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1985 Nucl. Fusion 25 1317

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# FIELD-REVERSED CONFIGURATION RESEARCH AT LOS ALAMOS

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**ABSTRACT.** Exploratory field-reversed-configuration (FRC) experiments, initiated at Los Alamos in the mid-seventies, demonstrated FRC lifetimes substantially longer than predicted from MHD stability theory. Subsequent experimental and theoretical advances have provided considerable understanding of FRC stability physics, the characteristics of the configuration loss processes, and the particle confinement scaling with size. The critical FRC physics issues, which directly relate to the development of an FRC fusion reactor and need to be addressed in a new generation of experiments, have been clearly identified.

## 1. BACKGROUND

The field-reversed configuration (FRC) is a prolate compact toroid formed with no toroidal field (Fig.1). It is the highest-beta fusion-oriented configuration known to exist, with volume-averaged betas [1] typically  $> 80\%$ . The plasma within the separatrix is confined by closed poloidal fields generated by internal toroidal plasma currents. The existence of this equilibrium has been confirmed experimentally [2, 3] and described theoretically [4]. In present experiments the FRC lifetime is limited by particle and energy losses across the separatrix, and by resistive decay of the trapped poloidal flux. An extensive review of the Los Alamos FRC experiments is in publication [5].

The FRC programme was launched at Los Alamos in 1976 with the FRX-A and FRX-B devices [1]. These machines were 25 cm i.d., 100 cm long single-turn theta pinches with reversed-bias fields of about  $-2$  kG and peak main fields of about 7 kG. Typical plasma parameters were  $T_e \sim 100$  eV,  $T_i \sim 150$  eV,  $n \sim 4 \times 10^{15} \text{ cm}^{-3}$ , with separatrix radii  $r_s \sim 5$  cm. Although the plasma lifetimes were limited to  $\leq 50 \mu\text{s}$  by the destructive  $n = 2$  rotational instability [6], the

lifetimes were significantly greater than the characteristic Alfvén transit times ( $\leq 10 \mu\text{s}$ ). This result disagreed with MHD predictions of a short-growth-time (about an Alfvén transit time) internal tilt instability [7]. To study this stability issue and to determine the characteristics of the loss processes and their scaling with FRC size, the FRX-C device [8] was constructed in 1980.

## 2. RESULTS FROM FRX-C AND FRX-C/T

FRX-C has a dual-fed, 50 cm i.d., 200 cm long coil. Typical data are shown in Fig.2 for high initial fill pressure. The density data are obtained with a single-chord side-on interferometer [3], and the data modulation beginning at about  $80 \mu\text{s}$  defines the end of the quiescent equilibrium phase and the onset of the

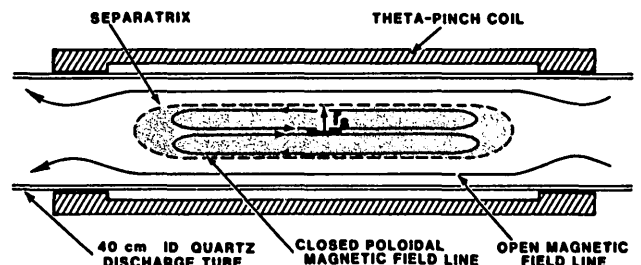


FIG.1. Field-reversed-configuration geometry in a theta-pinch coil.

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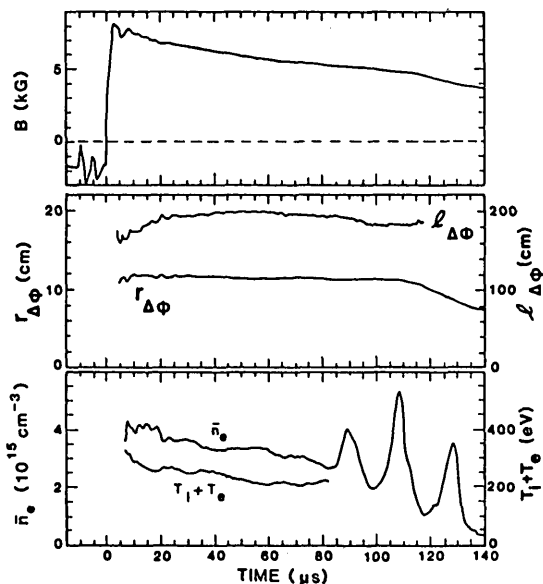


FIG. 2. Typical FRX-C data at 20 mtorr fill pressure;  $B$  is the external magnetic field waveform,  $l_{\Delta\phi}$  approximates the FRC length,  $r_{\Delta\phi}$  is the excluded flux radius at the coil mid-plane,  $\bar{n}_e$  is the volume-averaged density, and  $T_e + T_i$  is determined from pressure balance.

$n = 2$  instability. At lower fill pressure the temperatures are higher, the density is lower, and the quiescent period is shorter. The  $n = 2$  instability has been completely suppressed on FRX-C by applying weak quadrupole fields [5]. Using this technique the plasma lifetime exceeds 300  $\mu\text{s}$ , which is about equal to the decay time of the theta-pinch magnetic field. As in the earlier experiments, the FRX-C plasma shows no signs of internal tilting. This paradox may have been resolved by a recently developed kinetic plasma model [9] that predicts greatly reduced tilt-instability growth rates as a result of the large ion orbits of the high-beta FRC. This stabilizing effect is characterized by the parameter  $\bar{s}$  which approximates the number of ion gyroradii between the magnetic axis (field null) and the separatrix [10]. In present experiments [5, 10],  $\bar{s}$  is limited to  $\leq 2$ . The growth rate predicted from kinetic theory approaches the MHD growth rate at large  $\bar{s}$ , with the transition to a more MHD-like regime projected [5, 9] for  $\bar{s} \geq 3$ .

Particle diffusion out of the closed-field-line region is approximately ten times classical [11] and is the dominant loss process [12]. The high beta of the FRC equilibrium and the lack of confinement on the open field lines result in a steep density gradient at the separatrix and a driving mechanism for transport by lower-hybrid-drift (LHD) wave turbulence; a direct measurement of LHD turbulence in an FRC has yet to be obtained. The LHD model predictions [11] for the

particle confinement time  $\tau_N$  are generally in good agreement with experimental observations [13] (typically 100–200  $\mu\text{s}$ ), and the predicted LHD scaling,  $\tau_N \propto R^2/\rho_{i0}$ , has been observed [2];  $R$  is the radius of the field null ( $r_s/\sqrt{2}$ ), and  $\rho_{i0}$  is the ion gyro-radius in the external field. However, in the FRX-C/T experiment (discussed below) the prediction of LHD departs somewhat from experimental trends, with the temperature scaling being more favourable than is indicated by the  $1/\rho_{i0}$  dependence [13]. Particle diffusion is also predicted [10] to be a strong function of  $\bar{s}$ . At large  $\bar{s}$ , the density gradient length is large compared to an ion gyroradius, LHD activity becomes more localized in space near the separatrix, and particle confinement based on LHD resistivity is enhanced.

Particle transport accounts for at least 50% and radiation for less than 10% of the total energy loss [13]. Thus, thermal conduction, probably through the electron channel, appears to represent a significant energy loss mechanism. Internal poloidal flux loss is thought to occur at the field null by resistive annihilation. However, no annihilation process has been identified that explains the anomalously low experimentally inferred values [14] of the flux decay time  $\tau_\phi$  (typically 200  $\mu\text{s}$ ). Empirical scaling laws for  $\tau_\phi$  show an  $R^2$  dependence but only a weak dependence on electron temperature [5].

In 1983, FRX-C was modified to permit studies of FRC translation. In this experiment, FRX-C/T, the plasma is formed in the theta-pinch source, axially translated into a 40 cm i.d., 500 cm long chamber surrounded by a d.c. solenoid, and trapped by magnetic mirrors. Efficient FRC translation was obtained with no degradation of confinement properties over that observed in the in situ plasma [13]. The demonstration of FRC translation is supportive of the translating-plasmoid reactor concept CTOR [15], a linear reactor configuration in which the regions of plasma formation and heating are separated from the thermonuclear burn region.

### 3. CRITICAL FRC ISSUES

From accumulative FRC research, well-defined physics issues have emerged that will need to be treated in a new generation of experiments. These critical issues are: (1) the FRC stability and confinement properties in the MHD-like large- $\bar{s}$  regime; (2) the identification of the dominant electron energy loss mechanisms; and (3) the physics of internal poloidal flux loss.

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