Lockheed Martin Compact Fusion Reactor Concept, Confinement Model and T4B Experiment

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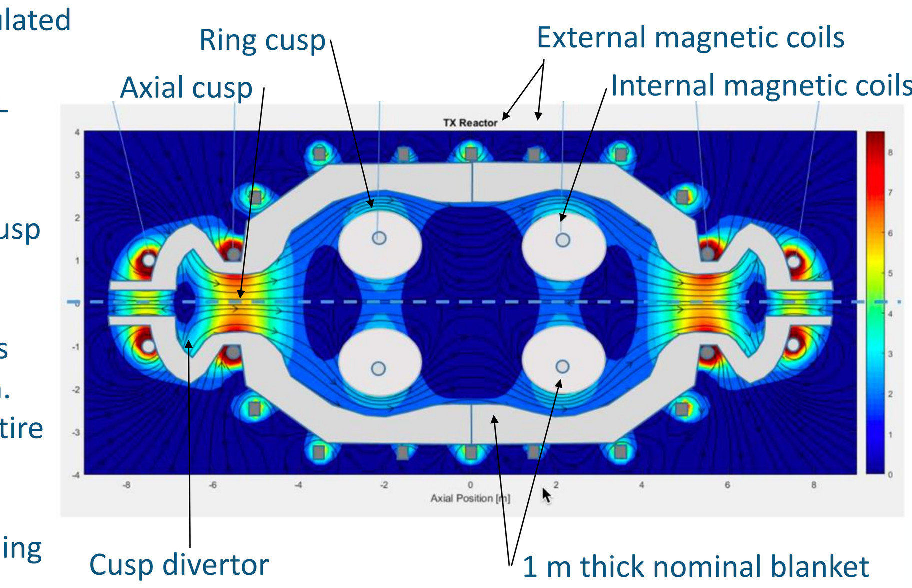
The Lockheed Martin Compact Fusion Reactor (CFR) concept relies on diamagnetic plasma behavior to produce sharp magnetic field boundaries and confine fusion plasma in a magnetically encapsulated, linear ring cusp geometry. Simulations show stable inflation to the high beta, sharp boundary state with constant thickness sheaths. Zero dimensional confinement models predict effectiveness of neutral beam heating to produce high electron temperatures in the T4B experiment. Those same models are used to determine feasibility of an operational reactor and determine required magnetic shielding performance for design closure. The T4B experiment will characterize and test plasma sources in the CFR geometry and conduct initial neutral beam heating experiments. The T4B experiment design and diagnostics suite are presented.

Lockheed Martin Compact Fusion Reactor Concept

The Lockheed Martin CFR concept is a magnetically encapsulated linear ring cusp that relies on high beta cusp confinement.

- Plasma confinement achieved in magnetic wells with self-produced sharp magnetic field boundaries.
- Design closes for 200 MW P_{th} reactor, 18 m long by 7 m diameter device assuming hybrid gyro-radii sheath and cusp widths and good coil support magnetic shielding.
- Neutral beam heats plasma to ignited state.
- The dominant losses are ion losses through the ring cusps into stalks and axially through the mirror confined sheath.
- Good global curvature gives interchange stability over entire volume.
- Bad curvature is confined to the bridge region, with significantly reduced density and non-Maxwellian streaming plasma.
- Compact size permits quick development iterations.
- The major physics concerns are the sheath size and stability, plasma inflation, stalk shielding, and blanket materials.



Preliminary Grad-Shafranov Equilibrium

COMSOL GS solver shows stable plasma inflation to high beta condition

Target Plasma
- $n = 1.8 \cdot 10^{20}\ m^{-3}$
- T_e, T_i = 14 keV
- $P_{target} = 8.07 \cdot 10^5$ Pa

Simplified GS equation without B_T in axisymmetric system:

$$\vec{J} \times \vec{B} = \nabla P$$
$$\nabla \cdot \vec{B} = 0$$
$$\nabla \times \vec{B} = \mu_0 \vec{J}$$

$$\Delta^* \psi = -\mu_0 R^2 \frac{dp}{d\psi}$$

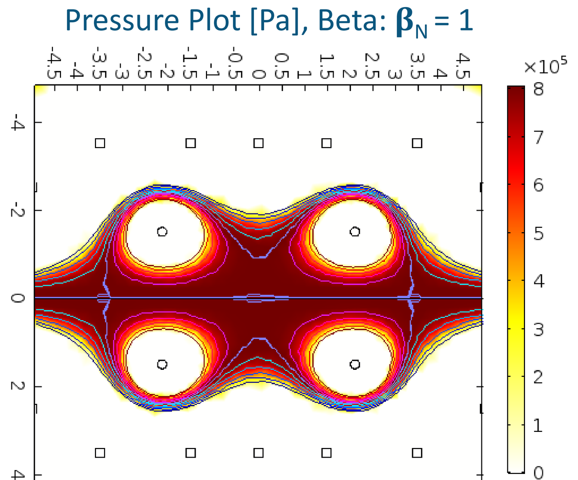
The elliptic operator Δ^* is

$$\Delta^* \psi \equiv R^2 \vec{\nabla} \cdot \left(\frac{1}{R^2}\vec{\nabla}\psi\right) = R\frac{\partial}{\partial R}\left(\frac{1}{R}\frac{\partial \psi}{\partial R}\right) + \frac{\partial^2 \psi}{\partial Z^2}$$

Peaked pressure function
- $p(\Psi) = \beta_N * p_{target} * \exp(-(\Psi)^2/Peak^2)$

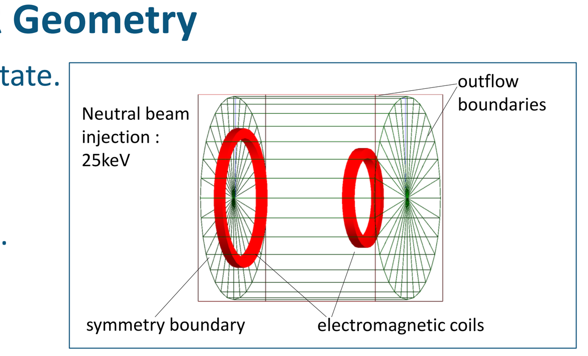
Credit: GS simulation work performed under contract by Enig Associates, Inc.

Pressure Plot [Pa], Beta: $\beta_N = 1$

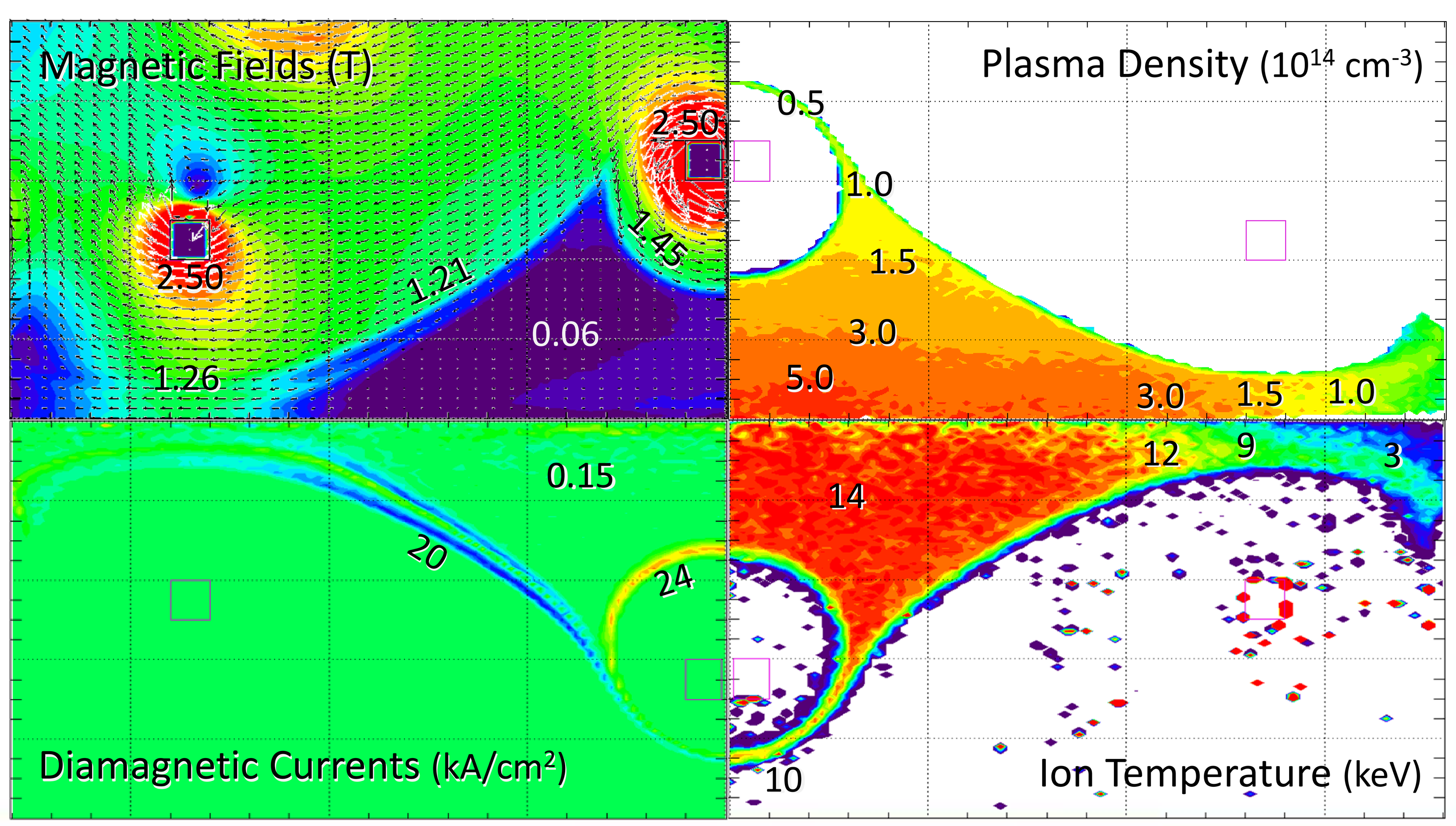


Preliminary PIC Simulation (LSP) of Subscale CFR Geometry

- With initial load, sim quickly settles into high beta equilibrium state.
- Diamagnetic currents create a near field-free region.
- Neutral beam fast ions are effectively confined.
- Cusp densities are reduced by x10 in the ring, x5 along the axis.
- Sheath width is effectively constant, dominated by electric field.
- Ring and axial cusp width are decoupled.
- Cusp widths: ~ $\rho_{L,\ ion}$ along axis, ~ $\rho_{L,\ hybrid}$ along ring
  - We hypothesize this will change with stronger mirror ratios.
- Future work includes looking at collisional steady state, sheath distribution functions, full geometry, realistic plasma start-up, matching of T4B experimental conditions, conductive walls, and porting to supercomputers.



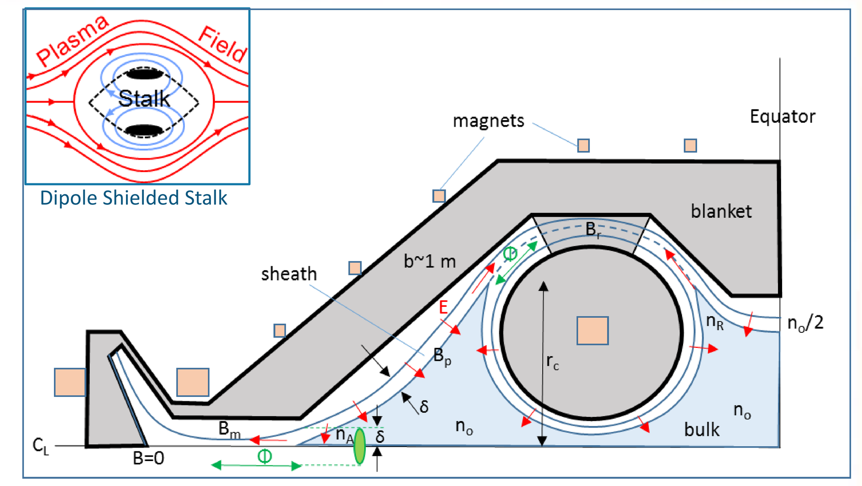
- LSP code
- RZ domain
- 10 cm x 18 cm
- 0.5 mm grid
- 2M particles
- 400 ns
- 20 processors
- 72 hr run



Zero Dimensional Performance Model

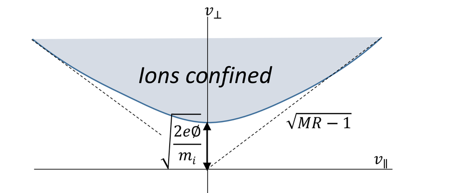
Goal: Model the performance of CFR plasmas for experiments and inflation of reactor plasmas to ignited conditions.
- Model all major power inputs and losses, march forward in time.
- Fast ions heat electrons, electrons heat ions, and ions carry majority of losses through sheath and cusps.
- Simulation terminates when trap is 'full' at beta = 1, not necessarily steady-state.

Assumptions:
- Constant density, variable volume based on beta = 1.
- Plasma is strongly positive due to ambipolar effects, potential = 4 * T_e, which holds for typical values of T_i/T_e and mirror ratios [BenDaniel, 1961].
- Due to potential, ions carry all convective power losses.
- Ion sheath loss is calculated using integrals over distribution function with 'mirror coil' mirror ratio and ion-ion collision rate with half of bulk density.
- Cusp losses are calculated using integrals over distribution function with assumed local sheath thicknesses for area and local mirror ratios and plasma potential.
- The magnetic field is modeled as linear with radius.
- Start with a small initial fast ion population created by neutral beam and then self-consistently solve for initial volume.
- Classical Spitzer rate is used to find energy transfer between bulk ions and electrons. [Rider, 1994]
- Fast ions and alpha particles are treated separately from bulk ions, energy transfer rate calculated with electron temperature. [Huba, 2013]
- Fast ions are confined longer than their energy transfer time and transfer all energy to bulk electrons for energies of interest, consistent with good fast ion confinement observed in mirror experiments.
- Losses to ring cusps are reduced due to geometric transparency and magnetic shielding.
- Ignore charge exchange losses, so heating powers are effectively realized power after charge exchange.



$$E = Ei + Ee + Efi + E_\alpha$$
$$V = VF\pi r^3 \quad SA = SAF\pi r^2$$
$$V = \left[V_F\pi\left(\frac{r_c}{B_{pD}}\right)^3\left(\frac{4}{3}\mu_o E\right)^{1.5}\right]^{0.4}$$
$$T_i = \frac{2Ei}{3enV} \quad T_e = \frac{2Ee}{3enV}$$
$$T_{fi} = \frac{2Efi}{3enV} \quad T_\alpha = \frac{2E_\alpha}{3enV}$$
$$\emptyset = Te \times phifactor$$
$$p = n(Ti + Te + Tfi + T_\alpha)$$
$$B_p = \sqrt{2\mu_o p}$$
$$r = \frac{B_p}{B_{pD}} r_c$$
$$v_{Ti} = \sqrt{\frac{2eTi}{m_i}} \quad v_{Te} = \sqrt{\frac{2eTe}{m_e}}$$
$$\rho_e = \frac{1}{B_p}\sqrt{\frac{2meTe}{e}} \quad \rho_i = \frac{1}{B_p}\sqrt{\frac{2miTi}{e}}$$
$$\rho_{ie} = \sqrt{\rho_i\rho_e}$$
$$MR = \frac{B_m}{B_p}$$
$$t_{GDT} = \frac{LM \times MR}{\sqrt{\frac{8eTi}{\pi mi}}}$$
$$\Lambda_{ii} = 23 - ln\left(Z_{eff}^3\left(\frac{2n}{1e6}\right)^{0.5} T_i^{-1.5}\right)$$
$$t_{ii} = \frac{2.08e13\ \mu^{0.5} T_i^{-1.5}}{n\left(\frac{n_s}{n}\right)\Lambda_{ii}}$$
$$G = \frac{2}{\sqrt{\pi}v_{th}^3}\int_{-\infty}^{\infty}\int_0^{v_{\perp lim}=\sqrt{v_\parallel^2\frac{1}{MR-1}+\frac{2e\emptyset}{m_i}}} v_\perp e^{-\frac{(v_\perp^2+v_\parallel^2)}{v_{th}^2}}\, dv_\perp\, dv_\parallel$$
$$t_s = \max(tGDT, \frac{t_{ii}}{G})$$
$$\Lambda_{ie} = 24 - ln\left(\frac{\sqrt{n}}{T_e}\right)$$
$$V_s = SA \cdot \delta$$
$$\Gamma_s = \frac{n\left(\frac{n_s}{n}\right)V_s}{t_s}$$
$$P_s = e(1.5Ti + \phi)\Gamma_s$$
$$P_{rad} = \%I \cdot 2 \cdot 10^{-34} n^2 V$$
$$P_{Bremms} = 1.7 \cdot 10^{-38} Z_{eff} n^2 T_e^{0.5} V$$

$$A_r = 2\pi r \cdot 2\delta \cdot 4 \cdot 0.5 \cdot S \cdot \left(\frac{N_s a}{2\pi rc}\right)$$
$$\Gamma_{ir} = \frac{4Arn\left(\frac{n_r}{n}\right)}{\sqrt{\pi}v_{th}^3}\int_0^\infty\int_0^{\sqrt{v_\parallel^2\frac{1}{MR_r-1}+\frac{2e\emptyset}{m_i}}} v_\parallel v_\perp e^{-\frac{(v_\perp^2+v_\parallel^2)}{v_{th}^2}}\, dv_\perp\, dv_\parallel$$
$$P_{ir} = \frac{4Arn\left(\frac{n_r}{n}\right)}{\sqrt{\pi}v_{th}^3}\int_0^\infty\int_0^{\sqrt{v_\parallel^2\frac{1}{MR_r-1}+\frac{2e\emptyset}{m_i}}} v_\parallel v_\perp \left[\frac{m_i}{2}(v_\perp^2+v_\parallel^2)+e\emptyset\right] e^{-\frac{(v_\perp^2+v_\parallel^2)}{v_{th}^2}}\, dv_\perp\, dv_\parallel$$
$$A_a = \pi\delta^2$$
$$\Gamma_{ia} = \frac{4Aan\left(\frac{n_a}{n}\right)}{\sqrt{\pi}v_{th}^3}\int_0^\infty\int_0^{\sqrt{v_\parallel^2\frac{1}{MR_a-1}+\frac{2e\emptyset}{m_i}}} v_\parallel v_\perp e^{-\frac{(v_\perp^2+v_\parallel^2)}{v_{th}^2}}\, dv_\perp\, dv_\parallel$$
$$P_{ia} = \frac{4Aan\left(\frac{n_r}{n}\right)}{\sqrt{\pi}v_{th}^3}\int_0^\infty\int_0^{\sqrt{v_\parallel^2\frac{1}{MR_a-1}+\frac{2e\emptyset}{m_i}}} v_\parallel v_\perp \left[\frac{m_i}{2}(v_\perp^2+v_\parallel^2)+e\emptyset\right] e^{-\frac{(v_\perp^2+v_\parallel^2)}{v_{th}^2}}\, dv_\perp\, dv_\parallel$$



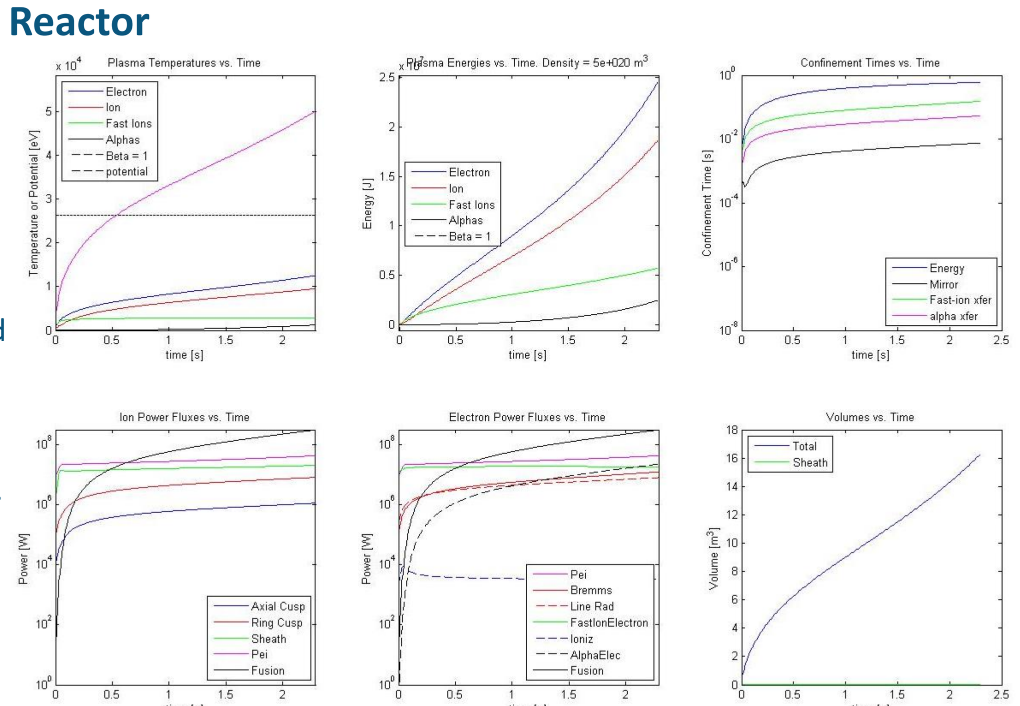
$$P_f = \frac{n^2}{4}\langle\sigma v\rangle YV \qquad P_\alpha = \frac{Y_\alpha}{Y_f}P_f \qquad Y = Yf + TBR \cdot Y_{breed}$$
$$P_{ei} = 7.61 \cdot 10^{-34}\frac{n^2 Z_i^2 \lambda_{ie}}{\mu_i T_e^{\frac{3}{2}}}(T_e - T_i)V$$
$$P_{fie} = -\frac{E_{fi}}{t_{fie}} \qquad t_{fie} = \frac{6.2e14\ \mu T_e^{1.5}}{nZ_i^2\left(2-\frac{3Te}{E_{NB}}\right)\Lambda_{ie}}$$
$$P_{ae} = -\frac{E_{ae}}{t_{ae}} \qquad t_{ae} = \frac{6.2e14\ \mu T_e^{1.5}}{4n\left(2-\frac{3Te}{E_\alpha}\right)\Lambda_{ie}}$$
$$P_{iT} = P_{ei} - P_{ia} - P_{ir} - P_{iS}$$
$$P_{eT} = -P_{ei} - P_{Bremms} - P_{rad} + P_{fi} + P_{ae}$$
$$E_{e,i+1} = E_{e,i} + dt(P_{eT})$$
$$E_{i,i+1} = E_{i,i} + dt(P_{iT})$$
$$E_{\alpha,i+1} = E_{\alpha,i} + dt(P_{ae} + P_\alpha)$$
$$E_{fi,i+1} = E_{fi,i} + dt(P_{fie} + P_{hfi})$$
$$\tau_E = \frac{E}{P_{hfi} + P_{he} + P_{ae}}$$

Zero-D Results for Ignited 200 MW TX Reactor

Required cusp performance,
- Cusp widths, ring ~ hybrid gyro radius to close.
- Stalk shielding, 2 orders density reduction req'd.

General behavior
- Neutral beam can be terminated after alpha population is able to heat electrons.
- Density plays key role in electron-ion transfer and steady-state electron to ion temperature ratio.
- Electron temp dictates potential and thus opens up the ion loss cone.
- Balance and optimize main losses, for constant B.
  - Fusion power ~ $n^2 * \langle\sigma v\rangle_{DT}$ ~ n
  - Sheath loss ~ $n^2 / T^{1.5}$ ~ $n^{3.5}$
  - Cusp loss ~ n * $T^{1.5}$ ~ $n^{-0.5}$
  - Bremmstrahlung losses ~ $n^2 * T_e^{0.5}$ ~ $n^{1.5}$

TX Parameters
- 7 m diameter x 18 m long, 1 m thick blankets
- 320 MW Gross
- 40 MW heating power, 2.3 sec
- $n = 5 \cdot 10^{20}\ m^{-3}$
- Beta = 1 (Field = 2.3 T)
- V = 16.3 m^3, 51 MJ Total Energy
- T_i = 9.6 keV, T_e = 12.6 keV

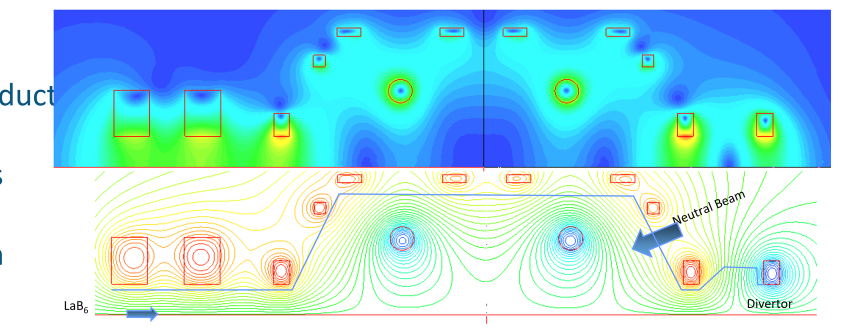


- Sheath loss = 20.8 MW
- Ring cusp loss = 8.3 MW, Assumes 5% shielding, n_R/n = 0.1
- Axial cusp loss =1.1 MW, n_A/n = 0.1
- Total Radiation = 20.8 MW, Assumes 1% Z=8 impurities
- 4.2 MW/m^2 neutron surface heating rate
- Total losses = Alpha heating power = 51 MW

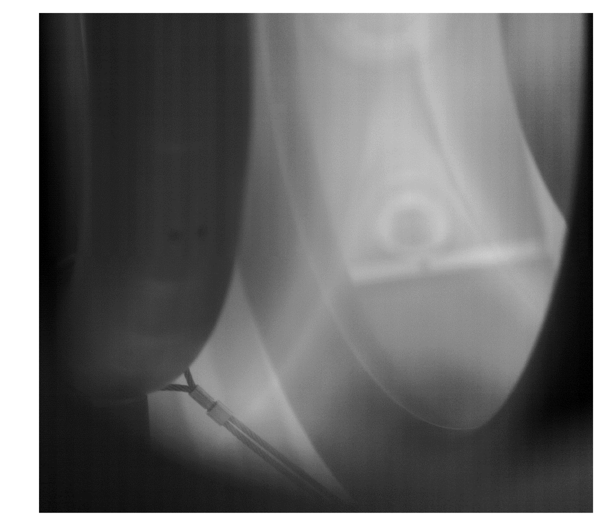
REFERENCES
1. D. J. BenDaniel, Plasma Phys. **3**, 235 (1961).
2. T. H. Rider, S.M. Thesis, MIT (1994).
3. J. D. Huba, NRL Plasma Formulary, (2013).

T4B Experiment

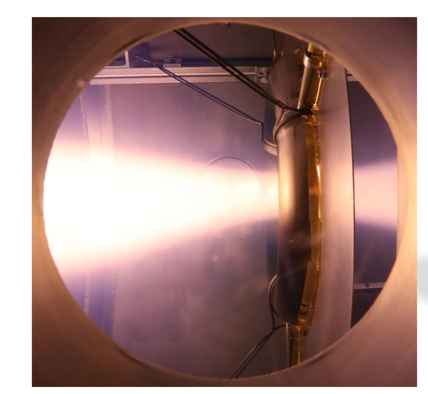
Goal: Characterize plasma sources in the CFR geometry and conduct initial neutral beam heating.
- LaB_6 Hot cathode, Plasma gun sources, mid $10^{19}\ m^{-3}$ densities
- 25 keV neutral hydrogen beam, 1 MW
- 100 ms shot duration, 1 min between shots, 10,000 shot plan
- 0.1 T equilibrium field, 0.6 T mirror field
- About 2 m long by 1 m diameter



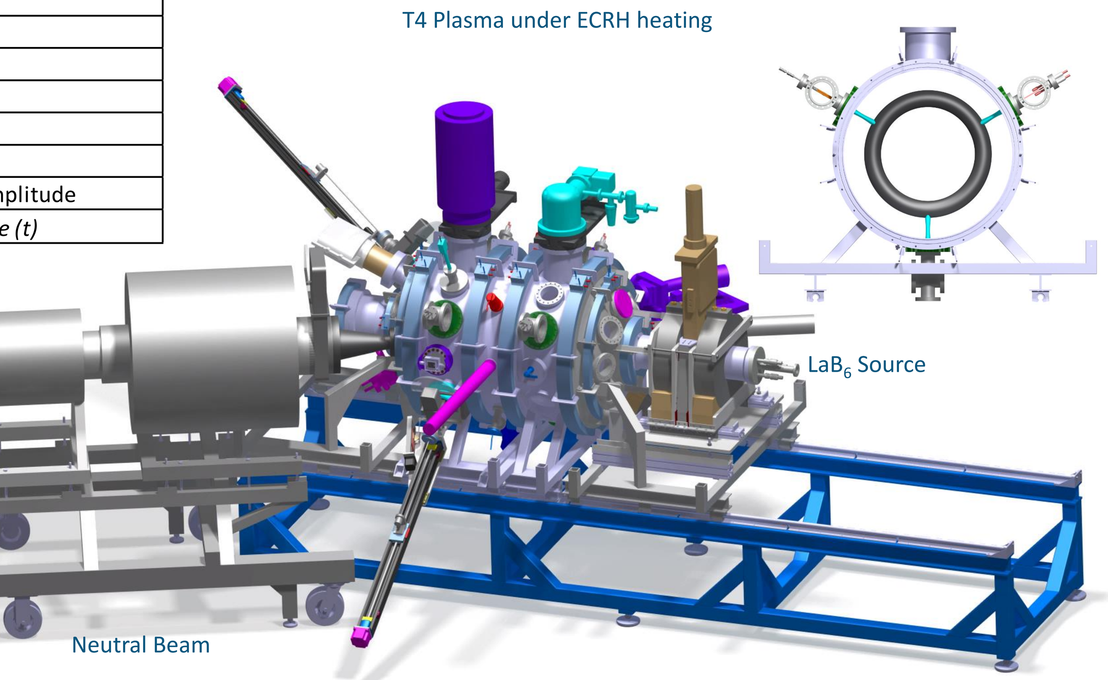
Diagnostic	Parameters
Microwave interferometer	<n-e>
Wobble Langmuir probe (single or triple)	n-e, n-I, T-e, EEDF, Vp, Vf, I-i
Wobble B-dot probe	flux(t), B(t), p(t), tau(t)
Plunge Langmuir probe (single or triple)	n-e(t), T-e(t), I-i(t)
Plunge B-dot probe	flux(t), B(t), p(t), tau(t)
Flux loops	flux(t), B(t), p(t), tau(t)
ES analyzer array	IEDF, EEDF, axial outflux
Thomson scattering, single point	n-e, T-e
Multiple high speed imagers	spatial intensity(t),shape(t), assess mode #, mode amplitude, rotation rate, sheath size
Bolometer	radiated power(t)
High res spectroscopy	T-i(t), n-e(t)
D-alpha, D-beta spectroscopy	T-i through CX
Impurity survey spectroscopy	Impurity content
Hard X-ray Detector	EEDF
RGA	Impurity content
Soft X-ray Spectroscopy	T-i(t), n-e(t)
Crown of thorns array	mode number and amplitude
Soft X-Ray Imaging (swap soft x-spec.)	*emission spatial profile (t)*



T4 Plasma under ECRH heating



T4 Plasma with LaB_6 injection

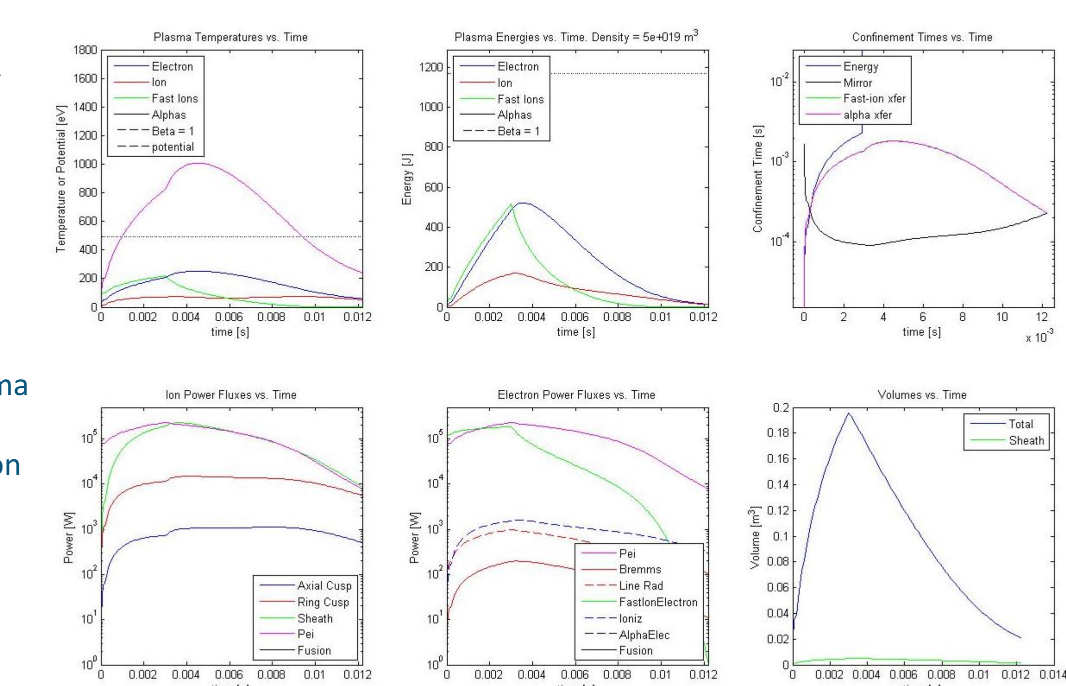


Zero-D Results for T4B Experiment

T4B goals are to characterize sources in the CFR geometry and to conduct the first ion heating experiments with neutral beams.
- Show inflation of CFR plasma to high beta.
- Characterize sheath widths and main losses.
- No stalk shielding is needed, the loss is not dominant at low temps.

General behavior
- Neutral beam lasts long enough to heat plasma to high beta conditions.
- At low densities, mid $10^{19}\ m^{-3}$, get hot electron plasma and fast neutral beam ions.
- At high densities, low $10^{20}\ m^{-3}$, get some ion heating and much lower electron temps.

T4B Parameters
- 1 m diameter x 2 m long
- 1 MW, 25 keV H-neutral beam heating power
  - 3 ms duration
  - Assume 500 kW is converted into fast ions.
- $n = 5 \cdot 10^{19}\ m^{-3}$
- Beta = 1 (Field = 0.1 T)
- V = 0.2 m^3, 1170 J Total Energy
- Peak T_i = 75 eV
- Peak T_e = 250 eV
- Peak sheath loss = 228 kW, about equal to P_{ei}
- Peak ring cusp loss = 15 kW
- Peak axial cusp loss = 1 kW



The T4B Experiment with moderate levels of neutral beam heating should show good confinement and millisecond duration plasmas, dominated by sheath losses.