White Paper for *Frontiers of Plasma Science* Panel

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Title:	Transport of magnetized kinetic plasma when $\mathbf{J} \cdot \boldsymbol{B} = \mathbf{0}$
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Transport of magnetized kinetic plasma when $\mathbf{J} \cdot \boldsymbol{B} = \mathbf{0}$

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I. The q = 0 frontier in the fields of classical and non-local transport and its importance

For decades,[1] major experimental and theoretical efforts have been focused on plasma transport in tokamaks and stellarators, nominally force-free ($\nabla\times\boldsymbol{B} = \lambda\boldsymbol{B}$) devices with plasma current (**J**) parallel to the magnetic field (**B**). Studies of transport in a different closed-field-line geometry – wherein the safety factor q will be 0 and **J**, including diamagnetic, is purely perpendicular to **B** – will be at a little-explored frontier of plasma science and offer new vistas, insights, and capabilities. Moreover, plasma configurations with $\mathbf{J} \cdot \boldsymbol{B} = \mathbf{0}$, *e.g.*, the levitated dipole,[2] the axisymmetric high-β mirror,[3,4] and especially a variety of FRCs,[5,6] often confine kinetic plasmas with far-from-equilibrium distributions and whose particles have gyroradii of size comparable to density and temperature scale lengths. Under these conditions, non-local transport can create new phenomena crucial to several important applications.

A flux-tube picture is not appropriate for hot q = 0 devices, particularly 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. New analytical theoretical methods will be needed for a 3-D weave model. Advanced, cutting edge, computational methods, notably full PIC[7] and hybrid methods[8], will be essential for studying transport issues and will create a demand for faster and more accurate computational methods and hardware, eventually at the exascale. New non-invasive diagnostics will be needed to probe the internal magnetic field[9] of these high-β devices, signally the FRC whose **B** will vary from 0 to many Tesla. This collection of activities place research on transport physics in small, hot FRCs, the levitated dipole, and the high-β mirror at the frontiers of computational, analytical, and experimental methods in plasma science.

The size of magnetic fusion reactors is largely dictated by their energy confinement time, τ_E, and heating method. For tokamaks, the *best* τ_E is neoclassical, $(1+q^2)\tau_{E,classical}$, with q ~ 3. Near-neoclassical confinement has been seen for energetic particles, *e.g.*, hot ions[10] and runaway electrons,[11] in tokamaks. The proffered explanation is that their large gyroradii allow skimming over the small-scale turbulence structures responsible for the transport of cooler plasma. In contrast, FRCs have recently (see Figure 1) achieved near *classical* confinement,[12,13] which, because q = 0, is about 10 times better than tokamak neoclassical. Classical confinement is far better than expectations based on lower-hybrid theory,[14,15] perhaps because the drift parameter, γ_D = electron drift speed/ion thermal speed, in a hot-ion FRC is so small – a hypothesis in need of testing. Also recently, particle confinement time has been increased by more than two orders of magnitude (see Figure 2) by the development and implementation of refined fueling, flux conservation, and heating methods.[16] Examining these confinement properties at higher plasma temperature and density and with the energetic plasma ions having distributions far from equilibrium – as would be created by RF heating – is research on the frontiers on plasma science.

Concerning non-local transport, the trajectories of energetic ions, such as fusion products, would bring them repeatedly across the separatrix and through the cool, dense, scrape-off-layer (SOL) plasma of small, hot FRCs. These fast ions will deposit their energy in the cool SOL through collisional and collective processes, such as two-stream instabilities. The slowing down and stopping of these fast ions is in a regime not studied in fusion, where the electron gyroradii are smaller than the Debye length. The slowing down, if sufficiently rapid, can accomplish naturally, without auxiliary equipment, the essential ash exhaust function in fusion reactors. This non-local heat and particle transport process is also critical for fusion-powered rockets to efficiently extract thermal energy from the fusion products and transform it into thrust.

For decades[17,18,19] it has been appreciated that fusion power in space would offer unique capabilities in propulsion.[20] 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.[21] With such capabilities, a fusion-powered rocket would make possible far-reaching missions such as manned travel to Mars[22] and asteroid/comet[23,24] intervention. (Comet impact, though highly unlikely, would cause catastrophic effects worldwide, see Figure 3.) An additional benefit is that 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.

Of the fusion devices considered for in-space applications, the FRC has most attractive features: 1) its geometry is a natural for producing a directed high-velocity propellant stream; 2) its high β allows the use of *aneutronic* fuels, reducing the mass of shielding and magnets required; 3) and relatively low-power (*ca* 1-10 MW) small FRCs would be far easier to place into orbit that the 1000x more massive tokamak.

Another often-discussed application of fusion power is terrestrial power generation, to reduce greenhouse gas emissions while avoiding many shortcomings of fission reactors, including proliferation and meltdown concerns. High-β devices allow *aneutronic* fuels, greatly reducing shielding thickness, neutron-resistant-materials development programs, and health/safety concerns, see Figure 4. The FRC's small size lowers development costs. Apparent roadblocks to this research path are the low power density of the most *neutron-free* fuel mixture, p-^{11}B, and the scarcity of ^{3}He – only sufficient terrestrial ^{3}He exists (or is produced) to provide about 100 MW for 100 years.[25,26] However, scientists have investigated a number of D-D fuel cycles[27,28] in which one fusion product, ^{3}He, is burned along with the D-D, while another, *viz.* T, is exhausted. This alleviates the ^{3}He shortage problem but does increase the neutrons generated. Further studies of these fuel cycles could produce game-changer paths for the development of terrestrial fusion power.

Decades ago, FRC research had been declared a dead end because of predicted global instability due to the internal tilt mode.[29] The recent achievement of stable FRC discharges for periods 10^5 times longer than the tilt-mode growth time demands theoretical work to discriminate between candidate causes, *e.g.*, low s, low S*/E,[30] and rippled magnetic field.[31] The long-duration FRC plasmas now achievable allow exploration of transport over periods longer than the plasma skin and current-rearrangement times.

II. Advancing the frontier: facilities and computational tools for q = 0 transport research

Experimental facilities for these transport studies exist. Levitated dipoles are at MIT and Columbia. Mirror machines are found in the domestic program, at Columbia and U-Maryland, and abroad, in Russia (see figure 5) and Japan. 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; and RF-heated FRCs are at Prairie View A&M University and the Princeton Plasma Physics Laboratory (PPPL, see Figure 6). Longer plasma duration experiments must be carried out at higher powers with full diagnostics, to explore physics at the inductive time scale.

Computational tools are at the PSI-center (U-Washington), LLNL, and PPPL. These include multi fluid codes, hybrid codes and PIC codes. Improvements in these computational methods would be necessary to scale up the studies from μs- to second-duration simulations.

III. Impact and societal benefits of this research

The above discussion makes clear the impact. In the area of plasma science, this research would greatly advance our knowledge in a barely explored region, q = 0. Small FRC reactors could have important, even profound, roles in space travel and terrestrial energy generation.

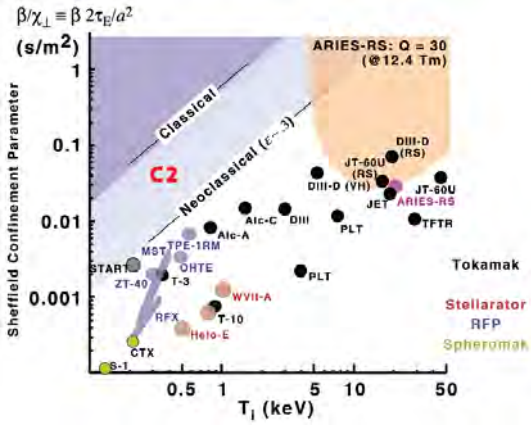

Figure 1. Sheffield (1985) confinement quality, with TriAlpha's recent C2 near-classical [12,13] data added. [Courtesy J. Kesner and M. Mauel]

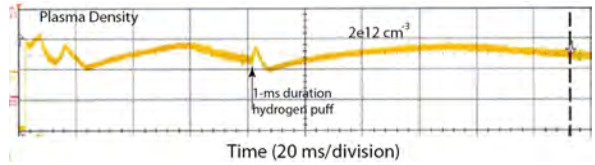

Figure 2. 214-ms-duration plasma in the PFRC-2 device. High-temperature superconducting flux conservers (FCs) internal to the vessel aid radial confinement. At 82 ms, a 1-ms-duration hydrogen gas puff was added; recycling is minimal off the Hi-T FCs. The density confinement time is longer than 100 ms. The plasma is formed and sustained by ~ 15 kW of odd-parity rotating magnetic fields (RMF_o). Approximate parameters: B_e = 100 G, T_e = 200 eV, T_i ~ 1 eV, and τ_A ~ 1 μs.

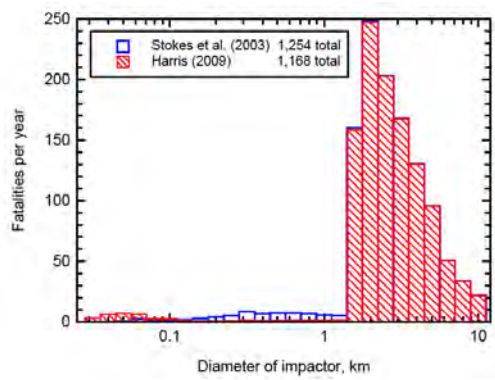

Figure 3. Estimated yearly fatalities, worldwide, due to asteroid/comet impact. Large-diameter comet impacts would also cause devastation of global infrastructure, meriting 20B$/year for development of preventive measures. ("Defending Planet Earth," National Research Council, National Academies Press (2010).)

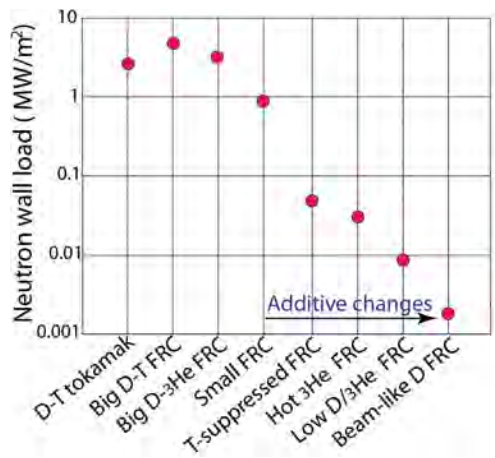

Figure 4. Reduction in neutron wall loading achievable by producing power in small D-^{3}He fueled FRCs. The large reduction would alleviate safety concerns and reduce the required materials-development efforts.

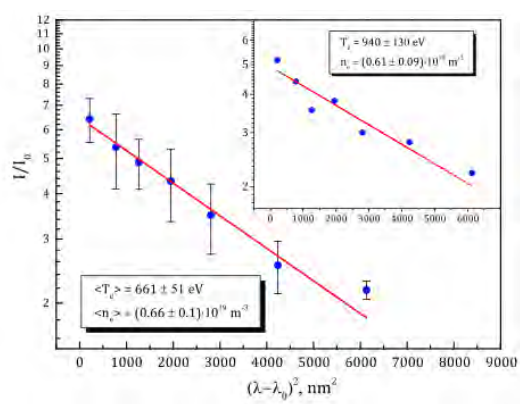

Figure 5. Electron temperatures tripled in the Budker Institute's GDT axisymmetric mirror device. Axial confinement is more than 20x better than Spitzer-Härm.[4]

Figure 6. Photograph of a hydrogen plasma in the PFRC-2 device. The RMF_o antennae are outside the 84-cm-long polycarbonate vessel (with p_{base} ~ 10^{-7} T); the superconducting flux conservers are inside. Mirror coils are at the left and right extremes of the photo. Electron temperatures to 400 eV were obtained in the PFRC-1. One PFRC-2 goal is T_e > 1 keV.

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