Implosion and scaling studies of field-reversed configuration targets in a MagLIF liner in 1D

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ABSTRACT

A field-reversed configuration (FRC) was placed in the target region of a MagLIF liner to study state parameters at peak compression. The 1D two-point equilibrium (2PE) magnetic field model was employed along side an alpha power law that relates density and temperature, to characterize the radially varying parameters of an FRC at equilibrium. The study also serves as a baseline for a more comprehensive 2D study of the target, which will focus on peak compression parameters as well as magneto-Rayleigh-Taylor (MRT) instabilities during the deceleration stage.

BACKGROUND

- Magnetized Liner Inertial Fusion (MagLIF) involves passing a current through a liner to compress fuel via the $\vec{J} \times \vec{B}$ force to a fusion state [1].
- MagLIF typically employs a spatially constant magnetic field ($\sim$ 10 T) to magnetize the preheated fuel ($\sim$ 100 eV). This serves as the control group.

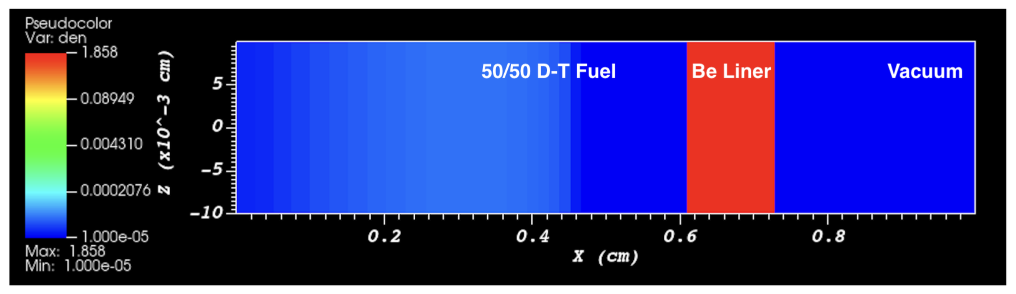

Figure 1: Initial MagLIF Setup with an FRC Density Profile

Table 1: Initial MagLIF Parameters

Parameter	Symbol	Value
Conducting Wall Radius	R_w	0.61 cm
Aspect Ratio	A_R	6
Initial Fuel Density	ρ_0	10^{-3} g/cm^3
Initial Fuel Temperature	T_0	100–300 eV
Initial Liner Density	ρ_{0l}	1.858 g/cm^3
Initial Liner Temperature	T_{0l}	298 K

- FRCs are a toroidal plasma confinement configuration similar to tokamaks [2].
- A notable advantage of FRCs is that they confine the plasma away from the device walls, reducing thermal conduction losses [1, 3]. The FRC target serves as the experimental group.

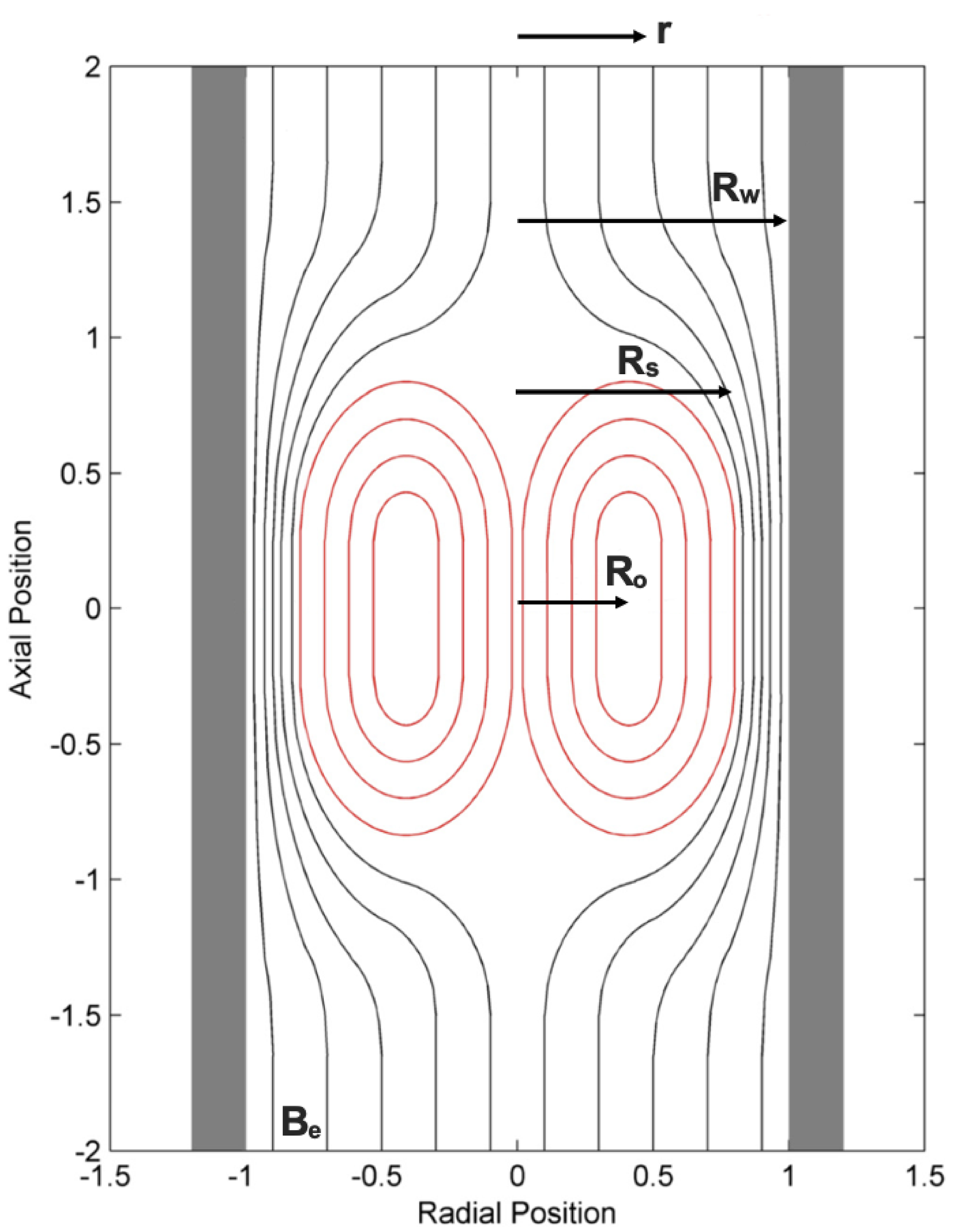

Figure 2: Illustration of an FRC [1]

MODEL

- The 2PE model of FRC equilibria accounts for corrections from simpler 1D models such as the polynomial model [1].
- The two free parameters $\{b_s, \sigma\}$ are the magnetic field strength at the separatrix and a profile parameter that particularly affects the current profile [4, 5].
- The 2PE model for FRC equilibria normalizes the radially-dependent magnetic field to the external [5]:

$$\frac{B(r)}{B_e} = b(u) = \begin{cases} b_s u e^{\sigma(u^4-1)} & |u| \leq 1 \\ 1-(1-b_s)e^{\sigma_2(1-u)} & u > 1 \end{cases}$$

where:

$$u = \frac{2r^2}{R_s^2} - 1; \quad \sigma_2 = \frac{(1+4\sigma)b_s}{1-b_s}; \quad b_s = \frac{B(R_s)}{B_e}$$

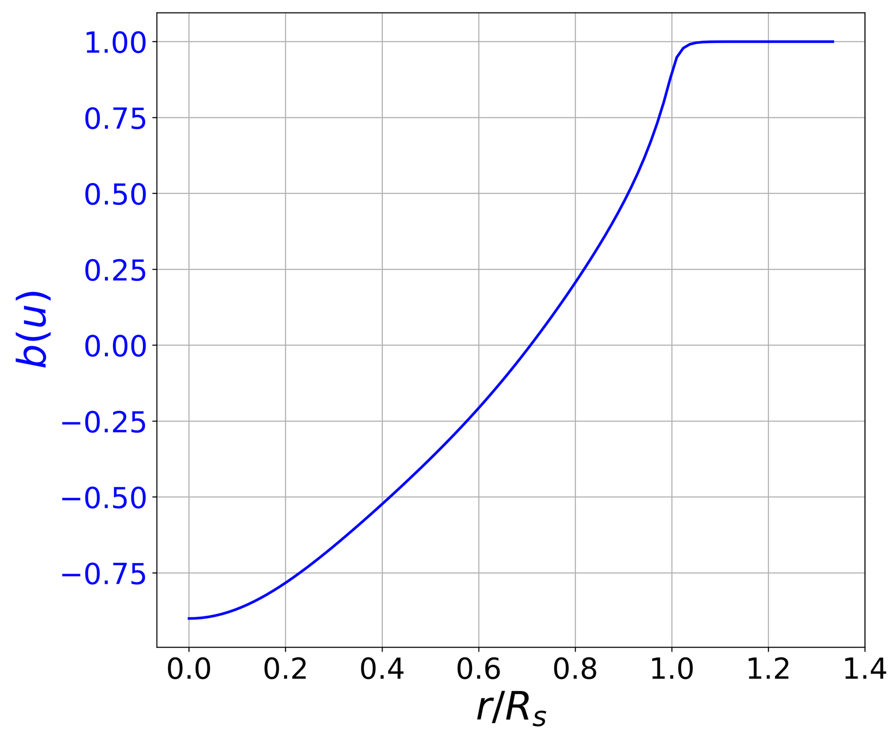

Figure 3: Normalized Magnetic Field Profile of 2PE Model

Table 2: Representative FRC Parameters

Parameter	Symbol	Value
Normalized Magnetic Field at Separatrix	b_s	0.9
Current Density Profile Parameter	σ	0.2
Normalized Separatrix Ratio	X_s	0.75
Separatrix Radius	R_s	0.4575 cm
Average Beta Parameter	$\langle\beta\rangle$	0.714

- Finding a profile for the number density or the temperature requires an assumption about the other.
- We assume a temperature profile from [6]:

$$T(r) = T_0 \left(\frac{n(r)}{n_0}\right)^{\alpha}$$

where α is the temperature profile parameter. A flat temperature exhibits $\alpha = 0$ and $\alpha < 1$ specifies that the density's profile is sharper than the temperature's.

- From the ideal gas law:

$$n(r) = n^* \left(1 - b^2(u)\right)^{\frac{1}{\alpha+1}} \ , \quad n^* = \left(\frac{B_e^2 n_0^{\alpha}}{2\mu_0 k_b T_0}\right)^{\frac{1}{\alpha+1}}$$

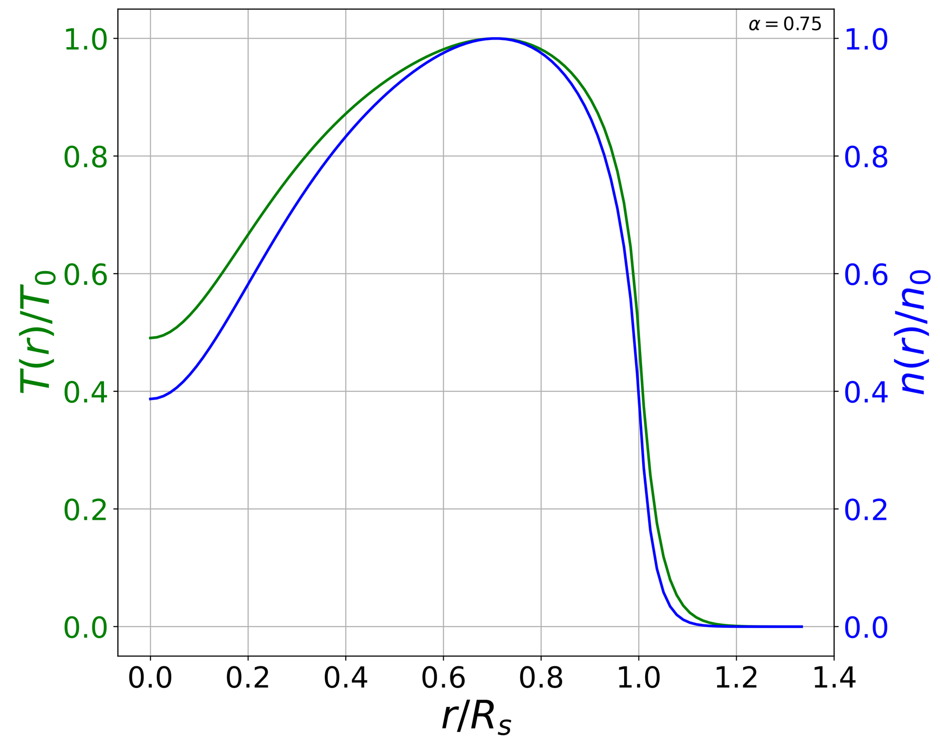

Figure 4: Alpha Power Law for Temperature and Density

MAGNETOHYDRODYNAMICS

- HYDRA - a single fluid, multimaterial, arbitrary Lagrangian-Eulerian (ALE) radiation, hydrodynamics code - is used to simulate the MagLIF implosions.
- The MHD model includes effects from Ohmic heating, Nernst, and Righi-Leduc.
- Anisotropic thermal conduction is determined with the Modified Lee and More conductivity model using Epperlein-Haines coefficients.

RESULTS

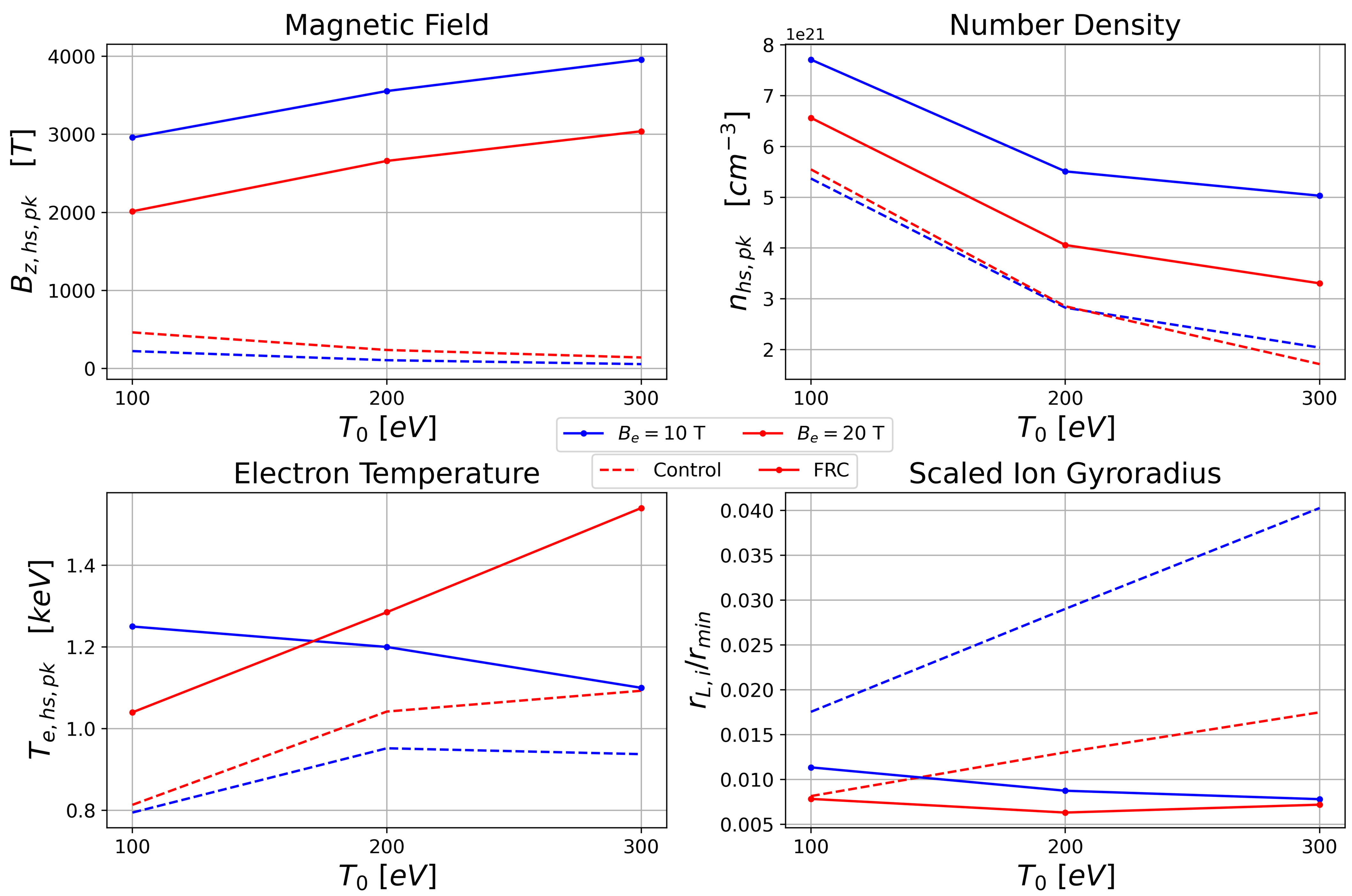

Figure 5: State Parameters and Length Scaling at Peak Compression

RESULTS

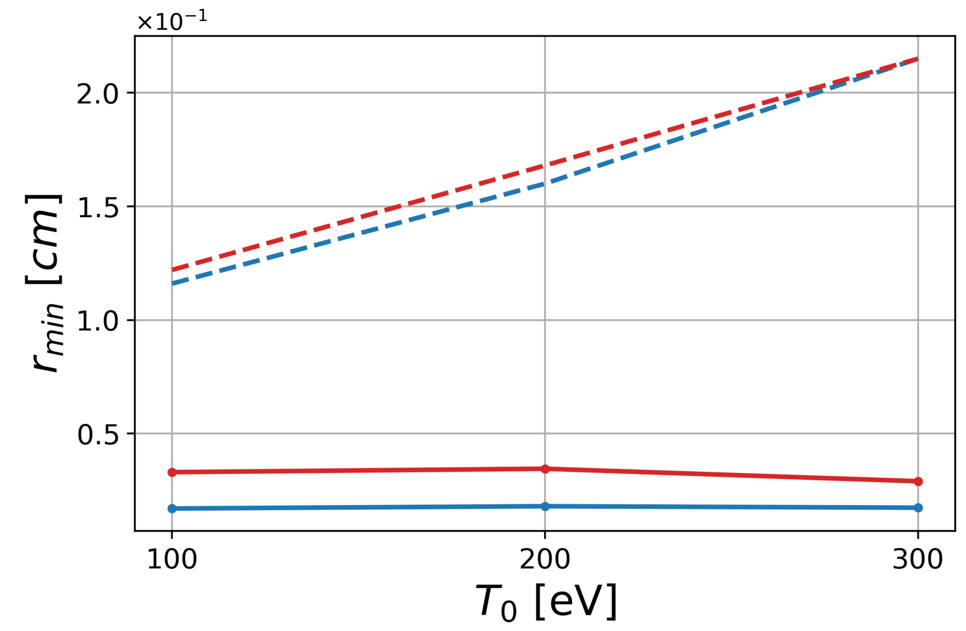

Figure 6: Inner Liner Radius at Peak Compression

- The 1D FRC target results in higher magnetic field strengths, densities, and temperatures at peak compression for all initial magnetic field strengths and temperatures, suggesting that FRCs require further study for MagLIF implosions.
- The peak magnetic field of the FRC target increases with initial fuel temperature, whereas it decreases with the control.
- Increasing the external magnetic field, decreases the peak density and peak magnetic field.
- The minimum inner liner radius is nearly an order of magnitude less than that of the traditional MagLIF target.

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