ReNeW White paper: Theme V, Improving the magnetic configuration
Improving energy confinement is the most rapid route to practical FRC reactors

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Abstract

FRCs have high β. Therefore, improvement of their performance must be gained by decreasing transport losses. If near-classical transport can be achieved, an FRC reactor could be so small that standard industrial practices for product development could be applied, making FRC reactors practical.

I. Reactor development methodology

Rapid prototyping technology (RPT)[1] is the gold standard for product research and development in industry, providing significant benefits in terms of development speed, cost reduction, and quality assurance. An early example of the process is Edison's invention of the carbonized-filament light bulb: success was only achieved after testing over three thousand candidate filament materials. The immense impact of the RPT process can readily be discerned in as disparate modern industries as airplane, automotive, PC, software, and pharmaceutical manufacturing. Not only must the main function of the product be tested, but also the fully integrated component parts, those that make the product safe, reliable, desirable, and practical.

A corollary to RPT is that commercial products evolve. At each stage of the evolution, products should be released into the marketplace where testing continues, greatly amplifying scrutiny of the product. Ideas and insights for further improvements often come from customers.

A requisite for RPT is low-cost prototypes, generally implying small size.

The mainline magnetic fusion program, which has resulted in the ITER project[2], has moved in a different direction. Fewer tokamaks operate now than decades ago. No commercially productive tokamak has yet been sold to a customer. Testing prototype components or operational scenarios will be increasingly harder in ITER, the high profile, hugely expensive, monumentally large, highly radioactive flagship of the fusion program. The situation would be even more difficult in a next-step DEMO device.

That tokamak reactors would likely be large has been stated since ~1974.[3] This need for large size – an overall diameter near 20 m – is due to the combination of the tokamak's low β, poor energy confinement quality, and thick radiation shielding.[4] Although more than a decade has passed since ion energy confinement in large tokamaks improved to neoclassical levels,[5-7] a significant reduction in the ITER design radius from values in 1970's reactor studies could not be made because of the low β. It is well appreciated[4] that high β allows smaller size, partially the logic for awarding the appellation "compact tori" to FRCs and spheromaks. Tokamak community efforts towards higher β, *e.g.,* through spherical-tokamak designs, are also motivated by the desire for more compact reactors.

In the FRC, β is an order-of-magnitude higher than in tokamaks. The attainable energy confinement quality, not β, sets the minimum-FRC-reactor-size requirement. (Other important factors, neutron shielding and confinement of charged fusion products for ignited operation, are commented on shortly.) Near-classical energy confinement in an FRC would allow a plasma diameter less than 0.7 m, about the size first envisioned by

Spitzer in his 1951 proposal for a stellarator reactor.[8] At this size, the FRC would have a volume less than 1/1000th of a tokamak reactor's and produce proportionally less power, a level suitable for a distributed power grid. From size alone, an FRC reactor's cost – and the cost of the preceding research devices – would be considerably smaller than for a tokamak reactor. The time for design, construction and testing of the FRC pre-reactor research devices would be far faster than ITER. Shortening construction time will markedly reduce the capital cost of fusion power plants. Having many small research devices would allow rapid and thorough testing of many promising and diverse ideas. The failure of any one proposed solution would not compromise the entire research effort.

For an FRC reactor to have its smallest size and most rapid testing protocols, it should burn *aneutronic* fuels like D-He_3 or p-B_{11}. This reduces the shielding and breeding requirements and radioactivity and radiation-damage issues, further lowering costs. Important questions are whether the ease of transporting He_3 from the moon[9] is greater than that of breeding tritium on earth and whether p-B_{11} fusion[10] can provide a net energy gain.[11] An affirmative answer to either would greatly accelerate fusion reactor development.

II. Small-size constraints on FRC design

A small *aneutronic* plasma would place restrictions on FRC heating and current-drive methods and operational modes. Operation with D-He_3 or p-B_{11} requires substantially higher ion temperatures than burning D-T, thus highly efficient heating methods and excellent confinement, no worse than 5 times classical, are required.

A small plasma would not effectively stop energetic (> 100 keV) neutral beams, eliminating this proven plasma-heating and current-drive method. Compression heating has been proposed for pulsed FRC operation,[12,13] but steady-state reactors offer marked engineering advantages. Radiofrequency waves could provide both heating and current drive[14] in the FRC; much research on RF physics in the FRC remains to be performed.[15]

A small plasma would not confine fusion products adequately to sustain plasma ignition. Hence, driven modes of operation must be investigated. These require highly efficient means for energy extraction and energy re-circulation. A promising though speculative approach is inverse Landau damping on the fusion products.[16]

The above paragraphs point out problems and restrictions that small *aneutronic* FRC reactor development faces. Counterbalancing these are the major benefits that would accrue from lower cost, accelerated research speed, and improved plasma stability. The latter is due to the reduction of s, $\sim 0.3 r_s/\rho_i$, to values below 10. Low s will improve stability against macroscopic MHD modes, notably the internal tilt. Excellent energy confinement at $s \sim 8$ would eliminate large-s operation as *the* Tier 1 issue.

III. Classical energy confinement and fusion research

At present, energy losses in FRCs are anomalous. Are there reasons to believe the situation can be improved?

Historically, tokamaks offer many examples of serendipitous substantial improvements in confinement time, τ. Early (1967-1977) tokamaks broke through the radiation barrier and away from the limitations of Bohm transport. In the 1980s, first runaway electrons[17] were observed to have $\tau > 1$ s, then energetic beam-injected ions were observed to have nearly as long confinement. Both improvements were attributed to the fast particles having gyroradii larger the scale of plasma turbulence. In the 1990s thermal particles in the now hotter tokamak plasmas showed large improvements in energy confinement, *e.g.*, H-modes and supershots, attributed to decreases in turbulence and temperature gradients, in part, due to reversed shear. Hot ions behaved neoclassically.

Impressive results were also achieved in linear plasma devices[18], including mirror machines[19]. Near classical radial confinement was observed when shear was generated through electric fields and plasma rotation.

Might such behavior be expected in small, hot FRCs? Conditions in these devices satisfy several of the aforementioned conditions: 1) RF-heated FRCs have now burned through the radiation barrier; 2) at $s < 10$ the gyroradii are expected to be larger than the turbulence scale; 3) small s favors low temperature gradients in the plasma core, lessening the likelihood of gradient-driven microturbulence; 4) $q = 0$ in FRCs, thus the neoclassical transport enhancement factor $(1+q^2)$ is eliminated; 5) because the FRC's toroidal field is zero, plasma fluctuations cannot rapidly propagate toroidally, to provide detrimental positive feedback and drive instability; and 6) certain RF heating methods, *e.g.,* RMF_o, provide shear in the magnetic field and closed field lines (drift surfaces).

Discovery of FRC operating modes that achieve classical confinement would be a *transformational breakthrough*. Meticulous experimentation, acute and critical observation, and detailed analyses are essential.

III. Steps on the path to an FRC reactor.

Currently there are three RF-heated FRCs in the US, all using rotating magnetic fields (RMF). Their highest temperature results, $T_e \sim 300$ eV, occurred at $s \sim 2$, $B_e \sim 100$ G, and $n_e \sim 3 \times 10^{12}$ cm^{-3}. The s value is so low that first orbit losses are likely, making tests of classical transport impossible. Proper tests require increasing s to near 10 at more reactor-relevant values of magnetic field, collisionality, and plasma temperature and density. A scaling relation[20] has been developed which shows the shortest path from present-day FRC devices to reactors is along $B_e r_s^{-3} \sim$ constant in the B_e-r_s plane. A sequence of four facilities, aimed at testing the physics important to small *aneutronic* FRC reactors, is shown in the Table 1. (Machine I is currently operating.) This staged approach would explore the main idea, whether classical confinement could be achieved, and simultaneously – using the *RPT* approach – test the integrated components and operational scenarios, *e.g.,* flux conservers, plasma shaping, superconducting coils, RF heating and current drive science and technology, energy extraction, divertors, and stability, that are required to make small *aneutronic* FRCs reactors practical.

Those parameters on a red background in Table 1 are highlighted to show the major challenges at each stage. Note, the ReNeW goal of keV electrons would be tested within three years and that of keV ions within eight years. Experiments at $s > 10$ would also occur in 3 years. Further information can be found in [20].

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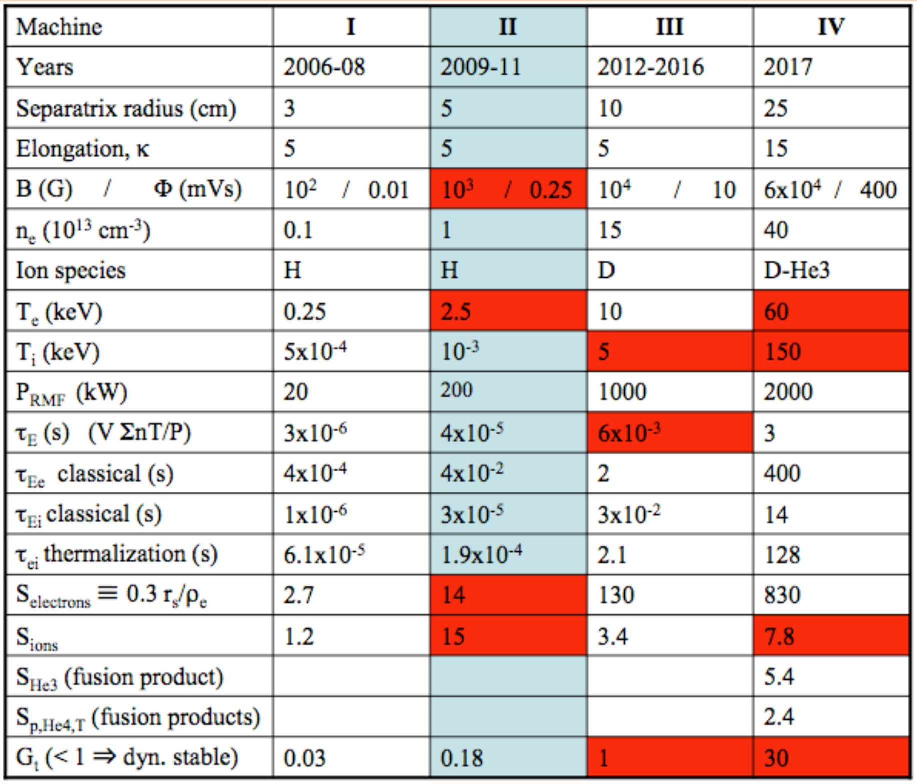
Table I. Sequence of proposed RMF-heated FRCs to explore confinement



Machine	I	II	III	IV
Years	2006-08	2009-11	2012-2016	2017
Separatrix radius (cm)	3	5	10	25
Elongation, κ	5	5	5	15
B (G) / Φ (mVs)	10^2 / 0.01	10^3 / 0.25	10^4 / 10	$6x10^4$ / 400
n_e (10^{13} cm^{-3})	0.1	1	15	40
Ion species	H	H	D	D-He3
T_e (keV)	0.25	2.5	10	60
T_i (keV)	$5x10^{-4}$	10^{-3}	5	150
P_{RMF} (kW)	20	200	1000	2000
τ_E (s) (V ΣnT/P)	$3x10^{-6}$	$4x10^{-5}$	$6x10^{-3}$	3
τ_{Ee} classical (s)	$4x10^{-4}$	$4x10^{-2}$	2	400
τ_{Ei} classical (s)	$1x10^{-6}$	$3x10^{-5}$	$3x10^{-2}$	14
τ_{ei} thermalization (s)	$6.1x10^{-5}$	$1.9x10^{-4}$	2.1	128
$S_{electrons} \equiv 0.3\, r_s/\rho_e$	2.7	14	130	830
S_{ions}	1.2	15	3.4	7.8
S_{He3} (fusion product)				5.4
$S_{p,He4,T}$ (fusion products)				2.4
G_i (< 1 ⇒ dyn. stable)	0.03	0.18	1	30