

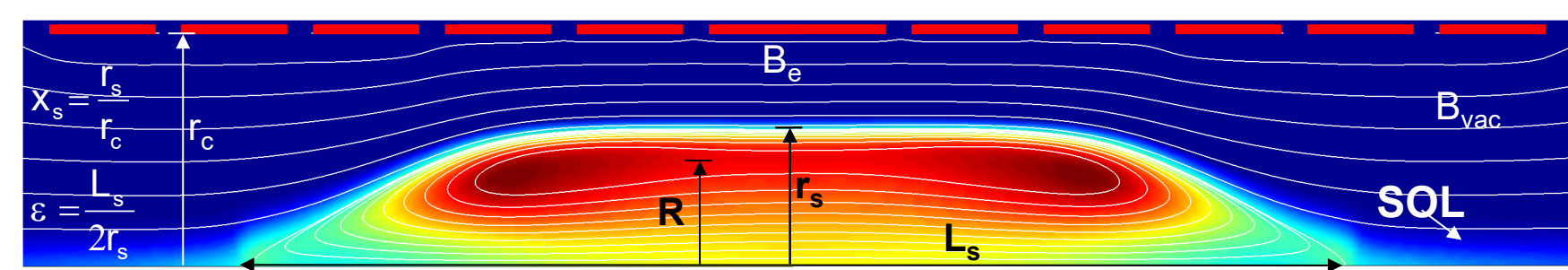
A Compact Fusion Reactor Based on the Staged Compression of an FRC

Description and Background

A new methodology for achieving the formation and compressional heating of a Field Reversed Configuration (FRC) plasmoid has been investigated both theoretically and experimentally at the University of Washington and MSNW [1]. The essential components of the Compact FRC Fusion Reactor (CFR2) staged compression method for achieving high fusion gain are a combination of high ion temperature, a steady FRC translation at subsonic velocity (100-150 km/s), along with small incremental radius reductions employing adiabatic and isentropic radial compression only. This method does appear to preclude the approach previously proposed by the author where supersonic merging was employed for compression and heating. This approach, however, avoids the catastrophic flux loss that occurs during the simultaneous acceleration and compression phase, as well as the adverse aspects of flux compression of the resultant merged FRCs needed to reach fusion temperatures. Also, with the CFR2 being a single-ended device, it makes possible a travelling fusion burn minimizing first wall thermal loading issues. With no need for flux compression in the burn chamber, a much more robust first wall can be employed providing for a close-fitting flux conservator at the maximum confining fields. It also provides a straightforward way to recover some of the remnant energy from the FRC in a remote chamber at termination. This approach, based on previous FRC empirical scaling, is expected to achieve fusion gain as large as 10. For the FRC, the fusion gain, $G \sim \phi_p B_e^2$ where ϕ_p is the FRC poloidal flux and B_e the confining axial magnetic field. G is essentially independent of the FRC radial scale making feasible a small, compact reactor. The necessary ϕ_p (> 60 mWb) is achieved by employing a large formation chamber (~ 0.8 m radius) combined with the requisite axial magnetic field reversal time ($E_\theta \sim 20$ kV/m) for generating a high initial temperature ($T_i > 1$ keV) FRC. By employing the dynamic formation procedure [2], the FRC is accelerated to ~100-150 km/s as it is formed. This subsonic velocity is maintained as the FRC is translated through a series of cylindrical coils of decreasing radius but of sufficient length (> L_{FRC}) and number (~ 10) to produce essentially an isentropic and adiabatic radial wall-compression of the equilibrium FRC. The final stage is a 12 cm diameter, 3-6 m long confinement and burn chamber with a vacuum field of 7-9 T produced by external solenoidal coils inside the flux conserving cylinder. The vacuum field is compressed by the FRC on insertion to 35 T resulting in fusion gain conditions for the 2-5 ms transit. The large ratio of FRC to inner wall radius (0.85) substantially lowers the FRC edge pressure thereby greatly reducing both particle and thermal losses. The resulting D-T fusion yield for the 3.5 MJ FRC is 20-40 MJ/pulse. The final ejection and expansion of the FRC into a large, low field mirror chamber provides a mechanism for FRC energy recovery. The experimental justification and the physics basis for the entire process from formation through burn of the Compact FRC Fusion Reactor (CFR2) concept is presented.

References:
[1] John Slough 2025 Nucl. Fusion **65** 106019
[2] Votroubek G., Slough J.T., Andreason S. and Pihl C. 2008 *J. Fusion Energy* **27** 123

Field Reversed Configuration (FRC) Magnetic Field lines and Pressure Contours



Key Equilibrium Relations:

$B_{ext} = \frac{B_{vac}}{1 - x_s^2}$

$P_0 = n_0 kT = \frac{B_{ext}^2}{2\mu_0}$

$\langle \beta \rangle = 1 - \frac{1}{2} x_s^2$

Flux Conservation
External measurements of B yield FRC separatrix radius $r_s(z)$, FRC length $L_s \Rightarrow$ volume, position, velocity

Radial Pressure Balance
Simple cross-tube interferometric measurement with r_s from yields $\langle n \rangle$ and T

Axial Pressure Balance
With above obtain plasma energy, Inventory, confinement times

FRC equilibrium constraints and the diagnostic measurements that together with the equilibrium relations that are employed to determine the basic parameters of the FRC

FRC Transport Scaling

Scaling based on Lower Hybrid (LHD) Drift :

$$\tau_N \sim \frac{r_s^2}{\rho_i} \quad (\text{first observed in LANL FRX Expts.})$$

From radial pressure balance ($T_e = T_i$)

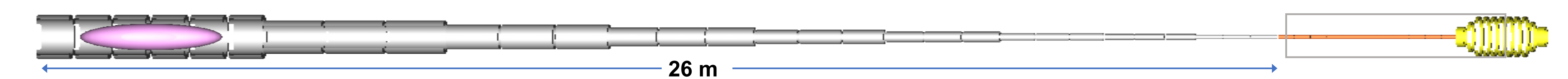
$$n_0 kT_i = \frac{B_e^2}{4\mu_0} \quad n_0^{1/2} \sim \frac{B_e}{T_i^{1/2}} \sim \frac{1}{\rho_i}$$

Restating: $\tau_N \sim n^{1/2} r_s^2$ **Note: Particle diffusion coef. depends only on n !**

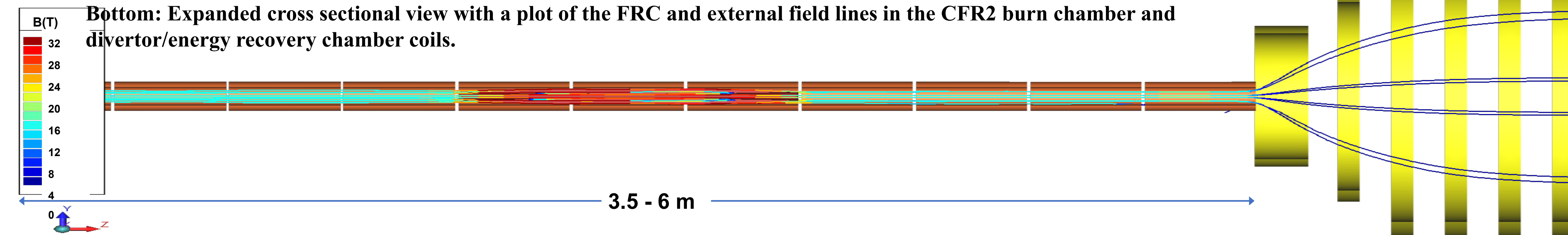
Empirical Scaling from LSX and other FRC experiments:

$$\tau_N = 4.8 \times 10^{-13} \epsilon^{1/2} x_s^{0.8} r_s^2 n^{1/2} \quad \text{for } 0.35 \leq x_s \leq 0.55 \quad \boxed{x_s = r_s/r_c \quad \epsilon = L_s/2r_s}$$

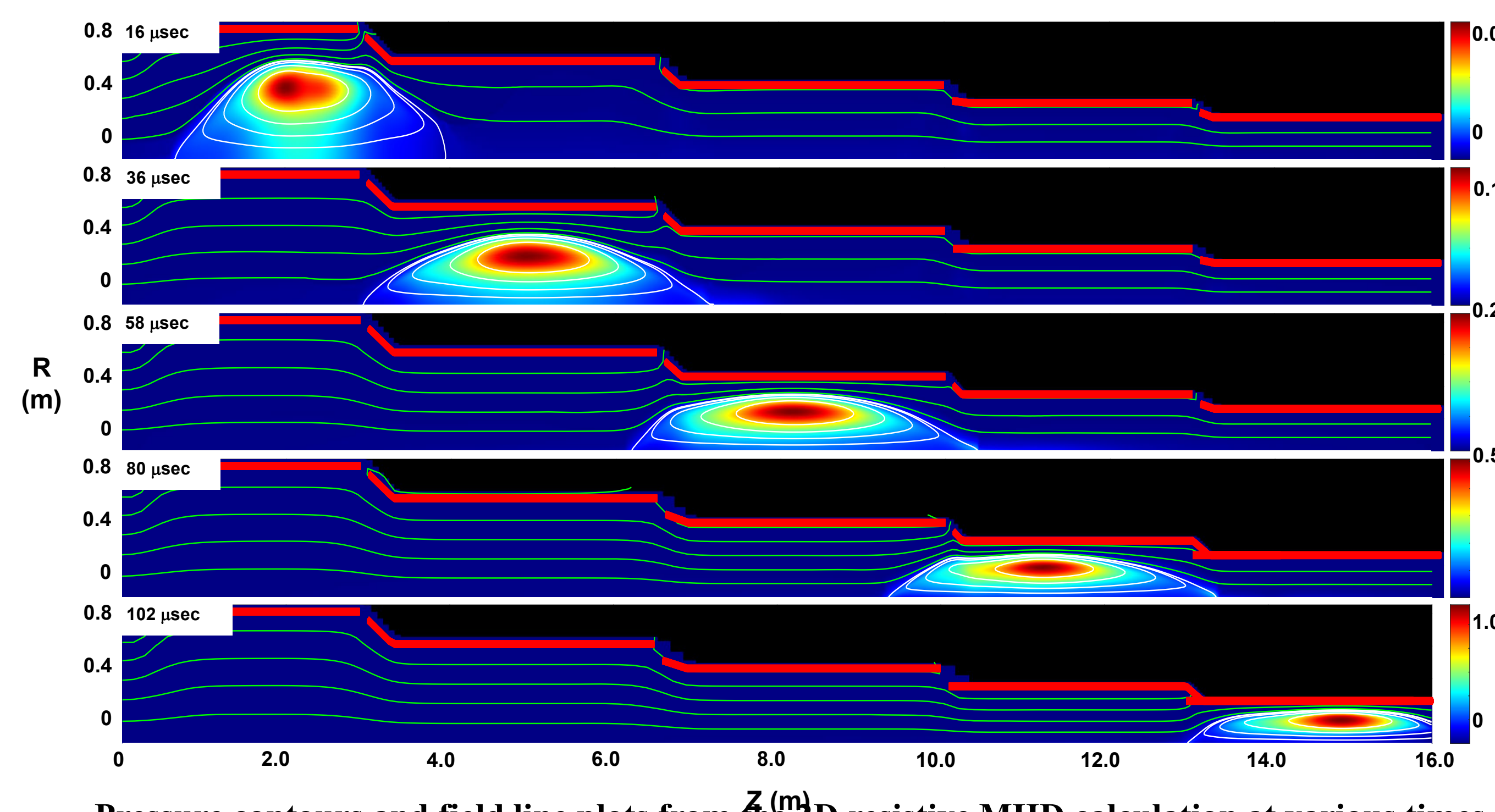
Consistent with the LHD Scaling



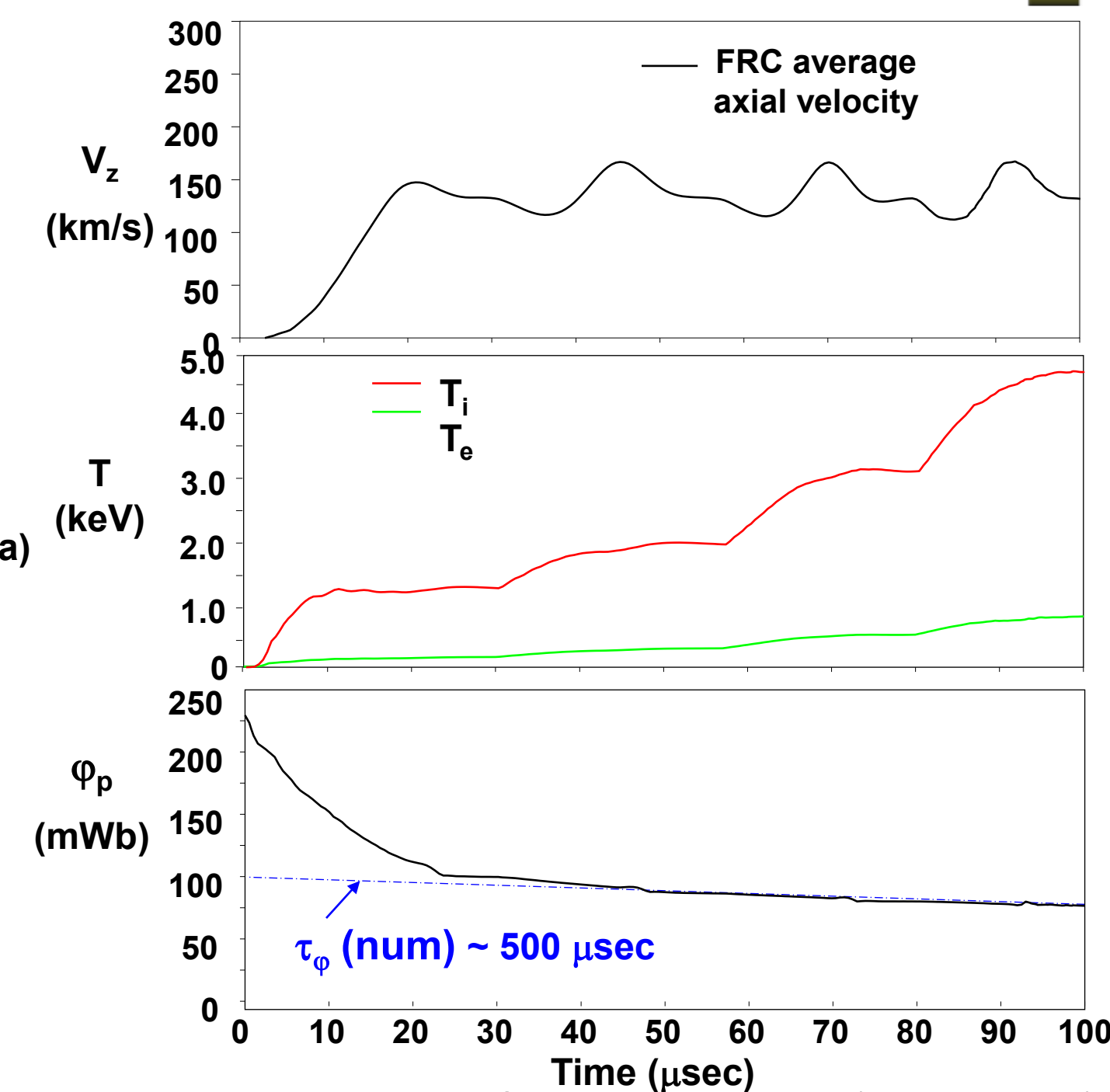
Top: The layout at scale of the CFR2 dynamic formation, staged compression, burn and divertor/energy recovery chamber.



Bottom: Expanded cross sectional view with a plot of the FRC and external field lines in the CFR2 burn chamber and divertor/energy recovery chamber coils.



Pressure contours and field line plots from the 2D resistive MHD calculation at various times during first five stages for the adiabatic wall compression of the FRC.



Temporal plots from the calculation shown in figure to the left for various key parameters

Fusion Gain Scaling Based on Past FRC Confinement

$$E_{fus} \approx 9 \times 10^{-13} n_0^2 \langle \sigma v \rangle \tau_N \langle \beta \rangle \text{Vol}_{FRC}$$

Fusion Collision cross section (7-13 keV):

$$\langle \sigma v \rangle \approx 1 \times 10^{-32} T^{5/2} \text{ (eV)}$$

Large x_s FRC scaling: $\tau_N = 1.9 \times 10^{-12} \epsilon^{1/2} x_s^5 r_s^2 n^{1/2}$

$$\Rightarrow E_{fus} \approx 1.67 \times 10^{-9} (n_0 k_B T_i)^{5/2} \langle \beta \rangle \epsilon^{1/2} x_s^5 r_s^2 \cdot \text{Vol}_{FRC}$$

$$\left(\frac{B_e^2}{4\mu_0} \right)^{5/2} \text{ for } T_e = T_i$$

FRC energy - also using radial pressure balance:

$$E_{FRC} = \frac{3}{2} n_0 k_B (T_e + T_i) \cdot \langle \beta \rangle \text{Vol}_{FRC} \approx \frac{3}{4\mu_0} B_e^2 \cdot \langle \beta \rangle \text{Vol}_{FRC}$$

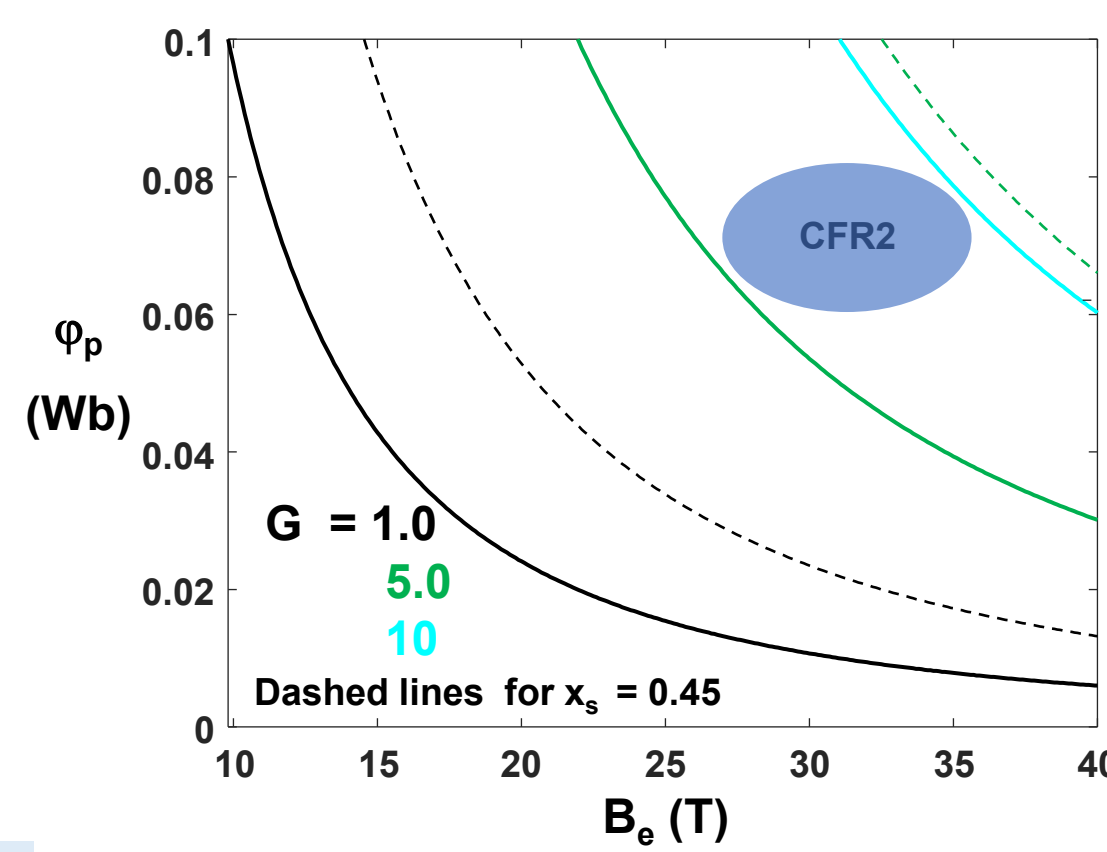
Fusion Gain G:

$$G = \frac{E_{fus}}{E_{FRC}} = 0.05 B_e^3 \epsilon^{1/2} x_s^5 r_s^2 = 0.05 B_e^2 \phi_p \epsilon^{1/2} x_s^4 \quad 0.8 \leq x_s \leq 0.95$$

$$G = 0.0126 B_e^3 \epsilon^{1/2} x_s^{0.8} r_s^2 = 0.0126 B_e^2 \phi_p \epsilon^{1/2} x_s^{0.2} \quad 0.35 \leq x_s \leq 0.55$$

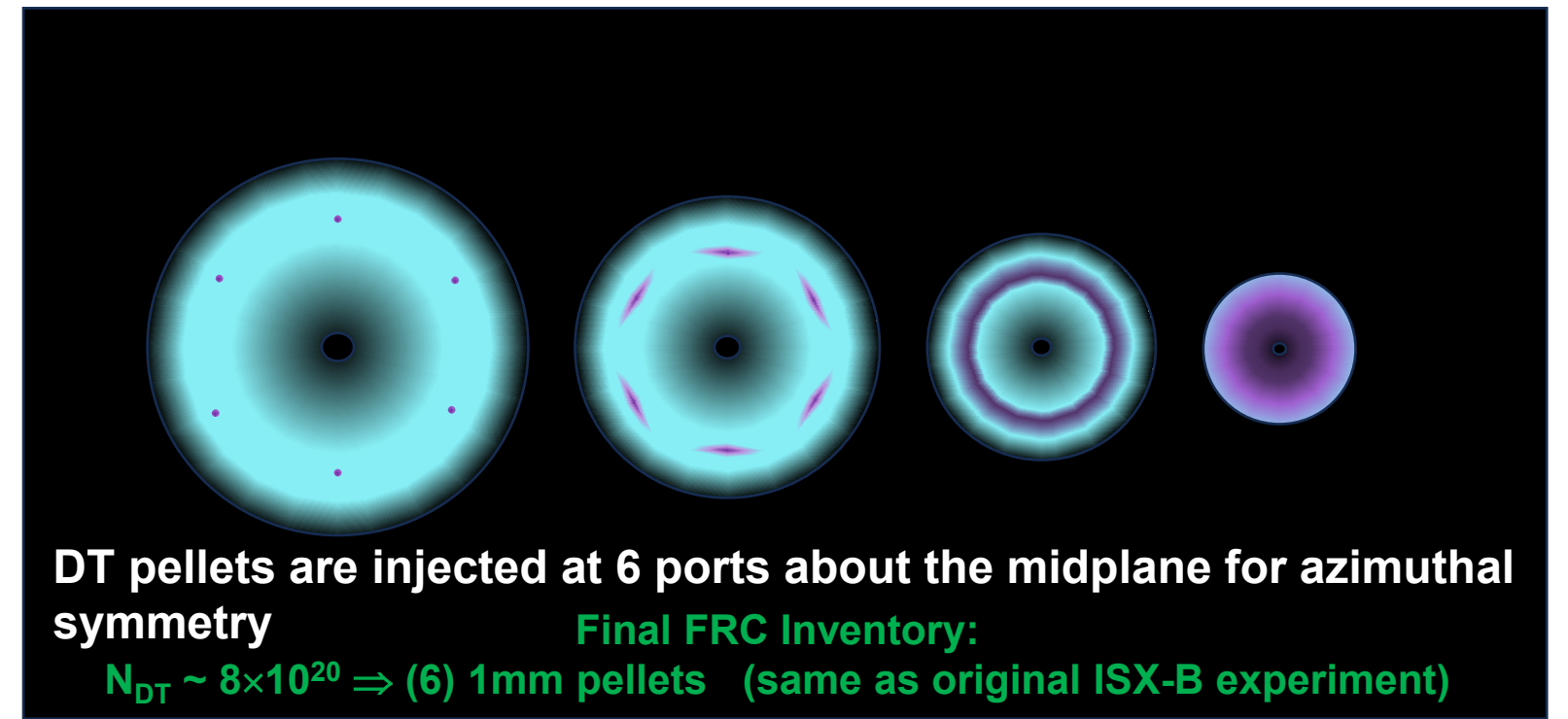
where $\phi_p \approx x_s r_s^2 B_e$ (Rigid Rotor profile)

For $x_s = 0.0.85$ and $\epsilon = 15$ $G = 0.1 B_e^2 \phi_p$



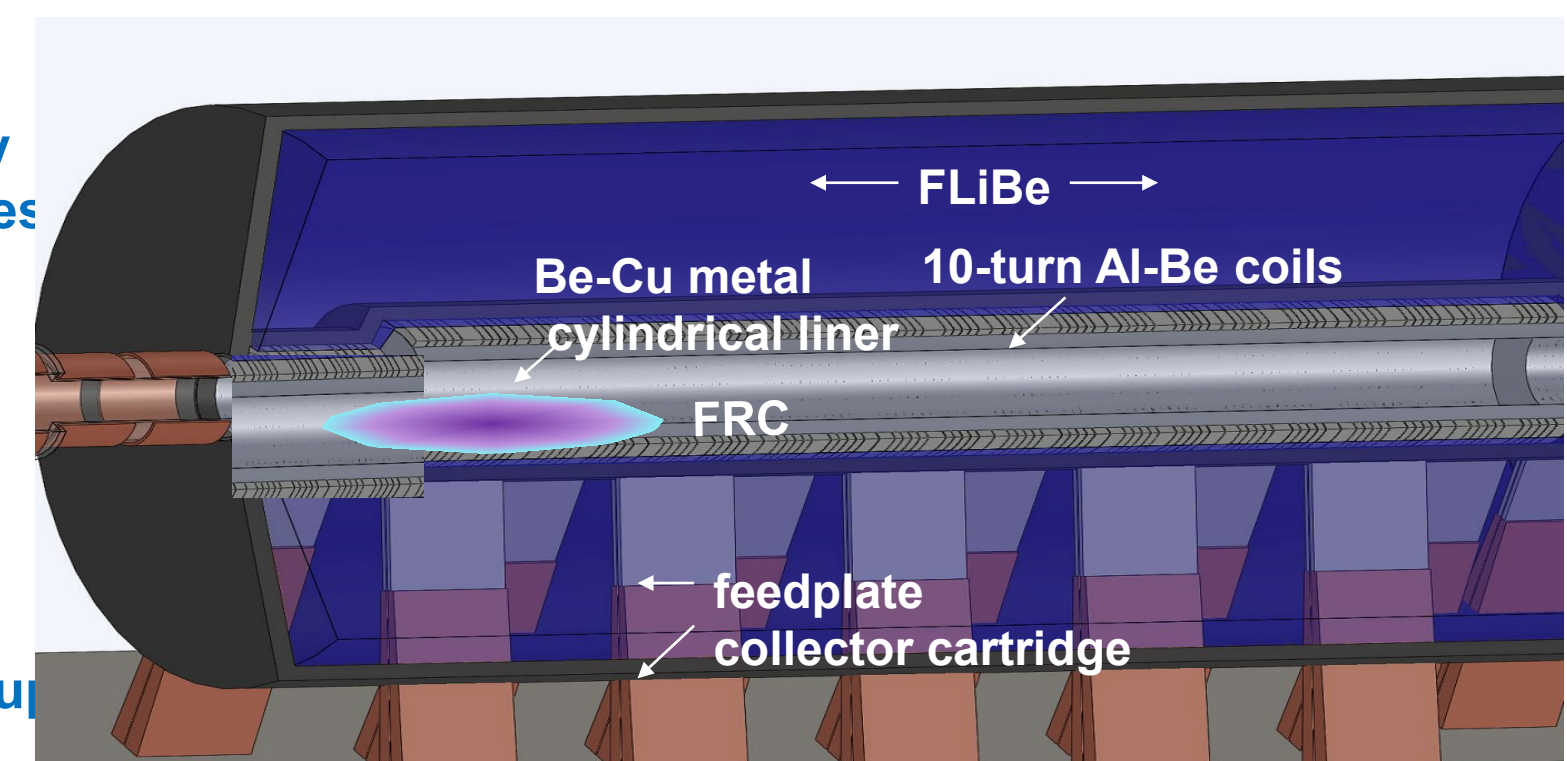
Gain contours as a function of the FRC poloidal flux and compression magnetic field for $x_s = 0.85$ ($\epsilon = 15$).

DT Pellet Fueling During Final Compression Stages of the FRC



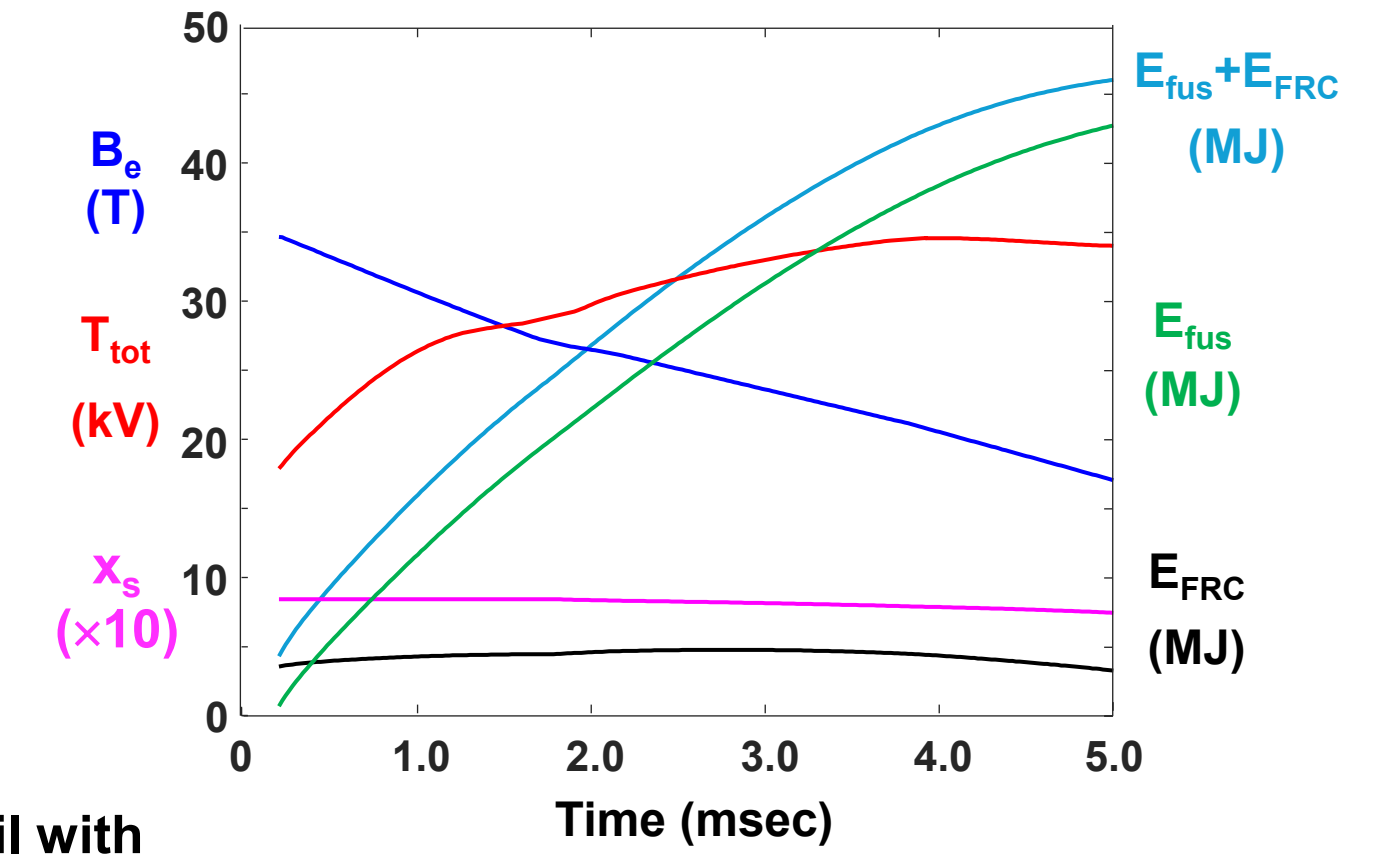
- DT Pellet fueling brings high-flux, low density RMF FRC to high density
- Pellet inward radial velocity is matched to that of the bands (~ 2 km/sec)
- Ablation thus occurs primarily at FRC null region $\Rightarrow$

- FLiBe has a high resistivity (> 10^6 Beryllium) - eliminates problem of an insulating solenoid coating
- Good breeding potential (breeding ratio 1.27 even without a multiplier)
- With the Al-Be coil as multiplier a breeding ratio up to 2 are feasible

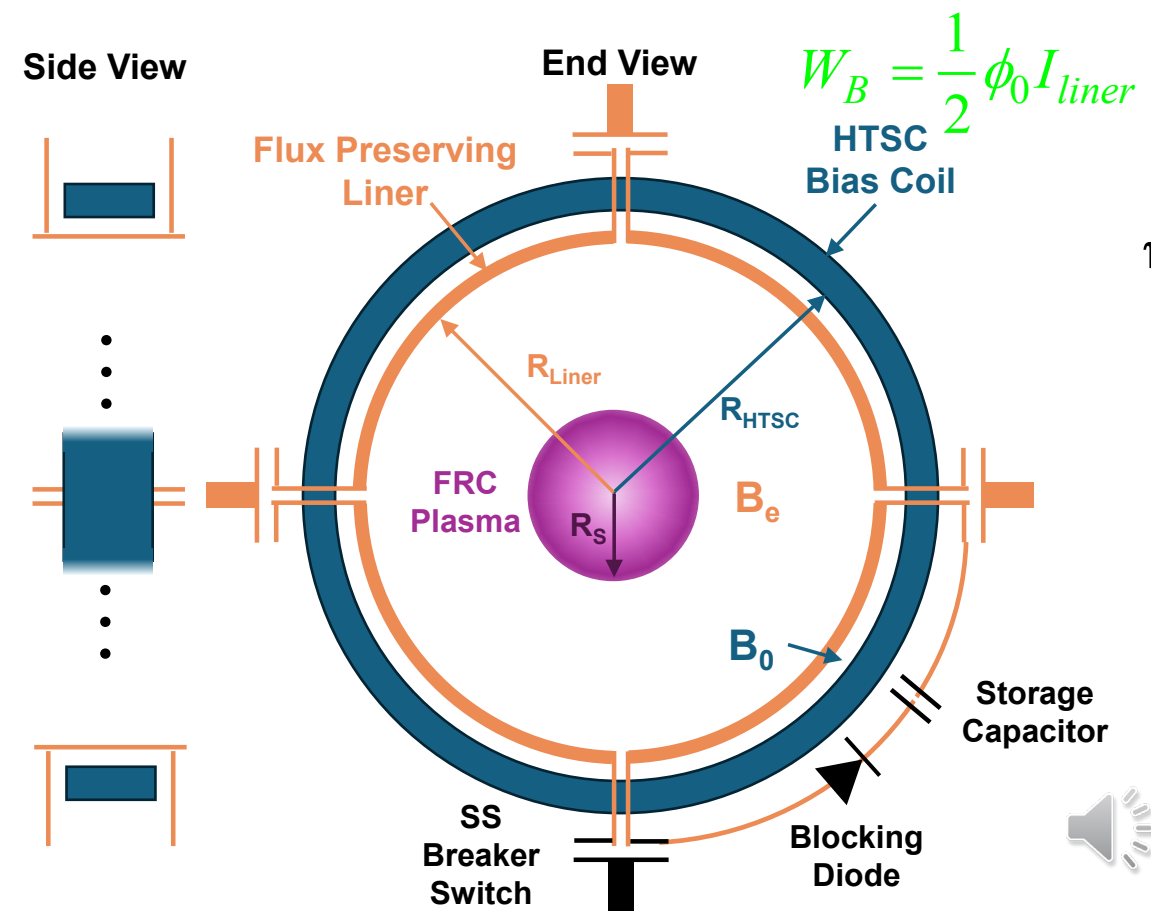
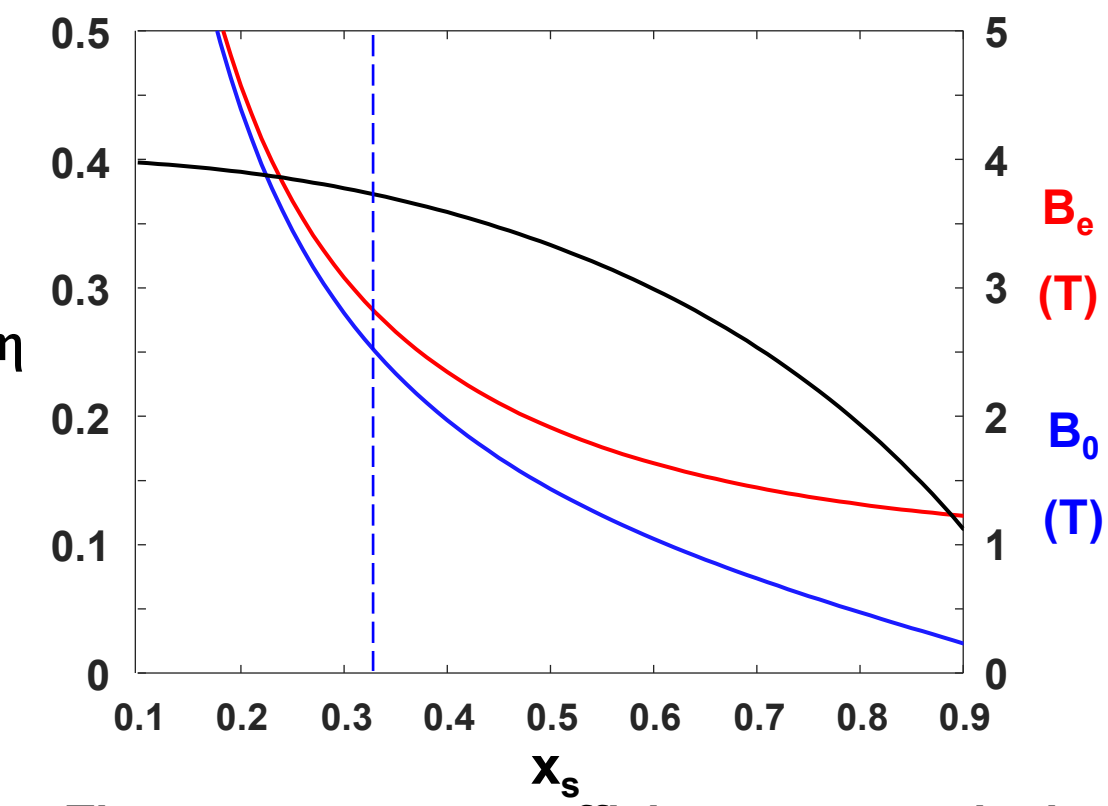


- ❖ The Al-Be metal solenoid coils (80% Be) undergo only a 6-8 T B field.
- ❖ The ~ 12 cm ID x 3+ m long cylindrical first wall experiences a transient field pressure of ~25 T (0.3 GPa) due to FRC compression
- ❖ This is well below the yield strength of Be-Cu alloy 25 (1.2 GPa)

Temporal evolution of key energy and plasma parameters during the fusion burn in CFR2.



A schematic of an ERC coil with encompassing liner and recovery circuitry.



The energy recovery efficiency, η , vs x_s in the ERC chamber along with initial bias, B_0 , and final external B_e after FRC insertion. Dashed line is $x_s = 0.33$ implying $\eta = 0.38$