MEETING REPORTS

REVIEW OF THE FIFTH SYMPOSIUM ON THE PHYSICS AND TECHNOLOGY OF COMPACT TOROIDS, BELLEVUE, WASHINGTON, NOVEMBER 16-18, 1982

This meeting, hosted by Mathematical Sciences Northwest (MSNW), was conducted in a workshop format divided into two sections: (a) formation of field-reversed configurations (FRCs) and spheromaks and (b) equilibrium, lifetime, and stability of FRCs and spheromaks. The Formation Workshop was chaired by Richard Milroy (FRC) and George Goldenbaum (Spheromak). The Equilibrium, Lifetime, and Stability Workshop was chaired by Richard Siemon (FRC) and Masaki Yamada (Spheromak). Review talks on the four subjects were given by Tom Armstrong, Stephen Paul, Loren Steinhauer, and Tom Jarboe, respectively. Additional review talks on particle ring formation, stability enhancement, FRC/spheromak comparisons, and reactor considerations were given by Hans Fleishman, Ravi Sudan, George Vlases, and Randy Hagenson. There were an additional 39 poster papers presented to the 70 registrants.

The formation workshop primarily addressed the questions of slower generation methods and scaling to large sizes. For FRCs, the principal emphasis was on the achievement of gentler density gradients through increasing $x_s = r_s/r_c$ (where r_s is the separatrix radius and r_c is the coil radius). Methods were proposed to increase x_s either by increasing the poloidal flux through better formation methods or by reducing the external flux through translation into a smaller flux conserver. Present theta pinch generation methods are limited to operating at relatively low-bias fluxes due to triggering destructively violent axial implosions if the trapped flux is too high. A strong desirability was also expressed to develop slower formation techniques that would allow high poloidal fluxes to be obtained and that would be compatible with reactor engineering requirements. It has recently been demonstrated on the triggered reconnection experiment (TRX) at MSNW that theta pinch flux trapping can occur on a diffusive timescale rather than the shorter radial Alfven time. However, during field reversal, the plasma rests on the wall, is unconfined at the ends, and is thus relatively cold. Although methods were suggested to alleviate these problems and the technique may still be acceptable for reactors, there was still a strong consensus to explore truly equilibrium formation techniques where the plasma can be hotter, the diffusive timescale longer, and strong axial implosions can be avoided. The coaxial theta pinch was proposed as part of such a formation scheme. Since slow formation schemes may not produce sufficient plasma heating, a desire was also expressed to investigate auxiliary heating techniques. The reactor desirability of translation and translation with adiabatic compression was also stressed.

The primary formation issue for spheromaks was the reduction of impurities and the attainment of higher electron temperatures. Slow formation has been demonstrated in the compact toroid experiment (CTX) coaxial gun at Los Alamos National Laboratory (LANL) and in the purely inductive proto S1 devices at Princeton Plasma Physics Laboratory. Spheromaks have also been formed in combination z-θ pinches and conical theta pinches. However, the temperatures have in all cases been limited to <40 eV. There is a strong indication that the LANL-gun-produced spheromaks may be beta limited. To increase the plasma temperature of beta-limited spheromaks, it is necessary to increase the magnetic field radius (BR) product, which means operating at higher currents. This scaling will be tested on the S1 device, and also on the LANL gun, if the impurity level can be held down as the current is raised.

The ability to form spheromaks using a wide variety of methods was taken as a strong indication of the universality of the principal of relaxation to a "Taylor" nearly force-free state. In a manner similar to reverse field pinch (RFP) formation, where helicity is added through the supply of poloidal flux, spheromaks can be formed with primarily toroidal flux addition. This raises the possibility of steady-state operation through purely toroidal flux (and helicity) addition using external electrodes. A method was proposed based on the slow formation techniques applied to CTX. However, no detailed calculations were presented on the effects of the electrodes on impurity generation or thermal energy loss.

Some discussion was also held on the formation techniques for energetic particle rings. These rings were thought of mainly as having applications for stabilizing otherwise unstable compact toroids, and a principal formation issue will thus involve the merging of these rings with previously formed compact toroids (CTs). While energetic, field-reversing rings have been formed in a number of experiments, no work has been attempted on merging them with compact toroid plasmas.

In the Equilibrium, Stability, and Lifetime Workshop, the large difference between FRC and spheromak physics was apparent. Spheromaks have more in common with the physics of RFPs than with FRCs, and FRCs are a rather unique plasma entity whose stability and transport may be governed by the high-beta equilibrium ($\langle\beta\rangle = 1 - x_s^2/2$) imposed by present elongated, low-x_s geometries. Common attractive features of the compact toroids are the simply connected geometry, the natural divertor action, and, at least for FRCs, the ability to translate the configuration from a generation point to a burner location. Since FRCs will have configuration lifetimes, set by flux loss, that may only exceed the particle lifetime by a factor of several, and since they will be difficult to reflux, they were mainly considered for pulsed reactors such as the moving ring type. The observed inherent stability, high density, and flux conserver geometry make them ideal plasma configurations for such applications. Spheromaks, on the other hand, are lower beta and thus will have configuration lifetimes at least an order of magnitude longer than their plasma energy lifetimes. Because of the Taylor relaxation process, there is also a possibility of refluxing them through the addition of toroidal flux alone. Based on this refluxing possibility, and on perceived difficulties in maintaining stability while translating, spheromaks were thus considered primarily for long burn time or steady-state applications.

One of the most significant accomplishments in FRC physics this last year has been the stabilization of the $n = 2$ rotational instability using multipole barrier fields. This has been demonstrated using octopole fields on TRX and quadrupole fields on a 15-cm-diam theta pinch (PIACE-II) at Osaka and preliminarily on the large 50-cm-diam field-reversed experiment (FRX-C) at LANL. The critical multipole field required for stability is accurately predicted using a magnetohydrodynamics (MHD) analysis, so that this solution should remain effective as the FRC size is scaled up. The MHD calculations on the tilting instability have been extended to the particular racetrack-like FRC equilibria and, if anything, the predicted instability growth rates are faster than for less prolate geometries. This discrepancy between MHD theory and experimental observations is believed to be due to kinetic effects of large orbit ions. Thus, it is possible that larger, lower average beta plasmas may not have the favorable stability characteristics of present FRCs, and it is desirable to extend the present experimental results to lower beta, larger FRCs.

Another important FRC result is the quadrupling of particle lifetime due to a doubling of plasma radius on the 40-cm-diam FRX-C device. This tends to confirm the expected R^2 scaling predicted by transport calculations based on lower hybrid drift (LHD) anomalous resistivity. There was considerable discussion over the exact form of the scaling, the true anomalous collision mechanism, and the expected behavior at lower beta and larger sizes when the internal plasma becomes more highly magnetized. Transport for present-sized FRCs is dominated by the high-density gradient near the separatrix, and the average diffusion coefficient is not predicted to decrease as the FRC radius increases, even though the drift velocity for the majority of the plasma inside the separatrix is decreasing. There is some hope that the particle loss rate will more closely approach classical as the device size increases to the point where the diffusion timescale for the inside plasma dominates the endflow rate of the plasma outside the separatrix. Present theory also predicts that the particle loss rate will decrease rapidly if x_s can be increased and the average plasma beta lowered. Both effects will reduce the pressure at the separatrix and tend to make the open field line loss processes less significant.

One other method proposed to lower the density gradients was to alter the equilibrium to make the FRC less prolate. However, this may result in the tilting or shifting instabilities endemic to spheromaks. It was suggested that energetic particle rings might be useful in promoting stability for these less elongated, more fluid-like FRCs.

One other potential problem with FRCs is a high-electron thermal loss rate. All present experiments produce FRCs with electron temperatures between 75 and 175 eV, while the ion temperatures may be several times higher. Although impurities may be a contributing factor, the present electron energy loss rates are on the order of the Bohm rate. The open field line plasma will always be cold since it is in contact with material walls, and the closed field line loss times must exceed Bohm diffusion times by over a factor of 100 for reasonable reactor energy gains to be realized.

It was apparent in the symposium that there is a strong need for more theoretical work, especially work encompassing kinetic ion effects, on the physics of the extremely high-beta FRC transport. The analytical modeling using localized LHD transport has been extremely effective in predicting particle loss rates, but cannot explain the measured flux decay rates, which are several times classical, nor the rapid electron thermal loss rates.

The discussion on spheromak equilibrium, lifetime, and stability was focused on stability issues since, in most experiments, the lifetime is governed by impurities and very little information is available on the relevant transport mechanisms. There is some evidence that the CTX-gun-produced spheromaks are beta limited, rather than radiation limited, and that this is reflected by a particle pumpout to low, 3×10^{13} cm^{-3} densities. The present spheromak energy loss rates are very high, with significantly lower $n\tau$ products than for smaller sized FRC plasmas. However, one might expect more favorable size and temperature scaling, similar to that seen on RFPs, where the density and temperature scale proportionately with the total current. In the regime where the beta limit applies, the energy lifetime increases as $T_e^{3/2}$. This is in contrast to the lack of a strong temperature dependence seen on FRCs. Thus, spheromaks might eventually be expected to have lower transport loss rates than FRCs, which would compensate in part for their lower densities. Considerable work remains to be done, however, to even begin to realistically estimate transport losses in the presence of the yet undefined processes that maintain the Taylor minimum energy configuration.

The most important recent spheromak results relate to stability. The gun-produced spheromaks in CTX exhibit MHD stability against all modes for a lifetime (1 ms) that is determined by energy loss rates. However, this is accomplished with a close-fitting flux conserver such that the separatrix rests against the metal wall. Rapid plasma terminations have been observed in the similar Osaka gun-produced spheromak experiment (CCTX) when titanium gettering cleanup procedures were followed to extend the lifetime. Both the CTX and CCTX flux conservers are oblate but have some geometric differences, so that the exact shape may be important. Great strides have been taken in the PS-1 z-θ pinch spheromak device at the University of Maryland, and in the proto S1 devices to achieve stability of spheromaks without closely fitted walls. The presence of the open field line flux needed for equilibrium makes these spheromaks naturally unstable to tilt modes. Combinations of figure-eight coils, saddle coils, and, in the case of the Maryland experiment, close-by resistive walls, are effective in simulating the image currents produced by a close fitting flux conserver. However, at least in the proto S1 devices, these mechanisms only delayed the onset of tilting, but did not prevent it. An internal conductor was found necessary to fully stabilize the tilt mode, which some would say violates the spirit of the compact toroid designation. However, reactor scenarios were presented that encompassed translation along a conducting core to a closely fitting burn chamber. One of the most important unresolved spheromak questions is how close this wall must fit to avoid tilting, and whether this close fit makes reactor applications impractical.

A general feeling of the CT researchers attending this symposium was that the CT program has made great progress in the past year in both experimental results and in an understanding of the remaining physics questions. The achievement of long lifetime and the demonstration of slow formation techniques for spheromaks, and the attainment of rotational stability and $n\tau$ products several times 10^{11} $cm^{-3}\cdot s$ for FRCs is truly impressive. We look forward in the next year to results from the Princeton S1 device, which should begin operation in the spring of 1983, and to continued progress in all present compact toroid experiments.

The proceedings can be obtained from Mathematical Sciences Northwest.

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