COMBINED FRC AND MIRROR PLASMA STUDIES IN THE C-2 DEVICE

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The Field Reversed Configuration (FRC) is a high-beta Compact Toroid that includes closed and open field line regions of poloidal magnetic field. Improving the transport properties of both regions is important for the overall FRC confinement and may be attempted in the C-2 device. The goal of this experiment is to explore FRC sustainment by combining heating and current drive from neutral beam injection and particle fueling from a pellet injector. Additions to the C-2 device may include magnetic mirror plugs, plasma guns, and electrically-biased limiters. These additions would permit us to explore combined FRC and mirror physics, with emphasis on improving the FRC confinement.

I. INTRODUCTION

FRCs are prolate compact toroid plasmas that are ideally confined by purely poloidal axisymmetric magnetic fields.[1] These very high beta plasmas offer many potential advantages as a fusion reactor, including the possibility of using aneutronic fuels. Fig. 1 illustrates typical FRC magnetic flux and density contours. These contours are obtained from a 2-D MHD numerical simulation of the C-2 device, performed with the Lamy Ridge code recently developed for our experiment.

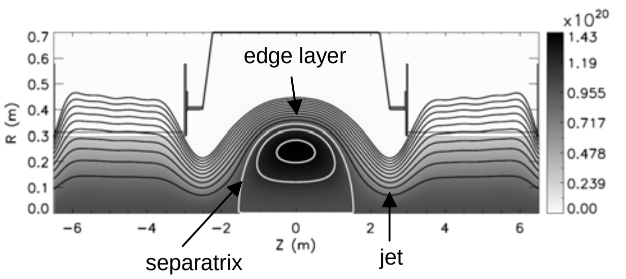

Fig. 1. The FRC magnetic topology

As seen from Fig. 1, the FRC consists of a torus of closed field lines inside a separatrix, and of an annular edge layer on the open field lines just outside the separatrix. The edge layer coalesces into jets beyond the FRC length, providing a natural divertor. The FRC topology coincides with that of a Field-Reversed-Mirror plasma.[1,2] However, a significant difference is that the FRC plasma has $\beta \sim 10$ (β is the ratio of the average plasma pressure to the average magnetic field pressure inside the separatrix). Present FRCs appear grossly stable, presumably because of strong kinetic effects (the internal ion gyroradius is comparable to the FRC minor radius a).

The energy confinement of present FRCs is dominated by particle loss. Particles diffuse primarily radially out of the separatrix volume, and are then lost axially in the edge layer. Accordingly, the FRC confinement depends on the properties of both closed and open field line regions. The particle diffusion time out of the separatrix scales as $\tau_\perp \sim a^2/D_\perp$ ($a \sim r_s/4$, r_s is the central separatrix radius), where $D_\perp$ is a characteristic FRC diffusivity. The edge layer particle confinement time $\tau_{//}$ is essentially an axial transit time in present FRC experiments, but it could be increased in future experiments. In steady-state, the balance between radial and axial particle losses yields[1] a separatrix density gradient length $\delta \sim (D_\perp \tau_{//})^{1/2}$. The FRC particle confinement time scales as $(\tau_\perp \tau_{//})^{1/2}$ for present FRCs that have substantial density at the separatrix.[1]

The C-2 experiment[3] aims at developing the scientific basis for steady-state FRCs. Sustainment will be attempted by combining heating and current drive from neutral beam injection, and particle fueling from pellet injection. To maximize success, it is desirable to first improve as much as possible the FRC confinement. Several techniques are being considered to improve both $\tau_\perp$ and $\tau_{//}$ on the C-2 device, as will be detailed later in this paper.

II. C-2 INITIAL RESULTS

The C-2 device[3] presently consists of a central confinement region surrounded by two reversed-field-theta-pinch formation regions, and by two divertors, as shown in Fig. 2. The confinement vessel and the divertors are made out of stainless steel. The pulsed formation regions are made of quartz. The system has a typical vacuum base pressure of about 10^{-8} Torr.

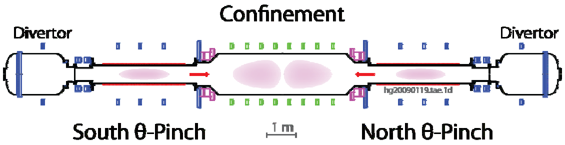

Fig. 2. Sketch of the C-2 device.

A coil set generates a quasi-static (3-s-pulse) magnetic field through the device. Typical axial magnetic fields are 0.1 T in the confinement region, and the end mirror ratios are presently limited to about 5. In addition, weak quadrupole fields (~ 10^{-2} T) can be used to control FRC rotational instabilities.[1] Two FRCs are formed in the theta-pinches with reversed bias fields ~ 0.05 T and main fields ~ 0.4 T. The latter fields are time-sequenced to form and accelerate the FRCs into the confinement vessel.[3]

The two FRCs collide in the center of the device, their axial kinetic energies are largely thermalized, and they appear to gradually merge into a single FRC, although some internal doublet structure may linger.[3] Many plasma diagnostics are available in the confinement vessel to study the FRC equilibria. After just one year of C-2 operation, record FRC lifetimes over 1 ms have been achieved with typical separatrix radii ~ 0.4 m, lengths ~ 3 m, external magnetic fields ~ 0.1 T, plasma densities ~ 5×10^{19} m^{-3}, ion temperatures ~ 0.4 keV, and electron temperatures ~ 0.1 keV.

Data from a representative C-2 discharge are shown as functions of time in Fig. 3. The theta-pinch main fields start at t = 0. The excluded flux radii at z = 0, 0.7, 1.2, and 1.7 m are shown in Fig. 3(a), from 4 (of an array of 17) B_z probes located just inside the confinement chamber stainless steel wall. The latter is a good flux conserver for present FRC lifetimes. The central excluded flux radius (top curve in solid line) approximates the FRC separatrix radius r_s.

Line-integrated densities are shown in Fig. 3(b), from a 6-chord CO_2/He-Ne interferometer[4] located at z = 0. Taking into account vertical (y) FRC displacement, Abel inversion yields the density contours of Figs. 3(c) and 3(d). After some axial and radial sloshing during the first 0.1 ms, the FRC settles with a hollow density profile. This profile is fairly flat, with substantial density on axis, as required by typical 2-D FRC equilibria.[1] The time zoom from 20 to 50 μs in Fig. 3(d) reveals a dense bicycle-tire toroidal structure during the collision (t ~ 30 μs), that quickly fills inward.

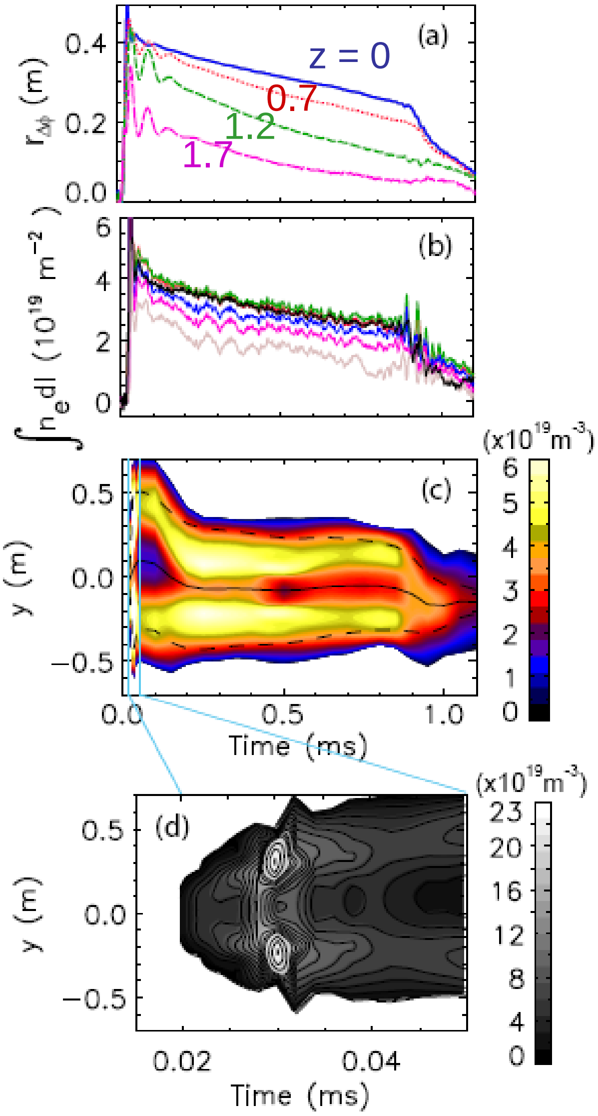

Fig. 3. Data from the C-2 discharge 11203. Shown as functions of time are (a) selected excluded flux radii, (b) 6 chords of line-integrated density from the midplane CO_2 interferometer, (c) and (d) Abel-inverted density radial profiles from the CO_2 interferometer data.

Analysis from the entire excluded flux array indicates that the r(z) shape of the FRC separatrix (approximated by the excluded flux axial profiles) evolves gradually from racetrack to elliptical. This evolution, shown in Fig. 4, may be consistent with a gradual magnetic reconnection from two to a single FRC. Indeed, rough estimates suggest that only about 10% of the initial FRC magnetic flux has time to reconnect during the collision.[5] Incomplete reconnection at early times is also observed in Lamy Ridge numerical simulations of the C-2 experiment. However, the inner magnetic structure of the FRC remains unresolved.

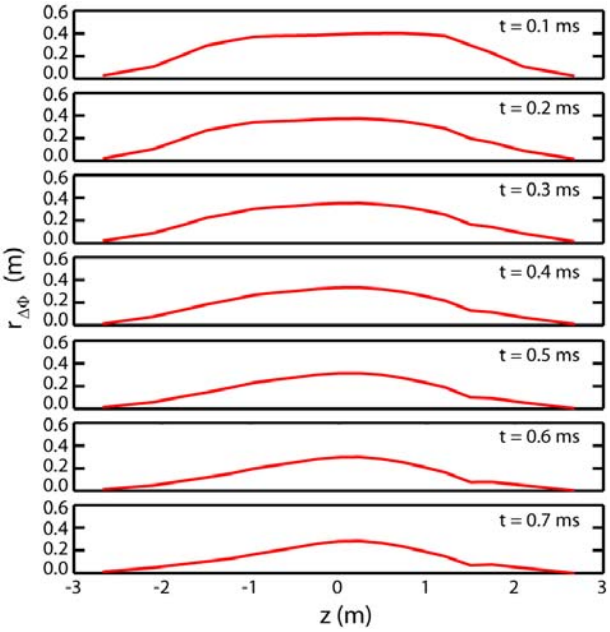

Fig. 4. Excluded flux axial profiles at selected times for the C-2 discharge 11203.

The FRC length shrinks steadily from 3 down to about 1 m during the FRC lifetime. This shrinkage, visible in Fig. 4, suggests that energy loss (mostly particle loss) dominates the FRC confinement. As the plasma pressure inside the separatrix decreases faster than the external magnetic pressure, the magnetic field line tension in the end regions compresses the FRC axially, restoring axial and radial equilibrium.

For the discharge in Figs. 3 and 4, the FRC magnetic flux, particle inventory, and thermal energy (~ 10 mWb, 7×10^{19}, and 7 kJ at t = 0.1 ms, respectively) decrease by about an order of magnitude by t ~ 0.9 ms, when the FRC equilibrium appears to subside.

III. IMPROVING THE INNER FRC

The example in Figs. 3 and 4 is characteristic of a decaying FRC without any sustainment. Several additions to the C-2 device are considered to further improve the inner FRC confinement. First, 20 keV neutral beams are being installed in the confinement region. The fast (H) neutrals are injected perpendicular to the axial magnetic field. The fast ions, created primarily by charge exchange, have betatron orbits that add to the FRC azimuthal current. Hopefully, a sufficiently large fast ion population may improve significantly the FRC stability and confinement properties.[6]

The fast ions slow down primarily on plasma electrons. Typical orbit-averaged slow-down times are 0.3 – 0.5 ms, which should result in significant FRC heating. The fast ions make large radial excursions outside of the separatrix because the FRC internal magnetic field is inherently low (~ 1/3 of the wall magnetic field). The fast ions may therefore be vulnerable to charge exchange loss if there are many neutrals outside of the separatrix. A major focus of present C-2 experiments is to minimize edge neutrals as much as possible with wall gettering techniques.

If a significant fast ion population can be built up within the FRC, together with higher electron temperatures and longer FRC lifetimes, frozen H or D pellets could be injected to sustain the FRC particle inventory. A 12-barrel PELIN pellet injector[7] is ready to be installed. The cylindrical pellets (D ~ 1 mm, L ~ 1 – 2 mm) would be injected into the FRC with a velocity in the range 150 – 250 km/s. Each pellet has ~ 5×10^{19} H atoms, which is comparable to the FRC particle inventory. The anticipated ablation timescales are sufficiently short to provide a significant FRC particle source.

IV. IMPROVING THE EDGE LAYER

IV.A Magnetic Mirror Plugs

Pulsed magnetic mirror plugs may be installed on the C-2 device between the formation regions and the end divertors. The plug magnetic fields would be in the range 2 – 3 T, yielding mirror ratios in the range 20 – 40. With a 15 m length between mirror plugs, the edge layer particle confinement time $\tau_{//}$ may be increased by at least an order of magnitude from present (~ 0.1 ms) values. Improving $\tau_{//}$ should increase the FRC particle confinement, as discussed in Section I.

The mirror plugs may also provide neutral gas control. The high-density plasma flowing through the plugs would provide efficient neutral ionization, as found in mirror machines.[2,8-10] Jet divertor recycling may be suppressed, and plasma gun (see next Section) neutrals would be mostly confined to the divertors.

IV.B. Plasma Guns

Plasma streams from end guns have been shown to improve plasma stability and neutral beam performance in mirror machines.[2,8-10] Such plasma guns may be mounted inside the C-2 divertors, delivering ~ 10 kA of fully ionized plasma for 5 - 10 ms. The gun plasma streams can penetrate strong end plug magnetic fields[2,8-10] and flow into the C-2 formation and confinement regions.

Assuming a 10% transfer efficiency through the end plugs,[8] the plasma guns could provide a particle source in excess of 10^{22} s^{-1}, sufficient for significant refueling of the FRC edge layer. The overall FRC particle confinement might then improve, as discussed in Section I.

IV.C. Electrical Biasing

Control of the radial electric field profile in the edge layer may prove beneficial to FRC research, as it is in many other magnetically confined plasmas. Radial electric fields can modify the azimuthal rotation of the edge layer, and improve its confinement by introducing E×B velocity shear.[11] The latter may also benefit the FRC confinement inside the separatrix.

Several methods to control the electric field of the edge layer may be explored in the C-2 device. The anode of the plasma guns could be electrically biased. Annular limiters electrically insulated from the confinement chamber walls may also be introduced to control the radial electric field of the edge layer.

V. CONCLUSIONS

The confinement properties of present FRCs depend on its closed and open field line regions, on either side of the separatrix. These FRCs are therefore hybrids between toroidal and open magnetically confined plasmas. Improving the confinement of both FRC regions is clearly desirable.

Large-size FRCs with record lifetimes have been recently produced in the C-2 device. These FRCs are suitable targets for neutral beam injection, similar to that in past Field Reversed Mirror experiments.[2] However, a significant difference is that the FRC target offers field reversal to begin with, rather than attempting to achieve it with the neutral beams.

Several tools are considered to further improve the confinement of C-2 FRCs. These tools include neutral beam injection and pellet refueling for the closed field line region inside the separatrix. Magnetic mirror end plugs, plasma guns, and electrically-biased limiters are also considered to improve the confinement of the FRC edge layer.

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