# Enhancing Understanding of Magnetized High Energy Density Plasmas from Solid Liner Implosions Using Fluid Modeling with Kinetic Closures

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VIRGINIA TECH

## Magnetized Liner Inertial Fusion

MagLIF is a fusion concept that involves imploding an initially solid cylindrical metal liner (Aluminum or Beryllium) on to a pre-magnetized Deuterium-Tritium (D-T) fuel target.[Slutz et al., 2010] The most detrimental instability toward achieving net gain is the magneto Rayleigh-Taylor instability (MRT) that occurs at the accelerating liner-vacuum interface during implosion. As the current from the pulse ionizes the solid liner the resulting process produces an exterior coronal region where the configuration is MRT unstable. Sinars et al. [2011] recently performed MRT experiments with the intent of providing a benchmark for new models. Peterson et al. [2012] suggests that the electro thermal instability (ETI) seeds the MRT instability early in the simulation. This project seeks to find more insight in the transition of the ETI to the MRT through the use of kinetic closures developed for moderately to weakly coupled plasmas.

## Simulation Setup

The USim code from Tech-X Corp. is used to simulate the MRT instability using the magnetohydrodynamic (MHD) model with the SESAME equation of state (EOS) tables from Los Alamos National Laboratory. USIM [2017] Simulations of linear waves, Brio-Wu shock propagation, and Rayleigh-Taylor were performed to verify the implementation of the SESAME EOS tables using test cases from the Athena code.Stone et al. [2008] These tests revealed that the sound speed needed to be reconstructed on cell interfaces instead of cell centers to obtain meaningful results using the SESAME EOS tables with the finite volume algorithm. Figure 1 presents the typical setup and parameters of the simulation to study the MRT instability.

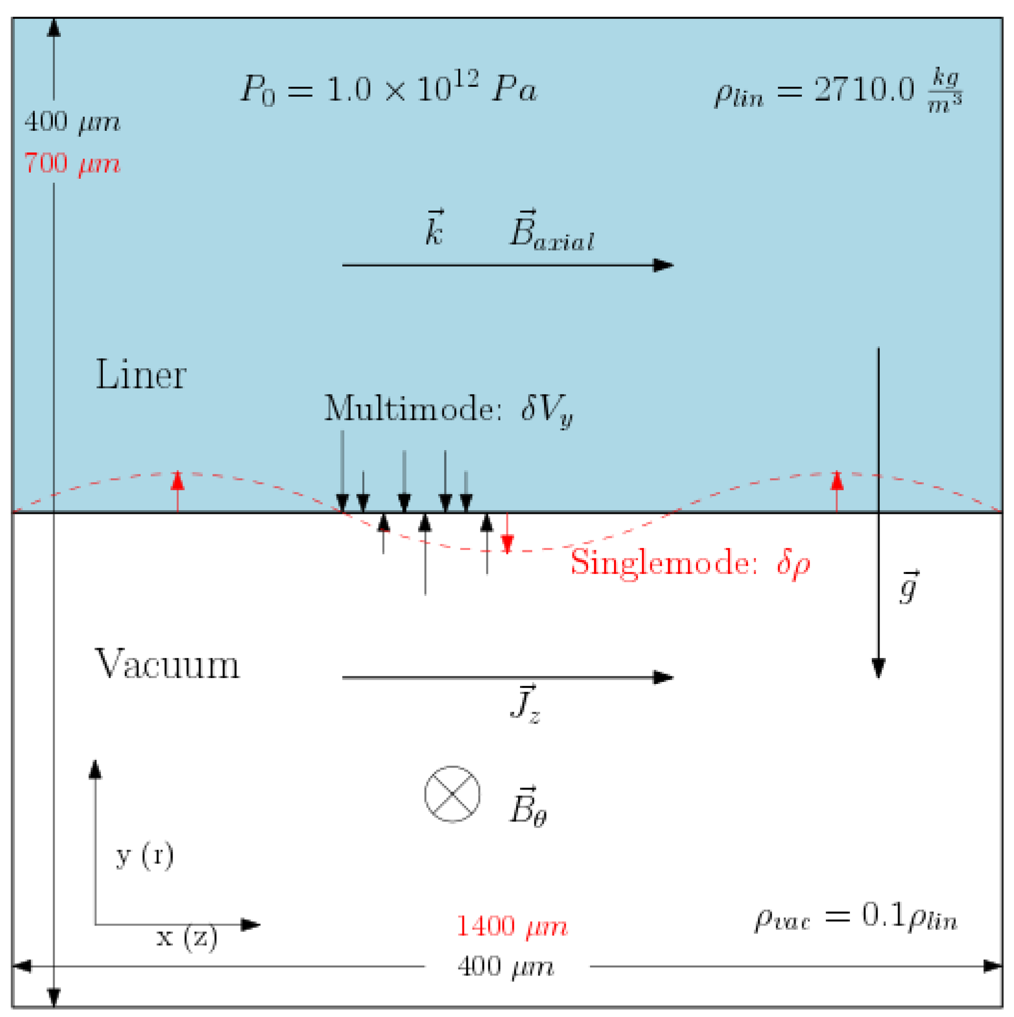


Figure 1: Overview of the simulation setup for both the multimode, and the singlemode (red) simulations including densities, perturbations, fields, etc.. This setup is to represent the cross sectional view of MagLIF in the $r$-$z$ plane where the MRT instability is present.

## Time Varying Terms

Figure 1 has a time-varying acceleration denoted by $\vec{g}$ for consistency with a pulsed power implosion. Figure 2 is a simplified representation of the MagLIF setup used in the preliminary simulations.

## Time Varying Terms - Continued

The figure shows parameters in cylindrical coordinates, but all simulations run thus far have been using Cartesian coordinates.
From the diagram $|B_\theta|$ at the outer liner radius is given by

$$|B_\theta(t)| = \frac{\mu_0 I_l(t)}{2\pi r_l(t)} \tag{1}$$

where $I_l$ is the liner current assumed to be concentrated at the surface, $r_l$ is the outer radius of the liner, and $\mu_0$ is the vacuum permeability. The magnetic pressure applied to the outer liner surface ($r_l$) is given by

$$P_B = \frac{B_\theta^2(t)}{2\mu_0}. \tag{2}$$

The force is obtained using $P_B$ and the surface area, which is used to obtain the acceleration. After applying some elementary approximations and simplifications, the acceleration is given by

$$g(t) = -\frac{\mu_0}{4\pi m_l}\frac{I_l^2(t)}{r_l(t)} \tag{3}$$

where $m_l = 2\pi r_{l_0}\Delta r_0 \rho_{l_0}$ with $r_{l_0}$, $\Delta r_0$, $\rho_{l_0}$, representing the initial liner outer radius, initial liner thickness, and initial liner density, respectively. $I_l(t)$, and $r_l(t)$, which are determined from Slutz et al. [2010], are given by

$$r_l(t) = r_{l_0}\left(1-\tau^4\right), \tag{4}$$

and

$$I_l(t) = I_x\left(\frac{27}{4}\right)^{\frac{1}{4}}\tau\sqrt{1-\tau^4} \tag{5}$$

where $\tau = t/t_p$ with $t_p$ representing the time of the current pulse (132 ns), and $I_x$ is the peak current ($\approx 20\ MA$). Thus Eqs. (3) - (5) complete the analytical form for the time varying gravitational acceleration for MagLIF-relevant conditions. All simulations conducted used MHD with either ideal-gas EOS, or SESAME EOS.

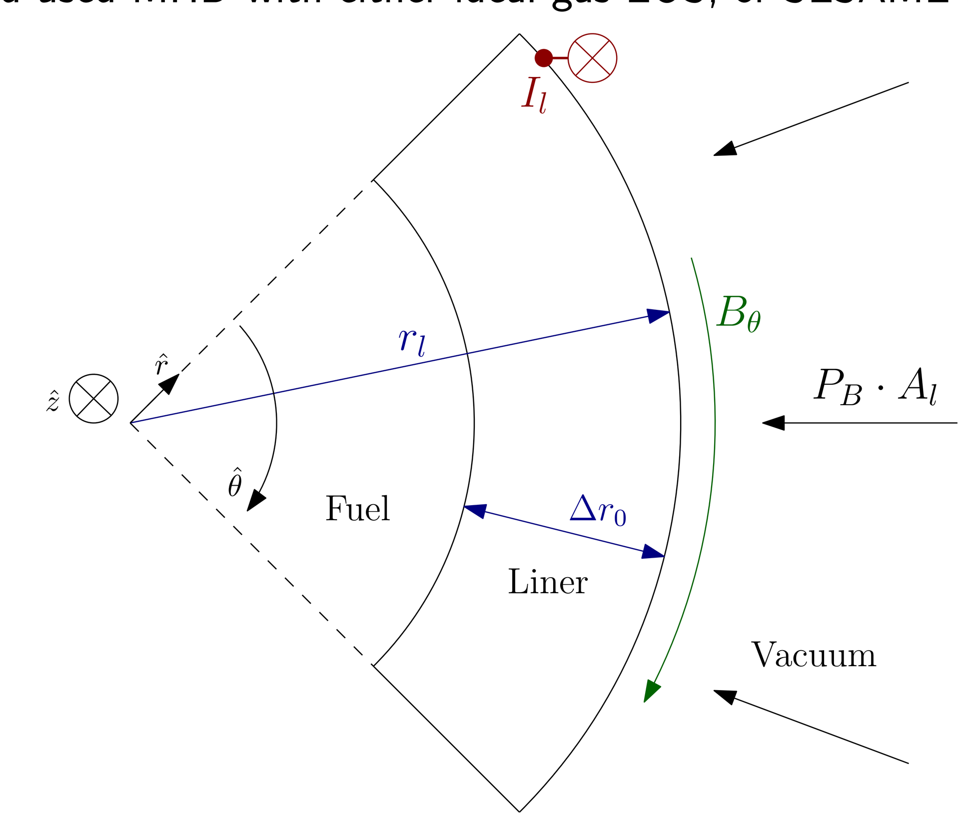


Figure 2: Cross-sectional end view of MagLIF where $I_l$ is the liner current in the z-dir, $r_{l_0}$ is the initial liner outer radius, $\Delta r_0$ is the initial liner thickness, $B_\theta$ is the azimuthal field created by $I_l$, and $P_B \cdot A_l$ is the pressure force acting radially inward.

## Single Mode

In Sinars et al. [2011] experimental tests on solid metal liners the MRT instability is seeded through machined sinusoidal perturbations. The sinusoids were of single wavelengths and were recorded with radiographs of the liner at various times in the implosion. The first series of experiments involved imploding two machined wavelengths of 200 and 400 $\mu m$'s on an aluminum liner.

## Single Mode - Continued

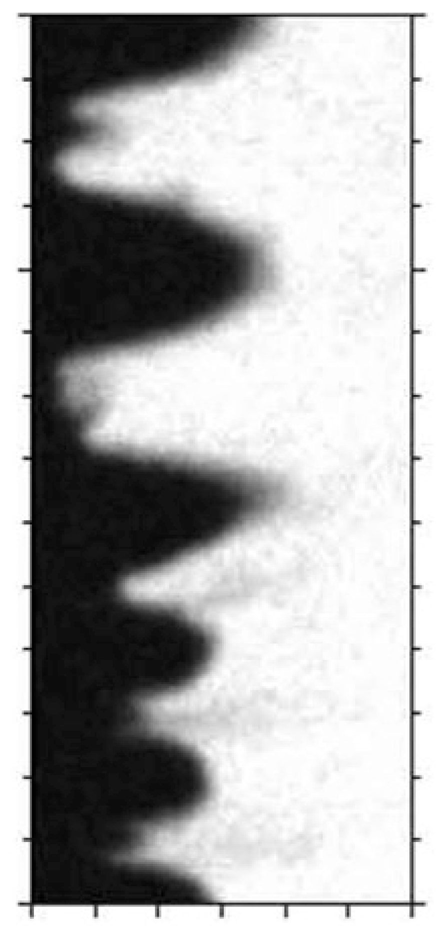

Figure 3: 7th experimental plot from figure 12 of [Sinars et al., 2011]

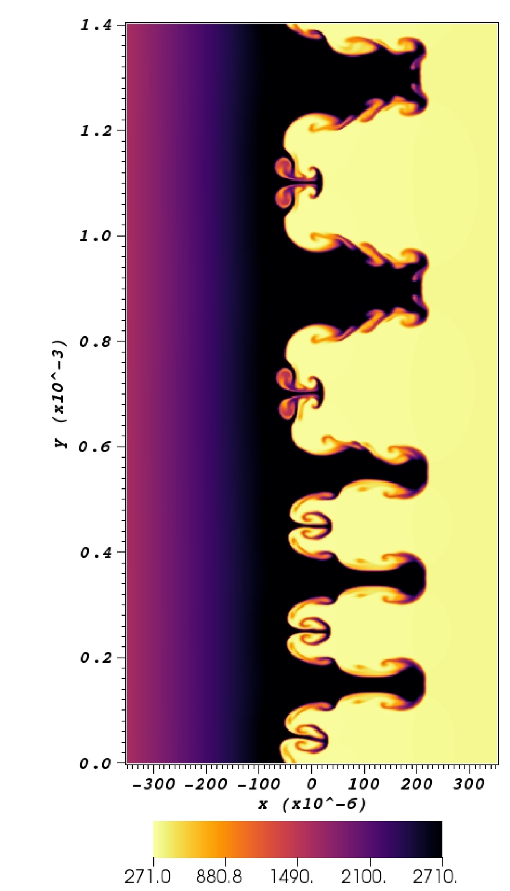


Figure 4: Ideal MHD single mode simulation of 400 $\mu m$, and 200 $\mu m$ wavelength perturbations. Taken at 70 $ns$ into the 132 $ns$ implosion.

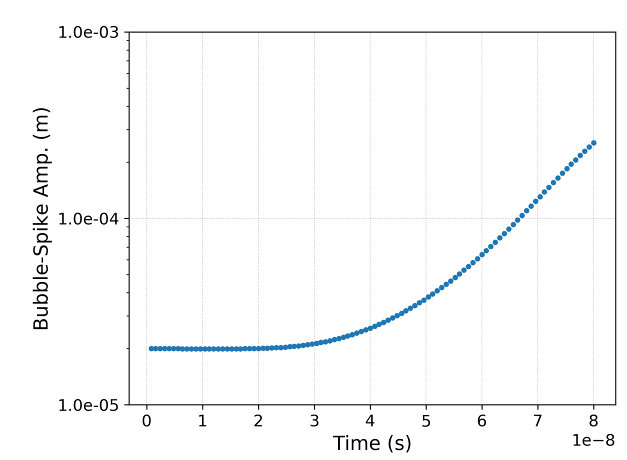


Figure 5: Bubble-Spike propagation distance for middle density contour with $\lambda = 400\ \mu m$.

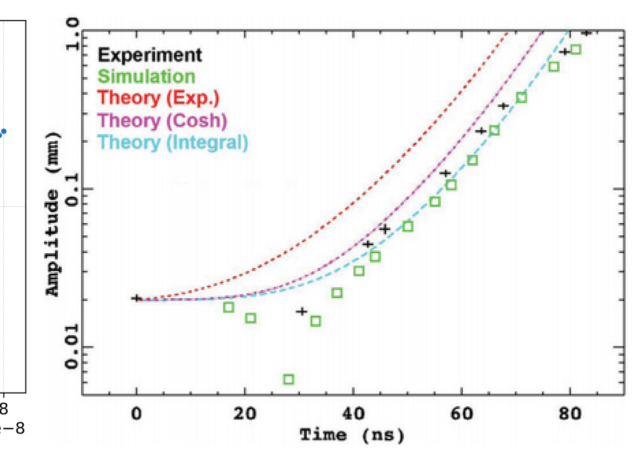


Figure 6: Figure 11 from [Sinars et al., 2011]

## Multimode

The functional form of the multimode perturbation used is

$$\delta V_y = \frac{1}{24}\sum_{m=1}^{m=24}\beta_m \cos\left[2\pi\left(\frac{m\cdot x}{\lambda_{max}} + \beta_m\right)\right] \tag{6}$$

where $\beta$ is a random number from 0 to 1, $\lambda_{max} = 200\ \mu m$ is the maximum wavelength associated with the lowest mode.
The multimode simulation incorporates the seeded magnetic field. The seeded magnetic field will vary during the implosion through flux compression. To accurately depict this, a piece-wise magnetic field ($B_l$=liner $B_v$=vacuum) source term is added, and is given by

$$\frac{\partial B_l}{\partial t} = -2B_0\frac{\partial r_l}{\partial t}\frac{2r_0-\Delta r_0}{(2r_l-\Delta r_0)^2}$$
$$\frac{\partial B_v}{\partial t} = 2B_0 r_l\frac{\partial r_l}{\partial t}\frac{r_{rc}^2-r_0^2}{(r_{rc}^2-r_l^2)^2}$$
$$\frac{\partial r_l}{\partial t} = \frac{-4r_0}{t_p}\left(\frac{t}{t_p}\right)^3$$

Table 3720 for Aluminum is used in all the simulations shown, as this incorporates the most recent relavent physics for EOS tables by using the GRIZZLY Lanl code with additional modifications.Crockett [Aug. 28] In addition work has been done to validate this table for use in other HEDP codes such as Alegra.Cochrane et al. [2006]

## Multimode - Continued

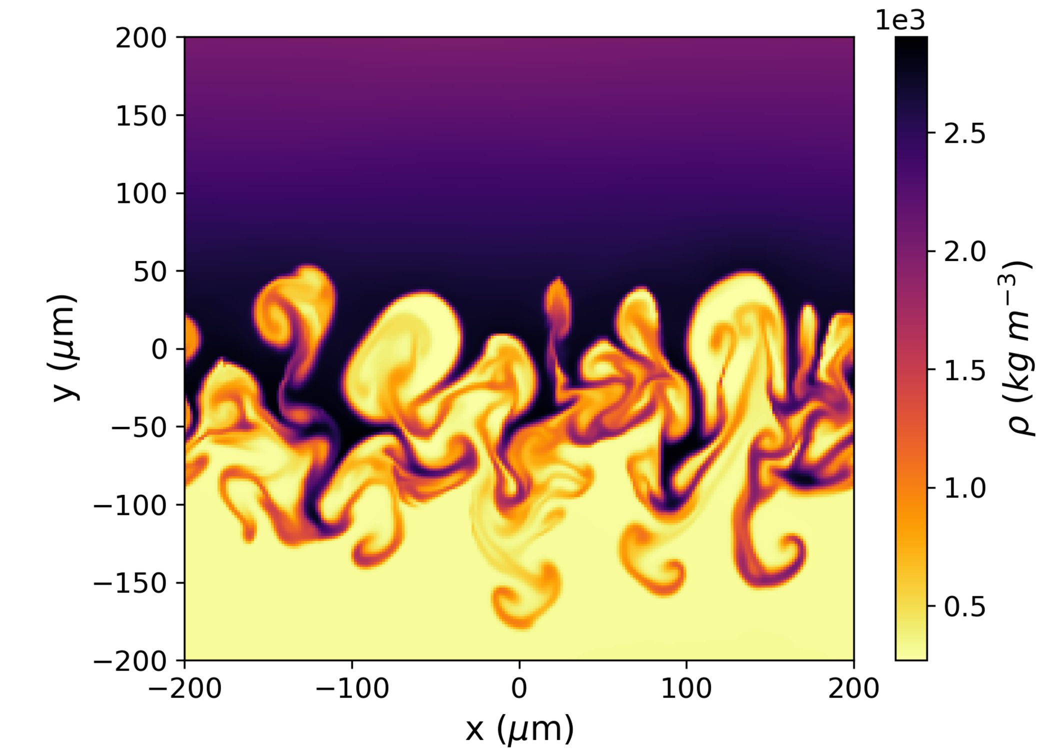


Figure 7: MHD multimode simulation using SESAME-3720 EOS without the magnetic field in MagLIF relevant conditions on a 240x240 grid at 72 ns into the implosion.

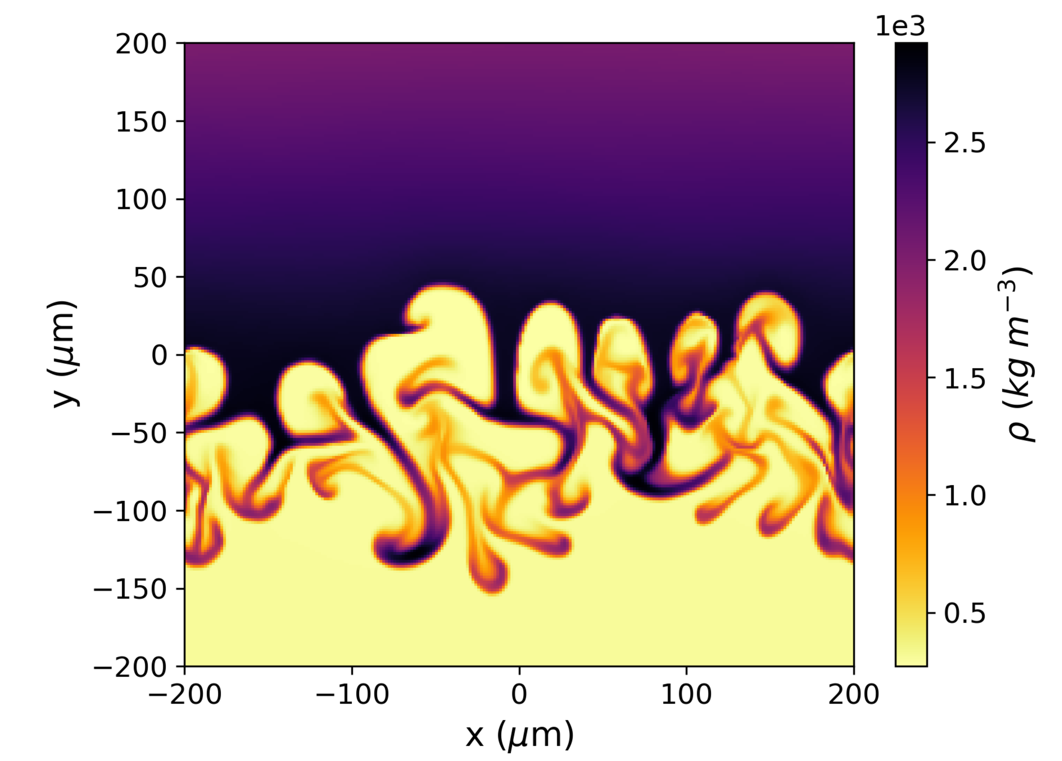


Figure 8: Same as figure 7, but with an added axial magnetic field that varies with time.

## Summary

A 2D planar simulation of MRT instability with different EOS is conducted using a time varying gravitational source term, and a time varying magnetic field source term (multi-mode only). The single mode simulation has shown promising agreement with the growth shown in the Sinars et al. [2011] paper. The multimode has shown the effect of the axial magnetic field on damping the smaller wavelength modes.

## Acknowledgements

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