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Initial Operation of FRX-C*

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Introduction

FRX-C, a field-reversed theta-pinch experiment that has recently been placed into operation, has as its objectives to:

- Determine the scaling of field reversed configuration (FRC) confinement with size and clarify the mechanism(s) that limit confinement of an FRC
- Increase the FRC lifetime by increasing the size by a factor of two (eight in volume) over past experiments
- Form FRCs with temperatures in the 0.1 to 1.0 keV range and densities in the range of 10^{15} to ^{16} cm^{-3}
- Build on the results of the smaller FRX-A and FRX-B[1] experiments

Preliminary results are given below based on the limited number of plasma shots (42) since the machine was placed into operation on September 2, 1981. Parameters of the experimental hardware are also given below.

Description of the FRX-C Experiment

FRX-C is a 45-cm diameter, 2-m long, field-reversed theta pinch.[2,3] Standard capacitor bank technology has been utilized to generate a main field swing of up to 16 kG with a 5 μs quarter period. The decay time of the crowbarred waveform following the peak of the magnetic field is ~ 300 μs. The initial, preionized (PI) plasma is created with an imbedded reversed-bias field of up to 5 kG. A vacuum magnetic field waveform typical of the initial operation is shown in Fig. 1. Electrical parameters of experimental hardware are listed in Table I and a detailed description is contained in Ref. 2. The vacuum system has a base pressure of 2 x 10^{-8} using a 40-cm diameter, 3.6-m long quartz discharge tube, stainless steel vacuum hardware and two cryo pumps.

The initial experiments have utilized a ringing theta pinch to generate the PI plasma. Since this technique requires bringing the axial (bias) field back to zero on the first PI cycle, the limited PI field restricts the usable bias field to < 2.0-2.5 kG. The ringing theta pinch PI, which starts ~ 20 μs prior to field reversal, is preceeded by two low level r.f. discharges to provide a target plasma. Passive mirrors are used at each end of the theta-pinch coil to initiate the reconnection process. At present, a 5% step in radius extends along the axis at each end of the coil for a distance equal to ~ 0.4 of the coil diameter.

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FRC Parameters

The present limited parameter set is compared with the predictions of a semi-empirical FRC scaling code[3] (used in the design of FRX-C) in Fig. 2. The good agreement of predicted and observed parameters supports the code predictions of parameters at other operating conditions. The data of the single operating condition presently studied are summarized in Table II. The inferred ratio of major radius to ion gyro-radius is ~ 26 (referenced to the external field). The achievement of a significant increase in this quantity over past smaller experiments (the device FRX-B achieved a value of ~ 13) is important in assessing the scaling of FRC stability and transport properties.

The diagnostics presently incorporated on FRX-C include an axial array of compensated field probes to determine the separatrix profile, a side-on 3.4 μm interferometer, a C-V Doppler broadening measurement for T_i, and an end-on framing camera. Early azimuthal asymmetry in the FRC formation is indicated by the end-on framing in association with the theta-pinch preionizer and the radial implosion in the presence of end-mirrors. However, the FRC is observed to regain azimuthal symmetry in ~ 10 μs after main bank firing. More serious axial asymmetries are observed in the separatrix profile data in association with reconnection and axial contraction. The data suggest shot-to-shot variation in FRC length (50 to 150 cm) and axial position. Short, displaced FRCs may result in less-than-optimum lifetimes. An increase in the on-axis mirror ratio from 4% to 6% is planned to further aid symmetric, reproducible reconnection.

Advanced diagnostics under development and installation include: single-point Thomson scattering for T_e, neutron and proton yield measurements for T_i, as well as O-VII Doppler broadening measurements for T_i. The redundant temperature measurements will aid interpretation of impurity radiation measurements (Doppler broadening of C-V and O-VII), and clarify interpretation of nuclear measurements (neutron and proton yields) which are sentitive to the tail of the ion distribution function. Detailed density measurements are planned through a multipoint, nonspectrally-resolved Thomson scattering diagnostic and an end-on cine-holographic interferometer. The Thomson scattering diagnostic will offer an axial density profile to be used in identifying internal tearing, as well as the ellipticity of the flux surfaces. The holographic interferometer provides radial density profiles critically needed to ascertain FRC transport properties.

Critical Issues

The principal objective of the FRX-C experiment is to establish the scaling of FRC stability and transport with increased plasma and coil size. In eliciting this scaling, detailed studies of the physical mechanisms leading to rotational instability and anomalous transport will be conducted. Theoretical modeling of FRC stability continues to evolve. Previous work indicated a large rotational velocity must be exceeded to induce the rotational instability.[4] Recent work suggests instability may occur at lower rotational velocities but with slow growth rates consistent with experimental quiescent periods.[5] Past experimental evidence[1] has supported a possible causality between particle transport and rotational acceleration. More recent experimental work has shown some contribution of end-shorting to rotational acceleration.[6] Finally, continuing analysis of particle transport dominated by the lower-hybrid-drift instability suggests rapid improvement in confinement with increased plasma radius.[7]

These various issues will be initially addressed on FRX-C by varying the particle inventory and closed flux to ascertain the basic confinement and stability scaling with respect to smaller devices. The present FRX-C data is too limited to impact on these issues. However, without optimized operation, FRCs formed on FRX-C have stable periods, which are substantially longer (> 2 times longer) than FRCs formed on the smaller FRX-B device with similar plasma parameters.[1]

Summary of Initial Results

The parameters of the FRC are near the design values that were chosen based on a scaling from earlier FRC experiments. Preliminary results give a positive increase in the FRC lifetime for nominal operation conditions. A comparison with predicted confinement from FRC models is not yet possible.

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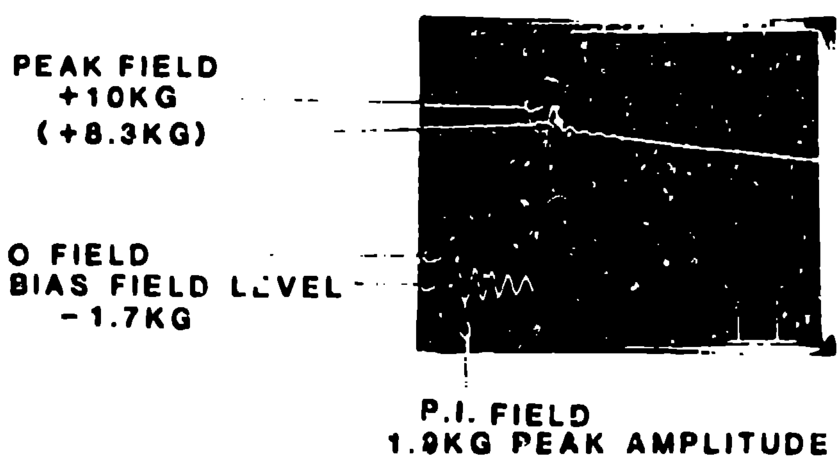

Fig. 1. The FRX-C vacuum magnetic field waveform (10 μs per division).

TABLE I: FRX-C MACHINE PARAMETERS

Coil Dimensions	
Diameter	.45 m
Length	2.0 m
End Mirror Ratio	1.1
Magnetic Field	
Typical Amplitude	10 kG
Risetime ($\tau_{1/4}$)	5 μs
Decay (L/R)	300 μs
Main Capacitor Bank	
No. of Capacitors (2.8 μf)	140
Stored Energy (55 kV)	600 kJ
Bias Bank	
No. of Capacitors (170 μf)	60
Stored Energy (10 kV)	500 kJ
Maximum Field	5 kG
Theta Preionization Bank	
No. of Capacitors (0.7 μf)	16
Stored Energy (50 kV)	14 kJ
Typical Field	1.9 kG
Frequency	200 kHz

TABLE II: FRC PARAMETER SUMMARY
20 mtorr, 42 kV

Stable lifetime	70-100 μs
Bias Field	1.7 kG
Equilibrium field	7.4 kG
Separatrix radius	~12 cm
FRC length	~100 cm
Trapped flux fraction	~25%
Density (interferometry)	~4 x 10^{15} cm^{-3}
T_e+T_i (pressure balance)	~400 eV
T_i (Carbon V)	~200-300 eV

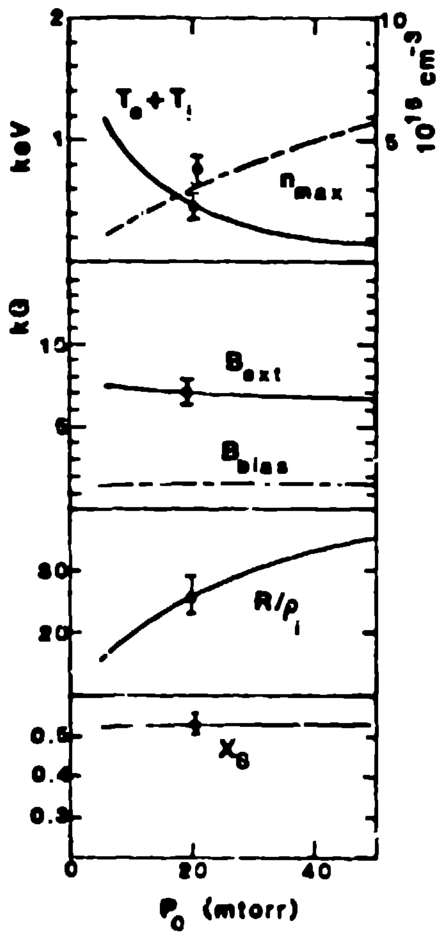

Fig. 2. A comparison of code predicted FRC parameters (lines) with FRX-C data (points). Error bars represent shot-to-shot variations.