Observations of Improved Stability and Confinement in a High-β Self-Organized Spherical-Torus-Like Field-Reversed Configuration

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An extremely high-β (over 85%) self-organized field-reversed configuration (FRC) with a spherical-torus- (ST-)like core is produced in the translation, confinement, and sustainment experiment by highly super-Alfvénic translation of a spheromaklike plasmoid. Substantial flux conversion from toroidal into poloidal occurs during the capture process, resulting in the ST-like core. This plasma state exhibits a remarkable stabilizing property for the ubiquitous $n = 2$ centrifugally driven interchange modes present in θ-pinch formed FRCs. This is explained, for the first time, by a simple model taking into account magnetic shear and centrifugal effects. The FRC-ST configuration has up to 4 times improvement in flux confinement times over the scaling of conventional θ-pinch formed FRCs and, thus, a significant improvement in the resistivity and transport.

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A field-reversed configuration (FRC) is a compact toroid with little or no toroidal fields [1]. An obvious attraction of such a configuration is its extremely high β, and singly connected magnetic geometry. This strongly self-organized compact toroid (CT) has been produced by various techniques such as field-reversed theta pinch [1], coaxial slow source [2], merging spheromaks with opposite hellicities [3,4], and rotating magnetic fields [5]. It can then be translated into a separated chamber for confinement and sustainment, which offers engineering advantages for a fusion reactor. The FRC appears to be extremely robust and can survive violent dynamics during the translation. The fundamental concern about this configuration is its stability to low-n magnetohydrodynamic (MHD) modes. The dominant global instability observed experimentally in FRCs is the $n = 2$ centrifugally driven interchange mode, which has been termed the $n = 2$ rotational instability because the principal drive force is the centrifugal force due to the plasma rotation [1]. This instability has usually been stabilized in θ-pinch formed FRCs by externally applied static multipole fields [6]. However, from technological and confinement considerations, multipole fields are highly undesirable; the steady magnetic fields should be axisymmetric. A new stabilization technique has been demonstrated recently in the translation, confinement, and sustainment (TCS) experiment [5] by rotating magnetic fields (RMF) for the RMF formed FRCs [7].

FRCs can be produced in TCS either by using RMF or by translating and expanding high density energetic compact toroids formed in an attached θ pinch. In the latter method the initial CT is formed at high magnetic field, and translated into a region with much lower field. The initial translated CT has little poloidal flux, but has strong toroidal fluxes at the ends, in opposite directions. After highly supersonic reflections at the end magnetic mirrors of the confinement chamber, the plasmoid *relaxes* into a preferred near-FRC state with only a small unidirectional toroidal flux remaining, forming a spherical-torus- (ST-)like configuration in the core region, but without a center column [8]. The toroidal field magnitude is much smaller than that of the poloidal field, and does not affect the high-β nature of the FRC-ST. However, when combined with the high elongation and small aspect ratio, it results in a safety factor exceeding unity over much of the configuration [9].

It has been noted in these TCS translation experiments, and in similar translation experiments in the Osaka FRC Injection eXperiment (FIX) [10] that the normally lifetime terminating $n = 2$ rotational instability does not develop despite the absence of multipole fields. The ion rotation velocities have been measured in TCS and are more than sufficient to drive the rotational instability, so its absence has been (pleasantly) surprising. Even the most sophisticated 3D hybrid simulations of standard FRCs to date fail to reproduce such a remarkable stability [11]. We develop a simple model, accounting for the magnetic shear of the unique ST-like FRC configuration, to explain, for the first time, the lack of development of this instability in the FRC translation experiments. We also present, for the first time, data on TCS for the enhanced lifetimes (compared to previous scalings) of these ST-like FRCs.

Experiments were carried out in the TCS facility with the LSX/mod (half scale Large s Experiment) field-reversed pinch attached, as shown in Fig. 1. High density compact toroids were formed in LSX/mod, and ejected at either 0.45 T (high energy) or 0.3 T (low energy). The initial compact toroids had typical conditions of $n_e = 6 \times 10^{20}$ m^{-3}, $T_t = 900$ eV, and $\phi_p^{\mathrm{RR}} \sim 2$ mWb (high energy) or of $n_e = 6 \times 10^{20}$ m^{-3}, $T_t = 400$ eV, and $\phi_p^{\mathrm{RR}} \sim 1.5$ mWb (low energy). $T_t = T_i + T_e$ is the sum of electron plus ion temperatures. ϕ_p^{RR} is the poloidal flux, which is estimated from the measured excluded flux, $\Delta\phi$, by the

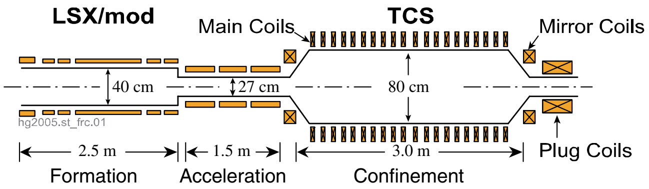

FIG. 1 (color online). Schematic of TCS device with LSX/mod attached.

rigid rotor (RR) approximation $\phi_p^{\mathrm{RR}} = 0.31 x_s \Delta\phi$. $x_s \equiv r_s/r_c$ is the ratio of separatrix radius to flux conserver radius, and r_s is generally taken to be the measured excluded flux radius $r_{\Delta\phi} = \sqrt{\Delta\phi/\pi B_e}$ where B_e is the external axial field at the flux conserver boundary.

Figure 2 shows time traces of ϕ_p^{RR}, B_e, and the line integrated density $\int n dl$, obtained from a two-pass $\mathrm{CO_2}$ interferometer, for the typical translated FRC conditions (low energy) at the center of TCS. The plasmoids were ejected from the LSX/mod source at a highly super-Alfvénic speed, ~ 300 km/s, and expanded into the large-diameter TCS confinement chamber with a lower bias field (~ 50 mT). After the extremely violent reflections at the end magnetic mirrors of the confinement chamber, the plasmoids settled down into a quiescent equilibrium with a substantial increase in the poloidal flux. The final confined FRC-like object has a separatrix radius $r_s \sim 0.22$ m, $n_e \sim 4 \times 10^{19}$ $\mathrm{m^{-3}}$, $T_t \sim 200$ eV. The detailed dynamics of translation were described in Ref. [8]. To illustrate the reproducibility, three discharges are shown in Fig. 2, including one with an internal probe inserted radially at the center of TCS, 2 cm past the axis, for the measurement of internal magnetic fields. The probe had 31 magnetic loops inside a 5 mm diameter boron nitride tube, and could be oriented to measure either $B_z(r)$ or $B_\theta(r)$ with a high time resolution. The data points shown in Fig. 2 were obtained from the detailed internal probe measurements. The measured poloidal flux is in agreement with the RR value obtained from diamagnetism, and the equilibrium value is substantially higher than that present during the first pass. There is essentially no difference between the discharges except for some small variations in densities, partially due to small changes in initial formation conditions, and partially due to variations in the centering of the FRC. The insertion of the internal probe only slightly reduces the lifetime.

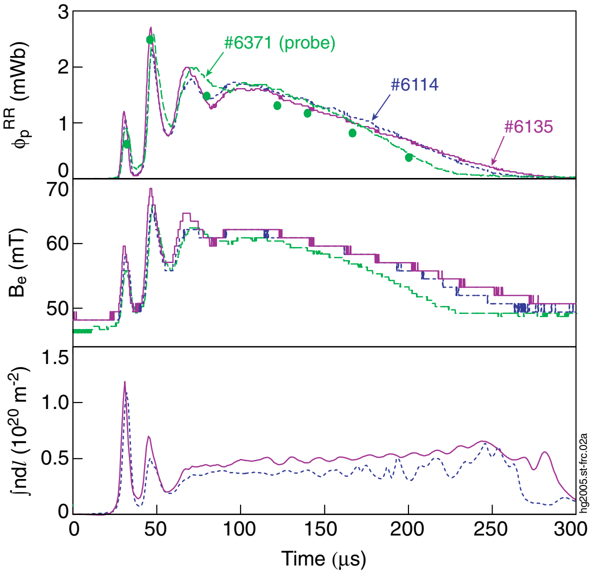

FIG. 2 (color online). Time histories of basic plasma properties at the TCS midplane for several translated FRCs, including one with the insertion of an internal probe 2 cm past the axis. The data points are obtained from the internal field measurements from the probe. Note that $\int ndl$ is not available for the discharge with the probe, which blocked the $\mathrm{CO_2}$ interferometer.

What appears to be truly remarkable is that the FRCs survived the violent reflection process and retained a long lifetime without developing rotational $n = 2$ instabilities. Theta-pinch formed FRCs generally develop a rotational $n = 2$ interchange mode when they spin up to close to the ion diamagnetic velocity, $\Omega \sim \Omega_D = 8 \times 10^3 K_{\mathrm{RR}} T_i(\mathrm{eV})/B_e(\mathrm{mT}) r_s^2(\mathrm{m})$ rad/sec, assuming a RR profile with the profile parameter $K_{\mathrm{RR}} \sim 0.7$ for typical translated FRC conditions in TCS. These instabilities take the form of a severe elliptical distortion that destroys the conventional θ-pinch formed FRCs in a few growth times. It has usually been stabilized by steady multipole fields of magnitude $B_m^2/2\mu_0 \sim 0.5\langle\rho\rangle\Omega^2 r_s^2$ [12].

The bulk deuterium rotation is not measured in TCS, but the Doppler-shift measurements from multichannel intensified charge-coupled device ion Doppler spectroscopy show a rotational speed for $\mathrm{C^{++}}$ ions up to $\omega_{\mathrm{C^{++}}} \approx 1.5 \times 10^5$ rad/sec, comparable to the ion diamagnetic rotation frequency. This suggests that the rotation speed of the bulk deuterium plasma ions could be well beyond the instability threshold. Nevertheless, no centrifugally driven $n = 2$ instability has been observed. This has been verified by detailed measurements from a visible tomographic system, which also provides information on the FRC centering.

Detailed internal probing shows that substantial flux conversion from toroidal into poloidal occurs during the highly supersonic reflection process at the end magnetic mirrors, producing a near-FRC state with only a weak toroidal field remaining [8]. The $B_z(r)$ and $B_\theta(r)$ profiles obtained from the internal probe for the final equilibrium state (~ 140 μs) are shown in Fig. 3(a). A striking feature is that the toroidal field is highly localized inside the field null (where the B_θ curvature is stabilizing), which is consistent with a "nearby-fluids" model for a high-β self-organized plasma with strong flows [13]. Because of low aspect ratio and large elongation, the highly localized B_θ, although small, produces a significant magnetic shear with a large q at the edge [9]. Figure 3(b) shows the q profile

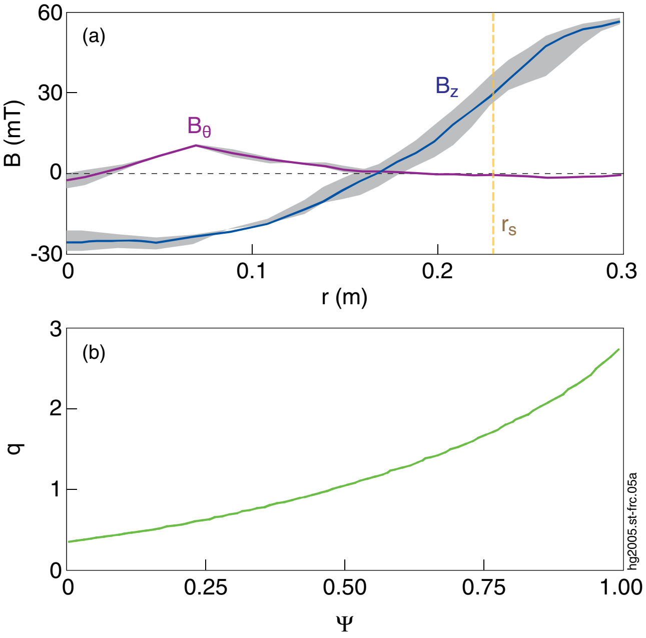

FIG. 3 (color online). (a) Radial profiles of axial and toroidal fields, $B_z(r)$ and $B_\theta(r)$, for the equilibrium FRC-ST state. Residual dynamical motions and shot-to-shot deviations are indicated by the shades. (b) q profile derived from the measured internal fields plotted against the normalized flux $\Psi = 1 - \psi/\psi_{\max}$, $\Psi = 0$ at the magnetic axis, and $\Psi = 1$ at the edge.

derived from the measured internal field, $B_\theta(r)$ and $B_z(r)$, profiles.

To investigate the significance of such a unique magnetic topology for the observed stability, we have developed a simple model for an *elongated* CT by extending the energy principle approach used by Bellan [14]. The added feature is the effect of rotation represented by an extra term in the expression for δW, which is, in effect, a *gravitational* potential energy arising from the centrifugal effect of rotation. Although the principal driving forces are different, both pressure gradient and centrifugally driven interchange instabilities are essentially Rayleigh-Tayler fluid instabilities driven by an unfavorable *gravitational* gradient [15]. The centrifugal effect may be taken into account by simply replacing the normal interchange drive with the effective centrifugal drive, i.e., $2\kappa P \sim \rho\Omega^2 r$; thus $2\kappa\nabla P \sim \Omega^2 r\nabla\rho$, where $\kappa = 1/R_c$ and R_c is the radius of the field line curvature. κ is very small over the central portion of an elongated FRC, and is not responsible for the rotational $n = 2$ instability. With a number of pessimistic approximations as in Bellan's treatment [14], we obtain

$$\delta W \approx \frac{1}{4}\int dV \xi_\perp^2 (B_{1\perp}^2/\mu_0 + \Omega^2 r\nabla\rho) \tag{1}$$

for a radial displacement $\xi_\perp$. Since the translated FRCs carry predominately a diamagnetic current, with a small toroidal field highly localized inside the field null, i.e., in the good curvature region, both the parallel current drive term and the curvature related pressure gradient drive term are neglected. Following Bellan's analysis in expanding the safety factor $q(\psi) = d\Phi/d\psi$ (where Φ is the toroidal flux and ψ the poloidal flux, $B_p = \nabla\psi/2\pi$) about a rational surface $\psi^{(m,n)}$ with $q = m/n$, the perpendicular component of the poloidal magnetic field perturbation becomes

$$B_{1\perp} = n(\psi - \psi^{(m,n)})\frac{dq}{d\psi}(B_p \cdot \nabla\theta) \tag{2}$$

with m the poloidal and n the toroidal mode numbers.

For an elongated FRC equilibrium,

$$B_p \cdot \nabla\theta = |B_z(u)|\sin^2\theta/y \tag{3}$$

where $u = (\frac{r}{R})^2 - 1$, $y = r - R$ is the minor radius, and $R = r_s/\sqrt{2}$ is the major radius at the magnetic axis. With the usual RR assumption for an FRC,

$$B_z = B_e \tanh(K_{\rm RR} u), \qquad \rho = \rho_0 \,{\rm sech}^2(K_{\rm RR} u). \tag{4}$$

We focus on the edge region, $r \sim 0.9 r_s$, where the centrifugal drive term, $\Omega^2 r\nabla\rho$, is most negative. $q \sim 2$ at this position, and the $m = 4$ mode would be the most unstable of the $n = 2$ distortions. The $n = 2$, $m = 1$ mode, seen in most untranslated FRCs without significant toroidal field, would be restricted to a small region near the magnetic axis. With the most pessimistic choice of $\psi^{(4,2)} = \psi_{\max}/2$, and counting only the unfavorable $\nabla\rho$ outer portion, again a pessimistic situation, the stability criterion $\delta W > 0$ becomes

$$\left(\frac{dq}{d\Psi}\right)^2 > \frac{3R^2 Z_0 \Omega^2}{n^2 V_A^2}\left|\frac{\nabla\rho}{\rho_0}\right|, \tag{5}$$

where $\Psi = 1 - \psi/\psi_{\max}$, Z_0 is the axial distance to the midplane, $V_A = B_z/\sqrt{\mu_0\rho_0}$ is the Alfvén speed based on the edge poloidal field, and $|\frac{\nabla\rho}{\rho_0}| = \frac{4r}{R^2} K_{\rm RR}\,{\rm sech}^2(K_{\rm RR} u)\tanh(K_{\rm RR} u)$.

For a typical translated FRC in TCS, $B_z \sim 30$ mT at the edge, $\langle n\rangle \sim 4 \times 10^{19}$ m^{-3}, $\Omega \sim 1.5 \times 10^5$ rad/sec, $R \sim 0.16$ m, $Z_0 \sim 1.0$ m, and $K_{\rm RR} \sim 0.7$, we obtain the following stability criterion for the centrifugally driven $n = 2$ mode: $(\frac{dq}{d\Psi})^2 > 1$. For the q profile shown in Fig. 3(b), $(\frac{dq}{d\Psi})^2 \sim 5$. Thus, it appears that the magnetic shear due to the appearance of the small and highly localized toroidal field is *sufficient* to stabilize the $n = 2$ rotational mode. Note that these translated FRCs are highly kinetic with s (the number of ion Larmor radii between the field null and the separatrix) about unity, but low s has not been noted to prevent the $n = 2$ rotational instability from developing in previous static FRC experiments.

For a given ratio of B_θ/B_z, the magnetic shear, $\frac{dq}{d\Psi}$, is proportional to the FRC elongation E. Thus, the stabilizing term $(\frac{dq}{d\Psi})^2$ in the energy analysis increases as E^2, while the destabilizing rotational term scales only with E.

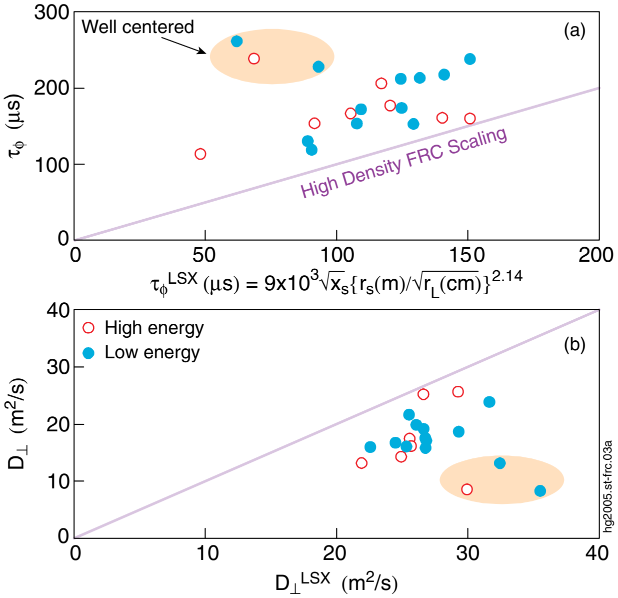

FIG. 4 (color online). (a) Measured magnetic flux lifetimes for the FRC-STs versus the LSX scaling for conventional θ-pinch formed FRCs. Those with low bias fields ($B_0 < 45$ mT) are not included due to strong impurity contamination from the surrounding quartz walls. (b) $D_\perp = \eta/\mu_0 = r_s^2/16\tau_\phi$ derived from the flux lifetimes assuming a RR profile.

Improvement with elongation is consistent with previous MHD simulations, which predicted a reducing growth rate, especially for high n modes, with increasing elongation [1,11]. On the other hand, the translated FRC is like an ST in that essentially all of the toroidal wrapping occurs on the inside leg of the poloidal surface. The stabilizing effect of the inside leg is communicated to the outside leg along field lines at the Alfvén speed with a communication time $\Delta t = Z_0/V_A$. The above analysis is valid if the growth rate of the $n = 2$ mode $\gamma_{n=2} < V_A/Z_0$. This is usually satisfied for FRCs with low s, in which the growth rates of the $n \geq 2$ modes are strongly reduced due to finite Larmor radius effect [1,11].

It is interesting that the magnetic flux lifetimes of the translated FRCs are much greater than the previous τ_ϕ scaling measured at high densities (LSX), $\tau_\phi(\mu s) = 9 \times 10^3 x_s^{0.5}\{r_s(\mathrm{m})/\sqrt{r_L(\mathrm{cm})}\}^{2.14}$ in conventional θ-pinch FRCs [16], where r_L is the Larmor radius. This is shown in Fig. 4(a), assuming $T_i = T_e$. The very best lifetimes, obtained with the FRCs well centered on the center line of the confinement chamber during the reflection process, have lifetimes about 4 times the conventional high density FRC scaling, very similar to the best results obtained in the FIX device [10]. The magnetic flux decays on a resistive diffusion time scale. For a rigid rotor profile and a uniform plasma resistivity, the flux lifetime $\tau_\phi \approx (\mu_0/\eta)r_s^2/16$ [16]. Figure 4(b) shows the corresponding values of $D_\perp = \eta/\mu_0$ plotted against the predictions of the high density LSX scaling. The resistivity and, thus, the radial transport appear to be significantly improved in these plasmas. Recent transport analysis by Ryutov *et al.* [17] shows that a small but nonzero toroidal field would reduce the electron thermal conduction and ion neoclassical transport in poloidal confinement configurations such as the FRC and levitated dipoles.

In summary, a self-organized FRC-ST configuration has been produced in TCS by super-Alfvénic translation, which has an extremely high-β (over 85%) and exhibits strong stabilizing properties. No centrifugally driven $n = 2$ interchange mode has been observed in spite of strong plasma rotation. The remarkable stability is attributed to the appearance of a weak toroidal field, which is highly localized inside the field null producing an ST-like q profile with strong magnetic shear. This plasma state also has a long flux lifetime, up to 4 times the conventional high density θ-pinch FRC scaling, suggesting a significant improvement in the resistivity and transport.

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[1] M. Tuszewski, Nucl. Fusion **28**, 2033 (1988).
[2] Z. A. Pietrzyk *et al.*, Nucl. Fusion **27**, 1478 (1987).
[3] Y. Ono *et al.*, Phys. Rev. Lett. **76**, 3328 (1996).
[4] C. D. Cothran *et al.*, Phys. Plasmas **10**, 1748 (2003).
[5] A. L. Hoffman *et al.*, Fusion Sci. Technol. **41**, 92 (2002).
[6] S. Ohi *et al.*, Phys. Rev. Lett. **51**, 1042 (1983).
[7] H. Y. Guo *et al.*, Phys. Rev. Lett. **94**, 185001 (2005).
[8] H. Y. Guo, A. L. Hoffman, K. E. Miller, and L. C. Steinhauer, Phys. Rev. Lett. **92**, 245001 (2004).
[9] L. C. Steinhauer *et al.*, "Field-Reversed Configuration with Large Safety Factor" (to be published).
[10] H. Himura, S. Okada, S. Sugimoto, and S. Goto, Phys. Plasmas **2**, 191 (1995).
[11] E. V. Belova, R. C. Davidson, H. Ji, and M. Yamada, Phys. Plasmas **11**, 2523 (2004).
[12] T. Ishimura, Phys. Fluids **27**, 2139 (1984).
[13] L. C. Steinhauer *et al.*, "Interpretation of High-β Self-Organized Plasma Equilibria Using a Nearby-Fluids Model" (to be published).
[14] P. M. Bellan, *Spheromaks* (Imperial College Press, London, 2000), Chap. 6.3.
[15] R. J. Goldston and P. H. Rutherford, *Introduction to Plasma Physics* (IOP, Bristol, 2000), Chap. 19.
[16] A. L. Hoffman and J. T. Slough, Nucl. Fusion **33**, 27 (1993).
[17] D. D. Ryutov, J. Kesner, and M. E. Mauel, Phys. Plasmas **11**, 2318 (2004).