

Investigating scaling MagLIF to higher current loads with Chimera simulations

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Abstract

The Magnetized Liner Inertial Fusion scheme is a magneto-inertial fusion scheme being pursued on the Z machine at SNL, where a centimetre-scale liner filled with fusion fuel axially pre-magnetized is preheated, then imploded by a Lorentz force generated by an axial 20 MA current⁽¹⁾. Next generation pulsed power facilities aim to produce $\approx 40 - 60$ MA, posing the question of how existing results will scale to higher currents. In⁽²⁾ Ruiz et al. proposed analytical scaling laws to estimate performance of higher load experiments. This work explored whether these were reproduced in 1D simulations using the MHD code Chimera⁽³⁾, developed by Imperial College London.

Chimera was able to replicate the results of HYDRA⁽⁴⁾ well for many metrics, such as T_{ion} and fusion yield, with inconsistencies likely due to the liner perturbations present in the 2D HYDRA simulations. Chimera was also used to investigate α particle trapping by the axial B_z field, finding that an applied B_z of 28.5 T results in a $\approx 40\%$ reduction in α radial mean-free path compared to the no B_z field.

Introduction

In⁽²⁾, Ruiz et al. determined dimensionless parameters significant to MagLIF performance, then derived scaling laws to preserve these parameters at higher load currents. These were used to set up simulations in HYDRA in⁽⁴⁾, the same laws were used in this work to set up Chimera simulations to act as an independent assessment of high-current MagLIF performance.

$$\frac{\rho'_0}{\rho_0} = \frac{h'}{h} \approx \left(\frac{I'_{max}}{I_{max}}\right)^{0.529} \quad \frac{B'_{z,0}}{B_{z,0}} \approx \left(\frac{I'_{max}}{I_{max}}\right)^{0.647} \quad \frac{E'_{preheat}}{E_{preheat}} \approx \left(\frac{I'_{max}}{I_{max}}\right)^{2.529}$$

Figure 1: A subset of the equations derived in⁽²⁾ that were used to scale MagLIF design in simulations.

Chimera Simulation Resolution

- It was found early in the work that the results of Chimera MagLIF simulations are dependent on simulation resolution, in particular yield and T_{ion} were found to increase as resolution decreased. The extent of the scaling reduced slightly as peak current increased.
- Figure 3 plots velocity and T_{ion} for the 115-120 μm region (the 28.5 T streak plot in Figure 5 shows this to be the liner-fuel interface at ≈ 119 ns). This region is one cell for the 5 μm simulation, five cells for the 1 μm simulation. The 1 μm data is taken as the mean velocity across all five cells at each timestep.
- Figure 3 shows significantly increased resolution of shocks for the 1 μm simulation, particularly as times approaching peak stagnation, which are coinciding with an increase in T_{ion} . The improved shock resolution is therefore likely driving the improved performance.

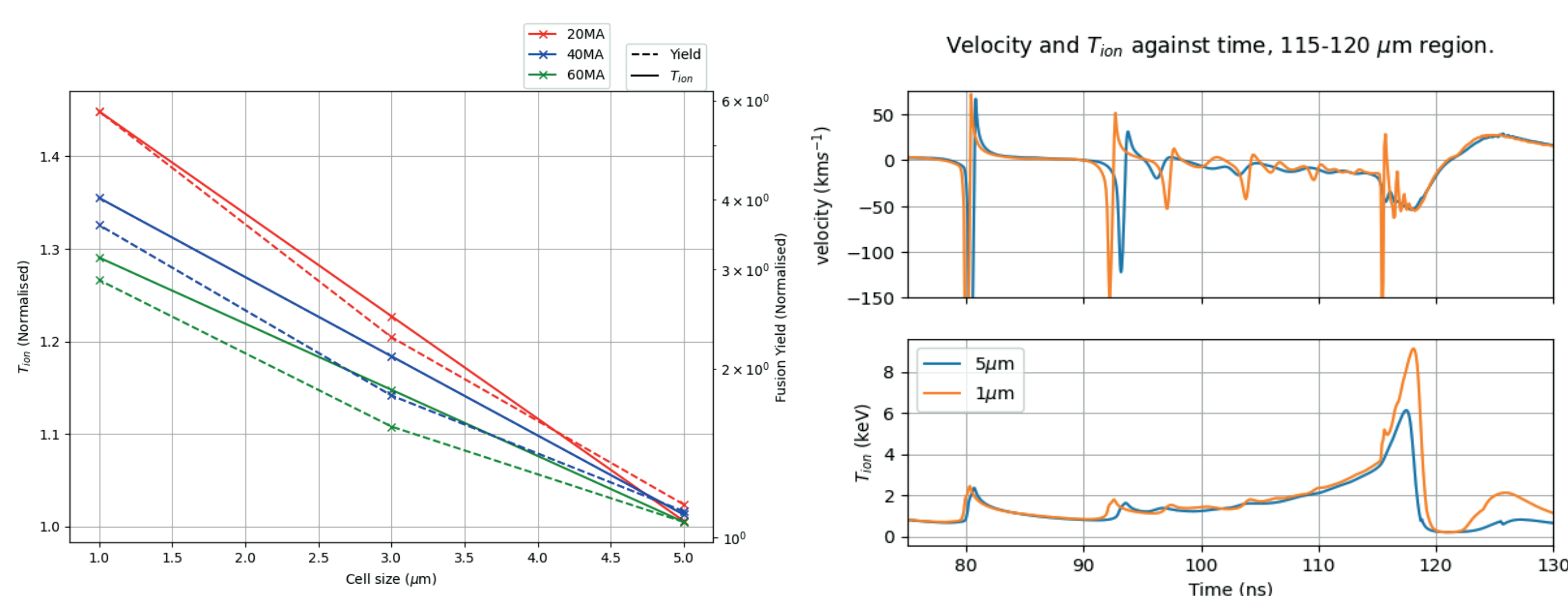


Figure 2: A plot of normalised fusion yield and peak T_{ion} against simulation resolution, showing how the performance of a Chimera MagLIF simulation improves as the cell size decreases for all peak currents.

Figure 3: Plots of the velocity and T_{ion} across a 5 μm region for the 5 μm and 1 μm simulation, implying increased shock resolution is causing increased T_{ion} in the 1 μm simulation.

Metric Comparisons

- In Figure 4 are plots comparing HYDRA and Chimera simulation outputs for various metrics, as well as the analytical scaling law for the parameter, derived in⁽²⁾.
- At time of writing Chimera does not have an α diffusion model. Due to the inconsistencies in the two codes' α models, all the results in Figure 4 are no- α simulations.
- The Chimera simulation results were consistent with HYDRA and the scaling laws for a number metrics, such as T_{ion} and fusion yield. Poor matching in other metrics, such as burn width and convergence ratio, may be due to uneven burn in HYDRA 2D simulations from liner perturbations not present in 1D Chimera simulations. Code inconsistencies, such as HYDRA using a circuit model and Chimera using current-time pairs, also contribute uncertainties.

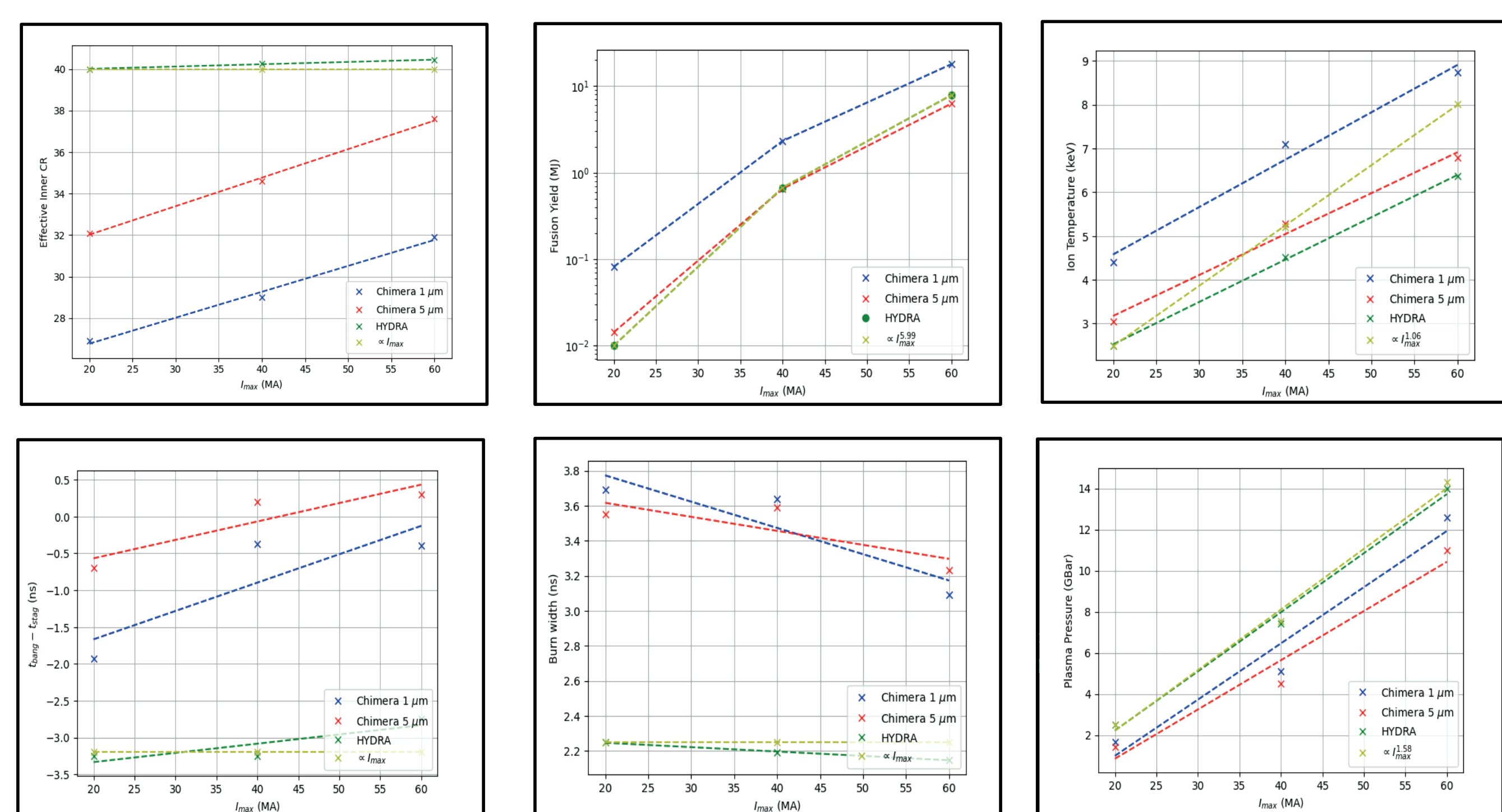


Figure 4: Plots of some results of MagLIF simulations computed in HYDRA, Chimera with a 5 μm resolution, and Chimera with a 1 μm resolution, with the analytical scaling law.

B_z α Particle Trapping

- The primary purpose of the B_z field is to limit thermal conduction to the liner walls. However, it is also expected to assist in the trapping of α particles in the fuel.
- 60 MA simulations with MC α transport were run with a range of B_z strengths, and the α mean-free-paths (λ) were compared to assess the α trapping. The radial λ (λ_r) is the λ in only the radial direction, while λ_{3D} is the λ accounting for α movement in all three directions.
- The radial λ decreased linearly as the B_z field strength increases, indicating α trapping. Evidence of increased α trapping towards the fuel centre can also be seen in the streak plots.
- Applying a B_z glues α 's to the field lines, with the α 's precessing around them. Increasing the strength at low B_z provides a strong decrease in r_L and a strong increase in ω_L , increasing the λ_{3D} .
- As the B_z reaches and exceeds ≈ 10 T the decrease in r_L , and therefore the increase in ω_L and λ_z diminishes, but λ_r continues to drop linearly. This results in a drop in overall λ_{3D} .

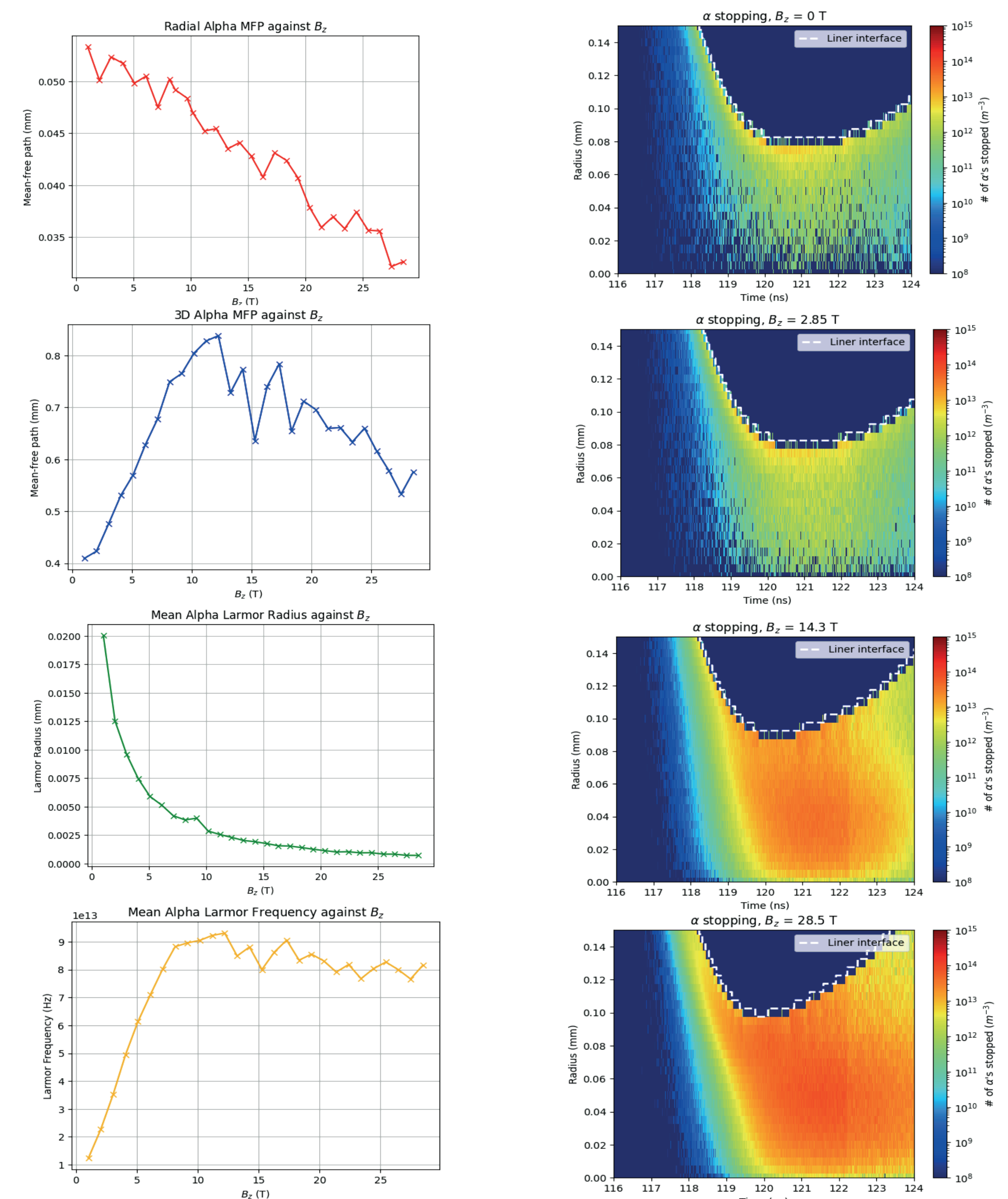


Figure 5: Left: Plots of various mean α properties against B_z , averaged across the burn period. Right: streak plots of amount of α 's stopped per cell across the burn period for various B_z 's.

Conclusions and Further Work

- The no- α Chimera simulations were able to replicate the HYDRA simulations to a good standard, providing confidence in Chimera's ability to study MagLIF and extensions to it.
- Increasing Chimera resolution led to an increase in simulation performance, possibly due to better resolving shocks.
- A study of how the axial B_z field affects the λ_α indicates that the B_z is effective at trapping the α 's by more tightly gluing them to the field lines, decreasing their radial mean-free-path.
- These simulations can be extended to 2D to incorporate the effect of liner perturbations and MRTI growth. This will also allow for further extensions of MagLIF e.g. a composite liner.
- Imperial are developing an α diffusion model, which can be tested against the α -on HYDRA simulations in⁽⁴⁾.
- Attempts to speed up the Chimera simulations, or use of more compute power, may enable reaching a mesh resolution convergence, for better analysis of shock resolution affecting performance.

References

- D.A. Yager-Elorriaga, "An overview of magneto-inertial fusion on the Z machine at Sandia National Laboratories", February 2022.
- D.E. Ruiz et al., "Exploring the parameter space of MagLIF implosions using similarity scaling. I. Theoretical framework", 2023.
- N. Chaturvedi, "Simulating radiatively cooled pulsed-power driven systems using static mesh refinement", 2023.
- D.E. Ruiz et al., "Exploring the parameter space of MagLIF implosions using similarity scaling. II. Current scaling", 2023.