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Magneto Rayleigh-Taylor instability growth in magnetically driven cylindrical liners

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Introduction

The magneto Rayleigh-Taylor (MRT) instability arises in magnetic direct drive inertial confinement fusion and can limit the attainable fuel pressures and confinement times [1].

In this work, we investigate MRT growth across a wide range of targets driven by a variety of current pulses and show that various trends can be accounted for by a simple phenomenological model that accounts for driver and target properties via the acceleration history.

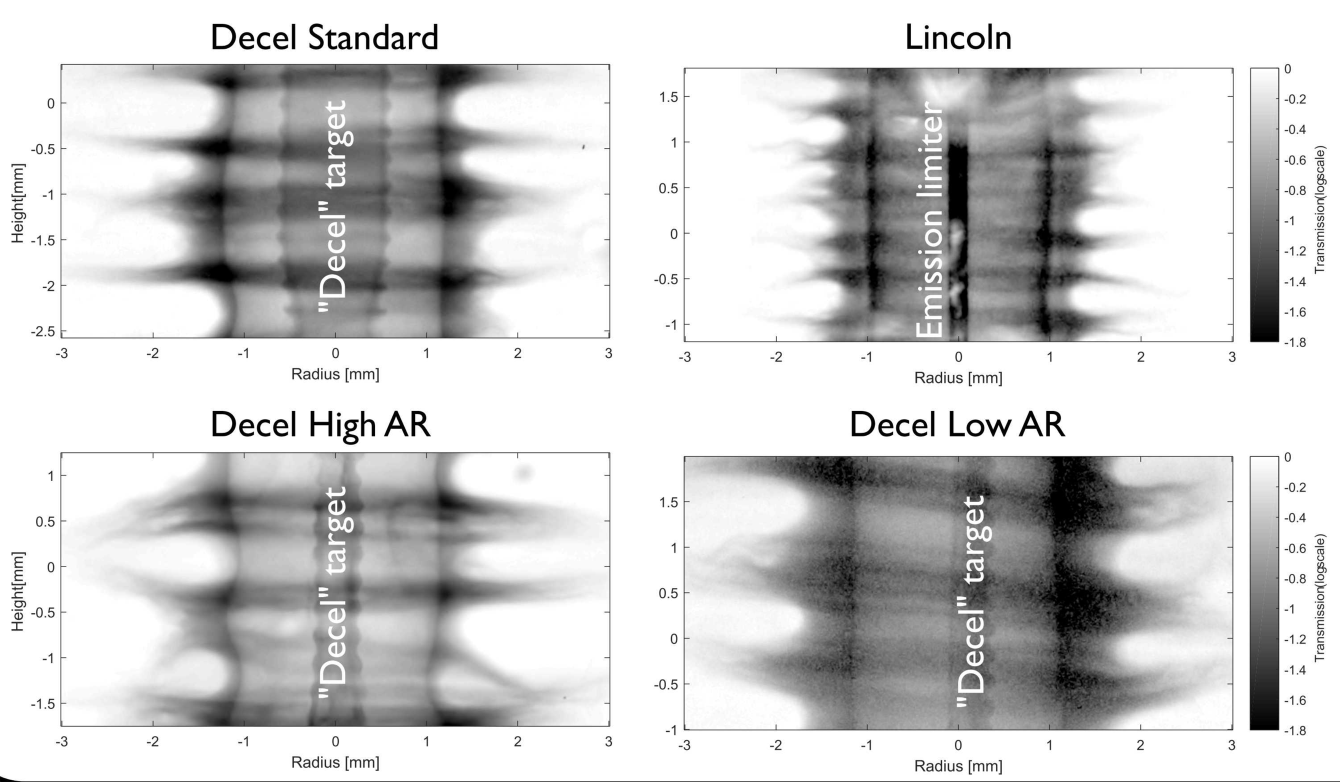
Establishing an understanding of MRT in present-day experiments is critical for understanding MRT on next-generation machines.

Scope of this work

We analyzed MRT growth in 54 radiographs over 31 experiments for a wide variety of targets and current pulses. Most of these experiments were not designed to specifically measure MRT!

Campaign	R_{outer} [mm]	Π-parameter	I_{max} (MA)	Aspect Ratio
MagLIF	2.79	0.7	16	6
Lincoln	3.47	1.0	23-24	6
Decel Standard	5.2	1.9	23-24	8
Decel Short Pulse	5.2	0.3	23-24	8
Decel Low AR	5.2	1.1	22	6
Decel High AR	3.74	2.1	16	12.5
Eddy	2.4	1.1	22	6

Sample radiographs from the "Decel" and "Lincoln" [2] campaigns

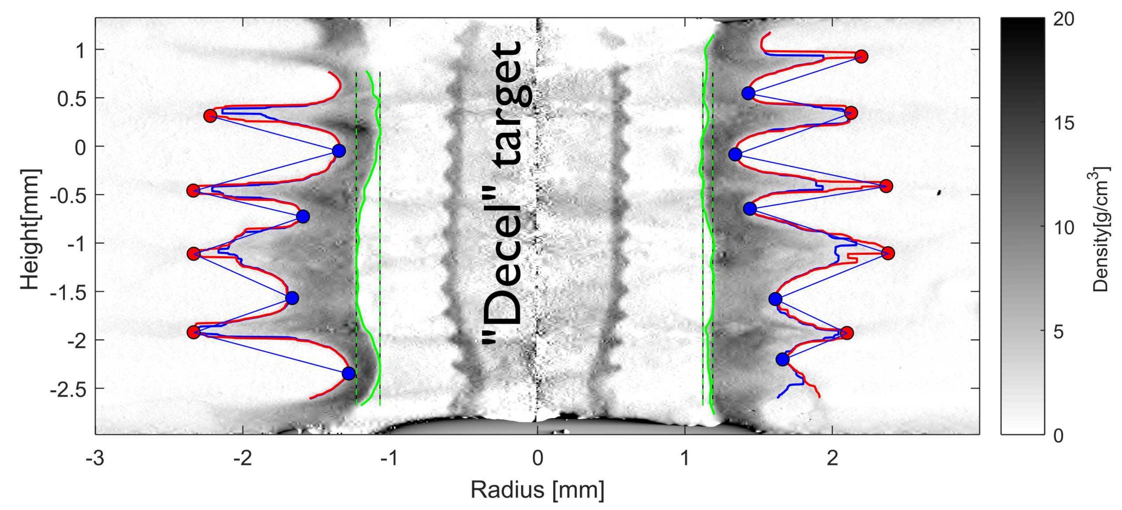


References

[1] P. F. Knapp et al., "Direct measurement of the inertial confinement time in a magnetically driven implosion," Phys. Plasmas **24**, 042708 (2017).
[2] R. D. McBride et al., "Penetrating Radiography of Imploding and Stagnating Beryllium Liners on the Z Accelerator," Phys. Rev. Lett. **109**, 135004 (2012).
[3] P. F. Schmit and D. E. Ruiz, "A conservative approach to scaling magneto-inertial fusion concepts to larger pulsed-power drivers," to be submitted.

Experimental Analysis

The MRT amplitude and wavelength were measured using contours identified by a threshold-based tracking algorithm. This analysis produces a distribution of amplitudes and wavelengths to quantify the variability of each data point.



Note: Transmission images were Abel inverted to obtain density maps. The areal-density threshold for contour tracking was typically $0.5 \cdot (\rho R)_{\text{initial}}$.

Phenomenological RT Model

Using a thin-shell implosion model, we can relate driver and target properties to instability growth via the acceleration history:

$$\Gamma = \int_0^t \sqrt{g}\, dt = \Gamma(\Pi, R_{\text{outer}})$$

(RT Growth function)

$$\frac{d^2R}{dt^2} = -\frac{2\pi R}{\hat{m}} P_{\text{mag}}$$

(thin-shell model)

$$\Pi \sim \frac{\mu_0\, I_{\max}^2 t_{\text{rise}}^2}{8\,\pi^2\, \rho_0\, R_{\text{outer},0}^4}\,\text{AR}$$

(Implosion Π-parameter)

$$\Gamma(R,\Pi) \cong \sqrt{\pi R_0}\left(1 - \frac{\Pi}{72}\right)\left[\text{Erf}\left(\sqrt{\frac{\Pi}{36} - \frac{1}{2}\ln\frac{R}{R(t_{\text{rise}})}}\right) - \text{Erf}\left(\sqrt{\frac{\Pi}{36}}\right)\right]$$

$$A \sim A_0 \text{Cosh}[\sqrt{k}\Gamma]$$

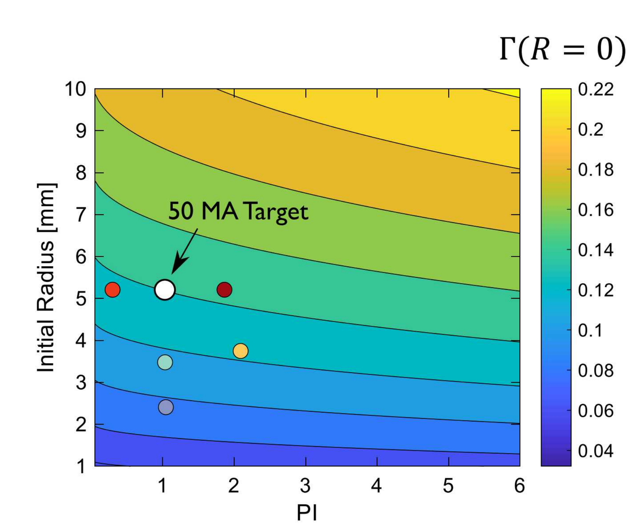
(Linear)

$$A \sim \alpha \Gamma^2$$

(Nonlinear)

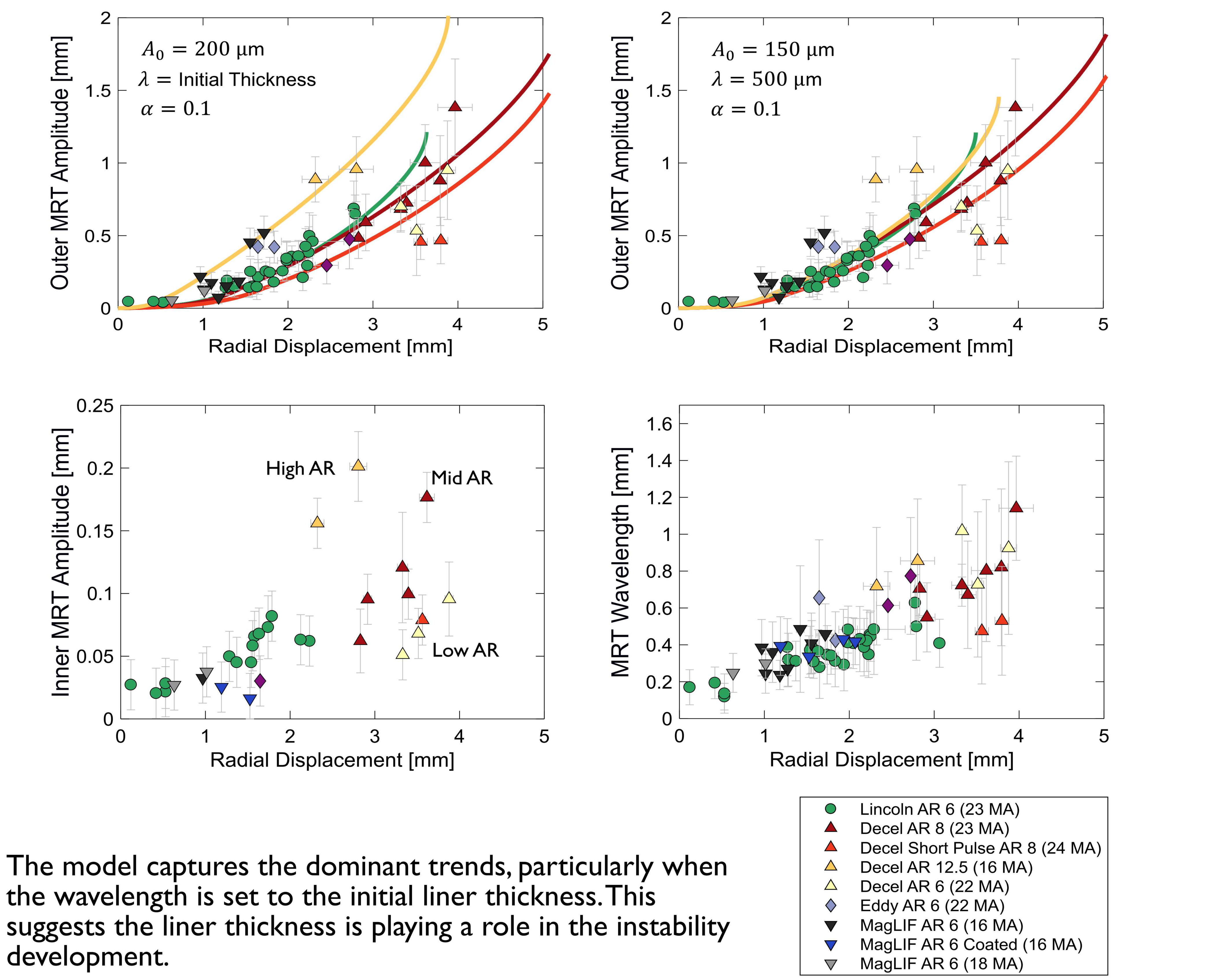
The saturation condition (and transition threshold from linear to non-linear models) is given by kA = 0.1.

The growth function depends on two parameters, the initial target radius and the Π-parameter.



The growth function at peak compression (R=0) is plotted and compared to calculated values for select experiments. A notional 50 MA target is highlighted.

Results and Conclusions



The model captures the dominant trends, particularly when the wavelength is set to the initial liner thickness. This suggests the liner thickness is playing a role in the instability development.

The enhanced stability of the short-pulse Decel target compared to the standard, long-pulse target can be understood by a decrease in the Π-parameter. Both targets were identical and were driven by the same peak current -- the only difference was the risetime of the current pulse.

The inner MRT amplitude shows the effect of aspect ratio on instability feedthrough, with lower AR targets being more robust compared to higher AR targets.

The wavelength increases approximately linearly with distance traveled across all experiments. This might be a signature of bubble competition or merging.

The ability of the model to capture the dominant trends in the experiments suggests MRT growth on the outside of conservatively scaled liners (Π~const) will scale with the initial outer target radius as $A_{\text{MRT}} \sim R_{\text{outer}} \sim I_{\max}^{2/7}$ [3]. This is very encouraging!

Future work is to incorporate simulated 1D acceleration histories into the model and to design 3D simulations to better our understanding of how MRT scales for different targets and currents.

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