Field-reversed configuration: Community input to FESAC

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1 Concept Description

The desirability of closed magnetic field lines for successful plasma confinement has long been recognized. Simultaneously, compelling engineering advantages are acknowledged for a linear, simply connected reactor geometry. Compact Toroids (CTs) possess both attributes.

CTs are magnetic confinement devices that maintain the plasma shape as a torus of nested flux surfaces primarily by currents flowing in the plasma. Importantly, there are no electromagnetic coils linked with the plasma. CTs come in two forms, spheromak and FRC. Spheromaks have comparable toroidal and poloidal magnetic fields in the plasma and zero toroidal field at the plasma boundary. FRCs have zero (or very small) net toroidal magnetic throughout the entire plasma volume and a field null on the magnetic axis.

In addition to their linear-toroidal magnetic geometry, CTs have other features favorable to a reactor, notably considerably higher $\langle\beta\rangle$ than tokamaks, and natural divertors. High $\langle\beta\rangle$ may allow smaller reactor size, lower magnetic field, and use of advanced, *e.g.*, *aneutronic*, fuels; natural divertors suit methods for efficient energy extraction and ash exhaust. The spheromak and FRC also have dissimilar features, including formation and sustainment methods, stability concerns, and $\langle\beta\rangle$ and $\mathbf{J} \times \mathbf{B}$ magnitudes. Goals for CTs may be discussed as a unit, but many scientific and technical issues must be addressed separately. This document concentrates on FRCs in the US, the world leader in this research field.

Attractive and unique engineering features of CTs that could lead to earlier development of a more economical and environmentally friendly fusion reactor than one based on ITER are:

- Simply connected vacuum system, easing design, access, and maintenance.
- No toroidal field coils, easing design, access, and maintenance.
- Circular unlinked magnet coils, operated well within engineering limits.
- Controllable outflow – along open field lines at the CT's edge – to remote natural divertors, allowing efficient energy extraction and impurity control.
- Little damage from off-normal plasma termination due to simple geometry, small magnetic-energy content, and natural exhaust regions.
- High $\langle\beta\rangle$, making smaller-sized reactors and advanced-fuel scenarios possible.

Accordingly, experiments at each stage of CT development should be less expensive to build and quicker to test than the corresponding tokamak-based experiments. Metrics for judging plans for and progress in each CT concept can be based on how well these advantages are incorporated. Success in the formation of stable, quasi-steady-state, high-temperature, well-confined CTs could create a paradigm change in the development of fusion power. The main physics and technology challenges, or long-term goals, for CT research are:

- Insuring stability for FRCs and attractive $\langle\beta\rangle$ values for spheromaks.
- Obtaining confinement sufficiently good for small-scale, *safe* reactors.
- Providing an efficient method for current drive, *e.g.*, flux sustainment.
- Proving efficient and robust heating methods.
- Proving methods for sustained fueling, ash removal, and impurity control.

2 ITER-era goal for FRCs

The goal for FRCs in the next 10-15 years is to demonstrate effective heating methods, quasi-steady-state operation, and excellent stability and confinement at near-reactor conditions, sufficient to provide theoretical understanding that would allow confident extrapolation to a burning-plasma experiment.

The definition of *steady state* contains both physics and engineering elements, such as pulse length compared to instability-growth, thermalization, energy-confinement, magnetic-diffusion, recycling, fuel-consumption and ash-exhaust time scales and thermal- and stress-load temporal variations small enough to avoid material fatigue or component failure. FRCs are also being pursued as targets for pulsed, high-compression reactor schemes. In this class are megabar-pressure FRCs which are being evaluated under a separate High Energy Density Physics panel and not covered here.

What *near-reactor conditions* are depends on the details of the reactor, such as fuel burnt or heating method: 1) advanced fuels, those that produce less than 5% of the neutrons of a D-T reactor of equal power output, require $5 - 10\times$ higher temperatures than D-T; and 2) compression heating requires smaller plasmas than beam heating, lessening stability concerns.

Present FRC devices have parameters far from a burning-plasma experiment. Factors of 30 and 300 increases are needed in density and temperature, respectively, and even larger multipliers are needed for energy confinement time, pulse length, and plasma current. To approach burning-plasma parameters, major advances will be needed in the key areas of stability, energy confinement, current drive, heating, fuel, ash exhaust and impurity control, energy extraction and operational mode. Requirements in these areas are connected. Examples are: 1) better confinement may allow smaller, more stable plasmas, smaller heating systems, and advanced fuels; 2) short-pulse operation may reduce ash-exhaust, current-sustainment, and stability requirements; and 3) efficient energy extraction could reduce reactor size, increase performance, and reduce the required Q value.

Present FRC research devices lack the extensive diagnostic tools, research manpower, and machine capabilities to address these key questions properly.

2.1 Research to achieve the goal: Scientific value, credibility, accessibility

2.1.a. Stability: The experimental goal is to display quasi-steady-state, stable FRC operation near s values (s is the number of ion gyroradii between the O-point null and the separatrix) and ν^* values (collisionality) required in a reactor. The required s value depends strongly on confinement quality: at $D = 0.5\ m^2/s,\ s = 30$ while at $D = 0.01\ m^2/s,\ s = 8$. The collisionality ($\nu^* \equiv 4\kappa r_s ln\Lambda)/\lambda_C$) would need to be less than $\sim 10^{-3}$. (κ = elongation, r_s= separatrix radius, and λ_C is the Coulomb 90°-scattering mean-free-path.)

The scientific value of stability studies is **very high**. Stability determines most factors of reactor design: 1) the required FRC shape, *e.g.*, oblate, spherical, prolate, or extremely prolate; 2) the characteristics of divertors, whether they should provide good curvature or strong axial flow to stabilize interchange modes; 3) the confinement characteristics required for fusion reaction products, including whether energetic fusion products must be confined to provide kinetic stabilization; and 4) whether a toroidal field and shear or toroidal flows are needed or must be avoided.

The credibility of the FRC concept rests heavily on the stability issue. At low s FRCs have proven to be extremely rugged, surviving dynamic formation, translation, and capture events in θ-pinch experiments[1] and spheromak-merging collisions[2,3]. There have been experimental demonstrations of quiescent stability in non-sustained FRCs with s values up to 4 in both oblate [4] and prolate FRCs[5]. At $s \sim 1$, FRCs have been sustained for times in excess of $10^4\tau_A$.[6] (τ_A, Alfven time $\sim$ 1/tilt-mode growth rate.) Toroidal flow and shear (created by toroidal field) have been calculated to enhance FRC stability[7]. Strong flows may drive an $n = 2$ rotational mode. Recent numerical calculations have shown complete stability of FRCs when a hot ion-ring component was added, even without bulk plasma flow[8]. There is experimental evidence that FRCs can be formed in high-β Minimum Energy States (MES)[9]. Odd-parity rotating magnetic fields (RMF_o) are predicted to stabilize the internal tilt mode[10], though in some regimes to cause an axial splitting of the plasma column[11].

The Pulsed High Density concept, (PHD), which relies on repetitive compressional heating, requires far less stringent stability criteria[12].

Microstability issues, such as the presence of the lower-hybrid-drift-wave (LHDW) instability[13,14], effect energy confinement and are implicit in the next sub-section.

Near-reactor s values cannot be accessed in the FRC devices presently operating.

2.1.b. Energy confinement: The experimental goal is to improve energy confinement in FRC devices having s, ν^*, and temperature values near those of a reactor. The target transport coefficients are reactor-design dependent and far smaller than the smallest achieved in an FRC, $D \sim 5m^2/s$[15]. In fully diamagnetic plasmas, such as FRCs, particle and flux loss rates are related. The measured energy loss rates in TCS appear to be entirely due to radiation and particle loss[16]. Earlier θ-pinch-formed FRCs, with $\phi_p \sim 12$ mWb, showed $\langle D_\perp \rangle = \langle \eta_\perp / \mu_o \rangle \sim 5m^2/s$, based on flux-decay rates. However, little is known about the internal thermal confinement. Diagnostics are needed.

The scientific value of this effort is **very high**. Energy confinement determines the FRC reactor size, operational mode, and fuel choices. Poor energy confinement would all but eliminate the possibility of advanced fuels. The FRC, along with the leviated dipole, are the only quasi-toroidal fusion-oriented devices that can explore the effects of toroidal field (B_ϕ) on transport in the extended range to $B_\phi = 0$. Over a dozen theoretical models of transport in FRCs have been published[17]. Predictions from these differ by six orders-of-magnitude.

The original[18] rotating-magnetic-field (RMF) method of current drive was predicted to generate open field lines, hence degrade confinement[19]. The novel (odd-parity) RMF$_o$[20] has been predicted to maintain field-line closure, essential for good confinement. First experiments are promising but far from conclusive[21,6].

Investigations, with detailed diagnostics, are needed on quasi-steady-state FRCs with intense auxiliary heating and near-reactor values of s, ν^*, T_i, T_e, and ϕ to allow for internal thermal confinement measurements. No FRC currently operating can create plasmas with the required values of these parameters nor has the diagnostics to measure these parameters. Upgrades are needed.

2.1.c. Flux sustainment: The experimental goal for current drive is to demonstrate a high efficiency method that can build-up and sustain magnetic flux to the level required for generating s, ν^*, T_i, T_e, and n_e near those of a burning-plasma experiment. An ambitious target for flux sustainment duration is the fuel burn-up time, a function of density and temperature. High efficiency, η_{CD} (A/W), is another crucial criterion in this research area. The target magnetic flux depends on the reactor scenario – ignited vs driven, D-T vs D-He$_3$ – and heating method.

For most FRC reactor concepts, the scientific value of current-drive research is **very high**. The PHD concept[12] is the exception. With repetitive regeneration of short-pulse fusion plasma, the PHD requires far less in the way of current sustainment.

The only method presently demonstrated for sustaining a true FRC (without any internal flux-adding coil) is RMF. Fluid theory for even-parity RMF (RMF_e) is well developed[22] and extensive tests at small s in collisional plasmas have been made[23, 16, 24]. When RMF torque on the electrons exceeds the frictional electron-ion resistive torque, flux-build-up occurred. Flux levels scaled with $\phi_p \propto B_\omega r_s/\langle\eta_\perp\rangle^{1/2}$, where B_ω is the RMF magnitude and $\eta_\perp$ the resistivity; so a simple means exists of increasing flux, by increasing B_ω and r_s. The input power is proportional to B_ω^2. Present experiments have observed average values of $\eta_\perp$ of 100 $\mu\Omega$-m, with central $\eta_\perp$ a factor of 5 lower.[25] To reach the current-drive goals, $\eta_\perp$ will have to be substantially reduced. Previous observations showed LHDW-like $\eta_\perp$ scaling, $D_\eta = \eta_\perp/\mu_o \propto D_B(v_{de}/v_{ti})^2$, where D_B is Bohm diffusivity, v_{de} is the relative electron-ion drift velocity, and v_{ti} is the ion thermal velocity. In FRCs, the drift parameter, $\gamma_{de} = v_{de}/v_{ti} \propto 1/(n_e^{1/2} r_s)$, is independent of T_e. A LHDW-like scaling favors larger, higher density FRCs.

RMF η_{CD} at high temperatures and ν^* is unknown. Is sufficient current simply generated by RMF-increased plasma diamagnetism? For FRCs with strong diamagnetic toroidal plasma currents, lowering D_η is a key to attaining the ITER-era goals, certainly in terms of sustainment since the power dissipated due to ohmic losses is proportional to $\eta_\perp B_e^2$. Large gains in near-term performance are possible if LHDW-like scaling is realized.

An important question is penetration of the RMF deep into the plasma. Penetration requirements differ with current-drive and heating scenarios.

Theory for RMF_o current drive is in its infancy, in part because the RMF_o's unique azimuthal electric field (E_ϕ) at the O-point null necessitates a kinetic treatment. E_ϕ should form a beam-like high-energy distributions of betatron orbits near the null, aiding stability and CD. [26, 27]

Tangential NBI has been proposed as a flux sustainment technology for both prolate[16] and oblate[28] FRCs. TNBI was applied to the 2XIIB mirror device to produce a field reversed mirror (FRM); field reversal was not achieved. In contrast, TNBI is expected to work well with already formed FRCs. (Colliding TNBIs are the basis of a privately funded *aneutronic*-fusion FRC research program[29].) In order for TNBI to be effective in forming trapped high-energy ion rings within the FRC separatrix, the neutral-beam energy should be below a critical value $E_{ic}(keV) = (0.0144/A_i)[\phi_p(mWb)/r_s(m)]^2$. Note, the allowed beam energy increases with r_s at fixed B_e. TNBI should contribute strongly to the CD goal. TNBI will also provide useful sources of particles and energy near the field null.

Thermoelectric-driven currents are predicted[30] to provide appreciable current sustainment, though need a seed current on axis. Experimental tests are needed.

In FRC reactors, fusion products could provide appreciable current drive[31]. Self-consistent effects need to be examined.

2.1.d. Heating: The experimental goal is to demonstrate efficient heating methods that raise both ion and electron temperatures to near burning-plasma values.

The science value is **very high**. The methods proposed for plasma heating are TNBI, RMF_o and compression. Questions are whether high heating powers can be applied and absorbed while improving confinement and stability and whether heating produces a good diamagnetic current profile. Neutral-beam heating physics has been studied extensively on tokamaks; drag and pitch angle scattering are well understood. Beam-driven instabilities in FRCs, such as TAE modes seen in tokamaks, have not been studied. The likelihood of heating both electrons and ions is high. The physics of compressional heating, as proposed for PHD, is also well understood, though again stability and transport behavior must cooperate to achieve the target temperatures. RMF_o heating of both electrons and ions has been predicted[26,32]. Average electron energies predicted by theory have been observed[6] but details of the electron energy distribution do not agree with the theory. Ion heating by RMF_o has not been attempted; it requires new facilities with higher heating power, and larger B_e and r_s, as do compressional and beam-heating experiments. The required B_e and r_s

values differ for these three methods. For all three methods, heating ions and electrons to multi-keV levels is the goal for D-T fusion and 10× higher temperatures for advanced fuels.

2.1.e. Fuel, ash exhaust and impurity control, energy extraction and operational mode: In the next 10 years, the scientific value of research in these key areas is of lower priority than the four aforementioned areas. To a large degree, which fuel mixture or operational mode is chosen will depend on the energy-confinement-time, current-drive and heating parameters achieved. Energy-extraction concepts, too, can be addressed at a later stage.

Impurity control issues, related to ash exhaust and τ_E, will arise naturally during heating and confinement studies.

Divertors are known to impact tokamak behavior greatly. Divertors representative of those for an FRC reactor should be in use when stability, heating, and confinement studies are made.

2.2 FRC contributions to fusion science

The research tasks required for achieving the FRC goal can make major contributions to broader fusion science, by addressing physics issues faced by other fusion-reactor configurations. FRC research will contribute to the general understanding of anomalous neoclassical transport by providing systems with varying ratios of toroidal to poloidal magnetic fields, including the extreme case of a purely diamagnetic system, $B_\phi = q = 0$.

Helicity conservation and Minimum Energy States (MES) are of importance to tokamaks, spheromaks and RFPs. The possibility of high-β MESs, which has been proposed as an explanation for FRC experimental stability, is of general interest to test MES theory at an extreme not accessible in non-CT devices, $\mathbf{J} \times \mathbf{B} \neq 0$, that is, FRCs can create the contrasting magnetics geometry with current perpendicular to B, outside the Taylor prescription for a force-free minimum-energy state. Edge-layer flows into FRC divertor channels can be studied in a carefully controlled, readily accessible environment. Highly variable power-density levels can be generated for plasma-surface interactions studies. FRCs can serve as component test facilities. The PHD-type FRC could be used for simulation of tokamak disruption conditions.

Kinetic effects and large Larmor radius effects should be readily created in FRCs, allowing tests of kinetic theory on a new platform.

The goal of achieving good confinement along with steady-state current drive with TNBI, a proposed component for furthering FRC development, or with RMF, will allow field-reversed-mirror concepts to be revisited.

FRCs, including the PHD variety, could be useful for deep fueling of tokamak reactors and to provide toroidal momentum.

The PHD concept has been proposed as a breeder of both fissile and fusile fuel.

3 Scientific and technical issues to reach the ITER-era FRC goal

3.1 Prioritized key issues

The four key issues identified in Section 2 – stability, confinement, heating, and current drive – are so interrelated and critical to the success of the FRC as a reactor that we do not differentiate between them on a priority scale.

Based on axial equilibrium and zero plasma pressure outside the separatrix, an important relationship for elongated FRCs in a cylindrical flux conserver is $\langle\beta\rangle = 1 - x_s^2/2$ where r_c is the flux-conserver radius, and $x_s \equiv r_s/r_c$.[33] The minimum $\langle\beta\rangle$ value is thus 0.5. Operating at minimum $\langle\beta\rangle$, equivalent to large x_s, may be desirable as it provides more insulating flux for confinement, though less separation between r_s and r_c. ($\phi_p = (x_s/\sqrt{2})^{1+\epsilon}\pi R^2 B_e$ is also an equilibrium constraint where $R = r_s/\sqrt{2}$ is the radius of the field null and $0 \leq \epsilon \leq 1$ depends on the $B_z(r)$ profile.) Providing FRC stability as the size, x_s, and s increase becomes more difficult. Large x_s operation may be impossible if flux conservers (or powered magnets) must located outside of a thick neutron shield, again illustrating the linkage of key areas.

Parameters needed to allow confident extrapolation to a burning-plasma experiment are listed in Table I. The ranges of s, D, $T_{e,i}$, n_e, and ν^* values span that required for ignited, beam-heated D-T operation to driven, RMF-heated, D-He$_3$ operation. Values for a pulsed, compression-heated D-T FRC are different.[12]

Table 1: Parameters to allow confident extrapolation to a burning-plasma experiment.

Parameters	Needed capabilities	SSX	TCSU	PFRC	MRX	PHDX
s	8-30	10	4	1-2	0.1-3	1-4
D (m^2/s)	0.01 - 0.5	10	100	50	10^3	0.5
ν^*	10^{-3}	10-100	0.1	0.01	1-0.1	NA
T_i (keV)	1-10	0.06	10^{-3}	4×10^{-4}	10^{-2}	0.1-1
T_e (keV)	1-10	0.02	0.2	0.3	10^{-2}	0.1-0.5
n_e ($10^{20} m^{-3}$)	$0.3 - 1$	1	0.1	0.001	0.1	10
ϕ (mWb)	1- 100	6	1	10^{-2}	2	5-20
P (MW)	1-10	1	2	0.02	1	10
η_{CD} (A/W)	10	10^{-4}	0.05	0.5	2×10^{-2}	NA
Shape	oblate, prolate	oblate	prolate	prolate	oblate	prolate
Pulse length (s)	1	10^{-4}	10^{-2}	10^{-2}	10^{-3}	10^{-3}
Divertors	closed	open	open	closed	none	closed
Heating	beam, RMF, inductuctive, compression	merging	inductive, $RMF_{e,o}$	RMF_o	merging, inductive, compression	adiabatic compression

3.1.a. Stability: The most important theoretical – but not experimental – issue for FRCs has long been considered to be stability. Two classes of stability problems are anticipated: interchange modes and co-interchange modes, including the n = 1 tilt.

FRCs with little toroidal field and magnetic shear would be susceptible to interchange instability. Radial modes are MHD-interchange unstable in an FRC. The rotational n=2 mode has been the only observed instability in quiescent FRCs. Higher order rotational modes are always seen during dynamic formation. Multipole fields have provided stability to these radial modes, as demonstrated in the early 1980s.[34] It was later calculated and demonstrated that RMF provided stabilization.[35] Divertors may improve stability against interchange modes by providing good curvature and rapid flow, the latter imported from the gas-dynamic-trap concept. Toroidal field has been observed in some FRCs. Though the toroidal field is much lower than the poloidal field, the safety factor, q, can be greater than 1, particularly at high elongation; stabilizing magnetic shear may result. Local shear is also predicted to exist in FRCs driven by RMF_o. Ponderomotive forces by RMF antennas may create both benefits and drawbacks.[11] Overall, the scientific basis for and technical implementation of solutions to interchange instability seem reasonable.

The principal stability concerns are axial modes. The n=1 tilt has been considered the most dangerous[36,37]. Calculations show[38] and experiments confirm[39, 40] that a close-fitting conducting shell can make a very oblate FRC MHD n = 1 tilt stable. No rotation was observed. In contrast to MHD predictions, prolate FRCs have been observed to be rather stable, a behavior primarily attributed to kinetic effects as characterized by the parameter s. Initial kinetic calculations indicated that tilt growth rates were greatly reduced for s values below 2, but never eliminated.[37]

The Large s Experiment (LSX) explored FRC stability and produced robust FRCs with s values up to 4 but poorly confined FRCs with s as high as 8; none exhibited tilt modes.[5] A fluid-based approach to FLR with gyroviscosity[41] showed the tilt mode stabilized if $S^*/E \leq 3$. (S^* is based on the ion skin depth and is $\sim$ 5-10 s; E is the elongation.) Full non-linear simulations with a hybrid model[42], more stringent than a fluid FLR code, showed non-linear saturation of the tilt. Excellent energy confinement or compression heating, both yielding smaller r_s and lower s FRC reactors, can mitigate the n=1 tilt instability.

Other contributions to the robustness of low-s FRCs are strong flow and magnetic shear. High azimuthal velocities have been measured in FRCs. Calculations including conservation of generalized helicity predict high-β MESs which have both poloidal and azimuthal flows and moderate toroidal fields. TCS produced FRCs with toroidal field and translated them at supersonic speeds. They survived extremely dynamic reflections off mirrors.[1] The TSC FRCs had sufficient toroidal field and large elongation to produce $q \geq 1$ and did not exhibit a rotational n=2 instability.[43] Small toroidal fields have also spontaneously arisen in FRCs sustained by RMF (TCS); the mechanisms for such B_ϕ generation are unknown.[44]

Calculations show that high-energy, axis-encircling – particularly betatron – ions may improve FRC stability.[45] Recent calculations for a non-rotating FRC normally unstable even in an oblate flux conserver have exhibited complete non-linear stability when high energy ions were introduced.[42] It is unknown what fraction of high energy ions, whether from TNBI, RMF, or charged fusion reaction products, and what amount of flow or toroidal field would be required to provide FRC stability. Experimental facilities leading to a burning plasma should have the ability to influence flow profiles and provide high energy ions.

Technology issues are associated with each tilt-mode stabilization technique. Operating multi-MW beam-heating systems or high-precision MW-level RMF systems on FRCs will pose technical challenges that are expected to be manageable with careful engineering design. Diagnosing plasma tilt will require multiple diagnostics, many of which do not exist on the currently operating FRCs.

More attention must be paid to modeling FRC stability, *e.g.*, increasing the capabilities of codes to properly handle RMF_o and TNBI. Realistic models of current FRCs are lacking many important features. For example, they do not include flux conserver rings, plasma outside the separatrix, RMF_o, or axially varying magnetic fields. Hybrid [HYM] and PIC[LSP] codes are now being improved for application to these problems; greater support is needed.

3.1.b. Confinement: Current FRCs confine plasmas with electron temperatures of several 100s eV [47,6]. $T_i \sim 2$ keV could be reached in LSX.[5] The LSX results involved pulsed FRCs lasting less than 1 ms, not long enough to establish an equilibrium edge layer with the surrounding plasma chamber, making assessments of thermal transport difficult. However, flux and related particle lifetimes give data on cross-field resistivities. LSX (θ-pinch) flux decay rates at higher densities and lower temperatures, with s = 3-4, yielded $D_\perp = \eta_\perp/\mu_o \sim 5m^2/s$. MRX, with their much cooler plasmas, had considerably higher values of $\eta_\perp$ over the classical $\eta_{Spitzer}$.[48] Clearly, FRCs with higher temperatures are needed to test this promising trend.

An important scientific question is the relation of transport processes in tokamaks to those in FRCs. An FRC with no B_ϕ would have far slower propagation speed for fluctuations in the toroidal direction than tokamaks. How this impacts transport must be measured. Also, the trapped particle population in FRCs is quite unlike that in a tokamak. Trapped particles exist above and below the midplane, rather than in the midplane. Moreover they scatter out of the trapped region stochastically, by crossing a phase-space separatrix. The FRC loss cone must be understood, including effects of divertor (mirror) fields and radial electric fields and the rotation they induce.

Steady-state reactor operating scenarios vary from ignited to driven. Whether reaction products or auxiliary heating supply the input power may alter confinement. Little is known about confinement in FRCs other than what was implied by the flux and particle lifetime measurements. The science of transport in FRCs is in an early and exciting stage.

Major challenges are to apply sufficient standard diagnostic techniques to measure transport in FRCs, with the same intensity as done early in the tokamak program, the 1970s, and to develop first principles models of plasma transport suitable for kinetic and MHD-like FRCS.

Long-pulse operation will require powered coils or superconducting flux-conserver rings. The latter technical challenge can be handled with innovative engineering.

3.1.c. Heating: TNBI and RMF_o have been proposed for steady-state heating of FRCs. Beam-heating physics in tokamaks is well understood and may be transferable to FRCs. Beam-driven instabilities in FRCs need analysis. Beam-heating experiments will require a larger, higher field FRC target than currently available in the US.

Theory and experiment of electron heating by RMF_o has yielded general, though not complete, agreement. RMF_o ion heating theory[49] in FRC has not been tested. RMF penetration at smaller values of B_ω/B_e must be achieved to get good ion heating at acceptably small circulating power. A larger, higher field FRC is needed to get appreciable ion heating by RMF_o.

There are many technical challenges associated with neutral-beam injection. Many have been successfully resolved on tokamaks. Skilled and experienced beam designers and operators are needed. RMF_o heating requires detailed and precise real-time control of the amplitude, phase, and frequency. Antenna currents and phases should be settable/balanced to better than 1%. The frequency must be controllable to better that 0.1%. In current machines, best performance requires frequency and amplitude modulation in typically 0.1 μs and 10 μs, respectively. In larger FRC these times may be somewhat longer.

3.1.d. Flux sustainment: Steady-state current drive has been demonstrated for FRCs using rotating magnetic fields (RMF) on rotamak devices at ANU and Prairie View, TCSU at UW, and PRFC at PPPL. The latter two devices achieved temperatures well over 200 eV at an input power density near $3 - 10\ W/cm^3$. RMF current-drive efficiency is low, $\eta_{CD} \sim 0.05 - 0.5$ A/W, possibly limited by anomalous resistivity. The target efficiency is 10 A/W. Achieving low resistivity at the parameters listed in Table I is key for overall FRC performance.

The power required to increase flux has been a limiting factor in present experiments. The ohmic power dissipated in an RMF_e-driven FRC is approximately $P_\eta(MW) \sim 10\langle\eta(\mu\Omega - m)\rangle B_e^2(T) l_s(m)$, where l_s is the CT length. It is thus important to have $\eta \leq 1\mu\Omega$-m , corresponding to $D_\eta \leq 1 m^2/s$. An oblate shape is advantageous for a minimum-size reactor but, since the fusion output scales as $R^2 l_s$, the power output will also be lower. However, the effective resistivity in an FRC is anomalous. FRCs with radial thermal gradients are likely to incur large power dissipation near the edge due to the lower temperatures. Related effects may make start-up fairly costly in energy.

Balance of RMF drive torque and electron-ion frictional torque lead to density and temperature scalings of $\eta_\perp$. TCSU results are consistent with LSX resistivities at low temperature.[51] The collisional resistivities correspond to Bohm-like scaling while the collisionless results exhibit an LHDW-like scaling, as formulated in the 1970s by Davidson and Krall [13] and observed in θ-pinches[14]. It is interesting that mirror plasmas with diamagnetic currents and lower values of the drift parameter γ_d have experienced near-classical scaling [50]. Several recent calculations of diamagnetic plasmas show rapid turn-off of small-scale turbulence as γ_d becomes less than unity.[52,53]

Tangential neutral-beam addition should have a profound influence by reducing the percentage of toroidal current carried by the bulk electrons. In addition, the particle source will create an outward v_r in the Generalized Ohms Law. Calculations show that absorbing the TNBI requires beam energy lower than $E_{ic}(keV) = (0.0144/A_i)[\phi_p(mWb)/r_s(m)]^2$, characteristic of a fast ion, injected at the field null and making an axis-encircling orbit with excursions between the field null and the separatrix. Monte-Carlo calculations for a *PoP-level* device show a 40 A, 20 keV deuterium beam could produce a ring current of 100 kA in a $r_s = 0.9$ m, $B_e = 600$ G FRC.[54] This should lead to lower resistive losses and increased flux generation. For a burning CT plasma, reaction products spiral primarily in the diamagnetic direction, and may greatly help sustain the toroidal current.

4 FRC facilities and gaps

4.1 Facilities

There are several small spheromak-merging experiments in the US and one larger one in Japan, primarily devoted to studying basic reconnection physics and CT formation – either FRCs or spheromak. There are also two US θ-pinch FRC facilities devoted to high-energy-density compression, and two small θ-pinch-based FRC experiments in Japan. The only quasi-steady-state FRC experiments utilize RMF to form and sustain the FRCs. The largest and most powerful is TCSU at the University of Washington. It is used to study current drive, transport, stability, and confinement. The PFRC RMF_o facility (PPPL) examines electron heating, fluctuations, flux conservers, divertors, and current drive. The original Australian rotamak RMF device has been transferred to Prairie View University and is used to study FRCs with varying amounts of B_ϕ added, non-linearities developed by RMF, and FRC merging.

US FRC facilities

1. TCSU: Produce and sustain FRCs using RMF (U. Washington).
2. IPA: Merging and thermalization of supersonic FRCs (MSNW LLC).
3. PHDX: Magneto-kinetic compression of kinetic FRC to fusion conditions (U. Washington).
4. SSX: Form CTs (spheromaks or FRCs) by merging spheromaks (Swarthmore College).
5. PFRC: Study electron heating, current drive, and stability with RMF_o (PPPL).
6. MRX: Form spheromaks or FRCs by merging inductively created spheromaks (PPPL).
7. Rotamak: Study plasma heating process by magnetic reconnection of two FRCs driven by RMF (Prairie View A & M).
8. PBX: Build-up flux through repetitive spheromak merging (Woodruff Scientific).
9. Colorado FRC: Study turbulence, flow and transport in FRC formed by merging spheromaks.
10. Tri-Alpha: Private Effort ($80M over 4 years) colliding-beam $p-B_{11}$ FRC. Tri-Alpha Energy Corp.
11. FRX-L: high-n_e, high-B_e conical θ-pinch-formed FRC for translation and capture studies related to MTF (LANL).
12. FRCHX: high-n_e, high-B_e conical θ-pinch-formed FRC for MTF compression (AFRL).

Japanese FRC facilities: FIX (Osaka University) and TS-3 (Tokyo University)

US Theory and Computation

1. Theory and computation development for CTs (PSI-Center, U. Washington). Collaborations with U. Wisconsin and Utah State, including kinetic particles.
2. 3-D hybrid (HYM code) calculations of FRC stability, as affected by beams, RMF, and shape (PPPL).
3. RMF code (LANL, PPPL) for studying non-linear dynamics of charged particles in FRCs under the influence of RMF heating.
4. LSP (PIC) code at Voss Scientific, for self-consistent simulations of RMF_o on FRCs.

4.2 Gaps

The world-leading US FRC research programs have gaps in machine capabilities, theoretical tools, diagnostics, and research manpower that hinder progress towards an FRC reactor. The latter two can be viewed jointly – little gain can be realized from excellent diagnostics without skilled physicists to operate them and interpret the data.

4.2.a. Machine capabilities: The primary physics gap is energy confinement at reactor-like conditions, embodied in the parameters s, D and ν^*, see Table I. To test transport issues, large increases will be needed in ϕ and s, requiring increases in machine size, magnetic-field strength, and heating power. Higher s values would concomitantly allow tests of stability issues. Note that lower ν^* at higher ϕ implies large increase in temperature. Both higher T_e and higher T_i are needed to test effects on D. Lower density and density control provide advantages for this research.

In the line of research towards a steady-state, prolate, beam-heated, ignited, D-T FRC reactor, these gaps would be narrowed or filled by construction of a new facility, with sufficiently higher r_s, B_e and heating power than TCSU. ϕ would be serially increased 100 fold, eventually to 0.1 Wb. A major innovation would be the inclusion of TNBI, allowing not only tests of heating and sustainment, but of stabilization.

In the line of research towards a steady-state, prolate, RMF_o-heated, driven, D-He$_3$ FRC reactor, the major experimental gap is a facility with precise higher-power RMF_o, larger B_e and r_s, better diagnostics, and long-pulse ($\geq$ 1 s) flux conservers than the PFRC. ϕ would be serially increased 1000-fold, eventually to 0.01 Wb by a sequence of upgrades to the PFRC device, approximately every 4 years.

Spheromak merging, with inductive amplification, can produce high ϕ, though at large ν^*. Methods to reduce n_e and increase T_e and T_i are needed to follow a path towards reactor-like dimensionless parameters. NBI injection[28] could fill this gap and increase the range of s from 1 to 15, the range of elongation, $0.5 \leq E \leq 4$, temperatures by factors of 10, and ϕ to 30 mWb, resulting in ν^* below 1.

In the line of research towards a pulsed, kilo-bar pressure, prolate, ignited, high-density D-T FRC reactor, the major experimental gap is facility with stronger acceleration and compression.

4.2.b. Theoretical tools: Numerical modeling of FRCs has advanced to the state where high, medium, and low frequency phenomena should be included in the same code, a necessary situation when heating time scales are short ($\leq 1\mu s$ for RMF), instability times scales moderate ($\sim$ 0.1 ms for rotational modes), and transport time scale relatively long (need to approach 1 s). Equally important is the need to treat FRC plasmas that range from kinetic, $s \leq 5$, to MHD,

$s \geq 10$. A third equally important issue is accurate boundary conditions, including gas source and recycling, segmented flux conservers, and axial variations of the applied external magnetic field. The effects of strong mirror fields on loss cones must be included.

Some codes, particularly the 3-D HYM hybrid code (PPPL), have been advanced near to the-above described state and are being applied to necessary analyses of stability. Others, such as NIMROD (UWash, UUtah, and UWisc), specialized to MHD, are being modified to address CT issues. PIC codes, at Voss Scientific and Tech-X, developed for other applications, are now being applied to these FRC problems. Understanding of basic stability and transport issues may result.

Single-particle Hamiltonian and symplectic codes have been useful for studying non-linear dynamics with RMF. Upgrades to include infrequent collisions are needed and confinement studies should proceed.

4.2.c. Diagnostics and research manpower: As FRC plasma temperatures and energy densities increase, probes can no longer be inserted into the plasma without causing perturbations. Access and capabilities should be added for non-invasive diagnostics, such as necessary to measure the radial and axial temporal variations of internal fields and currents. Several field- and current-measuring diagnostics have been suggested, ranging from deflections of particle beams to Zeeman-type atomic physics. It is essential to measure the total current so as to determine the current-drive efficiency, η_{CD}.

An important diagnostic is a multi-point Thomson scattering system, to measure radial and axial variations of T_e and n_e by this gold-standard technique. Better particle confinement will eventually allow spectroscopic determination of T_e, by such methods as dielectronic recombination and charge-state distributions of impurity ions. X-ray techniques can also add considerably to this area, both through transmission-filter-based tomographic methods, to provide spatially resolved rapid-time response, and pulse height systems, to provide T_e and impurity content. These X-ray arrays could provide definitive information on the tilt and rotational instabilities. Diamagnetic loops, a robust method in high-β plasmas, should be placed all along the major axis to provide essential plasma-pressure data on the open and as well as closed field and in the divertors.

As ion temperatures rise, measurements of T_i will be needed. Successful "gold-standard" methods use charge-exchange analyzers and Doppler broadening. These can also provide essential information on ion spin-up and on the s parameter.

Radially and axially resolved measurements of plasma density are essential. Multi-chord interferometers are necessary.

Radiated power losses should be measured with bolometers at several locations.

Coupled with diagnostics of the input/absorbed power, determination of the transport coefficients could be made, hence aid in deciding whether FRCs are indeed suitable as fusion reactors. For RMF_o, not only must power be measured, but also degree of symmetry and phase balance.

To understand transport, fluctuation measurements and analysis are necessary. The diagnostics suitable for this include a variety of probes – magnetic, electrostatic, and capacitive – and spectroscopic and wave scattering/propagation methods.

Particle accounting diagnostics will greatly help interpret power and particle flows. Rapid-time-response gas-pressure gauges in both the FRC region and the divertor regions are necessary. Other divertor diagnostics and controls, such as over radial potential, can improve control of the plasma and understanding its behavior.

Definitive diagnosis of stable, quasi-steady-state, high-temperature, well-confined FRCs would greatly strengthen the FRC's role in providing fusion power, as suggested by EPRI.[57]

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