

New Approach to Achieving Ignition in a Small-Scale FRC Fusion Reactor

Non-Destructive Wall Compression of the FRC to Fusion Ignition (Five Stages)

Motivation and Background

A new method for FRC formation and compression is presented here that based on previous FRC empirical scaling should achieve fusion ignition. This is accomplished at high electrical efficiency and in a manner consistent with long-term repetitive pulsing utilizing only solid-state pulse power. It is also capable of direct electrical conversion of the plasma and fusion alpha energy thereby offering nearly the same efficiency as steady-state operation. It is well known that fusion power density scales as $\beta^2 B^4$ (where beta is the ratio of plasma energy density to that of the confining magnetic field B). If one wishes to be competitive with fission and other energy sources, as well as significantly reduce the time and cost of producing fusion energy for electrical power, it is imperative to develop devices that can operate in a regime that maximizes both B and β . There is no simpler confining geometry than a Field Reversed Configuration (FRC), which is topologically the simplest, most compact, and highest beta of all magnetically confined plasmas. The methods required to achieve the reactor concept detailed here have been successfully demonstrated in a series of experiments at the University of Washington and MSNW, a small R&D company located in Bellevue WA. The FRC can be formed efficiently and at sufficiently high poloidal flux (> 50 mWb) by employing the Rotating Magnetic Field (RMF) formation technique to a chamber of sufficient size (~ 0.8 m radius). This is only a factor of two larger than that employed in the experiments at the University of Washington where FRCs were successfully formed and sustained at temperatures greater than 200 eV which was more than sufficient for the pre-compressed startup FRC desired. The compact, small-scale reactor can achieve fusion ignition at power densities comparable to fission. The new method for FRC compression presented here does not require exceeding the yield strength of the confining wall (a set of converging Lithium bands) which act as a sabot and performed in a manner that is consistent with reuse. The fusion burn occurs as the FRC drifts through a relatively low field ($B_{vac} = 6$ T, $B_c = 30$ T) cylindrical coil surrounded by a conventional Tritium breeding blanket. The reactor's small scale and simplicity of design require no materials or technologies that are not readily available today.

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

Fusion Power Density scales as $\beta^2 B^4$

- (1) The FRC has the highest β of all fusion plasmas ($\beta \sim 0.5-0.9$)
- (2) Compression and burn occurs in a simple linear geometry at highest possible B consistent with a repetitive pulsed solenoidal coil ($B_c \sim 5-10$ T)

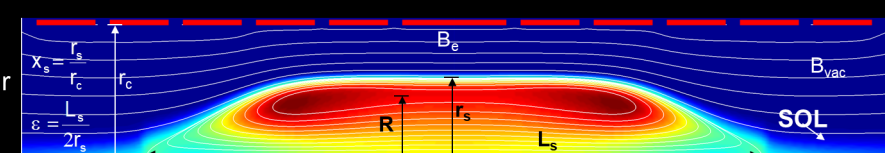
IDWC FRC based fusion provides

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

Key IDWC Physics Demonstrated:

- ✓ Kinetic stability expected from formation through fusion burn
- ✓ Observed transport scaling sufficient for $Q > 5$
- ✓ Magnetic field compression by Inductively driven bands at scale demonstrated beyond the magnetic fields required (~ 150 T)
- ✓ Confinement scaling better than prediction from *in situ* PHD FRC $\tau > \tau_{LHD} \sim r^2 n^{1/2}$

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



Key Equilibrium Relations:

$$\begin{aligned} B_{ext} &= B_{vac} \\ P_0 &= n_0 kT \\ \langle \beta \rangle &= 1 - \frac{1}{2} x_s^2 \end{aligned}$$

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 (n) and T

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

FRC Transport Scaling

Scaling based on Lower Hybrid Drift:

$$\tau_N \sim \frac{r_s^2}{\rho_1} \quad (\text{first observed in LANL FRX Expts.})$$

$$\text{From radial pressure balance: } \left(n_0 kT = \frac{B_c^2}{2\mu_0} \right) \quad n_0^{1/2} \sim \frac{B_c}{T^{1/2} \rho_1}$$

$$\text{Restating: } \tau_N \sim n^{1/2} R^2 \quad \text{Diffusion coef. scales only with } n$$

With data from LSX and other FRC experiments:

$$\tau_N = 3.2 \times 10^{-15} \varepsilon^{0.5} x_s^{0.8} n^{0.6} r_s^{2.1} \quad x_s = r_s/r_c \quad \varepsilon = L_s/2r_s$$

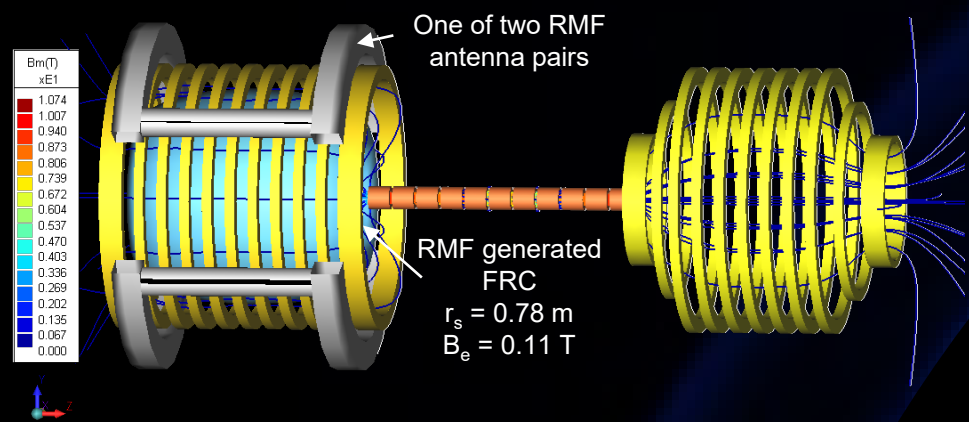
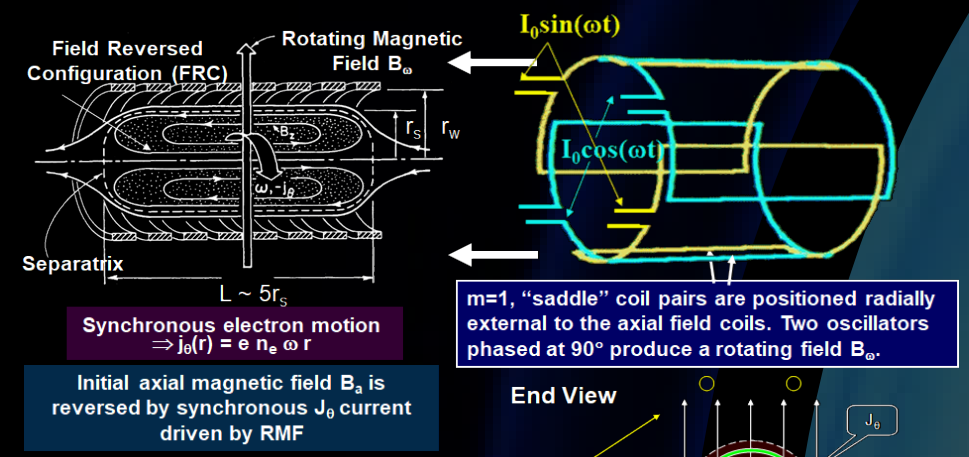
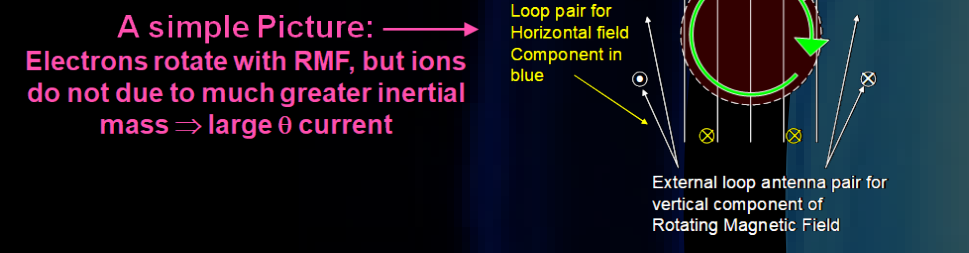
from Radial Pressure balance at fusion temperatures:

$$n_0 = 2.5 \times 10^{20} B_c^2 \quad (\text{where } kT = 10 \text{ keV is assumed})$$

$$\text{For RR profile: } \Phi_p \approx x_s r_s^2 B_c$$

$$\text{In terms of confining flux } \Phi_p: \quad nT \propto \Phi_p B_c^2$$

I. Rotating Magnetic Field Formation of the FRC (RMF FRC)



RMF Physics & Experimental Results

Ohm's Law: $\mathbf{E} + \mathbf{v} \times \mathbf{B} = \eta \mathbf{j} + \mathbf{j} \times \mathbf{B}/ne$ Faraday's Law: $|\mathbf{E} \cdot d\mathbf{l}| = d\phi/dt$

Consider the θ component:

Without RMF, $E_\theta = \eta j_\theta + v_\theta B_z$ and FRC is decaying
With RMF, $E_\theta = \eta j_\theta + v_\theta B_z - \langle j_\theta B_z \rangle$ and the FRC can be sustained
The RMF generated $\langle j_\theta B_z \rangle$ exceeds ηj_θ , and $d\phi/dt > 0$

Conditions:

- The Hall term, $\mathbf{j} \times \mathbf{B}/ne$, must be sufficiently large to cancel ηj_θ
- The e^- must be magnetized to the RMF, $\omega_{ce} \gg \nu_{ei}$
- The RMF must penetrate the plasma, $\delta_{RMF} \sim (\nu_{ei}/\omega_{ce}) \delta_{classical} \sim R_{plasma}$

These constraints are satisfied with a sufficiently large B_{RMF}

A balance between the RMF applied torque and electron-ion friction determine the peak plasma density:

$$n_0 = 6.7 \times 10^{21} \left(\frac{B_{RMF}}{\omega_{ce}^2 r_s^2} \right)^{1/2}$$

where δ^* is the effective skin depth of the RMF and ω_{ce} is the effective rotational freq. $\omega_c \sim \omega_{ce}$. Experimentally it is found that $\omega_c \approx 0.15 \omega_{ce}$ and $\delta^*/r_s \approx 0.18$, where ω_{ce} is the RMF frequency. The plasma resistivity, η , is that characteristic of FRCs due to the LHD instability. A good fit to the past FRC data is:

$$\eta = \frac{C_N}{n_0^{1/2}} \quad C_N = 1.5 \times 10^7 \Omega \cdot m$$

Substituting for ω_c , δ^* and η , one has solving for the null density:

$$n_0 = 5.0 \times 10^{21} \left(\frac{B_{RMF}}{\omega_{ce}^2 r_s^2} \right)^{1/2}$$

The best fit to most data had $n_0 = n_0 \text{sech}^2(u)$ for the center region and $n_0 = n_0 \text{sech}^2(1.5u)$ for the edge region. The following results apply for this DRR profile:

$$B_c = 0.27 \mu_0 n_0 \omega_{ce} r_s^2 = 0.407 \omega_{ce}^{1/2} r_s^2 B_{RMF}^{1/2}$$

Assume a minimal $\omega_c \sim 2\omega_{ce}$ and a reasonable $\omega_c = 10^6$ rad/sec (160 kHz). One has for a DT plasma at desired scale $r_s = 0.75$ m:

$$B_c = 1.305 \times 10^{-1} \omega_c = 0.013 \text{ T} \quad \text{and} \quad B_c = 0.108 \text{ T}$$

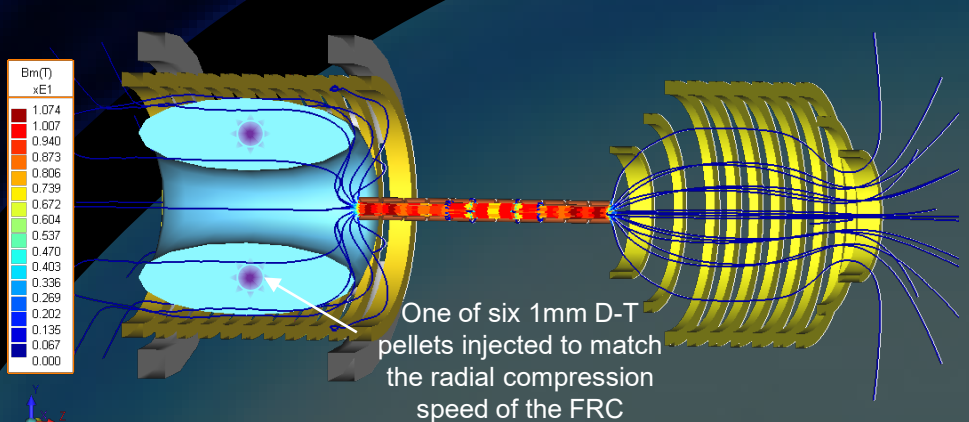
$$\text{and} \quad n_0 = 1.54 \times 10^{21} \omega_{ce}^{1/2} r_s^2 = 2.07 \times 10^{21} \text{ m}^{-3} \Rightarrow T_i = \frac{B_c^2}{2\mu_0 n_0} = 1.40 \text{ keV}$$

➤ Radiated power reduced. Recycling (as indicated by D_α line radiation) also strongly reduced.

➤ Temperature already close to synchronous $\zeta \rightarrow 1$ limit.

➤ B_c nearly doubled due to higher T_i for similar B_{RMF} .

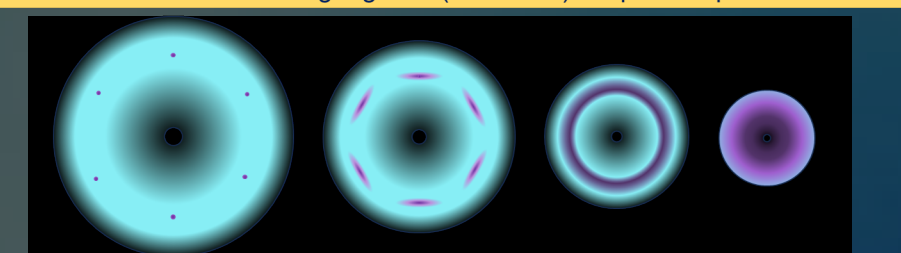
II. Radially injected D-T Pellet Fueling During FRC Compression



DT Pellet Fueling During Wall Compression

- 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 $\Rightarrow$
- Reduced flux loss (radial diffusion opposes inward flux diffusion into null)
- Increased particle confinement (bulk of plasma born at magnetic axis)

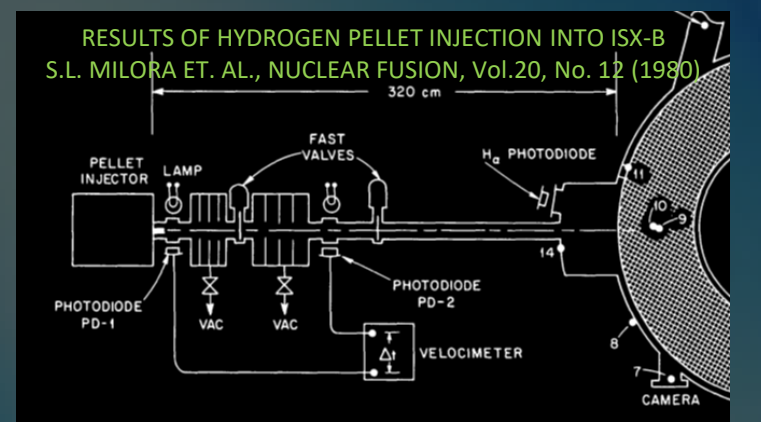
Pellets are composed of frozen hydrogen isotopes (tritium and deuterium) and accelerated with light gases (H and He) to speeds up to 3 km/s



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

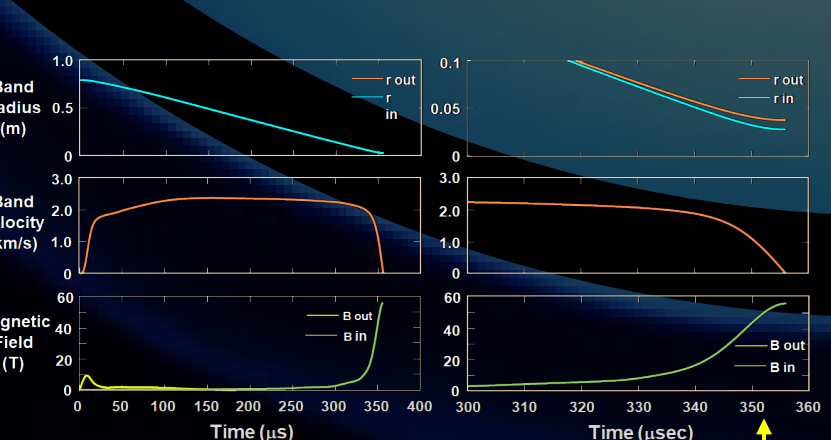
Final FRC inventory: $n_{FRC} \sim 5 \times 10^{21} \sim 16$ 1mm pellets (same as original ISX-B experiment)

Schematic of pellet injector as installed on the ISX-B device



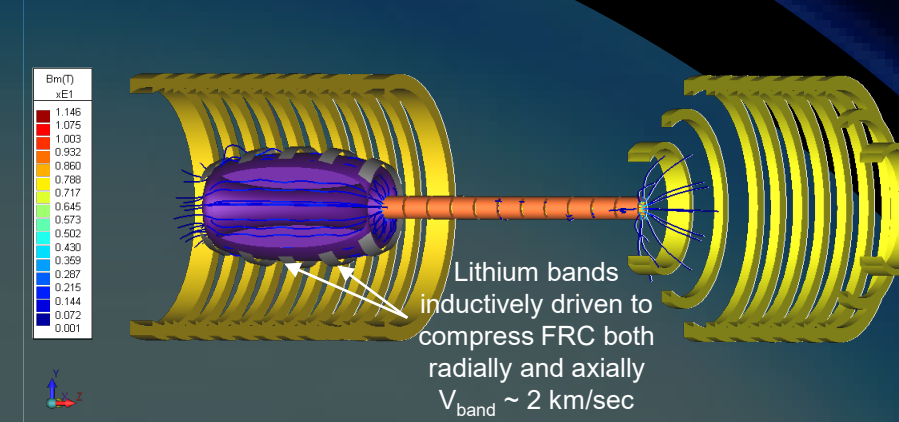
Density increases of $\sim 300\%$ have been observed without degrading plasma stability or confinement. Energy confinement time increases in agreement with the empirical scaling $\tau_E \sim n_e$

Various parameters from the 1D numerical code for optimized Li band radial & axial convergence for FRC compression

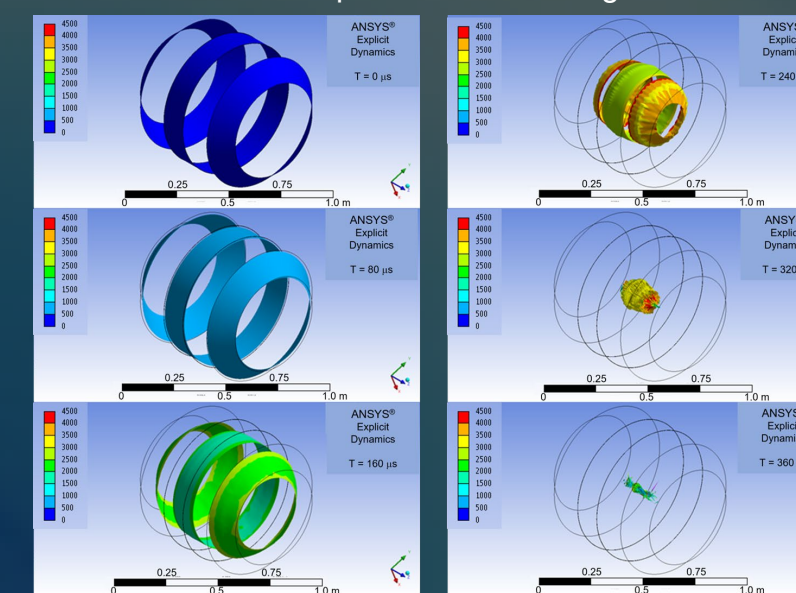


Key fusion parameters at the time of maximum FRC plasma compression.

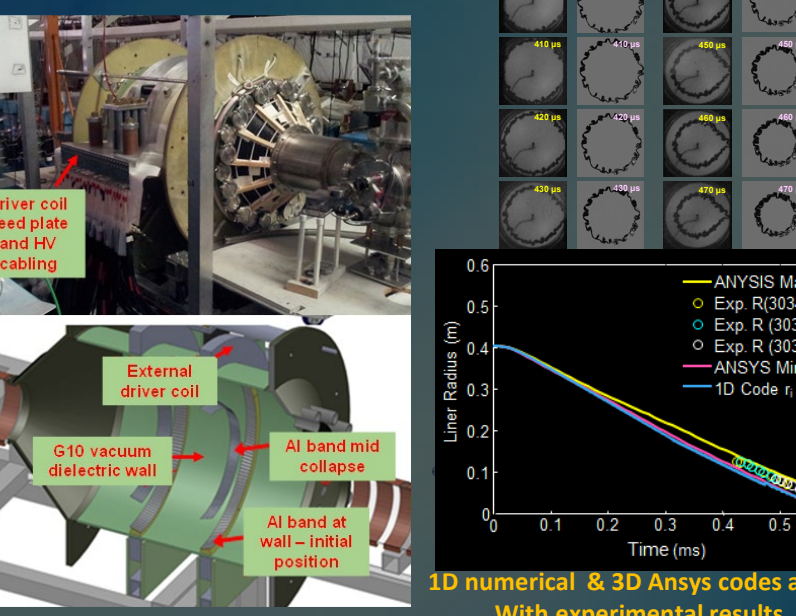
III. Wall Compression of FRC with Radially and Axially Converging Lithium Bands



Ansyz Explicit Dynamics Simulation (AEDS) of the 3D behavior of three metal bands driven to converge similar to that desired for FRC compression to fusion ignition conditions.

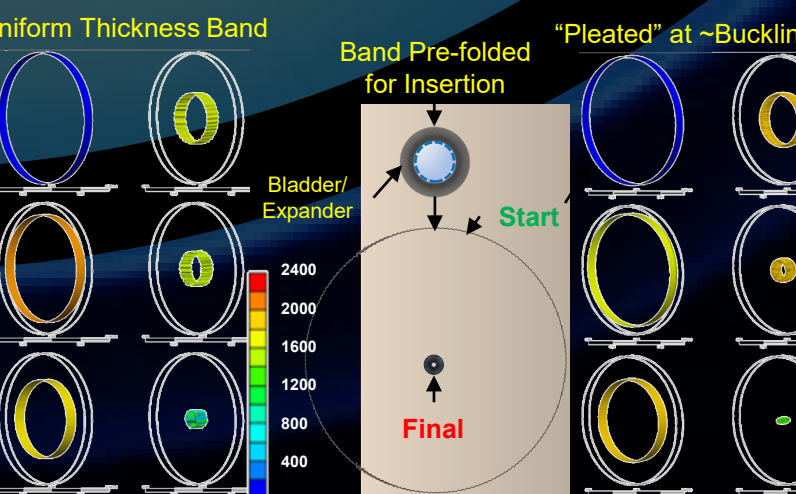


Experimental Layout & End-on images with AEDS Code comparison for a 0.16 kg Al band

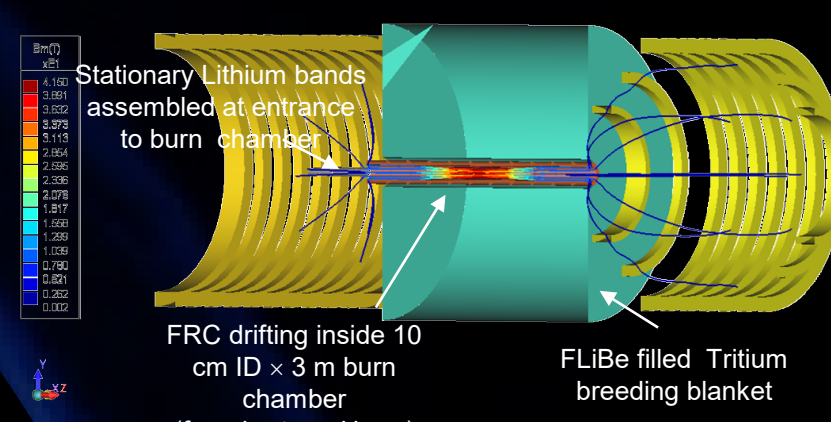


ANSYS® AEDS 3D calculations of a thin metal band implosion with (right) and without "pleating"

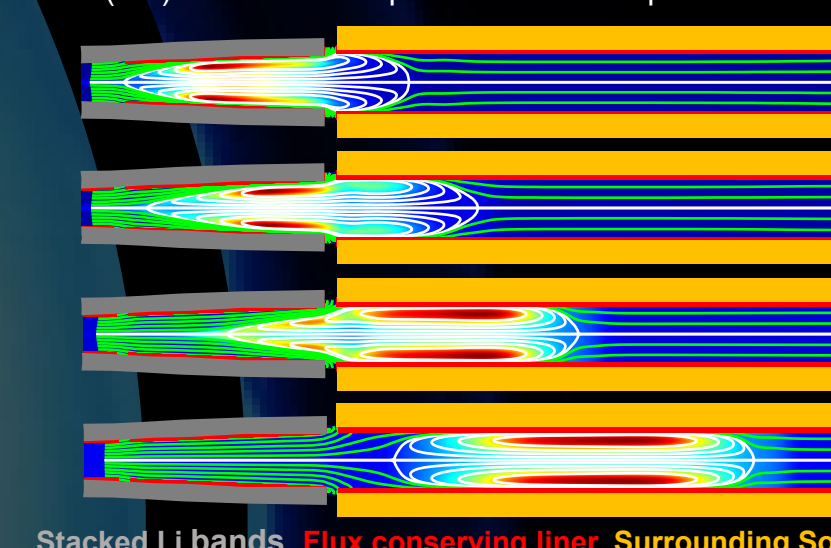
Central section CAD illustrates the process of insertion, start of the implosion and final state with a pleated metal band. Slower implosion for unpleated band is due to energy loss from internal stresses



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

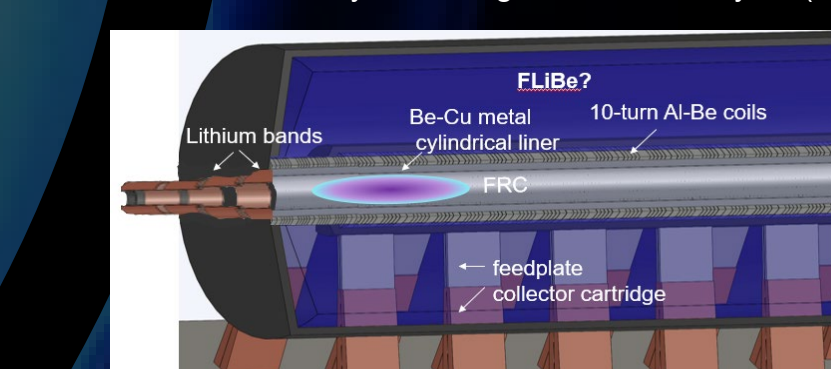


Li bands converge at entrance to the burn chamber with a transient internal field of 39T. The FRC is readily translated into the flux conserving burn chamber with a much lower vacuum field (6 T). The FRC compresses the field up to 30 T as it drifts.



Stacked Li bands Flux conserving liner Surrounding Solenoids

The Al-Be metal solenoidal coils (80% Be) experience only the steady 6 T field. The ~ 10 cm ID x 2.4 m long cylindrical first wall experiences a transient field (pressure) of 30T (0.36 GPa) due to FRC well below the yield strength of Be-Cu alloy 25 (1.2 GPa)



- FLiBe has a high resistivity ($> 10^6$ Beryllium) so that it eliminates the problem of an insulating solenoid coating
- Good breeding potential (breeding ratio 1.27 w/o multiplier from the Al-Be) and less expensive than $Pb_{83}Li_{17}$

Fusion Ignition Based on Past FRC Scaling

Based on past FRC scaling and the criterion for fusion ignition:

$$\tau_E n_0 \approx 2 \times 10^{20} \text{ m}^{-2} \text{ s} = 4.3 \times 10^{-15} \varepsilon^{1/2} x_s^{0.8} n^{0.6} r_s^{2.1}$$

where $10 \text{ keV} < T_i < 30 \text{ keV}$. For LHD the τ scaling goes like n/n_0 . For large x_s (~ 0.9), the x_s scaling should scale as $x_s^{3/2}$. To correct fit to the old scaling based on $x_s < 0.5$, the coefficient is increased by a factor of 1.624. With a typical $\varepsilon = 10$ for the FRC and assuming $x_s = 0.9$, one has for ignition:

$$n_0^{1/2} r_s^{1.6} = 1.07 \times 10^{14} \text{ m}^{-1/2}$$

A large but reasonable value for $B_c = 30$ T.

With $T_{tot} = T_i + T_e = 2 \times 10^4 \text{ eV}$.

$$n_0 = \frac{B_c^2}{2\mu_0 k T_{tot}} = 1.15 \times 10^{21} \text{ m}^{-3}$$

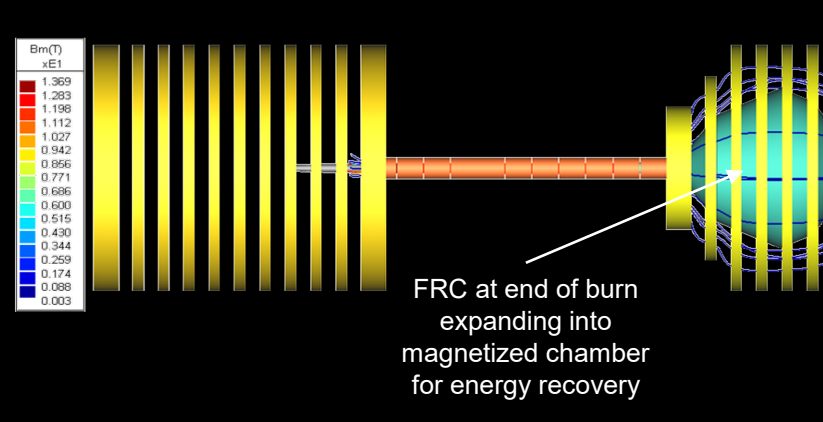
$$\text{Thus } r_s^{2.1} = 1.36 \times 10^{-3} \Rightarrow r_s = 0.043 \text{ m}$$

Note: $\tau = \frac{2 \times 10^{20}}{n_0} = 1.74 \text{ ms}$

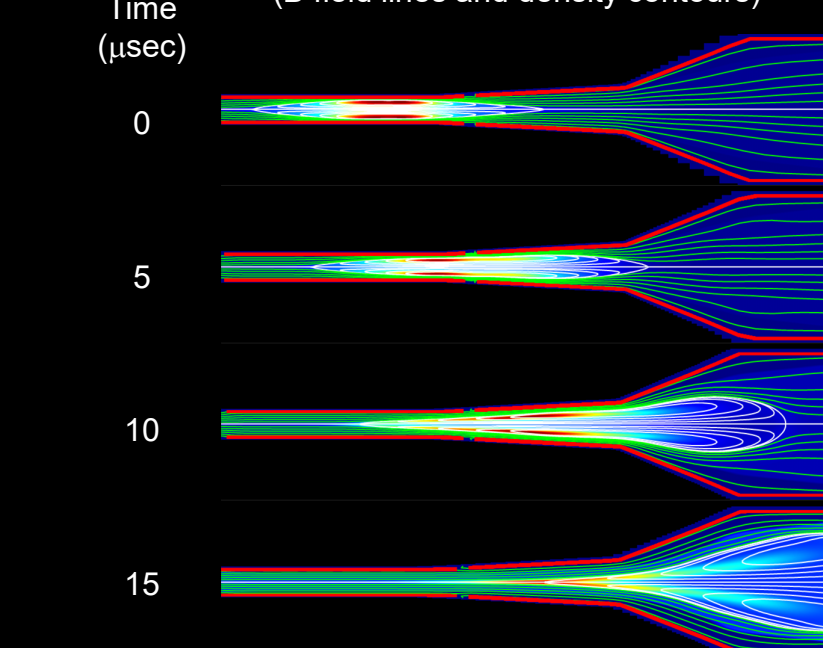
$$E_p = \frac{3}{2} (\beta) n_0 k T_{tot} \cdot \text{Vol} \quad \text{where } \text{Vol} = \frac{4}{3} \pi r_s^3 \varepsilon = 0.0033$$

$$E_p = 1.10 \text{ MJ} \quad \text{where } (\beta) = 0.6$$

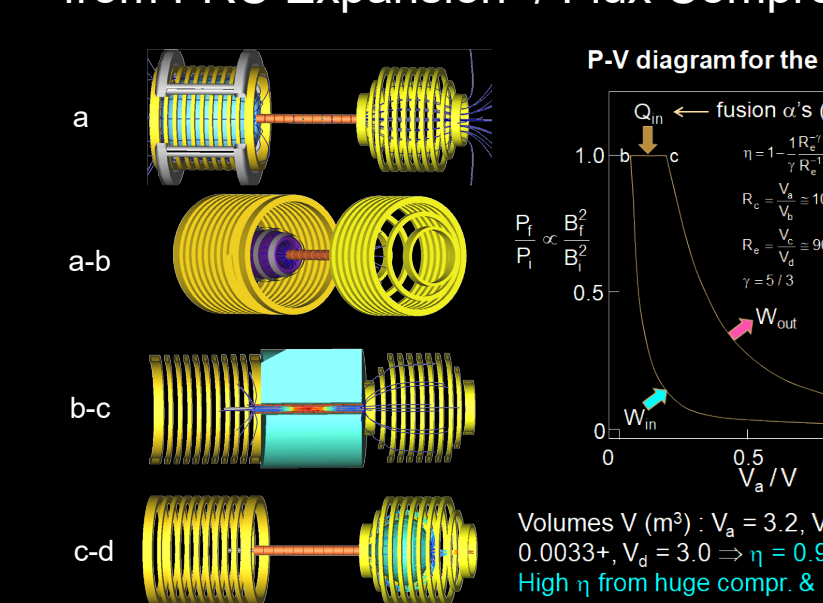
V. FRC Ejection and Energy Recovery



2D MHD Calculation for the Expansion of the FRC as It Drifts Out of the Burn Chamber (B field lines and density contours)



Direct Energy Recovery from FRC Expansion / Flux Compression



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) Linear, simply-connected topology solves both material exposure issues in blanket as well as exhaust plasma in diverters.

For confinement better than projected:
➤ Advanced fuel cycles for high efficiency direct energy conversion e.g. Self-sustained ^3He catalyzed D-D ($E_{Dd} \sim 95\% \text{ KE p/s} + 5\% \text{ n/s}$)

For confinement lower than projected:
➤ Can be of immediate utility to nuclear energy production in the near term, e.g.:

- (I) Fissile/fusile breeder
- (II) Waste transmutation/burner