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TITLE: FRC CONFINEMENT STUDIES IN FRX-C

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FRC Confinement Studies in FRX-C

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The measured particle containment times of up to 190 μs in FRX-C correspond to R^2 scaling and agree with predictions based on lower-hybrid cross-field diffusion. Further improvement in confinement may be possible by translating a field-reversed configuration (FRC) in such a way as to increase x_s.

I. Introduction

The particle confinement in FRC plasmas has been experimentally investigated in the FRX-C device over a significant range of parameters. The results from this study, and data from the smaller FRX-B machine, confirm the approximate scaling of particle containment time with R^2/ρ_{io}. In addition, these results are in excellent agreement with predictions by Tuszewski and Linford[2] based on a model that assumes lower-hybrid cross-field transport driven by the sharp density gradients that are characteristic of the high-beta FRC equilibrium. The model also predicts that reduced density gradients resulting from increased x_s (the ratio of FRC separatrix radius to conducting wall radius) should result in substantial increases in particle confinement time. The ratio x_s can be increased by axially translating an already formed FRC out of the theta-pinch coil (formation region) into an appropriately shaped and magnetically biased flux conserver. Experiments in the next two years will involve translating FRCs, increasing x_s, and testing the predicted increase of particle confinement time.

II. Description of Experiment

The FRX-C device is a field-reversed theta pinch. The coil is 2 m long and 0.5 m in diameter; passive mirrors 0.20 m in axial extent and 0.44 m in diameter provide an on-axis mirror ratio of 1.17 at each end. The quartz discharge tube has an inner diameter of 0.4 m. The bias field is variable to about 4 kG. The main field rises in 4.5 μs to about 10 kG and has a crowbarred decay time of 300 μs.

An axial array of magnetic field probes is used to determine the excluded flux radius $r_{\Delta\phi}$. In regions of straight field lines the separatrix radius can be approximated as $r_s = r_{\Delta\phi}$ and the major radius is $R = r_s/\sqrt{2}$. A side-on 3.39-μm double-pass interferometer is used to measure $\int n dl$ through a diameter of the FRC near the coil midplane. Measurements of T_e by Thomson scattering are taken with the scattering volume located 5 cm off the coil axis and 10 cm from the coil midplane. Neutron emission is measured with a scintillator and an activation counter. An end-viewing, double-pass, ruby-laser holographic interferometer is used to measure particle inventory and radial density profile. Visible and VUV spectroscopy are used for line intensities and line broadening measurements.

III. FRC Formation Phase

The process of FRC formation in a theta pinch has been described elsewhere.[1] To form long-lived FRCs it is necessary to adjust empirically the initial fill pressure, bias field level, passive magnetic mirror ratio, and preionization conditions. The mirror ratio appears to have a strong influence on the field-line reconnection at the plasma ends. When first operated, FRX-C had a mirror ratio of 1.05. With an initial pressure of 20 mtorr of deuterium, the FRC shape as deduced from the magnetic probe array often lacked symmetry and indicated an axial movement of the FRC out of the coil. According to MHD code simulations, reconnection proceeds more rapidly if the mirror strength is increased, thus reducing the likelihood of reconnection asymmetry. A larger mirror ratio (1.17) was installed on FRX-C and the result was improved symmetry of the $r_{\Delta\phi}$ profiles and a reduced tendency for axial motion.

IV. Typical Plasma Parameters

Data obtained on a typical discharge at 20 mtorr fill pressure and 1.7 kG bias field are shown in Fig. 1 as a function of time. The external magnetic field waveform, B, is recorded near the coil midplane. The FRC length, $\ell_{\Delta\phi}$, is defined as the distance between the axial positions where $r_{\Delta\phi}$ decreases to 65% of its maximum value. The average density is defined as $\bar{n} = \int n d\ell / 4 r_{\Delta\phi}$. The value of $\bar{n}$ differs little from the volume-averaged density. The electron temperature measured by Thomson scattering on similar discharges is $T_e = 100 \pm 20$ eV. The total temperature, $T_e + T_i$ is deduced from pressure balance. The quiescent plasma confinement phase is terminated by a rotational n = 2 instability that begins at about 100 μs. The growth of the n = 2 distortion can be identified by the modulation of the side-on interferometer density data. End-on holograms also show the n = 2 nature of the instability.

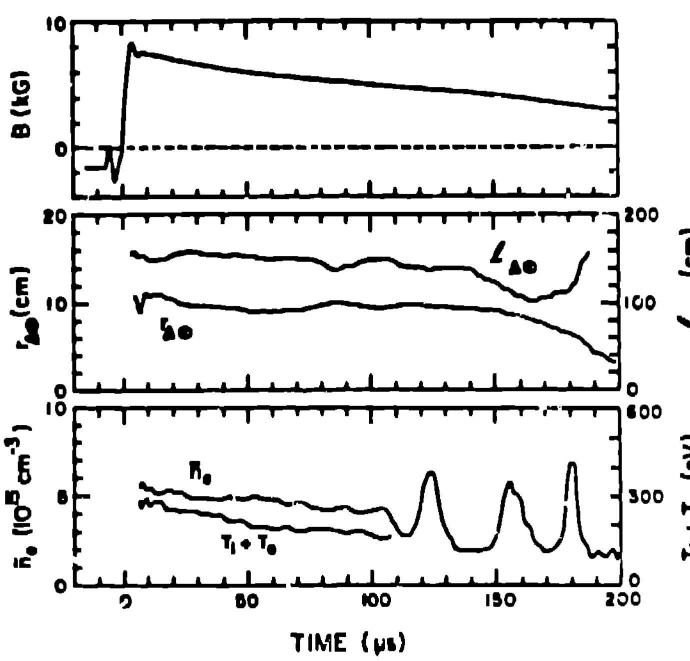

Figure 1.

Data obtained at 5 mtorr fill pressure display higher temperatures, measurable neutron emission, and shorter quiescent periods. Assuming a Maxwellian ion velocity distribution, the measured neutron emission, combined with density and volume measurements, corresponds to a peak ion temperature of about 1.0 keV at 10 μs. Line broadening of CV, if interpreted as thermal Doppler broadening, corresponds to T_i of about 3 keV at 10 μs, or about five times the pressure balance temperature, dropping to a factor of two at 30 μs. The pressure balance temperature of about 0.5 keV is considered the most reliable, but further study of this issue is needed. Electron temperature from

Thomson scattering is 175 ± 25 eV.

V. Scaling of Particle Confinement

It was reported for FRX-B at 17 mtorr filling pressure that the particle confinement time was τ_N = 39 ± 15 μs.[1] The magnetic field, temperature, and density were similar to the FRX-C parameters at 20 mtorr. The particle inventory in FRX-C at 5 and 20 mtorr has been measured by the end-viewing holographic interferometer, and independently estimated from the density measured by the side-on interferometer and volume measured by the magnetic probe data. A least-squares fit of an exponential to the more definitive holography data gives for the e-folding decay time τ_N = 68 ± 25 μs at 5 mtorr and τ_N = 187 ± 25 μs at 20 mtorr. Figure 2 presents the particle containment time as a function of the scaling parameter R^2/ρ_{io} (ρ_{io} = ion gyro radius). The solid dots are predictions of the Tuszewski-Linford lower-hybrid transport model. The open circles are the particle confinement times determined from holography. The half-open circles are from the side-on interferometer and magnetic probe data. Although the particle confinement time scales approximately linearly with R^2/ρ_{io}, as originally suggested by Hamasaki[3], it is also clear from the Tuszewski-Linford model that other factors such as x_s, open-field-line confinement, temperature, etc., are important. It is clear that the predictions of the lower-hybrid transport model and the experimental results are in good agreement, and confirm the R^2 scaling of particle confinement in an FRC.

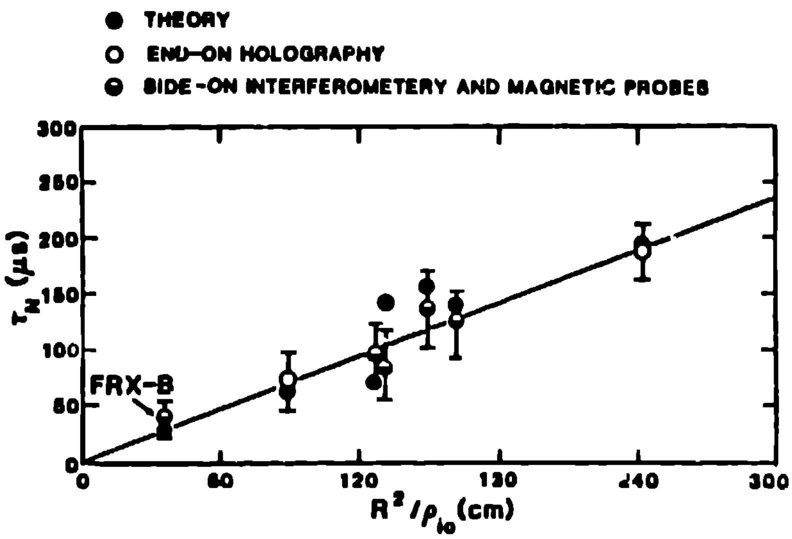

Figure 2.

The FRC stable period, defined as the duration of the quiescent phase before the onset of the n = 2 rotational mode, is observed to increase as the containment time increases. However, neither the experimental data nor the theoretical understanding of the n = 2 mode is sufficient to define the appropriate scaling of the stable period. It was recently reported by Ohi at Osaka that the n = 2 can be suppressed by application of quadrupole fields following FRC formation.[4] A quadrupole system has recently been added to FRX-C and preliminary results also demonstrate stabilization of the n = 2 mode. Presuming that quadrupole stabilization has no detrimental effect on confinement, the most important concerns for FRC research become transport scaling and MHD stability as the ratio of density gradient length to ion gyro radius is further increased.

VI. Translation Plans

Axial translation of an FRC without excessive losses of particles, flux, or energy leads to a variety of attractive fusion reactor possibilities. The process of translation should permit increased values of x_s and corresponding increases in the particle confinement time. The particle confinement can be improved because the density gradient is reduced when x_s is increased. In Fig. 3 the predicted radial beta profiles are compared for $x_s = 0.5$ and $x_s = 0.9$. Beta is defined here as local nT relative to external $B^2/8\pi$. Thus, for uniform temperature, β and density are proportional. The reduced density gradient seen for $x_s = 0.9$ is mostly a result of the average beta condition for an FRC, $\langle\beta\rangle = 1 - x_s^2/2$ where $\langle\beta\rangle$ is the volume-averaged beta inside the separatrix.[1] The predicted particle confinement time is increased by a factor of five for conditions that are similar to FRX-C.

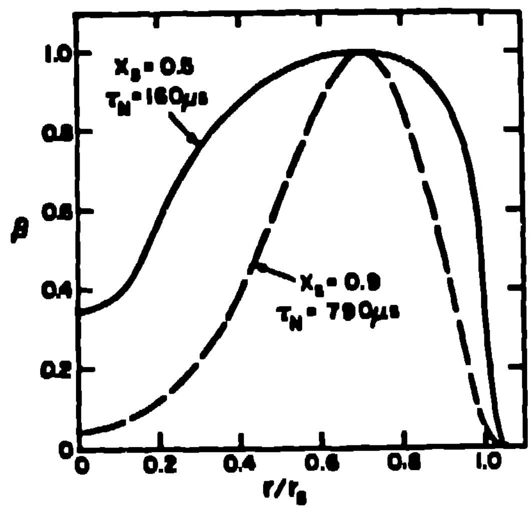

Figure 3.

The design for the transition region where the FRC enters a close-fitting flux conserver is still evolving. For a first approximation, it may be assumed that the FRC undergoes a completely adiabatic process with no losses of magnetic flux, energy, or particles. By assuming a particular uniform pressure profile, $\beta = \langle\beta\rangle$ that contains the maximum flux for a given x_s, analytic calculations are easily carried out. However, as discussed in these proceedings, more refined calculations are underway that take into account dynamic effects by use of a 2-D MHD code.[5] In addition, an analysis of the effects of diffuse profiles has also been carried out.[6]

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