Next Step Needs for FRC Stability And Sustainment Studies - LSX-SS

John Slough
University of Washington

The FRC is unique amongst the various fusion plasmas. Due to the simply connected nature of the confining magnetic field and intrinsic high beta, the FRC plasma has been considered for fusion applications extending over a vast range of densities that span six decades (see Table below).

Table I FRC Fusion Reactor Parameters in Different Density Regimes

Density Regime	B (T)	$^{\#}\varphi_p$ (mWb)	r_c	r_s	$^{*}s$	$^{!}E_p$
$n=10^{26}$	635	< 1	< 1 mm.	< 1 mm	< 1	1.2 MJ
10^{23}	20	40	12.6 cm	6.3 cm	4	1.3 MJ
10^{20}	0.64	70,000	15 m	12 m	39	6.9 GJ

FRC parameters required to achieve n·τ·T product of 10^{21} m^{-3}s-keV. * Triton mass assumed in s calculation. # Poloidal flux determined from past FRC confinement scaling: $\tau_N = 0.033\ \varphi_p^{0.9}B^{-0.2}$ for the mid density. The steady state value is 3/5 of τ_N reflecting energy confinement, and a value of $\tau = 1\mu s$ was assumed for the inertial (dwell) time provided by the liner. ! An FRC elongation $\varepsilon = 5$ was assumed.

At the high energy density end the FRC becomes the best target plasma for magneto-inertial fusion concepts with the requisite lifetime and stability assured for the duration of the liner compression even in the extreme case of Bohm scaling. At the low end, the FRC becomes an ideal candidate for advanced fuel cycles such as D-^{3}He and P-^{11}B. Major departures from past FRC confinement scaling are required however for these fuels. It is hoped that the presence of a very high energy beam component will change the underlying transport by the many orders of magnitude required. Hybrid particle-MHD code calculations are likely the most cost effective method at this time for evaluation of these applications. From the table it is clear that the midrange density provides the best and most promising regime for obtaining fusion power with D-T fuel. It is also the least demanding technologically and requires the smallest amount of extrapolation from current experiments. Because fusion based on the FRC operating in this regime doesn’t suffer from the stability, sustainment and transport problems facing operation in the low density, steady state regime of the FRC, it doesn’t apparently qualify under the ReNeW guidelines for research needs. Accepting this somewhat inverted logic, the challenge now becomes how to overcome the stability and sustainment problems at high s in the low density regime, and what would be the best method to achieve the daunting flux requirements for FRC fusion. The vast gap between results to date and those required for fusion certainly qualify this regime as in need.

The confinement scaling on which Table I is based was derived from past FRC experiments culminating in the large s experiment (LSX). This device was the largest Field Reversed Theta Pinch (FRTP) ever built and produced the best confined, largest flux FRCs [1]. This device was operated for less than one year, but was designed to be capable of operation at high s (~ 10) and flux (~ 40 mWb). The opportunity to explore this regime vanished as funding for alternate approaches was eliminated. There have been other methods employed to produce the FRC. A 10 MW array of neutral beams was employed in an attempt to obtain an FRC in a mirror device, but full reversal remained elusive. Recently the FRC has been formed by merging spheromaks (MS) generated with coaxial guns [2]. The MS method held the promise of providing for more confining poloidal flux and a possible means for longer sustainment. However FRCs formed by this method have exhibited poor confinement and stability resulting in a confinement parameter far less than obtained with the FRTP method. The intimate contact of large conductors inside the FRC separatrix required for flux addition make the MS method a questionable one for attaining high temperature. The other major effort was focused at forming the FRC with Rotating Magnetic Fields (RMF) [3]. While it was possible to sustain the time averaged magnitude of the magnetic field in a reversed direction, the presence of the RMF inside the plasma dramatically increased the anomalous diffusivity by orders of magnitude, with the result that no more flux was generated than what could be achieved in much smaller devices employing the FRTP method [4].

This leaves the FRTP as the only viable method for creating a stable, well confined FRC. The issue now becomes how to move forward with this device. The stability issue can be adequately addressed by essentially reproducing a FRTP on the scale of the LSX device. This has in fact has already begun in the form of the Pulsed High Density (PHD) experiment (see Fig. 1) [5]. In addition to being of the appropriate scale, there have been several improvements made over the previous LSX in pulse power as well as other capabilities added, the most significant being the ability to readily translate the FRC once formed. This capability will be a tremendous advantage in the sustainment phase in that the chamber used for sustainment and heating is not constrained to coexist with the

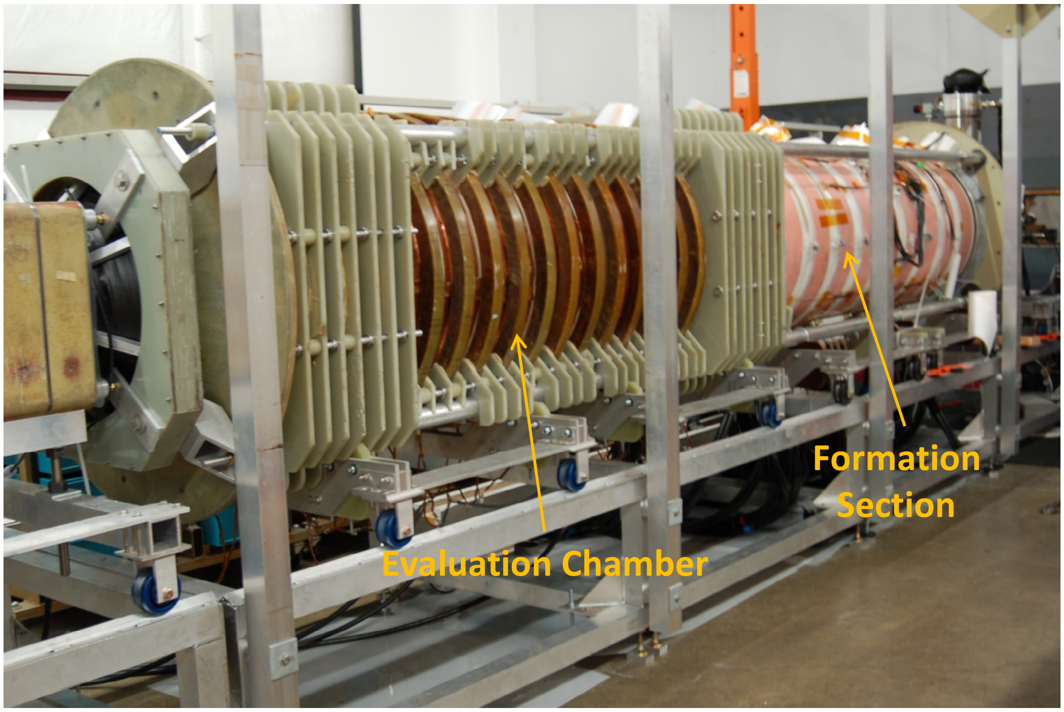

Figure 1. Current LSX Scale FRC Experiment: The Pulsed High Density Device

startup facility. It can be made much larger and appropriately ported for large neutral beams. This is not possible with the current configurations employing the MS and RMF formation methods. With the ability to work at the boundary of FRC stability, the question naturally arises as to how to stabilize the FRC beyond the apparent limit (s/ε ~ 0.5) reached in previous work. It has been known for a long time that adding a high energy ion component to the FRC can be stabilizing. In 3D hybrid MHD calculations [6] an LSX scale FRC was found to be stabilized with regard to the tilt instability when a small population of ions with a velocity of 1.5×10^6 m/s was added. Tilt stability was exhibited only when the beam energy was comparable to the plasma energy.

Neutral beams have been proffered as a possible method to create this beam component. There is a bit of a Catch-22 problem inherent with this approach in that the flux required to trap the beam (~ 40 mWb) puts the FRC immediately into the unstable regime it is meant to stabilize - well before the stabilizing influence of the beam can be obtained. This unstable startup situation will occur for virtually any reasonable FRC parameters. The timescale for beam build up will be several milliseconds which is greater than the best confinement found for even the well formed LSX plasmas. The tilt and other modes such as the mushroom instability grow on the Alfven timescale (a few μsec) so that there is small hope that neutral beams can be of help in suppressing theses rapidly growing modes. Attempting to sustain a turbulently unstable FRC with 40 mWb of poloidal flux during beam build up will demand tremendous power input. For instance employing the RMF method, based on the current power scaling observed in experiments [4], the plasma losses would be over 100 MW requiring a circulating antenna power of 2 GW.

The success of the FRTP method is due in large part to the fact that the technique generates a high ion temperature on an Alfvenic timescale during the formation of the FRC. It is the contention here that the injection of higher energy ions must take place on this rapid timescale in order to successfully extend the range of operation where quiescent FRCs can be created. If the FRC can be produced with sufficient flux such that the confinement time is comparable or longer than the time for beam build up, the employment of neutral beams can then be warranted. As noted, confinement scales roughly with the FRC poloidal flux when employing the FRTP method so that extending the quiescent operation to 40 mWb would provide for a FRC confinement time over 2 msec which should be adequate for neutral beam injection. Extension to even higher flux levels would be desirable. It is believed that this is possible, but first a brief discussion as to how the proper beam component can be generated is in order.

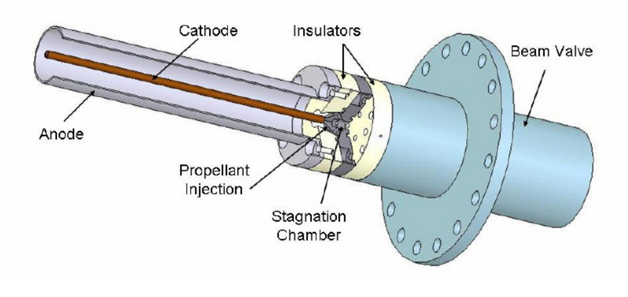

Figure 2: The Stanford 3 kJ CHENG Thruster [9].

At practically the inception of the fusion program, a method for producing a short burst of clean, high velocity hydrogenic plasma was discovered during the development of coaxial plasma guns [7]. It was noted that creating an immediate breakdown in a coaxial gun with the rapid injection of gas produced a plasma stream at the exit of the gun moving at exceptionally high velocity (1-3x10^6 m/s). It was later realized that the acceleration process was due to the coaxial gun operating in what was referred to as a deflagration mode as opposed to the usual snowplow mode employed in most coaxial gun experiments [8]. While a plasma source of this type was not appropriate for tasks such as spheromak formation, it is ideal for the production of the beam ions desired here for stable FRC formation at high flux. The coaxial device that has received the greatest development is called the CHENG gun [9]. It is suitably sized (5 cm diam. x 25 cm length) so that only small ports need be added to the existing LSX quartz chambers to accommodate them (see Fig. 2). The CHENG gun produces an energetic beam (~ 1-2 kJ) at typically 1-2x10^6 m/s with an efficiency of nearly 50%. It does this on a timescale of 5 to 10 μsec which is a good match to the FRC formation time on LSX (~ 15 μsec). For the short duration envisioned here the beam power can exceed 100 MW. To assure stability, a total beam energy of 10-15 kJ is desired, so that an array of 8 to 16 devices is envisioned to achieve or exceed this level. The ports would be dispersed along the central region of the LSX formation section. The injection of the plasma would be timed to coincide with the passage of the reversal layer of the FRC so that the plasma ions would be trapped in near betatron-like orbits. Aside from the obvious advantage in power and timescale for injection, another advantage of this method is tunability of the beam energy. There is no Child-Langmuir limit as the beam is neutralized. The plasma beam energy can be obtained over wide a range of velocities by varying the discharge parameters so that a beam suitable for trapping at much lower FRC fluxes is quite doable.

With the ability to form a stable and suitably well confined FRC at high s, the next task would be to extend the FRC flux to much higher values. There is basically only one method that can achieve FRC flux on the order of a fraction of a Weber in a manner consistent with the necessary alacrity in formation. It is based on a variant to the FRTP where the reverse flux is supplied by a separate inner coil. It has been referred to in the past as a coaxial source as this is the general structure of the device. This is not the same source employed in spheromak generation as only closed poloidal flux is generated by theta currents in pulsed inner and outer axial field coils.

Previous experiments at the University of Washington on the Coaxial Slow Source (CSS) attempted to achieve high flux FRCs with this type of device but, as the name suggests, on a slow timescale with respect to the characteristic Alfven time [10]. For the reasons stated above these experiments failed to form hot, quiescent FRCs. The plasma became unstable early in the formation, and the power required to form the high beta state at high flux was not available. What is required here, as it is in the FRTP, is a rapid FRC formation in the presence of high energy ions. FRC formation now consists of powering the old FRTP coils as well as this new inner coil, with all coils driven in parallel as shown in Figs. 3 and 4. By operating the coils in parallel the net flux within the formation annulus is negligible thereby avoiding

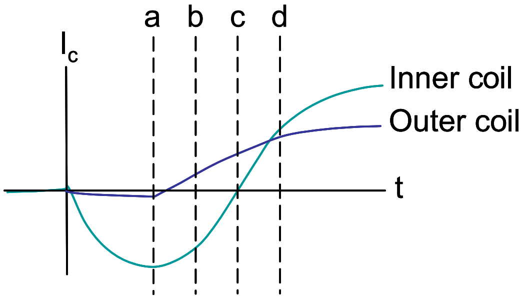

Figure 3. Theta current waveforms for the inner and outer coils operated in parallel. Dashed lines refer to time points illustrated in Fig 4.

unbalances in radial force on the FRC. By matching the inner and outer flux injection rates tearing reconnection is also avoided. It then becomes a simple matter to eject the FRC when appropriate. A sketch of the formation sequence is depicted in Fig. 4.

The modification needed to the LSX device would be the insertion of a fast coil similar to the compression coil employed in the FRTP mode. The inner single turn coil with a 0.2 m radius would be capable of producing up to a 3T inner axial magnetic field. Assuming a flux retention factor of 2/3, the potential FRC poloidal flux from coaxial FRC formation on a LSX scale device could be as large as 250 mWb. With individually triggerable coils as on the current PHD device, the formation process can easily produce a rapid ejection of the annular FRC plasma into a downstream chamber thus minimizing the time the FRC is in close contact with the coaxial source wall. To maintain stability during formation, it will still be necessary to continue to inject high energy plasma sufficient to stabilize the FRC. Simple translation into a larger flux conserver would produce a FRC of the appropriate density (10^{20}) and confinement time (~ 10 ms) for beam sustainment.

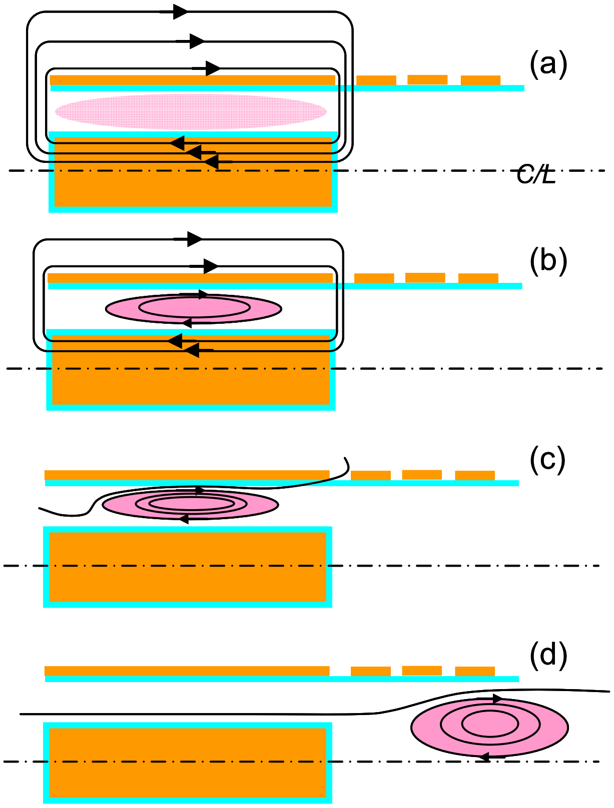

Figure 4. Programmed FRC formation sequence. (a) plasma introduced as inner coil reaches maximum stored flux. (b) flux injection commences. (c) inner coil flux exhausted and (d) the FRC is ejected.

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