Spheromak merging and FRC formation studies at SSX-FRC

C. D. Cothran, A. Fefferman, A. Falk, M. R. Brown
Swarthmore College

M. J. Schaffer
General Atomics

We report the results of coaxial co- and counter-helicity spheromak merging studies at the Swarthmore Spheromak Experiment (SSX). The present configuration of SSX is optimized to study FRC formation and stability by complete counter-helicity spheromak merging. In forthcoming experiments the merging will be magnetically restricted with a pair of midplane coils to determine how the stability of the resulting magnetic configuration, a "doublet-CT", depends upon the quantity of toroidal flux annihilated from the initial spheromaks.

The diagnostic set at SSX, featuring the capability of measuring up to 600 magnetic field components at 800~ns time resolution, permits detailed studies of the dynamic three-dimensional magnetic structures resulting from these merging experiments. A compact array of magnetic probes has been used for local reconnection measurements, while a distributed array of probes has been used to examine global magnetic structure. Counter-helicity merging produces an FRC that persists for many Alfvén times before an instability grows at a rate much slower than ideal. The oppositely directed toroidal field of the initial spheromaks does not completely annihilate. Co-helicity merging produces a single elongated spheromak that evolves on similar time scales and tilts. In addition to the magnetic activity, plasma flows and heating are being studied with a new mach probe and soft x-ray detector.

Until recently, research at the Swarthmore Spheromak Experiment (SSX) [1] has focused on studies of magnetic reconnection by merging counter-helicity spheromaks. As reported at the last US/Japan CT Workshop at the University of Washington in February 2002, the program at SSX has shifted to an examination of FRC formation by counter-helicity merging [2,3,4]. The research effort in this new direction has been dubbed SSX-FRC, and this paper reports some preliminary results.

The primary inspiration and motivation for SSX-FRC, as well as for much of the preceeding reconnection studies at SSX, has been the research program at the University of Tokyo led by Y. Ono. Results with the TS-3 device [5,6,7], and now continuing with TS-4 [8,9], on merging counter-helicity spheromaks have clearly shown how reconnection directly accounts for the relaxation to an FRC. Reconnection annihilates the initial helicities, and the consumed magnetic energy is converted to ion thermal energy and flow. Furthermore, the relaxation bifurcates to a spheromak if the initial helicity imbalance is too great.

With the question of formation by merging thus firmly established, the SSX-FRC project is particularly interested in FRC stability. SSX-FRC will produce FRCs with elongations slightly larger than 1 and with $s \approx 10$ (ratio of separatrix radius to ion gyroradius). In this parameter regime, the kinetic effects will be suppressed and the FRC should be tilt unstable according to the simplest single-fluid MHD analysis. However, recent numerical results [10] from a hybrid model indicate that stability in this regime is achieved non-linearly by self-generated toroidal fields at each end of the FRC with equal strength and opposite orientation. Interestingly, a similar toroidal field geometry is observed in the TS-3 and TS-4 FRCs, late in time and reversed from the toroidal fields of the original spheromaks. Unfortunately, tilt stability cannot be definitively addressed due to a structural column on axis in these devices. Theta-pinch formed FRCs have also indicated toroidal field generation, but at much larger elongations and lower s values.

The SSX-FRC design does not have any structural element on axis: the spheromaks are produced with coaxial magnetized plasma guns on either end of a simply connected cylindrical copper flux conserver. To examine the stabilizing role of toroidal field, two reconnection control coils (RCCs, or separation coils) are located at the midplane to regulate the merging process. It is anticipated that the quantity (and rate) of toroidal field annihilated during reconnection will be determined by the vacuum field strength from these RCCs. Moreover, it may be possible to magnetically limit the merging enough that a configuration dominated by two magnetic axes, a “doublet-CT”, is formed. Grad-Shafronov equilibrium calculations of such a configurations have been completed recently [3], and attempts are underway to numerically estimate the interchange instability.

The diagnostic set at SSX-FRC includes the capability of measuring up to 600 magnetic field components at 1.25 MHz [11]. A set of 20 internal magnetic probes with three-axis inductive loops at eight locations (2.5 cm spacing) on linear probe stalks is now complete. These probes will be inserted radially into SSX-FRC at up to eight toroidal angles ($\pi/4$ intervals) at each of three axial positions. SSX-FRC will therefore provide the most detailed study of the internal magnetic structure and dynamics of FRCs ever reported. In addition to the probes, the RCCs and flux conserver are also complete, and installation of all of this new SSX-FRC hardware is underway. Figure 1 shows a sketch of the SSX-FRC design.

As mentioned above, a preliminary set of merging experiments has been performed since the last CT Workshop, simultaneous with the construction of the new SSX-FRC hardware. These experiments required some modest modifications to the existing pair of flux conservers originally used for the magnetic reconnection studies. In addition, 12 of the 20 linear probes for SSX-FRC were installed for these measurements (four toroidal angles at each of three axial locations). No midplane coils were used in these experiments: the spheromaks were simply allowed to merge without restriction. However, image currents in a 5 cm annulus remaining in the facing midplane walls of the two flux conservers may have acted as dynamic RCCs during these experiments. Both co- and counter-helicity spheromak merging was examined.

Figure 2 shows a typical set of data for a counter-helicity merging shot. The scale of a 1.0 kG field is indicated at bottom left. The spheromaks are ejected from the guns at $t \approx 25\mu s$, and reach the midplane by $t \approx 30\mu s$. The data shown in this figure corresponds to $t \approx 64\mu s$, as indicated at the bottom right. Five views of the data are shown: r-θ projections for the three axial locations (bottom row), and r-z projections for the two possible poloidal cross-sections (top row, color coded red and blue). Black and green vectors indicate measurements where one or more of the coils in a triplet were broken. The flux-conserving boundary is shown in outline for each view (note the 5 cm annulus at the midplane seen in the poloidal cross-sections). The inner radius of the flux conserver is 25 cm, and the full internal length is 63 cm.

The poloidal cross-sections in Figure 2 clearly show field reversal in each z plane. Furthermore, the midplane probes indicate very little toroidal field strength. Both of these observations are obviously consistent with FRC formation. At large radii, however, toroidal components of comparable strength to the poloidal components remain at either end of the configuration. Shortly after field reversal is first observed at $t \approx 40$-$50\mu s$, the toroidal field of the original spheromaks appears to be dissipated, particularly at radii inside the null point. A mode analysis also shows that the m=0 toroidal field components reverse late in time ($t > 90\mu s$), consistent with the TS-3 observations. In this epoch, however, the configuration appears to be tilting. The stable $40\mu s$ interval from reversal to tilt corresponds to a few tens of Alfvén times.

Figure 3(a) shows the poloidal flux dependence on r at the same time as Figure 2. Figure 3(b) shows the time evolution of the peak poloidal flux. Note in particular that the poloidal flux reaches nearly 4 mWb: this is about 4 times the gun flux.

Typical data for co-helicity merging are shown in Figure 4. Co-helicity merging forms a single spheromak which rapidly tilts. These data are, in fact, consistent with a tilted spheromak in a cylindrical flux conserver [12]. The tilt is expected due to the aspect ratio of the flux conserver. In contrast to the counter-helicity merging case, the evolution of the tilt in the co-helicity case is extremely rapid, occurring in as little as $10\mu s$, or just a few Alfvén times. Subsequently ($t > 50\mu s$), the tilted spheromak persists much longer than the tilted FRC.

This comparison is evident in Figure 5, which shows the energies in the m=0 and m=1 (toroidal) modes for the same co- and counter-helicity merging shots as Figures 2 and 4. In agreement with the observations described above, the time at which the energy in the m=1 mode dominates is approximately $50\mu s$ and $90\mu s$ for co- and counter-helicity, respectively. The significantly longer decay time for the tilted spheromak is also evident in this Figure.

Finally, Figure 6 shows a comparison of the phase angle of the m=1 component of the toroidal field as a function of time for these co- and counter-helicity shots. In these plots, the phase angle is plotted in $[0,2\pi]$ bands at each radial probe position. There is very little rotation of the co-helicity phase angles. In contrast, the phase angles for the counter-helicity case rotate one to two periods before flattening. Interestingly, the phase rotation stops at about the same time that the tilt dominates for both cases. Since the same behavior is seen at all three z planes, it is possible that this phase rotation could represent a physical rotation of the plasma. Although a more detailed analysis is required, the velocities inferred from r dϕ/dt are slower than the sound speed (and the Alfvén speed).

The remaining part of this paper briefly describes the previous magnetic reconnection studies at SSX. For this work, the two spheromaks were contained in nearly independent flux conservers. The spheromaks were allowed to interact only through sector-shaped slots cut in the midplane walls of each flux conserver. Reconnection occurs when magnetofluid from the two counter-helicity spheromaks flows into and across the slots. The first goal of this design was to create this well-defined region where diagnostic attention could be focused. The primary tool used was a compact 5×5×8 array of three-component magnetic probes which permitted a detailed study of the reconnection magnetic field structure in three-dimensions and at sub-microsecond time resolution [11]. The second goal of this design was to examine the energetic ion distribution for indications of direct ion acceleration in the reconnection electric field. In the midplane gap (2.5 cm) between the two flux conservers, but outside of the immediate magnetofluid-filled region of the slots, energetic ions traversed a high-vacuum, field-free drift region to electrostatic detectors where their energy distribution could be analyzed.

Results of these reconnection studies by partial or “mechanically restricted” merging have been reported elsewhere [13,14,15]. To summarize, the three-dimensional magnetic structure measurements indicate that at the core of the reconnection region there is a magnetic field component normal to the reconnection plane; this component is not a guide field remaining from a net helicity imbalance, but rather seems to be self-generated [14]. The ion energy analyzers indicate that the energy distribution of ions ejected normal to the reconnection plane is consistent with the thermal distribution of the bulk, but with a super-Alfvénic drift energy [13].

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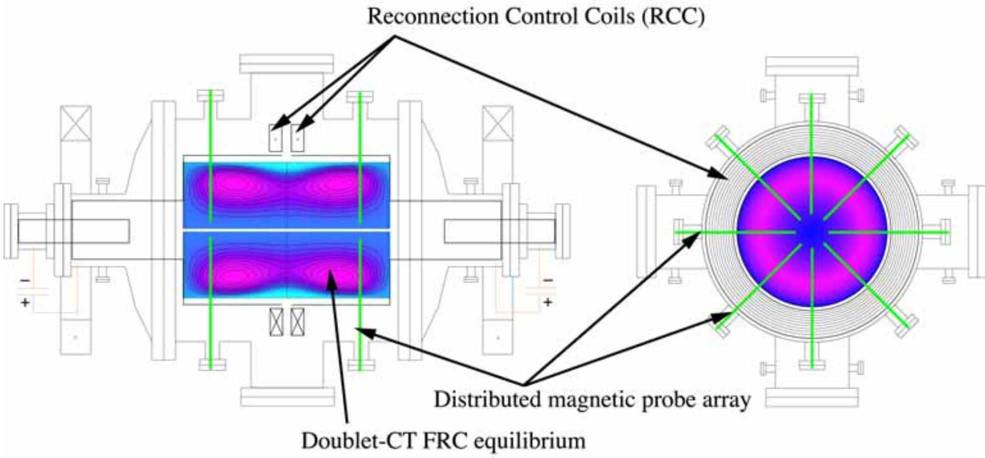

Figure 1

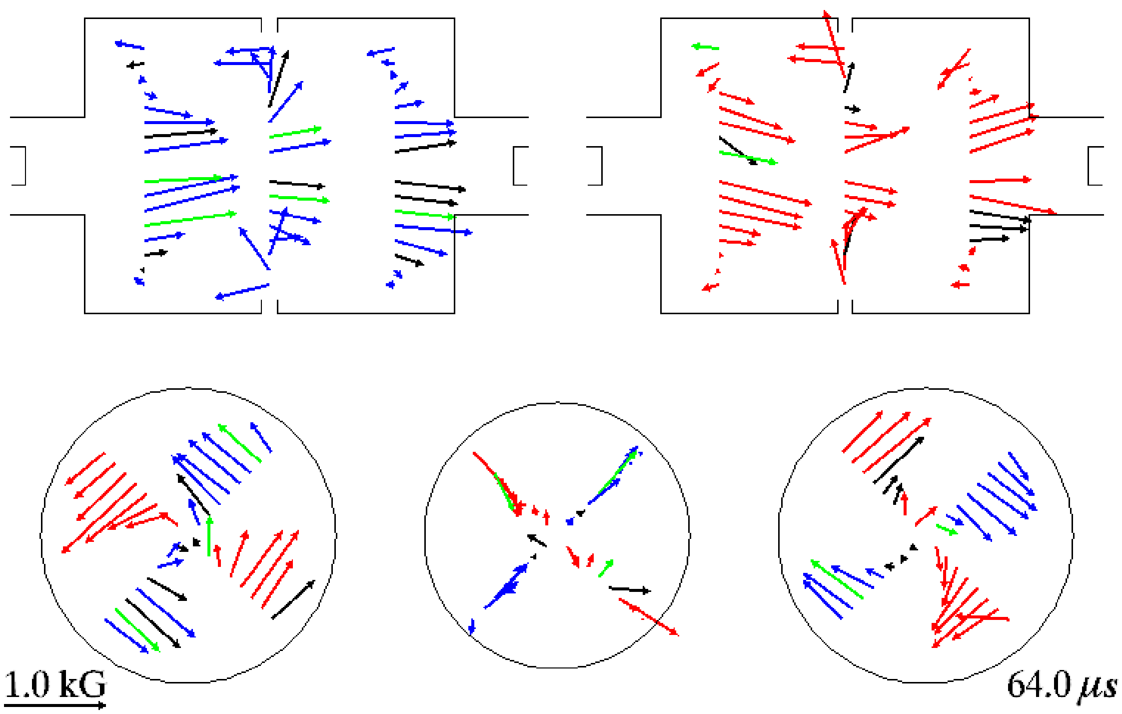

Figure 2

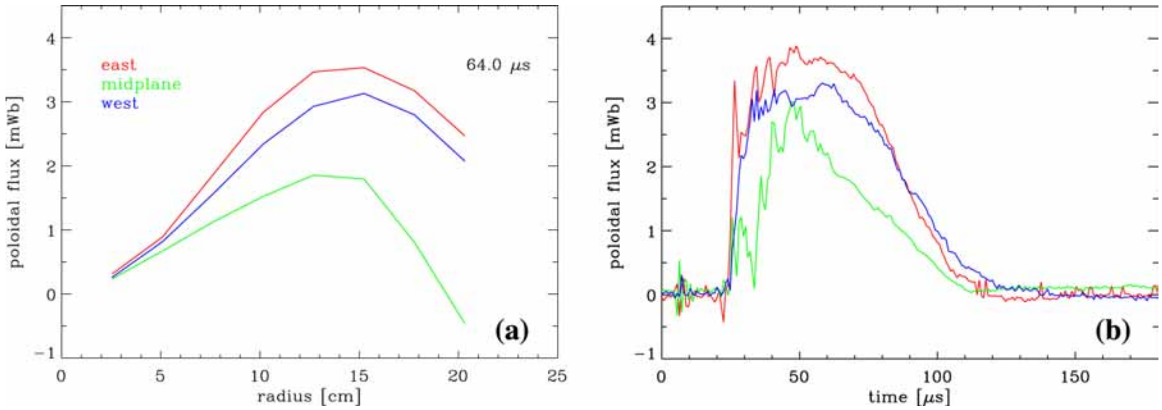

Figure 3

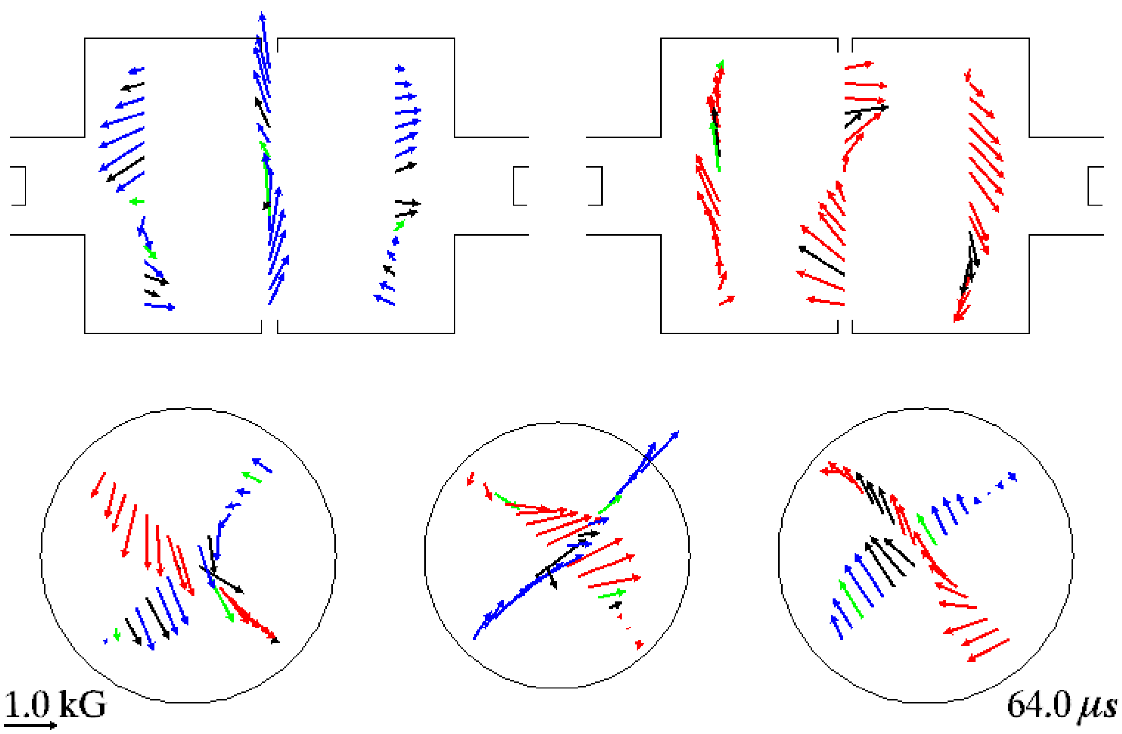

Figure 4

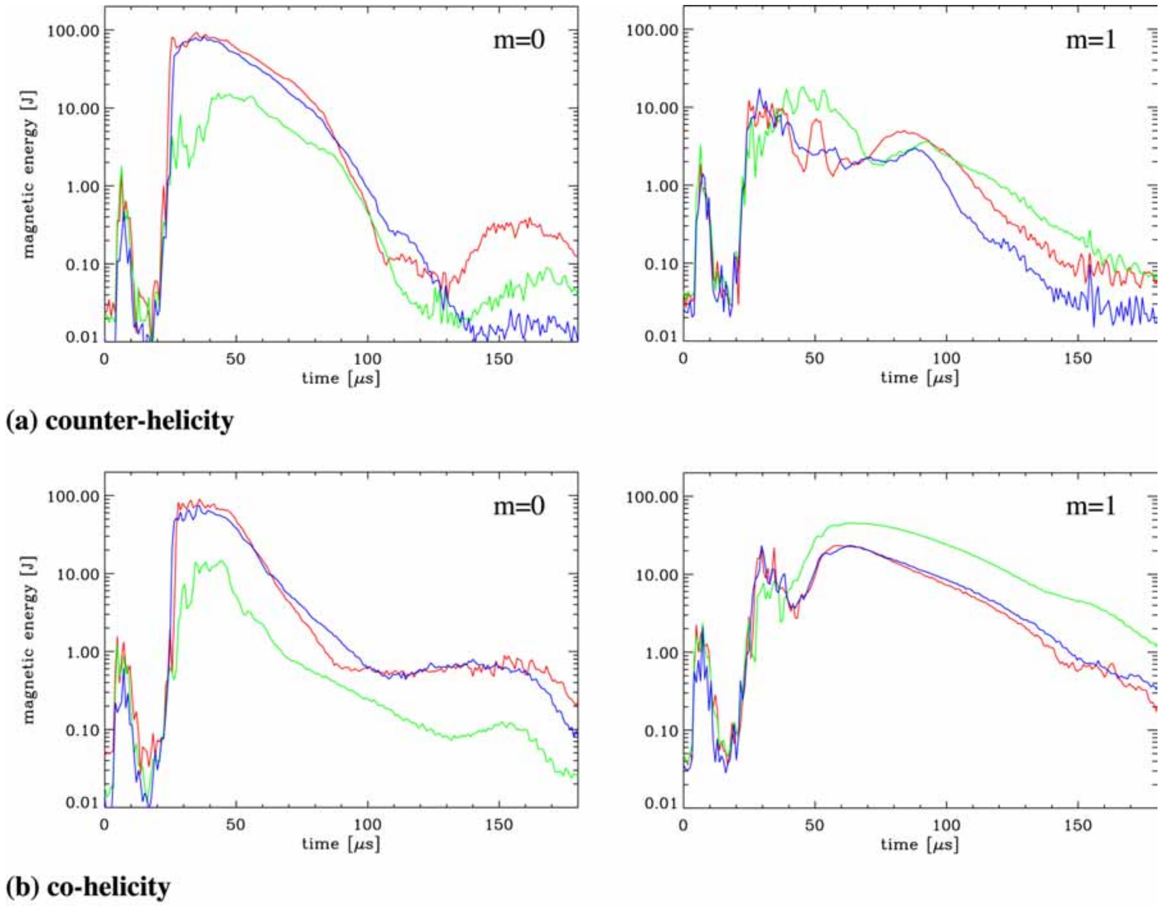

Figure 5

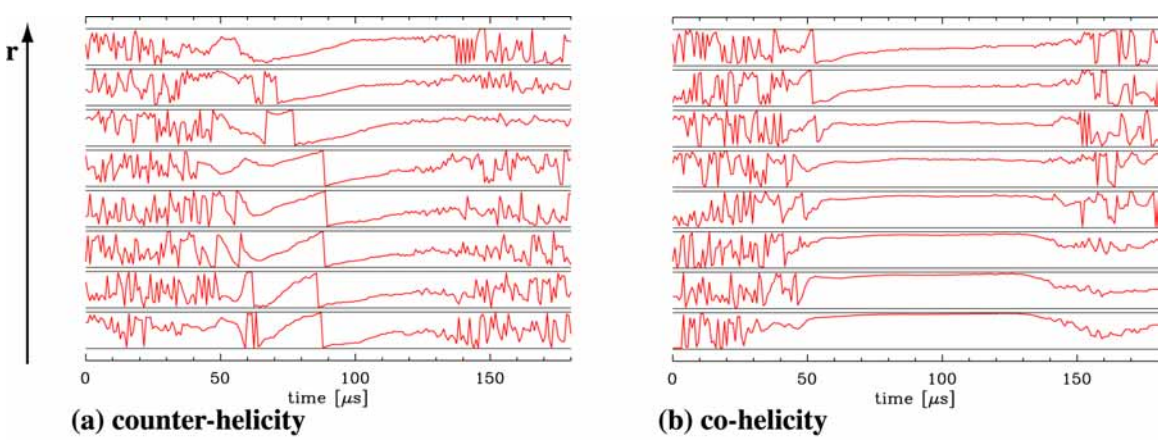

Figure 6