Happy New Year 2021 from SSX!

Here's the annual review from SSX for 2020 as well as plans for 2021. This has been an interesting year for SSX to say the least. COVID has affected us all. Classes went remote at Swat in Spring 2020, and continue now in Spring 2021 (only juniors and seniors on campus). SSX has been shut down since March 2020, and effectively since Summer 2019 when we last took data. The 2020 cohort of SSX students Ercong (Tony) Luo '21, Miriam (Miriam) Moore '22, and Shouzhuo (Gary) Yang '23 had an all-computational summer 2020 using the Dedalus platform with the assistance of Mati Mebratu '21, Carlos Cartegena, Adam Light, and Jeff Oishi (Bates).

My sabbatical year begins May 2021 and extends to September 2022. My current plan is to collaborate with Sett You at HelicitySpace (https://www.helicityspace.com/). He will be building a device similar to SSX to create twisted ropes of plasma that I call Taylor states (Sett calls them "plectonemes"). I may relocate to the Bay Area at HelicitySpace headquarters to help with construction. Depending on what happens with COVID, I would like to resurrect SSX during summer 2021 with a new student cohort.

In 2020, I organized the first all-remote meeting of the APS Division of Plasma Physics (DPP 2020) as DPP chair. Some of the technical logistics were challenging, but DPP 2020 had over 2200 registrants making it the largest DPP meeting in history. Tony, Miriam, and Gary all did remote posters.

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 either stalled them or merged them. 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 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 with a fusion Lawson product $nT\tau \cong 10^{22} \cdot 0.1 \cdot 10^{-5} = 10^{16}\ m^{-3} keV s$. 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. 2020 was all about simulating the merging process, understanding proton orbits in the Taylor state, as well as in the reconnection region.

Summary of 2020:

XSEDE simulations with Dedalus: The 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 600,000 core-hours (SUs), and 5000 GB storage units. The idea of the proposal was to begin a small college consortium of computational plasma physics involving Swarthmore, Bryn Mawr, and Colorado Colleges. Our plan is to grow the consortium in 2021.

APS-DPP 2020: DPP 2020 was all-remote during the week of November 9-13, 2020. The whole SSX team participated (see abstracts below): Tony Luo, Miriam Moore, Gary Yang, as well as David Schaffner, Carlos Cartegena, and SSX alums.

Publication: We had one paper appear in 2020:

- M. R. Brown, K. D. Gelber, M. Mebratu, "Taylor state merging at SSX: experiment and simulation", *Plasma*, 3(1), 27-37, doi.org/ 10.3390/ plasma3010004, (2020).

Students: Our excellent cohort of summer undergraduate researchers did simulations and participated in DPP 2020 remotely. Ercong (Tony) Luo '21 took over the Dedalus simulations from Mati focussing on magnetic reconnection at the midplane. Miriam Moore '22 took over the proton orbit project and has begun to identify the structure of twisted sheets of confinement in Taylor states. Shouzhuo (Gary) Yang '23 started a project studying particle orbits in a model reconnection geometry called a Harris sheet.

Plans for 2021:

XSEDE Dedalus MHD studies: Mati did a great job with preliminary simulation results in 2019 that we have continued since. 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.

Tony and Carlos now have 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.

Particle orbits: We had very good success working with 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 protons 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. Miriam and Gary have taken over this project. We are working on a paper about this too.

Science meetings: The APS-DPP meeting is November 8-12, 2021 in Pittsburgh, PA. I will preside over that as DPP Chair. The first Parker Solar Probe meeting (Parker One) will be held June 14-18, 2021 at Johns Hopkins in Baltimore. The excellent solar wind meeting called SHINE will be August 2-6, 2021 in Honolulu, HI. Either could be remote, COVID notwithstanding. The AGU Fall meeting is scheduled for December 13-17, 2021 in New Orleans.

cheers and happy new year for 2021, mb

APS-DPP student abstracts
2020 remote meeting
Student Session, Tuesday, November 10, 2020

Abstract: JP13.00045: Particle Confinement Structures in Relaxed Taylor States*

Miriam Moore, M. R. Brown (Swarthmore College), A. D. Light (Colorado College)

We study the orbits of particles confined in a relaxed Taylor state plasma. We seek to characterize the surfaces along which these particles move, which are significantly less studied than those in axisymmetric field configurations. We simulate motion for particles with many varying initial conditions of position and velocity, then characterize the surfaces upon which their orbits lie. We evaluate the magnetic field by solving the eigenvalue equation $\nabla \times B = \lambda B$ with the PSI-Tet program. We then simulate particle motion by using the Boris algorithm to solve the Lorentz force law equation of motion. The Boris code has been verified by simulating particle orbits in axisymmetric configurations with known paths (wire, dipole, spheromak).

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

Abstract: JP13.00046 : Studying the Relaxation and Merging of Taylor State Plasma with the Dedalus Computational Framework*

Ercong Luo, Michael Brown (Swarthmore College)

Here we present magnetohydrodynamic (MHD) simulations of three different plasma configurations using the Dedalus project as the computational framework of choice. First, we demonstrate the validity of our computational approach by presenting simulations of Hartmann flow, a well-known problem in MHD with analytical solutions. Secondly we will show a simulation of the evolution of a Taylor state plasma in a cylindrical flux conserver. Lastly we will show the time evolution of a system with two merging Taylor states. Magnetic reconnection has been observed at the Swarthmore Spheromak Experiment (SSX) for the last configuration. The goal of our simulations is to present both the effectiveness and limitations of using MHD numerical simulations to study plasma configurations that involve magnetic reconnection.

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

Abstract: JP13.00047 : Particle Tracing and Confinement Analysis in the Harris Sheet*

Shouzhuo Yang, Michael Brown (Swarthmore College), Adam Light (Colorado College)

We are interested in plasma particle properties in the Harris Sheet geometry, which is a good approximation for the interface of merging two relaxed Taylor states in SSX. We then seek to characterize the confinement properties of the Harris Sheet. We first use the Boris Algorithm to solve for the motion of the particle due to static electric and magnetic fields, and verify the calculation using an axisymmetric spheromak configuration. After generating $\sim 10^5$ protons with 10^2 velocities drawn from the Maxwellian distribution and applying Boris Algorithm, we find particles generally gain energy as they sample the sheet electric field, and a small fraction of the particles stay confined.

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

New Year's message from DPP Chair

Happy New Year to DPP members! I hope that 2021 brings you joy in your life and success in your endeavors.

My vision for DPP in 2021 is threefold. First, I want to embrace the breadth of our science as laid out in our decadal study Plasma 2020. Fascinating plasma science is being studied by physicists, engineers, physicians, and astronomers. I would like to continue to invite these scientists to present at our meetings, and publish in our journals. Second, we need to begin to unify the disparate scientific groups studying plasmas. Whether we study the solar wind, fusion plasmas, or high energy density plasma, it's all the same science. We can learn from each other.

Finally, and most importantly, we need to recognize that plasma science can't grow unless we expand the diversity of our field. Of our 2500 members, fewer than 10% are women; the lowest of any unit in APS. I encourage senior DPP leaders to support young women and under-represented groups to study plasma science.

These ideas were discussed during DPP 2020 at the Wednesday Banquet event: Breadth and Unification of the Field of Plasma Science Town Hall. I would encourage members to view that recorded event on the DPP 2020 platform.

Happy New Year!