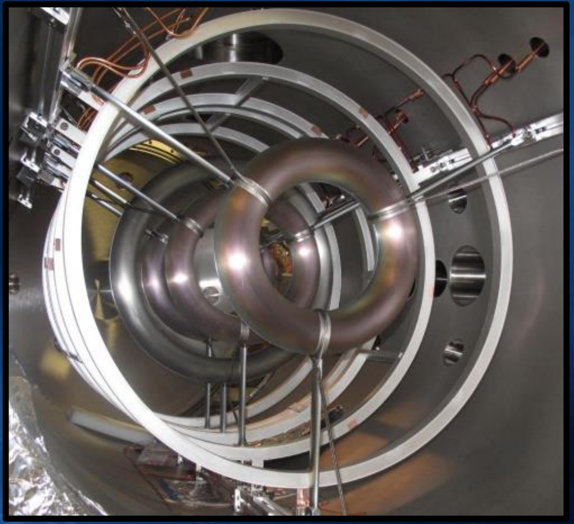
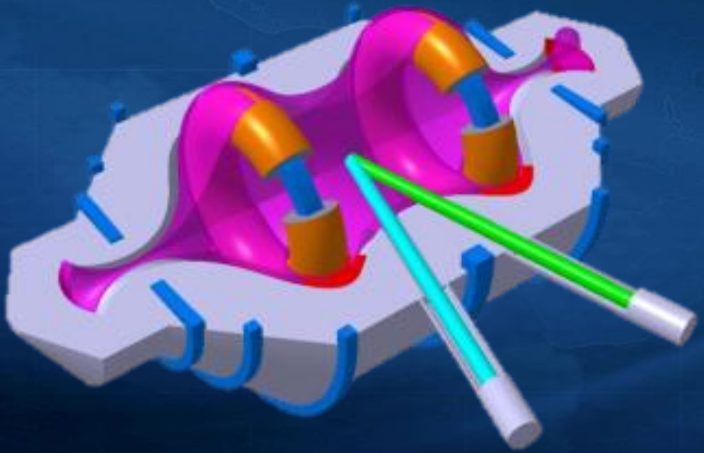
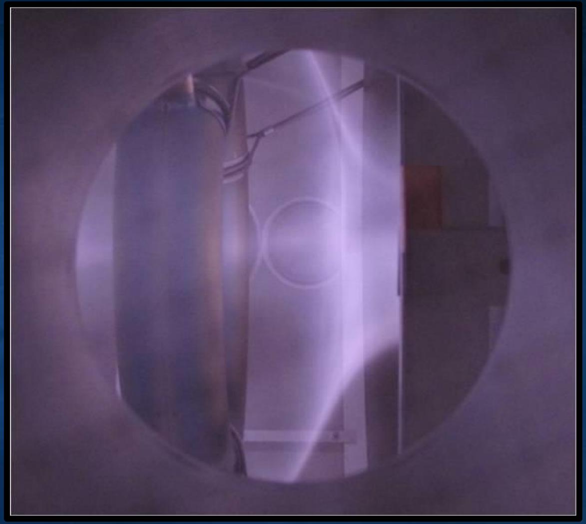
Compact Fusion Reactor, CFR







LOCKHEED MARTIN

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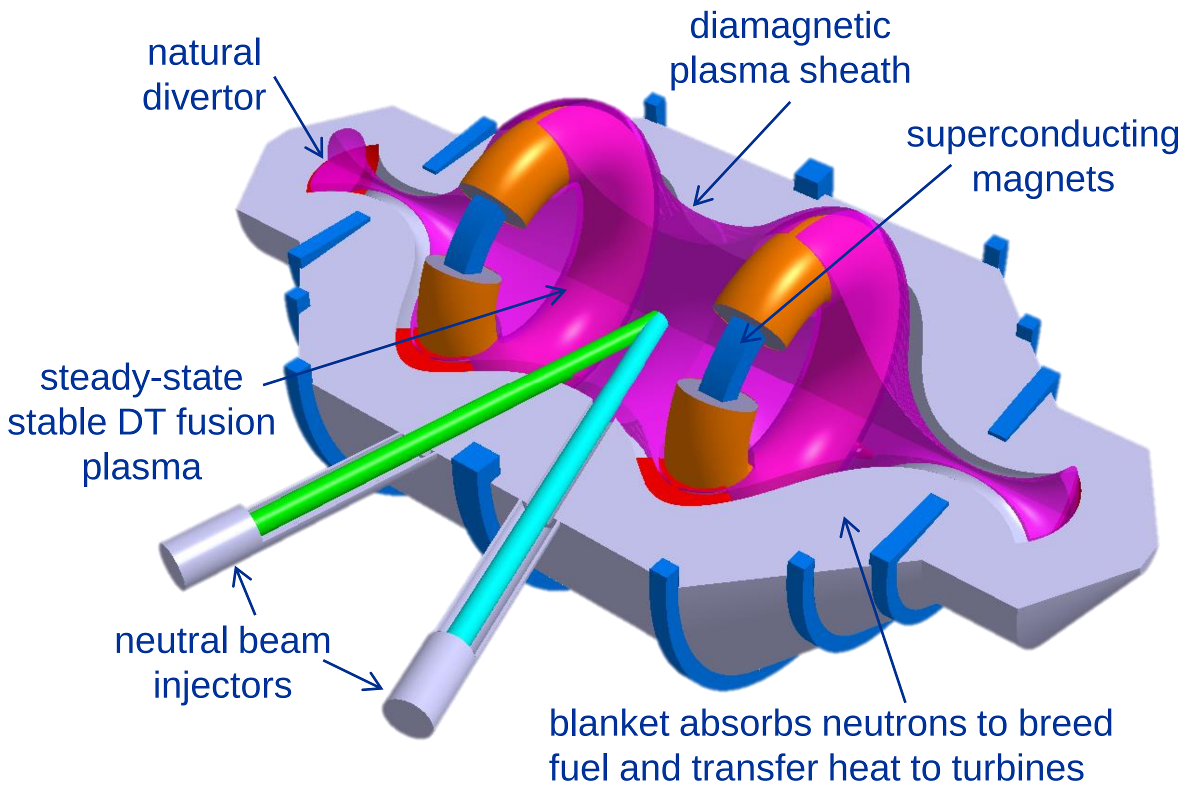
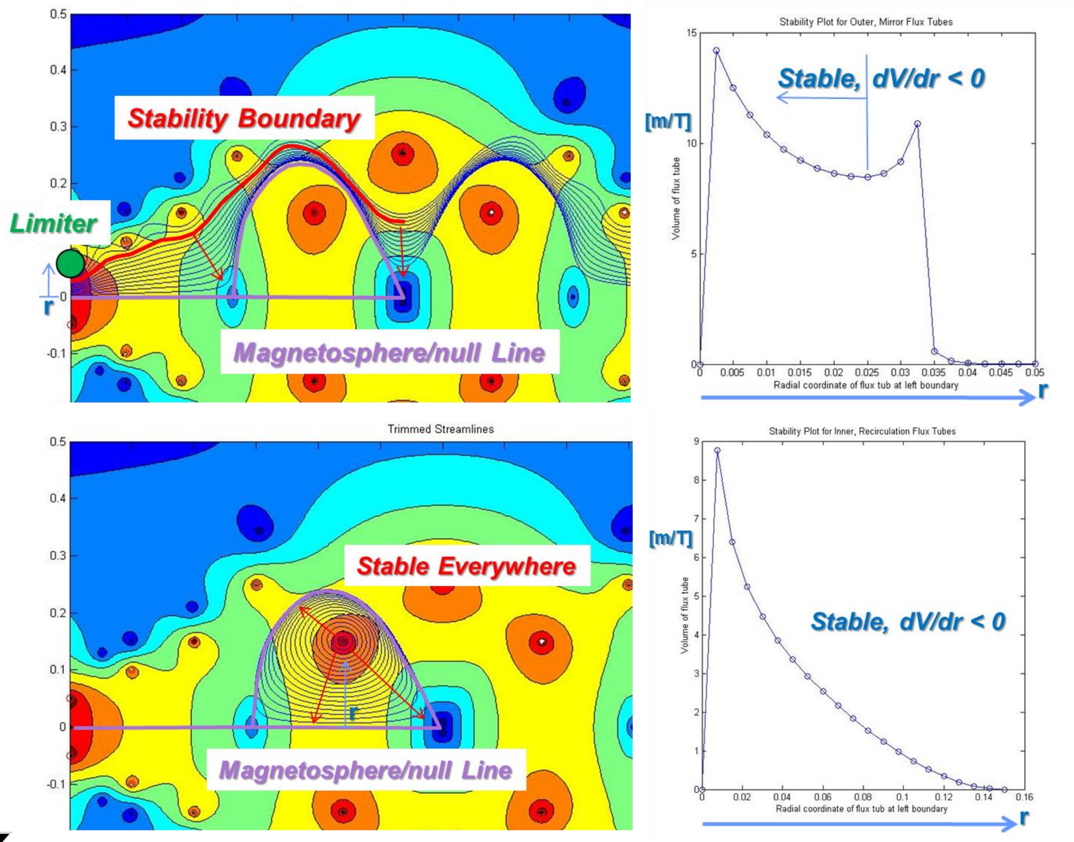
The Lockheed Martin CFR Concept

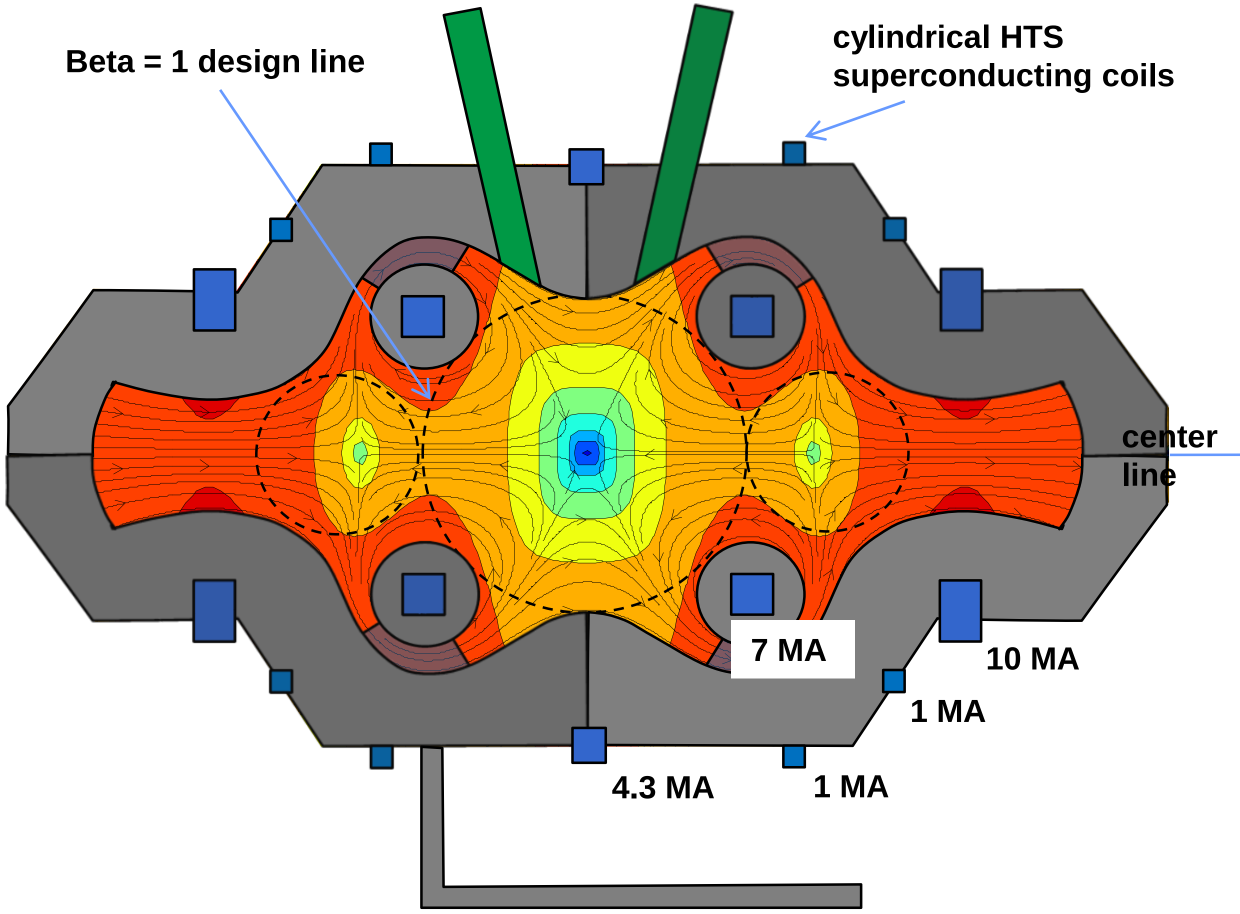
- **LM Philosophy, need and mission**
  - **1.3 B without electricity, 18% of world, EIA International Energy Outlook 2013 (IEO2013)**
  - **+56% energy consumption and +93% electricity generation from 2010 to 2040, EIA International Energy Outlook 2013 (IEO2013)**
  - **@ $3/W, $210B/yr in new electrical power plant sales alone**
- **Compact, elegant…rapid development, short cycles. High beta**
- **Favorable reactor geometry**
  - **Similar method: J. P. Freidberg, F. J. Mangiarotti, and J. Minervini, Physics of Plasmas 22, 070901 (2015).**
- **Nominal Reactor Design Point**
  - **200 MW Thermal, $T = 14$ keV, $n = 1.8\cdot10^{20}\ \mathrm{m}^{-3}$, $V = 30.8\ \mathrm{m}^3$.**
  - **1 m blanket, 80%/20% FLIBE/Steel, 3.2 g/cc, 4 $\mathrm{MW/m}^2$ neutron wall load**
  - **Core: 5.2 m diameter by 15.2 m long, 230 mt**
  - **$B_{\beta=1}$=1.4 T, p = 7.8 atm, B_{mirror} = 4.2 T, 9 MA mirror current**
- **Conservative Reactor Design Point**
  - **200 MW Thermal, $T = 14$ keV, $n = 6.3\cdot10^{19}\ \mathrm{m}^{-3}$, $V = 247\ \mathrm{m}^3$.**
  - **2 meter blanket, 5 g/cc, 1 $\mathrm{MW/m}^2$ neutron wall load**
  - **Core: 10.5 m diameter by 30.5 m long, 1900 mt**
  - **$B_{\beta=1}$=0.84 T, p = 2.8 atm, B_{mirror} = 5.0 T, 20 MA mirror current**



Vacuum Fields and Stability

- **Vacuum field is a set of linear ring cusps encapsulated by a bottle field**
  - **Beta = 1 surfaces are in-board of cusps**
  - **Line-averaged global interchange stability is achieved, only locally-bad curvature in ring cusps, $\int \frac{dl}{B}$**





High Beta Inflation

- Vacuum field is a set of linear ring cusps encapsulated by a bottle field
  - Beta = 1 surfaces are in-board of cusps
  - Line-averaged global interchange stability is achieved, only locally-bad curvature in ring cusps
- Interchange pushes plasma into magnetic wells, observed in initial low power experiments
  - Heating creates plasma at discrete locations in volume, propagates along field lines
  - Pressure gradients should kick off turbulence that will organize a diamagnetic plasma
  - As plasma pressure increases, Beta = 1 sheath boundary should ‘inflate’ and fill up chamber volume.
  - Need sufficient heating to fully ionize background gas and to raise temperature to levels that reduce CX collisions and mirror losses.

Magnetized sheath losses

$$P_S \approx \frac{L_M r_p n_s^2}{B_p} \approx \frac{r_p^2 n^{\frac{3}{2}}}{T^{\frac{1}{2}}}$$

$$P_{i,s} = \frac{3}{2} e\left(T_i + e\phi_p\right) L_s \quad [W]$$

$$P_{e,s} = \frac{3}{2} e\left(T_e - e\phi_p\right) L_s \quad [W]$$

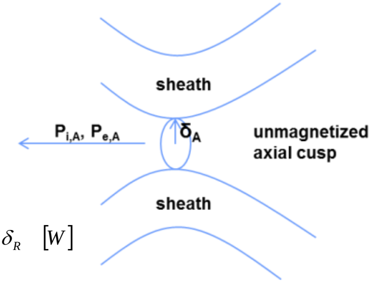
$$L_s = \frac{n_s V_s}{\frac{\tau_{ii}}{2}}, \quad \tau_{ii} = 2 \cdot 10^{13} \frac{\mu^{\frac{1}{2}} T_i^{\frac{3}{2}}}{n_s \lambda_{ii}} \quad [s]$$

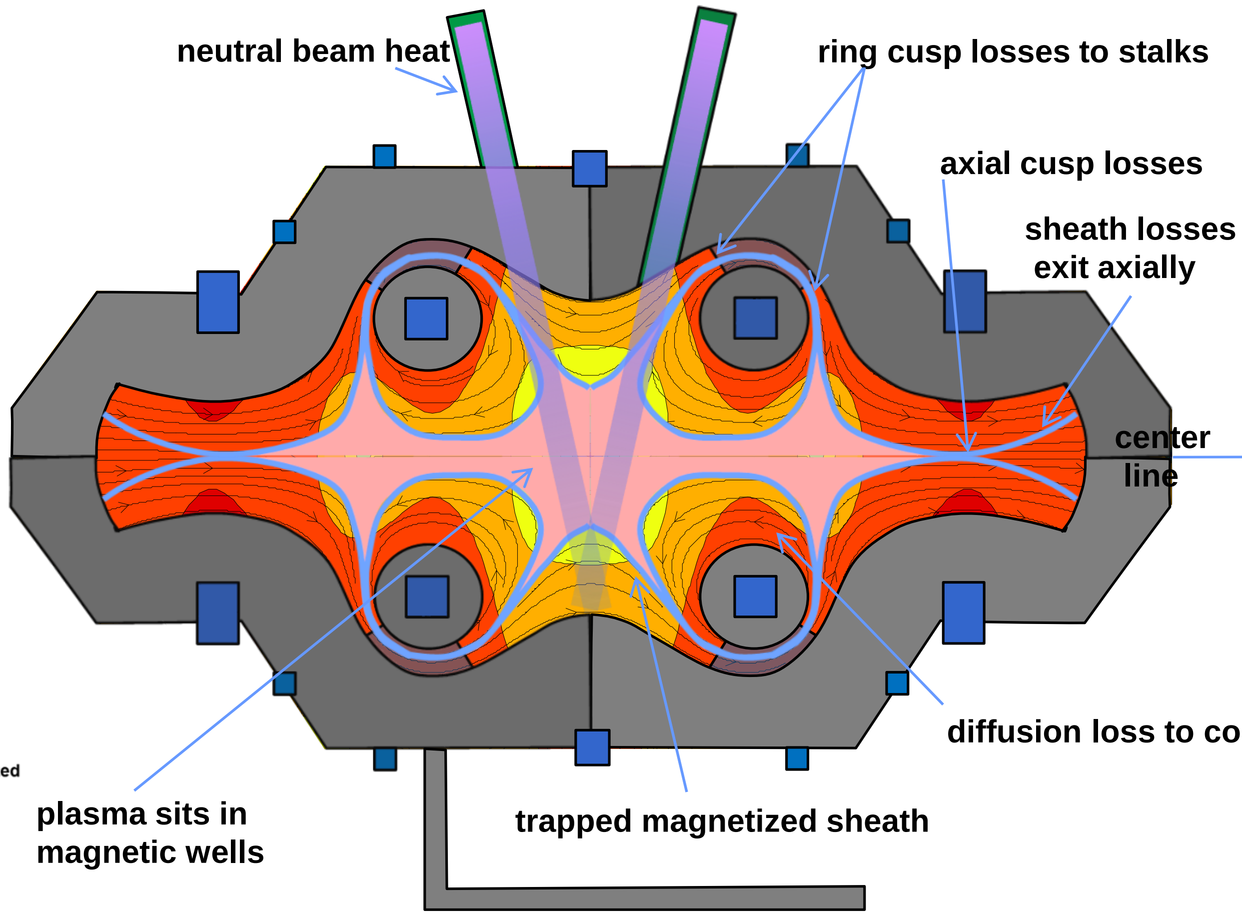
Unmagnetized ring cusp losses to coil supports

$$P_R \approx \frac{r_p n T^2}{B_p} \approx r_p n^{\frac{1}{2}} T^{\frac{3}{2}}$$

$$P_{i,R} = \frac{3}{2} e\left(T_i + e\phi_p\right) \Gamma_s A_R \%i \cdot S = \frac{24\sqrt{2}}{\sqrt{\pi}} e\left(T_i + e\phi_p\right) \sqrt{\frac{eT_i}{m_i}} n \left(\frac{n_R}{n}\right) e^{\left(\frac{e\phi_p}{T_i}\right)} \cdot \frac{N_s a R}{R_s} S \delta_R \quad [W]$$

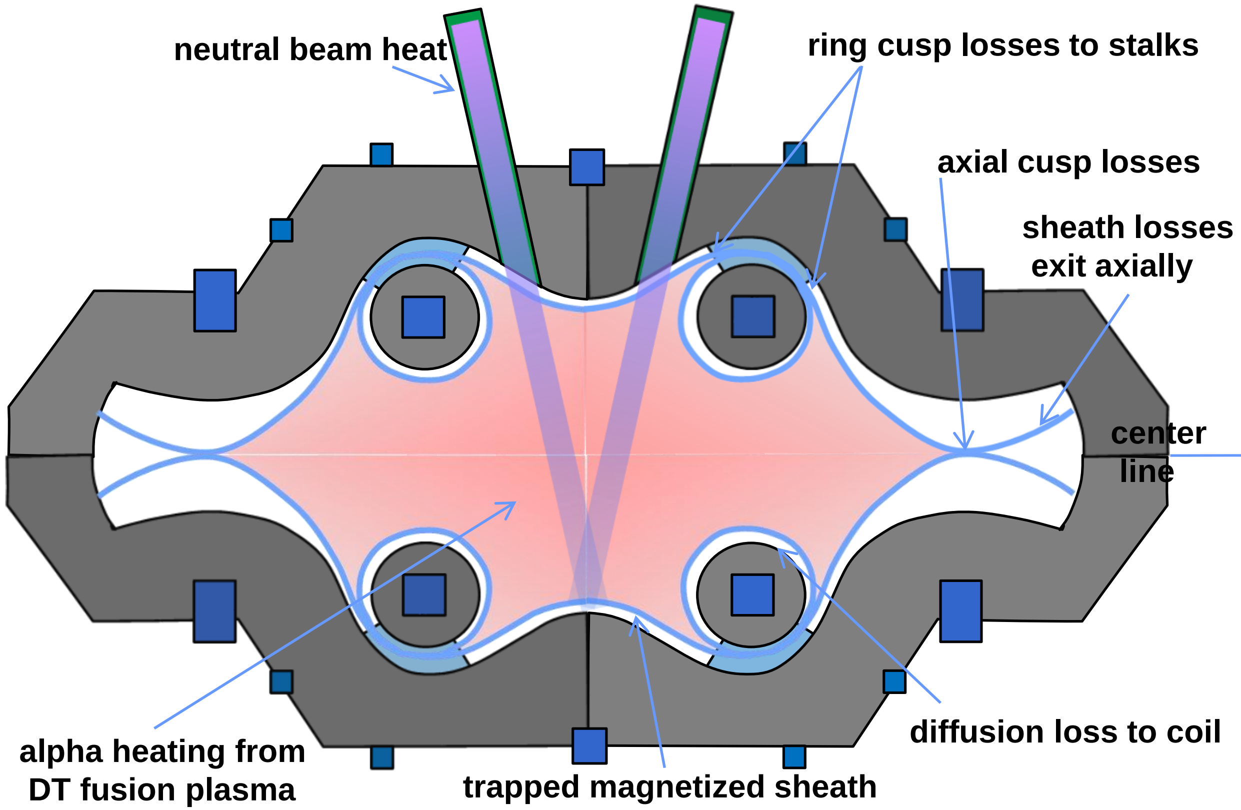
$$P_{e,R} = \frac{3}{2} e\left(T_e - e\phi_p\right) \Gamma_s A_R \%i \cdot S = \frac{24\sqrt{2}}{\sqrt{\pi}} e\left(T_e - e\phi_p\right) \sqrt{\frac{eT_i}{m_i}} n \left(\frac{n_R}{n}\right) e^{\left(\frac{e\phi_p}{T_i}\right)} \cdot \frac{N_s a R}{R_s} S \delta_R \quad [W]$$





Fully Inflated Confinement Scaling and Challenges

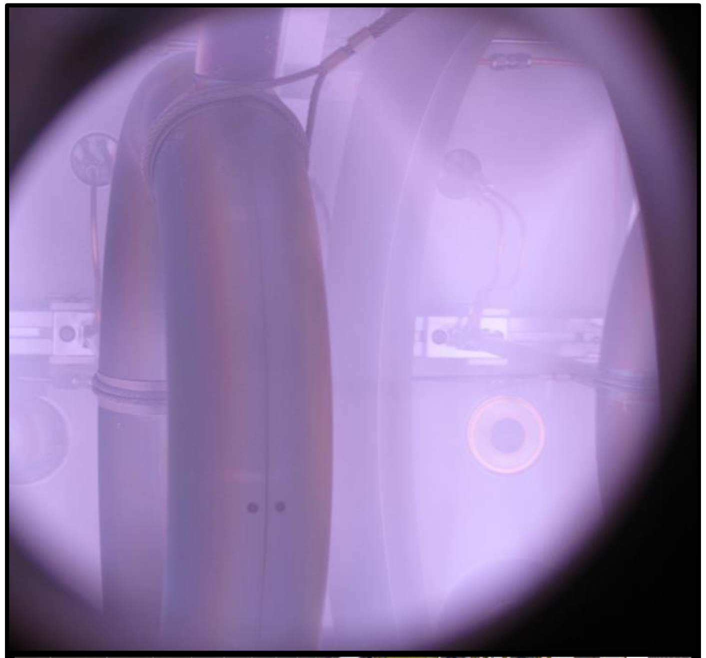
- Steady-state
  - Need a consistent equilibrium solution, complex kinetic plasma
- Main losses
  - Magnetized sheath, ion losses from positive plasma
  - Unmagnetized ring cusp losses to supports
  - Charge exchange losses
  - Line radiation
  - Bremmstrahlung radiation
  - Unmagnetized cusp losses on axis
  - Diffusion across magnetic fields to walls
- Ionization and heating
  - ECRH
  - LaB6
  - Plasma gun
  - Electron or ion beam
  - Neutral beam initialization
  - Alpha product self-heating
- Biggest challenges and questions
  - Cusp behavior – drives scaling and shielding requirements
  - Shielding implementation – 90% reduction needed for hybrid gyro
  - Microinstabilities, ExB and stability during inflation transient
  - Plasma facing surfaces, neutron damage and blanket design
  - Tritium lifecycle and containment

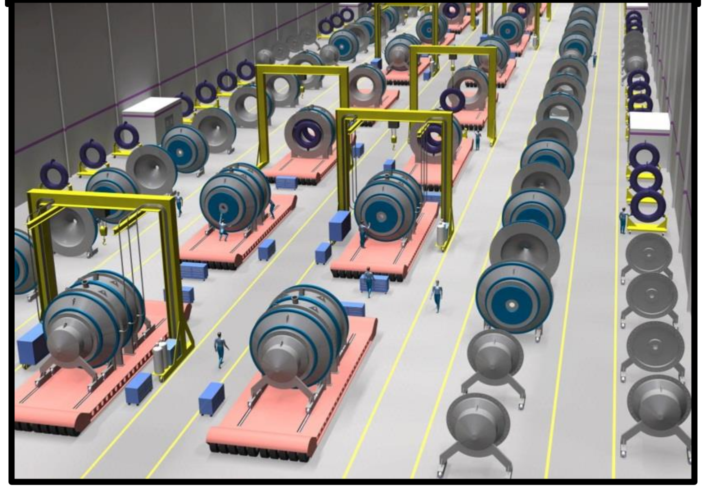


$$Q=\frac{P_f}{P_L}=\frac{1.3eY\langle\sigma v\rangle}{\underbrace{1.6\cdot10^{-33}\left(\frac{n_s}{n}\right)^2\left(\frac{1}{r_pB_p}\right)}_{\text{Sheath}}+\underbrace{2\cdot10^{-44}\left(\frac{n_R}{n}\right)S\left(\frac{T^3}{r_p^2B_p^3}\right)}_{\text{Support}}+\underbrace{5.2\cdot\%I\cdot Q_k+8.9\cdot10^{-38}Z_{eff}T^{\frac{1}{2}}}_{\text{Radiation terms}}}$$

Development Path

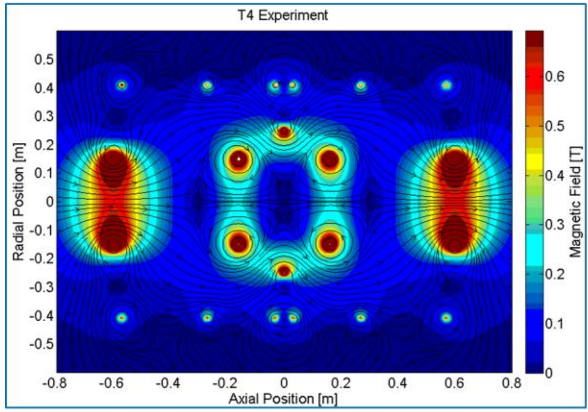
- **Progression of fast experiments with parallel sub-system work**
  - **T4 – Investigate CFR plasma configuration**
  - **T5 – Demonstrate high Beta**
  - **T6 – Demonstrate high power (1 MW), high temperature (1 keV)**
  - **T7 – Demonstrate reactor conditions with Deuterium plasma**
  - **T8 – Demonstrate ignited DT plasma for short durations (<10 sec)**
- **Parallel sub-system development**
  - **Plasma simulation**
  - **Neutral beam heating development**
  - **Superconducting magnetic field coils**
  - **Internal coil support shielding**
  - **Blanket design and power plant design**
- **Engineering and product development, towards a T-X Reactor**
  - **Energy conversion cycle**
  - **Materials, tritium cycle, servicing**
  - **Regulation, environmental impact, ITAR, military applications**

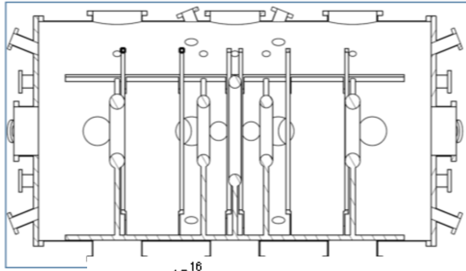




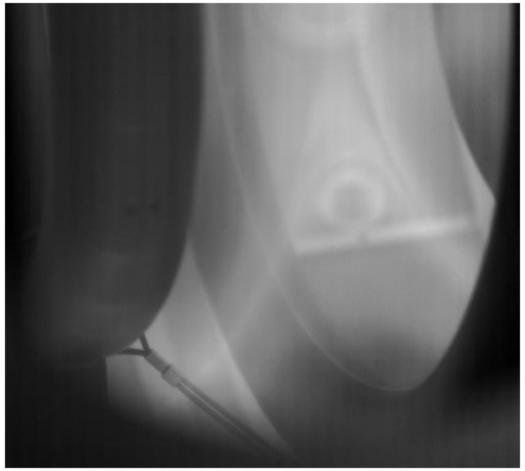
Current T4 Experiments

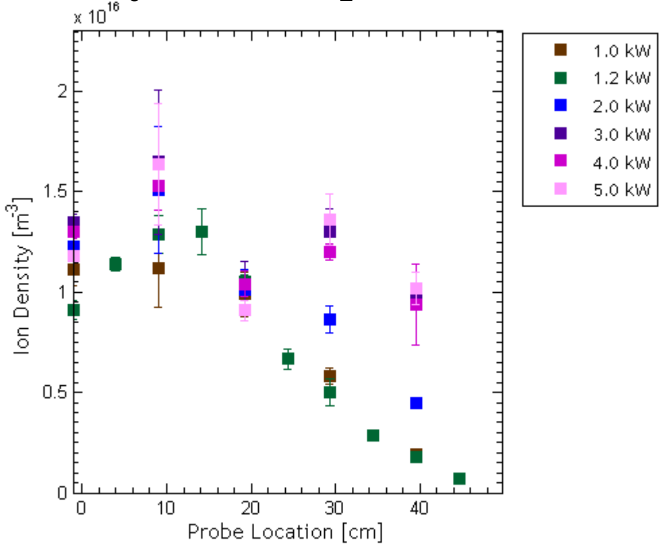
- T4 goal: Investigate CFR plasma configuration
  - $V_{plasma} = 0.33\ m^2$, $V_{chamber} = 2\ m^3$.
  - $n_{background} = 3{\cdot}10^{18}\ m^{-3}$ D2 gas
  - 0-15 kW 2.4 GHz ECRH, axial injection
  - Peak mirror magnetic field 0.6 T, shot duration ~1 sec.
- Results, 482 shots to date
  - Observe plasma organization in magnetic wells
  - ECRH cut-off limits ability to reach full ionization, <10%
  - At higher powers, observe outer regions filling with plasma
  - Peaked density profiles in core, flat T_e with increased power
  - Typical n = $10^{16}\ m^{-3}$-$10^{17}\ m^{-3}$, T_e = 10-25 eV, τ_E = 4-100 μsec

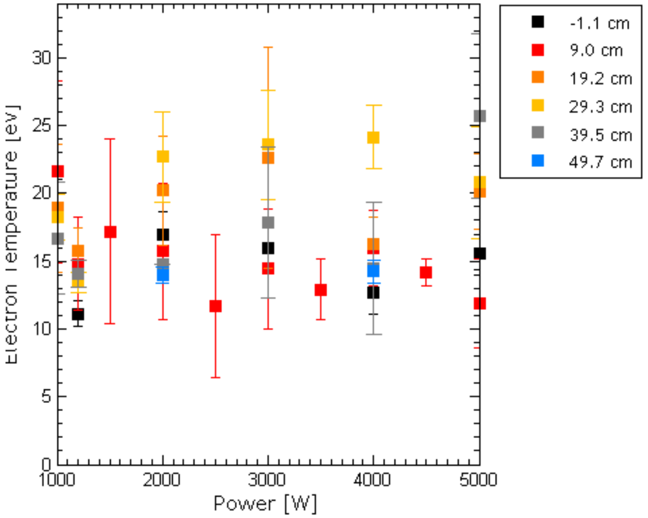


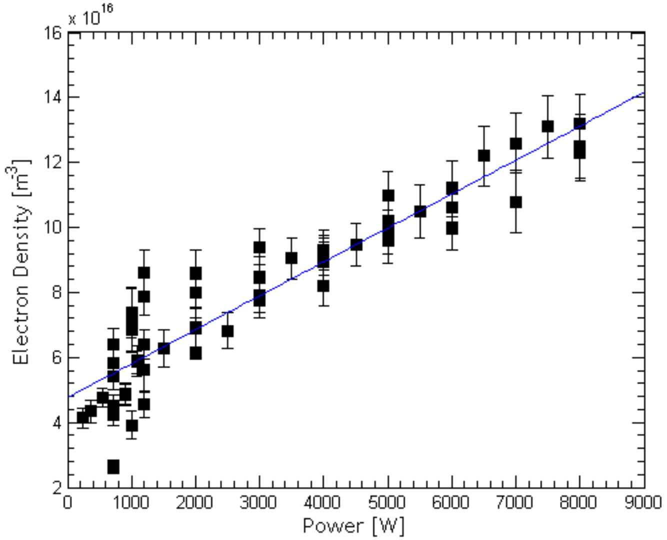


Diagnostics:
Microwave interferometer
Diamagnetic loops
Bolometer
Soft x-ray – UV spectrometer
Hard x-ray
Visible spectroscopy
High-speed imaging
Langmuir probe
B-dot probe



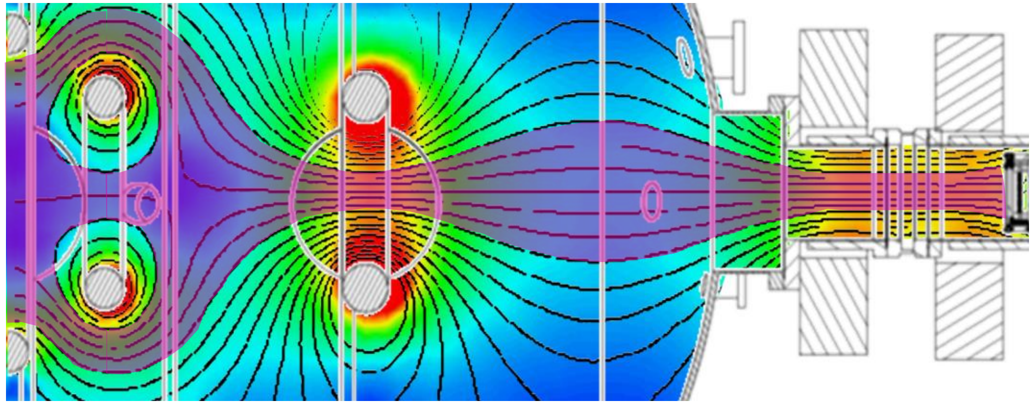


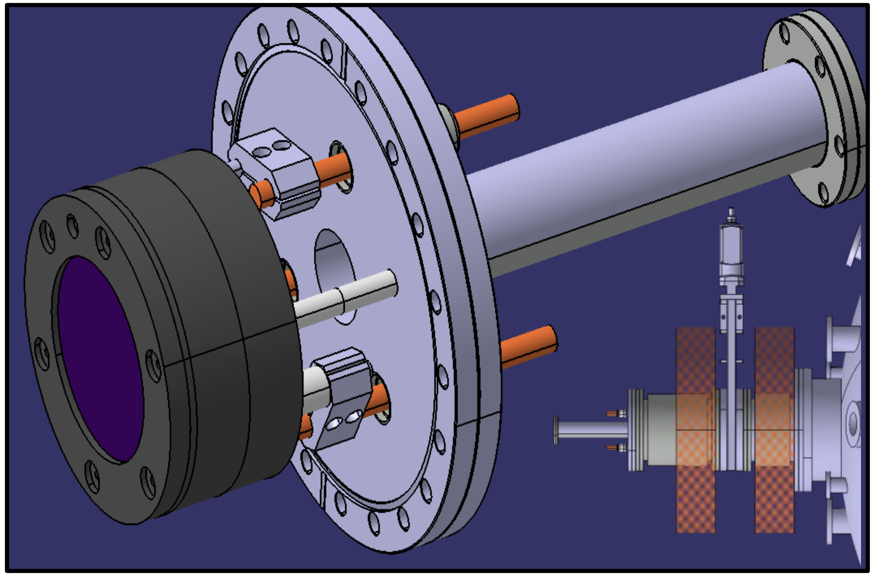




Plots: (far left) FastCam visible imager(left) ion density vs. probe location, (center) electron temperature vs. power at different probe locations. Error bars represent the standard deviation of values calculated from I-V sweeps taken multiple times during the run. (right) line-averaged density from interferometer averaged over shot. Error bars are the result of signal noise and magnetic field effects. Blue line is a linear fit to the data.

Future Work and Collaboration Opportunities





T5 plan

- **Fully ionized plasma, LaB_6 source and washer gun**
- **Improved diagnostics**
  - **Langmuir probes, b-dot probes, ES analyzer, spectroscopy, Thomson scattering, flux loops**
- **Neutral beam heating development, hot high beta**
- **Alternate heating: axial electron and ion beam heating**
- **Simulations**
  - **Plasma equilibrium**
  - **HPC PIC plasma studies, high Beta cusp behavior, inflation transients, magnetic shielding**
  - **Blanket design, lightweight and low-cost designs**
- **Magnetic support shielding and superconducting coil design**
- **Currently hiring in Palmdale, CA. 14 open positions**
  - **Plasma experimentalist, plasma theory, pulsed power, beam, laser, electronics, mechanical**