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HIFLUX:
Oblate FRCs, Double Helices, Spheromaks and RFPs in One System

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Abstract: High magnetic flux is required for thermonuclear FRC reactors and, more immediately, to advance the FRC experimental program in general. Oblate FRCs are of special interest because they are predicted to have certain improved MHD stability over elongated FRCs, and oblate FRCs may yield the most compact, magnetically confined fusion reactors. Neither oblate nor high-flux FRCs have been investigated experimentally to date. Our presently proposed technique is to make two high-flux, oppositely-handed plasmas by a pair of large, external, reversed-field pinch (RFP) sources. The plasmas would propagate as two Taylor-relaxed double-helix plasmas, to an oblate main plasma chamber, where they would relax further to a counter-helicity pair of spheromaks, which would finally merge into a single high-flux FRC. A concept for a new experimental facility, HIFLUX, to make and study high-magnetic-flux oblate Field-Reversed Configuration (FRC) plasmas, is described. Similar principles might also enable high flux non-inductive startup of other plasma devices.

1. Introduction

Field Reversed Configurations (FRCs) [1] are magnetically confined compact tori (CT) having $\beta \approx \beta_p \approx 1$ and little or no internal toroidal magnetic field B_t. The high β and the absence of magnet coils threading a central hole make FRCs very attractive fusion reactor candidates. Oblate and elongated FRCs have the same high equilibrium β, but oblate geometry might lead to more compact fusion reactors. If the cross field transport in an FRC, characterized by some $D_\perp$, is not strongly dependent on global geometry, then the plasma confinement time required for fusion, proportional to $a^2/D_\perp$, would require a similar characteristic radius a for both prolate and oblate FRCs. The fusion power, proportional to volume $\sim a^3(L/a)$, would then be smaller for oblate geometry.

Figure 1 shows an oblate FRC in a short, cylindrical volume. Like the familiar prolate FRC, the plasma is confined by a poloidal magnetic fields produced by combined plasma and external toroidal currents. FRCs have little or no toroidal magnetic field and magnetic helicity, $\beta \approx \beta_p \approx 1$, and an outward Shafranov radial shift larger than in spheromaks, which have lower β. Image currents in a conducting flux conserver can equilibrate the CT against radial and axial expansion and stabilize it against external global tilt and radial shift instabilities [2]. Image current stabilization is maximized by keeping the plasma close to the walls. A small flux soaked through the conserver may provide a diverted scrape-off layer and separatrix shape control. Oblate FRCs have been little studied to date.

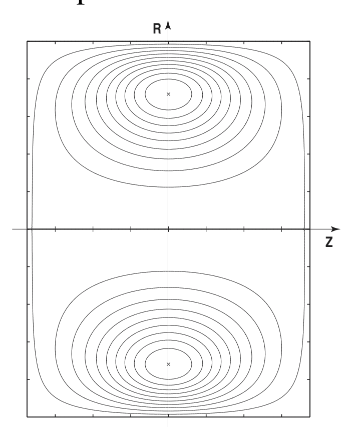

Fig. 1. A computed oblate FRC equilibrium within a cylindrical boundary

A key challenge for the FRC concept is to develop an FRC formation technique that is reliable, robust and that scales to larger polodial flux FRCs. There is no initial toroidal magnetic field to contain avalanching electrons, so high voltage is required for gas breakdown. Also, a $\beta \sim 1$ plasma must be generated simultaneously with the poloidal magnetic field B_p, because there is no toroidal field for B_p to pinch on. Furthermore, at $\beta \sim 1$, heating and burn-through are difficult to achieve. It is difficult to make FRCs having even 0.005 Wb of poloidal magnetic flux by the conventional ringing θ-pinch technique [1], and the θ-pinch technology is not readily scalable to larger flux and radius. Fluxes of several times 0.1 Wb may be needed for FRC proof of principle experiments and > 1 Wb for reactors. Recently, FRCs have been made by merging a counter-helicity pair of spheromaks [3], and the basic features of this process are now rather well understood. The merging technique was recently extended to the small SSX–FRC facility, where there is no central structure of any kind and the FRC is formed inside a close-fitting metallic flux conserver. FRCs of up to 0.004 Wb poloidal flux were made in SSX-FRC [4]. The technique may be scaled up to higher fluxes by starting with higher-flux spheromaks.

In the rest of this paper we show how to make high-flux plasmas outside of the main chamber, away from the constraints of the final plasma equilibrium and stability, and then propagate them usefully to the chamber. The same concepts may also be used for non-inductive plasma startup of other plasma devices.

2. Double Helix to Spheromak to FRC

The key concept of our proposed high-flux FRC experiments is a generalization of spheromak merging: reconnection of a counter-helicity pair of Taylor-relaxed, double helix (DH) plasmas after they expand into the main chamber as quasi-spheromak objects. Figure 2 illustrates the DH-to-FRC concept. Primary sources (discussed later) generate a counter-helicity pair of magnetized, current-carrying plasmas. They elongate along their corresponding drift tubes and then expand as loops into the main chamber. There the two counter-helicity plasma loops with near zero total helicity, now resembling oblate spheromaks, reconnect into an oblate FRC final plasma state. However, the quasi-spheromak loops, unlike the previous experiments [3,4], are not truly two-dimensional, and it is unknown at this time whether the somewhat three-dimensional reconnection will still efficiently produce an FRC. Experiments are needed.

The source plasmas are generated with most of their current density $\mathbf{J}$ flowing parallel to the magnetic induction, $\mathbf{B}$. High-current, low-β plasmas relax approximately to Woltjer-Taylor minimum-energy states in which $\mathbf{J} = \lambda\mathbf{B}$ with λ a constant throughout V, a volume of interest bounded by a conducting wall [5]. In the special case where no magnetic flux penetrates the wall, λ is an eigenvalue depending only on the shape and characteristic transverse dimension a of V; i.e., λa = constant. Also in this case, $\lambda = W/K$, where W and K are, respectively, the magnetic energy and helicity in V. In systems where K is conserved better than W, plasma relaxes to the minimum accessible values of λ and W. In a long circular tube containing no initial magnetic flux, the minimum-

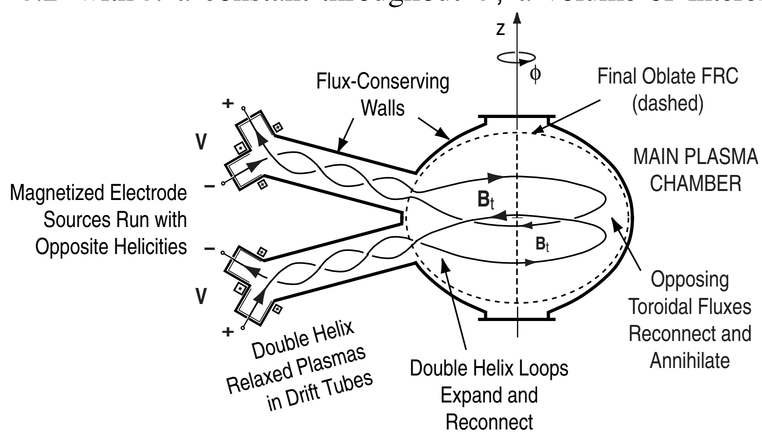

Fig. 2. Concept of FRC formation by injection and reconnection of a counter-helicity pair of DH plasmas.

energy state is the Taylor double helix, in which both the longitudinal magnetic flux and current flow out and back along the tube in a twisted double helix configuration [5]. The Taylor DH obeys $\lambda a \approx 3.11$. Very little is known about how well real double helix plasmas actually expand or propagate along a long conducting tube. Experimentally, small, very non-ideal DH plasmas decayed rapidly, e-folding in little more than half a helical wavelength [6]. Presumably, $\lambda = \mathbf{J}\cdot\mathbf{B}/\mathbf{B}\cdot\mathbf{B}$ decays in a tube of constant radius a, because the plasma is dissipative. Therefore, a must increase faster than $3.11/\lambda$ if a DH plasma is to propagate along the tube, so the tube must be tapered, expanding along the propagation direction. There is neither a quantitative theory of this phenomenon nor estimates of the required taper, and experiments are needed.

Relaxed plasma in the main chamber, with much larger a than the drift tube, has a smaller energy density than the propagating DH. Therefore, the DH will readily expand into the main chamber. The minimum-energy state with finite helicity in an oblate chamber is a single spheromak. With no helicity it is experimentally an FRC [4].

3. Plasma Sources

Figure 2 shows magnetized hollow-electrode plasma sources. We propose to start experiments with hollow-electrode sources, because they reduce expense and technological risk. Planar magnetized electrodes were used to make small DH plasmas [6,7], and magnetized hollow electrodes and a short double-helix drift tube were used successfully in the "m=1 helicity source spheromak experiment" at Los Alamos [8]. That experiment was a single-DH, fractional-period version of Fig. 2. Although magnetized electrodes may not ultimately scale to fusion reactor performance, much of the physics of DHs and their reconnection into a final FRC can be investigated first with these simple sources. Though simple, they may make higher-flux FRCs than previously possible.

If the drift tubes are many periods long, the two double helices may get out of phase if differences between the two sources make their respective DH wavelengths differ excessively. If this happened, the two DHs might not be oriented properly as in Fig. 2 for reconnection into an FRC in the main chamber. If the drift tube is not too long, the DH phases might be locked by imparting an elliptical cross section to the tube at its junction with the main chamber.

Drift tubes allow plasma sources to be set back from the main chamber rather than be incorporated into the chamber wall, which allows large sources to be used. A drift tube also accumulates and transiently stores magnetic flux and helicity from a source, reducing peak power demand. Helicity input is proportional to the time integral of the inter-electrode electric potential difference and to the characteristic $|B|$. Because the DH helicity, its poloidal-like flux, and the DH length are mutually proportional, the double helix grows along the drift tube as additional helicity is added by the source.

Magnetized electrodes are eventually limited by sputtering, melting, and vaporization of material. An inductively driven, toroidal, reversed field pinch (RFP), connected to a DH drift tube by a hole in the RFP torus is a possible non-electrode source. Figure 3 illustrates the concept. It has the potential to produce magnetized plasmas with more than 1 Wb of flux content.

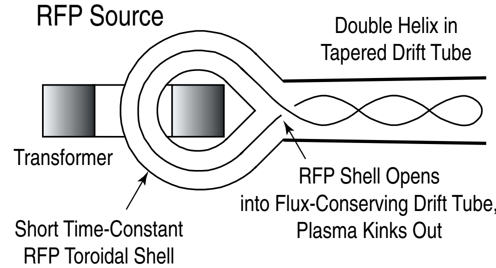

Fig. 3. Concept of RFP driving a double helix plasma.

RFP plasmas exhibit robust Taylor relaxation. At its simplest level, the RFP-to-DH transition reduces to sizing the DH drift tube to have a slightly lower energy eigenvalue λ than the RFP torus. This corresponds to making the drift tube radius a_d about $\geq \sqrt{2}\, a$, where a is the RFP minor radius. At a more detailed level the transition geometry is three-dimensional and needs to be developed so that unwanted energy and helicity losses do not occur there. It might take a few experimental trials to learn how to do this. Related half-torus helicity sources will soon be tested in the new HIT–SI experiment presently under construction, where they will be used to drive a spheromak [9]. The same concept of large, external sources coupled by DH drift tubes may also be applied to non-inductive startup of spheromaks, RFPs, spherical tokamaks, and perhaps even conventional tokamaks, including ITER. Figure 4 is a sketch of an RFP helicity source injecting into an ST chamber.

A major uncertainty with the RFP source is how to disconnect the DH from the RFP at the end of the injection phase without excessive loss of plasma and/or flux. However, the MAST spherical tokamak operates successfully with an inductive formation technique that depends on plasma disengagement from a linked coil [10].

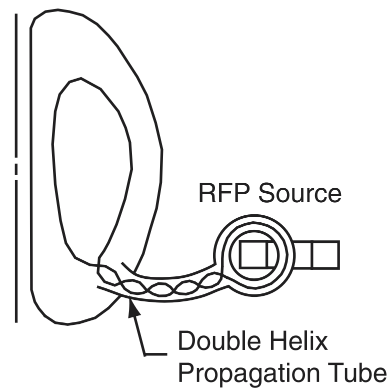

Fig. 4. Sketch of RFP source injecting into an ST chamber.

4. Experimental Approach

Possibly the most important dimensionless parameter for FRCs is the ratio of the plasma minor radius to ρ_i, the thermal ion gyro radius: $s \approx a_{FRC}/\rho_i$. Since the FRC magnetic field varies greatly, from zero at the magnetic axis to its maximum or near maximum value, B_e, at the outer equator, s is defined as the cross section average between the magnetic axis, $r_o \approx r_{sep}/\sqrt{2}$, and the separatrix equatorial radius, r_{sep}, and by custom it is normalized to r_{sep}. Finite ion gyroradius effects are stabilizing at low s in FRCs. However, thermonuclear fusion reactor FRCs will operate in the high-s fluid regime. Even if it had classical confinement, an FRC reactor would need $s > 10$ to meet the Lawson criterion, and if plasma loss were anomalous at about the tokamak level, then $s \sim 100$ would be required. Therefore, it is important to generate and study high-s FRCs experimentally. HIFLUX will advance in this direction.

One can decrease plasma temperature to reduce ρ_i and attain high s, but low temperature at fixed $\beta \approx 1$ yields an excessively dense plasma. Pinches tend to have an empirical density limit, $\bar{n}/\bar{J} = N/I \leq 10^{14}\ (\mathrm{A\ m})^{-1}$, and FRCs also operate best below this limit. Overbars indicate cross section averages, I and J are toroidal current and current density, respectively, n is particle density, N is particles per unit toroidal length, and units are SI. When the density limit is combined with s and an expression for the total energy W_{tot} of the FRC, W_{tot} at fixed I/N increases as the *fourth* power of s. Therefore, increasing n to raise s forces an increase of I in order to stay below the density limit, which increases B^2 and energy density. Furthermore, since β is fixed, the temperature must actually be increased somehow to maintain pressure equilibrium. Therefore, within the density limit constraint, large s can only be had with a large energy content. Some representative equilibrium values are shown in Table 1 for three values of s and an equatorial radius r_{sep}. of 0.5 m.

Table 1
Representative Parameters for HIFLUX FRC Plasmas vs. *s*
for r_{sep} = 0.5 m, $N/I = 10^{14}$ (A m)$^{-1}$, $Z_i = A_i = 1$ (hydrogen)

s	3	5	10	
Lundquist number	$1.5 \cdot 10^4$	$1 \cdot 10^5$	$2 \cdot 10^6$	
n	0.30	0.85	3.5	10^{20} m^{-3}
$T = (T_e + T_i)/2$	200	570	2300	eV
$p = 2nkT$	0.02	0.16	2.6	bar
$B_{equator}$	0.071	0.20	0.81	T
ρ_i (T_i and $B_{equator}$)	20	12	6	mm
W_{tot}	0.9	7	110	kJ
Poloidal flux	0.01	0.03	0.13	Wb

The HIFLUX experimental program could begin with the construction and operation of one DH drift tube and a magnetized electrode source. This would permit the study of double helix formation, relaxation, and propagation along a drift tube. The appropriate tube taper would be found experimentally. Addition of a main plasma chamber would permit the study of DH exit from the drift tube, its expansion into the main chamber, and relaxation into a single spheromak. This experimental configuration would be topologically equivalent to the Los Alamos one [8]. Further addition of a second double helix source and drift tube would allow investigation of FRC formation by merging a counter-helicity pair of non-axisymmetric quasi-spheromak loops. The outcome of this 3D reconnection process is the most crucial physics step for high-flux oblate FRC generation by the proposed method. If successful, we can proceed to investigate oblate FRC confinement physics as a function of s, n, B and T (only two of these four parameters are independent). All these topics could be addressed in a modest experimental device with a main chamber diameter of ≈ 1 m.

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