6. Compact Toroids

6.1 Concept Description

Compact Toroids (CT) come in two forms, spheromaks and FRCs, which have generally been studied separately, but have similar reactor benefits. The defining feature of a compact toroid is a closed field line configuration in a singly connected vacuum vessel. There are thus no toroidal field coils, but toroidal fields can be embedded during formation and sustained by helicity injection (HI). Transformer (ohmic current drive) sustainment of the toroidal current, or poloidal flux, is not available, which is a principal difference between CTs and most other toroidal confinement schemes. The historical distinction between spheromaks and FRCs has usually been that spheromaks had near equal poloidal and toroidal magnetic fields, moderate β, and were generally confined inside an oblate flux conserver with calculated MHD stability, wheras FRCs had zero toroidal field, very high β, and were generally prolate and confined inside a cylindrical flux conserver, and relied on kinetic and other effects for stability.

There have been many 'reactor' ideas for CTs, including high compression in repetitively pulsed devices, which involve batch burn, and steady, or near steady state operation with energy from fusion reaction products going toward maintaining the configuration. The high compression option is not covered here since it is being evaluated under a separate High Energy Density Physics panel.

Among the unique CT engineering attractions are:

1) Singly connected vacuum system.
2) No toroidal field coils – easing design, access, and maintenance.
3) Simple, circular poloidal field coils with low required magnetic fields.
4) Controllable outflow – along open field lines at CT edge to remote natural 'divertors' – allowing efficient energy extraction and impurity control.
5) Little energy content beyond *NkT* with large surface to volume ratio – contributing to robust vessel designs capable of withstanding 'off-normal' plasma termination.
6) Possible very high β, making high density or advanced fuel options possible.

The current main challenges for steady-state CTs are:

1) Insuring stability for FRCs and attractive β values for spheromaks.
2) Obtaining sufficiently good confinement for small scale safe reactors.
3) Providing an efficient method of current drive (actually flux sustainment).

The long term goal for CTs is a relatively small size, economic, fusion reactor with good safety and maintenance characteristics. Ideally the fusion core would be similar in size and engineering characteristics to a fission reactor, without the long-term waste storage problems.[1]

6.2a FRC Goals for the ITER era

An aggressive FRC goal for the ITER era would be a near-burning, near steady-state plasma that would provide sufficient demonstrations of stability, confinement, and current drive that, along with burning plasma scientific and technical data from ITER, would provide the knowledge to construct a CT demo. Since CTs are in such an early stage of development, it is reasonable to first propose more near-term goals. The near-term goal is to *demonstrate combined good confinement and steady-state current drive at kilovolt temperatures, and the theoretical understanding to allow for extrapolation to the burning plasma experiment.* Due to the low cost of simple FRC confinement magnets and plasma chambers, success in the near term goals could rapidly translate to attainment of the aggressive ITER-era goals.

Spheromak (and RFP) experiments have convincingly demonstrated that closed nested magnetic surfaces, in the absence of resistive and ideal MHD instabilities, confine plasma well, regardless of the value of safety factor q. FRCs, which have flux surfaces and drift surfaces, but not magnetic surfaces in the conventional sense (at least when B_ϕ is identically zero), are showing improved confinement in modern experiments, but the physical basis is different and not yet well understood. Stability has always been the principal concern about FRCs, with observed robust experimental stability of small FRCs usually attributed to their kinetic nature, as represented by the number s of internal ion gyro-radii between the field null and the separatrix. There have been experimental demonstrations of good, quiescent stability in non-sustained FRCs with s values up to 4 in both oblate and prolate FRCs, but much higher s values will be needed to provide adequate confinement with tokamak level transport coefficients in moderate density (n_e = 10^{20} - 10^{21} m^{-3}) steady-state FRCs. Other effects related to high energy ion components and strong flow, with shear, have been calculated to enhance FRC stability, and there is experimental evidence that FRCs can be a form of high-β Minimum Energy State (MES).

FRCs have proven to be extremely rugged, at least at low s, surviving extremely dynamic formation, translation, and capture events in theta-pinch experiments. It has also been observed that toroidal flux, produced during formation, has been converted to poloidal flux during the reflection events occurring during capture in a mirrored flux conserver. Measurements of the toroidal flow, and poloidal and toroidal field profiles are indicative of calculated high-β MESs. Many merging spheromak experiments have also demonstrated the dynamic formation of FRCs through the cancellation of oppositely directed toroidal fields. Higher s stability information for prolate FRCs has been obtained in the largest theta-pinch experiments. There has been some controversy about whether a tilt instability has limited the ability to form ever higher s plasmas, with the highest s values being achieved through careful control of the symmetry of the extremely dynamic formation process. Recent CT merging experiments have also shown FRC stability up to about s = 5 in oblate flux conservers, with β values well above the previously observed limits in spheromak experiments. The only steady-state FRCs have been produced and sustained using Rotating Magnetic Fields (RMF) whose development, particularly the torque based analysis, was pioneered by Ieuan Jones' group at Flinders University in Australia, but these have been of relatively low *s*.

Unless near classical confinement could be realized, it is necessary for steady-state reactor-grade FRCs to have much higher *s* values. A diffusivity value of ~0.5 m^2/sec and $s \sim 30$ is a reasonable reactor vision, with a near term, or next-step goal of $\langle D \rangle \sim 5$ m^2/s and $s \sim 10$. Theta-pinch made FRCs with $\phi_p \sim 12$ mWb have shown $\langle D_\perp \rangle = \langle \eta_\perp/\mu_o \rangle$ values of 5 m^2/sec based on the FRC flux decay rates.[2] However, little is known about the internal thermal confinement. Recent experiments with colder FRCs (and thus high *s* with lower flux, ~ 6 mWb) in oblate flux conservers have exhibited very quiescent plasmas. ($s = 1.52\phi_p(\text{mWb})/[r_s(\text{m})(A_i T_i(\text{eV}))^{1/2}]$ where r_s is the separatrix radius.)[3] In diamagnetic plasmas such as an FRC, particle and flux loss rates are related, and measured energy loss rates appeared to be predominantly due to radiation and particle loss (convection). Kilo electron-volt temperatures have been obtained in theta-pinch formed FRCs but, due to their pulsed sub-msec nature, there has not been enough time to establish an edge layer in equilibrium with the surroundings. Investigations are needed with quasi-steady FRCs with enough flux to allow for internal thermal confinement.

Steady-state, ~100 eV FRCs have been formed and sustained by RMF with MW level power inputs, but have only had poloidal fluxes of 3-4 mWb and *s* values of 1-2, depending on temperature. In order to meet the near term FRC goals, about 100 mWb of flux is required, with temperatures approaching 1 keV. Although such temperatures have been reached in theta-pinch experiments, the size and voltages required to reach 100 mWb flux levels with theta-pinch technology are impractical. Merging CT experiments could possibly reach such conditions, and next-step merging CT experiments have been proposed in the past, but not funded.

The only method presently demonstrated for sustaining a true FRC (without any internal flux adding coil) is RMF. The theory for this is well developed, with an RMF torque on the electrons exceeding the frictional electron-ion resistive torque resulting in flux-build-up. Sustained flux levels scale with $\phi_p \propto B_\omega r_s^2/\langle \eta_\perp \rangle^{1/2}$, where B_ω is the RMF magnitude, so a simple means exists of increasing flux by increasing B_ω and r_s. The input power will be approximately proportional to B_ω^2, but independent of r_s. Present experiments have observed average values of $\eta_\perp$ of ~ 100 μΩ-m, with central resistivities a factor of 5 lower. Attainment of $\langle \eta_\perp \rangle = 25$ μΩ-m is all that is necessary to reach the 100 mWb flux level required to investigate the principal near-term goals, while reaching the 5 μΩ-m resistivities realized in higher density, theta-pinch formed, pulsed FRCs would provide the knowledge necessary to rapidly extrapolate to the full ITER-era near burning plasma goal.

TNBI has also been proposed as an FRC current, or flux sustainment technology. TNBI was applied to the 2XIIB mirror device to try and produce a Field Reversed Mirror (FRM), but it was never possible to reverse the internal mirror field. TNBI should work well with already formed FRCs (in fact, it is the basis of a large effort at a private company [4]), but has not yet been tried. In order for TNBI to be effective in trapping high energy ion rings within the FRC separatrix, the neutral beam energy should be below a critical value $E_{ic}(\text{keV}) = (0.0144/A_i)[\phi_p(\text{mWb})/r_s(\text{m})]^2$. About 50 mWb is required for optimal TNBI usage at reasonable 10-20 keV beam energies.

It is possible to sustain 50 mWb poloidal fluxes using RMF drive in a device of about 2 m in diameter (2.5 times the diameter of the largest present machine) with B_ω values of 10 mWb (about twice present amplitudes) with average resistivities $\langle\eta_\perp\rangle$ no lower than the ~100 μΩ-m presently observed. There is good reason to believe that $\eta_\perp$ can be substantially reduced based on previous observations of LHD-like (Lower Hybrid Drift) resistivities which scale as $D_\eta = \eta_\perp/\mu_o \propto D_B(v_{de}/v_{ti})^2$, 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, $\gamma_{de} = v_{de}/v_{ti}$ is proportional to the ratio of ion gyro-radius to density scale length. $\gamma_{de} \propto 1/(n_e^{1/2}r_s)$, independent of temperature, so this LHD-like scaling would be extremely favorable for larger, higher density FRCs. In the RMF sustained FRCs, n_e was ~ $1\text{x}10^{19}$ m^{-3} and γ_{de} was of order 2 near the edge, which dominated the average resitivity. Theta-pinch formed FRCs had n_e ~ 10^{21} m^{-3} and much lower γ_{de}. n_e scales approximately as $B_\omega/\eta_\perp^{1/2}$, relatively independent of size and temperature, for RMF sustainment.

For FRCs with bulk diamagnetic toroidal plasma currents, lowering the effective value of D_η is key to attaining the ITER-era goals, certainly in terms of sustainment since the power dissipated due to ohmic losses is proportional to $\eta_\perp B_e^2$ where B_e is the external magnetic field. Exponential gains in near-term performance are possible if LHD-like scaling is realized. TNBI can contribute strongly to this goal by supplanting some of the bulk plasma current, and also by providing a source of particles and energy near the field null. It is possible, in reactors, that fusion itself could provide the bulk of the current drive.

Attaining the FRC goals will also make major contributions to fusion science. The possibility of high β MESs, which has been proposed as an explanation for FRC experimental stability, is also of great general interest. Taylor relaxation, based solely on magnetic helicity, is presently the only solid theory we have for MESs, but true Taylor states are zero β. High-β MESs have been calculated based on conservation of total magnetic plus flow helicity and their characteristics have been seen in experiments. Any contributions to non-zero β MESs will have resonances with astro and space plasma physics, as well as fusion plasma physics. In addition, FRC research will contribute to the general understanding of anomalous transport in diamagnetic systems with minimal toroidal field, such as magnetic mirrors. Edge-layer flows can also be studied in a carefully controlled environment, and even directed, at highly variable power density levels, for surface interactions studies.

6.3a FRC Scientific and Technical Issues

The most important theoretical (but not experimental) issue for FRCs has always been stability since FRCs contain little or no toroidal field, and thus might be thought of as having little or no magnetic shear. FRCs have been observed to have some toroidal field in many experiments but, by definition, and in contrast to spheromaks, the toroidal field is much lower than the poloidal field and thus FRCs must have high beta. Due to high elongation in some poloidal FRCs, however, the safety factor q has been observed to be greater than 1, with considerable magnetic shear. An important relationship for elongated FRCs in a cylindrical flux conserver, based solely on axial equilibrium, is $\langle\beta\rangle = 1 - x_s^2/2$ where r_s is the separatrix radius, r_c is the flux conserver radius, and $x_s \equiv r_s/r_c$. The *minimum* average β value is thus 0.5, and approaching this lower average β is desirable since it provides more insulating flux for confinement. $\phi_p = (x_s/\surd 2)^{1+\varepsilon}\pi R^2 B_e$ is also an equilibrium constraint where $R = r_s/\surd 2$ is the radius of the field null, B_e is the external magnetic field, and $0 < \varepsilon < 1$ depends on the $B_z(r)$ profile (typically $\varepsilon \sim 0.3$). Higher flux and higher average β values are possible with different flux conserver shapes. Maintaining FRC stability as the size increases carries the most risk in meeting FRC near-term and far-term goals. The other key experimental issues for FRCs have been confinement and current drive efficiency, which are related in a diamagnetic plasma. It is current drive inefficiency which has limited performance in present sustainment experiments, and which is predicted to improve dramatically as the device size increases and the electron drift velocity (and anomalous cross-field resistivity) decreases. Heating is a lesser issue since both RMF and TNBI have been demonstrated to be strong heating sources for plasmas. There are calculations that RMF, particularly odd-parity RMF, can preferentially heat different ion species, which could be important for advanced fuel schemes [5].

Stability: Radial modes are MHD interchange unstable in an FRC as they are in a mirror plasma, driven by rotation and centrifugal forces in an FRC as opposed to unfavorable magnetic curvature in a simple mirror. A rotational n=2 mode has been the only observed instability in quiescent, theta-pinch or RMF formed FRCs, developing as rotation builds up, but higher order rotational modes are always seen during dynamic formation. Just as in mirror plasmas, multipole fields have provided stability to these radial modes, which provided impetus to the FRC program when first demonstrated in the early 1980s.[6] It was later calculated and demonstrated that RMF provided the same stabilization.[7] The principal concern since that time has been axial modes, of which the n=1 tilt has been the most studied, beginning with calculations of the necessity of having a close fitting oblate shape for a CT to be MHD tilt stable.[8]

MHD tilt stability of oblate FRCs has been observed in the PPPL Merging Reconnection Experiment (MRX) and in the Swathmore Spheromak Experiment (SSX), where recent new measurements show very low fluctuation levels. [3] The natural rotation of an FRC could allow this wall stabilization to apply for long timescales. These plasmas had small gyro-radii and were not likely to be kinetically stabilized. (Similar stability has been noted in cold, highly collisional theta-pinch formed prolate FRCs.) Shorter wavelength kink instabilities of ≥ 4 toroidal periods may not be shell stabilized, but such modes were not seen in SSX. Because most of the oblate magnetic field lines are approximately circular, interchange instability is expected. However, preliminary SSX data revealed very peaked equilibrium profiles that may be at or near the stable adiabatic lapse rate.

In contrast to the MHD predictions, prolate FRCs have been observed to be stable in theta-pinch and RMF formed experiments. This feature has primarily been attributed to kinetic effects. Initial kinetic calculations indicated that tilt growth rates were greatly reduced for s values below 2, but never eliminated.[9] The Large s Experiment (LSX) was built in the late 1980s to explore FRC stability as the MHD limit was approached, and in its one year of operation produced robust FRCs with s values up to 4, and poorly confined FRCs with s as high as 8, which didn't exhibit tilting modes.[10] Ever more sophisticated kinetic codes have failed to adequately explain either prolate or oblate FRC experimental stability, but recent calculations including a high energy ion component have yielded full stability for an oblate FRC.[11] High energy, axis encircling ions have been calculated to improve FRC, stability[12], and their generation and study is an important part of the FRC goals.

Non-kinetic effects may also be responsible for observed FRC stability, primarily strong flow, with possibly high velocity shear. High azimuthal velocities have been measured in all FRCs, and calculations including conservation of generalized helicity (magnetic plus flow) predict high beta MESs which have both poloidal and azimuthal flows and moderate toroidal fields.[13] An example measurement is shown in Fig. 1 of an FRC which has been translated at supersonic speeds into the RMF driven Translation, Confinement Sustainment (TCS) FRC device, and survived extremely dynamic reflections off mirrors.[14] It is interesting that this FRC, due to its high elongation, has sufficient toroidal field to produce safety factor q values above unity (but not enough B_ϕ to affect the high beta nature). It is also interesting that these FRCs did not exhibit a rotational n=2 instability despite having neither multipole fields or RMF.[15] Small toroidal fields have also spontaneously arisen in FRCs sustained by RMF for long times (10 msec in TCS), but the mechanisms for such B_ϕ generation are unknown.[16]

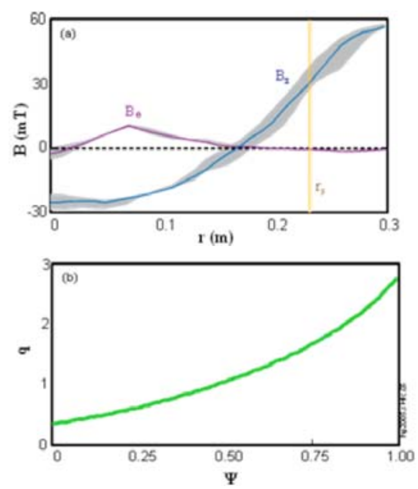

Figure 1. Internal probe measurements of translated FRC captured in TCS.

Confinement: Hot FRCs (T_e up to 0.5 keV and T_i up to 2 keV) were produced in the Large s Experiment (LSX) using GWs of formation power. However, the short lived, non-sustained FRCs did not have time to establish an edge-layer in equilibrium with its surroundings. Energy lifetimes were consistent with particle loss and radiation measurements ($\tau_E \sim \tau_N/2$), but the edge layer was still relatively hot and internal thermal transport rates could not be inferred. Flux and related particle lifetimes did, however, give accurate data on cross-field resistivities. Theta-pinch derived FRC lifetime data is shown in Fig. 2. At higher densities and lower temperatures where s = 3-4, LSX flux decay rates yielded $D_\perp = \eta_\perp/\mu_o \sim 5$ m^2/sec. In a diamagnetic plasma this is intimately related to particle transport, and may also be related to energy transport. A previously inferred empirical scaling from ~10^{21} m^{-3} theta-pinch formed FRC experiments, $\tau \propto r_s^2/\rho_i$ (as sketched in Fig. 2), equivalent to $\tau \propto r_s^2 n_e^{1/2}$ for high β FRCs, has not been seen in recent lower or higher density experiments. A physics-based scaling is one of the most important FRC needs.

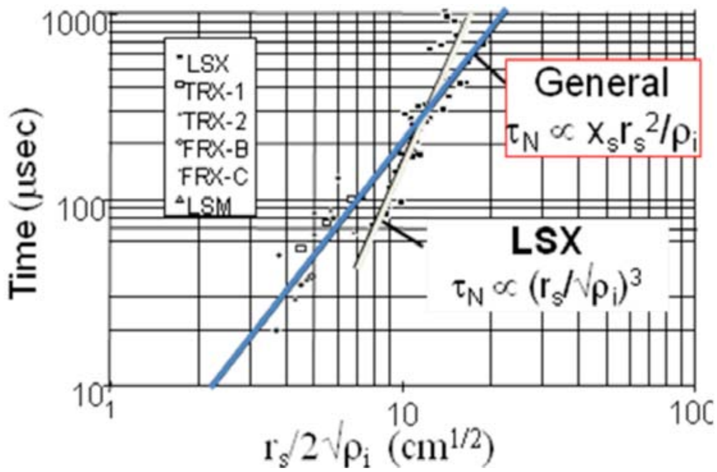

Figure 2. Particle lifetime scaling measured in LSX and other FRC theta-pinch facilities.

In the TCS experiment FRCs were formed and sustained by ~2 MW rotating magnetic fields. However, there was so little flux (there were only one or two ion gyro-radii between the field null and the separatrix, as represented by the s value) that the plasma was essentially isothermal. Great improvements in average temperature were made in TCS-upgrade (TCSU) by adopting stringent vacuum hygiene, baking, and glow discharge cleaning, as indicated in Fig. 3. This not only reduced radiation levels, but overall recycling, as evidenced by the D_α radiation level. The temperature in TCSU could be attributed to flux-limited thermal conduction along the low density open field line edge-layer plasma to remote end regions.[17] Low edge densities are a feature of RMF current drive since the RMF creates a positive E_θ, which not only sustains the flux, but acts as a $n_e(r)$ pinch.

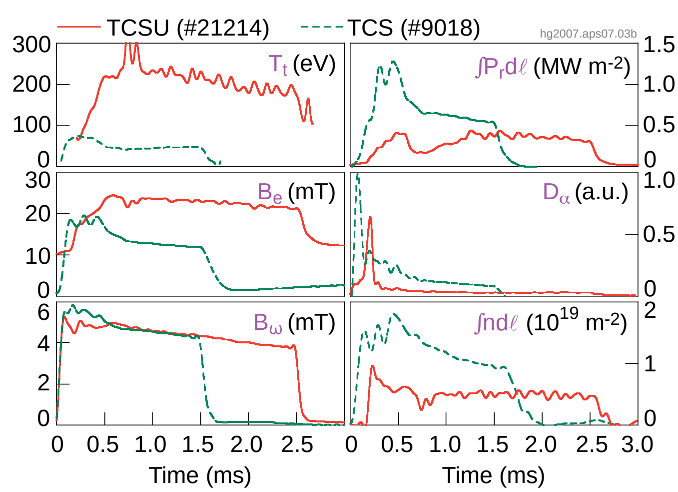

Figure 3. Temperature and performance improvements seen in RMF sustained FRCs with reductions in radiation

One objection that had been made about RMF in an FRC was that it would open all flux surfaces. This strictly applies when the toroidal field is zero, but an important idea developed by Cohen & Milroy for using an odd-parity RMF, with different cross-field directions in opposite halves of the FRC, can produce completely closed field lines.[18] Since optimal use of the RMF involves only partial penetration of the FRC, the magnetic field lines are mostly azimuthal (which provides the aforementioned radial stabilizing force), and further calculations showed that closed field lines could be maintained even under fairly high ratios of RMF magnitude, B_ω, to external field B_e.[19] In the low flux TCSU FRCs, with little internal temperature gradients, odd-parity operation had little effect, but it will most likely be essential for high flux FRCs.

In a steady-state reactor most of the input power required to maintain the plasma temperature must be supplied by heating from the reaction products (i.e. burning) to achieve good reactor economics. The ability to do this depends on the quality of energy confinement ($n\tau_E$). Little is known about this for FRCs other than what was implied by the theta-pinch flux and particle lifetime measurements. Any next step, steady-state experiment must have enough flux (50-100 mWb) to provide higher *s* values for confinement, as well as stability demonstrations, with valid determination of τ_E and its empirical scaling. Temperatures in the theta-pinch range of 0.5-1 keV with ~$5\text{x}10^{19}$ m^{-3} densities would also be desirable to provide very low collisionality. Building on the anticipated growth of plasma science, it may be possible to find a predictive theory for τ_E.

Current drive efficiency: CTs have a unique requirement for creating and maintaining the poloidal flux without an inductive transformer, and the power required to do this has been a limiting factor in present experiments. (In fact, flux sustainment is a more descriptive terminology for FRCs than current drive since diamagnetic current arises solely from pressure gradients.) Theta-pinches form FRCs by trapping some initial bias flux, and the merging spheromak approach merely conserves the poloidal flux of the larger spheromak. The only means currently demonstrated for sustaining FRC poloidal flux is RMF. Building-up/sustaining poloidal flux requires making $E_\theta = \eta_\perp j_\theta + \text{v}_{er}B_z + \langle -\text{V}_{ez}B_r\rangle$ greater than/equal to zero (using the convention that B_e is positive and the poloidal flux and azimuthal current are negative). This equation applies specifically to an elongated FRC, but the basic physics holds for any CT. The in-phase oscillatory $-\text{V}_{ez}$ and B_r is how RMF current drive works, but the torque on the electrons can be distributed throughout the FRC by reversing the outward radial diffusion (pinch effect).

The ohmic power dissipated in a CT is approximately $P_\eta(\text{MW}) \approx 10\langle\eta(\mu\Omega\text{-m})\rangle B_e^2(\text{T})\ell_s(\text{m})$, where ℓ_s is the CT length. It is thus important to have $\eta < 1$ $\mu\Omega$-m, or $D_\eta = \eta/\mu_o < 1$ m^2/sec. An oblate shape is advantageous for a minimum physicsl size reactor but, since the fusion output scales as $R^2\ell_s$, the power output will also be lower. Ignoring where the current drive power comes from, and the value of resistivity, high β is a huge advantage. However, the effective resistivity in an FRC is anomalous since the current is diamagnetic (cross-field with $\eta \sim \eta_\perp$). Any CT will most likely suffer from the power dissipation being much larger near the edge due to lower temperatures and higher resistivities there, which may also make start-up fairly costly in energy and pose an impediment to non truly steady-state operation.

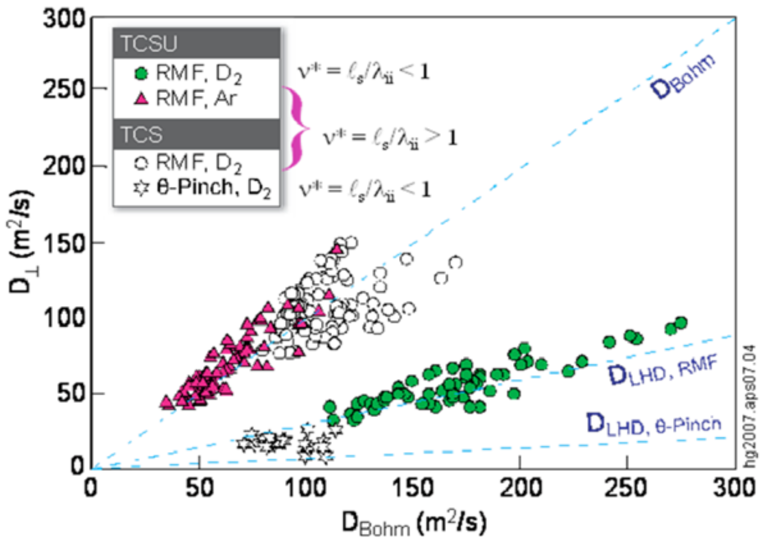

Figure 4. Comparisons of average FRC resistivities measured by torque balance during RMF sustainment.

A lot is known about anomalous cross-field resitivity from simple theta-pinch and FRC experiments. Well developed scaling laws based on equality between RMF drive torque and electron-ion frictional torque lead to an FRC field null density scaling of $n_m(10^{19}\text{m}^{-3}) = 14B_\omega^{4/3}(\text{mT})/[T_t^{1/3}(\text{eV})\langle\eta_\perp(\mu\Omega\text{-m})\rangle^{3/2}]$ which allows determination of $\eta_\perp$ from temperature and density measurements. Data are shown in Fig. 4 for the cold collisional TCS conditions, for cold experiments run in Argon in TCSU, and for the hotter collisionless TCSU deuterium experiments.[17] The listed $D_\perp$ values are based on the average resistivities. The RMF sustained FRCs had central resistivities about a factor of 5 lower than the average, edge dominated resistivities. The key to anomalous cross-field resistivity is thought to be the drift parameter ratio, $\gamma_d = v_{de}/v_{ti}$, which appears in all theoretical calculations, and is high near the edge of present FRCs. The central TCSU results are consistent with the lower γ_d theta-pinch formed FRC resistivities. The collisional resistivities correspond to Bohm-like scaling (dashed line in Fig. 4) with $D_B(\text{m}^2/\text{s}) = T_e(\text{eV})/16B(\text{T})$, while the collisionless results exhibit an LHD-like (Lower Hybrid Drift) scaling (lower dashed lines in Fig. 4) with $D_{LHD} = 0.15D_B[\gamma_d^2/(1+(\pi/8)\gamma_d^2)]$ (using the edge value of $\gamma_d = 2.3$), as formulated in the 1970s by Davidson & Krall [20] and observed in theta-pinches [21]. Since γ_d scales as $1/(n^{1/2}R)$ (independent of temperature for a high β FRC), this scaling would be highly favorable for reactors, and it is important to extend experiments to lower values of γ_d. It is interesting that mirror plasmas with diamagnetic currents and lower values of γ_d have experienced such near classical scaling [22] and several recent sophisticated calculations of diamagnetic plasmas show rapid turn-off of small-scale turbulence as γ_d becomes less than unity.[23,24] An edge γ_d of order 0.5 should be a design goal of future experiments.

All experimental CT results have been obtained with all the plasma current carried by bulk electrons (relative to bulk ions). Tangential neutral beam addition should have a very favorable influence by reducing the percentage of toroidal current carried by the bulk electrons (in an FRC the total toroidal current is determined by the pressure gradients, and will only change slowly as flux is created or lost). In addition, the particle addition will create an outward v_r in the Generalized Ohm's Law. For a burning CT plasma, reaction products spiral primarily in the diamagnetic direction, and can alone go a long way toward sustaining the toroidal current.

Calculations have shown that TNBI is most effective when the beam energy is lower than the energy E_{ic}(keV) = $(0.0144/A_i)[\phi_p(\text{mWb})/r_s(\text{m})]^2$ 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.[25] Monte-Carlo calculations for an r_s = 1 m, B_e = 60 mT, 300 eV, ϕ_p = 50 mWb FRC, capable of being produced and sustained with an RMF B_ω = 10 mWb for even the current high $\eta_\perp$ values, are shown in Fig. 5. The results correspond very well to the formula based on the ratio of ion beam slowing down time to the beam gyro time, as long as $E_b < E_{ic}$ to avoid excursions outside the separatrix, and $E_b > \sim 50T_e$ so that slowing down occurs mainly on electrons. Then, α(kA/A) $\approx 0.75T_e^{3/2}(\text{keV})E_b^{1/2}(\text{keV})/[A_i n_e(10^{20}\text{m}^{-3})R(\text{m})]$. A 40 A, 20 keV deuterium beam could thus produce a ring current of 100 kA, a considerable portion of the FRC diamagnetic current. Since the total FRC current is just set by its flux, and cannot change without changes in E_θ, the ring current will just supplant some of the bulk electron current, which should lead to lower resistive losses and increased flux generation. For a reactor, α values of ~100 kA/A are calculated with beam energies of 1 MeV, scaling as $E_b^{1/2}$.

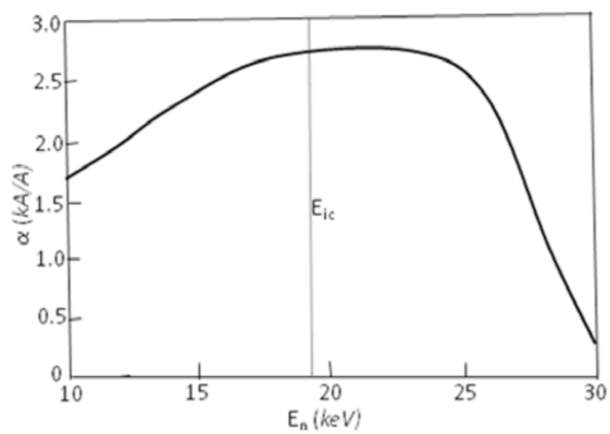

Figure 5. Efficiency of TNBI ring current production for b = 0.64 m as a function of beam energy, for

6.4a FRC Facilities & Gaps

Table 1. US FRC Facilities

Facility	r_s (m)	B_e (mT)	ϕ_p (mT)	T_t (eV)	n_e (10^{20} m^{-3})	s	Principal Effort
TCSU [26]	0.4	30	4	250	0.1	1	Steady State
PFRC [27]	0.03	10	0.01	300	0.01	0.03	Heating
PV Rotmk. [28]	0.2	3	0.1	20	0.01	0.25	Toroidal fields
Col. FRC [29]		(under	const.)				Fluctuations
MRX [30]			2	20	0.1		Formation & stability
SSX [31]	0.25	100	6	80	3.0	5	Formation & Stability
FRXL* [32]							Liner compression
PHD* [33]							Adiabatic compression

A list of the various facilities available to study steady-state FRC issues are listed in Table 1. (Two facilities, indicated by * are dedicated to the high compression scenario which, while not covered in this document, can provide useful information on FRC confinement and stability.) The first three involve using RMF, while the last two utilize merging spheromak techniques to study all CTs. These experiments have been very useful in demonstrating the possibilities of FRC stability and spurring much theoretical interest, but they are all too small to address the basic issues of stability, confinement, and current drive under conditions relevant to a burning plasma. (The listed s values are based on assuming $T_i = T_t/2$, and will be higher if T_i is lower.) MRX and SSX can investigate stability in various shaped flux conservers, but only for very short timescales as there is no means of sustaining the FRC. The larger experiments can contribute to understanding the basic fluctuation levels (assuming internal probes can be inserted in TCSU), but only under conditions where drift waves are presumed to cause high anomalous transport. The RMF current drive method is very well understood, but the additional heating noted beyond simple ohmic, has only begun to be calculated with numerical codes.

Several 2-D codes have been used to model FRC formation and RMF current drive. 3-D hybrid codes (HYM at PPPL) have been used to study FRC stability, including the effects of beams and RMF. NIMROD is being refined and benchmarked at the Plasma Science and Innovation Center (U. Washington, U. Wisconsin, Utah State) for a similar set of tasks. These calculations now include two-fluid effects and can resolve highly anisotropic transport, permitting the capture of more detailed physics than previous calculations. Effects of plasma rotation and boundaries can be added. PPPL has developed codes to study the non-linear heating of charged particles due to RMF. All these efforts will be continuing.

The principal gaps for FRCs are listed below. Only numbers 5, 6, and 7 can be addressed at all with present facilities, although RMF would have to be added to the merging spheromak facilities for number 7. Operating RMF at lower ω is important since most RMF experiments have operated at similar values of ωr_s^2. This is not essential, but it would be technologically desirable to reduce ω as the FRC size increased, to minimize required RMF voltages.

1) Higher s stability from quiescent state.

2) Confinement during long-term sustainment.
3) Power required to maintain flux.
4) Effects of TNBI on stability, confinement, and current drive.
5) Utility of RMF at lower ω.
6) Best geometry and needs for nearby passive flux conservers.
7) Use of RMF, particularly odd-parity RMF, on oblate FRCs.

Table 2. Desired Parameters of Larger Facility

Facility	r_s (m)	B_e (T)	ϕ_p (Wb)	T_e, T_i (keV)	n_e (10^{20} m^{-3})	s	γ_d = v_{de}/v_{ti}	$\langle\eta_\perp\rangle$ (μΩ-m)
1st Stage	1.0	0.06	0.05	0.325	0.15	4	0.75	100
Simple Ext.	1.0	0.12	0.1	0.65	0.3	6	0.5	25
Best Effort	1.0	0.5	0.4	2.5	1.2	12	0.25	5
Reactor	2.0	1.8	6	10	2.0	30	0.1	0.5

The first three gaps are the most important for FRC research, and can only be addressed in a larger facility. Table 2 gives the parameters needed to investigate those gaps. A reactor row is included for comparison. The first row gives density and flux levels which could be achieved with a simple extension of RMF methods using a B_ω value of 10 mT in a 2-m diameter device, even with currently high plasma resistivities. This would get γ_d below unity, where large reductions in $\eta_\perp$ would be expected. It also give conditions where TNBI would be very effective (as calculated in Fig. 5). The listed temperature is very realistic based on pulsed theta-pinch experience, but the actual value will depend on τ_E values for which we have no scaling available for steady-state FRCs. The thermal energy content of the 1st stage FRC would be about 15 kJ assuming a $\langle\beta\rangle$ value of 0.5 and elongation of 2.5. With 10 MW of RMF and TNBI power, the listed temperature would require a τ_E value of 1.5 msec. The input power needed with this energy confinement time would be lower for an oblate FRC.

The second row involves a simple extension of the first row conditions, assuming that the resistivity was reduced by a factor of four. The listed values of resitivity in the last column for the first two rows are the values that would be needed for sustainment of the FRC by RMF alone at a B_ω value of 10 mWb. In order to realize the second row temperature, τ_E would have to be ~ 6 msec. Ideally, some combination of TNBI and RMF would be applied. Attainment of these conditions would satisfy the FRC near term goals.

The parameters listed in the 'best effort' row would constitute satisfaction of the full ITER-era goals. They are such a large extrapolation that it is premature to take them too seriously, but the fact that they can be addressed with only 0.5 T coils gives some indication of the possible low cost of FRC development. The main new tool would be TNBI, which is not available in any current FRC facilities. The listed $\langle\eta_\perp\rangle$ given for this and the reactor case are what would be needed for RMF drive alone assuming a B_ω value of 20 mT. However, it is expected that TNBI and fueling (plus fusion reactions for the reactor case) would supply much of the current drive, and much lower values, if any, of RMF amplitude would be needed. Much of the ohmic dissipation (~15 MW/m) for the listed reactor conditions would ideally be supplied by the fusion process.

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