Research needs for developing small, clean, $\mathrm{RMF_o}$-driven FRC reactors

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1 Goal and Motivation

The FRC device has the highest volume-average beta, $\langle\beta\rangle$, of any candidate magnetic fusion reactor. If excellent energy confinement, τ_E, were achievable, fuller advantage of the high $\langle\beta\rangle$ attribute is possible, allowing:

- Smaller, more stable reactors, suitable for a robust distributed power grid.
- Advanced fuels, easing materials and environmental issues and accelerating reactor development.

Why might excellent confinement occur in FRCs? Other magnetic configurations have shown excellent confinement when gyroradii, ρ, are large compared to the relevant plasma scale lengths. Examples are neoclassical ion confinement, achieved in keV-ion-temperature tokamaks and STs, and confinement times exceeding one second for MeV electrons in tokamaks. Moreover, an FRC with zero toroidal magnetic field would have reduced toroidal propagation of fluctuations, linked to anomalous transport. Hotter FRCs could test these large-ρ regimes.

The ITER-era goal for this research concept is to explore means to achieve high τ_E in a quasi-steady-state **odd-parity** rotating-magnetic-field ($\mathrm{RMF_o}$)-heated FRC device, stably operating at near-reactor temperatures, density, collisionality, ν^*, magnetic field, B_e, and ratio of ion gyroradius ρ_i to the FRC separatrix radius, r_s. Stability will be enhanced by operation at small s parameter, where $s \equiv 0.3 r_s/\rho_i$.

2 FRC device parameters: defining components

FRC reactor designs occupy a 3-D parameter space defined by the choices of fuel (D-T, D-D, D-$\mathrm{He_3}$, or p-$\mathrm{B_{11}}$), heating method (RF, neutral beams, or compression), and operational mode (ignited or driven, pulsed or steady state). Choosing D-$\mathrm{He_3}$-fueled, RF-heated, and steady-state, driven operation results in the following advantages:

- Reduced technical challenges, *e.g.,* tritium breeding, neutron shielding, *etc.*, compared to D-T or D-D.
- Shorter τ_E's and lower T_i's than required for p-$\mathrm{B_{11}}$.
- Smaller reactors, for stability, rapid ash exhaust and speedier, lower cost development.

Research efforts, based on these choices, may be divided into three categories defined by components of the device: heating system, divertors, and flux conservers. Research into stability and τ_E are prominent in each category.

2.1 Heating system: $\mathrm{RMF_o}$

When RMF current drive (CD) was first tested, *ca.* 1962, even-parity ($\mathrm{RMF_e}$) was used. This technique successfully drives plasma current but shows poor energy confinement, attributed to its *opening* FRC field lines, causing energy loss at the ion sound speed, c_s. Nearly five decades later, full penetration of $\mathrm{RMF_e}$ into the plasma has not been achieved in a linear FRC.

In contrast, $\mathrm{RMF_o}$ is predicted to maintain closed field lines.[1] Our $\mathrm{RMF_o}$ experiments[2] have demonstrated current drive (5 kA), full $\mathrm{RMF_o}$ penetration, $\nu_e^* \ll 1$, and good confinement, though far from definitive proof of closed field lines. $\mathrm{RMF_o}$ phase, amplitude (B_R), and frequency (ω_R) must be precisely controlled during evolving plasma discharges, to effect the necessary time-dependent penetration and current drive. Additional CD issues that require research are efficiency and generation of far larger currents, above 10 MA, at lower B_R/B_e, below 10^{-2}.

Theoretical work also produced exciting predictions that $\mathrm{RMF_o}$ could fill other key non-CD roles:

- Electron heating.[3] Our experiments[2] show average electron energies close to predicted values. The detailed electron energy distribution differs from theoretical predictions, thus the heating mechanism is unconfirmed.
- Ion heating.[3−6] If ω_R is near the ion cyclotron frequency, ω_{ci}, ions will be heated. The parameters of current FRCs do not allow these studies. When hot ions are eventually produced, research on kinetic (in)stability, the FRC loss cone, electrostatic potentials on flux surfaces, ion currents, species-selective heating, thermalization, and plasma rotation will be necessary.
- Stabilization.[7] $\mathrm{RMF_o}$ produces radial oscillations, predicted to stabilize the FRC against the tilt mode, and shear in the magnetic field, expected to stabilize against interchange modes. Research on stability is needed.

2.2 Divertor system

Divertors offer many benefits:

- Divertors provide density control plasma purity, and reduced neutral-particle recycling in the FRC main chamber, lowering energy and momentum losses and detrimental plasma-wall interactions.
- Direct conversion of energy from charged-particle fusion products could lead to higher reactor efficiency, perhaps

a necessity for the viability of advanced-fuel reactors.

- Divertor field-line shaping (*e.g.*, cusps or strong mirror fields) may stabilize interchange modes.
- A strong divertor-throat mirror field can reduce the FRC loss cone.
- Large-ρ_i particles tightly connect the FRC scrape-off layer (SOL) to the plasma within r_s. SOL manipulation through divertor parameters may provide control of the bulk FRC plasma.

Divertors strongly impact tokamak behavior, supporting the assertion that divertors, prototypical of eventual reactor embodiments, should be an integral part of FRC experimental efforts.

2.3 Flux conservers

Though τ_E in current FRCs is less than 10 μs, other critical processes, *e.g.*, neutral depletion and field penetration, have characteristic times longer than 1 ms.[2] Moreover, quasi-steady-state reactors will require powered coils or superconducting (SC) flux conservers (FCs). An axially extended/continuous FC is incompatible with RMF; an array of discrete, coaxial SC FC rings is a possible solution. Modeling must provide realistic FRC equilibria, including the effects of discrete FC rings, non-uniform axial fields, elongation, RMF_o, and finite pressure in the SOL, to explore stability, CD, and heating. Experiments will test these predictions.

3 Present facilities and future needs

Of the dozen DOE-funded research FRCs in the US, the PFRC[2] is the only one devoted exclusively to RMF_o. Its precisely controlled RMF_o system, closed divertors, and discrete internal FCs are unique. Pulse rates and duty factor are 100× higher and ν^* is 20× lower than any other FRC. Testing of high-temperature SC FCs is now underway.

The research needs of the program outlined in Section 2 could be met by two upgrades to the PFRC. This progressive research path, with increases in r_s, B_e, power, pulse length, and diagnostic capabilities, is shown in Table I. Milestones in ν^*, s, τ_E, n_e, T_i, T_e and other parameters are $\underline{\text{underlined}}$. Based on results from the second upgrade, a decision could be made whether to proceed with a burning-plasma experiment. Spending in this 10-year CE-level program would be divided 60/40 between research manpower and technical expenses, with the latter including equipment, M&S, engineering, construction, maintenance, and much additional diagnostic hardware.

Table 1: Proposed PFRC sequence to test transport at reactor-relevant ν^* and s.

Machine	Present	Upgrade I	Upgrade II	Burning plasma
Years	2006-2008	2009-2011	2012-2016	2017-2025
B_e (T)	0.01	0.1	$\underline{0.7}$	5
Separatrix radius, r_s (cm)	3	5	10	25
ϕ (mWb)	0.006	$\underline{0.16}$	$\underline{4}$	250
Elongation, κ	5	5	$\underline{10}$	15
n_e (10^{13} cm^{-3})	0.1	1	$\underline{4}$	40
Working gas	H_2	H_2	H_2	D_2
T_e (keV)	0.25	$\underline{2.5}$	$\underline{\ 25}$	60
T_i (keV)	5×10^{-4}	10^{-3}	$\underline{\ 3}$	100
P = RMF_o power (MW)	0.02	0.2	2	5
B_R/B_e	0.1	0.04	$\underline{0.01}$	0.005
ω_R/ω_{ci}	100	4	$\underline{0.3}$	0.15
$\nu_e^* \equiv 4\kappa r_s ln\Lambda/\lambda_{Coulomb}$	2×10^{-2}	$\underline{3 \times 10^{-4}}$	4×10^{-4}	4×10^{-4}
ν_i^*	3×10^3	2×10^4	$\underline{4 \times 10^{-2}}$	1×10^{-3}
s $\equiv 0.3 r_s/\rho_i$,	1	$\underline{15}$	4	8
$\tau_{E,IA} \equiv \kappa r_s/c_s$ (s)	7×10^{-7}	3×10^{-7}	2×10^{-7}	10^{-7}
$\tau_{E,Required} \equiv V\Sigma nT/P$ (s)	2×10^{-6}	$\underline{2 \times 10^{-5}}$	$\underline{10^{-3}}$	3
Pulse length (s)	0.004	$\underline{\ 0.5}$	2	10

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