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STABILITY AND CONFINEMENT OF SPHEROMAKS AND FIELD REVERSED CONFIGURATIONS*

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Abstract

The formation, confinement and stability of two types of compact toroids, spheromaks and field reversed configurations (FRC), are reviewed. Spheromaks, which contain both toroidal and poloidal magnetic fields, have been formed with magnetized coaxial plasma guns, by a combination of Z- and θ -pinch techniques and by an electrodeless slow induction technique, and trapped in both prolate and oblate flux conservers. As predicted by theory, the prolate configuration is unstable to the tilt mode, but the oblate configuration with a conducting wall is stable. Configuration lifetimes of up to 0.8 ms are observed. The FRC is a high-beta, highly prolate compact toroid formed with field-reversed theta-pinch techniques and having purely poloidal magnetic field. Theory predicts unstable fluting and internal tilting modes, but they are not observed experimentally. Configurations with high densities $\sim 10^{15} \text{ cm}^{-3}$ and with lifetimes of 50 to 120 μs are terminated by an $n=2$ rotational mode of instability.

1. Introduction

A compact toroid (CT) is an axisymmetric, closed toroidal magnetic-confinement configuration that has no magnet coils, conducting walls, nor vacuum walls linking the hole in the plasma torus [1]. This feature provides a simple geometry that reduces

*Work performed under the auspices of the U.S. Department of Energy.

engineering complexity of proposed CT reactors. A compact toroid has a poloidal magnetic field, may or may not have a toroidal field, and current may be carried by plasma particles with either large or small gyroradii compared with plasma dimensions. The CT equilibrium requires either a conducting wall or an externally generated field, like the vertical field in a tokamak. If an external field is used, a separatrix is formed that divides these open field lines from the closed fields supported by plasma currents in the toroid.

The CTs can be classified into three major types: particle rings (Astron-like), spheromaks, and field reversed configurations (FRC). Particle rings are characterized by large ratios of ion gyroradius to plasma dimensions, and may have arbitrary ratios of toroidal to poloidal magnetic fields. Both the spheromak and the FRC have small gyroradii compared with plasma dimensions. The spheromak has poloidal and toroidal magnetic field components of comparable magnitude on the closed flux surfaces. An external field may be applied parallel to its major axis producing surrounding open field lines. The flux surfaces of the FRC have purely poloidal field lines. Open field lines exist between the separatrix and an external cylindrical conductor. The closed fields are supported by thermalized-plasma currents in the small-orbit configurations and by either energetic ions or electrons in the large-orbit particle ring configurations. Alternative techniques in formation, heating, and sustaining of CTs have resulted in variations of the three concepts.

The study of CTs is motivated in part by potential reactor advantages of this concept as well as providing an opportunity to study toroidal confinement properties in configurations that are

complementary to other axisymmetric devices. In contrast to the modest shear and minimum B of the tokamak, the spheromak, like the reversed field pinch (RFP), has stronger shear and no minimum B . FRCs share their purely poloidal field structure with other systems such as EXTRAP.

All CTs share at least three important potential reactor advantages: (1) The simple (cylindrical or spheroidal) coil, blanket, and vacuum chamber geometry considerably simplifies the engineering and maintenance. In particular, designs may facilitate rapid replacement of the first wall, allowing higher power densities and wall loadings; (2) A significant flexibility results from the simple geometry including the possible translation of the CT, allowing separation of the formation and heating regions from the fusion burn region; and (3) The pressure that must be supported at the walls or coils is smaller than in a tokamak because of the large engineering plasma beta β_e (ratio of the volume average plasma pressure to the magnetic field pressure at the conducting wall or coil) of the CT systems.

This paper addresses the formation, stability, and confinement of CTs, and is divided into two parts; spheromaks and FRCs. Recent experimental and theoretical results are presented.

2. Compact Toroids with Toroidal Field: Spheromaks

2.1. Formation

A typical CT spheromak configuration is shown schematically in Fig. 1, where R is the major radius, a is the minor radius, and r_s is the separatrix radius. Spheromaks, CTs containing both toroidal and poloidal magnetic fields, have been generated in the Los Alamos CTX

ility [2] and in the Livermore Beta II device [3] using magnetized coaxial plasma guns, in the Maryland paramagnetic spheromak (PS-1) using Z- and theta-pinch techniques to produce a prolate spheroid configuration [4], and in the Princeton prototype S-1 device utilizing a slow, electrodeless formation scheme [5]. In the CTX and Beta II experiments, CTs are generated utilizing in part a technique pioneered by Alfvén et al. [6] and extended to a higher-temperature fully ionized plasma regime. A solenoidal coil produces an axial magnetic field that diverges at the gun muzzle and becomes radial. Firing the gun produces a radial plasma current that generates a toroidal magnetic field between the electrodes. The $\vec{J} \times \vec{B}$ force accelerates the highly conductive plasma out of the gun, stretching the radial field lines in the axial direction. These elongated field lines reconnect behind the plasma forming the closed poloidal field of the spheromak, while the magnetic field generated by the gun current becomes the toroidal field. The gun-generated spheromaks are trapped in prolate and oblate cylindrically symmetric metallic flux conservers.

Spheromaks are formed in the Maryland PS-1 device using a field reversed theta pinch to produce the poloidal magnetic field and an axial current to provide the toroidal field [4]. The application of an initial bias field of 4 to 8 kG is followed by an axial current discharge (~ 150 kA) between electrodes at the ends of the cylindrical theta-pinch coil. The axial current creates an annular shell of plasma and an azimuthal magnetic field that slightly pinches the plasma column. The main theta-pinch bank produces a fast-rising axial field that compresses and heats the plasma annulus. Mirror coils at the ends also produce an axial contraction. Field line reconnection

takes place at the ends resulting in flux surfaces with closed poloidal and toroidal field line components.

In the Princeton prototype S-1 device, an initial poloidal field is generated by toroidal current inside a toroidal flux core, and is weakened on the inward (small-major-radius) side of the core by an externally applied vertical field [5]. The core also contains a toroidal solenoid that produces a toroidal-field flux on its interior, and induces a poloidal current in a sleeve-shaped plasma surrounding the ring. The associated toroidal field stretches the plasma-poloidal field sleeve towards the magnetic axis where the poloidal field is weakest. An increasingly large toroidal current is induced in the plasma as the toroidal core current is reduced through zero and "crowbarred" at a negative value. Magnetic reconnection of the poloidal field occurs, and a separated plasma toroid is produced on the small-major-radius side of the flux core. This toroidal spheromak configuration is held in equilibrium by the externally generated steady-state vertical field.

2.2. Gross Stability

In the initial CTX experiments [2], the gun-generated spheromaks were injected into a stainless steel, right-circular, cylindrical flux conserver. The CTs were stopped within the flux conserver by appropriate adjustment of the initial poloidal field strength at the coaxial source. In some cases the prolate-shaped toroid stopped with its major axis parallel to the axis of the plasma gun and the flux conserver, then rotated 90° , making a more "oblate" racetrack-like CT, so that its axis was orthogonal to the axis of symmetry as shown in Fig. 2. This tilting mode had been predicted by Rosenbluth and

Bussac [7]. In most cases the stopped toroid, when first observed, was already partially tilted. After the rotation or tilting, the deformed toroid appeared grossly MHD stable, and decayed with $\sim 100 \mu s$ time constant. The tilting mode has also been observed in the elongated configuration of the Maryland PS-1 device [4], and in both the Princeton Proto S-1A and S-1C devices [8].

Motivated by stability theory [7], which predicts that the tilting mode should be stabilized by an oblate flux conserver, CTX compact toroids were trapped in 80-cm diameter flux conservers having oblate regions as shown in Fig. 3 [1]. With the geometries of Figs. 3b and 3c the tilting instability does not occur and the spheromak configuration is stable throughout its lifetime. Similar observations have been made in the Livermore Beta II experiment [3]. The tilting instability is sensitive to the geometry of the entrance cylinder to the flux conserver and the gap spacing between the gun and the entrance region [1]. The tilting mode was stabilized in the Maryland experiment by rearranging the coil configuration to axially compress the plasma to a more oblate shape [9].

2.3. Plasma Characteristics

In the CTX experiment spheromaks are generated, trapped and stably confined within an oblate flux conserver [2]. The plasma and magnetic field properties are measured using magnetic probes, Thomson scattering, interferometry, quartz and vacuum UV spectroscopy, and bolometry. The electron density and temperature of the separated, trapped spheromak are typically $n_e \sim 0.2-2 \times 10^{14} \text{ cm}^{-3}$ and $T_e \sim 10 \text{ eV}$. Probes measuring all three components of magnetic field located along the axis of symmetry show that magnetic reconnection, leading to

separation of the spheromak from the coaxial source, is completed in 40 to 70 μ s. The peak field on the axis of symmetry is ~ 6 kG, and the total energy of the spheromak is ~ 6 kJ. Total lifetimes of the spheromak configuration are observed up to 0.8 ms (~ 4 times the characteristic decay time) and are consistent with classical resistive decay.

The Livermore Beta II experiment has operated at densities in the range of $1-20 \times 10^{14} \text{ cm}^{-3}$, $T_e \sim 10$ eV, and configuration lifetimes of ~ 0.2 ms [3]. The Princeton Proto S-1C device with a plasma minor radius of 8 cm and major radius of 12 cm has achieved $T_e \sim 40$ eV, $n_e = 1-5 \times 10^{14} \text{ cm}^{-3}$, and configuration lifetimes of ~ 0.1 ms [8]. Maximum ion temperatures of 200 eV and electron temperatures of 20 to 60 eV have been observed in the Maryland experiment [9].

2.4. Relaxation toward a Taylor Minimum Energy State

Radial profiles of the poloidal and toroidal magnetic fields in the CTX and Beta II experiments are found to be in approximate agreement with those of the Taylor minimum energy state theory [10], although some deviations are observed. In Fig. 4, the measured ratio of the toroidal field just outside the magnetic axis to the poloidal field on the major axis, in the CTX experiment, are plotted as a function of time. This ratio is compared with the calculated ratio for the Taylor state (dashed line). There is agreement following the spheromak formation, but in time the measured ratio deviates by as much as 50 percent and then a relaxation process restores the plasma configuration back to the Taylor minimum energy state. These relaxation processes, that tend to regenerate the equilibrium configuration against diffusive losses, need to be studied more

carefully, particularly when the resistivity and fluctuations are reduced under higher temperature conditions.

Sgro has developed a 2-D transport code that simulates the resistive evolution of the spheromak, after the initial inertial effects become small, following its formation [11]. The equilibrium is calculated in two dimensions, the poloidal angle being an ignorable coordinate. The diffusion is calculated in one dimension, perpendicular to the flux surfaces. The code is initialized with the minimum energy state and resistivity is set to a constant value corresponding to classical resistivity at 7 eV. The computed value of the field ratio B_T/B_P is indicated by the triangular points in Fig. 4. The computed magnetic field diffusion is in excellent agreement with the observed rate of deviation from the Taylor value, but of course, does not show the 3-D relaxation process. As time progresses, the simulation shows the field gradients becoming steeper near the magnetic axis. This suggests that these gradients eventually drive the configuration unstable and it relaxes back to the near minimum energy state on an inertial timescale.

2.5. Impurity Radiations

Bolometry and UV spectroscopic measurements have shown that impurity radiation is the dominant energy loss mechanism in the CTX and Beta 11 spheromaks. It appears that radiative losses are clamping the temperature in the 10 to 20 eV range. Metallic impurities have been reduced to negligible levels compared with lower Z impurities by appropriate choice of source operating conditions [12].

Immediately following a vacuum opening carbon is a prominent impurity, and the total lifetime for the spheromak configuration is typically 0.2-0.3 ms. After about 100 hours of dc glow discharge cleaning there is a large reduction in the carbon radiation and an increase in the total lifetime of the spheromak to ~ 0.5 ms. At this point oxygen dominates the radiation loss.

After discharge cleaning the total lifetime of the spheromak can be extended to 0.8 ms by use of a background fill of about 8 mT. For this fill case the total level of oxygen radiation is lower and the distribution is shifted towards the higher charge states [13]. The presence of the H_2 fill improves the lifetime by a combination of effects. It provides a particle source to maintain the density at low levels throughout the long life, and it extends the allowable range (determined by the ability to form stable spheromaks) of most operating parameters that are used to minimize the impurities in the spheromak.

Radiation and transport calculations indicate that at $n_e \sim 10^{14} \text{ cm}^{-3}$ oxygen impurity levels of 1-2% can be overcome by ohmic heating power; however, the present level appears to be higher. Steps are being taken to reduce this level and raise the temperature of the spheromaks in CTX.

2.6. Equilibrium and Stability

The equilibrium and the gross MHD stability of the spheromak in an oblate-shaped conducting shell has been extensively studied theoretically [7,14-16] and confirmed experimentally [1,17]. Okabayashi and Todd [15] have numerically analyzed the internal MHD stability of spheromak-type equilibria as a function of ellipticity,

aspect ratio and current profile shaping using the ideal and resistive Mercier criteria. It is found that oblate configurations with ellipticity of 0.5 have optimum stability properties against internal MHD modes and can be stabilized for engineering β_e of up to 15%. Non-ideal effects such as viscosity or finite Larmor radius must be invoked to stabilize the resistive interchange or "resistive-g" modes in the absence of minimum B. Current-profile flattening, which results from increasing gradients of current and safety factor near the plasma edge, tends to improve the MHD stability. Jardin has investigated the three-dimensional stability of axisymmetric spheromak equilibria to internal ideal MHD modes as a function of shape, safety factor profiles and pressure profiles [16]; and finds equilibria with stability windows for internal modes for similar values [15] of ellipticity and β .

In the absence of a conducting shell, a toroidal current carrying plasma tends to be unstable to one or more of the following three coupled global MHD modes: (1) Vertical or up-down instability, that tends to develop in tokamaks as a sliding along the vertical field; (2) The radial or shifting mode, the tendency of the plasma to shift radially into a region of weaker magnetic field strength; and (3) The tilting mode, the tendency of the plasma to tilt and align its magnetic moment with an external field. In tokamaks and reversed field pinches (RFP) the tilting mode does not occur because the separatrix is outside the plasma volume. The vertical instability occurs in tokamaks and RFPs if the field is not indexed properly. The spheromak is susceptible to the tilt and shift modes since free energy

to drive these instabilities may arise from the interaction of the toroidal plasma current with the external field.

Jardin [16] has studied the tilting and shifting modes for a spheromak plasma as a function of plasma shape, and finds, in the absence of a conducting shell, that the tilting and shifting instability regions overlap. For a prolate plasma shape the system is unstable to the tilting mode. As the plasma shape becomes oblate, the growth rate of the tilt mode decreases and the onset of the radial shift instability occurs. As the plasma becomes more oblate, the tilt mode becomes stable and the shift mode's growth rate increases. The addition of a conducting shell, Fig. 3, surrounding the spheromak provides wall stabilization for the tilt and shift modes as well as to other global $m=1$ modes through eddy currents induced in the shell. Okabayashi and Todd [15], and Jardin [16] have studied global MHD modes, driven primarily by parallel current, for spheromak equilibria as a function of ellipticity, current shaping, and conducting wall position with a vacuum region between the plasma edge and the wall. It is found that the tilting and shifting modes can be stabilized provided a conducting wall is located such that $r_s/r_c > 0.7-0.8$, and all other global MHD modes are stabilized for $r_s/r_c > 0.8-0.9$ where r_s and r_c are the separatrix and conducting wall radii measured from the magnetic axis. Theory predicts that the distance between the plasma boundary (r_s) and the conducting wall (r_c) can be increased as the aspect ratio or flux hole is increased [15,16].

The addition of high energy ions to small-orbit CTs has been proposed [18] and theoretically shown to enhance the stability to tilting and other gross modes [19], thereby reducing the required

values of r_s/r_c . These stability limits of wall separation have not yet been systematically studied experimentally, but stable spheromak configurations are routinely produced in CTX. Taylor-like minimum energy states, similar to those of the RFP [20], have been calculated and are consistent with the observed conversion of toroidal flux to poloidal flux without a global disruption. Thus, the equilibrium configuration tends to regenerate itself against diffusive losses.

The theoretical ideal MHD limit of the engineering beta is relatively high, $\beta_e \sim 0.15$ [15]. The Maryland PS-1 device [21] has produced $\beta_e \sim 0.3$, while $\beta_e \sim 0.16$ has been observed in the CTX spheromak experiment [22]. However, the experimental value of β_e that can be achieved with acceptable transport in the collisionless regime has not been determined.

The present substantial understanding of the equilibrium and gross stability of spheromaks indicate nothing to prevent their use in reactors. The oblate wall requirement imposes limits on their usage in moving ring systems, and on the reduction of r_s/r_c in an adiabatically heated system. The injection of high energy ions reduces these limits. The CT is a flexible configuration that allows a variety of applications.

2.7. Transport, Heating, and Sustainment

The immediate need in present spheromak experiments is to increase the electron temperature so that transport and heating studies can be performed in a relatively collisionless regime ($T_e > 100$ eV). The RFP experimental results indicate that the impurities must be low to allow an operating "window" in density between radiation at high density and drift-induced turbulence at low

density. Improved impurity control is being developed in the CTX spheromak experiment so that ohmic heating can increase the temperatures above 100 eV. Higher temperatures will allow collisionless confinement experiments and a variety of heating and sustainment experiments using rf, beams, and adiabatic compression.

3. Field Reversed Configurations (FRC)

The FRC shown in Fig. 5 is formed with negligible toroidal field and with a poloidal magnetic field that is generated by plasma currents carried by particles with small gyroradii. FRCs have been produced in the laboratory since the early 1960s using the field-reversed theta pinch. The FRC is produced by embedding an initial bias field into a cold preionized plasma and then reversing the direction of current in the theta-pinch coil. The resulting oppositely directed fields tear and reconnect at the ends, generating the closed field line structure of the FRC. Additional positive flux, generated by the rising magnetic field, produces open field lines separated from the reconnected field lines by a separatrix. As indicated in Fig. 6, the separatrix radius r_s in present-day experiments is comparable to the coil radius r_c (typically $r_s/r_c \sim 0.4-0.9$).

FRC experimental studies have encompassed diverse phenomena including formation techniques, heating, tearing instabilities, reconnection, radial compression, axial contraction, $n=2$ rotational instability, and field annihilation. A review of FRC experiments and theory is given in Ref. 23. Short-lived FRCs were observed in the early 1960s at Los Alamos [24], Naval Research [25], and Culham Laboratories [26]. Studies at the Jülich [27] and Garching [28]

Laboratories in the late 1960s observed the importance of low impurity levels in obtaining optimum plasma formations and stable quiescent confinement. Work at Los Alamos [29] and at the Kurchatov Institute [30] during the 1970s has been particularly significant. The Kurtmullaev group has studied lower compression, enhanced field reversal techniques, controlled field reconnection, and axial shock heating. Plasma lifetimes of $\sim 100 \mu s$ are limited by the decay of the external field, and the energy containment is projected to be $\sim 300 \mu s$ prior to the plasma lifetime limit. The Los Alamos FRX experiments have produced plasma temperatures in the 0.1 to 1 keV range, peak densities of $\sim 5 \times 10^{15} \text{ cm}^{-3}$, and configuration lifetimes of up to 120 μs .

In the last few years a good theoretical understanding has been achieved of the high-beta elongated FRC equilibrium. A useful result, independent of pressure profile, known as the "average beta condition" is the following [31,32]:

$$\langle \beta \rangle = 1 - r_s^2 / 2r_c^2, \quad (1)$$

where $\langle \beta \rangle$ is the volume average inside the separatrix of $8\pi P/B_{ext}^2$. The condition derived by considering pressure balance in both the radial and the axial directions, shows that the volume averaged beta must be very large (0.88 for $r_s/r_c \sim 0.5$) in order for an FRC to exist in equilibrium.

Stability is still an important issue for the FRC. Many MHD modes of instability originally expected for the FRC have been found to be stabilized either by the elongated geometry or by finite-Larmor-

radius effects often accentuated by the internal field null. An internal $m=1$ mode similar to spheromak tilting has been predicted theoretically [33-36], but it has not been observed experimentally. The only instability that occurs experimentally is a destructive $n=2$ mode that apparently results from a gradual build up of plasma rotation [36].

3.1. FRC Experimental Facilities and Results

Table I lists the parameters of some present day FRC experiments.

TABLE I
PARAMETERS OF FRC EXPERIMENTS

Experiment	Institution	Coil				
		Id/L	Energy*	Voltage*	τ/λ	B*
		(cm)	(kJ)	(kV)	(μ s)	(kG)
FRX-B	LANL	25/100	78	40	2.6	11
FRX-C	LANL	45/200	350	85	4.0	9
BS	Kurchatov	~20/100	--	35	3.5	12
TRX-1	MSNW	23/98	45	45	3.0	8
NUCTE	Nihon U.	16/200	--	20	2.0	10
STP-L	Sagoya U.	12/150	96	40	2.4	20
PLACE	Osaka U.	10/100	--	50	1.8	25

*Typical operation.

Both the FRX-B [23] and -C [37] devices have symmetric passive magnetic mirrors (mirror ratio ≈ 1.05 to 1.20) produced by decreasing the inside diameter of the coils near the ends. Figure 6

shows a typical magnetic-field time history used to form an FRC consisting of the following sequence: (a) A bias field of a few kG (~ 2) is applied with $\tau/4 \sim 100 \mu\text{s}$; (b) An oscillating ($\sim 400 \text{ kHz}$), 2.5-kG theta-pinch discharge preionizes the deuterium fill gas; (c) The main bank produces a field change of $\sim 10 \text{ kG}$ with $\tau/4 \sim 5 \mu\text{s}$, and (d) A passive crowbar clamps the externally applied field with an e-folding decay time of 100 to 300 μs .

Kurtmullaev's group at the Kurchatov Institute produce FRCs in reversed-field theta pinches using additional magnetic fields to control the formation process [30]. A pulsed octupole barrier field is used to maximize the trapped flux and minimize plasma losses to the wall during the field reversal process. Both mirror and cusp fields are used at the ends of the main coil to control the field reconnection process and to initiate an axial shock compression. The Soviets produce FRCs with $r_s/r_c = 0.7-0.9$ that last the full 100- μs L/R decay time of their magnetic fields and do not observe a rotational instability. The TRX-1 experiment [38] uses many features of the Kurtmullaev experiments including pulsed barrier magnetic fields to maximize flux trapping efficiency, and both cusps and mirror fields to control the reconnection through shaping and rapidly changing the magnetic field configuration at the coil ends. A Z-pinch discharge is used for preionization.

The U.S. experiments, FRX-A [23], FRX-B [23], FRX-C [37] at Los Alamos, and the TRX-1 [38] experiment at Mathematical Sciences Northwest; and the Soviet experiments [30] by the Kurtmullaev group have been successful in clarifying many features of the FRC during the past 10 years. The following important results are summarized from

the experimental work: (1) A CT without toroidal magnetic field (FRC) can be created using field-reversed theta-pinch techniques. The resistive tearing mode can be controlled by proper vacuum procedures, preionization methods, and experimental design; (2) A weakly compressed FRC inside a conducting wall is observed to be MHD stable; (3) The FRC displays a quiescent phase that is terminated by a growing $n=2$ mode most likely caused by rotation resulting from non-classical transport; (4) The confinement of plasma and energy during the quiescent period is much superior to plasma confinement in open field line configurations; and (5) Translation of the CT from one coil region to another has been successfully demonstrated.

3.2. Equilibrium

After the FRC formation, a quiescent stable period of plasma confinement is observed for 30 to 60 μ s before the onset of the rotational instability. During this stable period the equilibrium profile and parameters have been studied in the FRX-B experiment [23] with a fill pressure of 17 mtorr. The FRC separatrix radius determined from end-on framing photographs, is approximately 5.0 cm at $t = 9.5 \mu$ s. Radial density profiles from Thomson scattering measurements on the axial midplane yield a radius of ~ 5.5 cm in reasonable agreement with the end-on luminosity measurements. Excluded flux measurements as a function of axial position and time give a separatrix radius $r_s \sim 5$ cm assuming the diamagnetic contribution from the plasma on the open field lines is negligible. The excluded flux radius remains approximately constant in time until the rotational instability causes plasma wall contact and field disruption at $t = 50 \mu$ s.

The radial electron temperature profile, determined from Thomson scattering as a function of time on the midplane, is approximately flat at ~ 100 eV for radii less than the separatrix radius until the onset of the rotational instability at $t \sim 30$ μ s. Outside the separatrix, $r \sim 6$ cm, the temperature decreases with time from $T_e \sim 70$ eV at 4.5 μ s to ~ 10 eV at 30 μ s. Doppler broadening measurements of CV give ion temperatures of 200 eV at $t = 10$ μ s that approach the electron temperatures in the classical equilibration time of the two species ($t \sim 40$ μ s).

The axial density profile was determined from a 6328A laser interferometer that measured the integrated-line density across a diameter as a function of axial position and time. The axial length of the plasma is observed to be about 50 cm in the 1-m length coil and to be relatively constant during the plasma stable period. Excluded flux radius measurements, obtained from a series of loops and probes along the axial direction, indicate the FRC configuration is relatively stationary during the quiescent period. After the onset of the rotational instability the $n=2$ distortion grows until it causes plasma-wall contact ($t \lesssim 50$ μ s).

In the new FRX-C experiment [37] with a deuterium filling pressure of 20 mtorr, the FRC equilibrium is characterized at 20 μ s by the following parameters: separatrix radius $r_s \sim 12$ cm, separatrix length $l_s \sim 115$ cm, $B(\text{external}) \sim 7.4$ kG, peak density $\sim 4 \times 10^{15}$ cm^{-3} , $T_e \sim 80$ eV, $T_i \sim 200$ eV, $\tau_{\mu}(\text{stable}) \sim 80$ μ s, and $R/\rho_{f0} \sim 30$. At a filling pressure of 5 mtorr the equilibrium parameters are: $r_s \sim 9.2$ cm, $l_s \sim 100$ cm, $B(\text{external}) \sim 7.7$ kG, peak density $\sim 2.3 \times 10^{15}$ cm^{-3} , $T_e \sim 100$ eV, $T_i \sim 550$ eV, $\tau_{\mu}(\text{stable}) \sim 43$ μ s, and

$R/\rho_{10} \sim 15$. The lower fill pressure results in well-centered FRCs, but as the fill pressure increases the FRC length becomes comparable to the coil length and often one end or the other of the FRC appears to expand out of the coil. Characterization of FLR stabilization effects is typically given by R/ρ_{10} . These FRX-C experiments at 20 mtorr have $R/\rho_{10} \sim 30$ with a stable period $\tau_s \sim 30 \mu s$, against the $n=2$ rotational instability compared to previous FRX-B results that obtained $R/\rho_{10} = 7-8$ and $\tau_s \lesssim 40 \mu s$.

Theoretical study of FRCs has been impeded by difficulty in computing highly elongated or prolate equilibria of the type observed in field-reversed theta-pinch experiments. Recently Spencer and Hewett [39] have developed a new approach to the computation of FRC equilibria in a conducting cylinder that avoids the previously encountered difficulties. They find equilibria by inverting the Grad-Shafranov equation by means of a Green's function and by solving the resulting non-linear integral equation for the particular case $p'(\psi) = cH(\psi)$. Long prolate equilibria are obtained only for values of the constant c very near a critical-value; the equilibria change from 2:1 elongated to infinitely long as c varies by only 0.3%. This critical value of c is predicted by the average beta condition, Eq. (1). The elongation and the shape of the separatrix near the field nulls are restricted by the requirement that the field lines outside the separatrix satisfy conducting wall boundary conditions. To change the shape of the transition region it is necessary to either change the boundary conditions or the pressure profile. The sharp singularity in the elongation as a function of the parameter c is not unique to the particular $p(\psi)$ studied and this feature makes looking

for long equilibria by varying parameters in the pressure profiles very difficult.

3.3. Stability

For highly elongated FRC equilibria having proper profiles and boundary conditions, theory predicts all ideal MHD modes to be stable except for two types: (1) the $m=1, n=1$ tilt mode [40]; and (2) high n -number axial and radial kinks with poloidal mode number $m=1$ [41]. All FRC experiments with high elongation ($l_s/r_s \gg 1$) have exhibited gross stability. No large scale MHD instabilities except rotationally driven ones are observed in the experiments even though the FRC exists for many Alfvén transit times. The tilt mode is not observed except when an FRC is highly contracted axially ($l_s/r_s < 3$). The tilt mode may be stabilized in the experiments by single-particle effects [42]. The $m=1$ low n -number radial kink modes are stable provided the FRC separatrix is sufficiently close to the wall. The $m=1$ high n -number kink modes are not observed in the experiments, and are assumed to be finite Larmor radius (FLR) stabilized. A question for FRCs centers on the trade off between confinement and FLR stabilizing effects since confinement improves as $S = R/a_1$ increases and the FLR effects decrease. The FRX experiments have operated with S in the range of 6 to 30.

Most of the FRCs eventually go unstable to an $n=2$ rotational flute instability where n is the toroidal mode number. The experimental observations are in agreement with predictions of a Vlasov fluid code analysis of the mode [43] which indicates instability when the plasma rotation exceeds a critical angular velocity. End-shorting and diffusion mechanisms have been proposed as

causes of rotational acceleration in the FRCs [23]. End shorting of open field lines on insulating walls by wall plasma results in a rotation of the open-field-line plasma. Steinhauer [44] has studied the end shorting case for FRCs, and postulates that the torque applied to the open field-line plasma by end-shortng currents is transmitted across the separatrix to the closed field-line plasma through viscosity. The instability threshold condition requires in addition either ambipolar potentials or transient shorting effects. Although it has been too difficult to measure the internal FRC plasma profile with sufficient accuracy to quantitatively assess the coupling strength of this end-shortng mechanism in the present experiments, Hirano's work [45] demonstrates the influence of end shorting on rotation.

The diffusion mechanism involves the transfer of net angular momentum through particle loss across the separatrix and then out of the system. Barnes and Seyler [31] have developed a kinematic theory that indicates particles with orbits near the separatrix have a preferred angular momentum. Loss of these particles leaves the closed field-line plasma with a net angular momentum of the appropriate sign. The instability threshold is predicted to occur in the FRX-B plasma when the fraction of particles lost $F \approx 0.57$ compared with the experimental observation $F \approx 0.55 \pm 16$ [29]. If the diffusion mechanism is correct, i.e., the radial flow velocity driven by particle transport gives rise to a finite pressure anisotropy in the azimuthal direction resulting in a net torque on the confined plasma, the $n=2$ rotational mode would not be a limitation for a reactor. Rather, loss of plasma could limit the fusion output before the mode

went unstable. Therefore diffusion, not instability, is the limitation.

Results reported by Kurtmullaev on FRX-like experiments indicate no rotational instability during the observation period [30]. There are several differences in device operation and plasma parameters between the Soviet and FRX experiments that might explain these contrasting observations. The larger ratio of r_s/r_c ($\sim 0.7-0.9$)

in the Soviet experiments appears to result in reduced plasma confinement. It may be that the resulting slower rotational acceleration does not lead to instability on the l/R time scale of their field crowbar circuit.

D. Confinement

It is important to assess the particle and energy containment of FRCs in order to determine transport rates, correlate plasma loss with stability, and identify future experimental directions. In the present FRX experiments the FRC lifetimes are limited by an $n=2$ rotational instability, whose development appears to be caused by particle diffusion across the separatrix [46,23]. Also, in the FRX-B experiment the energy confinement time is found to be comparable to the particle confinement time [23]. Therefore, particle loss may be the crucial issue for FRCs. In considering particle transport for FRCs the following features are important: (1) The density gradient length is a small fraction of the coil radius; (2) An unmagnetized volume exists around the field null where particle gyroradii are much larger than in the separatrix region; and (3) The plasma pressure decreases to zero outside the separatrix within a few ion gyroradii. This, combined with a high average β of 0.5 to 0.9 inside the

separatrix volume results in strong density gradients in the vicinity of the separatrix.

Particle loss has been investigated by Tuszewski and Linford [46] using a steady-state, one-dimensional model for radial particle transport which approximates the experimental observation of elongated FRC equilibrium with approximately constant separatrix radius. The model is characterized by: (1) The magnetic field structure at the midplane is assumed constant; (2) The balance of plasma and magnetic field pressures is taken into account both radially and axially; and (3) The diffusive flow of particles across the separatrix is assumed to equal the end loss rate of particles on open field lines. Various diffusion coefficients, including classical and anomalous transport, with assumed profiles were investigated. It is found that anomalous transport from the lower-hybrid-drift (LHD) instability [47] with the wave energy bound on the saturation level dominates the particle confinement over classical effects, particularly for larger devices. It is also found that typical FRC radial profiles have a classical core near the field null and an anomalous region in the vicinity of the separatrix. The particle confinement time τ_N , determined by LHD transport, is given by [46]

$$\tau_N = 4 \frac{(M_i/\pi M_e)^{1/2}}{(1 + T_e/T_i)\omega_{ci0}} \cdot \frac{(1 - \beta_s)^{3/2}}{\beta_s} \cdot S \cdot w^3, \quad (2)$$

where β_s is the plasma β on the separatrix, $S = a/a_{i0}$, and w is the ratio of the gradient length at the separatrix to the vacuum ion gyroradius ρ_{i0} . This analytical result is in qualitative agreement

with a one-dimensional anomalous transport code developed by Hamasaki [48]. The code incorporates in its transport coefficients, contributions from classical processes as well as from the LHD instability, the latter contribution being dominant.

The FRC experiments suggest that an additional energy loss channel exists for the electrons [23]. In the FRX-B experiment it was observed that for $r < r_s$, and $t < \tau_s$, T_e is constant in time, space, and with fill pressure. However, the electrons receive energy from both ohmic heating and the higher temperature ions through electron-ion collisions. The impurity level was not well known but thought to be too low for a radiation barrier to account for the T_e limitation. Another candidate for electron energy losses is enhanced thermal conduction due to the electron temperature gradient driven micro-tearing mode [49], which has been suggested to explain enhanced electron energy transport in tokamaks. In this model the loss rate scales as $T_e^{4.5}$, so that an upper bound on T_e would be reasonable. In addition the electron temperature gradient length needed to produce the losses is of a realistic magnitude, the order of ρ_i .

E. Scaling

Scaling studies of plasma behavior and parameters have been performed in the FRX-A and -B experiments [50,51,23], and are underway in the larger FRX-C [37] device. The variation of the FRC stable configuration time, τ_s , with plasma parameters is of particular interest. Data from the FRX experiments show that τ_s scales linearly with the scale length parameter, $\tau_s \approx 6.0 \times 10^{-7} R^2 / \rho_i$ where $R = r_s / \sqrt{2}$ is the radius of the field null. The experiments also indicate that τ_s is insensitive to the ion temperature when R^2 / ρ_i is held

approximately constant. The one-dimensional, Lagrangian, transport model of Hamasaki [48], with the quasi-linear diffusion coefficient for the LHD instability, has similarly indicated that the time for half the particle inventory to be lost across the separatrix scales as R^2/ρ_{i0} , but is independent of the ion temperature. The particle and energy confinement times determined from the FRX-B experiments [23] are in approximate agreement with the Hamasaki code results. The linear scaling of τ_N with the plasma density scale parameter R^2/ρ_i indicated by the code and the strong experimental correlation of τ_S with these parameters suggest that $\tau_S \approx \tau_N$. This agreement supports the hypothesis of the rotational acceleration being driven by diffusion.

Tuszewski and Linford [46] show that longer confinement times for the LHD transport can be achieved by increasing the initial trapped flux in the FRC to give larger values of $x_s = r_s/r_w$. The resulting equilibria have lower values of $\langle\beta\rangle$ and the change in radial profile increases the confinement time which scales approximately as $x_s^{2.3}$. Improving the open field line particle confinement (larger values of w , cf. Eq. (3)) by some end-plugging technique would also increase the confinement times since τ_N scales approximately as $w^{1.6}$ [46]. In addition an increase in w may also produce a substantially lower bound for the saturation level of the LHD instability by reducing the value of the drift parameter v_d/v_i at the separatrix. This could greatly reduce anomalous transport if a different saturation mechanism such as ion trapping is relevant in the weak drift parameter regime.

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FIGURE CAPTIONS

Fig. 1. Schematic of spheromak configuration.

Fig. 2. Schematic of the CT's orientation and shape (a) before and (b) after its major axis rotates by 90° .

Fig. 3. The magnetized coaxial gun electrodes and three CTX flux-conserver spheromak geometries shown to scale. The observed stability to the tilting mode is indicated. The length (120 cm) of the (a) flux conserver was longer than indicated.

Fig. 4. Plot of the ratio of the measured (solid line) toroidal field to poloidal field as a function of time in the CTX spheromak. The triangular points are computed using a 2-D transport code.

Fig. 5. Schematic of FRC configuration.

TABLE I

PARAMETERS OF FRC EXPERIMENTS

Experiment	Institution	Coil				
		Id/I _c	Energy*	Voltage*	τ/μ	B*
		(cm)	(kJ)	(kV)	(μ s)	(kG)
FRX-B	LANL	25/100	78	40	2.6	11
FRX-C	LANL	45/200	350	85	4.0	9
BN	Kurchatov	~20/100	--	35	3.5	12
TRX-1	MSNW	23/98	45	45	3.0	8
NUCTE	Nihon U.	16/200	--	20	2.0	10
STP-1	Nagoya U.	12/150	96	40	2.4	20
PIACE	Osaka U.	10/100	--	50	1.8	25

*Typical operation.

6/82CTR2602

Fig 1

5/62CTR2520

FIELD-REVERSED CONFIGURATION (FRC)

TYPICAL FRC MAGNETIC PROBE WAVEFORM