Happy New Year 2003 from SSX-FRC!

I just had a look at the e-mail I sent one year ago. We had a very successful 2001 but 2002 may have been better! It's interesting to look back to see how far we've come (check out last year's new years message, plus the monthly updates, esp April and May). We have successfully switched the machine over to SSX-FRC this year. Our scientific focus has switched from local structure of 3D reconnection to global structures resulting from reconnection and merging. In 2001, we discovered the local 3D magnetic structure of reconnection (on the tee shirts!). In 2002, we discovered the global structure of the doublet compact torus or CT (kind of two spheromaks with opposite toroidal fields on the ends and a poloidal-field-only field reversed configuration or FRC in the middle).

We've been fully merging spheromaks with equal and opposite helicities (left and right handed) so that we create a null helicity object (like an FRC but we call it a doublet CT). We always find that there is residual toroidal flux at the ends (again in nearly equal but opposite amounts). We have some results with mis-matched helicities (ie one side with a little more left handed or a little more right handed so that the final object has net helicity). Eventually, all of our objects wobble and tilt but there has been some indication that the objects with nearly null helicity live a little longer. Certainly, the straight spheromaks (all left handed or all right handed) tilt violently and completely in an Alfvén time. We have some nice data from Matt's high resolution 3D probe that shows rapid tilting of objects with finite residual twist (ie non-zero helicity) and only very slow tilting if the field lines are very straight (nearly null helicity). It's important from a fusion standpoint that these objects remain stable, straight, and coaxial. We often run with a background magnetic field at the midplane (called the RCC field). The RCC field should be stabilizing (experimentally, it seems to only have a small effect). We have some evidence of flow (from Abram's Mach probe, see below) which should also be stabilizing.

The structure of the residual toroidal field is poorly resolved in z (and only at 4 locations in θ at the moment). Radially, the toroidal field looks like a spheromak. In fact, our doublet CT objects seem to be spheromak-like on the ends (finite toroidal field, magnetic axis at $2.4048/3.8317 = 0.62R$... ratio of Bessel function zeros) and FRC-like in the middle (no toroidal field, high β, magnetic axis out at $R/\sqrt{2} = 0.71R$).

Papers and manuscripts (2002): Several manuscripts completed in 2001 appeared in 2002 or are about to appear in 2003. Our energetic particle paper originally submitted to Science (remember that?) has been published in Astrophysical Journal Letters. Chris' 3D structure paper originally submitted to Physical Review Letters will now appear in Geophysical Research Letters. Also, my Physics of Plasma paper appeared as expected in May 2002.

This year, Matt submitted and had accepted by Review of Scientific Instruments a manuscript called "Rapid Multiplexed Data Acquisition: Application to Three-dimensional Magnetic Field Measurements in a Turbulent Laboratory Plasma". Chris submitted a Physics of Plasmas paper based on his APS-DPP invited talk.

Chris will be the point person coordinating experimental publications in 2003. It behooves Chris more than any of us to establish a strong publication record as he moves on to the next level. Next up will be more papers on 3D reconnection (with Bill Matthaeus and Matt) and 3D measurements of doublet CT equilibria (with Mike Schaffer, Andrew and Abram)... maybe gun physics (with Simon Woodruff at SSPX). Slava's also working on a paper on density and temperature from spectroscopy (based on his thesis from several years ago).

1. M. Landreman, C. D. Cothran, M. R. Brown, M. Kostora, and J. T. Slough, "Rapid Multiplexed Data Acquisition: Application to Three-dimensional Magnetic Field Measurements in a Turbulent Laboratory Plasma", *Review of Scientific Instruments* (to appear 2003).

2. C. D. Cothran, A. Falk, A. Fefferman, M. Landreman, M. R. Brown, and M. J. Schaffer, "Partial and complete spheromak merging at SSX: 3D studies of reconnection and FRC formation", *Physics of Plasmas* (submitted 11/02).

3. M. R. Brown, C. D. Cothran, M. Landreman, D. Schlossberg, and W. H. Matthaeus, "Observation of Energetic Ions Accelerated by Three-dimensional Magnetic Reconnection Activity", *Astrophysical Journal Letters* **577**, L63 (2002).

4. C. D. Cothran, M. Landreman, W. H. Matthaeus, and M. R. Brown, "Three Dimensional Structure of Magnetic Reconnection in a Laboratory Plasma", *Geophysical Research Letters* (to appear 2003).

5. M. R. Brown, C. D. Cothran, M. Landreman, D. Schlossberg, W. H. Matthaeus, G. Qin, V. S. Lukin, and T. Gray, "Energetic Particles from Three-dimensional Magnetic Reconnection Events in SSX", *Phys. Plasmas* **9**, 2007 (2002).

Students: Our students have been extremely successful this past year. I think they are the highlight of 2002. Each one has had excellent experimental results to appear in a senior thesis (due March 2003). Each did a great job at the student poster session at the American Physical Society Division of Plasma Physics (APS-DPP) meeting in November 2002.

Abram Falk's thesis will be on dynamics (heating and flow measurements) from spheromak merging. His APS-DPP poster was entitled "Experimental observation of dynamical energy flow in SSX". Abram was a finalist for the Rhodes and is waiting to hear about several other fellowships. He's applied to several grad schools for the fall (including Berkeley, Columbia, and Cornell which have strong plasma programs). His four channel SXR array continues to give nice data and his analysis is getting more sophisticated. Each element of the array has a different thin (0.1 μm) metal foil in front which acts as a filter. Initial analysis involves fitting the four energy channels to a bremsstrahlung model to extract temperature. More sophisticated analysis includes the effects of line radiation from impurity ions. It turns out adding 1% of C or O has an effect but at modest temperatures (20-30 eV), lines in the 10-100 eV range "burn out" so that (counter intuitively) you get the simple bremsstrahlung picture back. Abram is also in charge of the 6-sided Mach probe diagnostic which is also yielding results. It has a simple interpretation involving ratios of upstream to downstream ion current (due to Hudis and Litsky) and a more sophisticated one involving pre-sheaths (due to a recent paper by Hutchinson).

Andrew Fefferman's thesis will be on three dimensional equilibrium studies on SSX-FRC. His APS-DPP poster was entitled "Experimental observation of an FRC in SSX-FRC". Andrew has applications in for several grad schools focusing on the west coast (Caltech and UCLA have strong plasma programs). Andrew's work has focused on a large array of magnetic probes. Each probe consists of 24 pickup coils (which Andrew designed, constructed, and calibrated) inserted in stainless steel tubes. We have now completed 20 such probes (a total of 480 sensors!). The magnetic data is being compared to an equilibrium model (the Grad-Shafranov equation). Andrew is using a code developed by Mike Schaffer and colleagues at GA. We hope to compare

magnetic dynamics to results from a two-fluid code at PPPL (see below). Andrew was also very helpful with the RCC coil winding and analysis (see below).

Matt Landreman's thesis will be on 3D structure of magnetic reconnection in SSX. His APS-DPP poster was entitled "Fully 3D measurement of reconnecting magnetic field in SSX" for which he won an APS award for best student poster. Matt also recently won a Rhodes scholarship so he'll be at Oxford in the fall! He's looking into Chicago (home of astroplasma guru Bob Rosner) when he returns in two years.

Matt's thesis is developing into a major tome beyond simply describing his 3D magnetic probe array and results. He's done some work rotating the data to a "natural" coordinate system and looking for quadrupole structure. Also, he's taken the curl of the generalized Ohm's law $\mathbf{E} + \mathbf{v} \times \mathbf{B} = \eta \mathbf{J} + (\mathbf{J} \times \mathbf{B} - \nabla P)/ne$ and notes that curl of grad = 0 and curl of E = -dB/dt (Faraday's law). He obtains an expression for the drive or convective term in the induction equation

$$\nabla \times (\mathbf{v} \times \mathbf{B}) = \frac{\partial \mathbf{B}}{\partial t} + \eta \nabla \times \mathbf{J} + \frac{\nabla \times (\mathbf{J} \times \mathbf{B})}{ne}.$$

This hasn't been measured before but we have the data for every term on the right hand side. Finally, we'd like to include statistical studies of the data (using structure functions and correlation functions), comparing structure with partial and complete merging, scaling studies, etc.

Finally, I'm in touch with SSX alum **Dave Schlossberg**. He's applying to about 10 grad schools (plasma and space physics mostly, including Dartmouth, Wisconsin and Maryland where we have friends). He's sure to get in somewhere excellent.

Talks and presentations (2002): I guess the big presentation this year was Chris' invited talk at the APS Division of Plasma Physics meeting in Orlando this past November. Chris did a great job (I have pictures!) and mostly emphasized our most recent stuff (SSX-FRC). His talk was entitled "Partial and complete spheromak merging at SSX: 3D studies of reconnection and FRC formation". Chris also gave an invited talk at the CT workshop in Osaka in September (interested folks, esp students, should see conference proceedings). I gave talks the Magnetic Reconnection 2002 (MR2002) workshop in Tokyo in November and the CT workshop in Seattle in February (see proceedings). There was also the SSX roadshow in which

Chris and I pitched our stuff at Princeton, New Hampshire, Dartmouth, Iowa, Wisconsin, Maryland, Delaware, West Virginia, Colgate. Coming up in 2003 is the innovative confinement concepts meeting (ICC 2003) and the plasma experiments in lab and space meeting (IPELS 2003) in Montana this summer.

Review of 2002 operation: This past year, our focus has been on un-restricted reconnection and global structure (equilibrium and stability). We did some experiments this summer with our original 0.5 m flux conserver and the compact 3D magnetic probe array as well as the distributed array (12 stalks). Finally, we installed the 0.4 m flux conserver (with newly tungsten coated electrodes) and reconnection control coils at the midplane. Mike Schaffer was around for the changeover in September (week of 9/16). Steve and Andrew were instrumental in winding the RCC (it was vacuum welded off campus). The RCC is powered by a new capacitor bank (0.5 F, 100 V, 50 coulombs, 2500 Joules, 500 A) that works well thanks to Jim. We did a series of experiments with only 4 magnetic probe stalks at the midplane of the 0.4 m flux conservers scanning RCC field (among other things). We added more probes (12 stalks total, 3 axial sets of 4... 288 probes total) and repeated the RCC scan. This is the main data Chris presented at his invited talk at APS-DPP in Nov 2002. By the end of the year, Chris had the He-Ne interferometer as finely tuned and well-understood as it's ever been. Abram's SXR diagnostic is among our most reliable. We find that a large x-ray signal is indicative of an energetic merging event. If the plasma is too dense or dirty or if the timing is off, the SXR signal vanishes. Clean, hot plasmas give us a nice signal. We've also amassed a huge amount of Mach probe data that awaits analysis.

Plans for 2003: We will be shutting down SSX-FRC in six months (June 2003) for a move and lab renovation. In the coming year we will continue to take (and later analyze) lots of data. Our main goal is to discover a more stable operating regime for our doublet CT objects. We're in the midst of scans in which we vary gun parameters like current and flux, their product is proportional to helicity, their ratio is the λ parameter from $\nabla \times B = \lambda B$. These scans adjust magnetic energy and helicity. Stuffing bank is 0.025 F, up to 400 V, about 1 kJ, a few mWb which we can scan by about a factor of 2. We're scanning gas valve timing (which adjusts density by a factor of two or so). Scanning the stuffing flux adjusts helicity and density. Of course,

switching the sign of the stuffing flux generates co-helicity merging (both the same, L/L or R/R). We're running with 12 probe stalks now and we're planning on adding 8 more. We will also add to our main capacitor banks to increase current and energy. We intend to add external end coils to flatten the RCC field (more like a solenoid field). Chris will be ordering a pair of new 10" ports with 5 conflats each. This should free up more azimuthal ports and give us more midplane access.

Near term plans (Winter 2003): Mike Schaffer is planning a visit to the east coast (SSX and PPPL) Jan 12-24. We're planning a meeting with Elena Belova of PPPL to discuss results from her FRC simulations. Elena studies the FRC $n = 1$ tilt mechanism with hybrid and two-fluid simulations. It looks like some of her results might be applicable to our experiment. We have a proposal renewal due in March 2003. The plan is to report on our successes the past year or two (see above) and propose a next step for our newly renovated SSX lab space (available 2004). I think we'll be able to say something about doublet CT equilibrium and stability with all our magnetics (Andrew's array). We have good density data and I think we'll have something to say about flow with Abram's Mach probe and heating with his SXR array. Chris and I have been talking about proposing an ion doppler spectroscopy diagnostic to look at flow. This technique has been used in Japan (Nagata on HIST and Ono on TS-3/4), U Washington (ZAP and HIT) and SSPX. We'll want to measure flow speeds from $M = 0.1 - 1$ or about $3 - 30$ km/s ($10^{-5} - 10^{-4}c$). This will require resolution better than $0.5\mathring{A}$ at $\lambda = 5000\mathring{A}$. Mike Schaffer suggests adding more ports to the primary vacuum chamber as part of the renewal proposal. It would help to have some 2.75" ports at an intermediate z location in addition to more ports on the 10" flanges. Perhaps also some ports (maybe smaller than 2.75") on the end domes, too. Some kind of an axial magnetic probe array capability would be very helpful. Mike also wants to discuss the pros and cons of putting an oblate FRC stability phase in the renewal proposal. This would be the only oblate FRC in the world and it would have a close-fitting flux conserver/stabilizer.

Finally, my main teaching assignment in the spring will be a plasma seminar with Chris and all the students (Matt, Abram, Andrew). It should be a spring plasma-fest!

cheers and happy new year, mb