The Cornell Ion Ring Program

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The Cornell Field Reversed Ion Ring Experiment, FIREX, has the goal of studying FRC's with a substantial fraction of the current carried by energetic,large-orbit ions. This goal is being approached by producing diamagnetic ion rings, using pulsed-power ion beam generation technology. FIREX now produces rings whose current and diamagnetism easily would satisfy the requirements for our goal, if their lifetime were long enough to inject into an FRC. However, we have found that these very strongly diamagnetic rings lose energy very fast to interactions with waves of the background plasma, and the Cornell program is presently focused on understanding this interaction.

The FIREX beam is generated in a magnetically-insulated ion diode by a 600 kV, 1.4 ohm, 150 ns accelerating pulse. The 10-15 cm radius, annular beam is injected axially through a magnetic cusp into a 6 kG solenoid. The flux crossed in traversing the cusp induces rotation in the beam, and produces a diamagnetic, rotating ring of protons whose orbits encircle the axis. FIREX has reached a regime where ring diamagnetism (magnetic field change from inside to outside the ring) is routinely more than one-third of the initial 6 kG solenoid field, with more than 1.5 kG self-field appearing on axis. The rings have ~10 cm radius, are ~ 30 cm long axially, and have over 100 kA current. These are the strongest self-fields ever produced with ion rings.

Very large-amplitude waves are launched in the preionized background plasma by the entering ring, and the momentum exchanged between the ring and these alfven waves very strongly affects the ring dynamics. The good effect of this interaction is to brake the ring axial motion as predicted by theory and simulation, but a bad effect is the development of unstable azimuthal modes that take energy from the ring ions and limit the ring lifetime. These very strongly nonlinear interactions have considerable interest as a basic plasma physics phenomenon, and in a practical sense they must be understood and controlled if FIREX is to reach its goal of studying field-reversed ring configurations. These phenomena may also have important implications for other magnetic fusion concepts.

The FIREX background plasma is made by an axial discharge in low-pressure (1 mTorr typical) hydrogen, and has an initialdensity of order 10^14/cm3 and temperature of ~3 eV. We observe heating of this plasma to over 100 eV ion temperature when the ring is injected, by Doppler broadening of spectral lines. This heating is much faster than can be explained by ring proton- plasma particle collisions, and clearly comes from anomalous dissipation of the very large-amplitude waves excited by the ring. Analysis of these results is underway to develop an independent measure of the energy coupled from ring to waves to plasma. So far, this diagnostic has been used with microsecond time resolution to observe the plasma heating and relaxation on a timescale long compared with the ring injection time, but the sensitivity is very high and our results indicate that it may be possible to resolve plasma response even on the submicrosecond ring timescale, which would give detailed information on the ring-plasma dynamics and would represent a substantial diagnostic achievement.

To fully track the ring dynamics, we have developed new ring proton diagnostic arrays which are now bringing us to a final quantitative accounting of the ring from injection to loss from the system. We have found that a substantial fraction of the ring exits the system by losing energy to azimuthal wave modes, which reduces the transverse (azimuthal and radial) velocity of the ring protons. The result is that a large population of ring particles appears at radius less than about 8 cm, which is inside the inner ring radius of 10 cm predicted by axisymmetric (r-z) simulations, but consistent with the (r-theta) simulations which show energy loss. Since these protons lose much more azimuthal than axial velocity, their pitch angle decreases, and they easily exit through the loss cone of the downstream magnetic mirror field in FIREX. The basic picture of azimuthal instability has also been clarified by using diagnostic arrays with azimuthal resolution which show strong modulation of the ring current developing as the ring moves downstream in the plasma.

Effort has also been devoted to development of magnetic probe arrays to give detailed measurement of the magnetic field of the wave modes. These probes also show strong modulation at frequencies near the ion cyclotron frequency. We are presently obtaining data on the detailed radial and azimuthal structure of the waves, for comparison with simulations. Arrays of Bdot loops show waves propagating from the ring annulus inward to the axis, and the speed is consistent with an initial Alfven Mach number of <3 for the ring ions, which is in the range of very rapid energy loss in simulations.

All of this work has served to establish firmly that the very short ring lifetime in FIREX, only about five ion gyroperiods, is largely due to energy loss to azimuthal alfven unstable modes, a basic effect which was not previously examined in detail in the long history of ion ring theoretical work. This fundamental result has led to a reorientation of the Cornell program toward understanding and controlling this instability to find a regime of long-lived ring formation, and to find its implications for other magnetic fusion concepts, since fusion alphas would have similar alfven mach number in burning plasmas.

Theory and simulation efforts in our program are centered on the investigation of the azimuthal ring-plasma dynamics. The 2D hybrid code FIRE developed at the beginning of this program has been adapted from its original r-z geometry to run in the r-theta plane (actually x-y) geometry to look at the azimuthal dynamics, and has found instability which has features similar to experimental observations, as we will discuss. The analysis of these results is leading to understanding of this new regime, and has suggested several important questions for further investigation.

New code diagnostics have been developed to allow visualization of electric and magnetic fields and test particle orbits in the transverse plane. As a result we have been able to better characterize the physics of the azimuthal ring instability first identified last year. Studies of the character of ring-wave interaction and instability growth rate have been done as a function of alfven speed and resistivity in the background plasma.

Not surprisingly, the regime of resistivity and alfven mach number that result in rapid braking of the ring axial motion also gives strong growth of azimuthal modes and results in very short ring lifetime. Simulations in a regime similar to FIREX conditions give ring lifetime of order 5-10 ion cyclotron times, similar to experiment. The ring protons lose energy in the wave electric fields. The structure of these fields is dominated by the development of very sharp gradients on the scale of c/ω_{pi} implying an important contribution by two-fluid physics. Though the code physics is adequate to model the development of these structures, dissipation mechanisms may not be adequately modeled, and theoretical effort is now being devoted to analysis of this issue. Similar issues have arisen recently in other areas of FRC theory, and we hope to be able to make a significant contribution to the general understanding of the role of two-fluid effects with this work. The ion ring-plasma system appears to be an ideal system for the observation and analysis of these collective effects of super-alfvenic ions.

FIRE has also been used this year to produce simulations of ring distributions other than the standard axis-encircling cusp-injected rings. In particular, we have found that ring distributions that are less highly singular but rather are quasi-thermal, show much greater stability against energy loss than the standard FIREX rings. Such distributions would be produced by orbits that do not symmetrically encircle the ring axis, for instance rings in which the injected ions have larmor radius in the initial field that is half or less of the ring radius.

One long-standing question has recently been answered by a simulation which shows a ring in which the initial ion orbits are not axis-encircling undergoing a relaxation process in which angular momentum is exchanged among particles and waves resulting in axis-encircling orbits and finally field reversal on axis. This regime of physics with diamagnetic pressure supplied by the kinetic ion species is entirely different from and complementary to the MHD picture of FRC's. Thus our simulation efforts are now directly attacking the overall goal of our program, to study and understand the physics of FRC's with large-orbit (high-pressure) ion distributions.

Following the prediction of simulation that rings with more “thermal”, broader distributions are more stable than the narrow-annulus present FIREX rings, we have designed and carried out the first test of an entirely new scheme for strong ion ring formation, using a coaxial ion diode and radial injection into the solenoidal confining field. This first run was successful in showing that substantially more ion charge, at least a factor of two more, could be produced in the solenoid than with the standard FIREX axial cusp injection. The run was terminated to make engineering improvements to the new systems. This scheme appears to be the best route to achieving the amount of ring charge needed for full field reversal and the improved systems will be installed for a second run beginning at the end of this year.

Briefly, the new diode consists of a coaxial, biconic self-magnetically insulated feed to a diode with 5 cm radius anode composed of a preionized hydrogen plasma confined radially in the solenoid field. Protons are accelerated radially outward from the anode plasma, rotate in the solenoid and form a ring. In summary, in the first run this diode produced more than 19 mC of proton charge in a remarkably uniform beam produced over more than 30 cm axial length of the diode, versus 8 mC in optimized operation of the standard FIREX cusp diode. This increased charge, if it can be formed into a well-organized ring, could produce field reversal in FIREX. During this run, the diode operation was not reliable because of high-voltage breakdowns in the plasma source driver. The run was therefore terminated without being able to attempt to tune the diode voltage and solenoid field to properly confine the rings. Redesign of the high-voltage plasma driver is complete, and new parts are being fabricated for a second run at the end of this year. With reproducible operation of the plasma source, the system should be ready for optimization of proton output and first observations of ring dynamics.

During the next year, we intend to aggressively develop the new radial injection scheme, due to its demonstrated ability to provide a large increase in the total ring charge and therefore field reversal. We believe this is the best candidate for achieving full field reversal by ions on FIREX. We will continue to analyze the ring stability and lifetime issues we have identified, to find if the ring distribution provided by the radial injection configuration can indeed produce a much more stable, long-lived ring.