A theoretical approach for shock strengthening in high-energy-density laser compression experiments

Michael Wadas[1], Griffin Cearley[1], Jon Eggert[2], Marius Millot[2], and Eric Johnsen[1]
[1]Mechanical Engineering, Univ. of Michigan, Ann Arbor, MI. [2]Lawrence Livermore Nat. Lab, Livermore, CA.

Introduction

- Details of many planetary interior compositions remain unknown.
- Simulations predict superionic ice in Jovian planets, but accessing these conditions experimentally is challenging [1-3].
- **Objective: develop a method for extending experimental access to extreme conditions found in planetary interiors.**

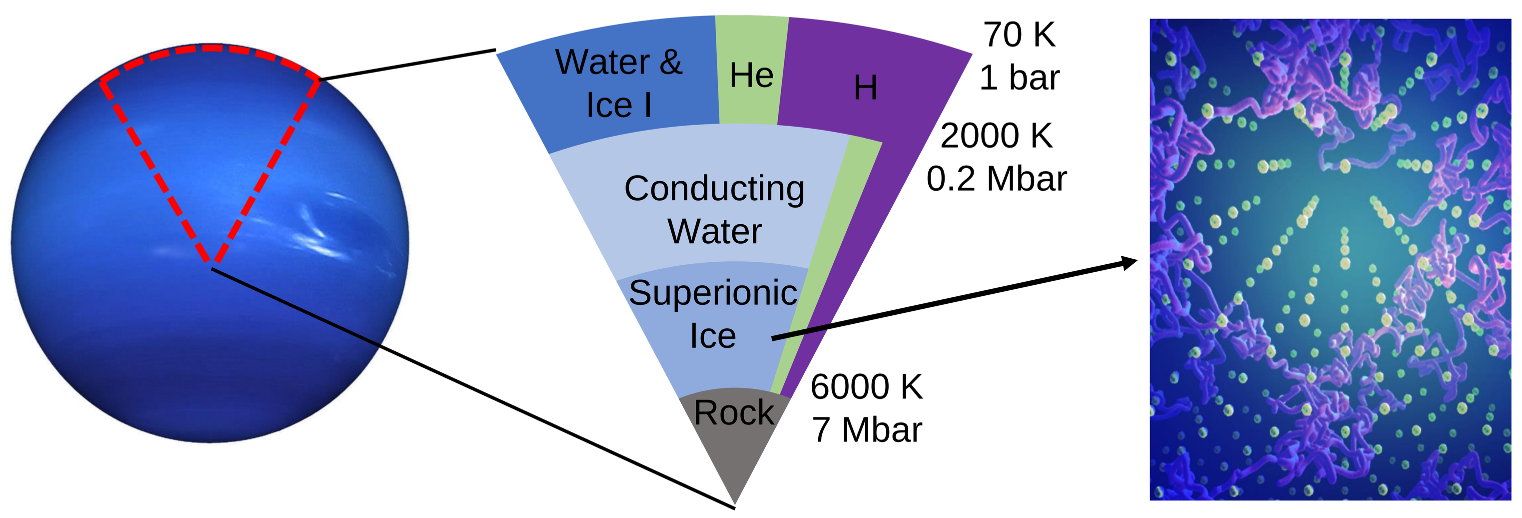

Figure 1: The hypothesized composition of the planet Neptune with superionic ice [4].

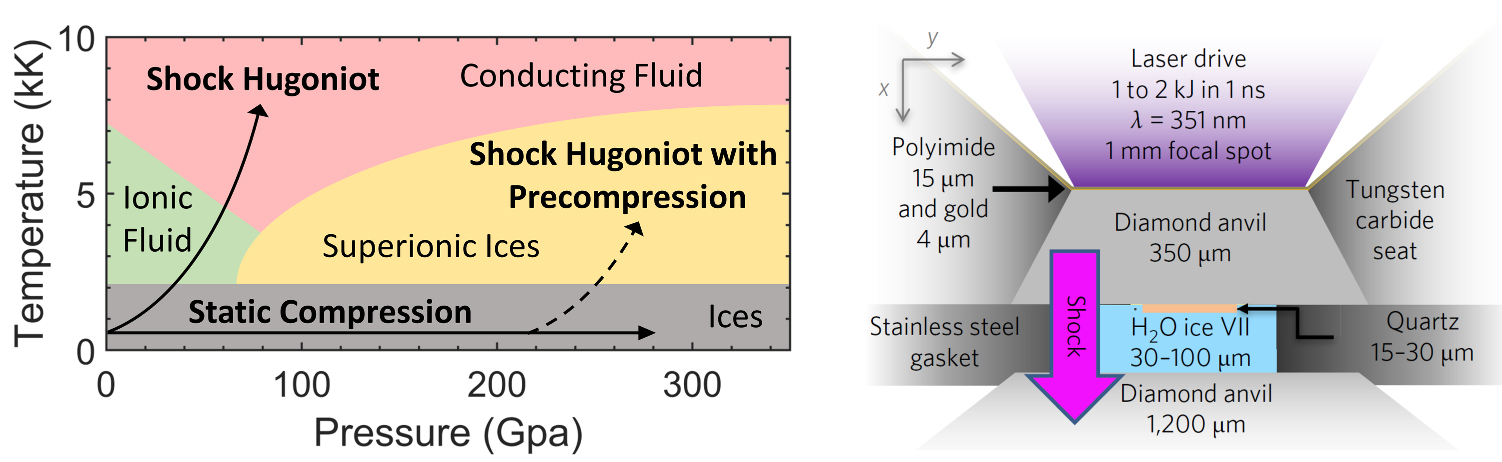

Figure 2: The thermodynamic path (left) and experimental schematic (right) of a diamond anvil cell.

Method of Analysis

- The method of characteristics (MoC) reduces PDEs to ODEs along specific paths, enabling solutions to 1D nonlinear hydrodynamics.
- The Riemann problem describes a system after diaphragm release.
- The analysis leverages the MoC with a boundary condition from the Riemann problem. A calorically perfect gas is assumed.

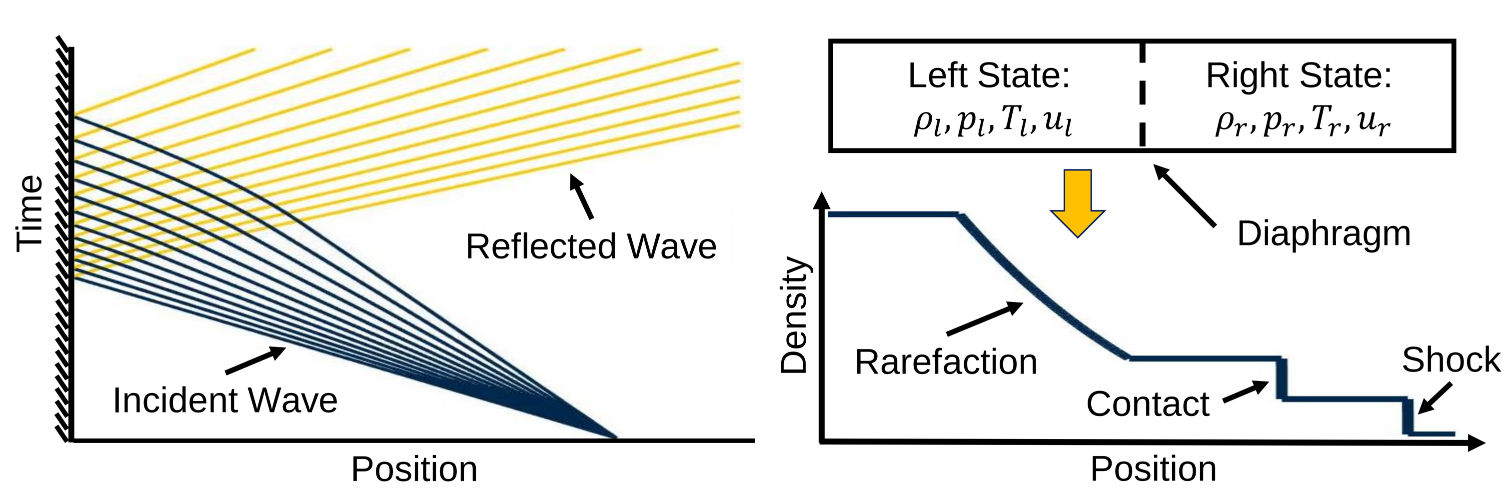

Figure 3: The MoC solution for a wall-reflected rarefaction (left) and a solution to the Riemann problem (right).

Results: Single Step

- An intermediate step enables a stronger shock in the target material than without the step until reflected waves weaken it.
- Optimal shock strengthening occurs when the step density is the geometric mean of the densities of the left and right materials.

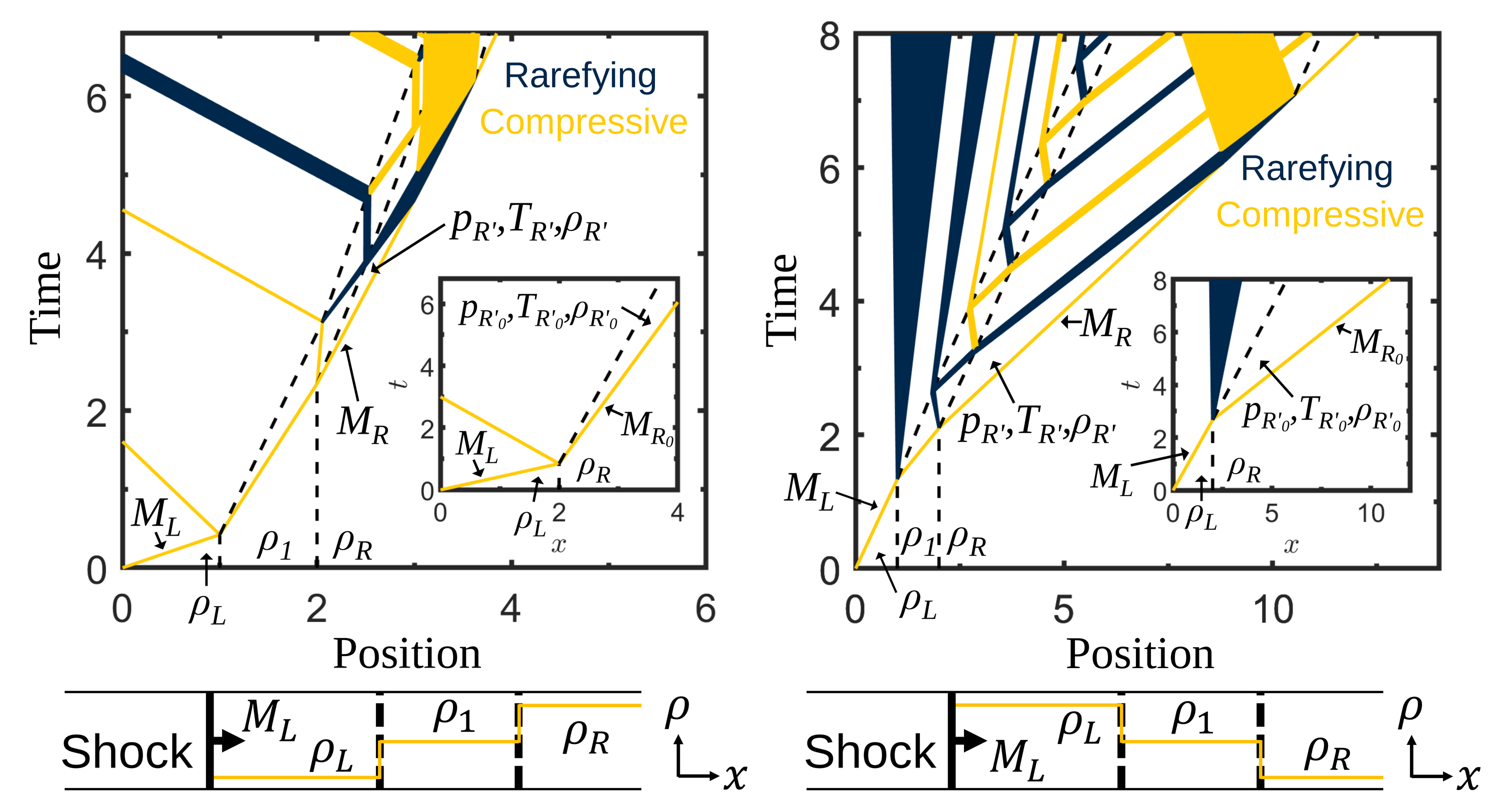

Figure 4: The MoC solution for a shock passing through steps of increasing (left) and decreasing (right) density.

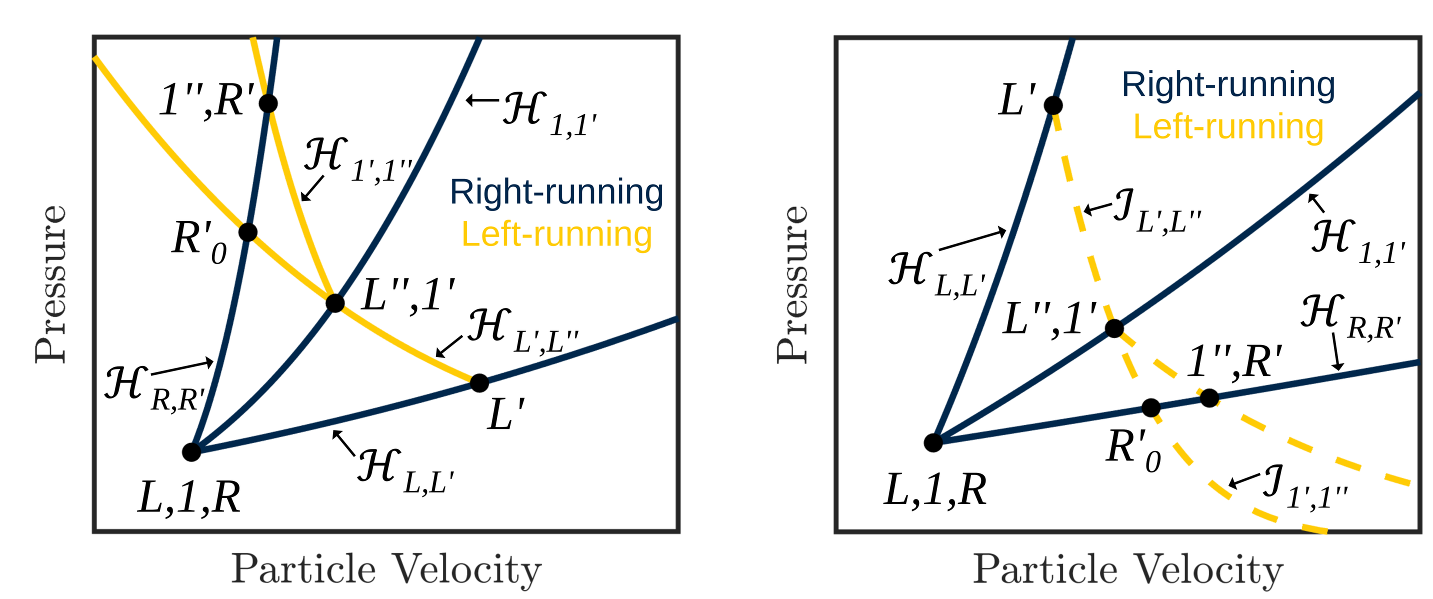

Figure 5: The Hugoniots and isentropes that fix the states for increasing (left) and decreasing (right) density.

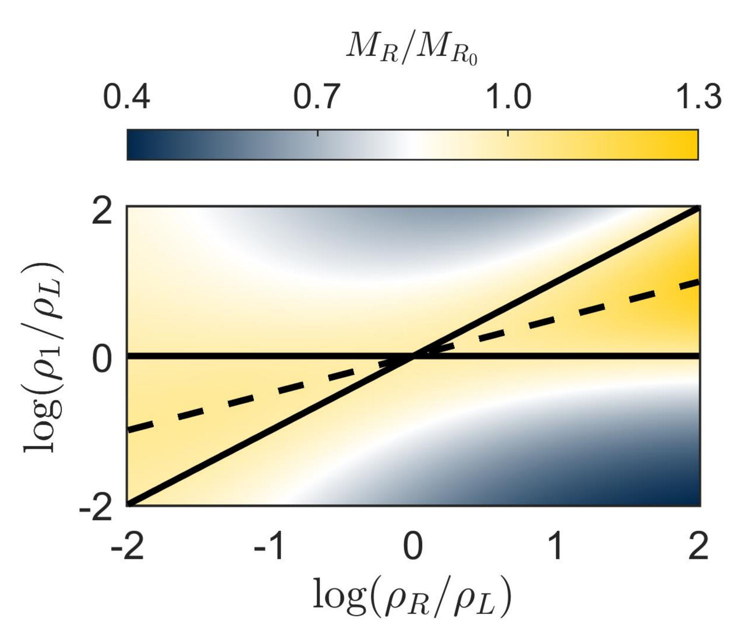

Figure 6: Shock strengthening for a given interface and intermediate step density.

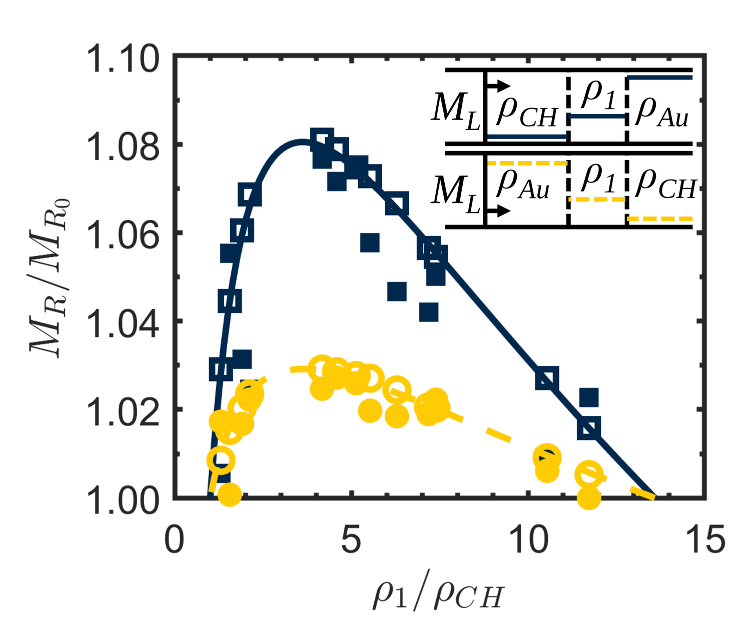

Figure 7: Shock strengthening from theory (lines) and Hyades simulations (open, ideal gas; filled, tabular).

Results: Multiple Steps

- Incorporating multiple steps can further strengthen the shock.
- Exponential density profiles optimize shock strengthening.

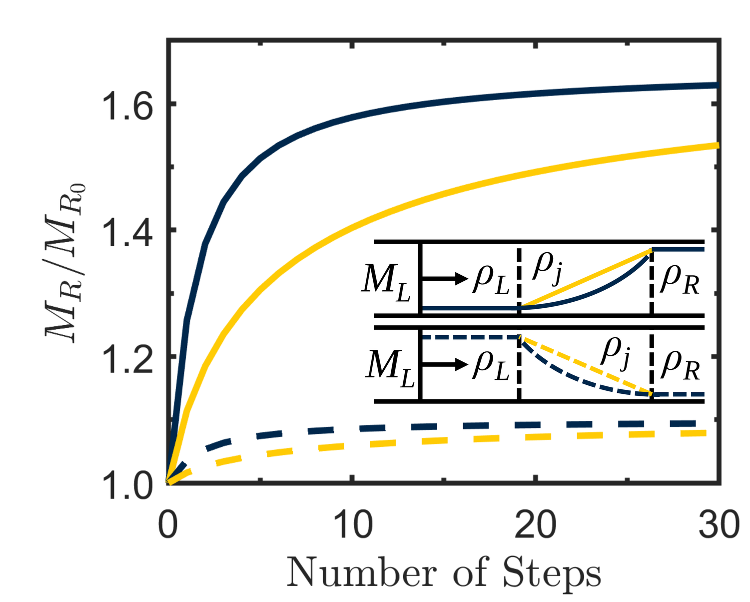

Figure 8: Shock strengthening vs number of steps distributed exponentially (blue) and linearly (yellow).

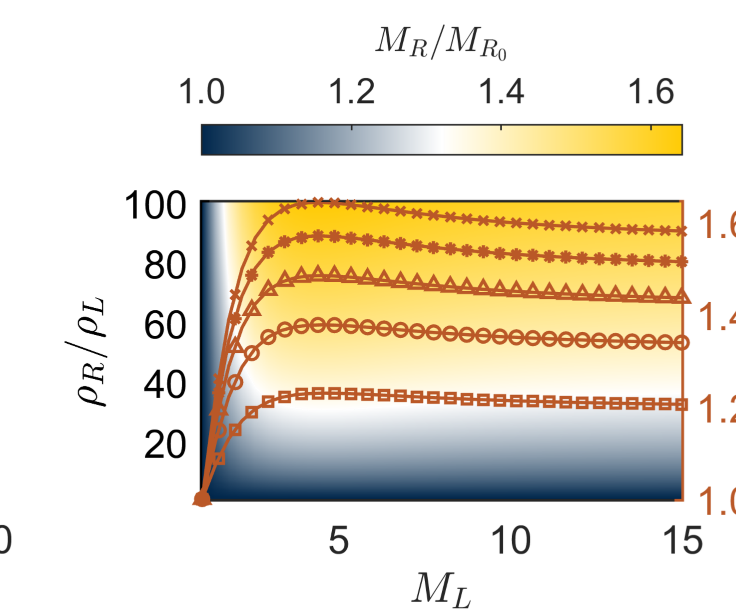

Figure 9: Shock strengthening vs overall interface density ratio and incident shock Mach number.

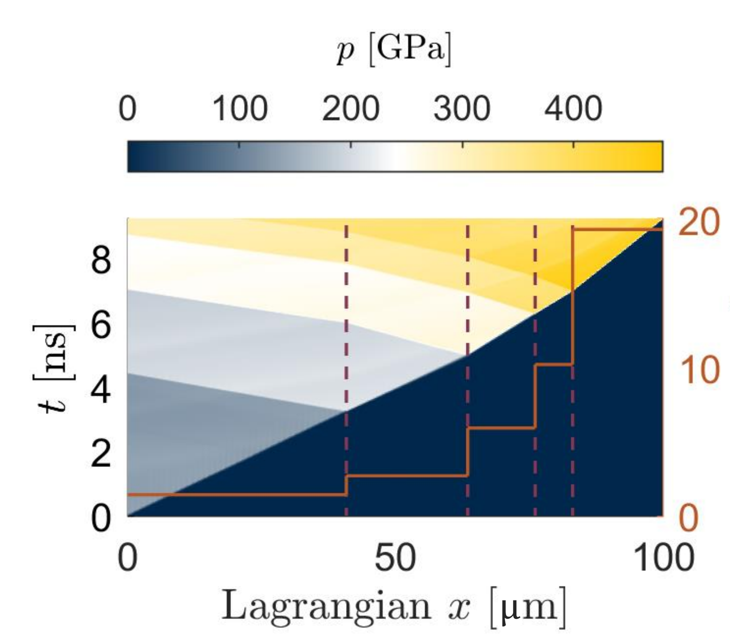

Figure 10: Hyades simulation showing wave diagram colored with pressure for three intermediate steps.

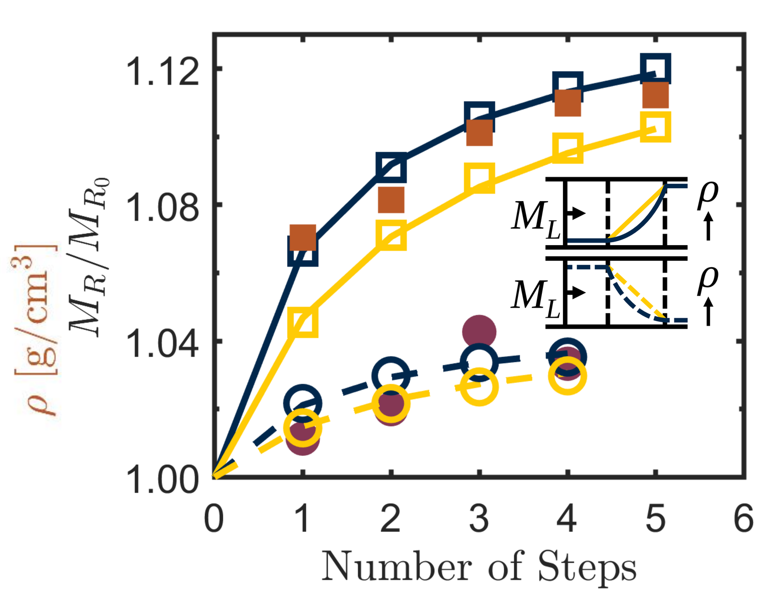

Figure 11: Shock strengthening vs number of steps from theory and Hyades simulations.

Conclusions and Acknowledgement

- A semianalytical method was developed to explore shock strengthening in anvil-based laser compression experiments.
- Density steps can be used to locally strengthen shock waves.
- For one step, a density $\rho_1 = \sqrt{\rho_L \rho_R}$ maximizes the shock strength.
- Exponential density profiles yield optimal shock strengthening, enabling access to new experimental states of matter.

[1] P. Demontis et al., Phys. Rev. Lett. **60**, 1988. [2] M. Benoit et al., Phys. Rev. Lett. **76**, 1996. [3] C. Cavazzoni et al., Science **283**, 1999. [4] M. Millot et al., Nat. Phys. **14**, 2018.

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