuir probe about 5 mm from a small magnetic probe. We calculate $C_{nB} = \langle \tilde{n}\tilde{B}_{\|} \rangle / \langle \tilde{n} \rangle \langle \tilde{B}_{\|} \rangle$ for short epochs ($1 - 5$ μs) and find periods of strong negative correlation $C_{nB} \approx -1$ during the turbulent phase of the discharge (around 50 μs).

- **Particle orbits:** We had very good success working with Hari 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. A paper is being prepared for submission in 2019.

- **NSF-DOE project:** We are in year 2 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 two different plasma machines: the Swarthmore Spheromak Experiment (SSX) and a new experiment in development 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.

- **XSEDE proposal:** The SSX experiment exhibits a wide variety of fundamental plasma physics phenomena that can be directly modeled by large-scale simulations. 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. On the other hand, realistic simulations of a galactic jet, solar corona, solar wind, or even a large scale plasma device such as a tokamak are beyond the state of the art with $R_m = 10^6 - 10^{12}$. The first model we wish to implement is a MHD simulation of the general evolution of the SSX plasma, from formation through turbulent evolution and relaxation to a final structure. Fluctuations of magnetic fields necessarily generate electric fields that can accelerate and heat charged particles, but our next step will be to study the statistics of charged particle (proton) orbits in static SSX magnetic fields. Ultimately, we plan to merge these two studies into a comprehensive model with evolving magnetic and electric fields, and associated proton acceleration and heating.

- **MHD summer school at Swarthmore:** We are working on a GPAP-sponsored plasma astrophysics summer school for summer 2019. The inaugural session will be held at Swarthmore College the week of June 17, 2019. Confirmed instructors include Prof. Matt Kunz (Princeton), Dr. Jason TenBarge (Princeton University), Prof. Kris Klein (Arizona), Jimmy Juno (University of Maryland), and Prof. Mike Brown (Swarthmore). There will be a nominal enrollment fee, and students will stay in Swarthmore College dorms. Interested students and post-docs must be or become members of GPAP. The format will include morning lectures, followed by small group work sessions in the afternoons. Preference will be given to astrophysics students and post-docs not trained in plasma physics. Enrollment will be limited to 20 persons.

  The topics will include fundamental plasma physics appropriate for astrophysical contexts, and plasma astrophysics topics such as MHD waves and turbulence, magnetic reconnection, the magneto-rotational instability, and the dynamo problem. PDF notes will be provided.

- **Science meetings:** The APS-DPP meeting is October 21-25, 2019 in Fort Lauderdale, FL. The meeting I'll be organizing is November 9-13, 2020 in Memphis, TN. We will likely go to SHINE in Boulder, CO August 5-9, 2019. IPELS 2019 will be in Tokyo, September 2-6, 2019 which will be difficult to attend because of classes.

cheers and happy new year for 2019, mb