Particle Confinement Scaling in Field-Reversed Configurations

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The particle confinement time in field-reversed configurations has been experimentally investigated in the FRX-*C* device. The measured confinement times of 70 to 190 μs are consistent with R^2/ρ_{i0} scaling and are in good agreement with theoretical predictions of lower-hybrid-drift–induced particle transport.

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The field-reversed configuration (FRC), a low-aspect-ratio, highly prolate, compact toroid of plasma formed with no toroidal magnetic field, has unique features that offer advantages for potential application to magnetic fusion. For example, the FRC intrinsically has very high volume-averaged plasma beta and the plasma-confining configuration can be translated intact along the axis of the solenoid. The plasma contained within the FRC separatrix is confined by closed poloidal magnetic fields generated by toroidal plasma currents. The loss of particles and energy[1] across the separatrix and the resistive decay of the trapped poloidal flux[2,3] at the field null limit the lifetime of the FRC. Nonclassical diffusion of particles appears to dominate the loss process and a primary focus of present FRC research is the determination of the scaling of the particle confinement time with size of the FRC. This Letter reports the results of FRC particle confinement-time measurements obtained in the FRX-*C* device over a significant range of plasma parameters. These particle confinement measurements, and data from the smaller FRX-*B* device,[4] scale approximately as R^2/ρ_{i0} where R is the FRC major radius and ρ_{i0} is the ion gyroradius in the external magnetic field [with the ion thermal speed as $(T_i/m_i)^{1/2}$].

FRX-*C* is a field-reversed theta pinch. The quartz discharge tube has an inner diameter of 0.4 m, and the coil is 2 m long and 0.5 m in diameter; passive mirrors of 0.20 m in axial extent and 0.44 m in diameter provide an on-axis vacuum mirror ratio of 1.17 at each end. To generate strong initial implosion heating, the large-diameter coil has a double–feed-slot geometry with each feed slot being driven by 70 2.8-μF capacitors. With a charge voltage of 42 kV the main field rises in 4.5 μs to about 9 kG and has a crowbarred decay time of 300 μs. Gas preionization is accomplished with a 200-kHz capacitor discharge through the theta-pinch coil. The present experiments were carried out with initial deuterium fill pressures of 5 and 20 mTorr and corresponding negative bias fields of 0.7 and 1.7 kG.

An axial array of compensated magnetic field probes is used to determine the axial distribution of the excluded flux radius,[4] $r_{\Delta\varphi}$. In regions of straight field lines, if we neglect plasma pressure outside the separatrix, the separatrix radius can be approximated as $r_s \approx r_{\Delta\varphi}$ and the major radius is $R = r_s/\sqrt{2}$. A side-on 3.39-μm interferometer is used to measure $\int n\,dl$ through a diameter of the FRC near the coil midplane and the volume-averaged density is defined as $\bar{n} = \int n\,dl/2r_{\Delta\varphi}$. Measurements of T_e by Thomson scattering are taken with the scattering volume located 8 cm off the coil axis and 15 cm from the coil midplane. The total plasma temperature, and thus T_i, are estimated from pressure balance, $T_e + T_i = \langle\beta\rangle B^2/8\pi\bar{n}$, where[4] $\langle\beta\rangle = 1 - x_s^2/2$ is the volume-averaged beta within the separatrix, with $x_s = r_s/(\text{coil radius})$, and B is the measured external magnetic field.

The FRC formation is characterized by a rapid inward radial implosion (initiated by the main-bank discharge at $t = 0$) and field-line reconnection process which is followed by a damped radial-oscillation and axial-contraction phase. At the termination of these events a well defined and quiescent FRC is observed. In the absence of auxiliary stabilization fields,[5] the quiescent confinement phase is terminated by a rotational $n = 2$ instability. Near the beginning of the quiescent phase, $t \simeq 15$ μs, the equilibrium plasma parameters for 5-mTorr fill pressure are $T_e + T_i = 800$ eV, $T_e \simeq 175$ eV, $\bar{n} \simeq 1.9\times10^{15}$ cm^{-3}, $r_s \simeq 9$ cm, $B = 8$ kG, and $\tau_s \simeq 40$ μs where τ_s defines the onset time of the $n = 2$ instability. At 20-mTorr fill pressure the equilibrium conditions are $T_e + T_i \simeq 250$ eV, $T_e \simeq 100$ eV, $\bar{n} \simeq 5\times10^{15}$ cm^{-3}, $r_s \simeq 10$

cm, $B \simeq 7$ kG, and τ_s ranges from 55 to 110 μs.

The FRC total electron inventory was measured by means of a 30-ns pulsed holographic ruby-laser interferometer. A modified Michelson end-on interferometer was used to provide double-pass sensitivity. Figure 1 shows a time sequence of interferograms taken during the FRC quiescent phase for 20-mTorr fill pressure. The straight-line background fringe pattern on each interferogram was generated by a small angular deviation of the reference beam introduced between exposures taken with and without plasma. Plasma electron refractivity results in a displacement of the background fringes. The system resolution was $\frac{1}{4}$ fringe or better. Each interferogram was obtained from a separate plasma discharge.

The abrupt discontinuity in the interferogram fringe pattern at the outer edge of the plasma identifies steep density gradients in the vicinity of the FRC separatrix; this determination of the separatrix radius, although averaged over the FRC length, agrees with that obtained from the excluded-flux probe array. The characteristic density-gradient scale length, estimated from the early-time interferograms to be on the order of 1 cm, is only 3–4 ion gyroradii in thickness. This sharp density gradient, which is a result of the high $\langle\beta\rangle$ (low x_s), is thought to drive anomalous cross-field particle diffusion through microinstabilities like the lower-hybrid-drift instability. The straight-line fringes observed at radii somewhat greater than r_s indicate the absence of measurable plasma density outside the separatrix.

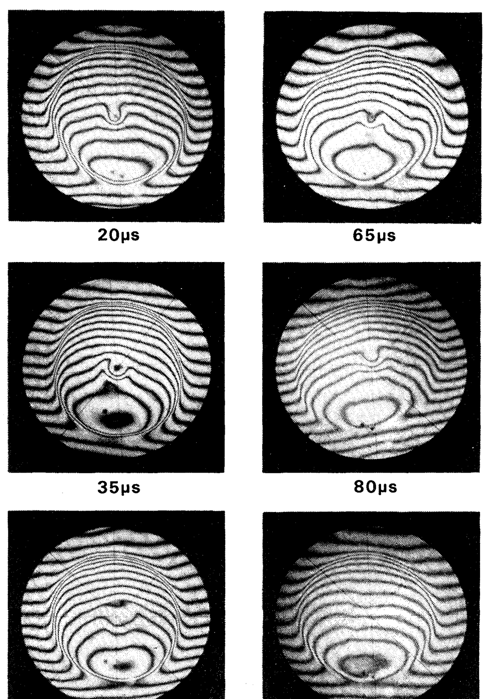

FIG. 1. Time sequence of interferograms taken during the FRC quiescent phase. Each interferogram was recorded separately on a single discharge, and the diameter of the interferometer field of view was 30 cm.

The total electron inventory N_e, for a given plasma discharge, was determined from an area integration over the interferogram fringe-shift profile. The electron inventory is plotted as a function of time in Fig. 2 for 20-mTorr fill pressure. As can be seen, the data scatter at a given time is small and reflects the reproducibility of the FRC plasmas and the quality of the interferograms. The solid line is a least-squares exponential fit to the data and yields an e-folding particle decay time $\tau_N = 187 \pm 25$ μs. The indicated particle inventory at $t = 0$ is 2.5×10^{20} which corresponds to about 80% of the initial 20-mTorr fill inside the 2-m coil length. The error bar represents the estimated error in reducing the interferograms and accounts for the finite system resolution. Additional errors to the electron inventory which could arise from plasma outside the separatrix have been estimated to be small.

Particle loss from FRC plasmas has been treated theoretically by Hamasaki and Krall[6] using a one-dimensional time-dependent numerical transport code, and more recently by Tuszewski and

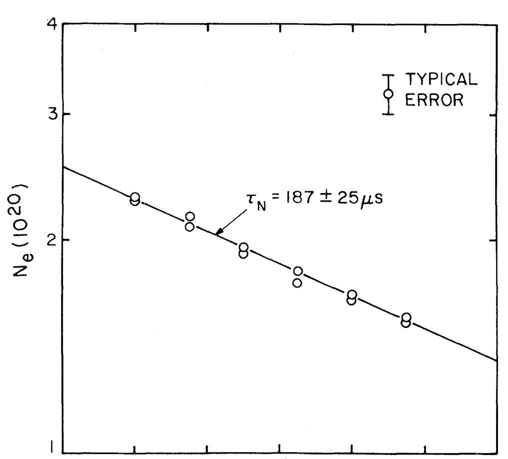

FIG. 2. Time history of the FRC total electron inventory from end-on holography.

Linford,[7] who have developed a one-dimensional, steady-state numerical model. Both analyses indicate that of the mechanisms considered, particle transport across the separatrix should be dominated by the lower-hybrid-drift instability and, for the plasma parameters of the FRX-C and FRX-B devices, that the particle confinement time should scale approximately linearly with R^2/ρ_{i0}.

Figure 3 presents the measured particle confinement times as a function of the scaling parameter R^2/ρ_{i0}. The open circles are the data obtained from the end-on holographic interferometry measurements on FRX-C, and the triangles represent an estimate of the confinement time, under different plasma conditions, obtained from the time-history density $\bar{n}$ determined by the side-on interferometer and volume defined by the axial $r_{\Delta\varphi}$ profile; for the same plasma conditions the two techniques agree within experimental error. The FRX-B data point shown in Fig. 3 was obtained at 17-mTorr fill pressure which produced an FRC plasma with magnetic field, temperature, and density similar to the FRX-C plasma obtained at 20 mTorr; the FRX-B device was one half as large as FRX-C in both radial and axial dimensions.[4] The solid circles in Fig. 3 are the predictions, using the measured plasma parameters at $t=\tau_s/2$ for a given set of experimental conditions, of the Tuszewski-Linford lower-hybrid transport model. The choice of $t=\tau_s/2$ insures that the calculated value of τ_N from the time-dependent model is close (within 10%) to the time-averaged value of τ_N over τ_s. It is clear that the experimental results and model predictions are in good agreement and confirm the R^2/ρ_{i0} scaling of particle containment in the present generation of FRC plasmas.

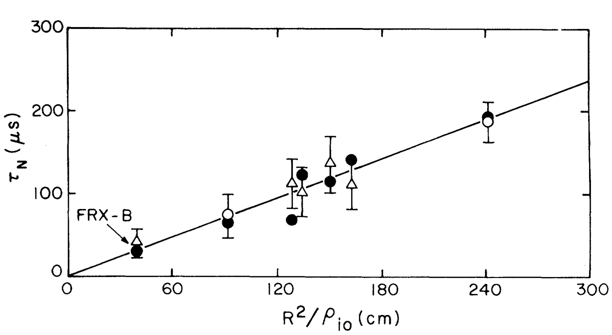

FIG. 3. Scaling of particle confinement time, τ_N, with R^2/ρ_{i0}; open circles, from end-on holography; triangles, from side-on interferometer and $r_{\Delta\varphi}$ axial profile; and solid circles, predictions from Tuszewski-Linford lower-hybrid transport model. The solid straight line represents an empirical fit to the experimental data.

More precisely, scaling with R can be obtained by considering the FRX-B 17-mTorr and FRX-C 20-mTorr data with similar plasma parameters (density, temperature, magnetic field, ρ_{i0}, and x_s). An increase in τ_N of a factor of about 4 resulted from an increase in R of a factor of 2, suggesting $\tau_N \propto R^2$. This result is characteristic of diffusive losses out of a toroidal configuration and implies that gross magnetohydrodynamic instabilities did not contribute measurably to the FRC transport with values of R/ρ_{i0} of about 30.

Some information on the plasma resistivity can also be obtained by considering the FRX-C 5-mTorr and 20-mTorr data obtained with approximately constant values of R, x_s, and B. The electron temperature T_e decreased from about 175 eV at 5 mTorr to 100 eV at 20 mTorr, so that, for a given value of Z, particle transport models with classical resistivity[8,9] would predict larger values of τ_N at 5 mTorr than at 20 mTorr ($\tau_N \propto T_e^{3/2}$) in contradiction with the available experimental data. Furthermore, when the fill pressure was increased from 5 to 20 mTorr, $\tau_N \propto 1/\rho_{i0}$ increased by about a factor of 2 as T_i decreased by a factor of 4. This approximate scaling of $\tau_N \propto T_i^{-1/2}$ is in contradiction with another classical particle-transport theory from ion-ion loss cone scattering[10] which predicts τ_N to be an increasing function of T_i. However, the temperature dependence of τ_N observed experimentally is consistent with lower-hybrid-drift resistivity.

The observed agreement between current experiments and the lower-hybrid transport theory has significant impact on future experiments. Specifically, the theory also predicts that the particle confinement time can be greatly increased if the current x_s values of 0.4–0.5 can be extended to the 0.8 to 0.9 range; increasing x_s decreases the density gradient near the separatrix, thus reducing the lower-hybrid transport. Provided other loss mechanisms such as energy loss and flux loss do not dominate, this predicted increase in confinement time can be investigated on FRX-C by translating the plasma into a smaller-diameter flux conserver.

In conclusion, measurements on FRX-C confirm that the FRC particle confinement time scales linearly with R^2/ρ_{i0} in agreement with lower-hybrid-drift transport models.

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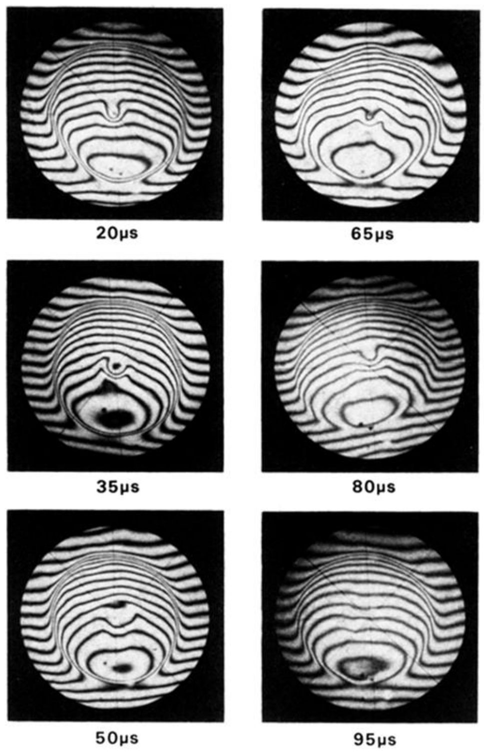

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