Happy New Year 2022 from SSX!

Here's the annual review from SSX for 2021, as well as plans for 2022. This is year 28 for SSX, and there are now nearly 70 SSX alums spread across the world. Progress in 2021 has been slow, but even though COVID continues to affect us all, we were able to pump down and run SSX for the first time since Summer 2019. We ran with summer students Kya Butterfield, and Alberto Felix. David Schaffner was able to drop in and help us. We got some good preliminary results of Taylor state merging. Our plan is to do detailed comparisons of our Dedalus simulation with experiments. Dedalus is being run by Shouzhuo (Gary) Yang '23 and Carlos Cartegena at Bryn Mawr. Alberto Feliz will begin to help with Dedalus in 2022.

Some big milestones from 2021 include a large allocation from NSF XSEDE to support our simulation efforts, and year one of a three-year effort to build a mirror machine at Wisconsin called WHAM. These are discussed below.

My sabbatical year began May 2021 and extends to September 2022. My main effort has been on the WHAM project, as well as maintaining operation of SSX. I also am collaborating 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"). Sett and I are writing a small proposal to DOE under the INFUSE program to support HelicitySpace by doing experiments here at SSX.

As chair of the APS Division of Plasma Physics, I helped organize our annual meeting in Pittsburgh. We again set a new record for participation at a DPP meeting with over 2300 registrants (we had 2200 in 2020). I also served on FESAC for 2021.

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, compressed 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 $nT\tau \cong 10^{22} \cdot 0.1 \cdot 10^{-5} = 10^{16}\ m^{-3}keVs$. 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. 2021 was all about studying the merging process, understanding proton orbits in the Taylor state, as well as in the reconnection region.

Summary of 2021:

WHAM: I am collaborating with Cary Forest on a new project at Wisconsin called WHAM. WHAM is an axisymmetric, super-conducting magnetic mirror machine being built at the University of Wisconsin. The superconducting mirror magnets (manufactured by Commonwealth Fusion Systems, CFS) will operate at 17 T (2 $kADC$, 3 MJ each), while the two central cell magnets (copper, from W7-A in Germany) will operate at 0.8 T. The field at the end wall is 0.05 T. First plasma for phase-I will be June 2022.

The mirror ratio for phase-II will be $R_m = 17/0.8 \cong 20$. ECH will heat electrons at the 4 T layer (110 GHz) at 1 MW. NBI will provide sloshing ions at 25 keV and 2 MW. Fast wave ion acceleration will be at the 2^{nd} harmonic of D at 2 T (26 MHz) at 1 MW. The central cell plasma will have $R = 0.08\, m, n_e = 3 \times 10^{19}\ m^{-3}, T_e = 1.3\ keV, \langle E_i \rangle = 20\ keV, \beta = 0.4$. Plasma length is about $L = 1$ meter, mirror-to-mirror length is 2 meters (350 *ton* attractive force), and overall machine length is about 5 meters. Plasma volume is about 20 liters (same as SSX). The throat has $r = 0.0275$ m (about an inch). Pulse length will be about 20 ms.

XSEDE simulations with Dedalus: Exciting news is that we secured a large allocation to run magnetohydrodynamic (MHD) and particle simulations of the SSX plasma experiment at Swarthmore College. We will be using the Pittsburgh Supercomputing Center (PSC) Bridges-2 Regular Memory machine, and implementing the Dedalus computing environment (http://dedalus-project.org). Our research allocation on PSC Bridges-2 Regular Memory (Bridges-2) is 2.2M Core-hours (!), with storage PSC Bridges-2 Storage (Ocean) is 10 TB. We have now begun a small college consortium of computational plasma physics involving Swarthmore, Bryn Mawr, Colorado, and Bates Colleges.

APS-DPP 2021: DPP 2021 was a hybrid meeting for the week of November 8-12, 2021 in Pittsburgh, PA. Kya Butterfield '24 and Gary Yang '23 presented in person in Pittsburgh. The meeting had about 900 participants in person, and another 1400 remote. Through APS GPAP, we hosted another MHD summer school at Swarthmore June 7-11, 2021.

Publications: We have started a draft of our paper comparing Dedalus simulation results with experimental results.

Students: We had another excellent cohort in 2021. Kya Butterfield '24 was in the lab, and Shouzhuo (Gary) Yang '23 ran Dedalus simulations. Alberto Felix Bojorquez '21 helped us with analysis in the Fall of 2021 before the meeting. I have been engaging a younger team recently with the hope of training and maintaining expertise for several summers. It looks like for summer 2022, we will have Kya Butterfield again, with Ayla Cimen '24 helping in the lab. Alex Skeldon '25 will be taking over the simulation project.

Plans for 2022:

WHAM: I will be spending more time in Madison once WHAM is under vacuum. My interest and expertise is with magnetic fluctuations at the edge of WHAM, with an eye towards taming interchange and ballooning instabilities. Perhaps a Swarthmore student could help in Summer 2022.

SSX Taylor states: SSX is back in good shape for runs in 2022. Kya rebuilt and calibrated the 4×4 magnetic probe array (see abstract below), and understands the HeNe interferometer well. We need to have reliable magnetics, IDS, and HeNe on every shot. Having visible spectroscopy and VUV spectroscopy would be helpful too. We need good merging statistics for our paper comparing experiment with simulation. If Sett and I are able to secure funding from DOE INFUSE, we will be able to upgrade our data acquisition, and maybe our IDS system.

XSEDE Dedalus MHD studies: Gary and Carlos were able to do a big production run at the end of 2021. 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. With the 2.2 M CPU hours from XSEDE, we are in a position to do about 10 big production runs in 2022. We would like to tweak parameters to be as close to the experiment as possible.

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. Adam is working on a paper on this.

Science meetings: The 64th Annual Meeting of the APS Division of Plasma Physics with be during the week of October 17-21, 2022, in Spokane, WA. SHINE will be June 26 to July 1, 2022 in Honolulu, HI. The Second Annual Parker Solar Probe Conference, will be 21-24 June 2022 in Washington, DC. There is a magnetic reconnection meeting planned May 16-20, 2022, in Monterey, California. Of course, these meetings may or may not be in person.

Best wishes, and Happy New Year for 2022, mb

APS-DPP student abstracts
Pittsburgh, PA
Student Session, Tuesday, November 9, 2021

Abstract: JP11.00120: Taylor State Merging Studies: Experiment

Kya M. Butterfield, Alberto Felix, M. R. Brown (Swarthmore College)

We present the results of a series of experiments that investigate the dynamical merging of large aspect-ratio plasmas in the Swarthmore Spheromak Experiment (SSX) device. In SSX, two plasmas evolve and collide within a copper flux conserver with an aspect ratio of $\ell/R \cong 10$. Plasmas twist into relaxed Taylor states, with typical velocity 40 km/s, density $n_e = 0.5\times10^{16}\ cm^{-3}$, proton temperature $T_i \approx 10\ eV$, and magnetic field $B \approx 0.4\ T$. As the plasmas collide, measurements of interest are line-averaged plasma density, fluid-scale vector B-field (distance between probes $\sim 32\ \rho_i$), and plasma temperature, acquired via Helium-Neon interferometry, a 2D 4×4 grid array of B-dot probes, and Ion-Doppler Spectroscopy (IDS) respectively. We compare measured data to Dedalus-framework simulations (see S. Yang *et al.* this session). We merge Taylor State configurations of both co- and counter-helicity (either with the same or opposite directions of twist). We observe appreciable ion heating, consistent with magnetic reconnection. Finally, we discuss the suitability of merged Taylor states for use as Magneto-Inertial Fusion (MIF) targets.

Abstract: JP11.00121: Taylor State Merging Studies: Simulation

Shouzhuo Yang, Michael Brown (Swarthmore College)

We present the results of a resistive Magnetohydrodynamic (MHD) simulation of the evolution and merging of two Taylor state plasmas. We write our simulation program in the Dedalus framework, a module that solves differential equations with spectral methods (http://dedalus-project.org/). The computation is performed with the Pittsburgh Supercomputer Center. The simulation models merging experiments at the Swarthmore Spheromak Experiment (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. We compare data generated through the simulation and the experimental data collected at SSX using 16 magnetic probes (see K. Butterfield *et al.* this session). Quantities of interest are the line averaged plasma density, vector B-field, and plasma temperature. We simulated the merging of both co- and counter-helicity Taylor states. Simulations are run on a rectangular grid ($(N_x, N_y, N_z) = (72, 72, 540)$). We initialize our configuration with a $2 \times 2 \times 10$ rectangular box using two spheromaks with perturbation and dense plasma regions at each end and low-density regions in the middle. We impose free slip and perfectly conducting boundary conditions.

Abstract: TP11.00067: Physics considerations in design of the Wisconsin HTS Axisymmetric Mirror

A new magnetic mirror (WHAM) is under construction at UW-Madison with the primary mission of achieving MHD- and kinetically- stable plasmas in a low-collisionality regime, where the particle confinement increases rapidly with average ion energy. Several factors of the design benefit from expertise, experience and experimental data through collaboration with the GDT team at Budker Institute. The vessel diameter and pumping scheme (in both central and expander regions) are chosen to allow low-neutral pressure operation and minimize charge exchange losses of fast ions. Axisymmetric MHD stability is achieved via biasing end rings with respect to a central limiter (the vortex confinement scheme) and will allow modest plasmas in initial experiments, and electron temperature approaching 1 keV following the boost of the central magnetic field in the second experimental phase. Electrical and geometrical design of the electrodes follow development of similar systems in the GDT device. Scenarios have been developed for fast ion deposition via neutral beam injection and electron cyclotron resonant startup in the strong field device.