Estimating Formation and Equilibrium Parameters for a High Density FRC

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Abstract

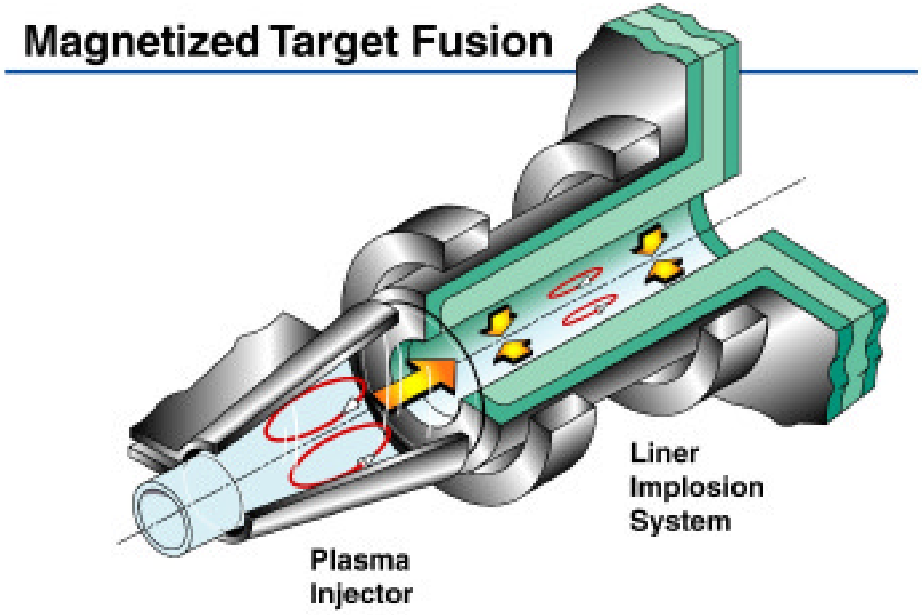
Magnetized Target Fusion (MTF) could achieve fusion conditions by compressional heating of a magnetized target plasma, such as imploding a Field Reversed Configuration (FRC). We are modeling these large density and temperature FRC's similar to those of the early theta pinch days using a variety of approaches. A physics based semi empirical scaling law model [1,2] is used to benchmark our designs against the existing (but limited) world database. 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 ($n > 5x10^{16} cm^{-3}$, $T_e+T_I > 500 eV$. Key issues such as stability and flux retention seem to be amenable to scaling laws. On the other hand the fundamental FRC physics and MHD that form the basis of these scalings need to be investigated, as we ramp up to a large density collisional regime. This is the goal of the FRX-L physics experiment carried out 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).

§ MTF will require us to

- create the initial plasma configuration,
- inject it axially into a flux-conserving shell
- compress plasma to fusion-relevant density, temperature



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

What physics parameters are necessary if we choose an FRC for Magnetized Target Fusion?

- Target plasma will need closed flux surfaces and be able to survive volume compression of 100:1
- Field Reversed configuration is a robust candidate

- High density $n \approx 10^{17} cm^{-3}$
- Reasonable temperature to exceed radiation barriers $T_e \approx T_i \approx$ 200-300eV

Only a few basic assumptions suffice

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

$$s = \int_R^{r_s} \frac{r\,dr}{r_s \rho_i}$$

History shows: high density FRC's are attainable

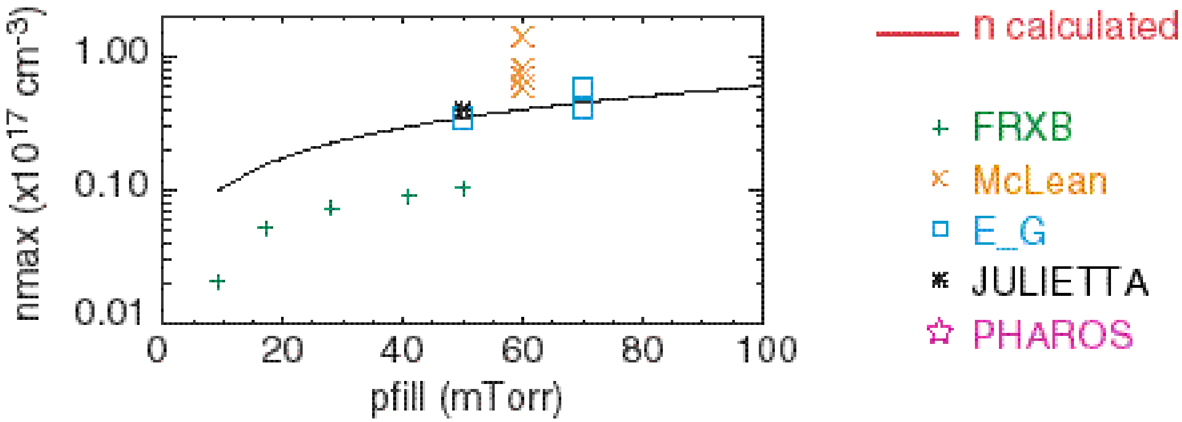
- PHAROS at NRL
  - Kolb
  - McLean
    - 1.2 MJ bank, 18kV
    - r_{coil} = 5.25, 6.75 cm
    - P_0 = 60mTorr
    - N ≈ 10^{17}cm^{-3}
    - $T_e \approx T_i \approx$500-1000eV
- Garching
  - Eberhagen & Grossman
    - 15kJ bank, 40kV
    - r_{coil} = 5.25 cm
    - P_0 = 50mTorr
    - N ≈ 4x10^{16}cm^{-3}
    - $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 ≈ 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 ≈ 10^{15}cm^{-3}
    - $T_e \approx T_i \approx$100-600eV

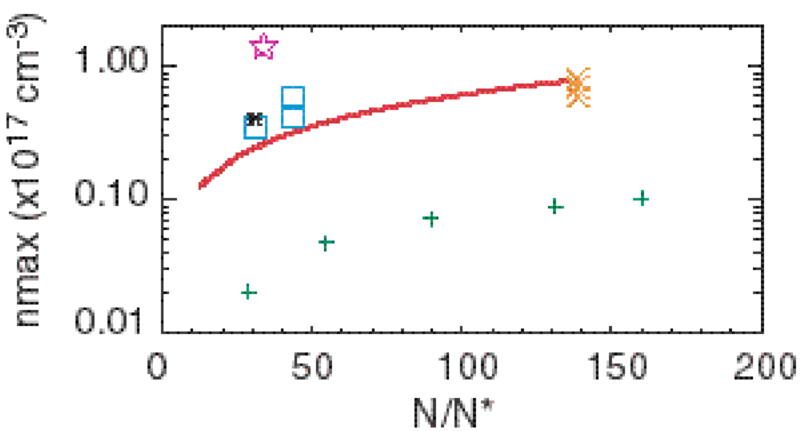
Meaningful comparison of different data sets requires normalized parameters

- Reference line density
  - $N^*[\mathrm{cm}^{-1}] = 2\pi m_i/e^2\mu = 3.23\times10^{15} \times m_{ion}/m_p$
  - Line Density > N* => $r>\delta_i$ threshold for anomalous ion diffusion, sheath broadening
  - density of a β=1 column whose radius is
    - $r=2r_{i,\,ext}$ (gyro radius at external B field)
    - $r=2\delta_i$ (ion skin depth)
- Normalized line density >>1 for large region $\beta\approx1$

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

FRC database shows a wide range of densities





Recast this in terms of normalized line density

Maximum density vs N/N*

- Model shows similar dependency on N/N*

Include actual coil and magnetics geometry for each experiment

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Plasma Physics

Compare different data sets:
normalized parameters

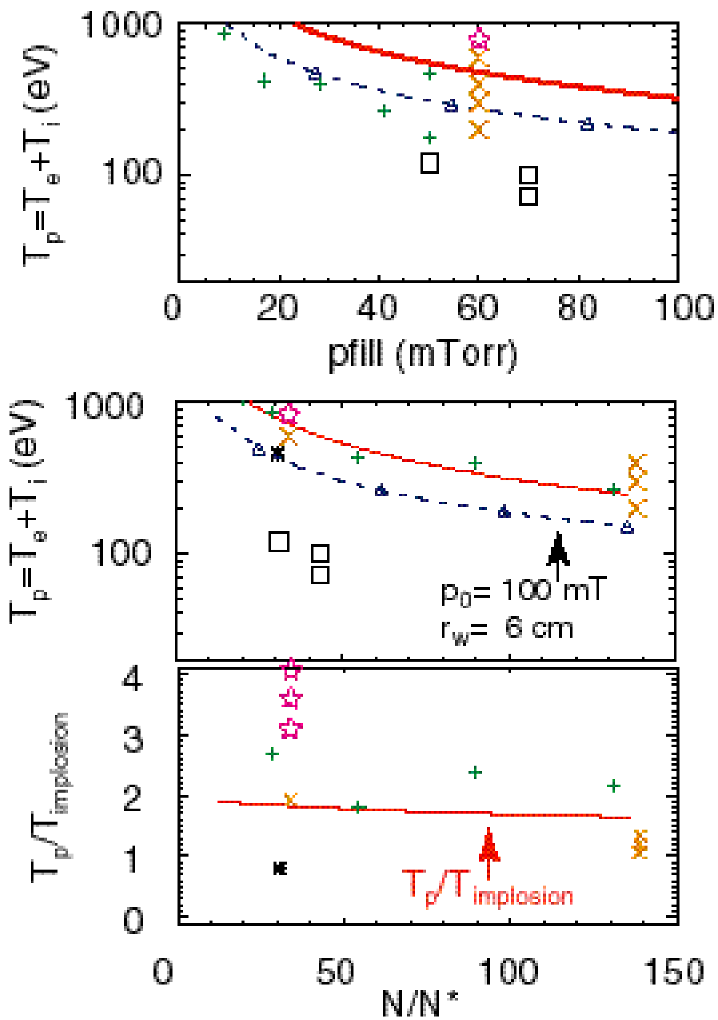
- Normalize equilibrium flux to
  - Green Newton field and flux
  - Bias flux
  - Lift off flux
- Normalize temperatures to
  - Implosion temperature
- Normalize line density to
  - Critical line density
  - $N/N^* \approx s^2$

Compare FRC data base & model predictions for T_e, T_i

Scan fill pressure

Recasting plot vs normalized line density reduces scatter

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



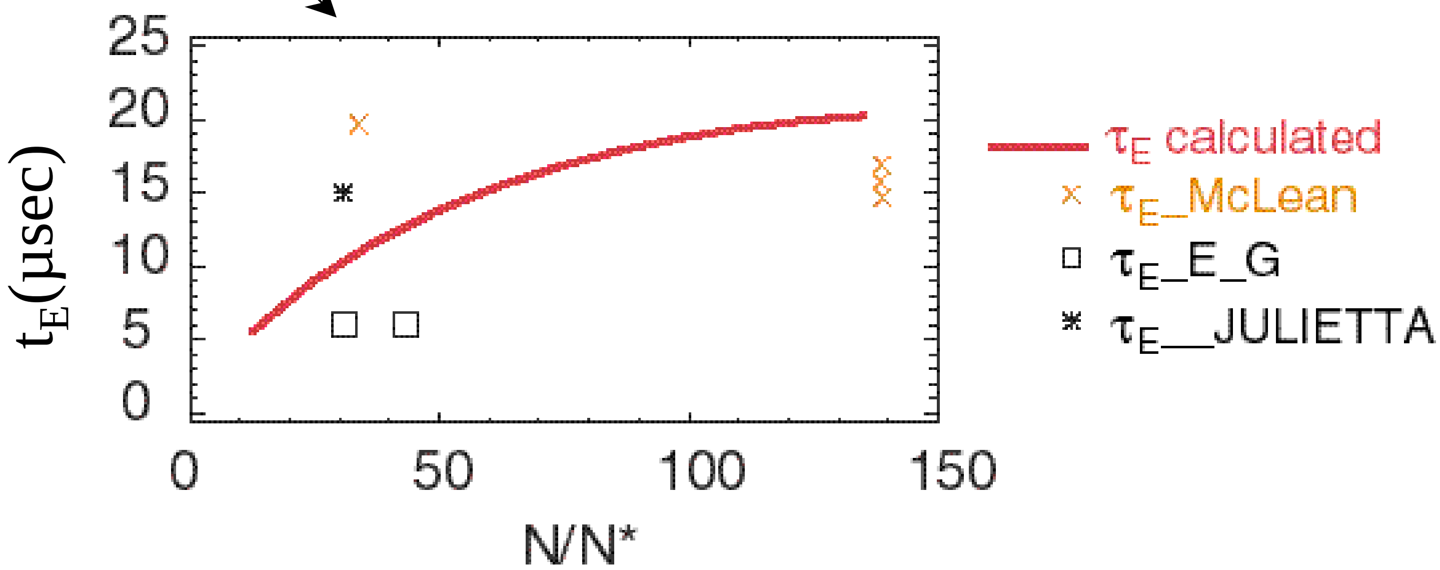
density normalized to critical line density where FRC radius equals ion skin depth $r_w/(c/\omega_{pi}) >>1$

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

Energy Confinement Lifetime is adequate

even at high density $n<10^{17}cm^{-3}$

lifetime (hundreds of Alfven transit times) will decrease once the FRC is compressed



FRC scaling to large density

- Build on the extant 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)
    - $G_{LO} > 0.4$

Summary

- Dimensionless parameters provide a way to compare experiments of different sizes, magnetic fields and density
- Zero - dimensional [semi empirical] 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
  - Even our pessimistic modifications to Flux retention model will allow access to regimes more collisional than the FRX-L experiment

- => FRX-L point design for Magnetized Target Fusion has a reasonable expectation of success