Answers to FESAC Questions on FRCs

1. **Goals:** We agree with this goal statement. The far-term burning plasma goal was only mentioned because Ray Fonck said our near term goal was too modest. However, one aspect of FRC physics is that experiments are inexpensive and low field, so that rapid advances can be made if the near-term experiments are successful.

2. **Current Drive & Sustainment:** Improving RMF current drive, or flux sustainment requires that the anomalous cross-field resistivity be significantly reduced. We believe this will be accomplished by reducing the drift parameter ratio $\gamma_d \equiv v_{de}/v_{ti}$ below unity. Additionally, high energy ion components can carry a significant portion of the toroidal current with low effective resistivity. The drift parameter will be reduced and the RMF current drive efficiency should be improved by increasing FRC size and density ($\gamma_{de} \propto 1/r_s n_e^{1/2}$), as well as having enough flux for TNBI to be efficient. The RMF also can produce high energy particles. Next step experiments to get these conditions can be reached even with present resistivity values, as shown in our 15-page submission. There is evidence from RMF scale-ups, previous theta-pinch experiments, and recent numerical calculations that γ_{de} is an important parameter governing cross-field resistivity. Tandem mirror plasmas have also exhibited near classical cross-field radial transport. Partial penetration is the only RMF means of sustaining flux in a large FRC since full penetration requires near synchronous electron rotation, which eliminates the torque on the electrons. Partial penetration results in mostly azimuthal field lines which provide a strong radial stabilizing force, and partial penetration also makes odd-parity operation more effective in keeping field lines closed.

   NBI was not successful at LLNL since it wasn't able to achieve field reversal. If an FRC has enough reverse flux to begin with, TNBI is calculated to be very efficient in producing a hot ion ring, which is the main lesson learned. Calculations show that even a small neutral density outside the FRC separatrix (or penetrating a short distance inside) can be very detrimental, so there must be enough flux (~50 mWb) to keep the fast ion ring well inside the separatrix. To do this the injection chord must have a width of no more than $0.1r_s$, just outside the field null, which determines the FRC size ($r_s \sim 1$ m if a neutral beam has a diameter of 10 cm).

   RF means of driving currents in diamagnetic configurations such as an FRC have not been studied.

3. **Transport:** The drift parameter $\gamma_d \propto 1/s$, so that LHD resitivity scales as s^{-2}. This would lead to exceptional FRC confinement scaling (assuming FRCs can be made stable at high s). Experiments should be designed to increase s gradually in a quasi-steady experiment to explore stability boundaries. All stabilizing methods, such as flux conserver shaping, fast ion components, flow shear, and toroidal field contributions should be made available. γ_d drops below unity for the rather modest scale-up from TCSU described in our 15-page submission.

4. **FRC Configuration:** In both theta-pinch formed translated non-sustained FRCs and RMF sustained FRCs small toroidal fields have been seen to develop. These have led to minor

improvements in FRC flux lifetime, or effective anomalous resitivity. Small toroidal fields put in RMF sustained FRCs by using a central current carrying rod have led to factors of two improvement in RMF current generation. It is hard to say if any FRCs have exactly $B_t = 0$.

5. **Stability:** The best way to address the large *s* stability issue is to gradually increase *s* in a sustained FRC. The requirements to address this issue are given in answer #3.

6. **Confinement:** RMF has been calculated to confine particles despite transient opening of the field lines, so the main worry is electron conduction along transiently open field lines. Odd parity drive has been calculated to keep field lines closed, as long as the configuration is kept very symmetric, which is the main issue. Partial penetration, as occurs in all large FRC and rotamak facilities, greatly reduces this concern since the radial component of the RMF is small. Also, for RMF to be effective its magnitude must be very small compared to the poloidal confinement field, which also greatly reduces any field opening effect. Experiments performed to date have shown odd-parity drive to be equally effective in driving current or sustaining FRC flux, so its use on low *s* FRCs is just as well developed as even parity drive. Since low *s* FRCs have little internal confinement their temperatures tend to be limited by radiation and convection along the low density edge-layer. The true utility of odd-parity drive in limiting interior thermal conduction can only be tested in a larger *s* facility of the type outlined in our 15-pager, but calculations of field-line closure are very encouraging.

   Large edge currents are seen in all theta-pinch formed FRCs since $x_s \equiv r_s/r_c$ is usually under 0.5, and $\langle\beta\rangle = 1 - x_s^2/2$ is large, producing high separatrix densities and large electron drift speeds. RMF sustained FRCs have $x_s \sim 0.9$ and much lower separatrix densities, producing larger scale lengths and lower electron drift speeds. However, if RMF frequencies must be kept high (a desirable scaling is $\omega \propto 1/r_s^2$) for other reasons, then high edge drift speeds may be a concern. It is important to determine how low an RMF frequency can be used (it also makes the technology simpler). A facility with widely variable RMF frequency can address these issues.

   NBI could lead to beam-driven instabilities, as were seen in pure ion rings. The physics will be different inside an FRC, so the question is how much of the toroidal current can be carried by the beam. (A large private effort is directed toward aneutronic beam fusion inside an FRC.) Both more detailed numerical calculations (already being done) and experiments in a large, quasi-steady (lifetime well exceeding the beam slowing-down time) FRC can address this issue.

7. **Aneutronic Fuels:** Aneutronic fuels may be considered as the ultimate long-range application for fusion. FRCs, due to their high beta, would be the most suitable configuration for utilizing fuels requiring high plasma temperatures. Several researchers have been, or are presently greatly interested in FRCs because of this ability, and a large private effort has been started devoted to such a fusion system. Most FRC researchers think that the next step goals and required research efforts are independent of ultimate fusion fuel, but there is at least one disagreement.

8. **Scientific Roadmap**: The only way to answer these questions is in a next-step experiment. It is impossible to reach large s in present quasi-steady facilities with reasonable ion temperatures. There have been many indications of FRC stability, and high-β minimum energy states in present experiments and all methods contributing to such stability should be explored. The main justification for a next-step facility is the wealth of methods than can explored in a careful manner, and the huge benefits to be realized in physics knowledge and reactor attractiveness. The fact that such a facility can be built for the about the same cost (in inflation adjusted dollars) as the old LSX facility is testimony to the economic savings inherent in the CT approach to both development and final reactors.

   High s experiments are essential!

9. **Pulsed Approach**: In order to reach the same $n\tau_E \propto r_s^2 B_e^2 / D_\perp$ at a given temperature and $D_\perp$, the kinetic parameter $s \propto r_s B_e$ will be the same, so the stability requirements are similar. An advantage of the high density pulsed approach is that the required flux, $\phi_p \propto r_s^2 B_e$, will be lower, and a possibility that the transport coefficients may be lower. However, it would require $D_\perp \sim 0.01$ m^2/sec to bring s values into the ~4 regime where FRCs have been currently observed to be stable, and there is no evidence of such low transport (based on flux lifetime measurements) in the high density FRXL experiments. Still, the low density steady-state FRCs presently produced require a greater reduction in $D_\perp = \langle \eta_\perp / \mu_o \rangle$ than the theta-pinch formed high density FRCs to get to reasonable values of 0.5 m^2/s. An alternate application of FRCs for fission-fusion could operate with lower values of $n\tau_E$ and s, and the pulsed approach could find better application here due to the lower required flux values.

Concept Key Parameters (Steady-State Version)

Parameter	**Present value†**	**ITER-era Goals***	**Reactor Target**
Confining Field[a] (T)	0.03	0.12 – 0.5	1.8
Plasma current[b] (MA)	0.1	1 - 4	5 - 25
Pulse length Δt (sec) and $\Delta t/\tau_E$	0.01 / 75	0.1 / 20	∞ / ∞/2
External sustainment/current drive type	RMF	RMF TNBI	+ fusion products
External sustainment/current drive power[‡] (MW)	2	5	10 - 50
Current drive efficiency (η) (A/W)	0.05	0.25 – 1.0	0.5
Major Radius[c] (m)	0.25	0.65	1.5
Minor Radius[c] (m)	0.10	0.27	0.62
Elongation (κ)	4	4	0.8 - 4
Central density n_e (10^{20} m^{-3})	0.1	0.3 – 1.2	4
Central T_e or $\langle T_e \rangle$ (keV)	0.2	0.65 – 2.5	10
Central T_i or $\langle T_i \rangle$ (keV)	~ 0.05	0.65 – 2.5	10
Average beta	0.6	0.6	0.6
Energy confinement timed (s)	0.000150	0.005 – 0.025	2
Fusion power density $B\tau_E$ (T-s)	$5x10^{-6}$	10^{-3} – 0.025	3.6
Core electron transport[d] (χ_e m^2/s)	~ 20	~ 5 - 1	0.5
Core ion transportd (χ_i m^2/s)	?	~ 5 - 1	0.5
$\rho^* = \rho_D /a$ or $S_D = L^*/ \rho_D$			
$S_\alpha=L^*/ \rho_\alpha$			
Collisionality (ν^*)			
Normalized pulse length (τ/τ_r)[#]			
Normalized pulse length ($\tau/\tau_{Ti=Te}$)[#]	75	20	∞
Estimated Fusion Power (MW)			200 - 1000
Estimated wall loading (MW/m^2)			10
Estimated plasma exhaust power (MW/m^2)			1

*The ITER era goals contain near-term and far-term values, depending on the plasma resitivity. The reactor target contains values for an oblate and a prolate CT. If the wall loading is too high the radius can be made larger and the magnetic field and density lower.