High Density Field Reversed Configuration Model

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Abstract

Magnetized Target Fusion (MTF) could achieve fusion conditions by compressional heating of a magnetized target plasma, such as imploding a Field Reversed Configuration (FRC). We are modeling these large density and temperature FRC's similar to those of the early theta pinch days using a variety of approaches. A physics based semi empirical scaling law model [1,2] is used to benchmark our designs against the existing (but limited) world database. The two dimensional MagnetoHydroDynamic (MHD) fluid code MOQUI[3] is also being used to validate the time evolution of non ideal MHD equilibria during formation, compression, heating and translation. Other particle fluid hybrid models are being built to investigate the non MHD electron response to toroidal precession by eliminating the usual assumptions that tie electrons to magnetic field lines. The goal of the modeling effort is to extend our predictions to the MTF regime of interest ($n > 5\text{x}10^{16}\text{cm}^{-3}$, $T_e+T_I > 500\text{eV}$. We have identified several key FRC physics and MHD issues, including stability, flux retention, scaling into the collisional regime, and scaling to large density. The results are guiding us in this year's design and fabrication of the FRC physics experiment at Los Alamos National Laboratory with AFRL participation.

[1]R Siemon, R Bartsch, Proc 3rd Symp Physics & Techn of Compact Toroids, Los Alamos NM, LA-8700-C (1980)

[2]M Tuszewski, Nucl Fusion, 28, 2033 (1988).

[3]R Milroy, J Brackbill, Phys Fluids 25, 775 (1982).

Physics Basis for FRC Understanding

- Stability
- Flux retention
- Scaling into collisional regime at large density
- There exists FRC data base that covers the parameter space we are looking at
- Need for some dimensionless variables to compare different size experiments on the same graph

Model is Simple

- Radial pressure balance $P_m = P(\Psi) + \frac{B_z^2}{2\mu_0} = \frac{B_{ext}^2}{2\mu_0}$
- Axial pressure balance $<\beta>=1-x_s^2/2$
- Poloidal flux, ε parametrizes fuzzy boundary
  - $\varphi_{eq} = \pi r_c^2 B_{ext}(x_s/2^{1/2})^{3+\varepsilon}$
- Radial size scale

$$s = \int_R^{r_s} \frac{rdr}{r_s \rho_i}$$

Temperature scaling - no reverse B_{bias}

- Even without a reversed bias field, kinetic shock and radial compression to crowbar field Bc => implosion temperature

$$k_B T_I = 0.3 B_c^{4/5} B_{GN}^{6/5} (kG) A_i^{3/10} / \mu_0 n_0$$

- Where the Green Newton reference magnetic field where the $E_\theta \times B_z$ speed = v_A at the edge

$$B_{GN} = 0.3 E_\theta^{1/2} (\mu_0 m_i n_0)^{1/4}$$

- Formula for implosion temperature is

$$T_I = 470 E_\theta^{3/5} (kV/cm) B_c^{4/5} (kG) A_i^{3/10} / p_0^{7/10} (mTorr)$$

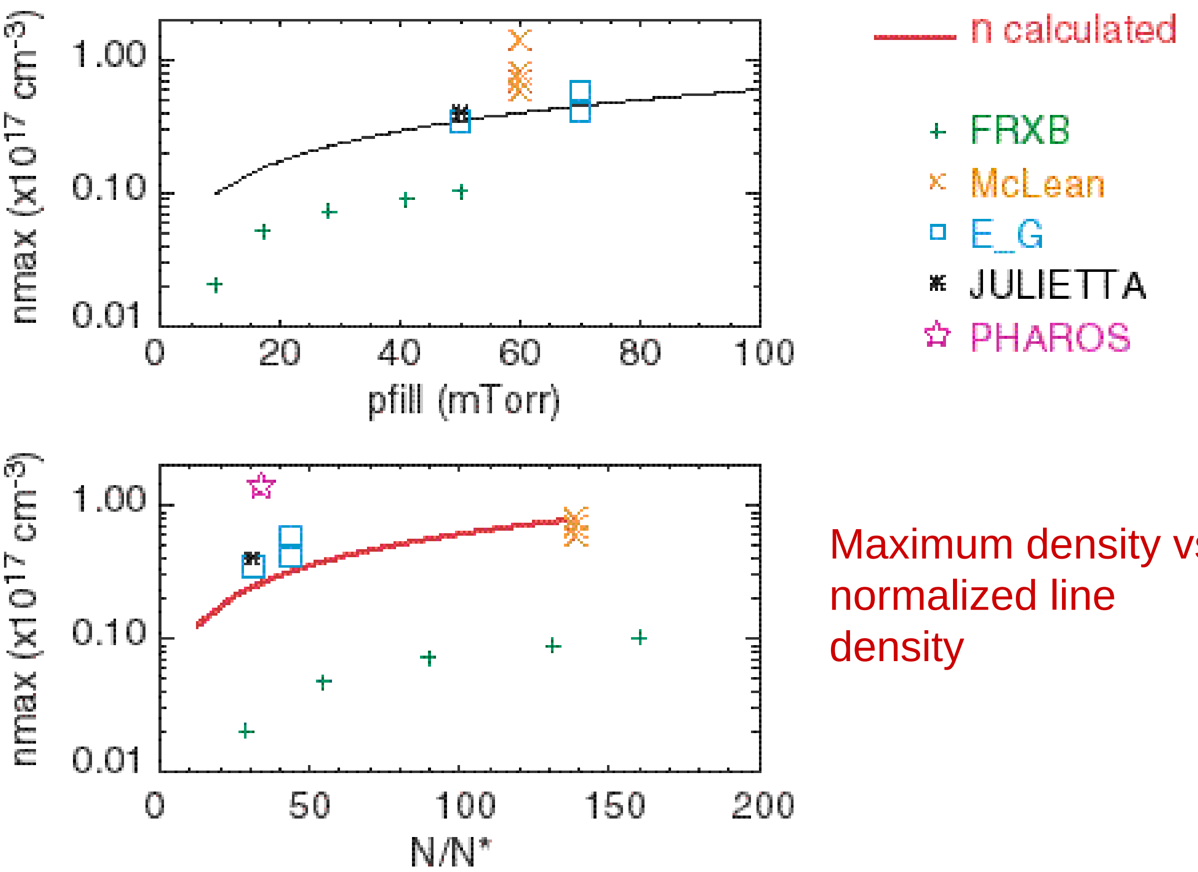
Scaling parameters with reversed B_{bias}

- As external field reverses, separatrix "lifts off" the wall at ExB speed
- Lift off field B_{LO} = some fraction of B_{GN}, B_{bias}
  - $B_{LO}/B_{bias}=[1+1.7(B_{bias}/B_{GN})(N_*/N_0)^{1/4}(1-\eta_t)^{2/5}]^{-1} \approx 1-(B_{bias}/B_{GN})^2$
  - N_0 =initial line density, N_*=threshold for anomalous ion diffusion
  - η_t = circuit transfer efficiency
- Add resistive (poloidal flux dissipation) + axial contraction heating to radial shock heating
- $T/T_I=h_t=(3^{1/2}/2)(1+1.7G_{LO}{}^{1.5})^{-1}+2.7G_{LO}{}^{1.2}$
  - This can get large (T/T_I >2-3) for $G_{LO}\approx 1$

FRC experiments from the days of yore

- PHAROS at NRL
  - Kolb
  - McLean
    - 1.2 MJ bank, 18kV
    - r_{coil} = 5.25, 6.75 cm
    - P_0 = 60mTorr
    - $N \approx 10^{17} cm^{-3}$
    - $T_e \approx T_i \approx$500-1000eV
- Garching
  - Eberhagen & Grossman
    - 15kJ bank, 40kV
    - r_{coil} = 5.25 cm
    - P_0 = 50mTorr
    - $N \approx 4x10^{16} cm^{-3}$
    - $T_e \approx T_i \approx$40-60eV
- JULIETTA at Julich
  - Kaleck
    - 1 MJ bank, 18kV
    - r_{coil} = 5.25, 6.75 cm
    - P_0 = 50mTorr
    - $N \approx 4x10^{16} cm^{-3}$
    - $T_e \approx T_i \approx$230
- FRX-B at LANL
  - Tuszewski, Lipson
    - 60kJ bank, 40kV
    - r_{coil} = 12.5 cm
    - P_0 = 5-50mTorr
    - $N \approx 10^{15} cm^{-3}$
    - $T_e \approx T_i \approx$100-600eV

FRC database shows a wide range of densities with reasonable agreement with a model



Maximum density vs normalized line density

Compare different data sets using normalized parameters

- Reference line density
  - $N^* = 2\pi m_i/e^2\mu = 3.23 \times 10^{15} \times m_{ion}/m_p$
  - density of a β=1 column whose radius
    - $r=2\rho_{i,\,ext}$ (gyro radius at external B field)
    - $r=2\delta_i$ (ion skin depth)

$$\tilde{N} = N / N^* = 0.032\, r_w^2[cm]\, p_0[mTorr]$$

Compare different data sets using normalized parameters

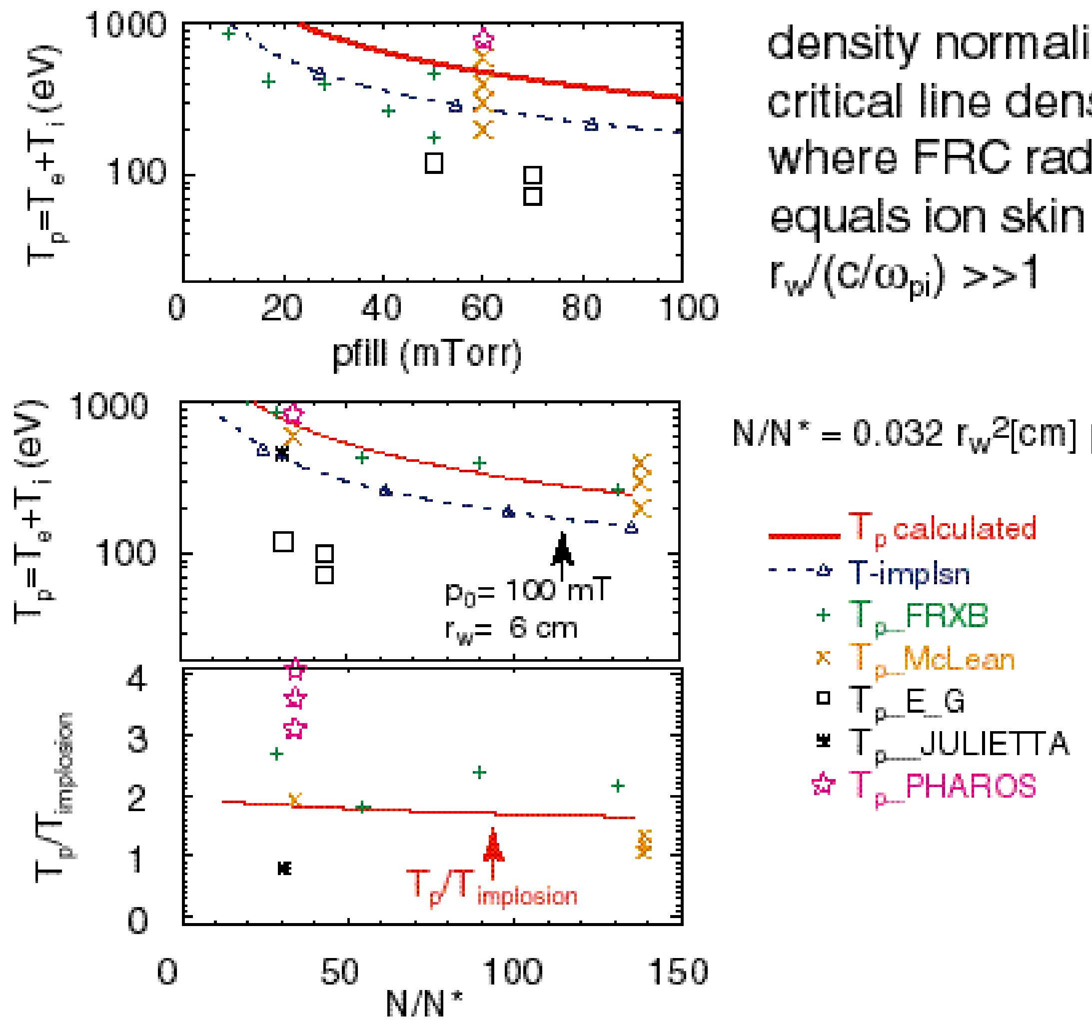
- Normalize equilibrium flux to
  - Green Newton field and flux
  - Bias flux
  - Lift off flux
- Normalize temperatures to
  - Implosion temperature

Compare FRC data base & model predictions for T_e, T_i

Scan fill pressure

equivalent to normalized line density

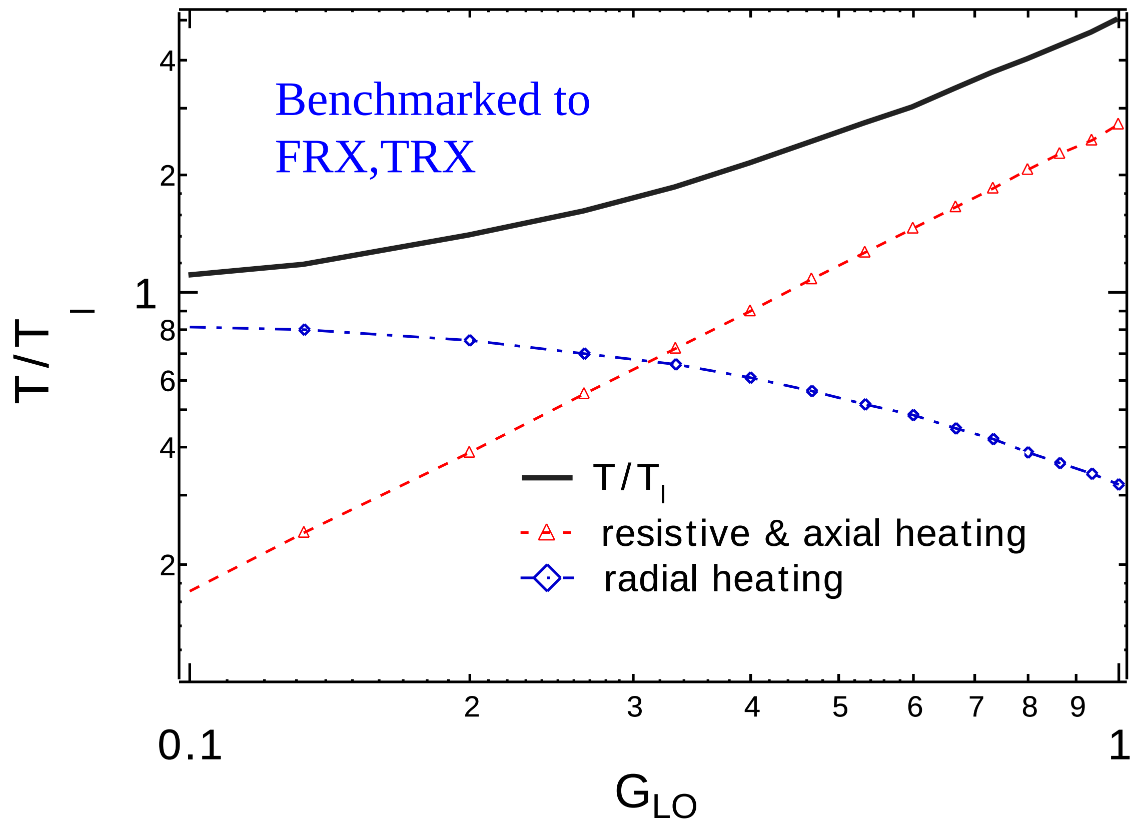
High fill pressure is not necessarily the upper limit of N/N* in the FRC database



density normalized to critical line density where FRC radius equals ion skin depth $r_w/(c/\omega_{pi}) >>1$

$N/N^* = 0.032\ r_w^2[\mathrm{cm}]\ p_0[\mathrm{mTorr}]$

More lift off field B_{LO} increases temperature beyond radial implosion value



B_{LO}/B_{bias}
$\approx 1- (B_{bias}/B_{GN})^2$
$\approx 0.4 - 0.6$

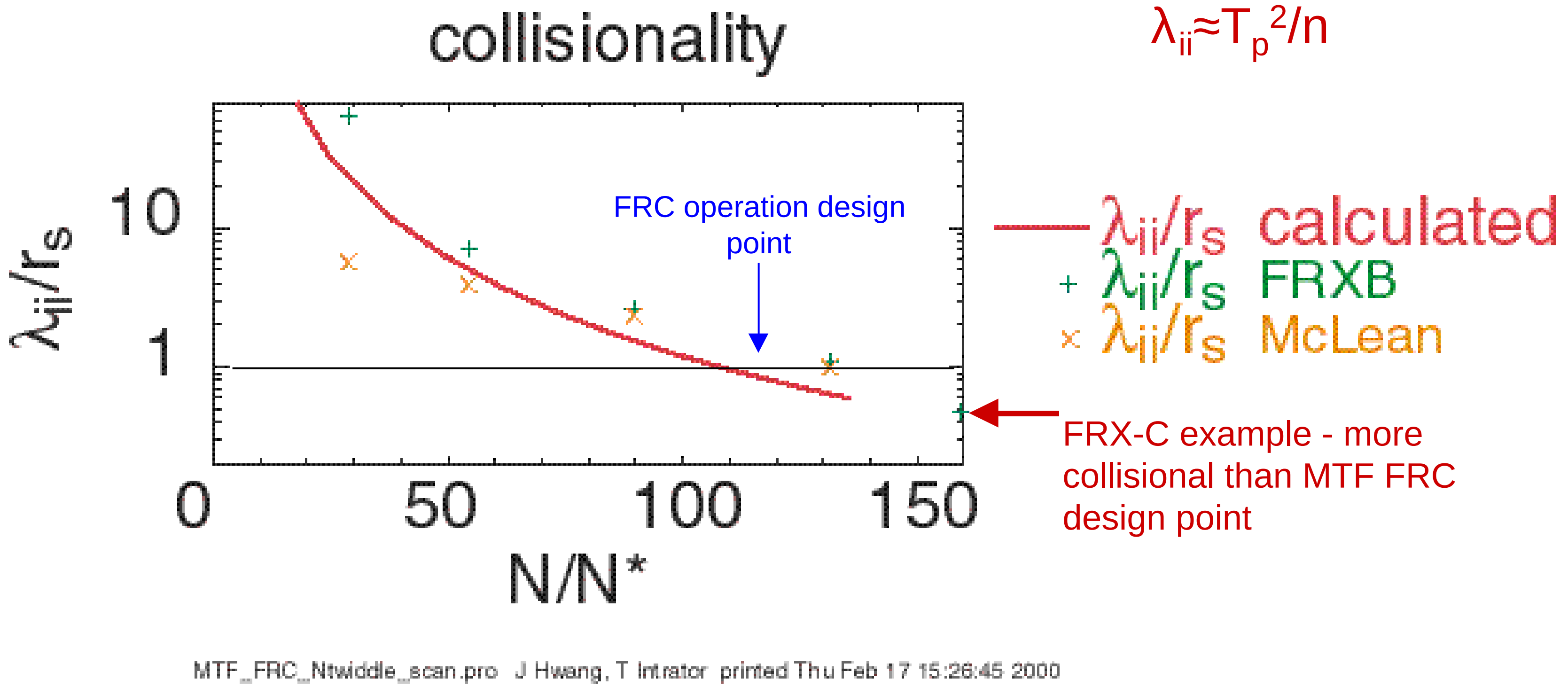
$G_{LO}= B_{LO}/ B_{GN}$
$G_B= B_{Bias}/ B_{GN}$

G_{LO}
$\approx G_B (1- G_B^2)$

However, typical operation at smaller values of G_B than max G_{LO}

FRC data exists in regimes even more collisional than the high density FRC for MTF

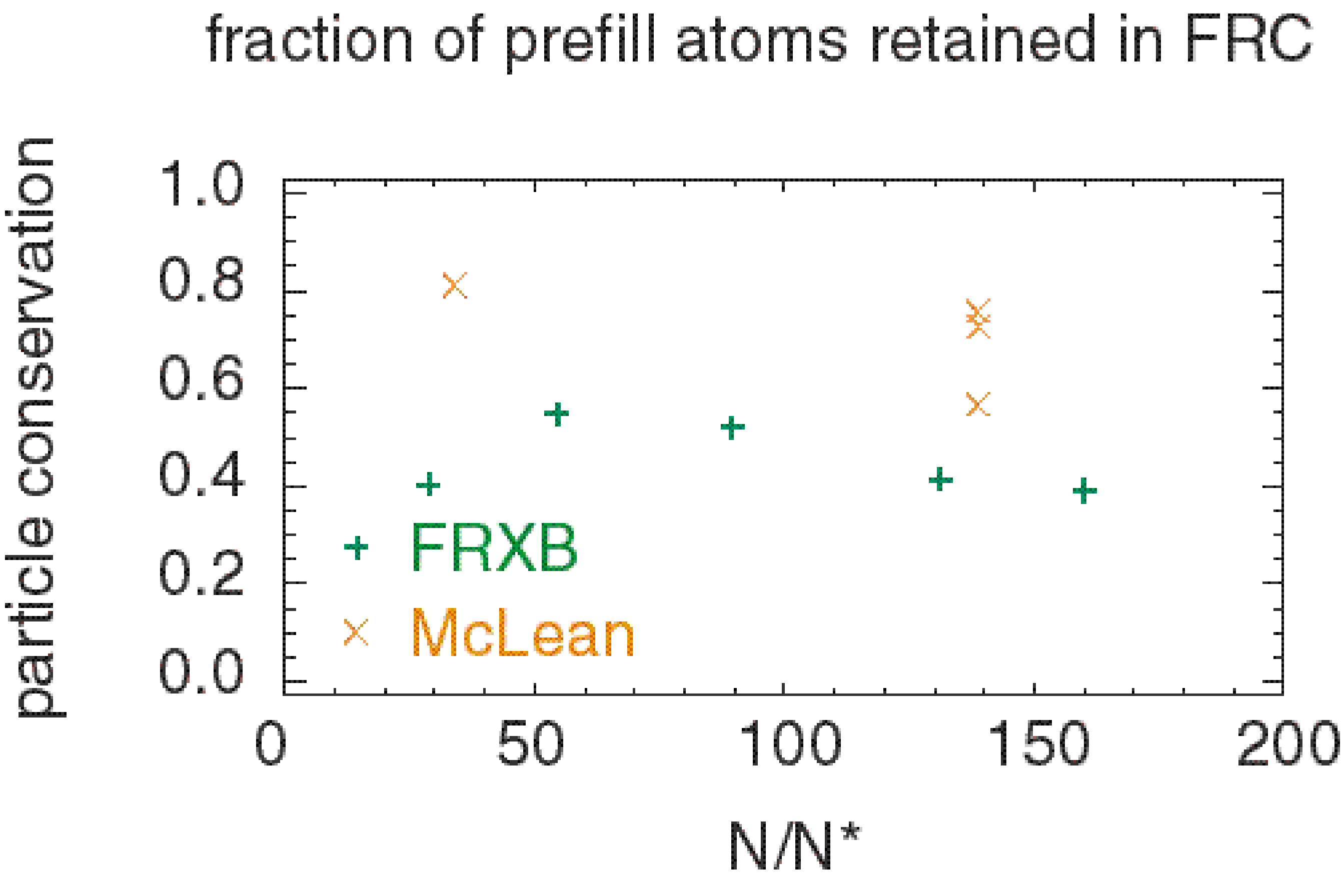
$\lambda_{ii} \approx T_p^2/n$



Internal Flux Retention

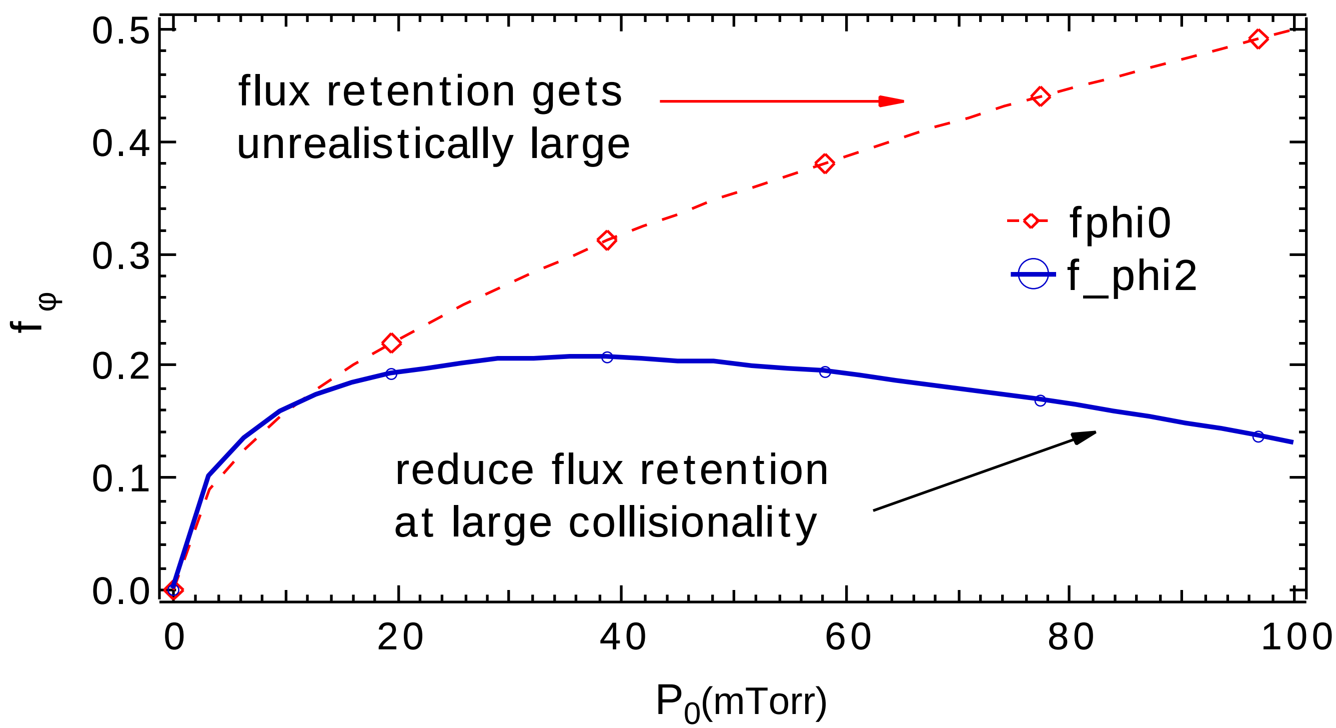
- FRC internal flux decays from φ_{LO} at lift-off to equilibrium value φ_{eq}
  - $\varphi_{eq} = \pi r_c^2 B_{ext} (x_s/2^{1/2})^{3+\varepsilon}$.
- Flux loss may result from
  - 1. Diffusion relaxation across sharp magnetic field gradients until a diamagnetic drift parameter is small enough
  - 2. Dissipation => heating (especially for dirty plasmas!)
  - 3. Possibly faster diffusion at large collisionality

Fraction of atoms from prefill gas retained in the FRC is approximately 50-75%

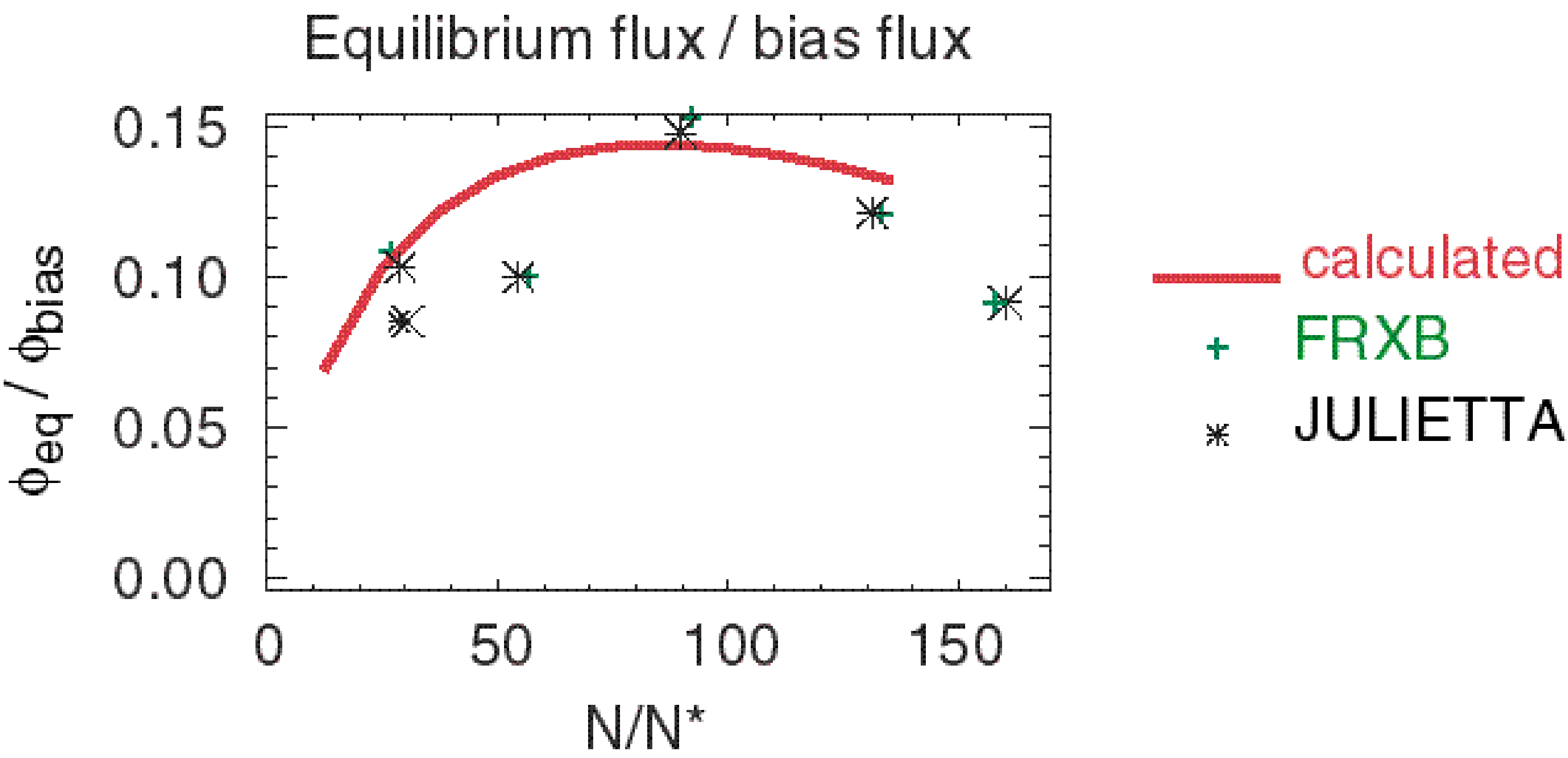


Internal Flux Retention

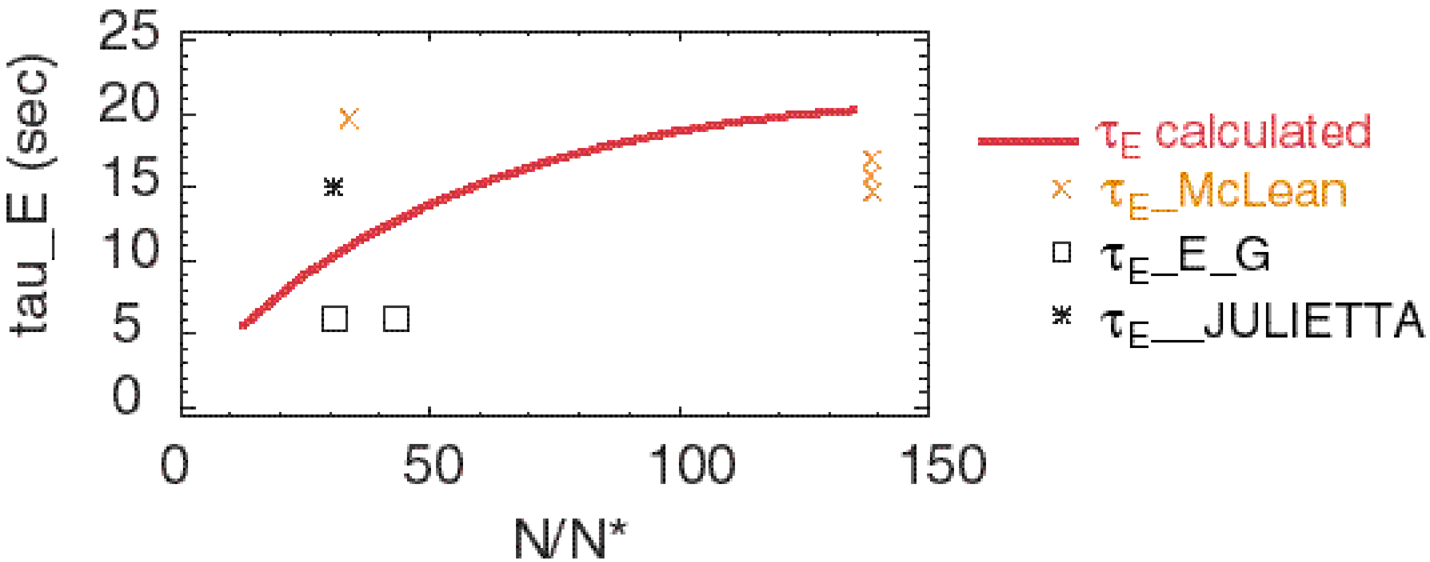
- Flux retention factor $f_\varphi = r_t(m)p_0^{1/2}(mTorr)$???!!!
- Using the φ_{eq} equation $\varphi_{eq}/\varphi_{LO} = 1.1(x_s/2^{1/2})^\varepsilon f_\varphi$



Equilibrium flux is approximately 10-15% of bias flux even at large line density and collisionality



Energy Confinement Lifetime is adequate even at high density



FRC Stability

- Stability
  - Competing speculations
    - S < 4-8 — Univ Washington, TRX, LSX advocates
    - S*/E < 3.5 — LANL, FRX A,B,C data advocates

- Independent knobs are
  - Bias field - but may get pegged at some fraction of Green Newton field $B_{bias}/B_{GN} \approx$ constant?
  - Coil and vessel radius - at constant B_{bias}, B_{bias}/B_{GN}

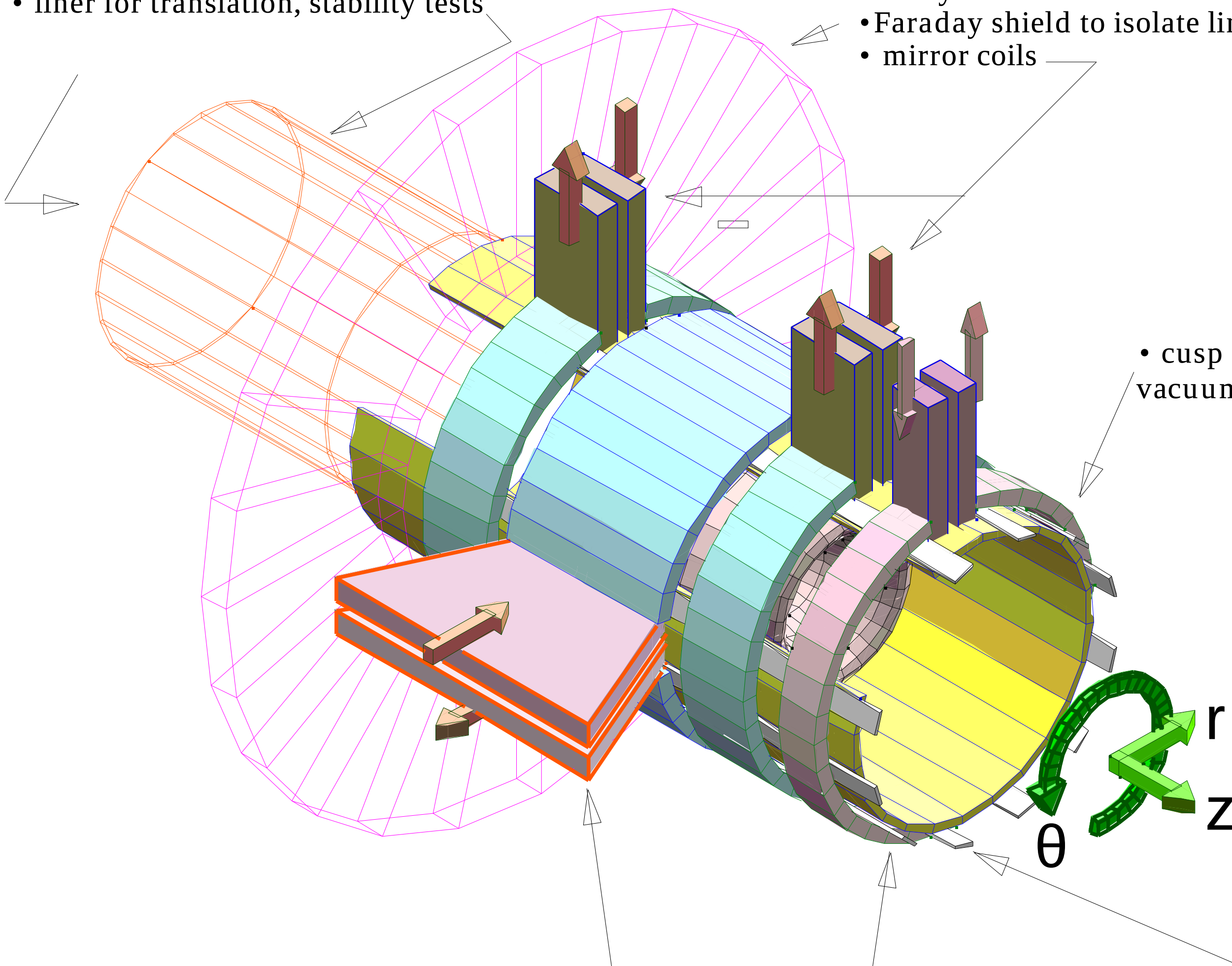
FRC flux retention

- Possibly the most crucial issue
  - Steinhauer theory assumes
    - $f_\varphi \approx r_{tube} P_0^{1/2}$, increasing without limit
    - But we aiming at large and collisional densities (and P_0) that may dissipate flux in new ways.
    - large compression will be needed, axial implosions avoided
  - Independent knobs are
    - Bias field - B_{bias}
    - Coil and vessel radius
    - Crowbar B field [compression]
    - Fill pressure

FRC scaling to large density

- Build on the PHAROS and JULIETTA data
  - Density scaling experiments
  - Large adiabatic compression
  - Large B_{bias} consistent with B_{GN} limits
  - Several sizes for coil + vessel iterations, scan
  - Require significant ohmic heating (flux dissipation)
    - $G_{LO} > 0.4$

FRC θ pinch sketch



Incarnations of PHAROS

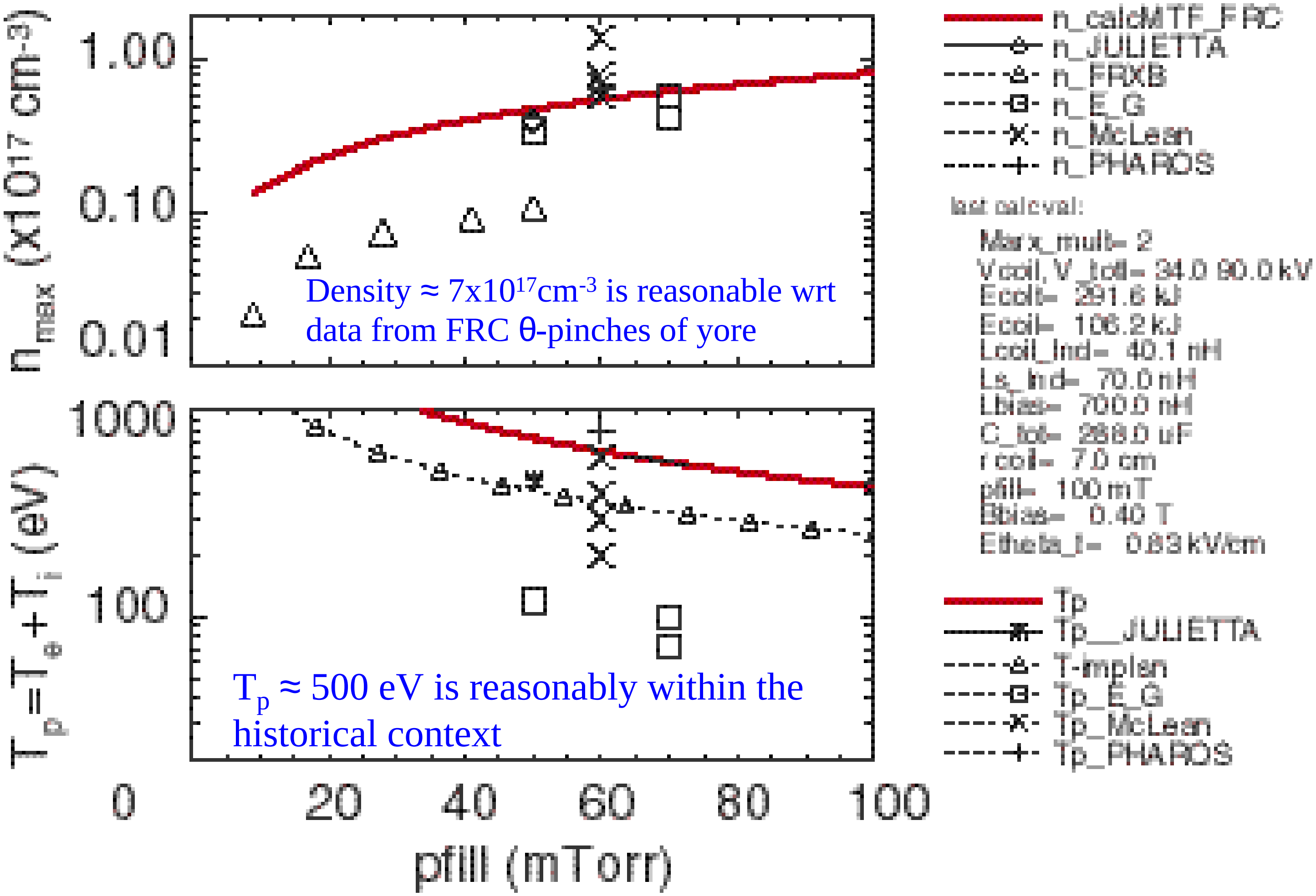
- Kolb et al - full PHAROS 1.2MJ bank
  - T_p>1-2 keV ≈ $2T_e$
  - $n>10^{17}cm^{-3}$
  - τ_{part}= 10-15μsec

- McLean et al PHAROS
  - T_e = 300eV
  - $n > 10^{17}cm^{-3}$
  - τ_{part} = 24μsec

COLT FRC parameters

Marx_mult= 2
Vcoil, V_totl= 27.2 80.0 kV
Ecolt= 115.2 kJ
Ecoil= 37.9 kJ
Lcoil_Ind= 34.4 nH
Ls_Ind= 70.0 nH
Lbias= 700.0 nH
C_tot= 144.0 uF
r coil= 6.0 cm
pfill= 80 mT
Bbias= 0.40 T
Etheta_t= 0.79 kV/cm

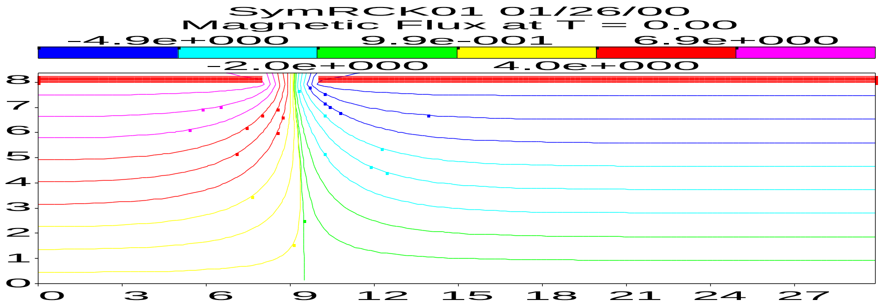
MTF FRC with 2x COLT bank

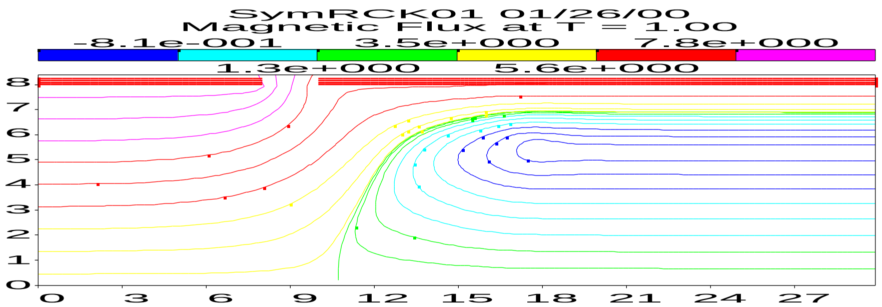


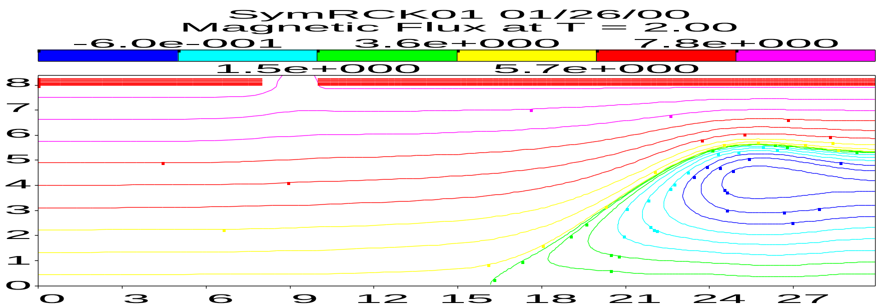
MOQUI calculations

- **R Kirkpatrick, RD Milroy**
- **Sensitivity Studies**
  - Start with nominal conditions and vary each parameter for FRC formation
  - MOQUI gives time history
  - Formation needs to be calibrated to actual benchmark startup data set

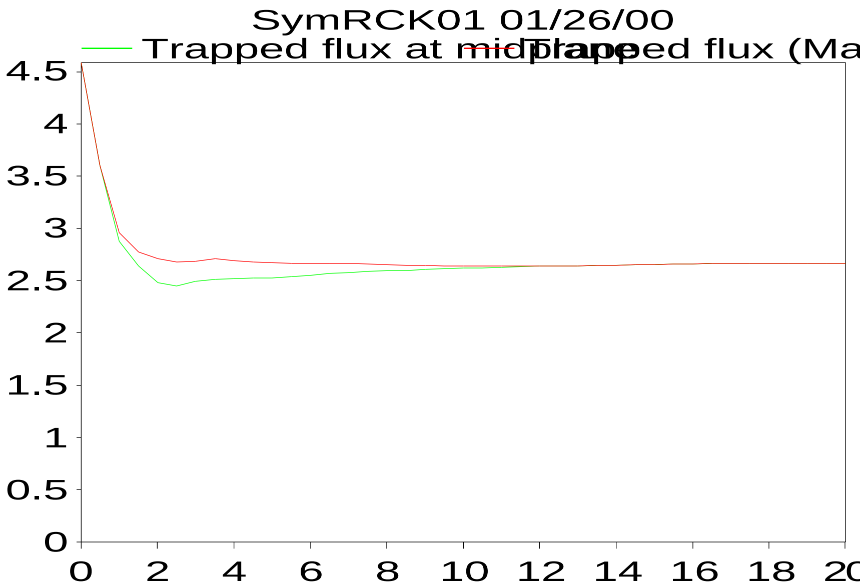
MOQUI: Target plasma formation

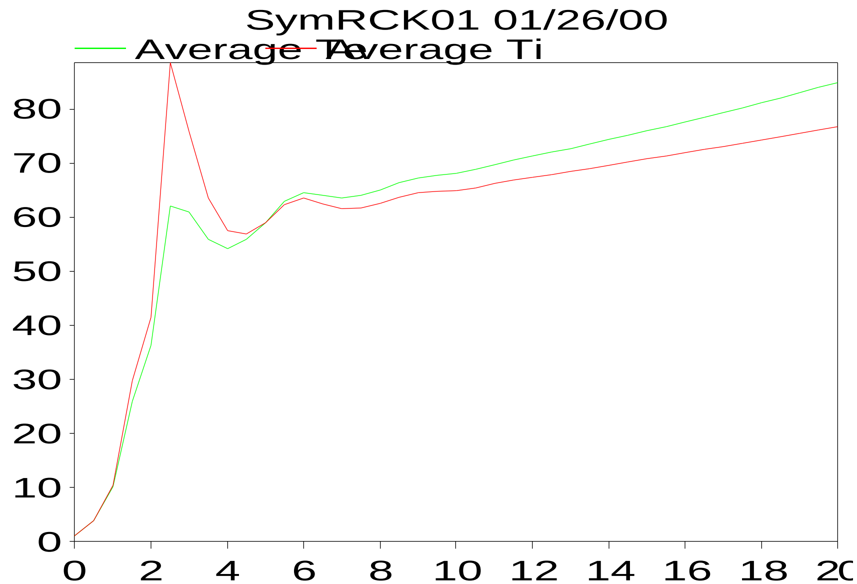






MOQUI: Gross Quantities





Kinetic model

- D. Barnes et al
- Bounce-averaged drift-kinetic model
  - Hope to demonstrate application to FRC stability calculations
  - FRC stability work will initially focus on effects of electron physics on macroscopic modes.
  - Such effects come about from the rapid toroidal precession of electrons due to curvature and   B drifts of the electrons
  - Neglected in previous stability studies, where a local, fluid Ohm's law was used

Staged experiments can be small scale

- Physics goals require
  - Interesting density $n > 5 \times 10^{16}\ cm^{-3}$
  - $T_e + T_i > 500 eV$ - burn through impurity C lines
  - Several sizes for coil + vessel iterations, scan
  - Significant and diverse diagnostic complement
  - Retention of a large fraction of lift off flux

Summary

- Zero - dimensional model
  - Data sets from high density theta pinches (1960's & 1970's) can now be easily compared with lower density FRC's that were much better characterized and modeled
  - Flux retention appears to be good enough even in regimes more collisional than MTF FRC point design
- Time dependent 2D model
  - MOQUI time evolution formation and evolution offers another design tool
- Computational kinetic model
- => confidence to proceed with FRC design for Magnetized Target Fusion.