White Paper for *Frontiers of Plasma Science* Panel

Date of Submission:	June 16, 2015

Indicate the primary area this white paper addresses by placing a "P" in the right column.
Indicate the secondary area(s) by placing "S" in the right column

	"P","S"
• Plasma Atomic physics and the interface with chemistry and biology	
• Turbulence and transport	
• Interactions of plasmas and waves	S
• Plasma self-organization	P
• Statistical mechanics of plasmas	

Indicate the type of presentation desired at the Town Hall Meeting

	"X"
Oral	X
Poster	
Either Oral or Poster	

Title:	Self-organization of steady-state FRCs: a frontier in plasma science
Corresponding Author:	S.A. Cohen
• Institution:	Princeton Plasma Physics Laboratory
• email:	scohen@pppl.gov
Co-authors:	

White paper

Self-organization of steady-state FRCs: a frontier in plasma science

S.A. Cohen
Princeton Plasma Physics Laboratory, Princeton, NJ 08543

I. The research frontier: self-organization (SO) of *sustained* FRCs

FRCs are arguably the most self organized of all plasmas. Steinhauer[1] offers two reasons why FRCs should be considered to have self-organized into a natural state: 1) their ability to survive a turbulent, violent birth; and 2) profile consistency of their current channel. He then describes two perspectives from which to explore this assertion, a variational principle, *i.e.*, an extremized quantity, with global constraints and tearing-mode-stability principle. The first follows Taylor's insights.[2] The second relies on marginal stability.

To appreciate the uniqueness of the FRC in the field of SO, consider that its plasma current (**J**) is perpendicular to its magnetic field (**B**), hence FRCs are *not* characterized by the force-free $\nabla\times\boldsymbol{B} = \lambda\boldsymbol{B}$ condition so successfully and extensively applied to plasma relaxation[3] in RFP and spheromak devices and to a lesser degree in tokamaks and stellarators. Moreover, the FRC's β is high while that in Taylor's model is 0. By these two measures, the details of how FRC plasmoids self organize, form, and become robust are mysteries on the frontiers of plasma science. In fact, in 2011 Steinhauer stated, "no FRC-relevant simulations have been made."

The field-reversed configuration *name* derives from the original formation method: rapidly reversing the current (hence field) in θ-pinch coils, trapping magnetic flux in a previously formed on-axis plasma, and driving tearing modes and magnetic reconnection at X points near the plasma's axial extremes.[4] The resulting closed-field-line plasmoid then decayed resistively in typically 50 μs or was rapidly destroyed by global modes. Subsequent experiments developed better magnetics techniques and showed that FRC plasmas are not fragile; they survive rapid translations and repetitive impacts with metal walls yet merge when interacting with other FRCs, other examples supporting a *natural state*. Moreover, sustaining FRCs far longer than their resistive decay time places this research activity at the forefront of research into SO.

II. Advancing the research frontier: longer pulses, improved heating, diagnostics, and codes

Advances in FRC heating and current drive techniques have provided controlled methods to create FRCs and sustain them for over 200 ms,[5] limited by technology not physics. Some of these methods add magnetic flux at the O point, deep inside the separatrix, not at the X points on the separatrix surface. How the magnetic flux is grown and the FRC's natural state sustained against resistive decay and without apparent tearing modes is another mystery.

An early method[6] used to form high flux FRCs was merging ($v = 5 \times 10^5$ cm/s) of two spheromaks formed by counter-facing conical θ-pinch coils. The resulting plasma, with a peak ion temperature $T_i = 200$ eV, $n_e \sim 3\times10^{16}$ cm^{-3}, a volume of 10^3 cm^3, and a magnetic field of 1T, decayed resistively in 100 μs. Later experiments[7] increased the plasma parameters to $T_i = 5$ keV, $n_e \sim 2\times10^{17}$ cm^{-3} and B = 12 T but the FRCs lasted only 5 μs. Recently this technique was vastly improved[8] by increasing the merging velocity a factor of 60, to a super-Alfvén value. The ion temperature reached 500 eV, the plasma persisted for 1 ms, and the energy confinement time was ~1 ms, nearly classical. The lifetimes, ion temperatures, and plasma currents of these FRC plasmas were then further increased (Figure 1) by the injection of energetic neutral beams.[9,10]

Research into a radiofrequency method – rotating magnetic field (RMF) – for FRC formation and sustainment was begun in the 1960s.[11] The current drive mechanism was second order: first the RMF's time-varying B field created an axial current in the plasma; then this current interacted with the radial component of the RMF ($J_z x B_r$), resulting in an azimuthal current of sufficient intensity to form a high-β plasmoid. In harsh contrast to experience with tokamaks, increases in device radius (x10) and RMF power (x10^3) hardly improved the plasma parameters,[12]

a phenomenon explained as being due to the opening of field lines.[13] A fundamental change made in the symmetry of the RMF antenna system, from even to odd parity (RMF_o),[14] produced major improvements, electron temperature nearly 10x higher than before and improved energy[15] confinement, both attributed to RMF_o's capacity to maintain closed field lines[16] inside an FRC's magnetic separatrix. (See Figure 2.) At present there is no analytic model of odd-parity RMF field penetration and current drive, an omission that must be rectified to understand how FRC's self organize. PIC simulations have shown the field reversal and RMF_o penetration.

The addition of superconducting flux conservers has allowed these plasmas to be sustained for over 200 ms, without wall contact and with major reductions in plasma turbulence, see Figure 3. This duration far exceeds the resistive, energy confinement, and inductive times of the plasma but not the particle confinement time. Even longer duration higher power plasma experiments are now needed, with an emphasis on achieving higher plasma parameters, especially ion temperature, and better diagnostics of the turbulence. At high ion temperature two important new effects can be studied: 1) whether electron drag on ions will damp the plasma current; 2) whether the lower hybrid drift parameter $\gamma_D = v_{D,e}/v_{th,i}$, where $v_{D,e}$ is the electron azimuthal drift speed and $v_{th,i}$ is the ion thermal speed, affects plasma turbulence.

Improvements are needed in the techniques to study the plasma dynamics leading to the natural states and self-organization. A flux-tube picture is not appropriate for hot small FRCs, because energetic particle orbits create a 3-D interlocked weave rather than nested 2-D foliated surfaces (prone to slippage and dynamical evolution) and because both O- and X-point magnetic nulls exist. Advanced, cutting edge, computational methods, notably full PIC[17] and hybrid methods[18], will be essential to studying dynamical issues, including merging and RMF_o current drive in larger hotter FRCs (see Figure 4). New non-invasive diagnostics will be needed to probe the internal magnetic field[19] of these high-β devices whose **B** will vary from 0 to many Tesla. These activities place research on plasma dynamics leading to SO in small, hot long-pulse FRCs at the frontiers of computational, analytical, and experimental methods in plasma science.

Experimental facilities for these studies exist. A large beam-heated FRC is at TriAlpha Energy Corp; several θ-pinch-formed FRCs are in the Pacific Northwest, at U-Washington and MSNW, at LANL, and in Japan; and RF-heated FRCs are at Prairie View A&M University and the Princeton Plasma Physics Laboratory (PPPL). Computational tools are at the PSI-center (U-Washington), LLNL, U Maryland, MIT,LANL, and PPPL. These include multi-fluid codes, hybrid codes, and PIC codes. Increased manpower, coordination, and computer time are needed.

III. Impact of this research and societal benefits

For decades[20,21,22] it has been appreciated that fusion power in space would offer unique capabilities in propulsion.[23] The propellant exhaust velocity of a fusion-powered plasma rocket would exceed that of chemical rockets by more than two orders of magnitude and the specific power (kW/kg) of an in-space fusion reactor could exceed that of conventional or fission rockets by factors greater than 10.[24] With such capabilities, a fusion-powered rocket would make possible far-reaching missions such as manned travel to Mars[25] and asteroid/comet[26,27] intervention. Importantly, the MW-power levels available from a fusion-powered rocket would allow a **million-fold increase in data transmission rates** from spacecraft surveying the far planets, the Kuiper belt, the Oort cloud, and beyond – a major contribution to exploring the solar system.

Another application of fusion power is for terrestrial power generation, to reduce greenhouse gas emissions. The FRC's high β allows *aneutronic* fuels, greatly reducing shielding thickness, neutron-resistant-materials development programs, and health/safety concerns. The FRC's small size lowers development costs. Scientists have investigated a number of D-D fuel cycles[28,29] in which one fusion product, ^{3}He, is burned along with the D-D but another, T, is exhausted. This alleviates the ^{3}He shortage problem but requires improved confinement. Progress in these fuel cycles could be a game changer in the development of terrestrial fusion power.

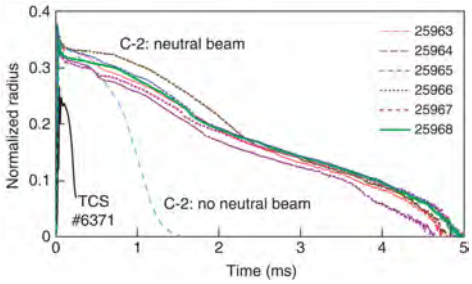

Figure 1. Normalized excluded flux radius in the C-2 device, obtained with neutral beam heating. [10]

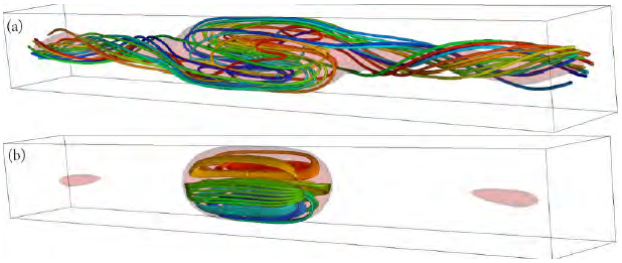

Figure 2. MHD simulation. Field lines launched from the mid-plane 20 μsec after the RMF has been ramped off for (a) an even-parity calculation, and (b) an odd-parity calculation. Note the open field lines for the even-parity case and closed for odd parity, a natural state for a true FRC. [15]

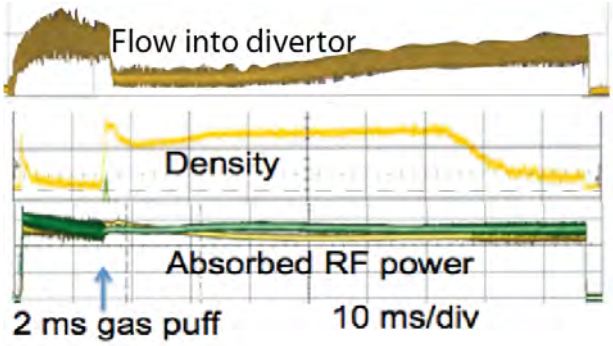

Figure 3. Data from a 95-ms duration pulse in the PFRC-2 device. Top: flow into divertor chamber 2; middle: plasma density; bottom: absorbed RMF power. A gas puff is injected at 15 ms. At the injection time the density rises and stays high for 60 ms, the fluctuation level in the RF absorbed power drops and the flow into the divertor decreases. [5]

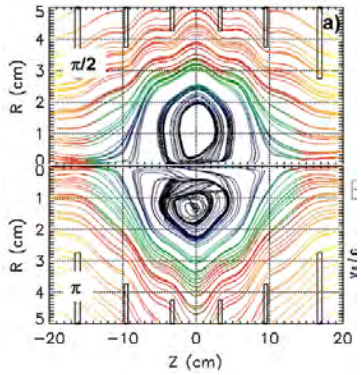

Figure 4. Formation of an FRC by RMF_o. 3-D LSP PIC simulation of FRC formation by odd-parity RMF show field reversal, a separatrix, and close field lines. The predicted electron density and temperature agree well with measurements in the PFRC-1.[30] Calculations are need for larger and hotter FRCs.

References

[1] L.C. Steinhauer, "Review of field-reversed configurations," *Phys. Plasmas* **18**, 070501 (2011).

[2] J.B. Taylor *Rev. Mod. Phys*. **58**, 741 (1986).

[3] J. B. Taylor, "Relaxation of toroidal plasma and generation of reverse magnetic fields," *Phys. Rev. Lett.* **33**, 1139 (1974).

[4] A. Kolb, *et al.*, "Field mixing and associated neutron production in a plasma," *Phys. Rev. Lett.* **3**, 5 (1959)

[5] S.A. Cohen, *et al.*, "Long pulse operation of the PFRC-2 device," *Bull. Am. Phys. Soc*. **58,** 128 (2013).

[6] D.R. Wells, "Injection and trapping of plasma vortex structures," *Phys. Fluids* **9**, 1010 (1966).

[7] D.R. Wells, *et al.*, "High-temperature, high-density plasma production by vortex-ring compression," *Phys. Rev. Lett.* **41**, 166 (1977).

[8] M. Binderbauer, *et al.*, "Dynamic formation of a hot field-reversed configuration with improved confinement by supersonic merging of two colliding high-compact toroids," *Phys. Rev. Lett.* **105**, 045003 (2010).

[9] M. Tuszewski, *et al.*, "Field reversed configuration confinement enhancement through edge biasing and neutral beam injection," *Phys. Rev. Lett.* **108**, 255008 (2012).

[10] H.Y. Guo, *et al.*, "Achieving a long-lived high-beta plasma state by energetic beam injection" *Nature Communications* **6,** 6897 (2015).

[11] H. Blevin, *et al.*, "Plasma confinement using an alternating magnetic field," *Nucl. Fusion:* Supplement, Part I, 55 (1962).

[12] A.L. Hoffman, *et al.*, "Advances in singly connected closed field line plasma devices and extrapolation to POP level experiments and reactors," *Nucl. Fusion* **49**, 055018 (2009).

[13] P. M. Bellan, "Rotamak confinement-power-current relationships and r.f. loading resistance" *Plasma Physics and Controlled Fusion* **31,** 879 (1989).

[14] S.A. Cohen, *et al.*, "Formation of collisionless high-beta plasmas by odd-parity rotating magnetic fields," *Phys. Rev. Lett.* **98**, 14500 (2007).

[15] R.D. Milroy, *et al.*, "Extended magnetohydrodynamic simulations of FRC formation and sustainment with RMF current drive," *Phys. Plasmas* **17**, 062502 (2010).

[16] S.A. Cohen, *et al.*, "Maintaining the closed magnetic-field-line topology of a field-reversed configuration with the addition of static transverse magnetic field," *Phys. Plasmas* **7**, 2539 (2000).

[17] T.C. Genoni, *et al.*, " A fast implicit algorithm for highly magnetized charged particle motion," *The Open Plasma Physics Journal* **3**, 36 (2010).

[18] E. Belova, *et al.*, "Advances in the numerical modeling of field reversed configurations," *Phys. Plasmas* **13**, 056115 (2006).

[19] D.R. Farley, *et al.*, "Coherent population trapping as a magnetic-field diagnostic for hydrogen plasmas," *Phys. Rev. A* ***85***, 033412 (2012).

[20] J. C. Nance, "Nuclear Pulse Propulsion," in *Proceedings of the 11th Nuclear Science Symposium of the IEEE*, (1964).

[21] F.J. Dyson, "Interstellar transport," *Physics Today*, 41 (October 1968).

[22] E. Teller, *et al.*, "Space propulsion by fusion in a dipole magnetic field," *Fus. Technology* **22**, 82 (1992).

[23] J.F. Santarius, "Magnetic fusion for space propulsion," *Fus. Technology* **21**, 1794 (1992).

[24] Y. Razin, *et al.*, "A direct fusion drive for rocket propulsion," *Acta Astronautica* **105**, 145 (2014).

[25] M. Paluszek, *et al.*, "Direct fusion drive for a human Mars orbital mission," *Proc. 65th International Astronautical Congress*, IAC-14, C4, 6.2 (2014).

[26] J.B. Mueller, *et al.*, "Direct fusion drive rocket for asteroid deflection," *Proc. 33rd International Electric Propulsion Conference (Washington, DC 2013)* IEPC-2013-296.

[27] G.A. Wurden, *et al.*, "A new vision for fusion energy research: fusion rocket engines for planetary defense," submitted to *J. Fusion Energy* (2015).

[28] V.I. Khvesyuk, *et al.*, "Low-radioactivity D-^{3}He fusion fuel cycles with ^{3}He production," *Plasma Phys. Control. Fusion* **44**, 253 (2002).

[29] J. Kesner, *et al.*, "Helium catalyzed D-D fusion in a levitated dipole," *Nucl. Fusion* **44,** 193 (2004).

[30] D.R. Welch, *et al.*, "Formation of field-reversed-configuration plasma with punctuated-betatron-orbit electrons," *Phys. Rev. Lett.* **105,** 015002 (2010).