1 Introduction and Overview

This is a proposal to continue a project formerly entitled "Turbulent Magnetohydrodynamic Acceleration Processes: Theory, Reconnection Experiments and Simulation." The project was submitted as PHY-0105914 to the NSF-DOE plasma physics partnership program, and was funded as DOE grant ER54490. The program was originally funded in 1998 and was renewed in 2001. This project has supported research carried out by Co-Principal Investigators Prof. W. H. Matthaeus (Bartol research Institute of the University of Delaware), and Prof. M. R. Brown (Department of Physics, Swarthmore College). The purpose of the proposed project is to continue theoretical and modeling support to the Swarthmore Spheromak Experiment (SSX), and to make connections to basic plasma theory and astrophysical applications. We propose continuing research which is a natural extension of our efforts on the past three years.

Scientific Overview. The scientific motivation for our studies can be summarized in a brief outline.

- *Laboratory plasma studies and space/astrophysical studies,* often distinct in their specific goals, may be concerned with phenomena that have strong similarities at the level of basic plasma physics.

- *Reconnection, turbulence, and charged particle acceleration* are interrelated to one another in many circumstances. They are encountered frequently in astrophysical and laboratory contexts. None of these phenomena are completely understood at present.

- Reconnection and turbulence can involve both *boundary related* effects associated with externally supported electromagnetic fields and plasma flows, as well as *local effects* that are relatively insensitive to specific configurations, and which depend upon a few basic plasma or magnetohydrodynamic (MHD) parameters. It is desirable to develop an overall understanding of observed dynamics that takes both these perspectives into account.

- Both local and global dynamics can be greatly influenced according to whether the system is strongly driven or is spontaneously evolving, In addition, it is of interest to understand whether a significant part of the available energy resides in force free configurations, which are often the targets of nonlinear relaxation or turbulence.

- A number of features of reconnection and particle acceleration can be modeled in ways that suggest *scaling* properties that can be valuable in extrapolating physical expectations from one application to another. This might include employing simulations to understand laboratory experimental results, or extrapolating laboratory data to astrophysical parameters.

The present project is organized around the Swarthmore Spheromak Experiment (SSX), employing the above strategy for improving physical understanding of the role of turbulence and reconnection in the generation of suprathermal energetic particle populations in plasmas. SSX is a very good experimental device for this approach. It is a highly dynamic plasma device that is set up to take advantage of a full complement of diagnostic probes. Unlike some programmatically constrained fusion devices, SSX is dedicated to the study of basic plasma physics. In SSX a pair of plasma guns generate an ionized plasma that expands to fill respective halves of the confinement vessel, forming Spheromak configurations (or, plasmoids) using established laboratory technologies [3, 45]. On its own each spheromak would seek a force free state similar to what is expected from relaxation theory [42]. In the original "reconnection configuration," relaxation in SSX is punctuated by an distinctive interaction between the two spheromaks that occurs in the vicinity of two cutout regions in the metal liner that separates the vessel into halves. (see Fig. 1). In the present Field Reversed Configuration (FRC, see Section 4,) the plasmoids are less confined and interact in

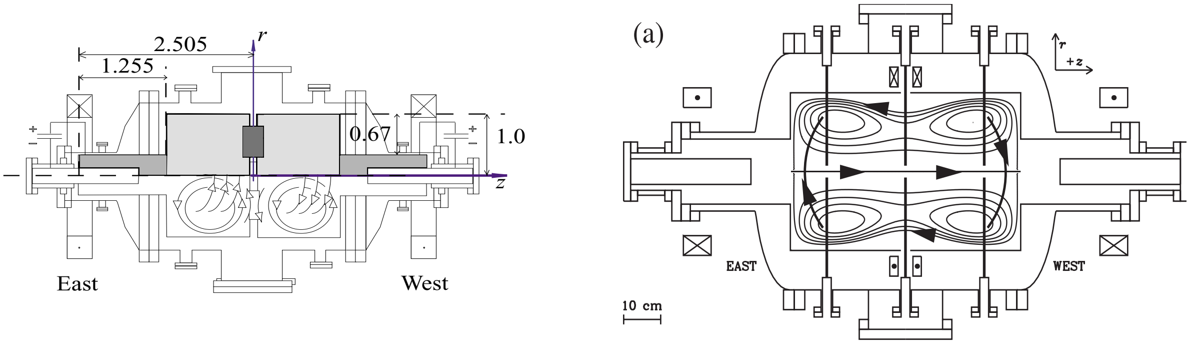

Figure 1: Swarthmore Spheromak Experiment (SSX). Spheromaks are formed by magnetized plasma guns well removed from the region of mutual interaction. (Left) Reconnection setup. A slotted conductor stabilizes the spheromaks, allowing interaction, including reconnection, in the slotted midplane regions. Magnetic fields, energetic particles and soft x-rays are monitored at the midplane. Magnetic fields, electron density and temperature as well as impurity emission are monitored in the spheromak (plasmoid) regions. Shaded area represent cross section simulated in axisymmetruc approximation (see Fig 2). (Right) Field Reversed Configuration (FRC) setup. Magnetic probes are distributed through out the volume. The spheromak interaction is unconstrained. See Sec. 4.3. The "doublet-CT" equilibrium has a high β FRC region at the midplane confined only by poloidal field that links private, unreconnected spheromak regions centered on two separate magnetic axes. In order to maximize the opportunity to study FRC instabilities, the elongation selected for this experiment is deliberately MHD tilt unstable for a single axis CT.

a highly nonlinear and turbulent reconnection scenario. Reconnection is also studied at the MRX experiment at Princeton [45, 44, 20], which differs considerably from SSX in the way the plasma is set up and driven.

To study the dynamics of these interactions, the SSX team employs a variety of experimental tools, described further below. In the present project we employ simulation tools, including direct MHD numerical simulation of SSX. These simulations (see below) are idealized in many respects, but include realistically shaped conducting boundaries, MHD models with additional Ohm's law terms, a reasonable portrayal of the formation of the plasmoids, and an emphasis on computation of the interactions between the two spheromaks [6, 45, 44, 20]. For reference, an overview of an earlier 2D simulation of SSX dynamics is illustrated in Fig. 2. which shows a time sequence of magnetic field intensity maps. Current emphasis is on 3D effects, kinetic effects, and particle acceleration.

The overall purpose of our proposed project can be stated in terms of two goals: *First*, we seek to provide further theoretical understanding of ongoing SSX experimental results. *Second,* we will theoretically examine SSX experimental and simulation results to understand whether the observed basic physics, correctly scaled, is relevant to understanding phenomena involving reconnection and energetic particle populations in astrophysical applications.

2 Methods and Approach

2.1 Experimental Summary

The Swarthmore Spheromak Experiment (SSX) has been operational since 1996 and is now a mature facility dedicated to studying the physics of magnetic relaxation and reconnection using merging spheromaks. Two experimental setups are of principal interest – the *reconnection setup* and the *Field*

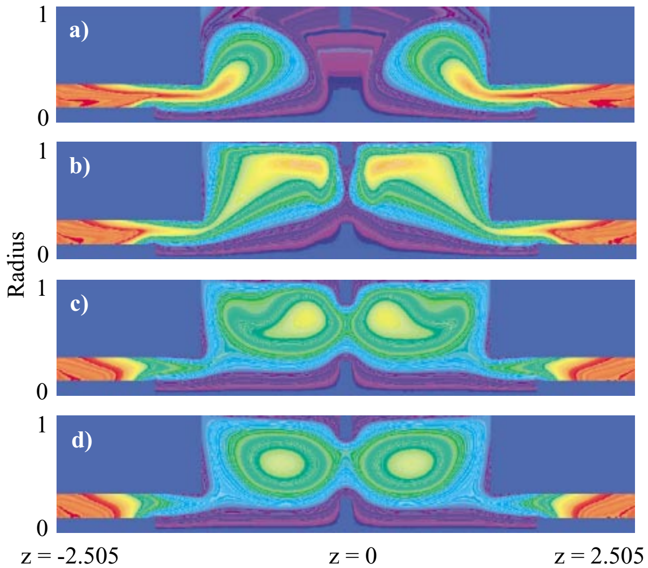

Figure 2: Evolution of magnetic flux intensity $|\mathbf{B}|$ from 2D axisymmetric TRIM simulation. (a) Formation $t = -2.73\mu$s, (b) Merging $t = 0\mu$s, (c) Relaxation $t = 13.5\mu$s, (d) Equilibrium $t = 23.4\mu$s. $t = 0$ is defined as the time of maximum magnetic energy in the reconnection zone.

Reversed Configuration (FRC) setup (see Fig. 1). Spheromak equilibria and magnetic reconnection structures have been measured with probe arrays [16, 22, 6], including a well-calibrated localized 3D magnetic probe array (with 600 separate magnetic probes) [23, 11] that is used in the reconnection setup. A distributed magnetic probe array is employed in the FRC setup. A multiplexer (MUX) system to enable us to economically expand our 80 channels of 10 MHz data acquisition to 640 channels at 1.25 MHz.

We use a HeNe laser interferometer system to measure line averaged electron density ($\int n_e dl$) coupled with a 4-tipped movable Langmuir probe for local measurements of n_e and T_e. In the reconnection setup energetic ions are measured with a suite of 3 retarding grid energy analyzers (RGEAs). Energetic photons are measured with a reverse-biased soft x-ray diode, a wide band bolometer and a 0.2 m vacuum ultra-violet (VUV) monochrometer.

We have recently fielded an IDS system to measure ion flow and temperature in SSX (funded through our main DOE grant). The system features a 1.33 m McPherson spectrometer with a high resolution Echelle grating. The SSX IDS instrument measures with 1 μs or better time resolution the width and doppler shift of the CIII impurity (H plasma) 229.7 nm line to determine the temperature and line-averaged flow velocity during spheromak merging events.

Using the SSX diagnostics and making use of the reproducibility of the experiment, the team has been building a set of solid experimental results in both reconnection and FRC setups. Some **Recent Major experimental results** are: *(i) Use of magnetic probe array to provide a 3D picture of the reconnection process; (ii) Measurement of magnetic terms in generalized Ohm's law; and, (iii) Measurement of out-of-plane-magnetic field associated with Hall effect.* These will be discussed further below.

2.2 Simulation

We have at our disposal a significant array of numerical tools that span both the laboratory plasma and turbulence approaches to simulations.

Spectral Method Simulations of Homogeneous MHD Turbulence. Spectral methods remain the technique of choice for direct numerical simulation of MHD and fluid turbulence [18, 9, 31].

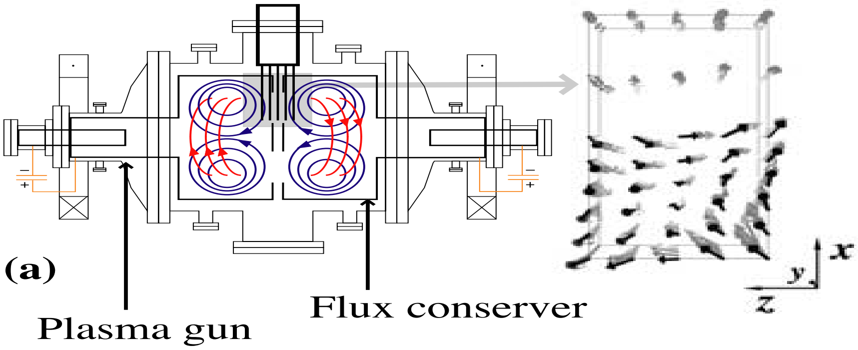

Figure 3: Diagram of SSX showing position of the magnetic probe "forest" used to map the 3D structure of the reconnection zone, and to measure magnetic contributions to Ohm's law.

Homogeneous MHD turbulence involves a wide range of interacting scales, and spectral methods compute these interactions accurately, consistent with known conservation laws, thus producing accurate cascade and relaxation processes. Electromagnetic field data from homogeneous (periodic) MHD simulations were employed previously to describe test particle acceleration due to 2D turbulent magnetic reconnection [29, 1] due to 2D homogeneous turbulence [19], and due to 3D turbulence [21, 15]. Periodic MHD and associated test particle simulations remain important in our strategy to study scaling properties of reconnection and associated acceleration processes.

Realistic Boundary Simulations. A important part of our past work and future plans revolves around use of numerical simulation codes that solve equations of the MHD equations (or, generalized MHD equations) in "realistic" spatial domains time scales, meaning that the boundaries are constructed to approximate the SSX configuration. In addition, the length and time scale in the code are attuned to SSX parameters. (see, e.g., [25]). This allows us to simulate the dynamics of the fluid SSX plasma, and provides MHD electromagnetic fields for test particle calculations (see below.) In general these code solve resistive MHD equations, in some cases with added terms from generalized Ohm's law, in cylindrical geometry and with boundary conditions (usually no slip perfectly conducting boundaries) to emulate SSX:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0, \tag{1}$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \frac{\eta}{\mu_0} \nabla^2 \mathbf{B}, \tag{2}$$

$$\rho \left[\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} \right] = \mathbf{J} \times \mathbf{B} - \nabla p + \rho \nu \nabla^2 \mathbf{v}. \tag{3}$$

In prior grant periods we employed a 2D axisymmetric non-ideal single fluid MHD code – TRIangular Magnetohydrodynamics (TRIM), (written by Dalton Schnack, see [39]), to simulate the time-evolution of electromagnetic fields, momentum density and plasma density in SSX. Our present operations and future plans involve use of more sophisticated and complete 3D MHD codes that at least include Hall effect in Ohm's law. See Section 4.2.

Since we are interested in fluid and kinetic effects in low collisionality plasmas such as SSX and astrophysical applications, a number of our numerical, experimental and observational studies will

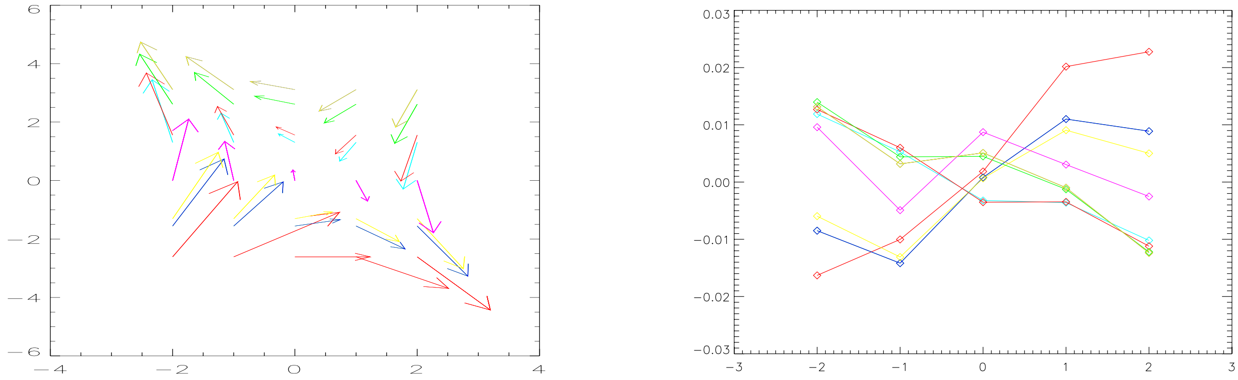

Figure 4: (Left) Measured magnetic field vectors in SSX within the merging region,[11] projected on to a plane that best approximates the expectations of a 2D reconnection model. An X-point is evident, between the merging spheromak fields, as expected. (Right) Quadrupolar out of plane magnetic field measured near the reconnection zone. This is expected as an indication of the Hall effect electric field. Color coding, indicating the row of the probe array, is the same as in left panel, and in the right panel of Fig 5 below, to facilitate interpretation.

employ or examine various terms in the generalized Ohm's law:

$$\mathbf{E} + \mathbf{u} \times \mathbf{B} = \eta \mathbf{J} + \frac{1}{ne}\mathbf{J} \times \mathbf{B} - \frac{1}{ne}\nabla \cdot \mathbf{P_e} + \frac{m_e}{ne^2}\frac{\partial \mathbf{J}}{\partial t}. \tag{4}$$

The first term on the right side, usually the classical collision resistive dissipation, can be more broadly construed to include a "turbulent resistivity" associated with fluctuations. Next, the Hall term involving $\mathbf{J} \times \mathbf{B}$, associated with differential flow of ions and electrons, becomes appreciable at the ion inertial scale $\rho_{ii} = c/\omega_{pi}$. The electron pressure tensor term is formally of the order of $\beta_e \rho_{ii}$ (where $\beta_e$is the ratio of electron pressure to magnetic pressure). The final term in Eq. (4), the electron inertia term, is due to electron dynamics and is appreciable at the electron inertial scale c/ω_{pe}.

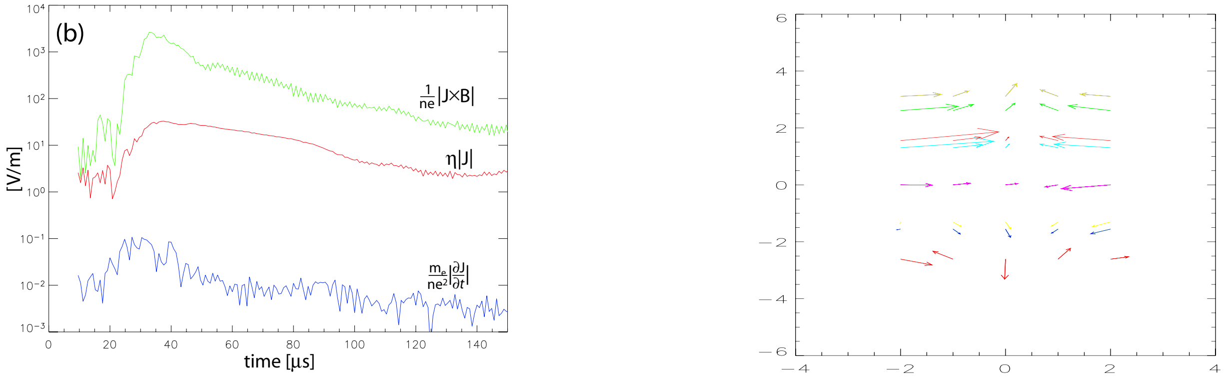

Figure 5: (Left) Measurement in SSX of several contributions to the electric field in a generalized Ohm's law, using the magnetic probe array, and averaging over 36 shots. (Right) Measured Lorentz force $(\nabla \times \mathbf{B}) \times \mathbf{B}$ projected into the same plane as in the panels of Fig (4). Note the color coding is the same in these as in Fig 4.

Test Particle Model and Trajectory Calculations. To examine suprathermal particles as they respond to electromagnetic fields primarily of MHD origin, we adopt a test particle approximation, widely used in cosmic ray physics, which enables us to extend physical insights derived from the MHD model. We numerically compute trajectories of charged particles. For the ith particle at position $\mathbf{X}_i$, $d\mathbf{X}_i/dt = \mathbf{U}_i$ and $d\mathbf{U}_i/dt = \alpha(\mathbf{U}_i \times \mathbf{B}(\mathbf{X}_i) + \mathbf{E}(\mathbf{X}_i))$, where $\mathbf{B}$ and $\mathbf{E}$ are the MHD magnetic and electric field, respectively, and $\alpha = \Omega\tau$ is the product of the gyrofrequency and the characteristic Alfvén timescale. In numerical implementations, the MHD fields are obtained from numerical simulation (either realistic boundary codes or spectral method turbulence codes), or analytical representations of random fields [38, 37]. Accurate test particle simulations are computationally challenging for a variety of reasons – number of particles, length scale separation, and stiffness of the equations for large dimensionless parameter α [26, 17]. Kinetic theory treatments, such as quasilinear theory, provide complimentary tools to develop understanding of test particle scattering and acceleration.

The time integration of the particles employs an embedded $4th$ order Runge-Kutta method with adaptive timestepping [35]. Simulation runs are broken down into a number of sub-steps each with time interval $\delta t \ll \Delta t$, where Δt is the total length of the run. The routine steps each particle in turn through the time interval δt while maintaining a local relative accuracy of $\epsilon = 10^{-9}$ at each step. This process repeats until the run ended and all particles had been stepped through the time interval Δt. The routine has been extensively tested and used [26, 36, 38, 37] and is currently implemented in a portable MPI parallel version that allows very large numbers of particle trajectories (typically $> 10^7$) to be readily computed.

2.3 Observations and Theory

A variety of approaches may aid in theoretical understanding of the basic physics of SSX and its potential applicability to astrophysical problems of vastly different scales. Our studies of the basic physics of SSX, reconnection and particle acceleration borrow from some of these approaches, including:

- Turbulent Reconnection
- MHD relaxation
- MHD Phenomenology
- Transport Theory (in real space)
- Diffusion models
- Scaling and similarity analysis
- Observations of energetic particles in space and astrophysics (see e.g., [28, 5, 4])

3 Results from Prior Support

The predecessor grant, entitled "Turbulent Magnetohydrodynamic Acceleration Processes: Theory, Reconnection Experiments and Simulation," commenced funding on 9/15/2001 for a period of three years. The grant is currently in a one year no cost extension for the period 9/15/2004 to 9/14/2005.

The purpose of the project has been to provide theoretical and modeling support to the Swarthmore Spheromak Experiment (SSX). The main goals have been

- to develop an increased understanding of SSX plasma dynamics through magnetohydrodynamic (MHD) modeling and simulation; and,

- to further understanding of the energetic and suprathermal charged particle populations produced and observed within the SSX facility, and
- to examine the implications that SSX results may have upon theoretical modeling of nonlinear MHD and reconnection processes in space physics, especially, for example, with regard to solar flares, magnetospheric reconnection, and interplanetary and interstellar turbulence.

Our theoretical effort is tightly integrated into the SSX experimental effort, and is also making advances. In the past several years, Michael Brown and his experimental collaborators at Swarthmore, with assistance from W. Matthaeus as appropriate, have made substantial progress in understanding the physics SSX plasmas. Highlights include:

1. Demonstration that the magnetic field configuration near the spheromak interaction zone forms dynamic X-points, with O-points (closed magnetic structures) sometimes in the center. *This was further investigated using TRIM simulations of SSX, see Lukin et al, 2001)*
2. Demonstration that flows at approximately the Alfvén speed are generated in the plane orthogonal to the X-line. (Also see Lukin et al, 2001)
3. Experimental determination that more energetic particle fluxes are seen in detectors along the X-line, and that these particles appear about an Alfvén time after commencement of the thermal (Alfvénic) flows. (*This effort was supported by theoretical and modeling studies, see Qin et al, 2001; Brown et al, 2002a,b.*)
4. Experimental study of the three dimensional structure of the reconnection zone, using a multiplexed array of tri-axial magnetic field probes. (*see Cothran et al, 2003a*) [11].
5. An experimental study of the relative magnitude of several of the important terms in the generalized Ohm's law that describes various contributions to the electric field in the low collisionality SSX plasma. (*see Cothran et al, 2004a*)
6. Detection of a quadrupolar out-of-plane magnetic field relative to the quasi-planar magnetic X-point configuration that dynamically emerges in the reconnection zone between the interacting spheromaks. This is likely associated with the Hall effect contribution to the Ohm's law [27, 40], which is large, and even dominant, within an ion inertial scale of the X-line. As far as we are aware, this is the first such detection in a laboratory plasma. (However see caveats below.) (*see Cothran et al, 2004b*)

The present project, while not for carrying out the experimental projects *per se*, supports the interpretation and application of the information gained from the experiments, especially with regard to implications for and relationship to space and astrophysical observations and related theoretical issues. This project has also supported modeling efforts, such as our older 2D axisymmetric magnetohydrodynamic (MHD) simulations (see Fig. 2) of SSX using the TRIM code [39]). Associated test particle simulations allowed us to explore both the fluid plasma dynamical effects and the energetic particles that are observed in the experiment. Test particle codes have been further adapted into load balanced parallel codes for running on small clusters. (See *http : //www.bartol.udel.edu/ whmgroup/Streamline/streamline.html*) Additional studies were carried out to investigate whether the estimates of particle energization in SSX and in earlier theoretical studies [1] would be seen to scale the same way in models of homogeneous turbulence (*see Dmitruk et al, 2003*)

The above scenario continues to be consistent with the picture that the thermal spheromak plasmas are exhibiting kinetic-modified MHD reconnection, while energetic (less collisional) particles are responding to the MHD electromagnetic fields. We have experimentally identified and in some cases theoretically modeled most of the relevant dynamical features. The scaling of the energetic particle energy is consistent with reconnection/particle acceleration models (e.g., [29]) and with so-called "V-B-L" scaling of astrophysical energetic particles [28]. One of our main goals remains to elucidate more fully the relevance of models such as these to SSX.

The following publications described work supported by this grant:

- Characterization of Magnetohydrodynamic Activity in the Swarthmore Spheromak Experiment, V. S. Lukin, G. Qin, W. H. Matthaeus, M. R. Brown, *Phys. Plasmas* **8**, 1600 (2001).
- Energetic particles and magnetohydrodynamic activity in the Swarthmore Spheromak Experiment, G. Qin, V. Lukin, M. R. Brown and W. H. Matthaeus, *Phys. Plasmas*, **8**, 4816 (2001)
- Energetic particles from three-dimensional magnetic reconnection events in the Swarthmore Spheromak Experiment, Brown MR, Cothran CD, Landreman M, Schlossberg D, Matthaeus WH, Qin G, Lukin VS, Gray T, *Phys. Plasmas*, **9**, 2077-2084 (2002a)
- Observation of energetic ions accelerated by three dimensional reconnection, M. R. Brown, C. D. Cothran, M. Landreman, D. Schlossberg and W. H. Matthaeus, *Astrophys. J. Letters* **577**, L63 (2002b)
- Three dimensional structure of magnetic reconnection in a laboratory plasma, C. D. Cothran, M. Landreman, W. H. Matthaeus and M. R. Brown, *Geophys. Res. Lett.*, **30** 1213 (2003) doi:10.1029/2002GL016497,2003
- Test particle acceleration in three-dimensional magnetohydrodynamic turbulence, P. Dmitruk, W H Matthaeus, N. Seenu and M R Brown, *Astrophys. J. Lett* **597**, L81 (2003)

In addition, there are two publications currently in stages of review by journals:

- Generalized Ohm's law in a 3D reconnection experiment C. D. Cothran, M. Landreman, M. R. Brown and W. H. Matthaeus, *Geophys. Res. Lett.* submitted (2004a)
- Fluid and Kinetic Structure of Magnetic Merging in the Swarthmore Spheromak Experiment, C. D. Cothran, M. Landreman, M. R. Brown and W. H. Matthaeus, *Geophys. Res. Lett.* submitted (2004b)

This multidisciplinary project in experimental laboratory plasma physics and theoretical plasma physics has been active and rewarding, and we believe it is examining basic and applied plasma physics issues in a way that is rather unique. We are able to efficiently cross fertilize the projects with efforts geared towards and supported by other, mostly space physics, research efforts. In addition, SSX parameters are very similar to other reconnection experiments (MRX at Princeton and TS-4 in Japan) so our study and modeling of SSX continues to have more general applicability.

4 Proposed Research

We propose to continue our research on reconnection experiments, simulations, and theory focusing on three aspects: coordination of large codes (magnetic probes data, test particles and spectroscopy), FRC dynamics, and the generalized Ohms law.

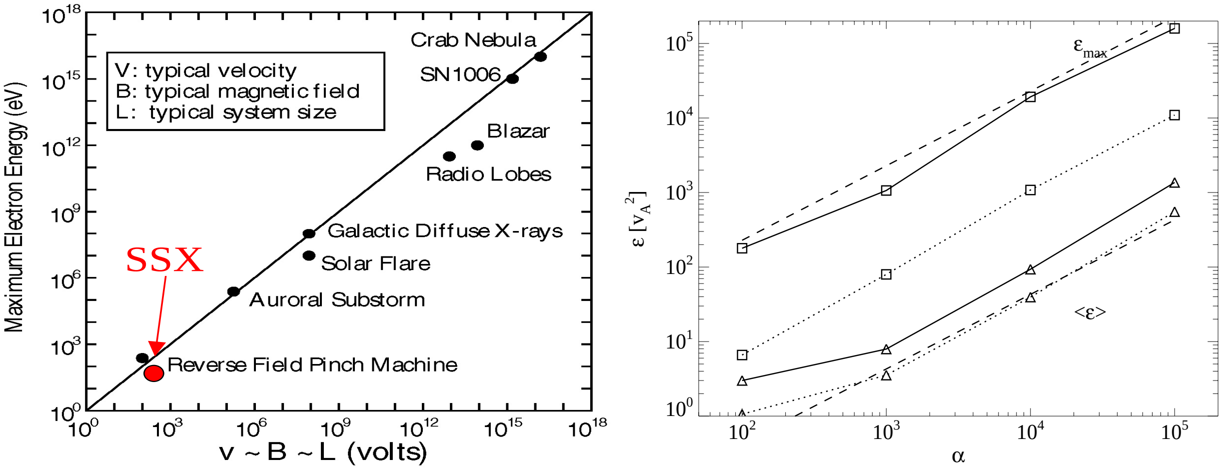

Figure 6: (Left) the well-known "V-B-L" scaling of astrophysical energetic particles, with a point added for SSX. Adapted from Makishima [28]. Maximum energy is plotted vs. product of characteristic speed, magnetic field strength, and scale. (Right) Scaling of mean and maximum energies of test particles after a nonlinear turnover time, using electromagnetic fields from 3D compressible Hall MHD turbulence simulations. From Dmitruk et al (2003).

4.1 FRC Experiments and data analysis

The proposed research includes a major effort to understand the nonlinear dynamics of SSX when it is run in a new mode– the so-called FRC or Field Reversed Configuration. In this case the initially generated spheromaks are less constrained than they were in the reconnection configuration, because the slotted conducting plates between them have been removed. Reconnection can, and still does occur. But now the spheromaks can fully merge, tilt, and seek a new lower energy equilibrium state. Note that the FRC configuration allows us to explore the close connection between reconnection and turbulence in detail. Reconnection phenomena include current filamentation, magnetic topology change, plasma jetting and energization of particles by MHD electric fields. Reconnection is usually studied in configurations in which the large scale magnetic field geometry is supported by boundary conditions (e.g., applied electric field or externally supported currents). However reconnection is also a characteristic feature in homogeneous MHD turbulence, where it may occur at many sites, between merging magnetic islands or plasmoids. This profound connection between large scale reconnection and MHD scale turbulence is expected to give rise to distinctive signatures in both laboratory and astrophysical plasmas. Study of the FRC is expected to be particularly useful in this regard because the initial state is highly reproducible, and the final state is predictable, while the intermediate dynamical evolution is highly complex and involves many degrees of freedom of the plasma. In the coming grant period we will broaden our theoretical and modeling efforts through study of the nonlinearity, turbulence and particle energization that occurs in FRC dynamics. This will include new three dimensional simulations of both SSX and homogeneous turbulence, associated test particle calculations, and theoretical modeling.

SSX-FRC description: The Field Reversed Configuration (FRC) [43] is a high β compact toroidal (CT) plasma. In its idealized form, it has closed, purely poloidal field lines. Until recently, research at the Swarthmore Spheromak Experiment (SSX) [6] has focused on local studies of magnetic reconnection by merging counter-helicity spheromaks [7, 8, 22]. In the prior funding period, the program at SSX, now called SSX-FRC, began to examine the general issue of FRC stability and dynamics [12]. Stability was addressed by magnetically restricting the merging process with a set

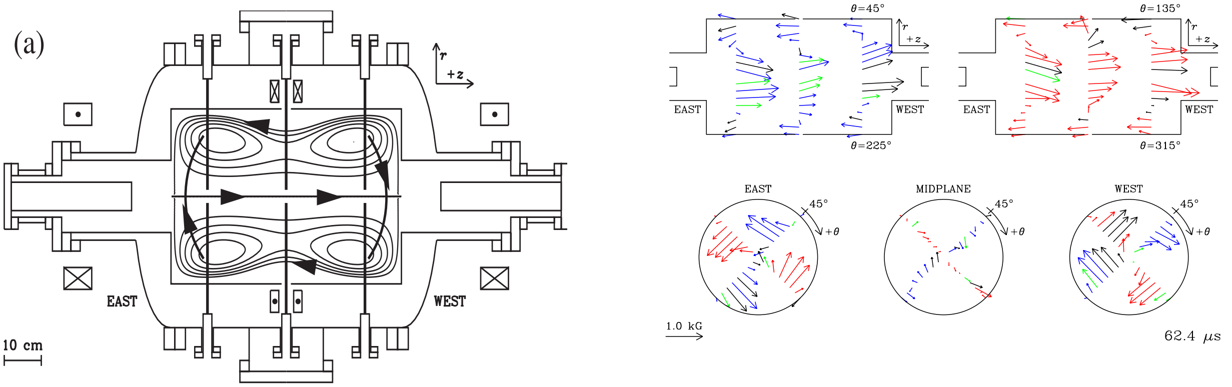

Figure 7: (Left) Diagram of the FRC setup (same as right panel of Fig 1), and "(Right) Magnetic data from the FRC mode of operation. The two possible rz cross sections (top) and three possible $r\theta$ cross sections are shown for the set of 12 linear probes used.

of midplane reconnection control coils (RCC) to limit the quantity of toroidal field annihilated from the initial counter-helicity spheromaks: stability as a function of the residual toroidal field strength was systematically investigated. The global, three-dimensional magnetic structure of the configuration was measured with up to 600 internal magnetic probes with three-axis inductive loops at eight locations (2.5 cm spacing) at 1.25 MHz acquisition rate[23], much faster than the relevant dynamical time scales. The SSX-FRC project has provided the most detailed internal examination of FRC magnetic structure to date. Typical characteristics of SSX-FRC plasmas are 3–4 mWb poloidal flux, 1 kG edge field, $1 \times 10^{15}/\text{cm}^3$ density, 30 eV temperature ($T_e + T_i$), and $s > 10$. As shown in Figs (7) and (8), twelve probes are installed, four each in the east, midplane, and west.

4.2 MHD simulations & Coordination of computational leverage from Centers.

The SSX team has links with several Centers and collaborators around the plasma physics community: the NSF-DOE Center for Magnetic Self Organization (funded member), the new DOE Fusion Center for Innovative Confinement Concepts (unfunded participant), and Dr. Elena Belova's HYM simulation project (unfunded collaborator). The primary output of these links will be a full 3D fluid (MHD or two fluid) simulation of the SSX formation and merging (see table). We have essentially no funding explicitly for simulation support of SSX. We propose here to coordinate the leverage we have from participation in these Centers. Our goal is to enhance the synergy between Center participants. We have experience doing this in prior funding periods (eg coordination of Delaware graduate student Gang Qin and Swarthmore senior honors student Slava Lukin). We also propose to involve Swarthmore College assistant professor David Cohen and post-doc Chris Cothran in spectroscopy aspects of the project. We have in hand several resistive 3D MHD runs from Dr. Belova's HYM simulation. Runs with other codes are forthcoming.

Table 1

collaboration	*contact*	*code*	*features*
NSF CMSO	Sovinec	NIMROD	3D, resistive MHD, Hall
DOE ICC	Milroy	MH4D	3D, resistive MHD
SSX FRC	Belova	HYM	3D, resistive MHD, Hall, hybrid
NSF CMSO	Chicago	FLASH	3D, resistive MHD

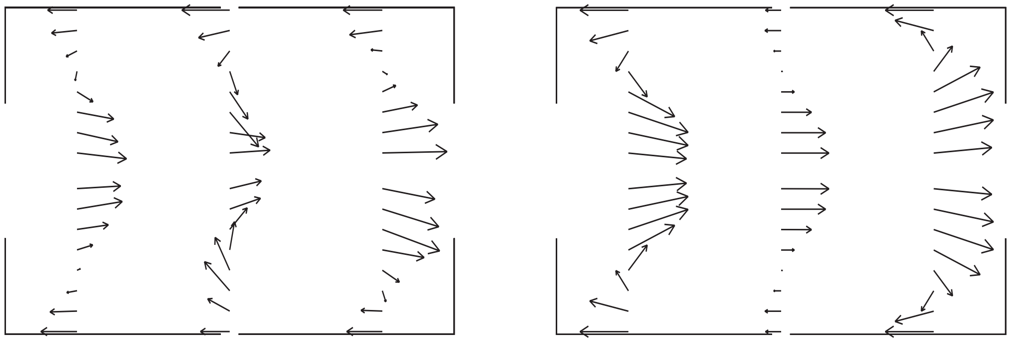

Figure 8: (Left) Experimentally measured magnetic structure in the FRC setup (one r-z projection only) and (right) 3D MHD simulation result at the same time during the merging process (same r-z projection and same spatial locations as experimental probes). The 3D HYM simulation is at S=1000, $Re = 200$, with $128 \times 64 \times 16$ grid in r, θ, and z.

4.3 Specific Goals

FRC Investigations: Our initial goal will be to benchmark the codes against SSX-FRC magnetic data and against each other. We are able to measure vector $\mathbf{B}$ at 200 locations (600 separate components). In Fig (8), we show an example of a direct comparison of output of the single fluid HYM code for S=1000 and data from the SSX-FRC merging experiment. Both data and simulation results are for a counter helicity merging shot, several microseconds after the main reconnection event. The initial condition for the simulation was two spheromaks at rest, back-to-back. The boundary condition is a perfectly conducting cylinder. Neither initial or boundary condition is particularly realistic, nonetheless, the comparison is close. Note that this is **not** a fit but independent measurement and *ab initio* simulation that agree very well.

Test particles: The present NSF-DOE collaboration (Matthaeus, Brown) has had experience with test particle simulations in time dependent MHD fields (up to 10^5 protons in 2D axisymmetric fields [25, 36]. We showed that MHD activity related to magnetic reconnection was responsible for accelerating charged particles. The process included two distinct phases: a strong but short lived direct acceleration in the quasi-steady reconnection electric fields, and a weaker longer lived stochastic component associated with turbulence. We are now in a position to integrate orbits for 1-2 orders of magnitude more particles integrated in a full 3D MHD simulation of SSX. We propose to run 10 million test ions through simulated MHD fields. Protons can be injected into the simulated fields at random positions and gyrophases. We will be able to track distribution functions of ions as a function of space and time. Perhaps we can localize sources of particle energization (heating and tails) and identify regions of flow. This project will require dedicated runs at high time cadence. The fluid simulation could be from NIMROD or HYM. The particle orbit code will be the Bartol parallelized Runge-Kutta orbit code, run on a parallel cluster at Bartol. (Bartol has SAMSON, 132 Athlon nodes 1GHz, WULFIE, 16Nodes2GHz, and much more powerful clusters being acquired presently.)

Soft X-ray (SXR) with David Cohen: We have an array of SXR detectors implemented under our main DOE grant. The array features matched AXUV PIN diodes with 100 nm metal foils (Al, Zr, Ti, In). The diodes sit behind 0.5 T magnetic fields from pairs of Nd-Fe-B permanent magnets to suppress energetic ions. Each element in the array is sensitive to a particular band in the SXR spectrum (like a coarse x-ray spectrometer). We show the response curves of the four detectors in Fig. (9a). The relative intensities measured in each detector provides information about the temperature, density, and impurity level along a chord through the SSX plasma, as a

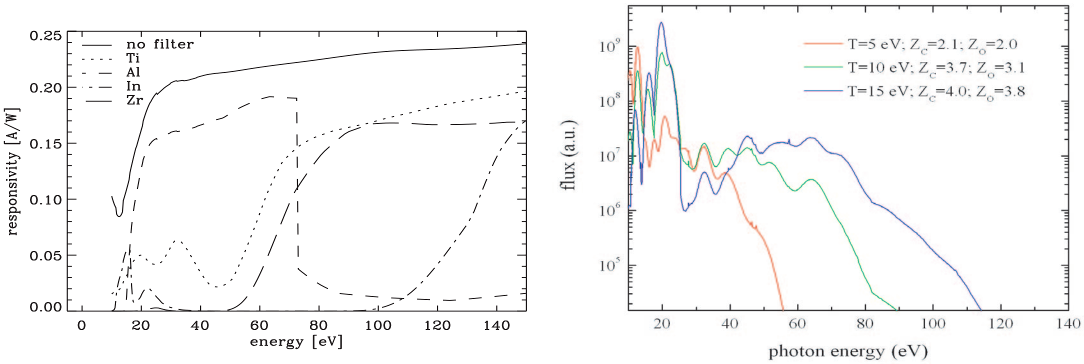

Figure 9: (a) Responsivity of the photodiodes, (b) Computed spectra for a non-LTE SSX plasma (10^{15}, 1% C and O) convolved to a very coarse resolution. This figure makes it easy to see general spectral trends, and predict what would be seen in the four SXR channels for different plasma properties.

function of time.

Preliminary work ([11]) indicates that relatively tight constraints can be put on the spatially averaged temperature of the SSX plasma by spectrally modeling the detector fluxes. We propose to use the Spect3D, ATBASE, PrismSpect suite of atomic, non-LTE ionization and level population, and spectral synthesis codes to model the plasma emission, which we have found to be dominated by line emission from impurities (primarily carbon and oxygen) in the relevant bandpass, once the impurity level is above about 1 percent by number. In Fig. (9b) we show the results of three spectral simulations using PrismSpect, for plasma temperatures of 5, 10, and 15 eV, respectively. The temperature sensitivity of the spectral energy distribution is apparent.

Co-I Cohen has extensive experience using the suite of atomic and spectral synthesis codes for modeling laser fusion experiments [10] ATBASE and the associated Atomic Model Builder tool custom computes an atomic model (energy levels, transition probabilities, cross sections) of arbitrary complexity (e.g. fine structure splitting), and its output has been tested extensively against experimental data. The PrismSpect code uses these atomic models as input and solves the statistical equilibrium equations under a given set of assumptions about the physical conditions in the plasma, and then performs the radiation transport necessary to synthesize a spectrum. Using this combination of tools, we can constrain the temperature, density, and composition of the SSX plasma based on SXR measurements.

In addition to this basic modeling for the purpose of constraining physical properties of the hot plasma, we can perform detailed post-processing of the results of fluid-code modeling (NIMROD, HYM), synthesizing spectra from an arbitrarily complex 3-D, time-dependent plasma distribution, using the Spect3D code. This code is very much like PrismSpect, as described above, but can model 3-D spatial distributions of plasma, doing the optically thick line transport, and can also model non-equilibrium plasma conditions. We propose to post-process the results of the fluid-code simulations discussed in Sec. 4.2 of the proposal using Spect3D and thereby evaluate the fluid-code results as constrained by the SXR measurements.

Ion Doppler Spectroscopy (IDS): (with Postdoctoral Fellow Dr. Chris Cothran) We have recently fielded an IDS system to measure ion flow and temperature in SSX (funded through our main DOE grant). The system features a 1.33 m McPherson spectrometer with a high resolution Eschelle grating. Using the SPECT3D code, Prof. Cohen can again port the output from one of the fluid codes (NIMROD, HYM) that has been benchmarked against SSX data and compute the shape of an emission line of interest. As an example, in Fig (10) we present a prediction of the lineshape for C_{III} emission at 229.7 nm from a 5 eV plasma flowing at 10 km/s. For comparison, we also show some preliminary data from the SSX IDS spectrometer for the same line. As part of this project, we will be able to compute effects of flow shear on the lineshape. If different parts of the line of sight of the spectrometer are flowing at different speeds (in regions of different density and temperature), then the shape of the line will be affected. Results of the 3D fluid code will be imported by SPECT3D to calculate these effects. *This new diagnostic technique provides added synergy between modeling and experiment, and should provide valuable constraints on flows and turbulence – similar methods (UVCS/SOHO instrument, see* $http://cfa-www.harvard.edu/uvcs/$*), have led to major observational advances in solar physics.*

The SSX IDS instrument measures with 1 μs or better time resolution the width and doppler shift of the CIII impurity (H plasma) 229.7 nm line to determine the temperature and line-averaged flow velocity during spheromak merging events. The instrument temperature is approximately 15 eV. Velocity resolution is about 7 km/s, corresponding to approximately $0.1 v_A$. The design employs a single lens to select the observed chord through the plasma, sending the collected light to the spectrometer via a round-to-linear, UV fused silica, solarization resistant fiber bundle. The Czerny-Turner spectrometer has 1.33 m focal length, f/9.4, and uses a 316 $groove/mm$ Echelle grating blazed for a 63.5° angle. The CIII line is observed at 25th order where the spectrometer achieves a dispersion of 0.03 nm/mm. An output optics stage magnifies the spectrometer focal plane by 4× in the dispersive direction and de-magnifies the non-dispersive direction by 0.25×. This will accommodate the 0.8 mm wide (1 mm pitch) by 7 mm tall elements of the Hamamatsu linear photomultiplier array used for detection.

2.5D compressible Hall reconnection code: (with Swarthmore undergraduates) We will use a 2.5D compressible Hall MHD code developed at Bartol to further explore particle acceleration by turbulence and reconnection [41] which can be run on a workstation or small cluster. The code features periodic boundary conditions, the Hall term in the Ohm's law, and solves the MHD equations using a spectral method. This code does not model a fully 3D merging process, but it can be run with very high spatial resolution and for many runs. Thus it is complementary to particle energization studies that will be done using one or more of the large scale simulations described above (NIMROD, HYM, FLASH, MH4D). This use of the 2.5D code will also provide an opportunity for a Swarthmore undergraduate to participate directly in the computational study of SSX-related phenomena.

Punctuated equilibria in turbulence, truncated model of FRC dynamics. In the SSX-FRC mode, the initial and final states are thought to be either force free or near-equilibrium, the process by which this transition occurs may be thought of as an experimental paradigm for interaction of low-nonlinearity coherent structures in plasma turbulence. Indeed many turbulent relaxation processes can be thought of as a sequence of such interactions. For example, when the process is a scale-invariant sequence conversions between distinct near-equilibrium states, with bursts of nonlinearity connection them, one has a viable model for a turbulence cascade. In this regard we note that turbulence, unless it is very strongly stirred or near its initial conditions, tends to rapidly and locally relax to states in which parcels of fluid are in quasi equilibrium. The large forces are relaxed, and nearly balanced. Such parcels are generalizations of force free states. When two such parcels encounter one another, strong nonlinear dynamics ensue, that is, bursts of turbulent activity. The paradigm for this is the well studied case of 2D incompressible hydrodynamics turbulence (see [32]), which relaxes locally to a maximum entropy state. This is visualized as a distribution of isolated vortices with $\mathbf{v} \cdot \nabla \omega = 0$. Occasionally vortices collide and interact, and the bursts of activity that follows can be thought of as the "Atoms of non-linearity" that drive a cascade. The

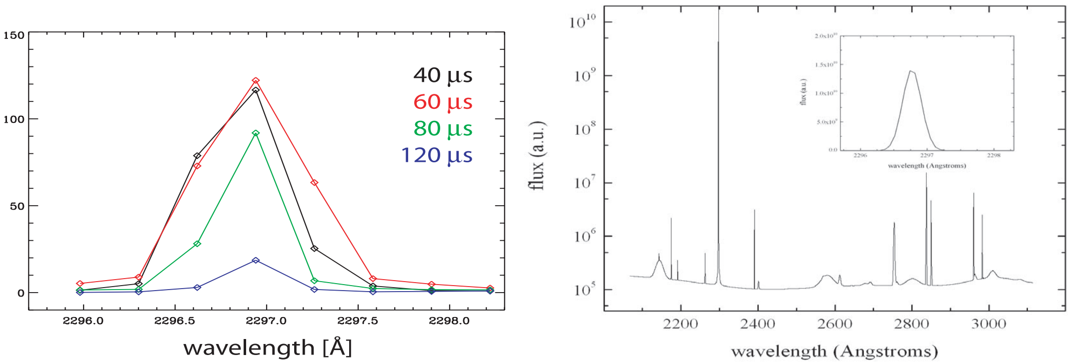

Figure 10: (left) Experimentally measured C_{III} emission at 229.7 nm at 4 times during the merging process and (right) SPECT3D non-LTE, steady state simulation (same conditions as figure 9, 5 eV).

analogy with the interaction of quasi-force free spheromaks in SSX is clear. We propose to further develop this perspective of nonlinear MHD turbulence in the coming grant period, employing a combination of SSX experimental data, as well as numerical modeling and theoretical approaches. **Ohm's law comparison.** We continue to be very interested in the decomposition of the generalized Ohm's law in SSX [13], as it provides the force that accelerates particles, while also providing keys to understanding kinetic effects in semi-collisionless plasmas such as SSX. We are interested in establishing the values of various terms in the generalized Ohm's law (see Eq. (4)). We propose to continue analysis of Ohm's law in SSX, and in concert with this, to include analysis of data from 3D compressible MHD spectral method codes, and space craft observations of solar wind fluctuations. These will be studied in comparison with the analogous results from SSX. At present we believe that SSX is the only MHD scale laboratory device that can be used for such a comparative study.

4.4 Scaling to space and astrophysical plasmas

We observed and analyze reconnection, turbulence and particle acceleration in SSX, and we would like to understand how to apply this knowledge to other systems. We have already obtained some relevant results of this type in connection with the scaling of energetic particles produced by reconnection and turbulence. We want to extend such studies to the scaling of SSX reconnection processes, including rates, current intensities, and time scales. An important scaling parameter is the ratio of the size of the device L (the minor radius), and the dimensionless parameter $\alpha = \Omega \tau_{Alf} = \Omega L_0 / V_A = L_0 / \rho_{ii}$. The latter appears in the particle equations of motion written in Alfvén speed units, and has been shown in homogeneous simulations [1, 19, 15] to control the maximum and mean energies of charged test particles. In SSX this parameter is equivalent to the ratio of device size to the ion inertial scale ρ_{ii}. Thus the parameter that controls particle acceleration also is involved in establishing the thickness of current sheets. There is both theoretical [27, 40] and solar wind observational evidence [24] for this. Another pair of parameters of importance are the magnetic Reynolds number and Lundquist number. We propose:

- To continue examination of the scaling of reconnection and particle acceleration [1, 19, 21, 15] in turbulence and in SSX-like configurations using available high resolution turbulence codes and SSX codes as described above.
- Study of the effects of particle escape. In SSX simulations this happens when particles hit the

wall. In the homogeneous simulations we will model escape, a crucial ingredient in theoretical models (e.g., [2]) This will enable us to sort out "pure scaling" from SSX boundary effects.

- To study effects of varying Reynolds number, Lunquist number and other parameters, on the interpretation and extension of SSX results to astrophysical situations.
- To examine how SSX results on Ohm's law and the kinetic structure of the reconnection region compare quantitatively to magnetospheric spacecraft observations [34, 33].

5 Summary

State of current understanding. Substantial progress has been made in studies centered around SSX and supported by this project. Baseline reconnection studies in SSX have described the energetics of the merging region, Alfvénic flow, the existence of X-points and turbulence/fluctuations, and current channels. In addition, we have attained an understanding of the reconnection rates, and the energy spectra and time variation of energetic particle fluxes produced during reconnection.
Ongoing work includes study of:

- Production of energetic particles, now to be examined in FRC setup
- Ohm's law contributions, to be examined in FRC and compared with 3D SSX simulations, turbulence simulations, and solar wind observations of MHD turbulence.
- Three dimensional structure, to be continued in the FRC setup and compared with 3D codes.
- Quadrupolar magnetic field signatures of kinetic processes, which studies will be continued.

Extensions, and new studies and questions include:

- An emphasis on understanding dynamics in the FRC setup
- Use of 3D codes in modeling
- Direct comparison with to turbulence and solar wind observations
- Development of a nonlinear dynamics model based upon FRC dynamics

We look forward to continued progress in this exciting and cros disciplinary research.

6 Educational and training component

The budget includes a support line for a University of Delaware PhD grad student, and a small amount of participation of a Bartol postdoc on numerical issues. Swarthmore students continue to be the mainstay of the SSX project and have contributed significantly to this research.

7 Management

This is a collaborative proposal, submitted jointly by Prof. W. Matthaeus from The University of Delaware Bartol Research Institute, and by Prof. Michael Brown from Swarthmore College Department of Physics. Each Co-Pi will separately manage the budgets and activities for their respective institution. There is a significant component of collaborative research that will be supported by this project, and this will be coordinated by the Co-PIs as it has been in prior years. Swarthmore and Delaware are separated by only a 45 minute drive, which facilitates regular meetings and visits for collaboration.