New Approach to Achieving Fusion Ignition at Small-Scale:

Fusion Reactor Based on the Inductively Driven Wall Compression (IDWC) of FRC

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IDWC of the FRC provides

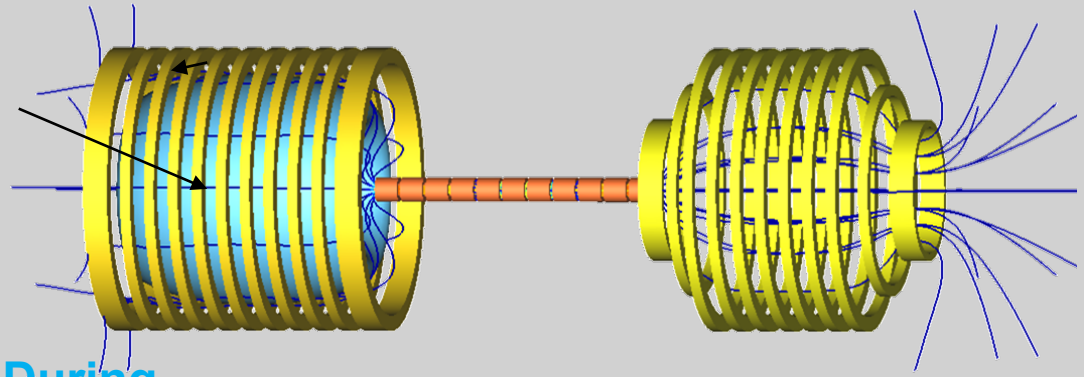
- Remote burn in ideal breeding geometry
- Greatly simplified PFC management readily replaceable cylindrical tube
- Direct, high efficiency heating to fusion temps (~ 90% electrical to thermal)
- Small, compact fusion maximizes surface to volume ⇒ higher power density

Key IDWC Physics :

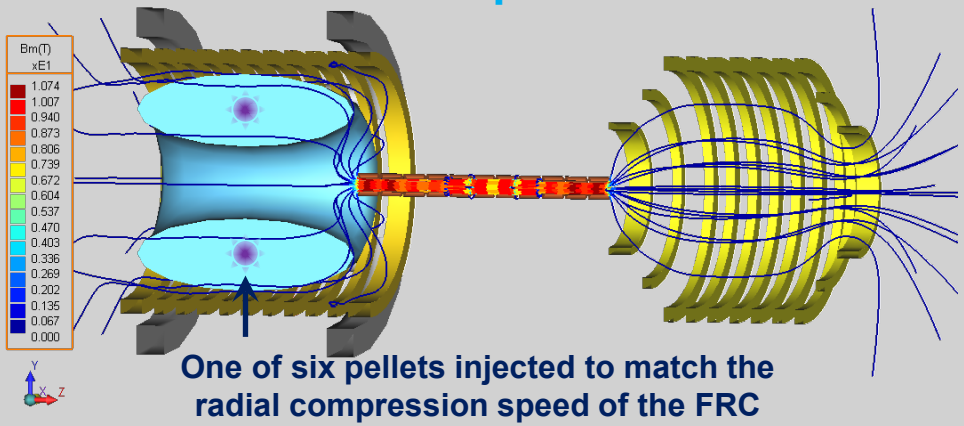
- ✓ Kinetic stability expected from formation through fusion burn
- ✓ Observed transport scaling sufficient for Q > 5 even with $\tau = \tau_{LHD} \sim r^2 n^{1/2}$
- ✓ Magnetic field compression by Inductively driven bands is non-destructive
- ✓ Lithium bands remain solid throughout compression allowing for reuse
- ✓ Inductive band compression has been performed and validated at scale
- ✓ B Field compression well beyond the magnetic fields required (~ 200 T)

I. Formation and Injection of FRC into Compression Chamber

Large, High flux FRC:
r_s = 0.78 m
x_s ~ 0.9
B_e = 0.16 T

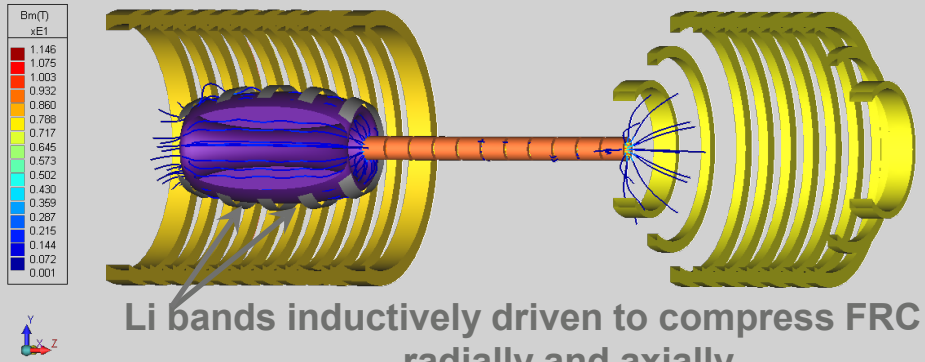


II. Radially injected D-T Pellet Fueling During FRC Compression



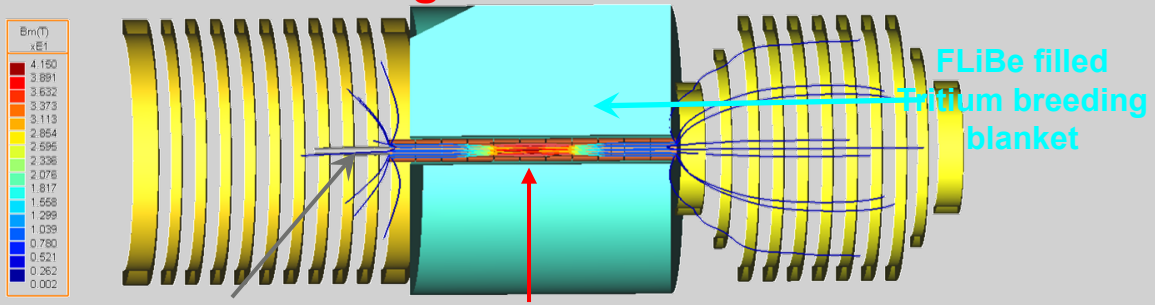
One of six pellets injected to match the radial compression speed of the FRC

III. Wall Compression of FRC with Radially and Axially Converging Lithium Bands



Li bands inductively driven to compress FRC both radially and axially
V_{band} ~ 2.5 km/sec

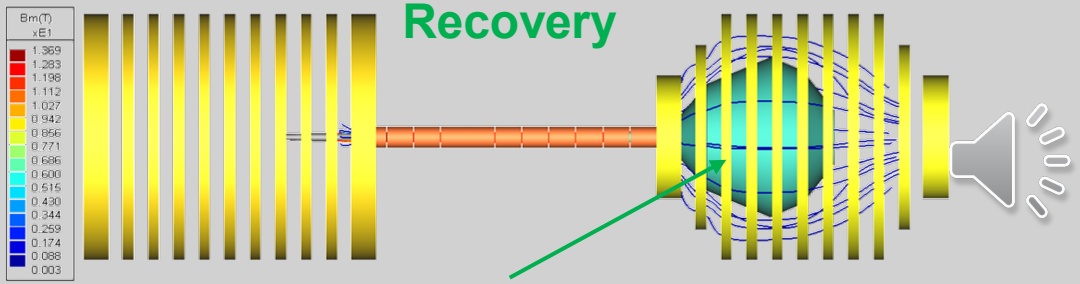
IV. Lithium Shell "Docking" at Burn Chamber With Drifting FRC Fusion Burn



Stationary Li bands assembled at entrance to burn chamber

FRC drifting inside 12 cm ID × 3 m burn chamber (foreshortened)

V. FRC Ejection and Energy Recovery



FRC at end of burn expanding into magnetized chamber for energy recovery

FRC Transport Scaling

Scaling based on Lower Hybrid (LHD) Drift :

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

From radial pressure balance: $\left(n_0 k T_i = \frac{B_e^2}{4\mu_0} \right)$ $n_0^{1/2} \sim \frac{B_e}{T_i^{1/2}} \sim \frac{1}{\rho_i}$

($T_e = T_i$)

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:

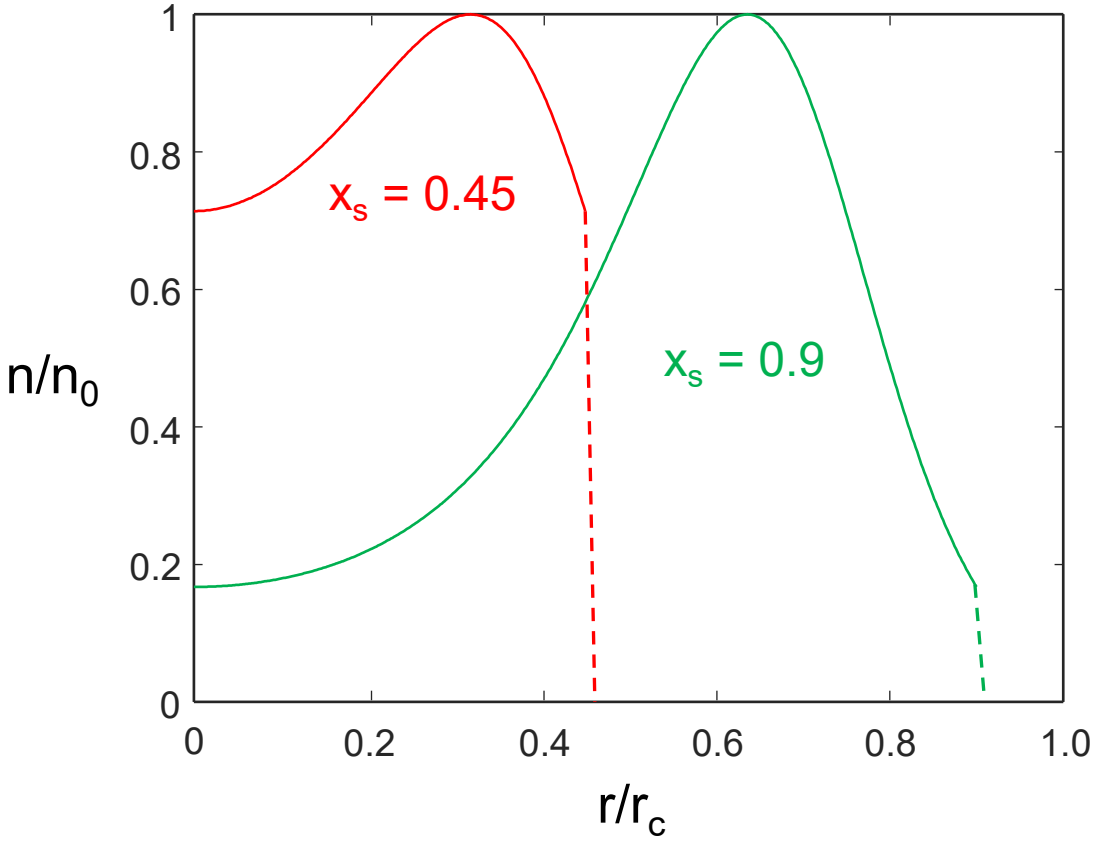
$$\tau_N = 4.8 \times 10^{-13}\, \varepsilon^{1/2}\, x_s^{0.8}\, r_s^2\, n^{1/2} \quad \text{for } 0.35 \le x_s \le 0.55$$

$x_s = r_s/r_c \quad \varepsilon = L_s/2r_s$

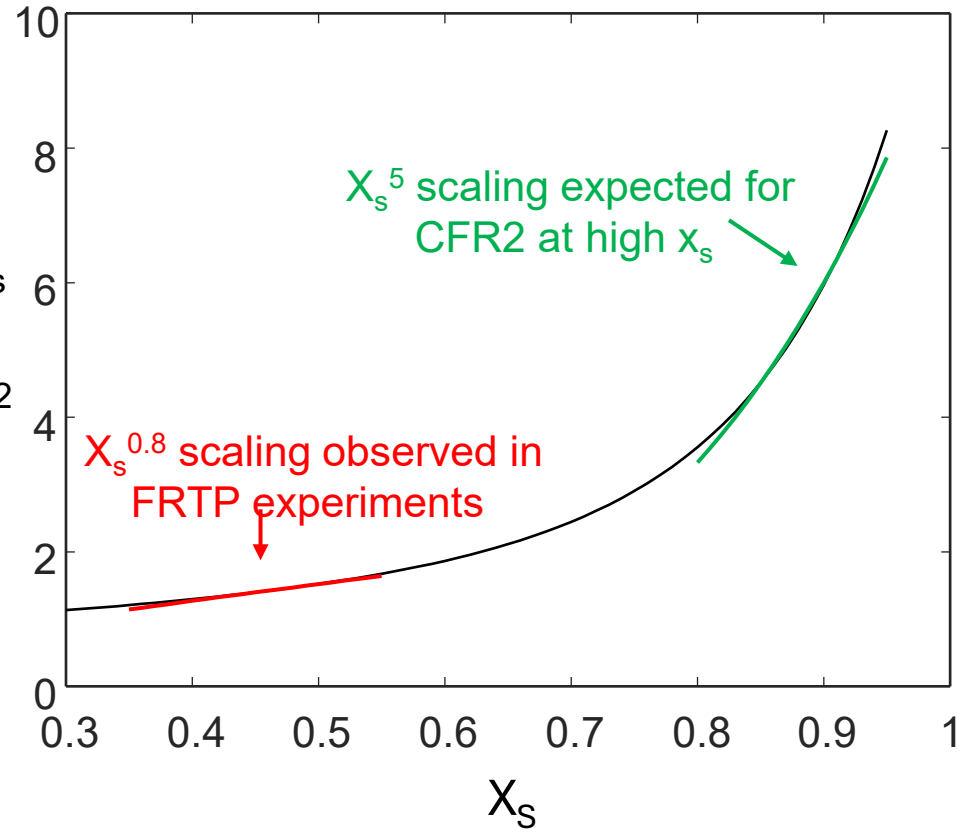
Consistent with the LHD Scaling

MSNW

Particle Confinement x_s Dependence Should Reflect Density Drop at Separatrix Density



$\tau_N \sim n_0/n_s$
=
$\cosh[Krr]^2$
(for RR)



$$\tau_N = 4.8\times10^{-13}\,\varepsilon^{1/2}\,x_s^{0.8}\,r_s^2\,n^{1/2} \quad \text{for } 0.35 \le x_s \le 0.55$$

$$\tau_N = 1.9\times10^{-12}\,\varepsilon^{1/2}\,x_s^{5}\,r_s^2\,n^{1/2} \quad \text{for } 0.85 \le x_s \le 0.95$$

Fusion Gain Scaling Based on Past FRC Confinement

$$E_{fus} \cong 9\times10^{-13}\, n_0^2 \langle\sigma v\rangle \tau_N \langle\beta\rangle Vol_{FRC}$$

Fusion Collision cross section (7-13 keV):

$$\langle\sigma v\rangle \cong 1\text{x}10^{-32}\, T_i^{5/2}\,(\text{eV})$$

Large x_s FRC scaling: $\tau_N = 1.9\times10^{-12}\,\varepsilon^{1/2}\, x_s^5\, r_s^2\, n^{1/2}$

$$\Rightarrow \quad E_{fus} \cong 1.67\times10^{-9}\underbrace{(n_0\, k_B T_i)}_{\left(\frac{B_e^2}{4\mu_0}\right)}^{5/2} \langle\beta\rangle \varepsilon^{1/2} x_s^5 r_s^2 \cdot Vol_{FRC} \quad \text{for } T_e = T_i$$

FRC energy - also using radial pressure balance:

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

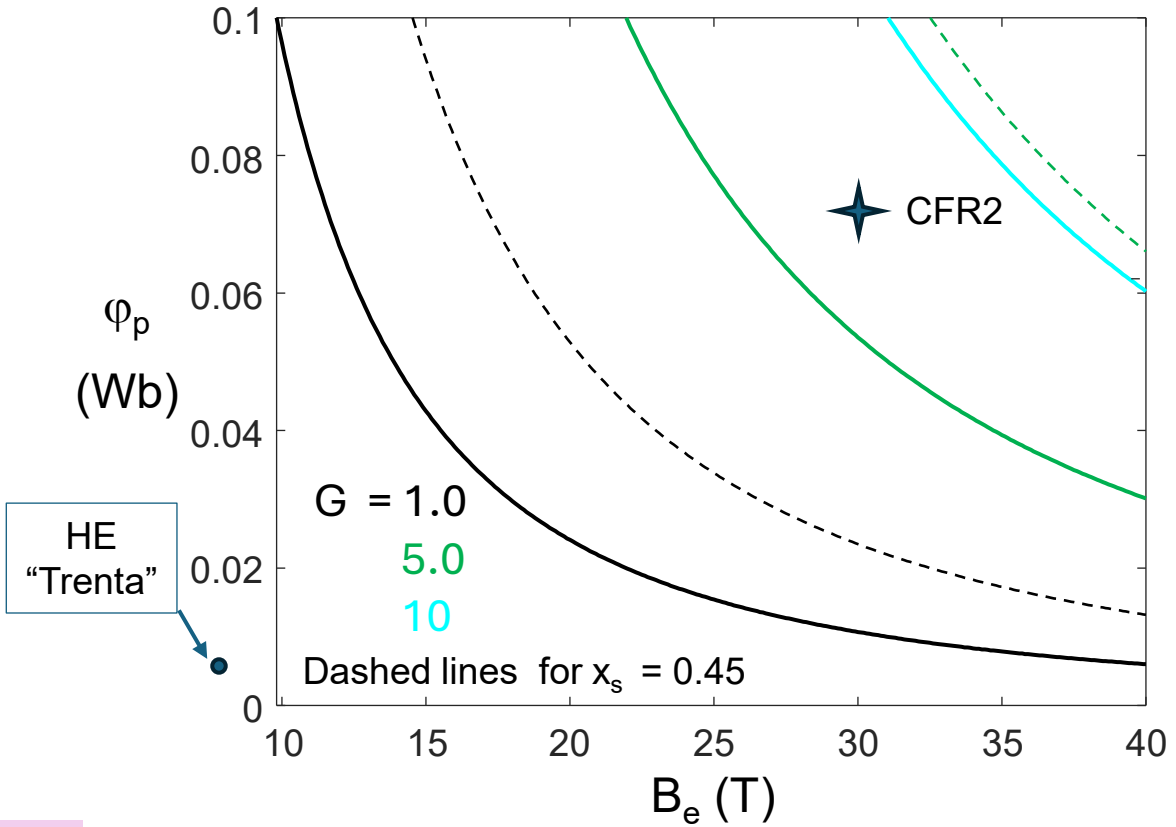
Fusion Gain G:

$$G = \frac{E_{fus}}{E_{FRC}} = 0.05\, B_e^3 \varepsilon^{1/2} x_s^5 r_s^2 = 0.05\, B_e^2 \varphi_p \varepsilon^{1/2} x_s^4 \qquad 0.8 \le x_s \le 0.95$$

$$G = 0.0126\, B_e^3 \varepsilon^{1/2} x_s^{0.8} r_s^2 = 0.0126\, B_e^2 \varphi_p \varepsilon^{1/2} x_s^{-0.2} \qquad 0.35 \le x_s \le 0.55$$

where $\varphi_p \cong x_s r_s^2 B_e$ (Rigid Rotor profile)

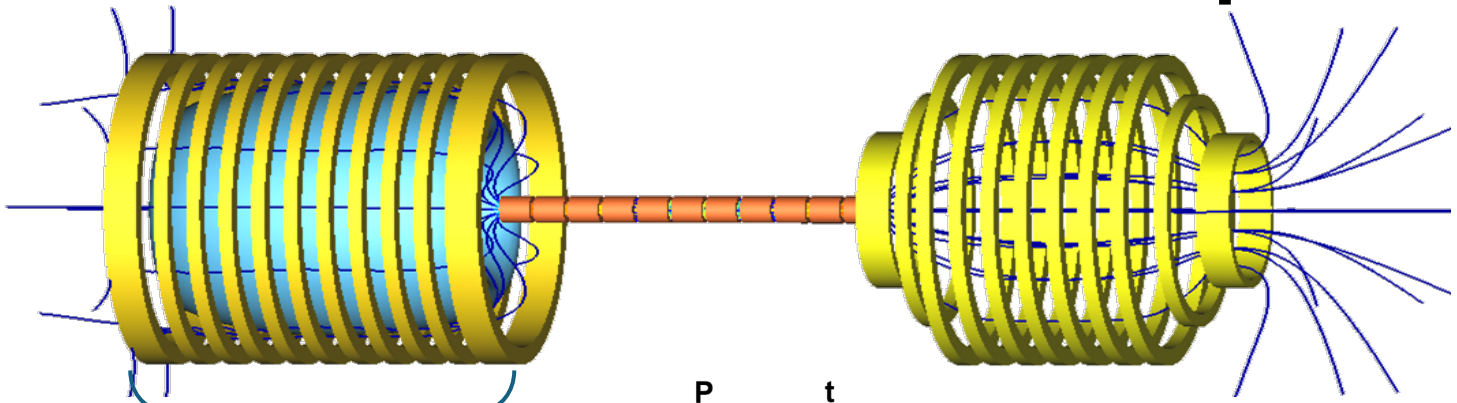
For $x_s = 0.9$ and $\varepsilon = 10$: $G = 0.1\, B_e^2 \varphi_p$



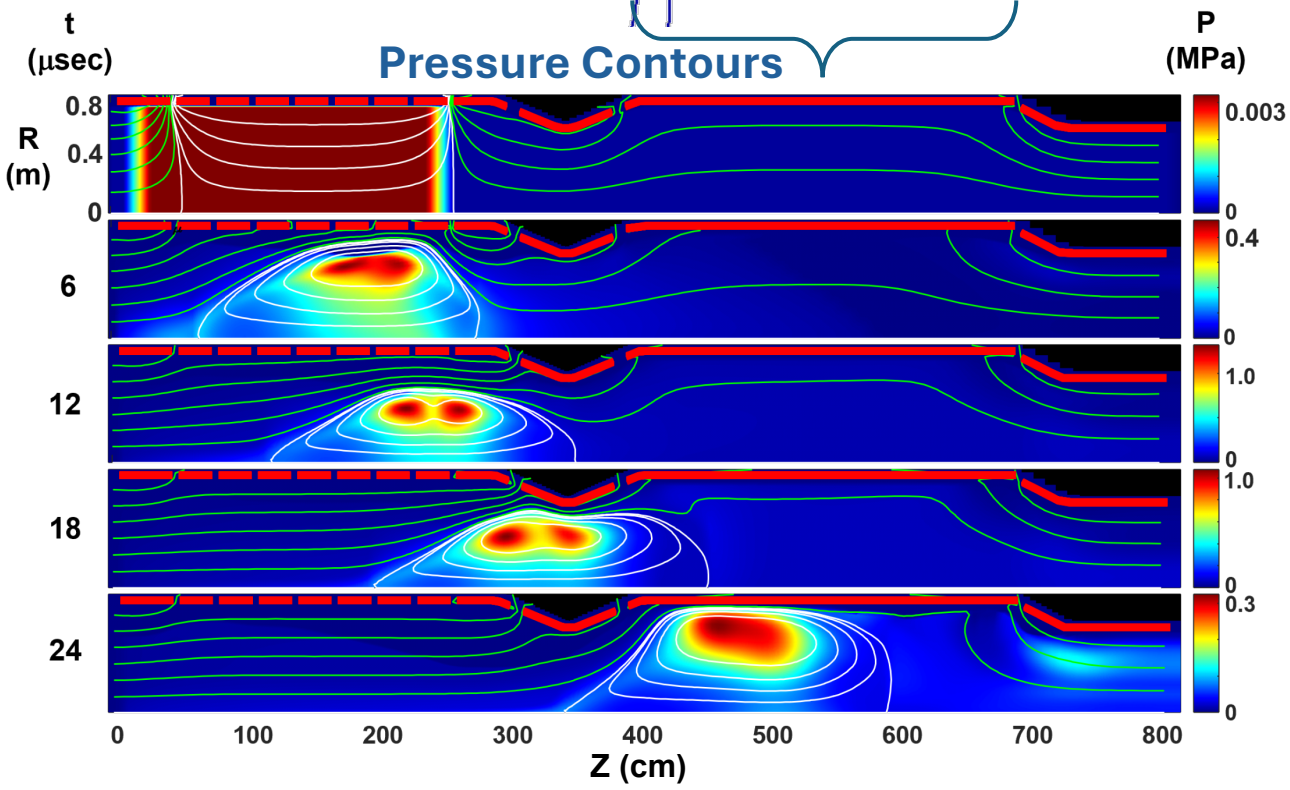
Gain contours as a function of the FRC poloidal flux and compression magnetic field for $x_s = 0.9$ ($\varepsilon = 10$).

No current or past FRC experiment would appear on this graph

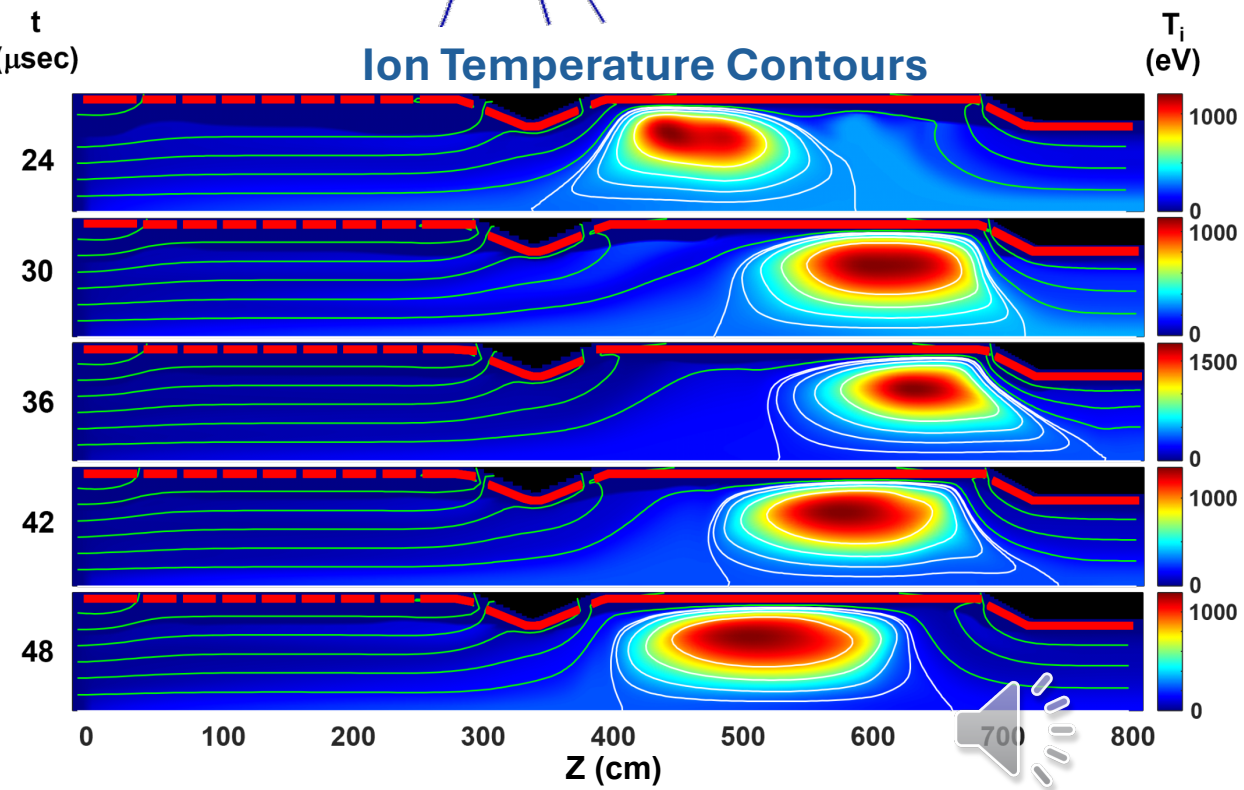
I. FRC Formation & Translation into Compression Chamber



Pressure Contours



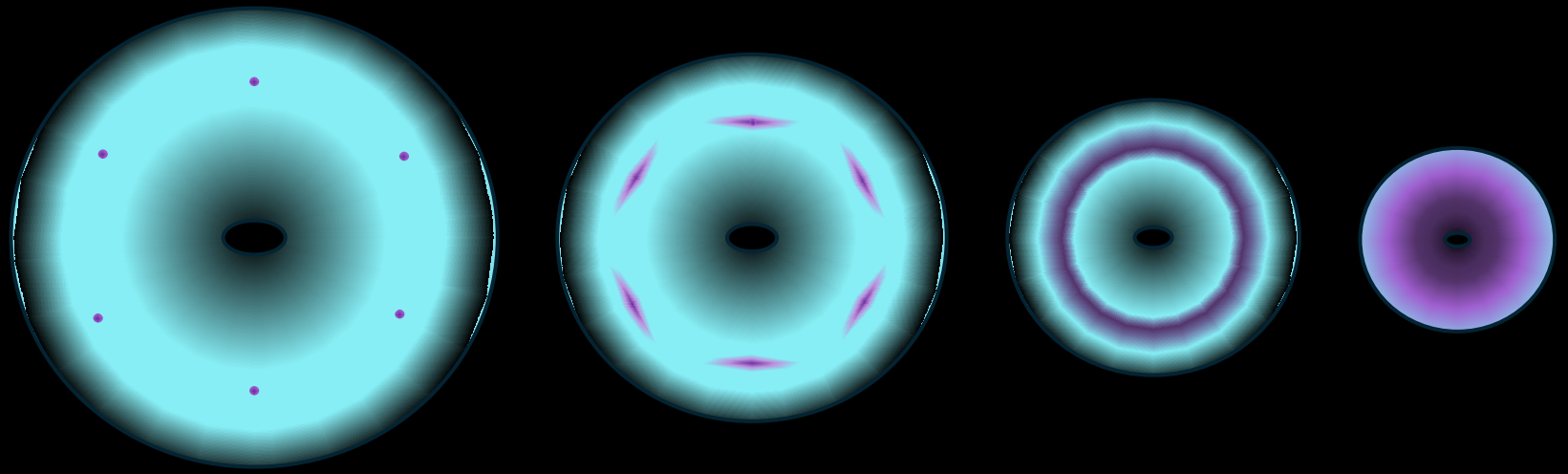
Ion Temperature Contours



Standard FRTP FRC formation but at large scale (R_c = 0.82 m) and low fill (1 mTorr D_2) for high T_i (> 1 keV) and final φ_p > 80 mWb

Step 2: DT Pellet Fueling During Band Compression of the FRC

Pellets are composed of frozen hydrogen isotopes (tritium and deuterium) and accelerated with light gases (H and He) to speeds up to 3 km/s



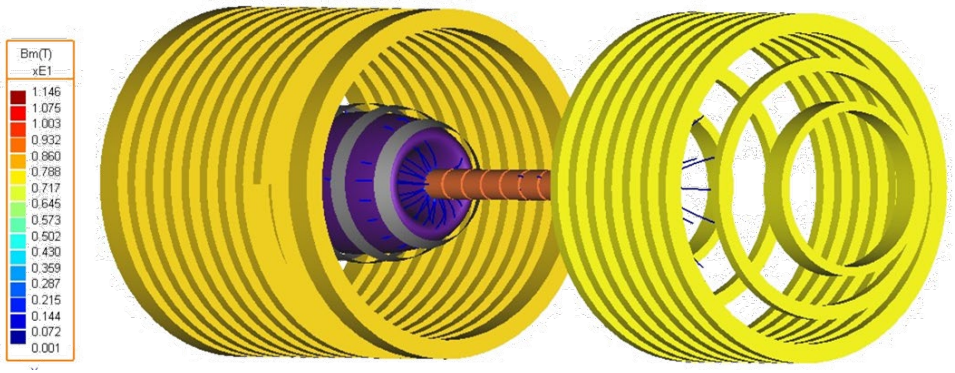
DT pellets are injected at 6 ports about the midplane for azimuthal symmetry

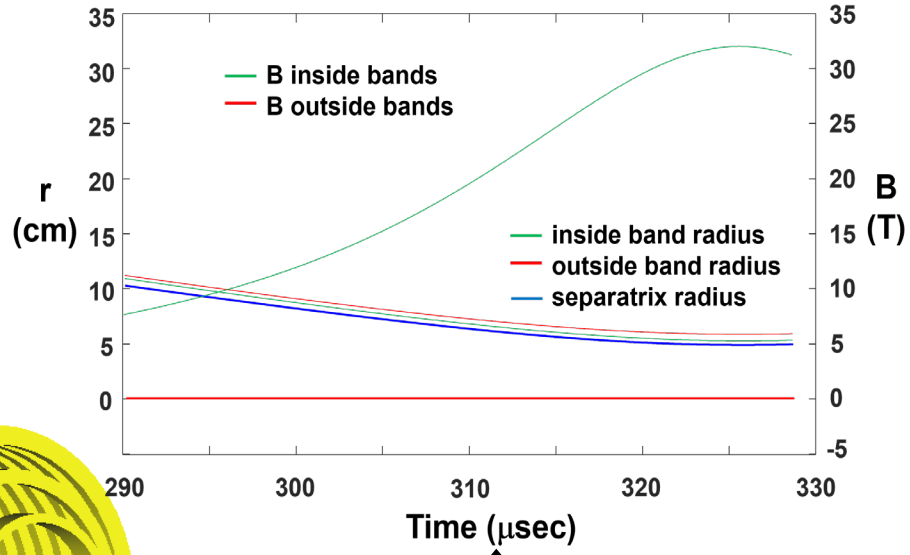
Final FRC Inventory:

$N_{DT} \sim 4\times10^{20} \Rightarrow$ (6) 1mm pellets (same as original ISX-B experiment)

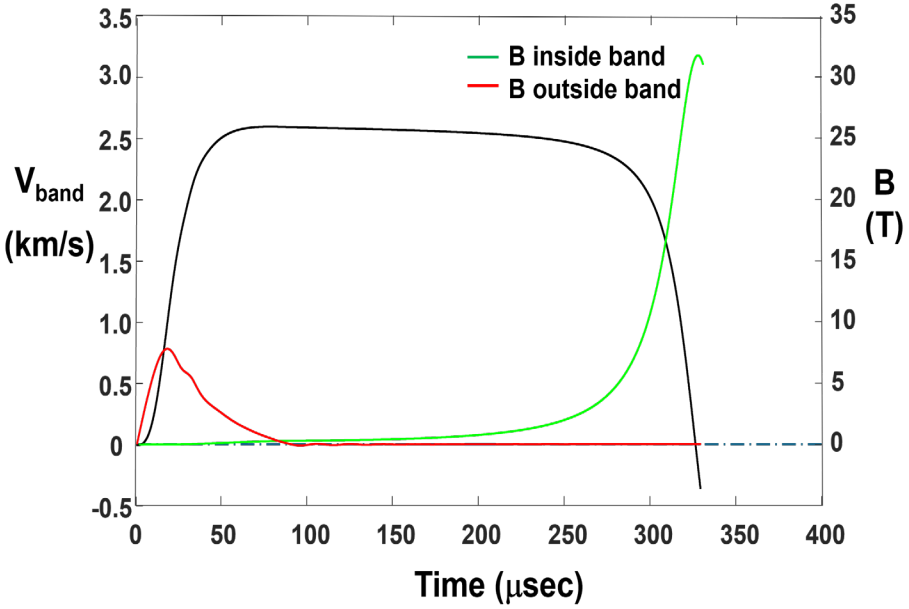
- DT Pellet fueling brings high-flux, low density RMF FRC to high density
- Pellet inward radial velocity is matched to that of the bands (~ 2 km/sec)
- Ablation thus occurs primarily at FRC null region ⇒

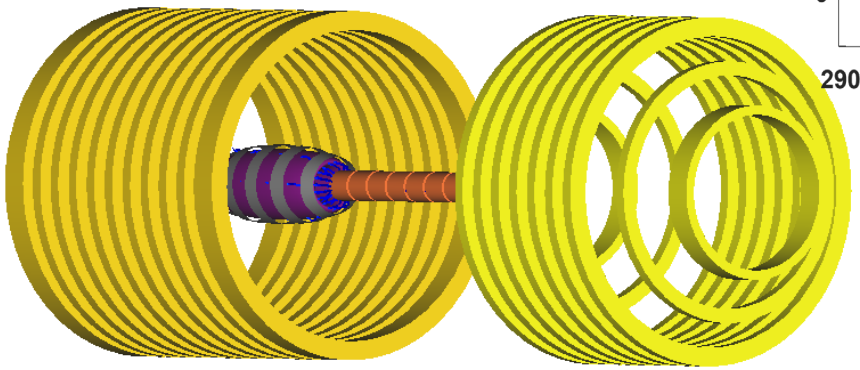
III. Wall Compression of FRC with Radially and Axially Converging Lithium Bands



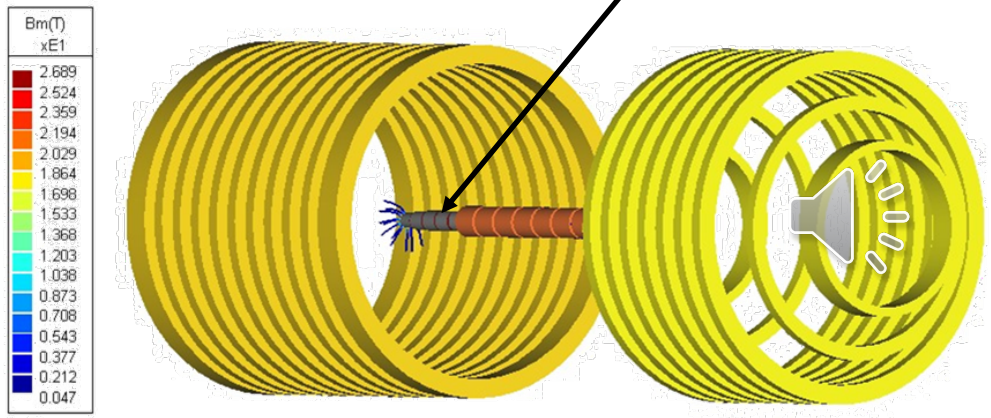


Results from 1D numerical code analysis with full electrical driver circuit

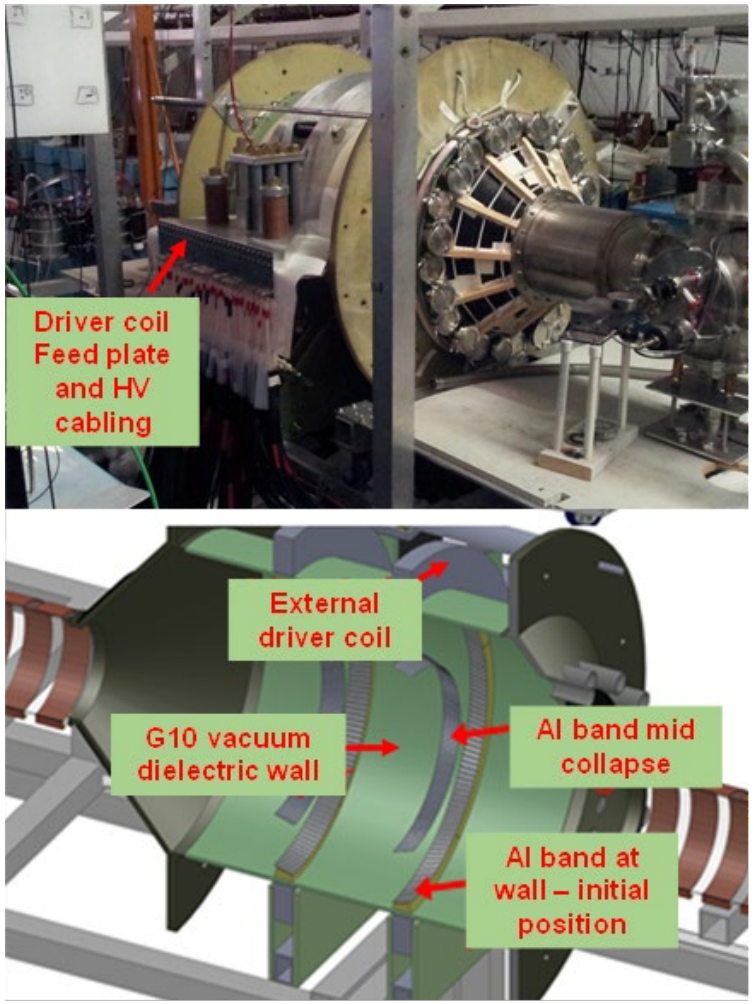




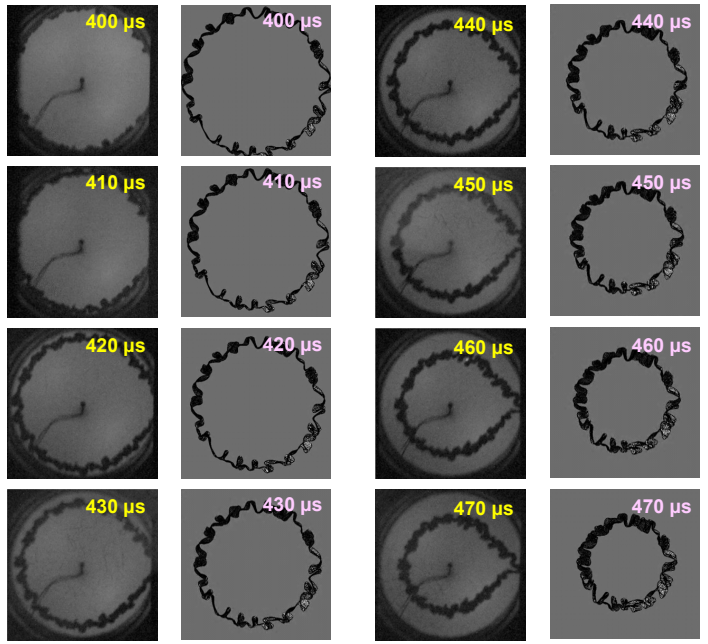
80 cm band parameters near full compression



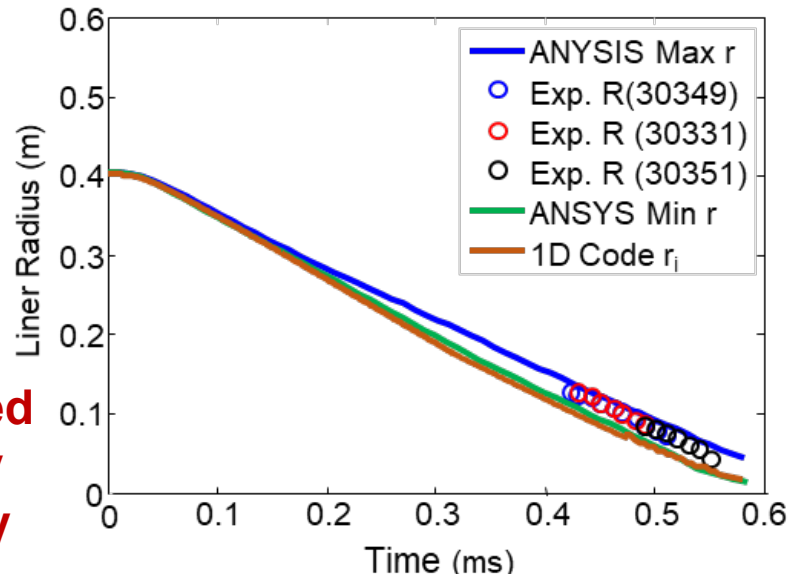
Experimental Validation of the Large-Scale Band Compression Method



Large scale metal band compression test bed for FDR validation experiments at University of Washington Plasma Dynamics Laboratory

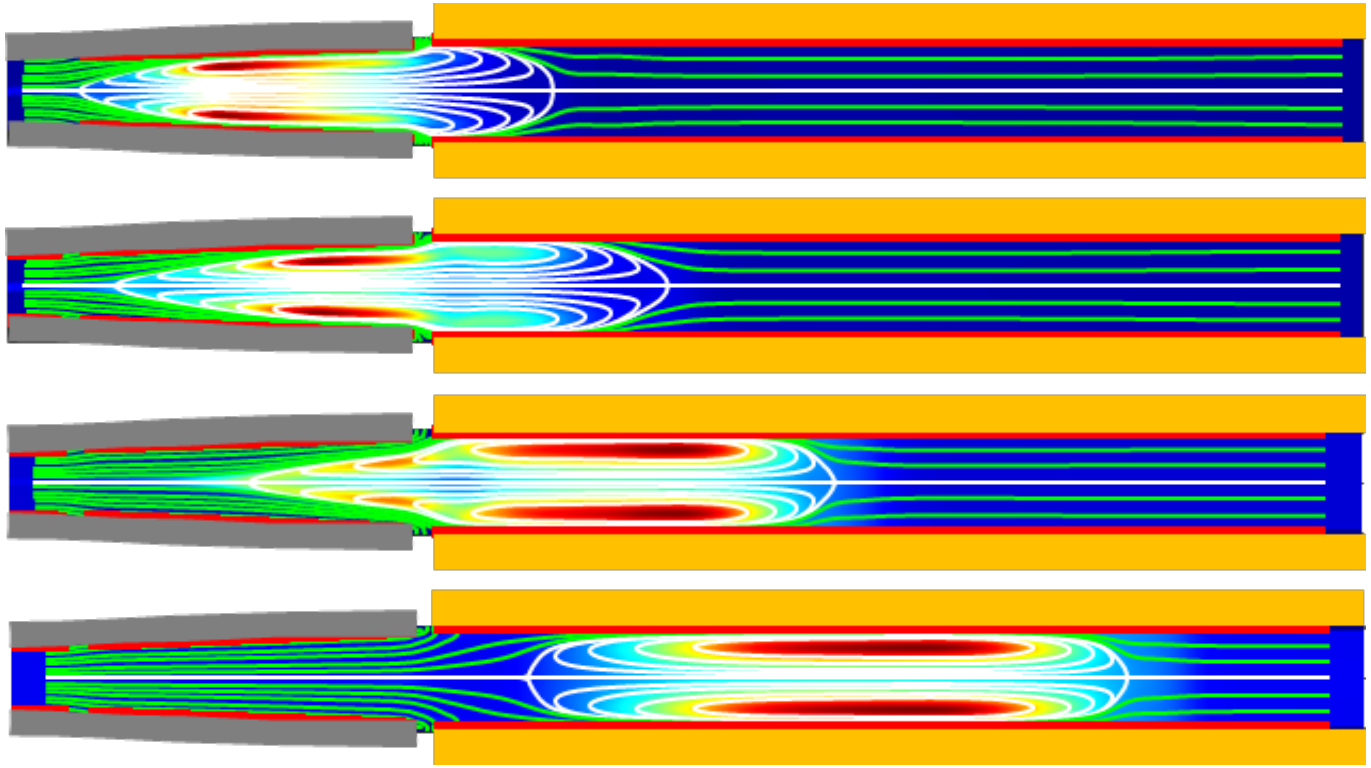


Experimental End-on images (left) and AEDS code results (right) for a 0.4 m radius, 0.16 kg aluminum band.



Comparison of experimental results with both the 3D AEDS and 1D numerical code predictions.

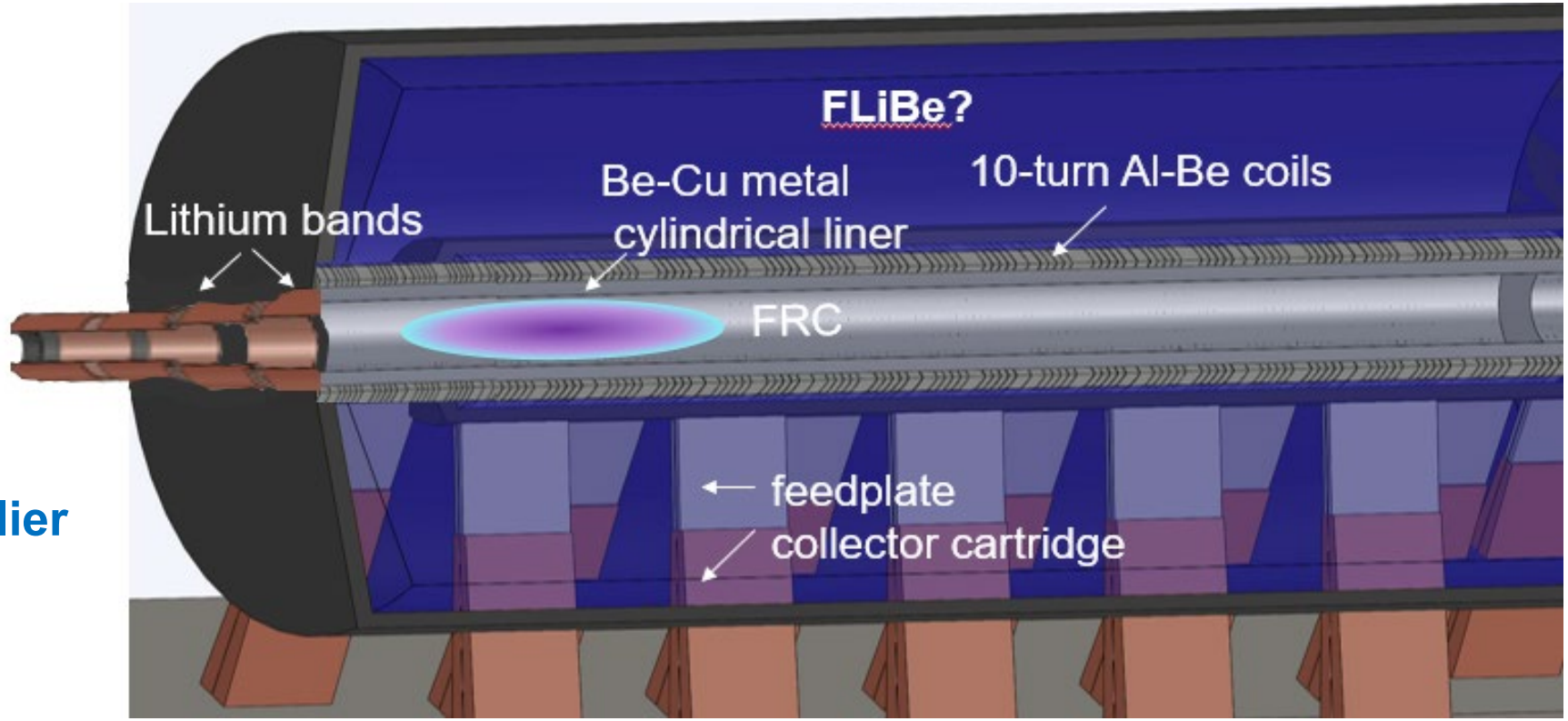
IV. Lithium Shell “Docking” at Burn Chamber and Drifting FRC Fusion Burn



Li bands converge at entrance to the burn chamber with a transient internal field of 33 T. The FRC is readily translated into the flux conserving burn chamber with a much lower vacuum field (6 T). The FRC compresses the vacuum field up to 30 T as it drifts in. The shell B field compression continues as the back pressure dramatically falls with FRC exit

Compact FRC Fusion Reactor (CFR2) Features

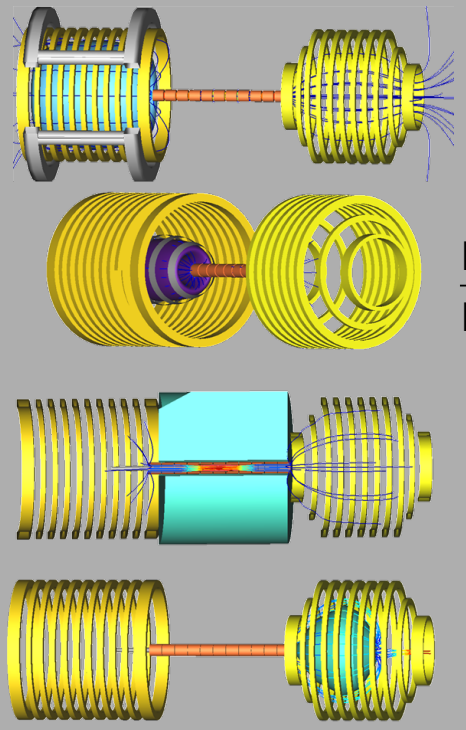
- FliBe has a high resistivity (> 10^6 Beryllium) - eliminates problem of an insulating solenoid coating
- Good breeding potential (breeding ratio 1.27 even without a multiplier
- With the Al-Be coil as multiplier a breeding ratio up to 2 are feasible



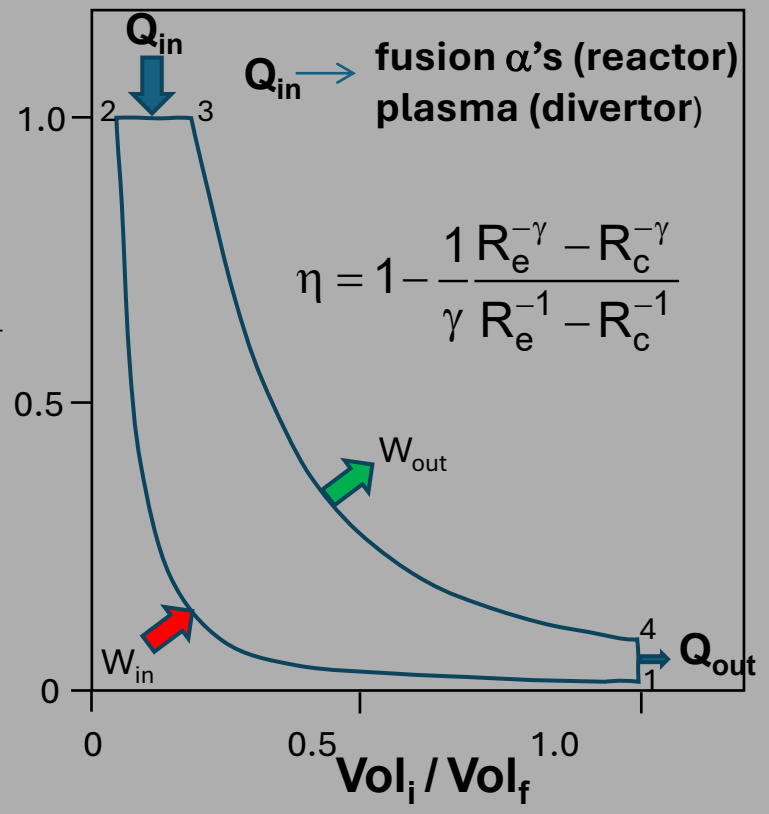
- The Al-Be metal solenoid coils (80% Be) experience only the steady 6 T field.
- The ~ 12 cm ID × 3 m long cylindrical first wall experiences a transient field pressure of 30T (0.36 GPa) due to FRC compression
- This is well below the yield strength of Be-Cu alloy 25 (1.2 GPa)

V. FRC Ejection and Energy Recovery

Direct Energy Recovery from FRC Expansion / Flux Compression



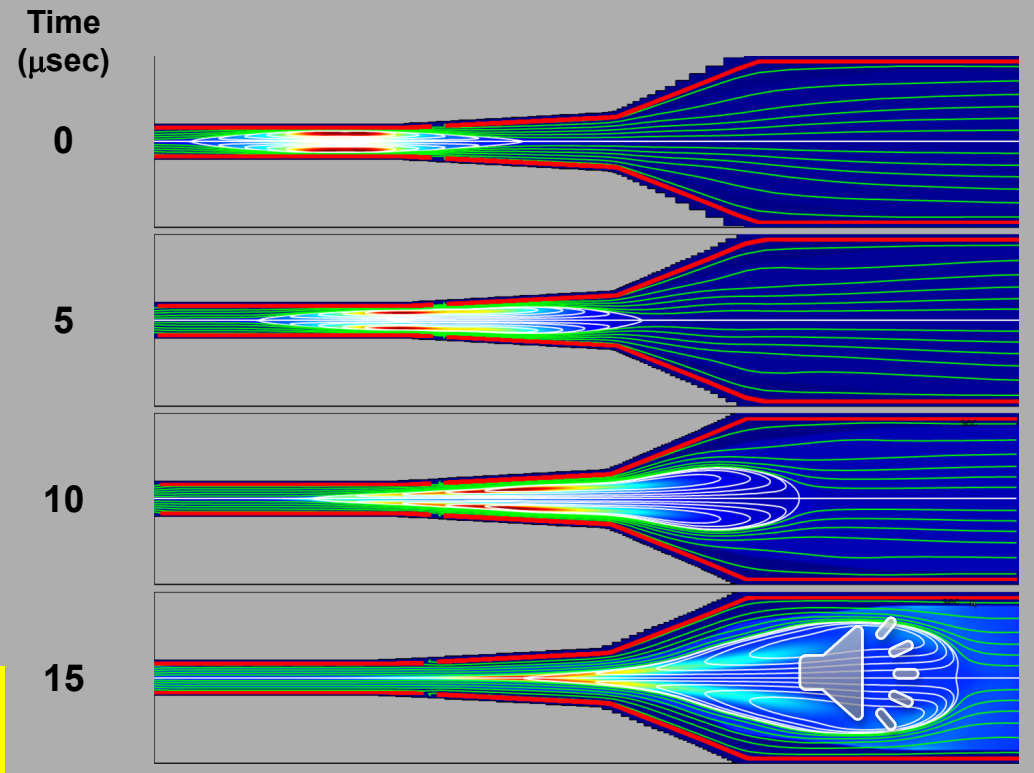
P-V diagram for the diesel cycle



In expansion chamber/divertor (m^3):
$V_1 = 32$, $V_2 = 1.1$, $V_3 = 3.2$, $V_4 = 32$
$\Rightarrow R_c = 29$, $R_e = 10 \Rightarrow \eta = 0.84$

2D MHD Calculation for the Expansion of the FRC as It Drifts Out of the Burn Chamber

(B field lines and density contours)



Why Inductively Driven Wall Compression for High Power Density FRC Based Fusion?

(1) Reduces by orders of magnitude the scale and complexity involved in the development of a fusion energy reactor compared with any other MFE or IFE concept

(2) Provides for a vastly lower cost, risk and a much shorter timescale for implementation

(3) Employs a linear, simply-connected topology that solves long term material exposure with easy replacement, breeding issues due to blanket coverage as well as exhaust plasma in diverters.

For confinement better than projected:

- Lower energy recycling for more productive and lower cost electricity. Advanced fuel cycles such as self-sustained ^{3}He catalyzed D-D (E_{fus} ~ 95% KE p's + 5% n's) are unrealistic as the energy confinement would need to be over 300 times that of DT!

For confinement lower than projected:

- Can be of immediate utility to nuclear energy production in the near term, e.g.:

(I) Fissile/fusile breeder (both Thorium and Tritium)

(II) Waste transmutation/burner