Hydrodynamics of Shocked Interfaces

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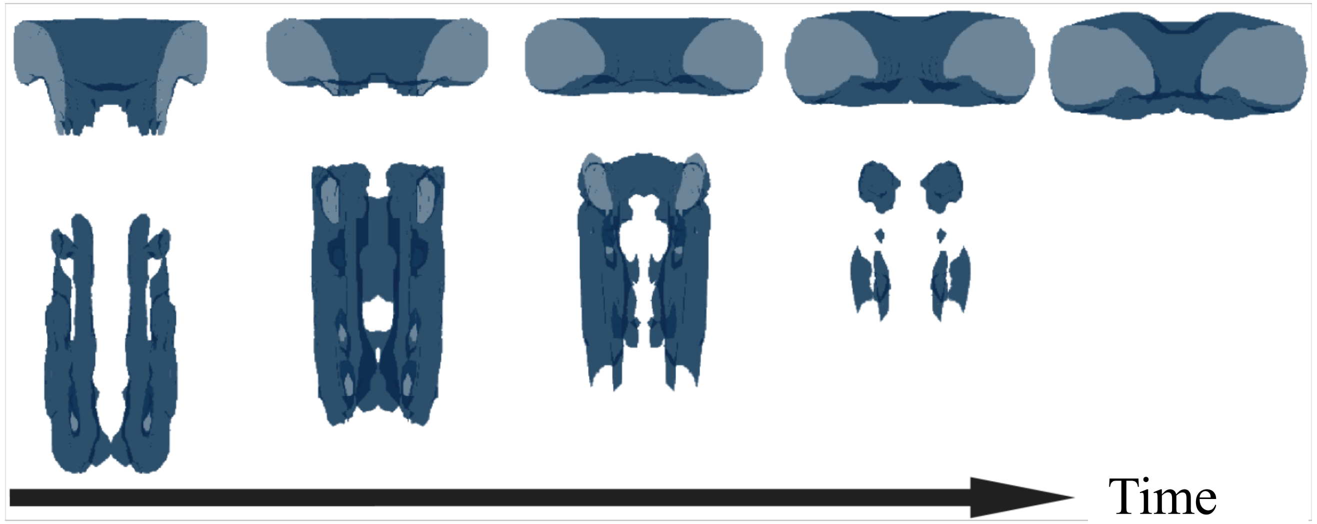
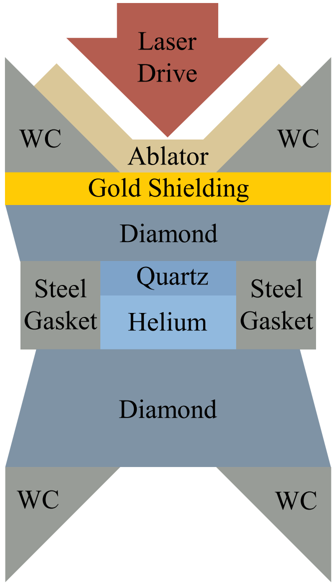
Summary

1. Shock waves occur in a wide range of engineering and scientific contexts including laser experiments, astrophysics, and inertial confinement fusion (ICF).
2. High-powered lasers can drive strong waves in materials, enabling their study in extreme pressure environments. We developed a method for further strengthening such shocks.
3. Shocked interfaces mix via the Richtmyer-Meshkov instability (RMI), possibly leading to the escape of high-vorticity ejecta with important implications for turbulent transitions.

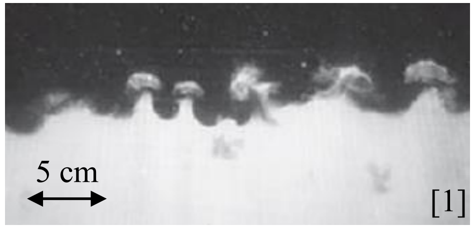


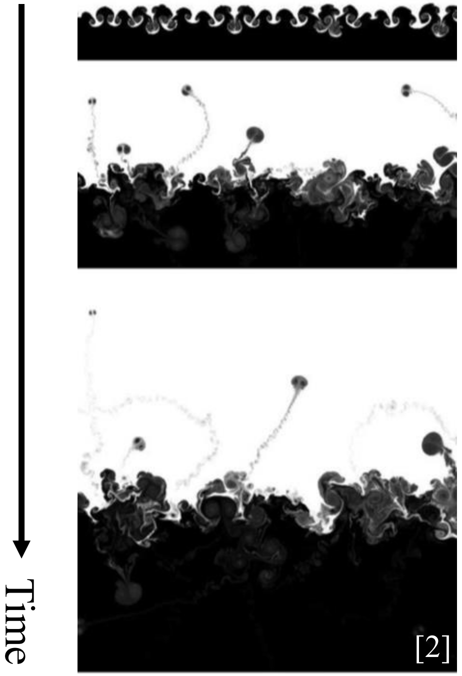
Shock waves occur in a variety of engineering and natural contexts where they interact with fluid interfaces.

Compression Experiments

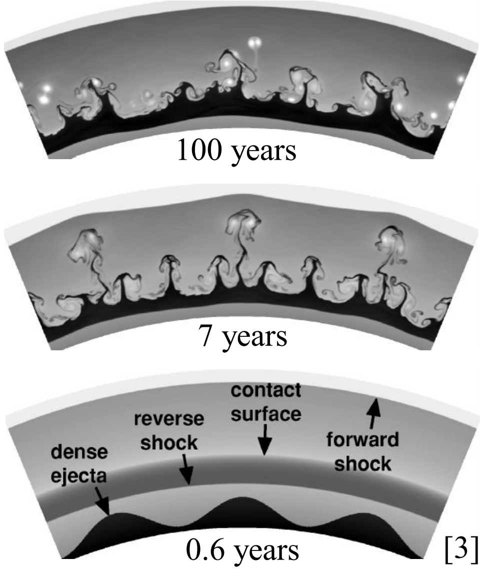


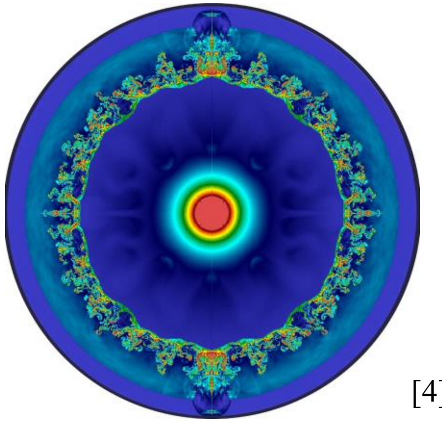
Richtmyer-Meshkov Instability (RMI)



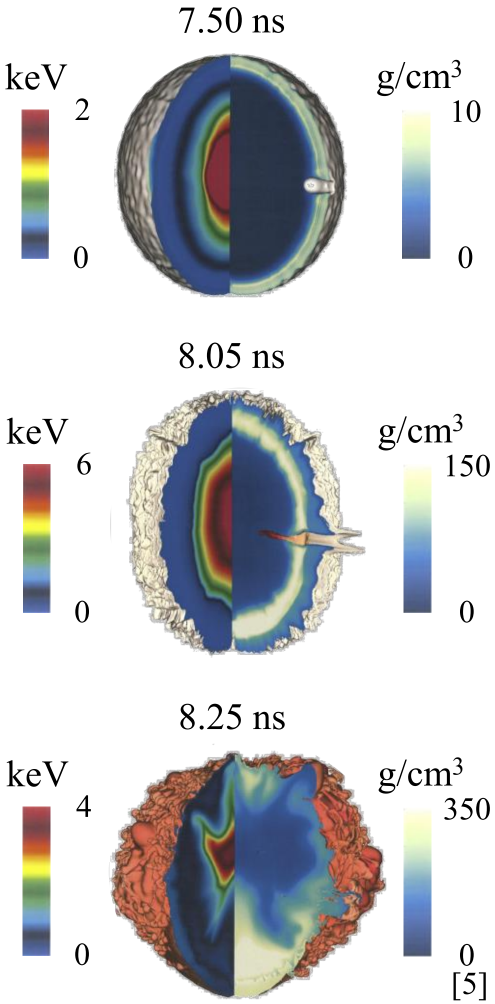


Supernovae

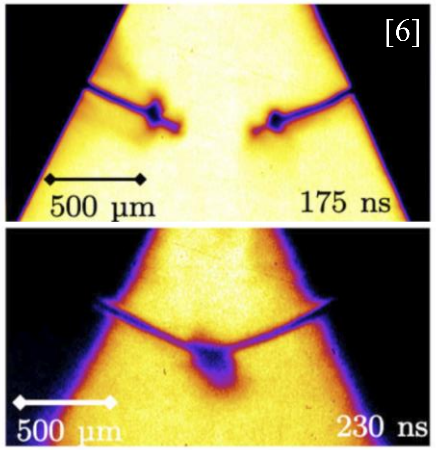


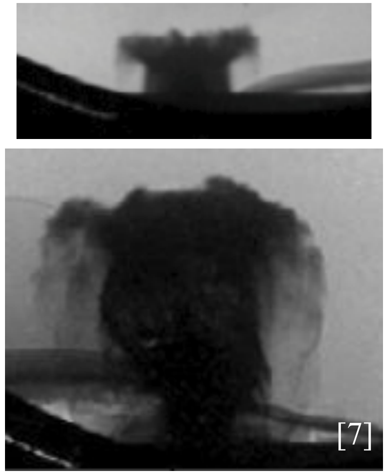


Inertial Confinement Fusion (ICF)



Ejecta/Jet Physics





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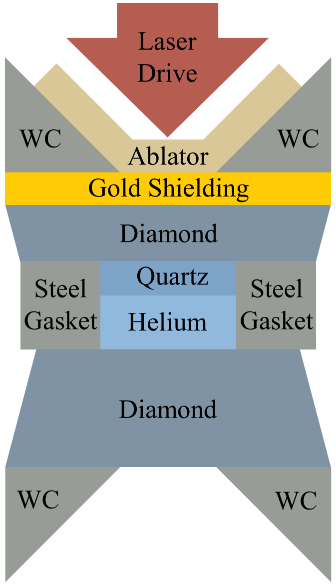

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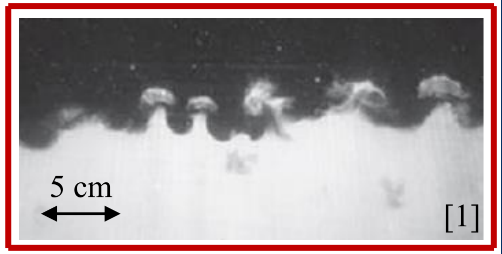

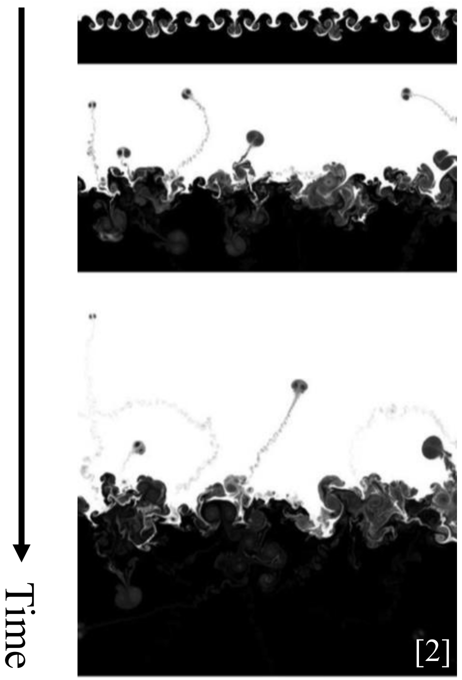

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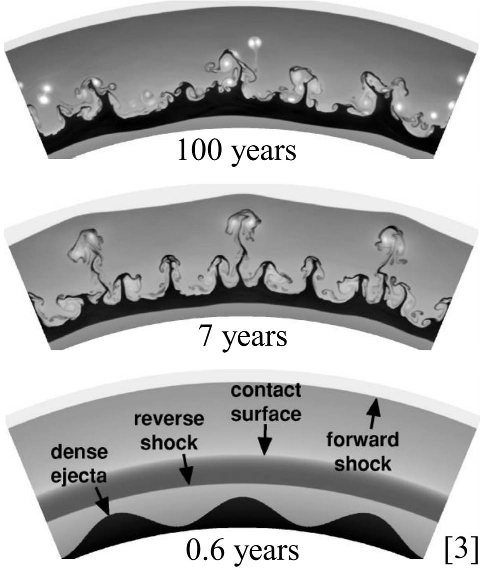

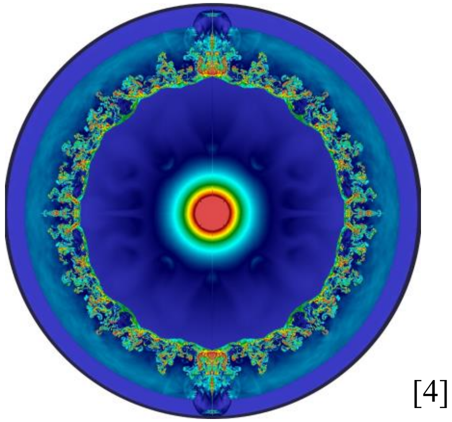

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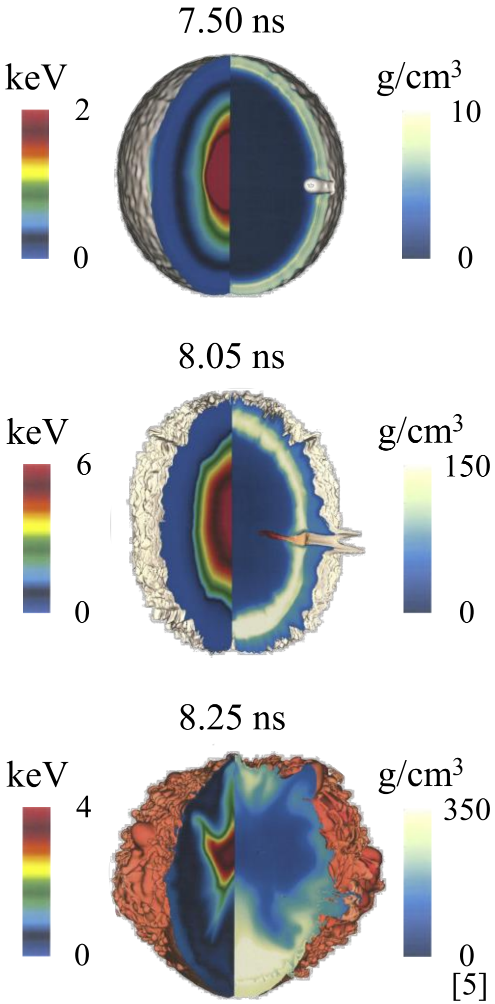

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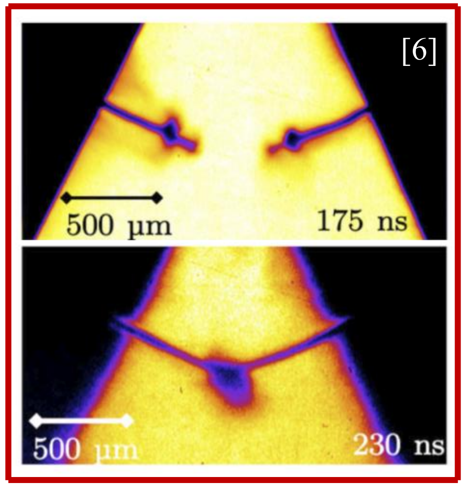
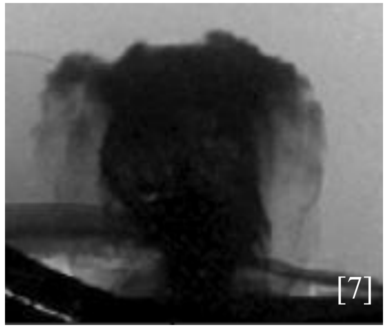
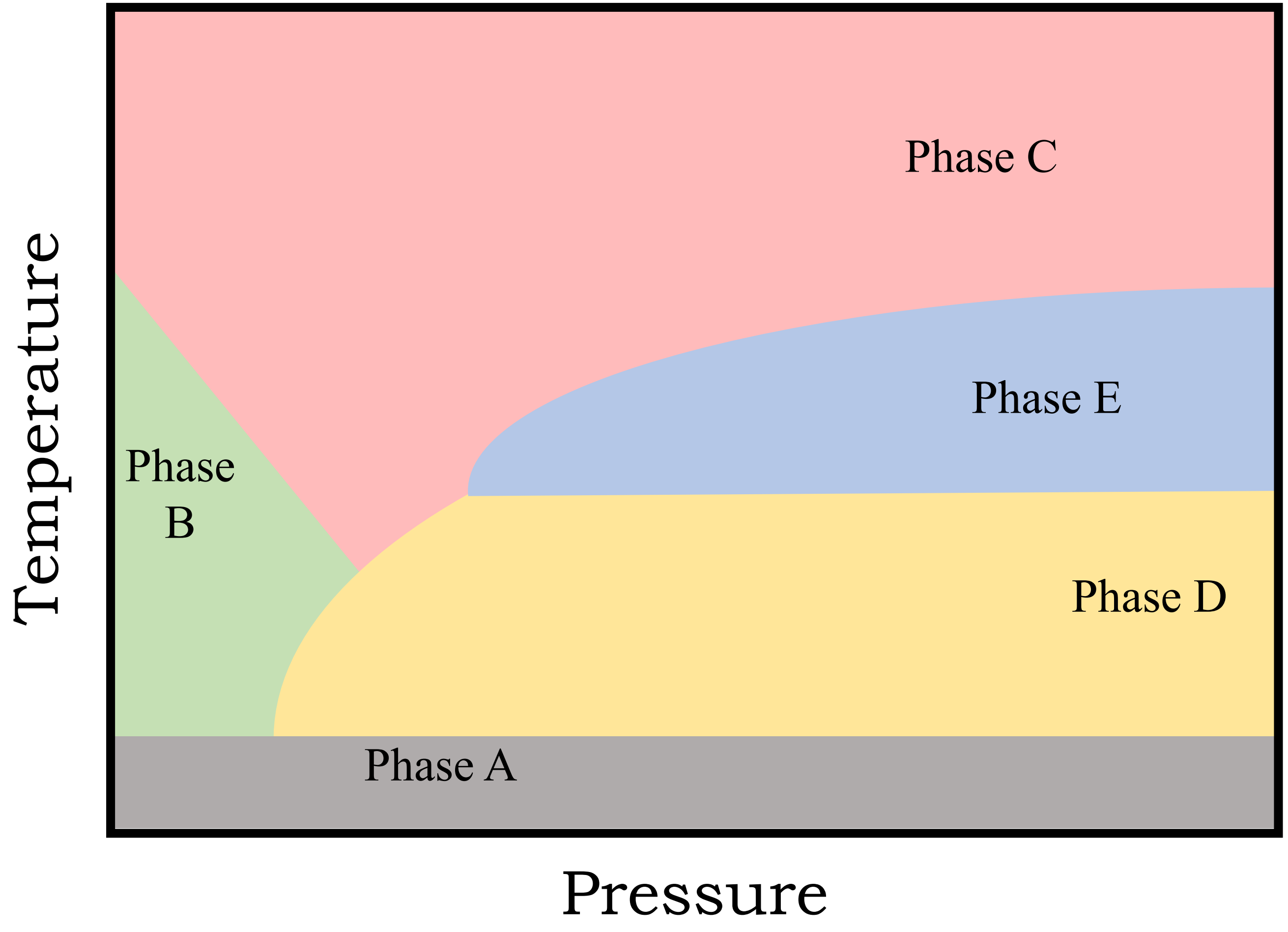




Dynamic compression experiments utilize lasers to generate shocks that compress materials to extreme pressures in a nominally 1D system.



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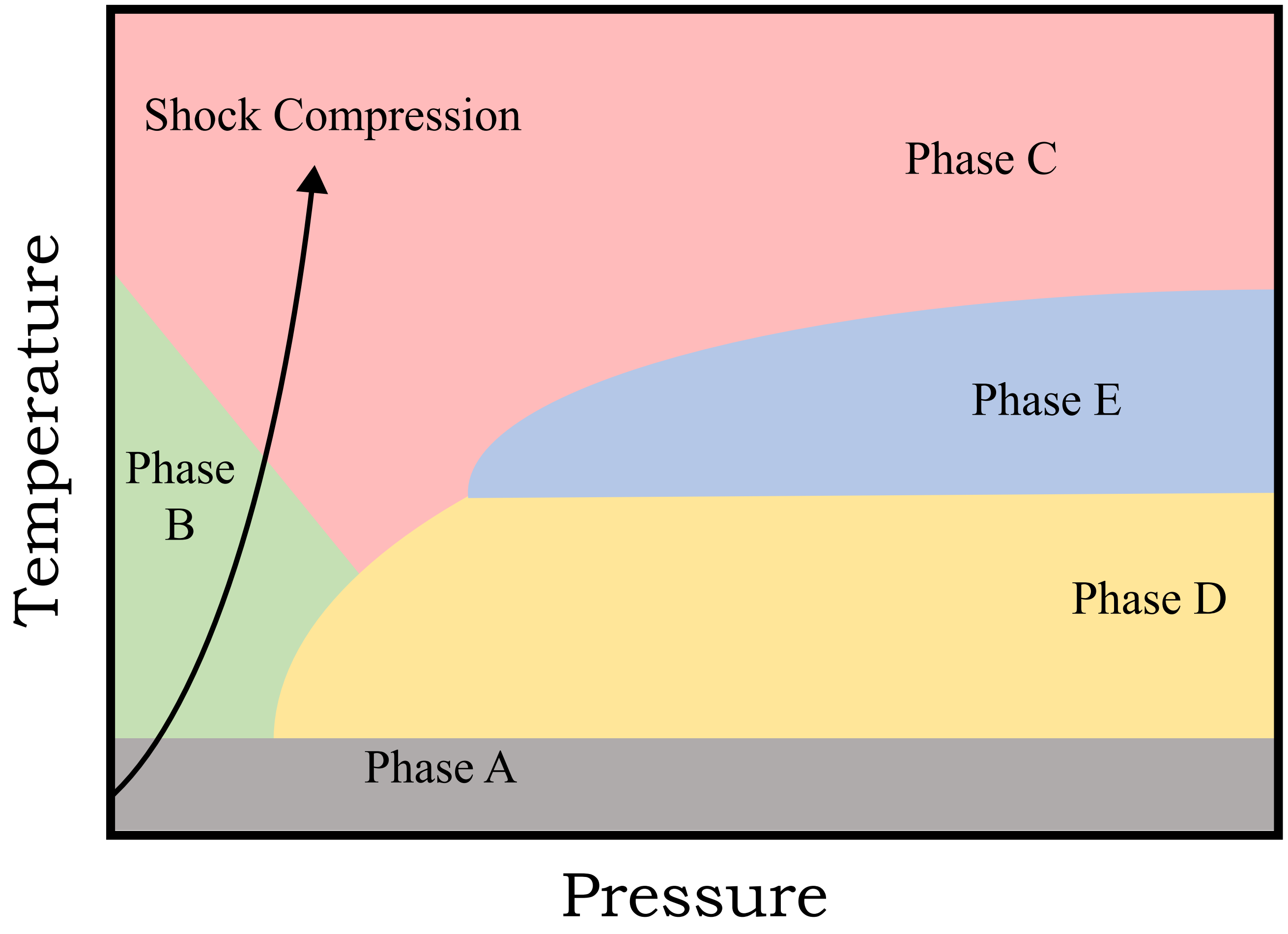

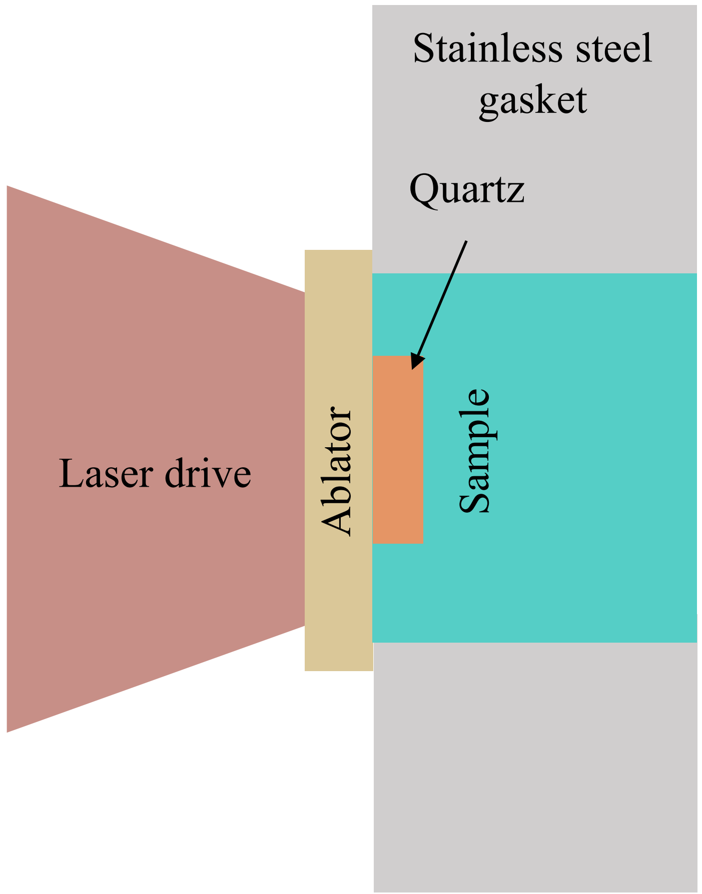

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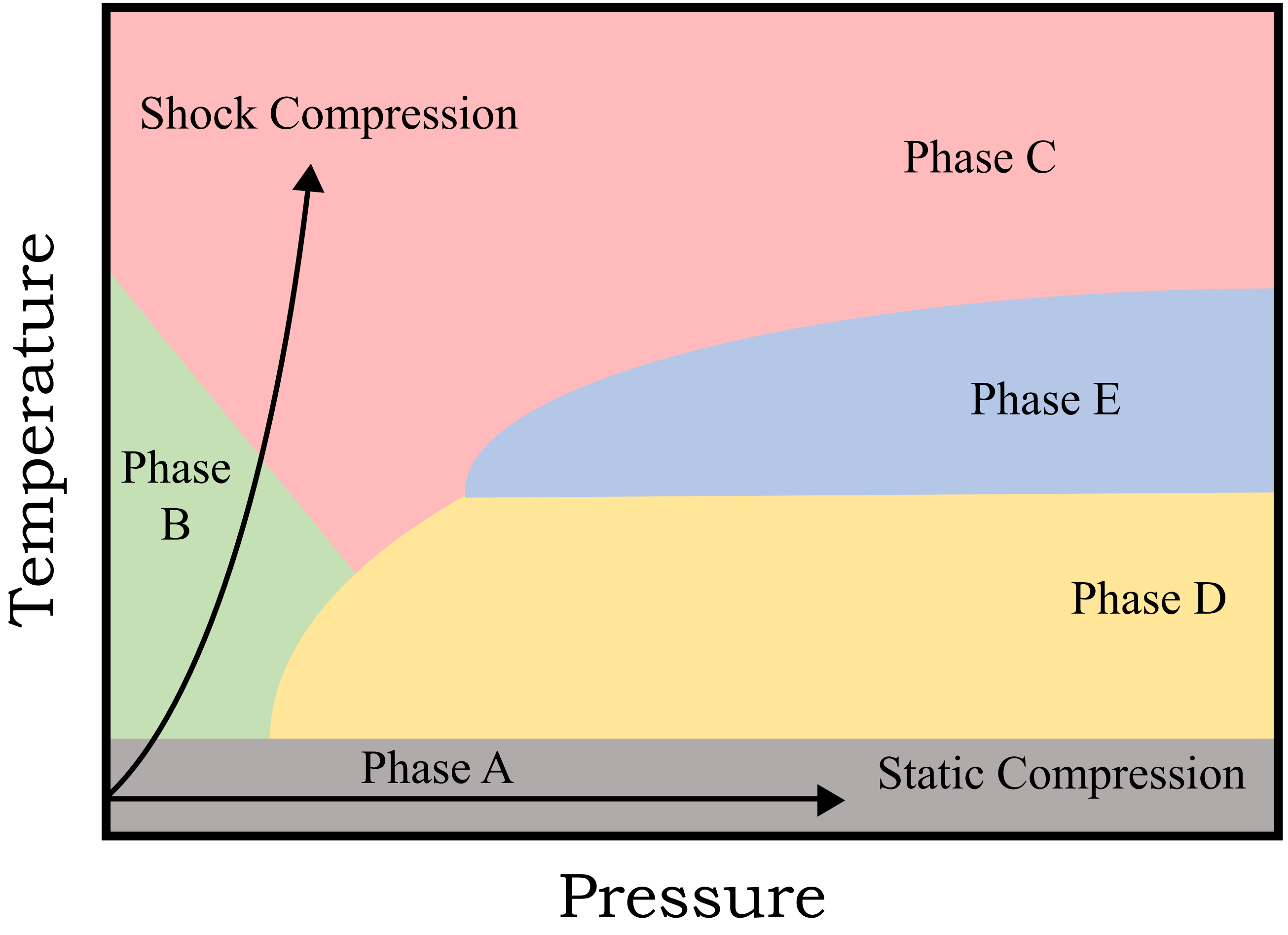

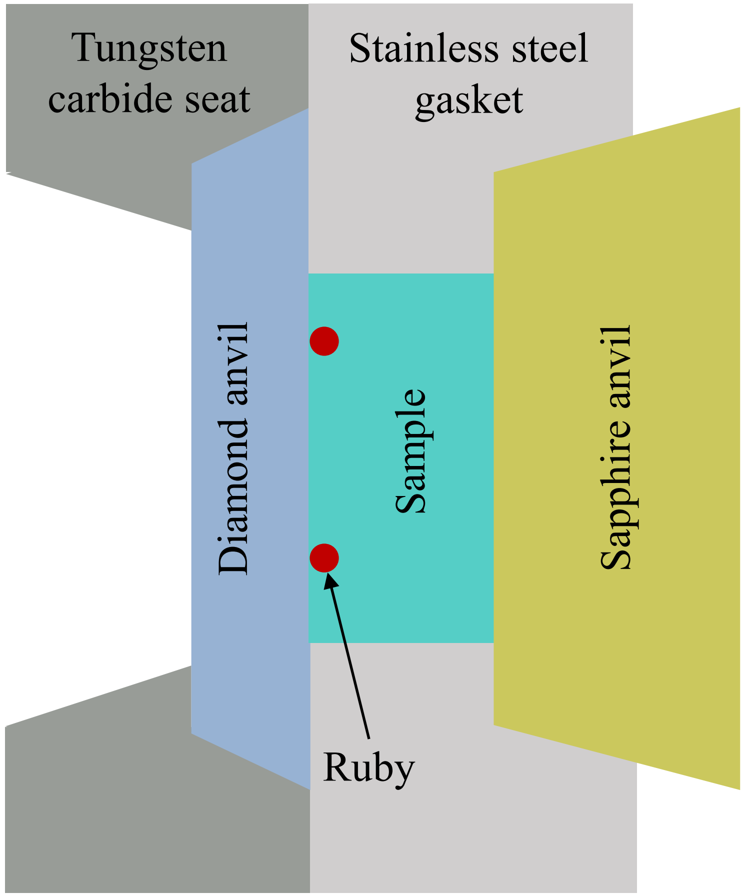

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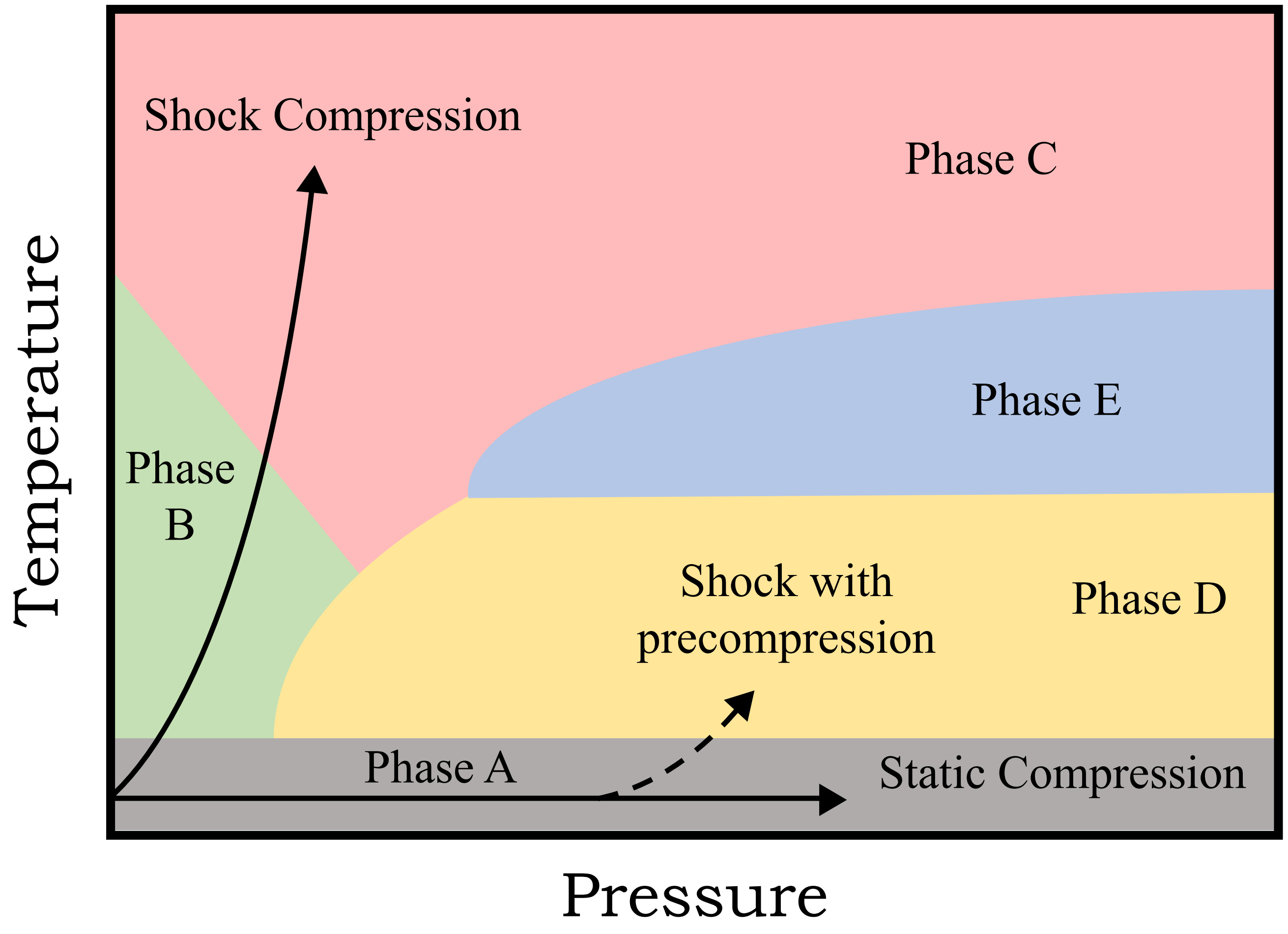

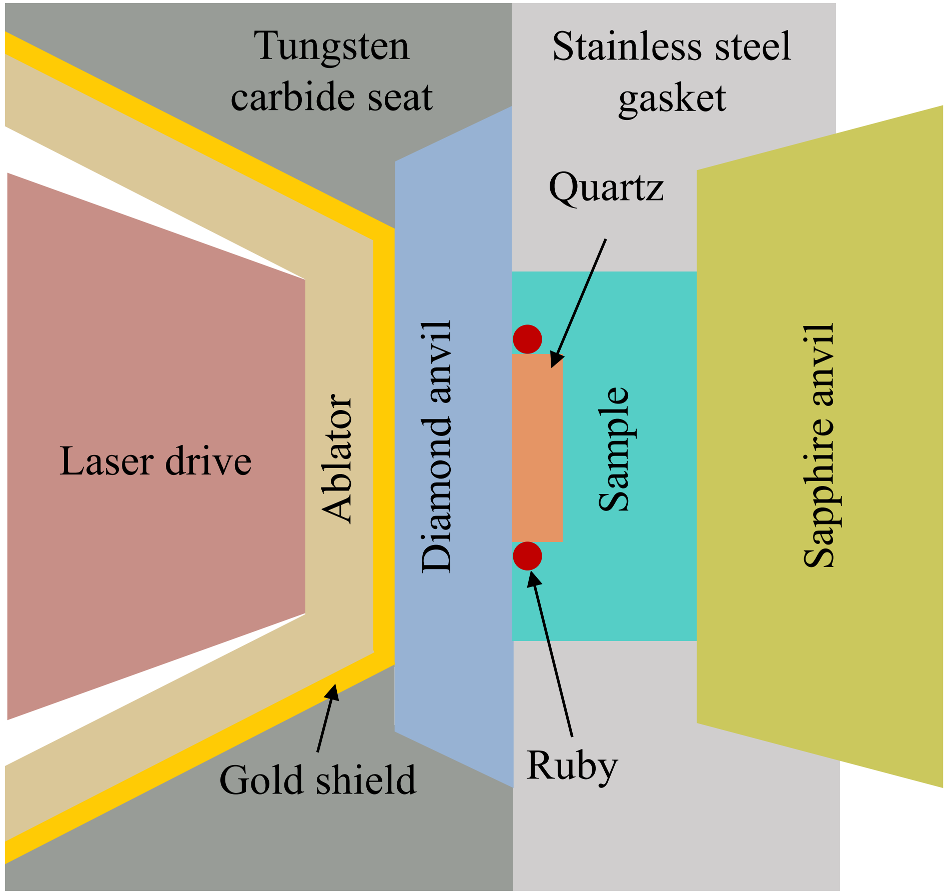

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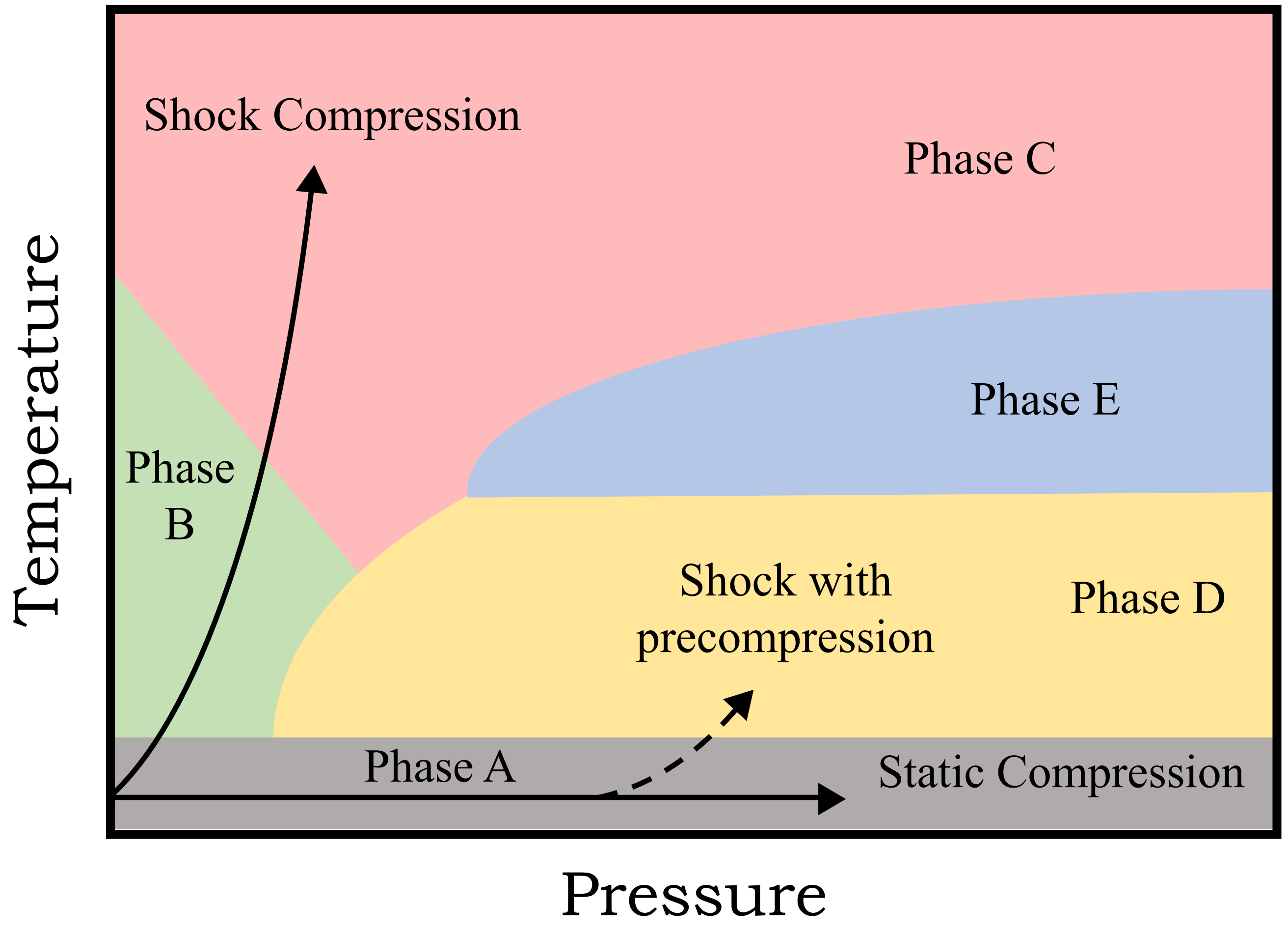

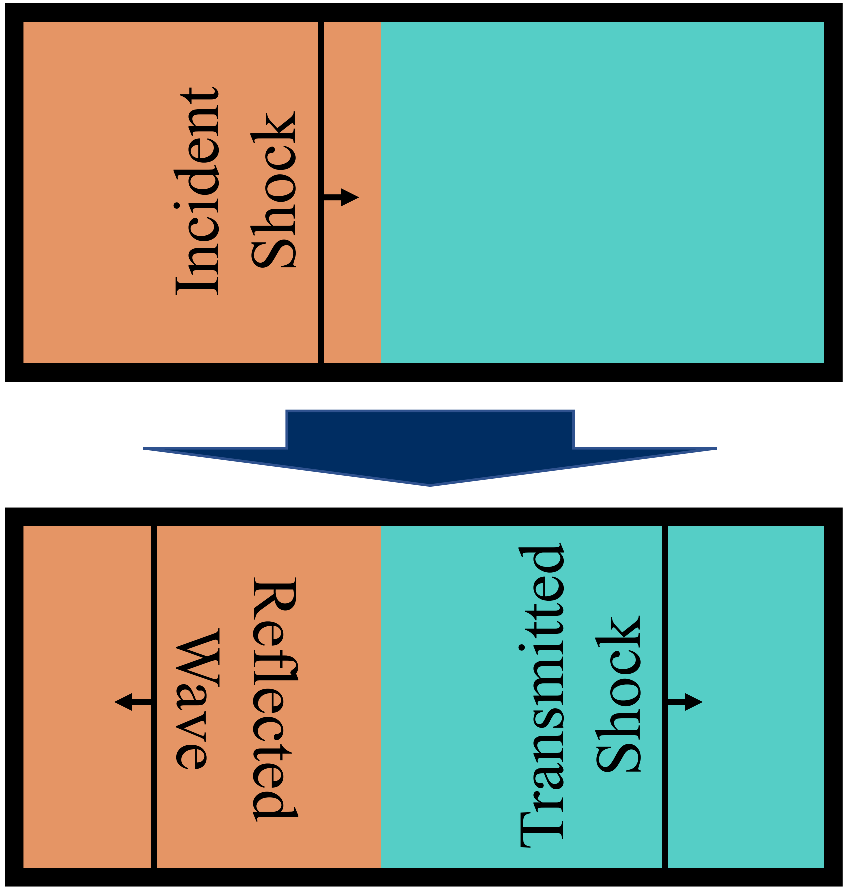

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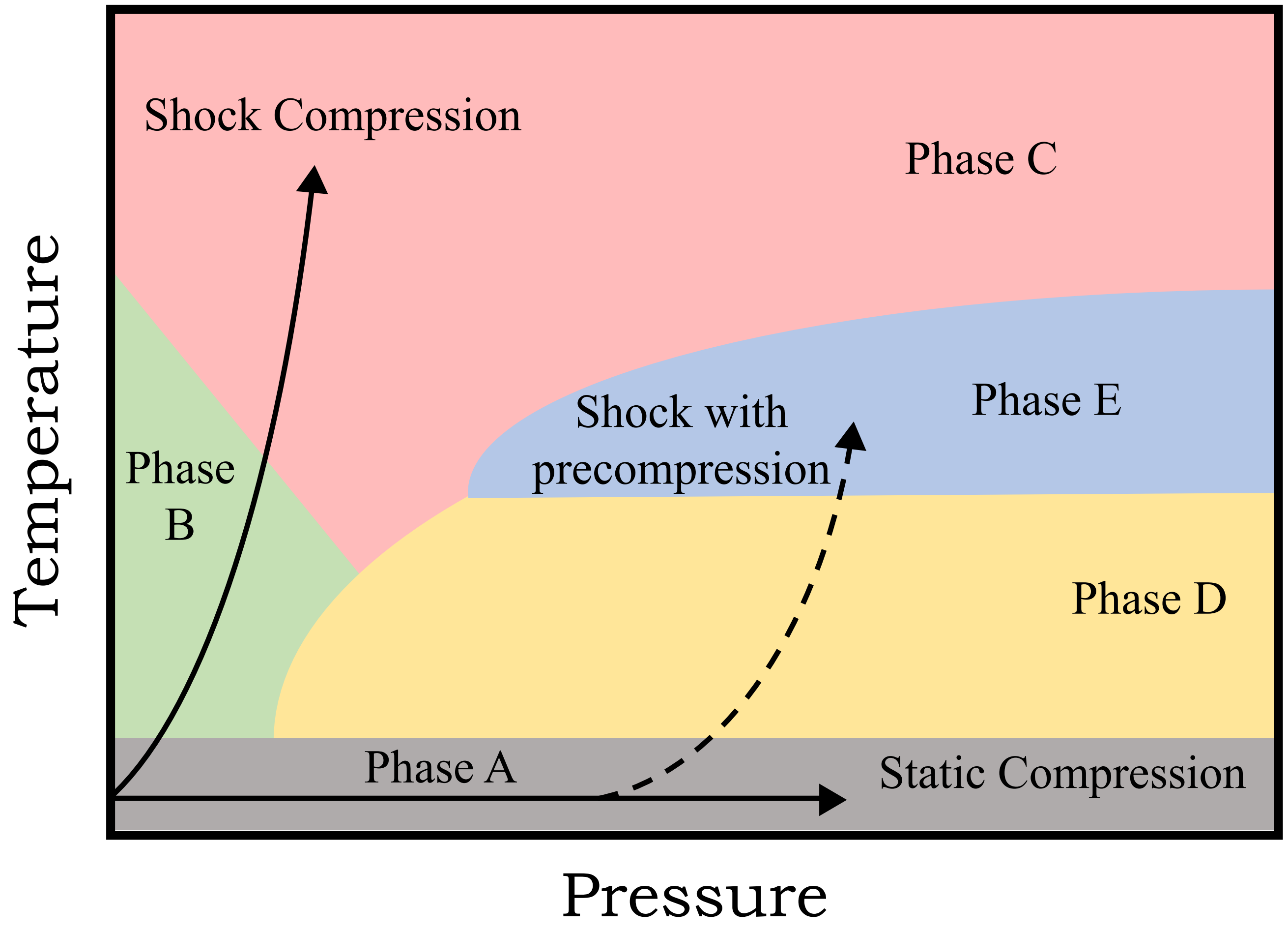
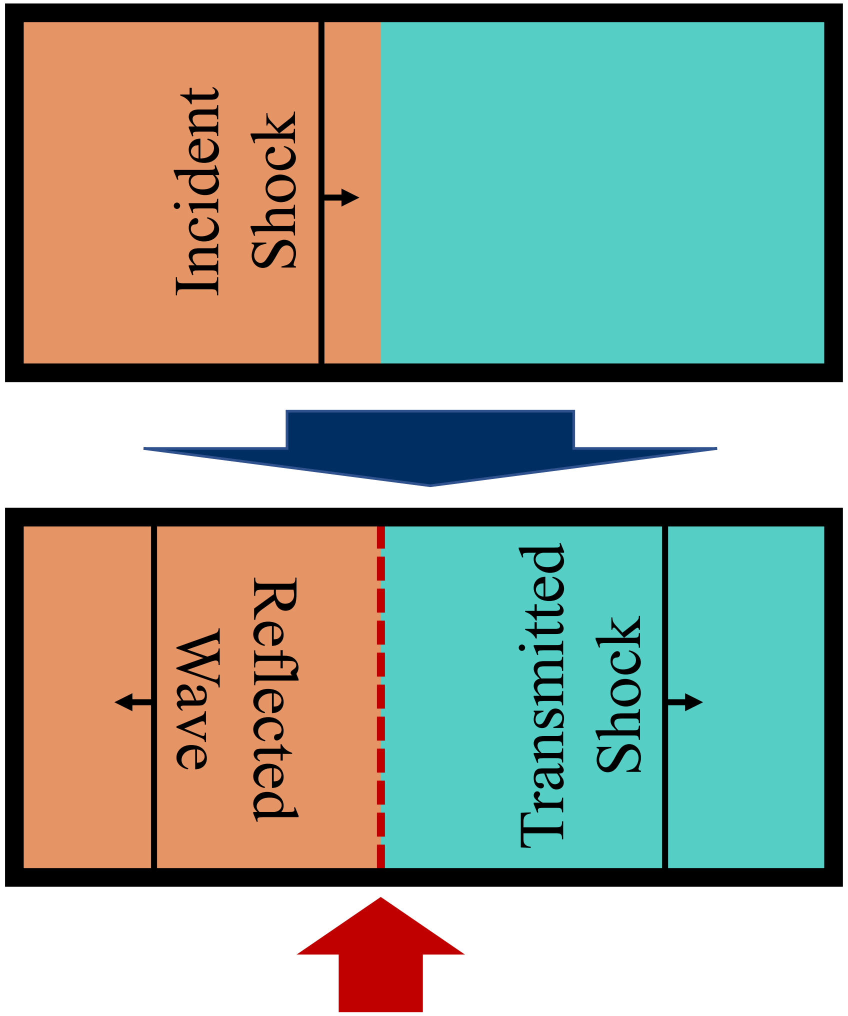
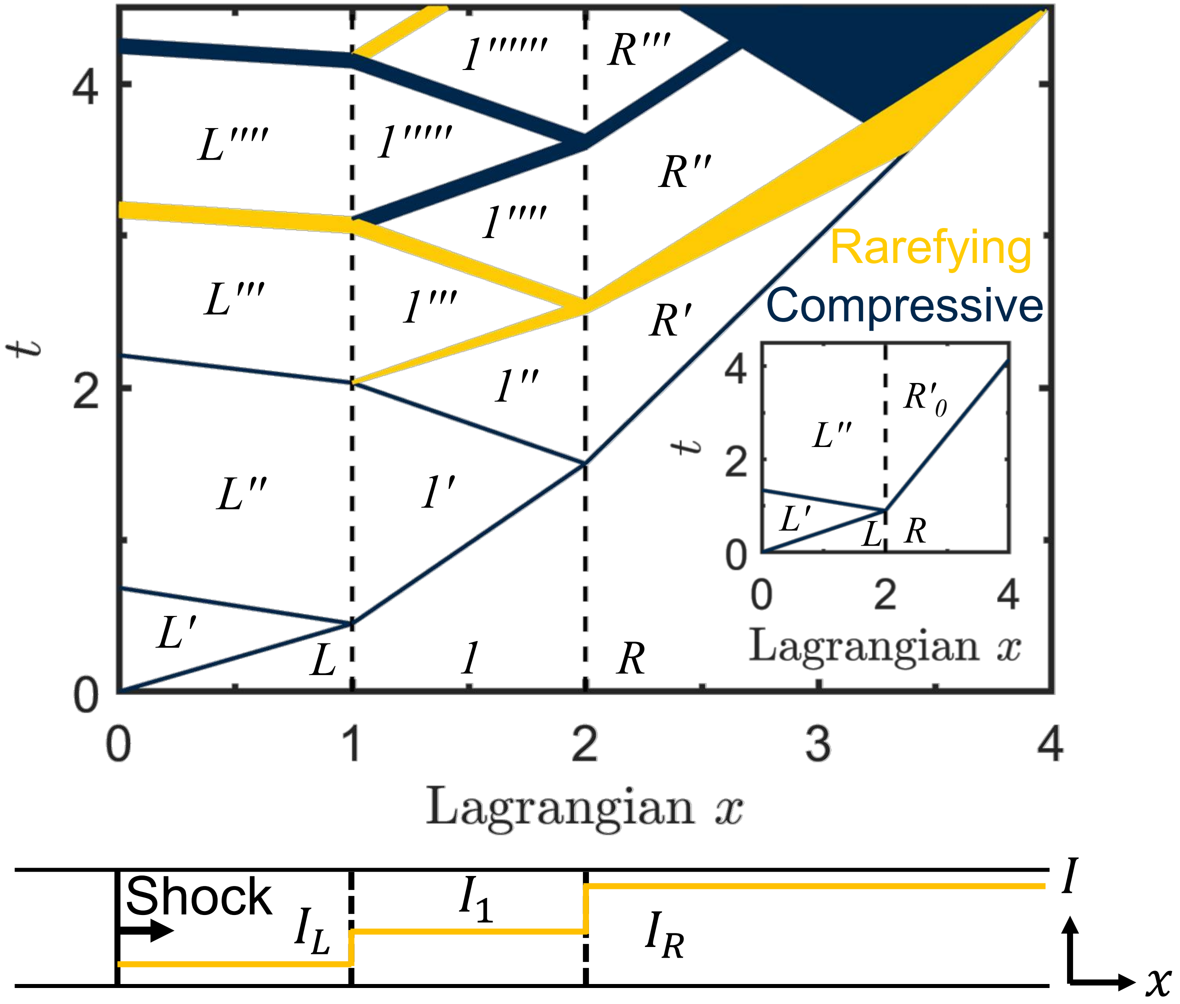




An intermediate material bridging an impedance discontinuity can transiently strengthen a shock wave in a material of interest.



[8]

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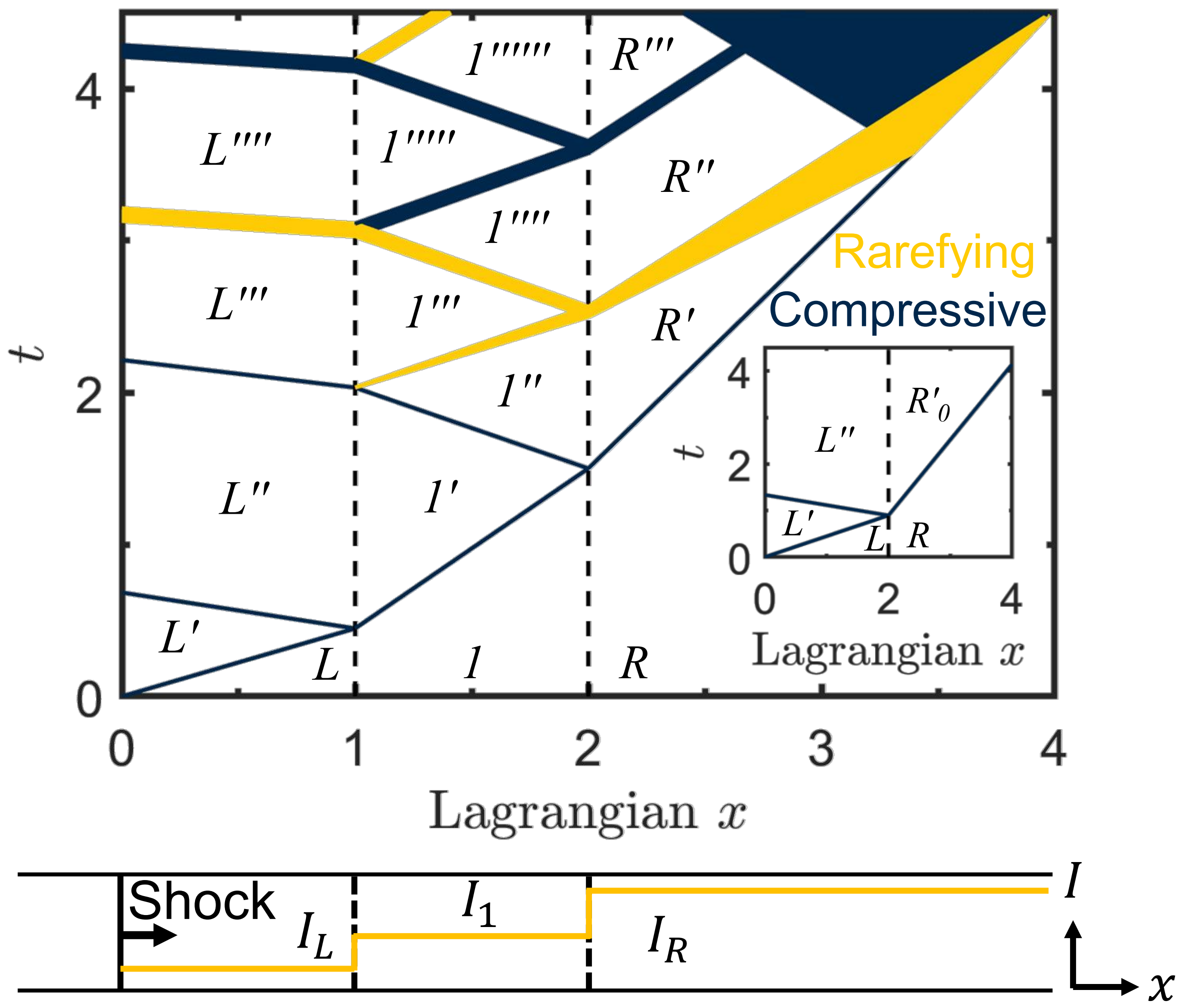

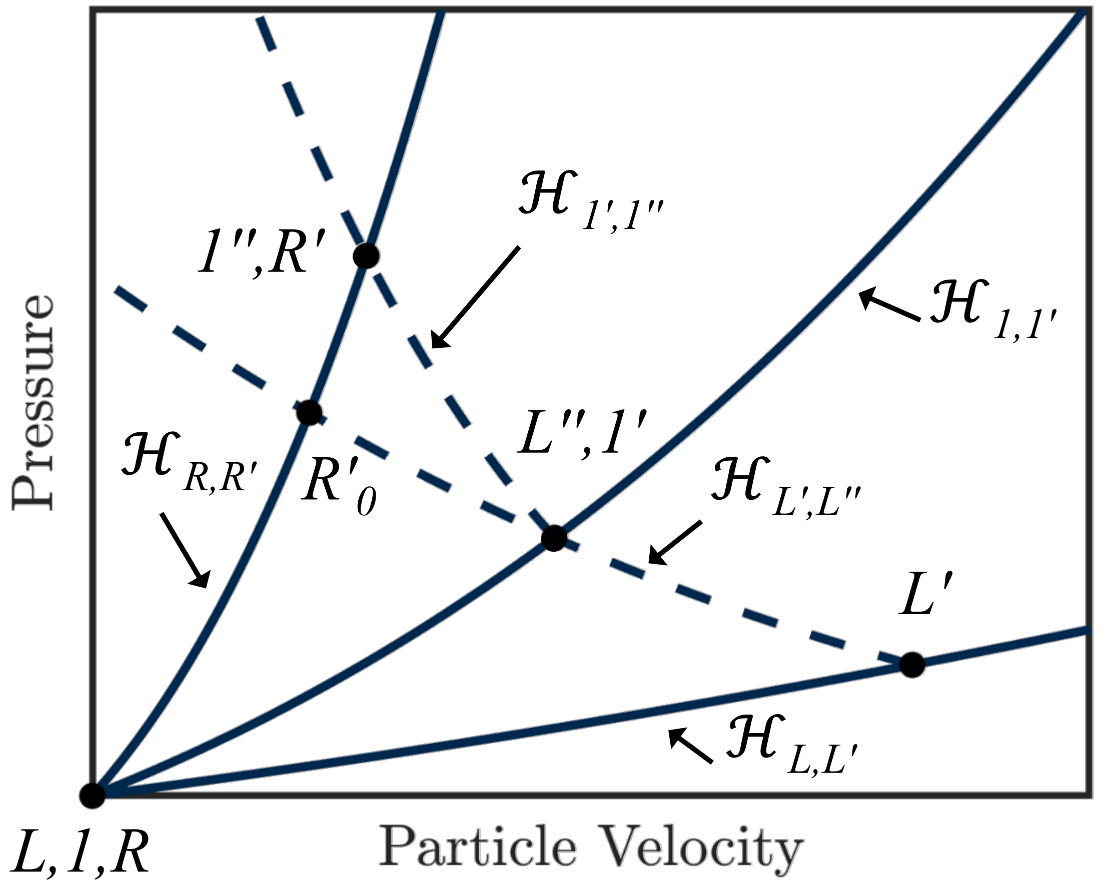

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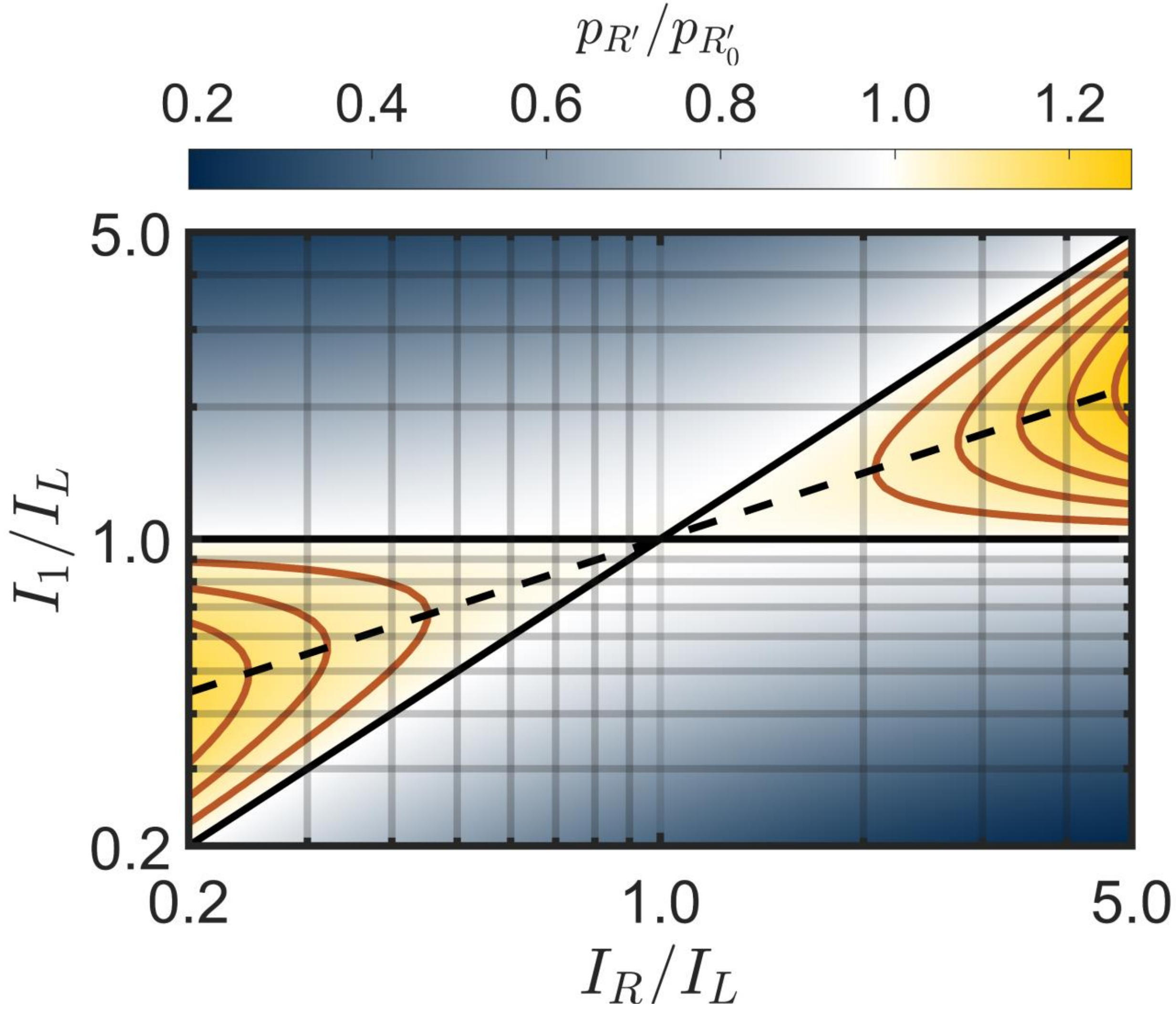

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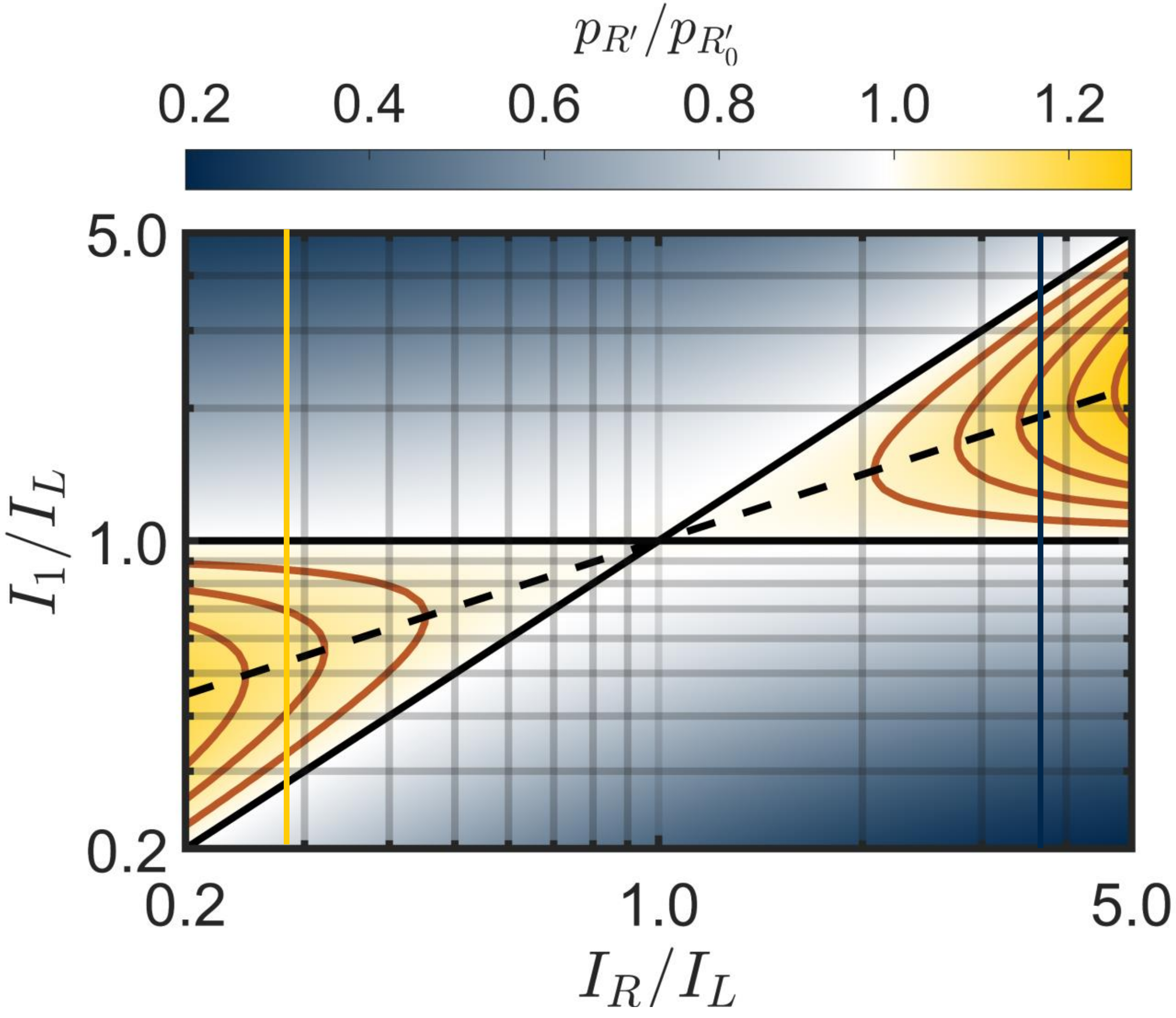

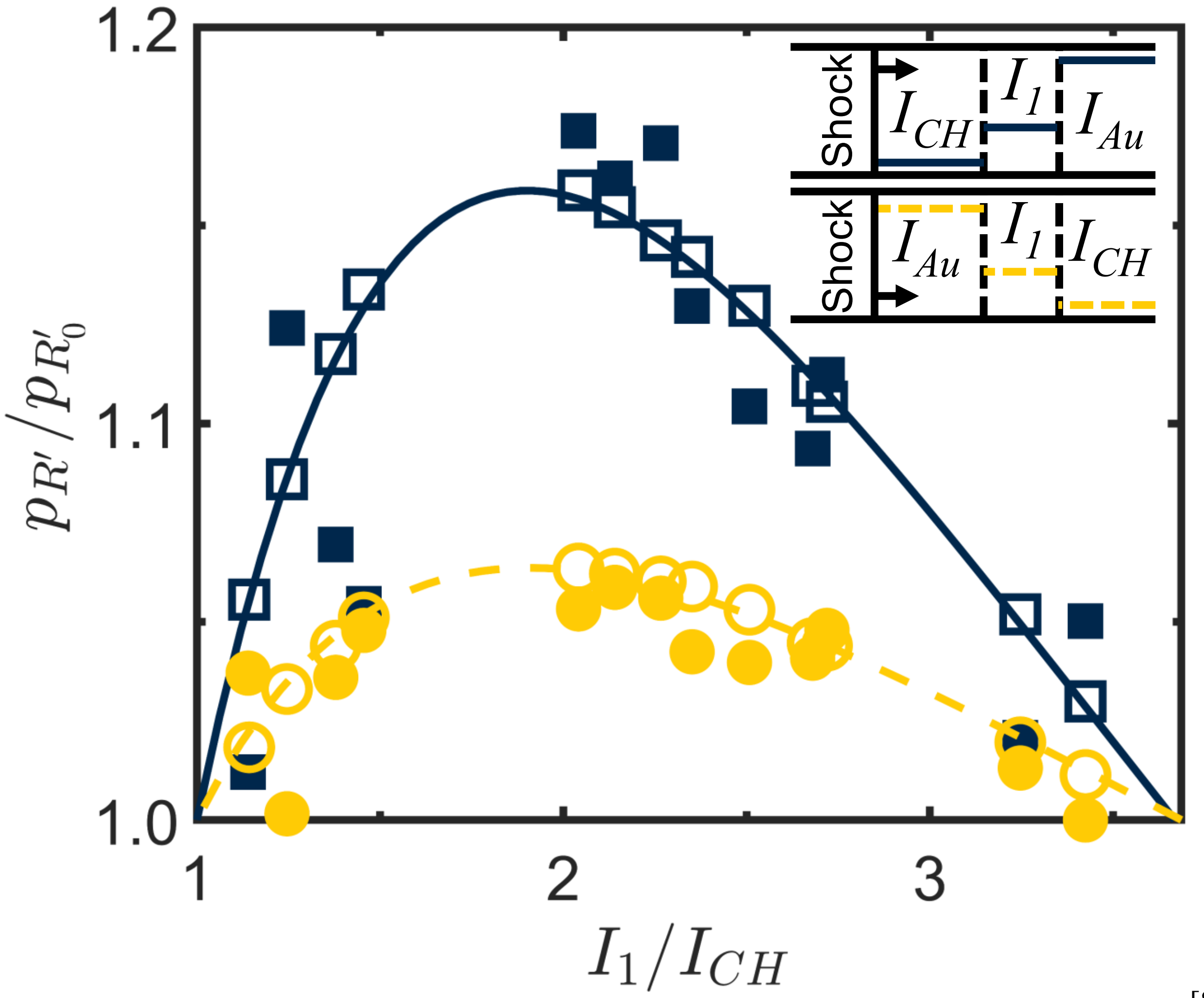

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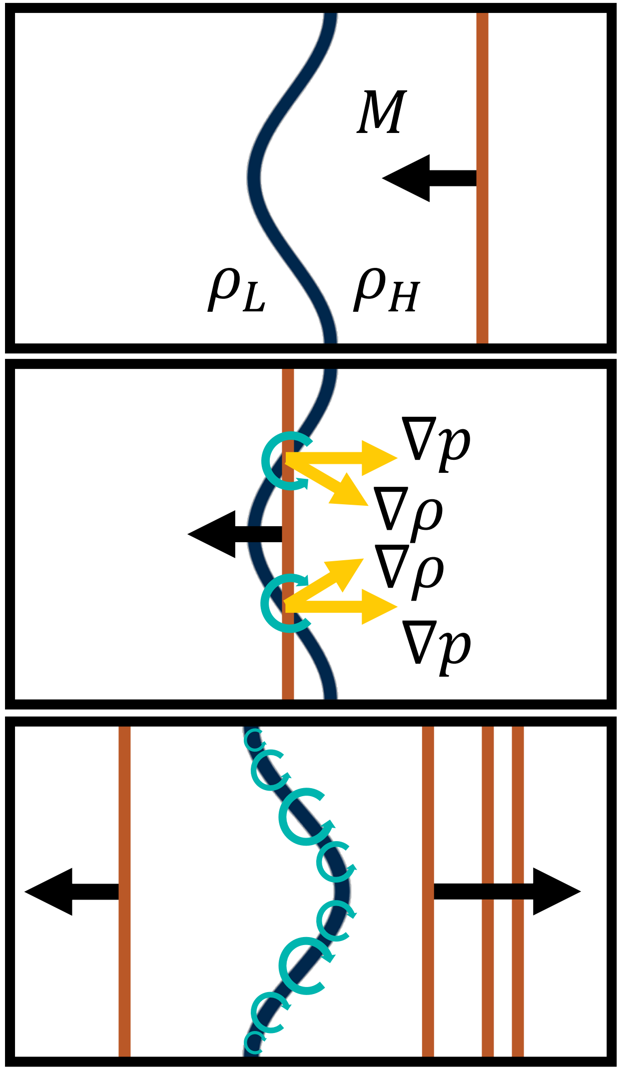
Energy and circulation deposited when a shock wave passes through a perturbed interface leads to significant interfacial mixing.



Shock impinges on heavy-to-light interface

Shock deposits baroclinic vorticity

Rarefaction reflects and interface evolves

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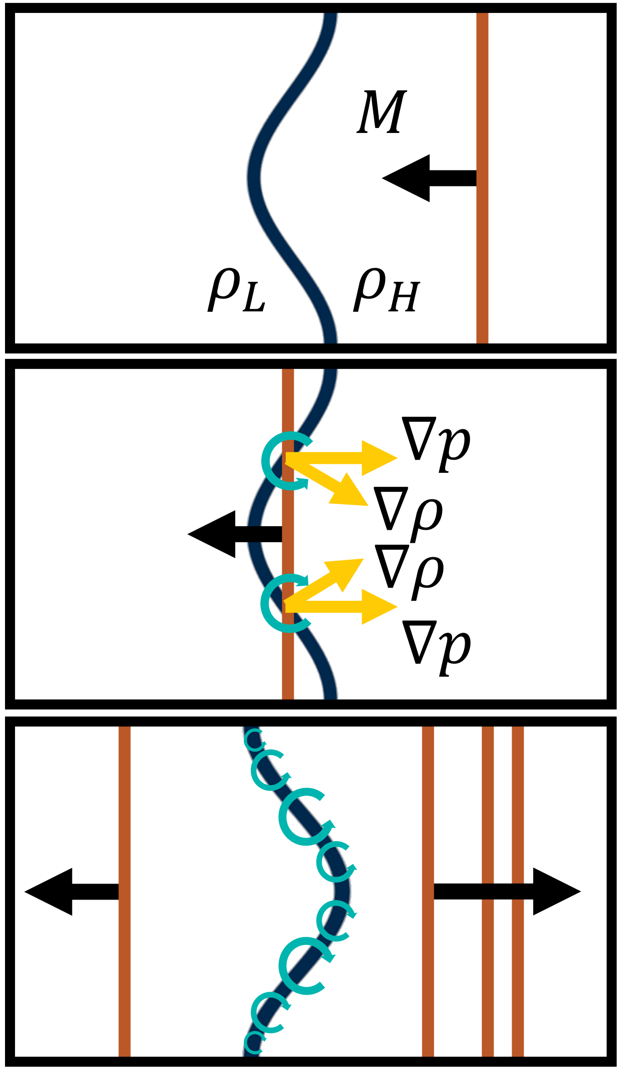

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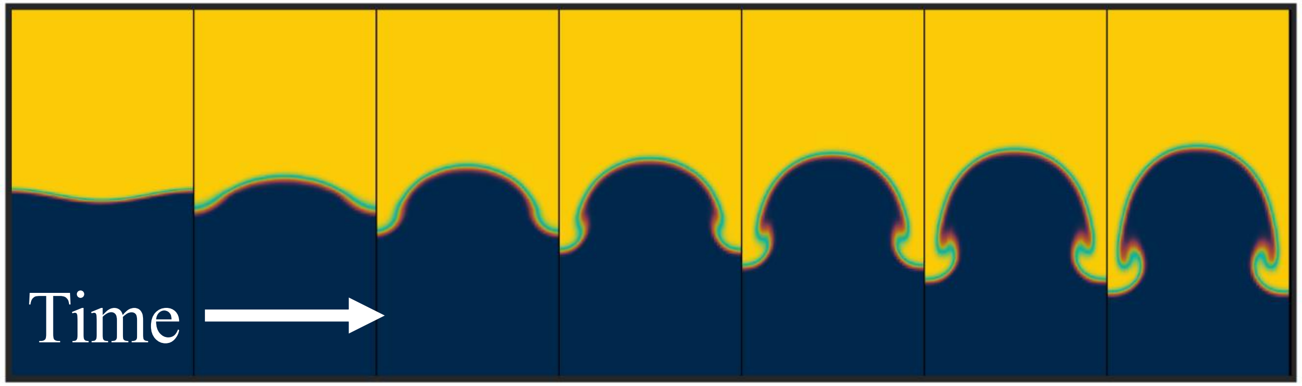

[1]

Linear theory and nonlinear models predict the width of the mixing layer for multimode interfaces, with an eventual handoff to turbulence models.

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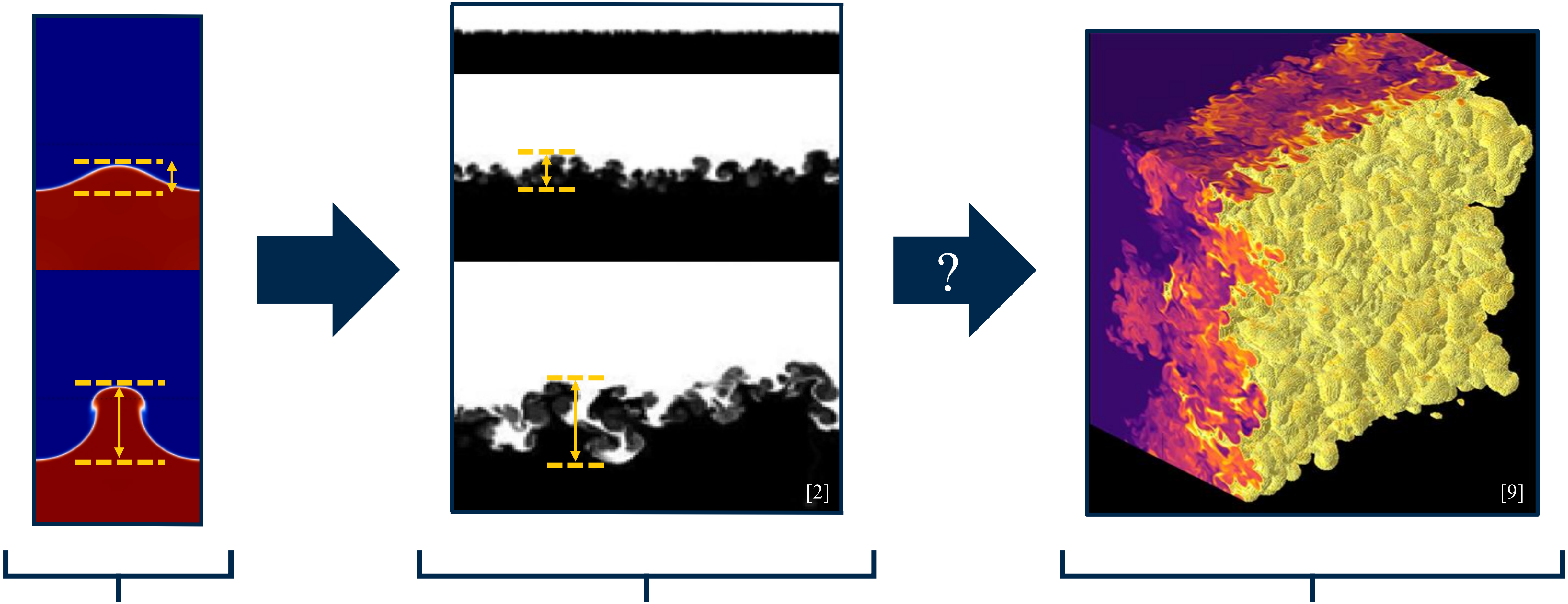

Linear theory

Nonlinear models

Turbulence models

The transition to turbulence of the RMI is not well understood and involves several complicating transport mechanisms.

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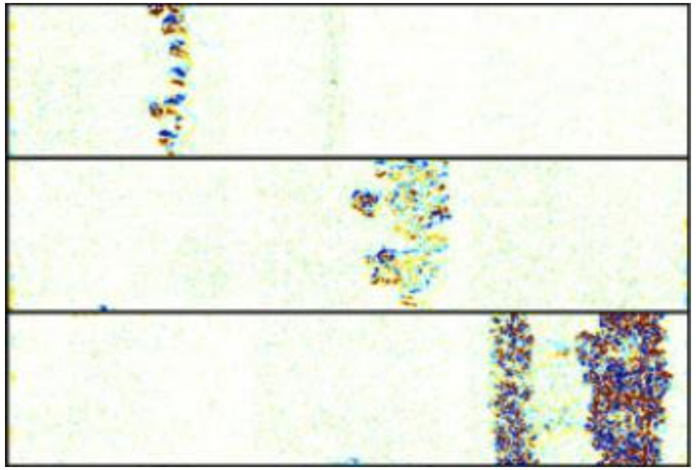

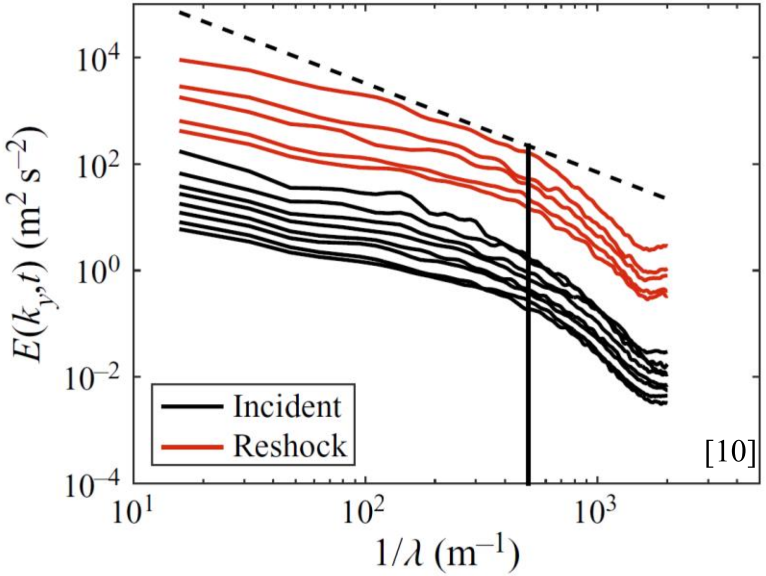

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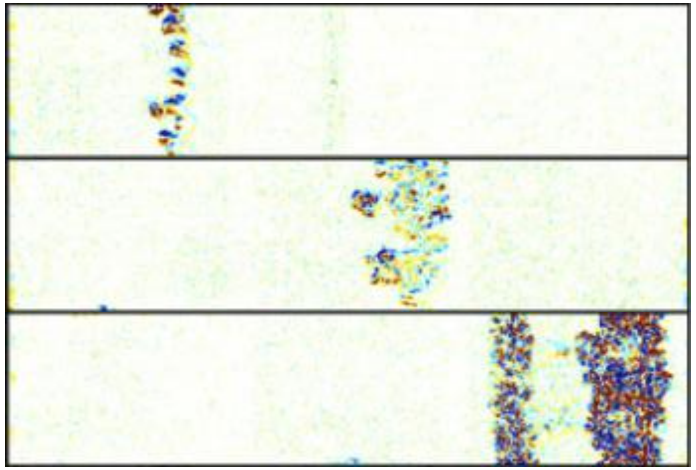

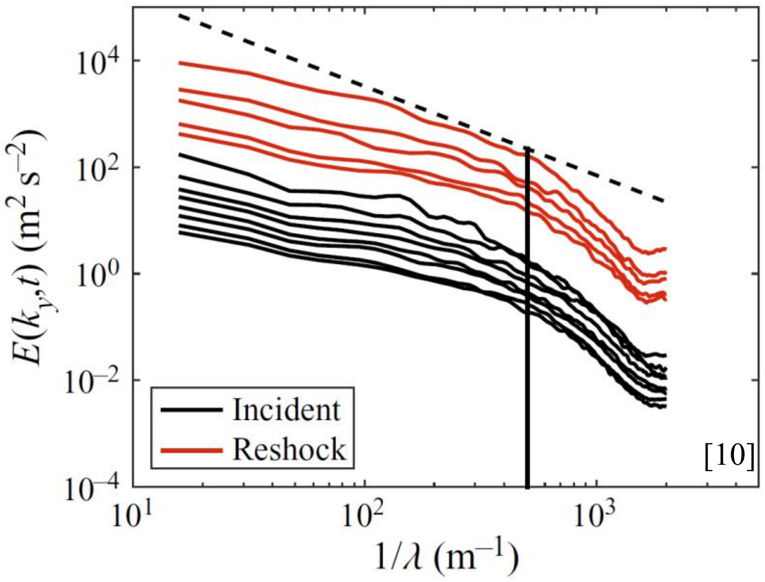

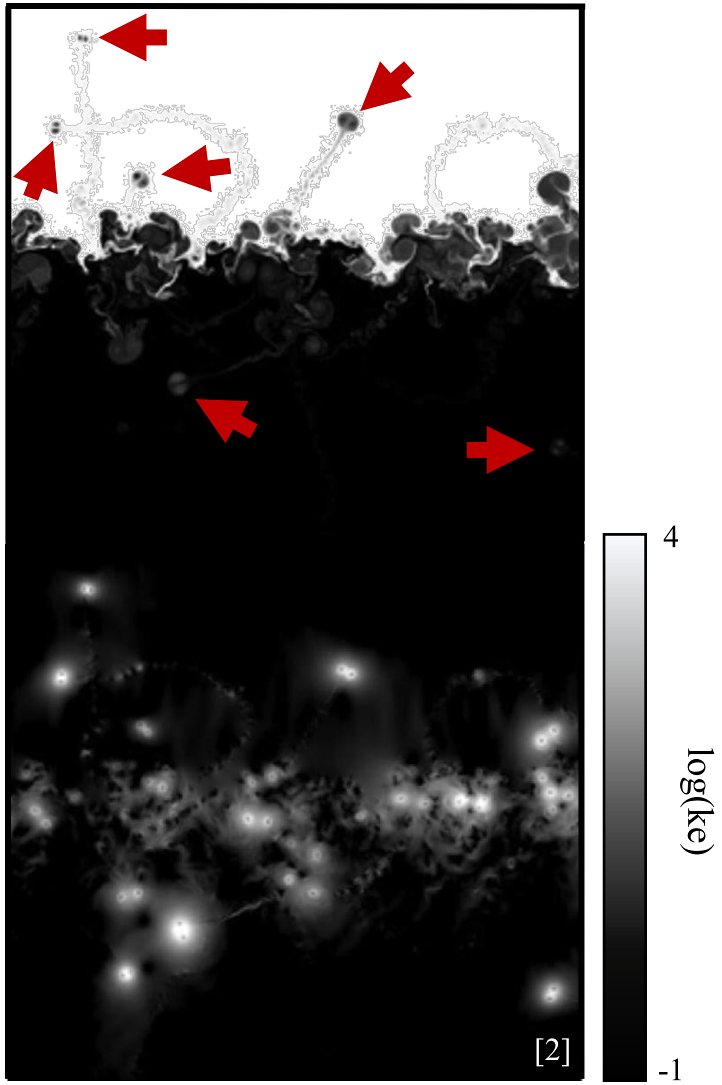

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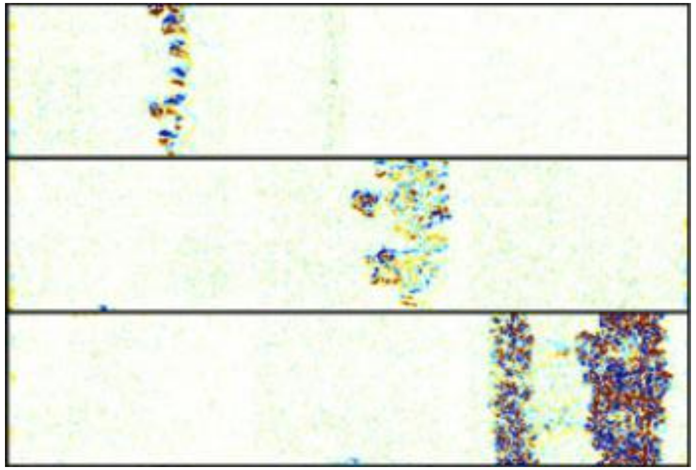
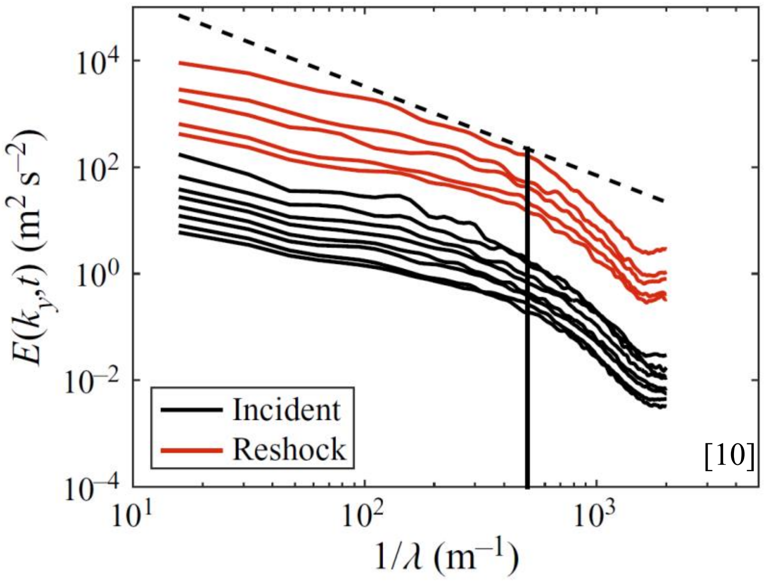
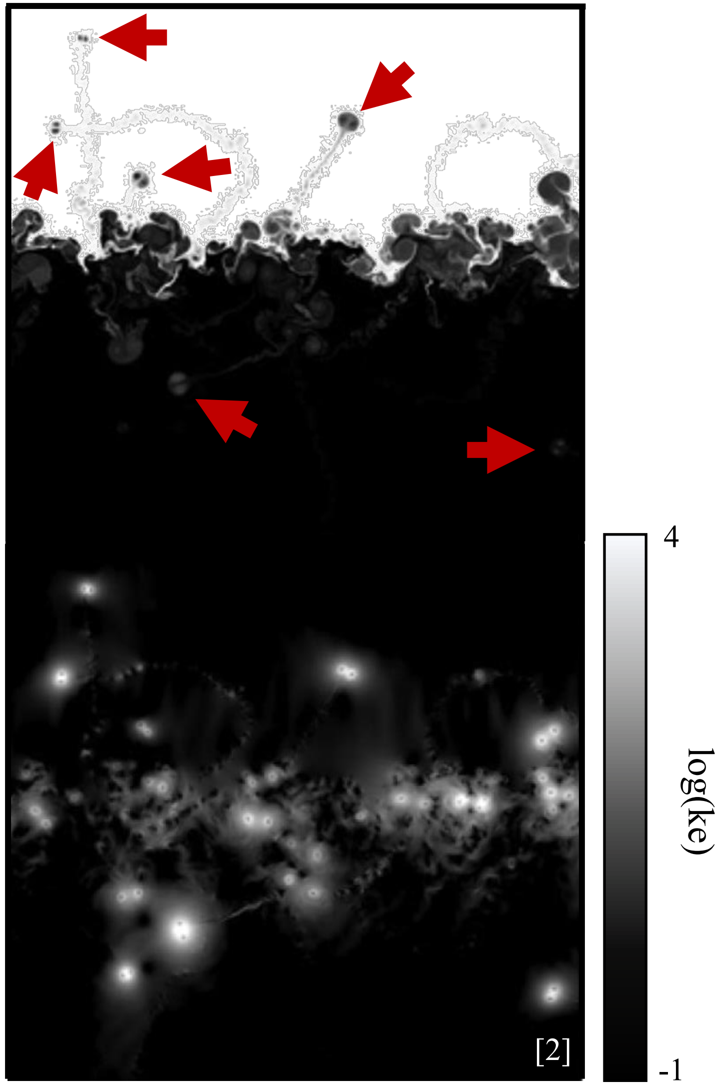
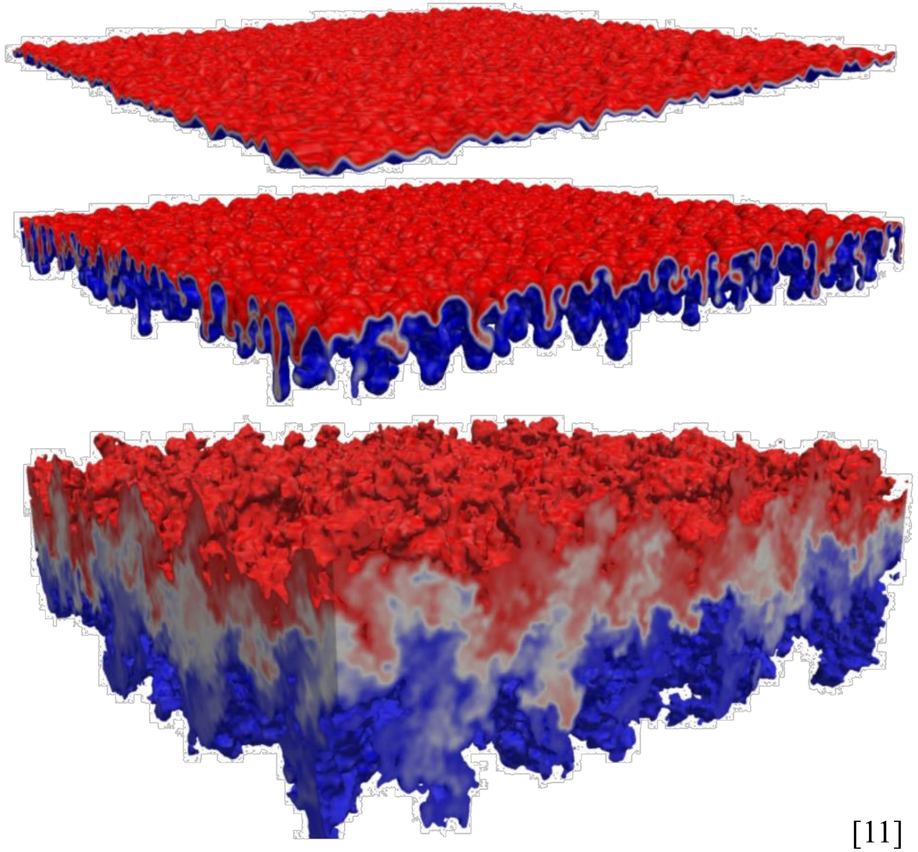
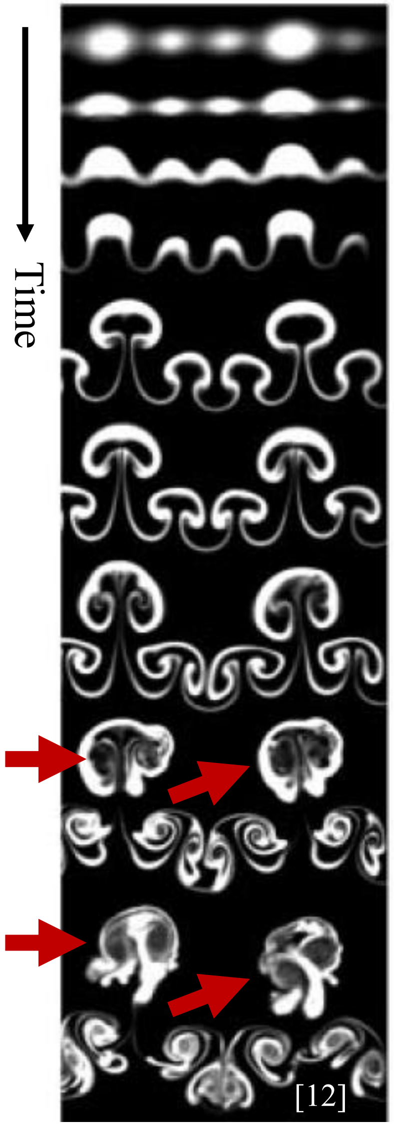


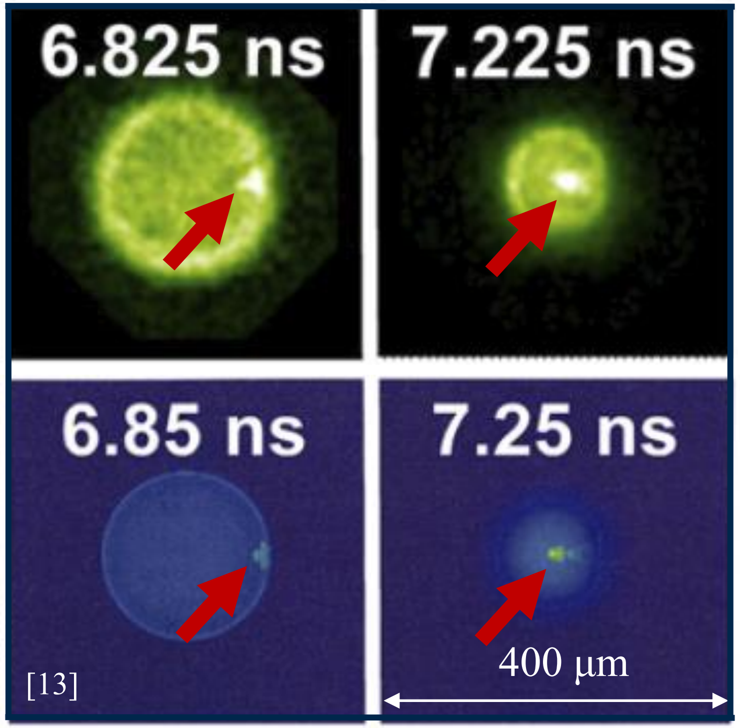


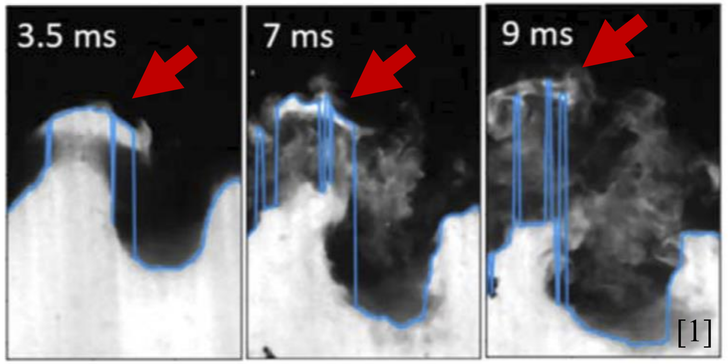


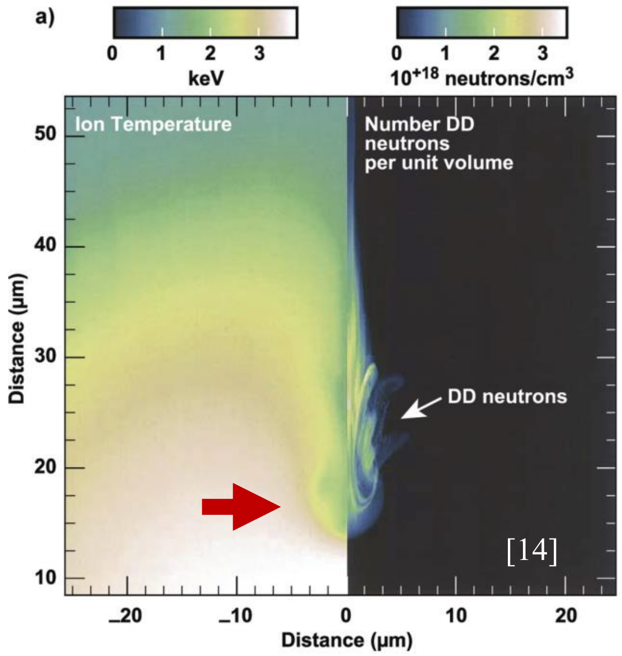


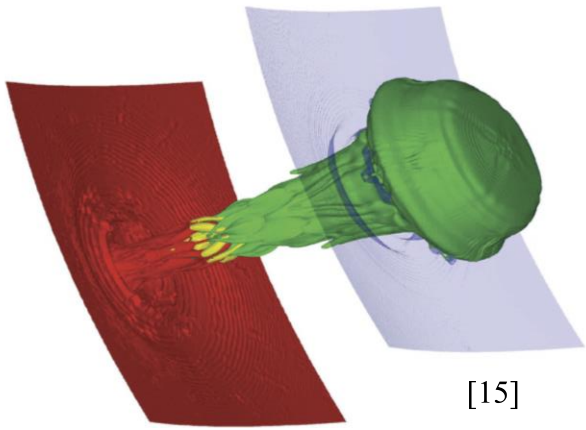
In addition to the RMI, shocked interfaces can generate jet/ejecta flows with important applications in ICF, ejecta physics, and astrophysical jets.

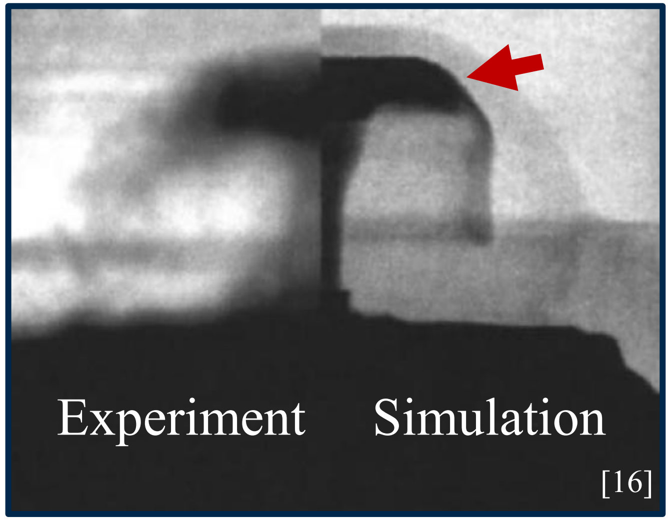


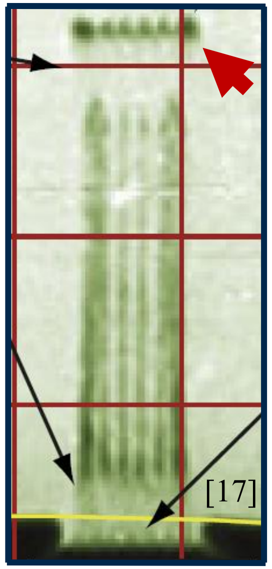


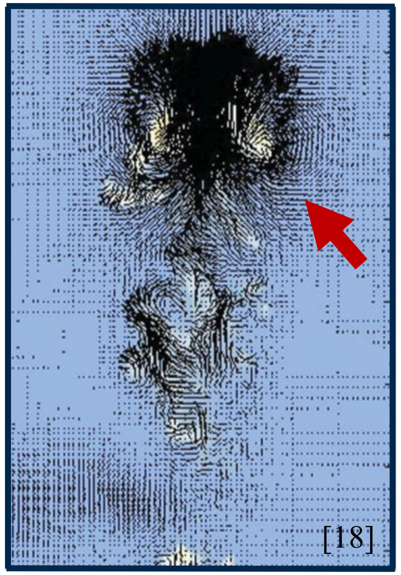




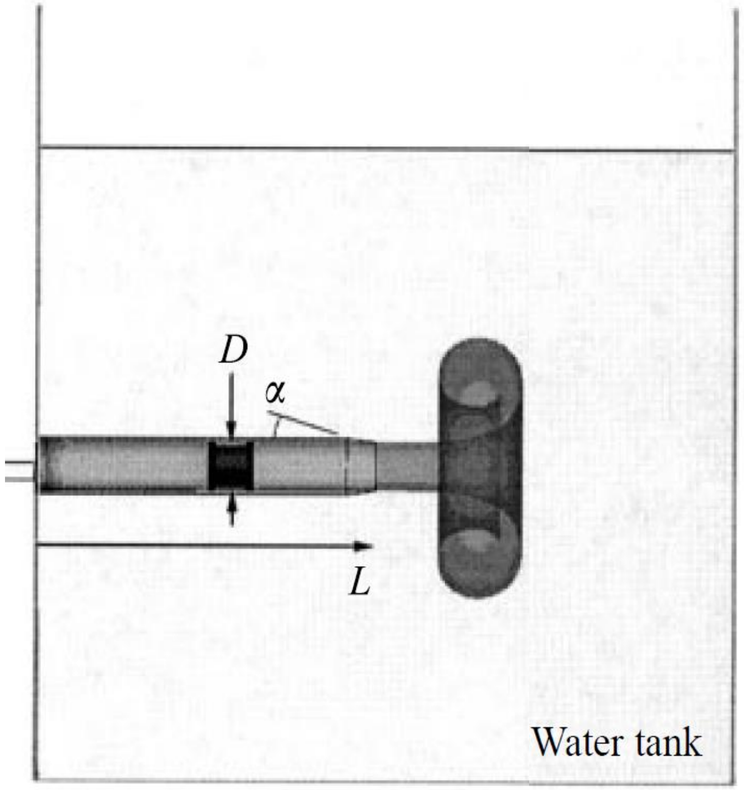








Classical studies focus on vortex rings generated in a piston-cylinder apparatus and have uncovered key insights into their scaling behavior.



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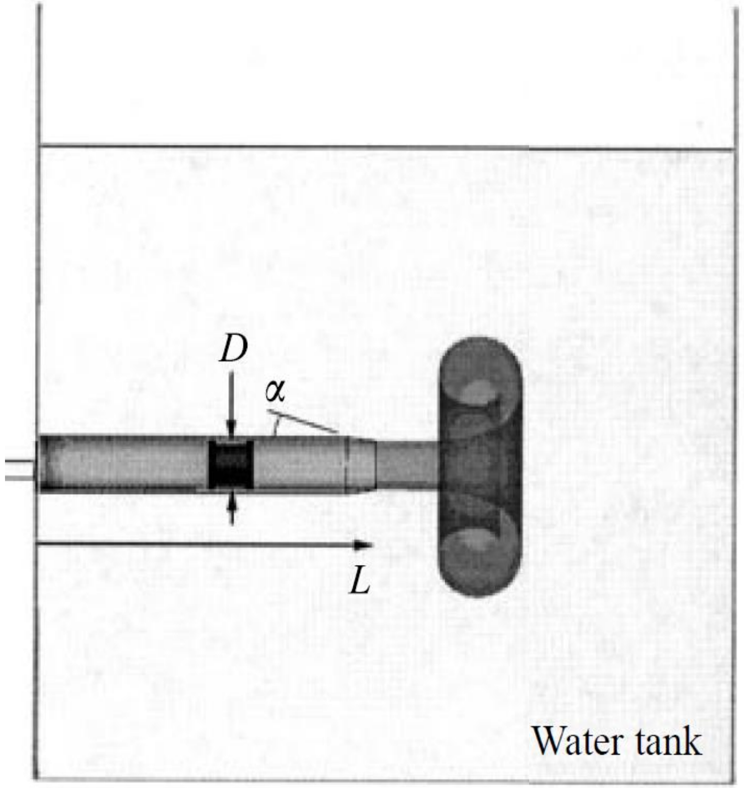
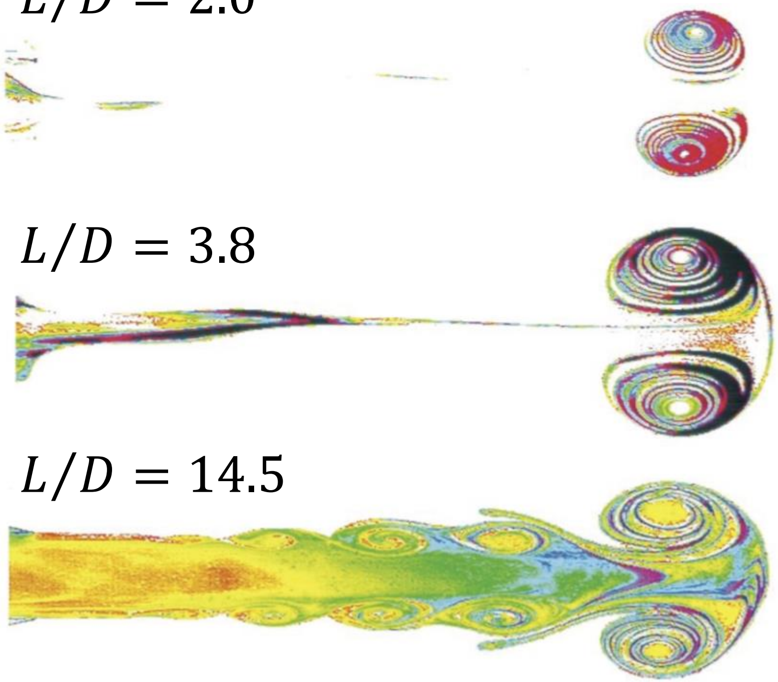


$L/D = 2.0$

$L/D = 3.8$

$L/D = 14.5$



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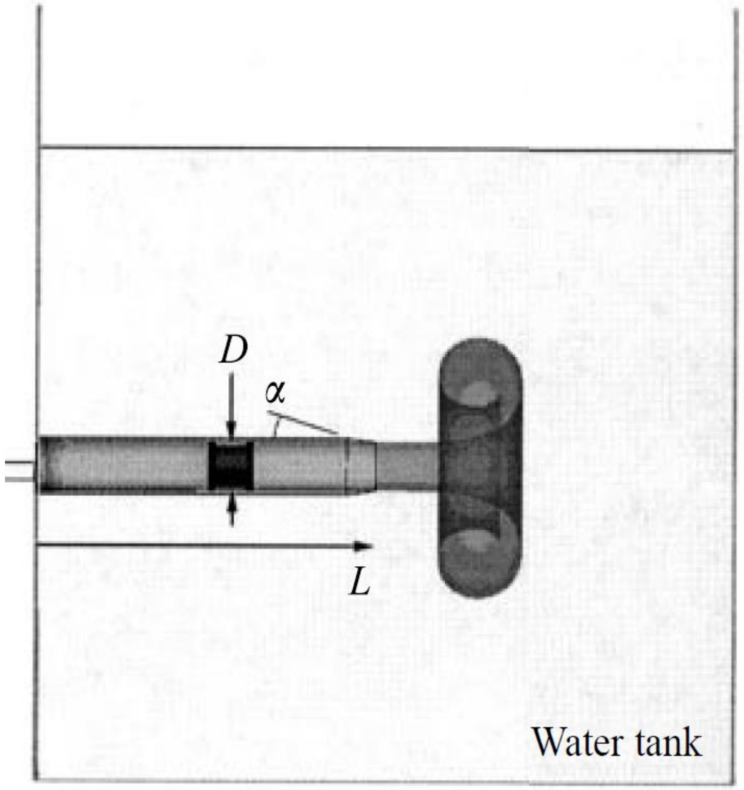
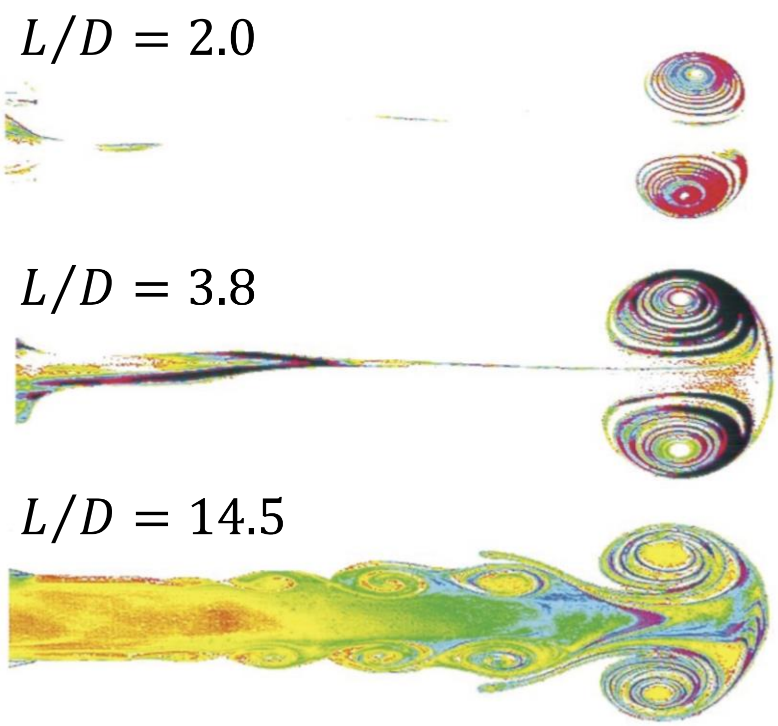
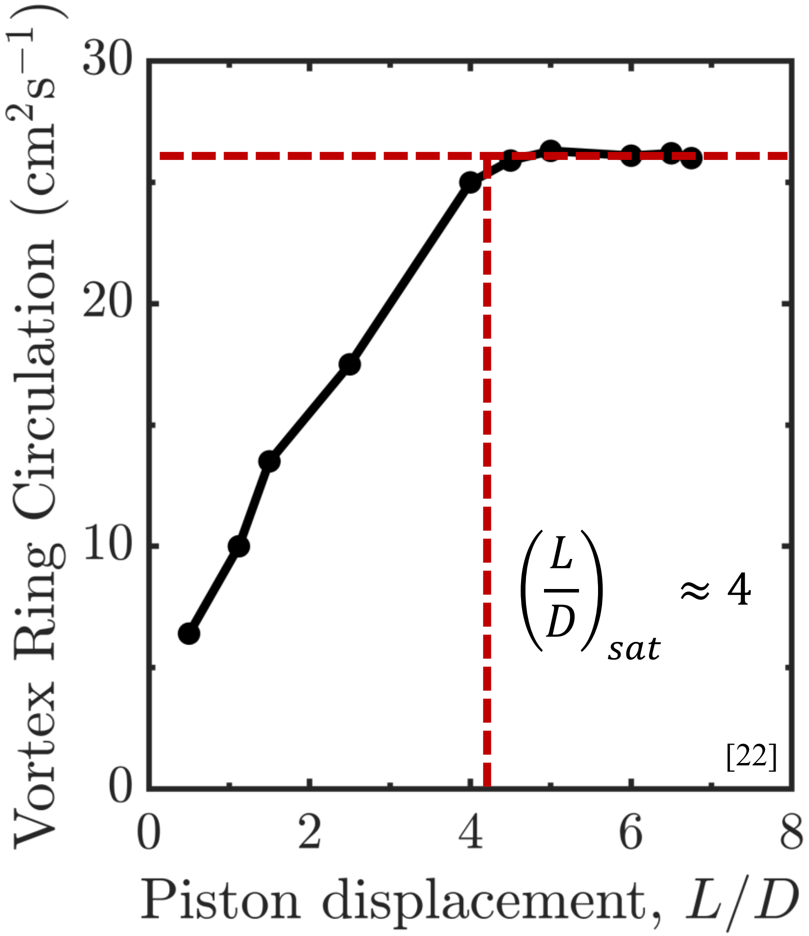
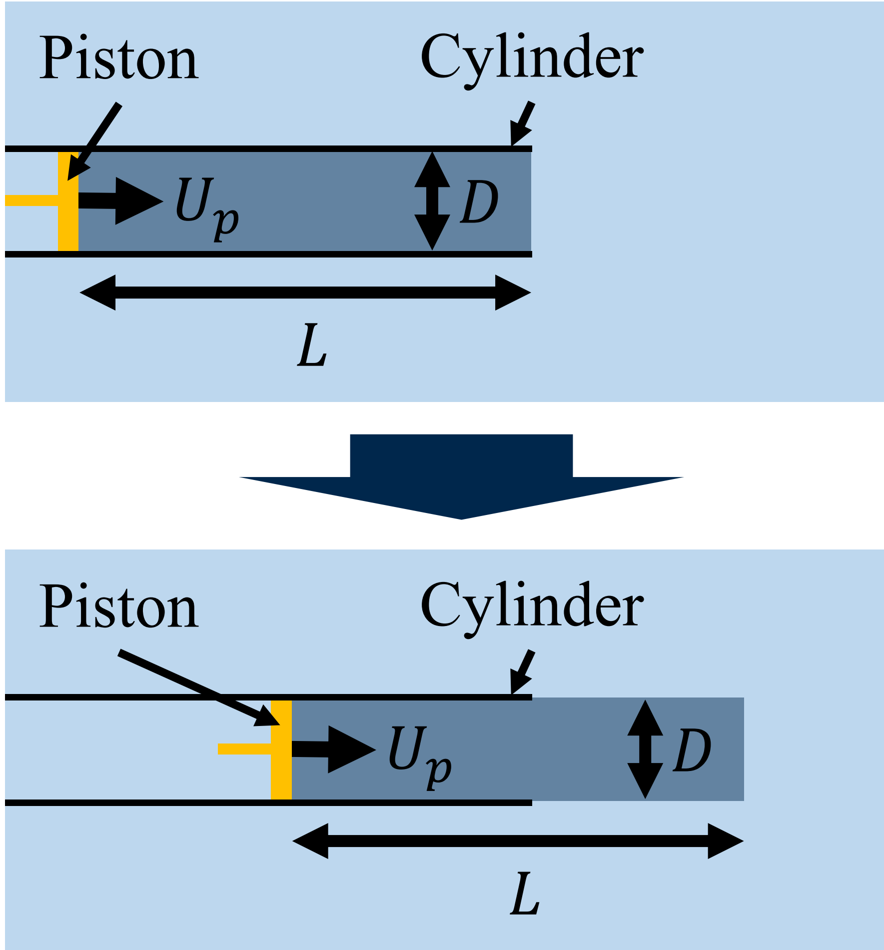






[19]

The formation number is based on analysis comparing the amount of energy supplied by the piston to the energy that can reside in the ring.



Slug Flow	
$E = \frac{1}{8}\pi D^2 L U_p^2$	
$\Gamma = \frac{1}{2} L U_p$	
$I = \frac{1}{4}\pi D^2 L U_p$	
$U_{tr} = \frac{\partial E}{\partial I} = \frac{1}{2} U_p$	

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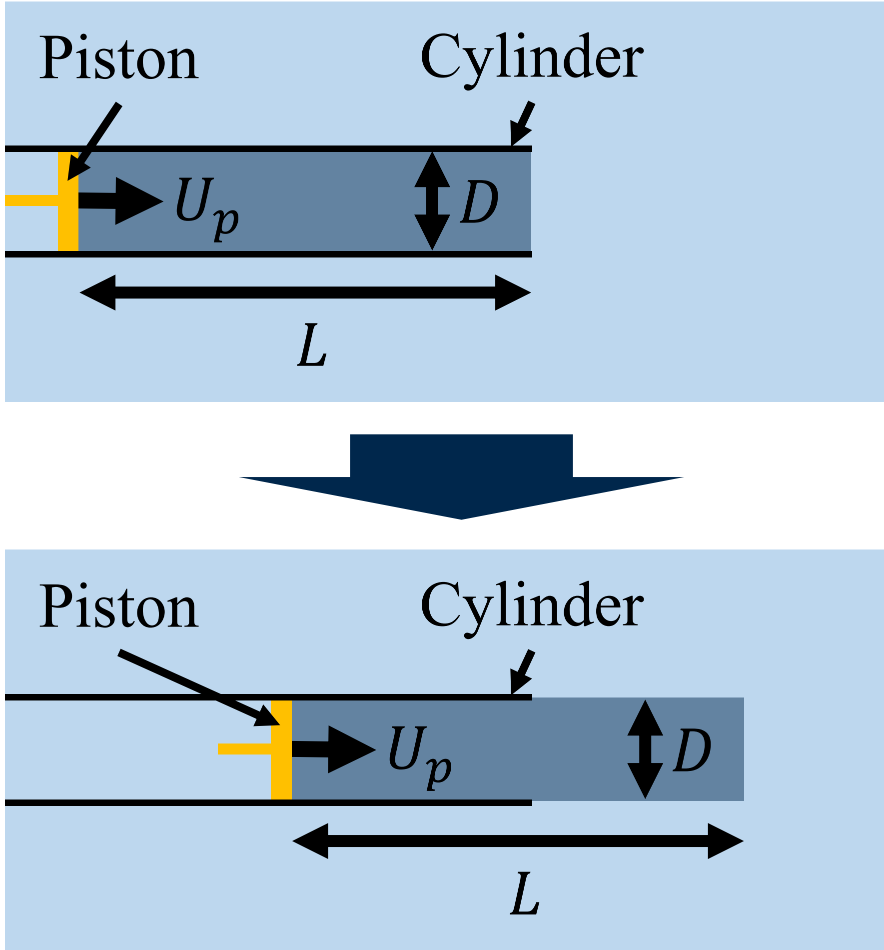
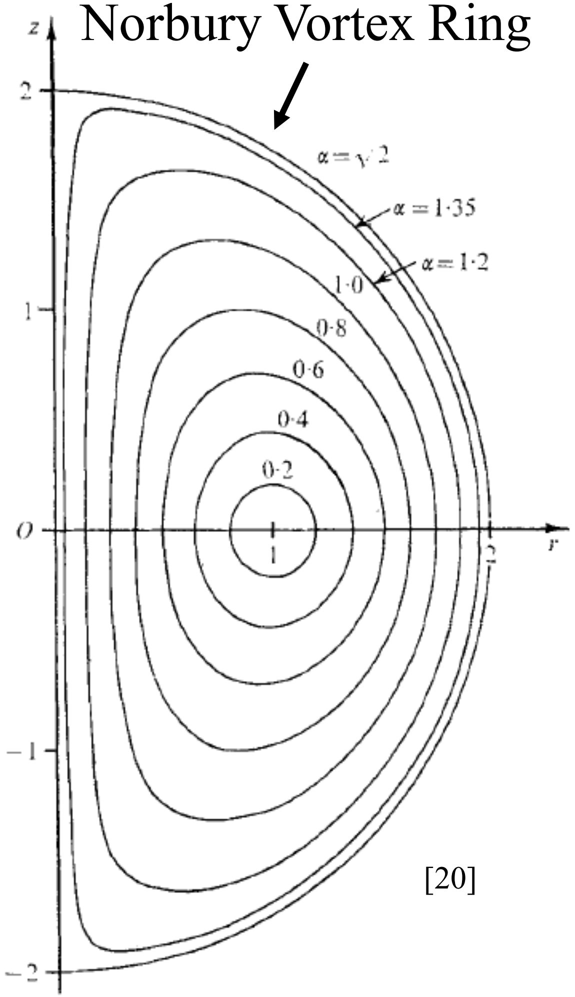
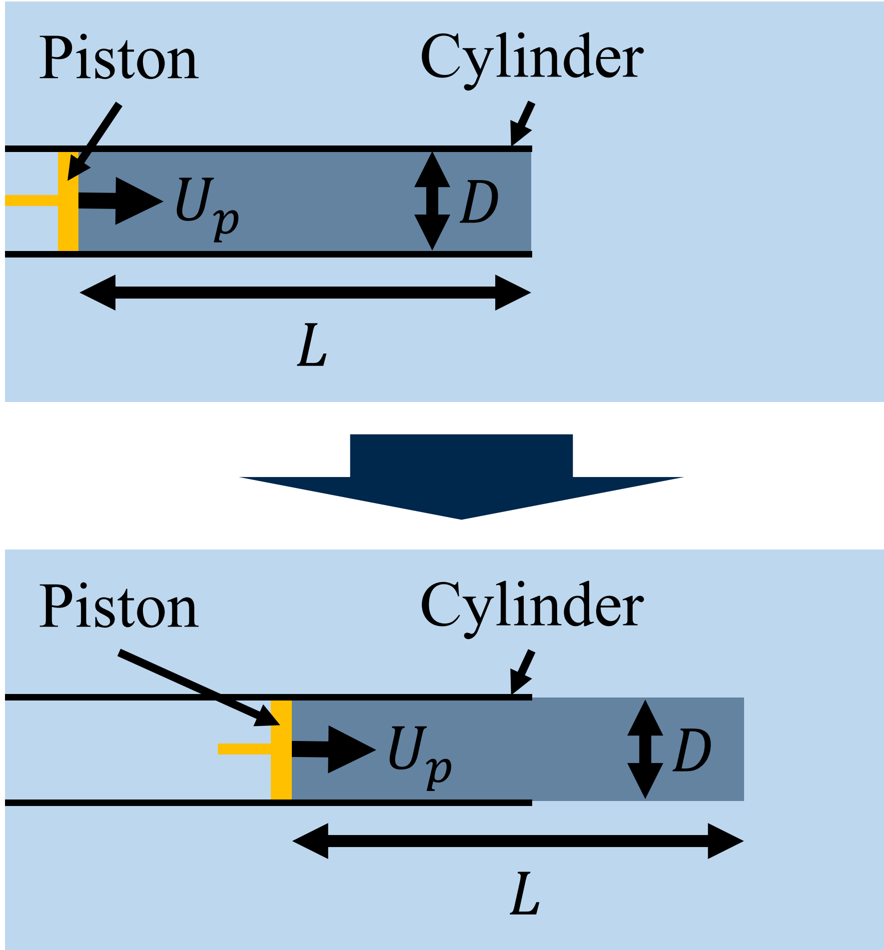


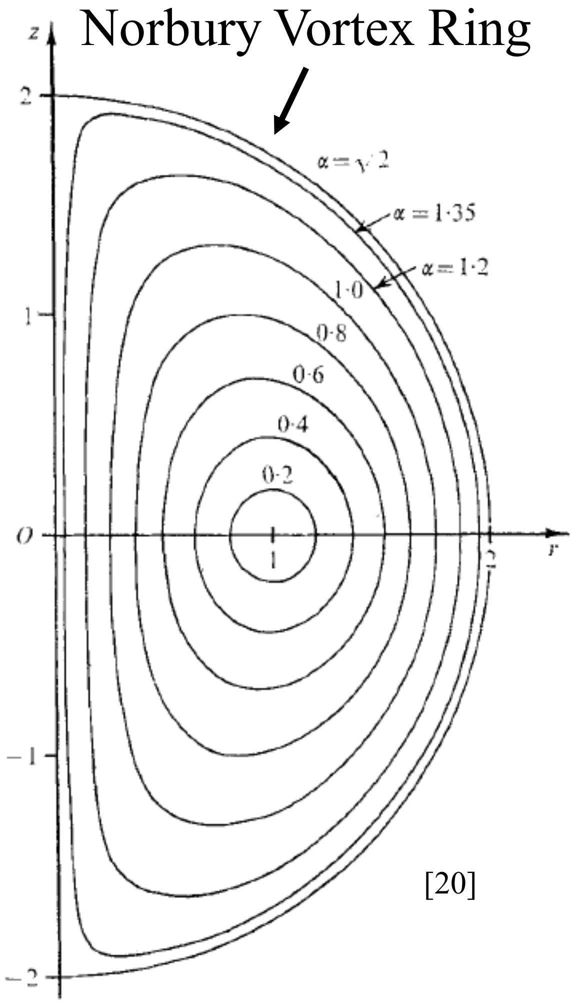


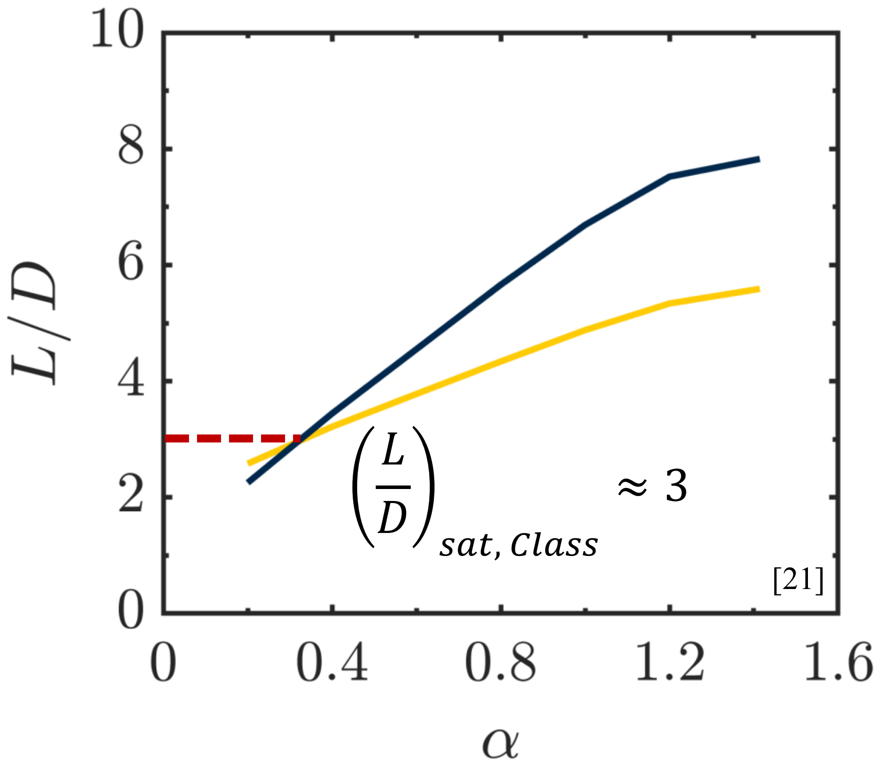
Slug Flow	Norbury Vortex Ring
$E = \frac{1}{8}\pi D^2 L U_p^2$	$E = (\Omega\alpha l)^2 l^3 E_N$
$\Gamma = \frac{1}{2} L U_p$	$\Gamma = (\Omega\alpha l) l \Gamma_N$
$I = \frac{1}{4}\pi D^2 L U_p$	$\mathrm{I} = (\Omega\alpha l) l^3 \mathrm{I}_N$
$U_{tr} = \frac{\partial E}{\partial I} = \frac{1}{2} U_p$	$U_{tr} = (\Omega\alpha l) U_N$ [21]

$$\frac{L}{D} = \sqrt{\frac{\pi}{2}} I_N^{\frac{1}{2}} \Gamma_N^{\frac{3}{2}} E_N^{-1} \quad \frac{L}{D} = \sqrt{\frac{\pi}{2}} I_N^{-\frac{1}{2}} \Gamma_N^{\frac{3}{2}} U_N^{-1}$$

The formation number is based on analysis comparing the amount of energy supplied by the piston to the energy that can reside in the ring.



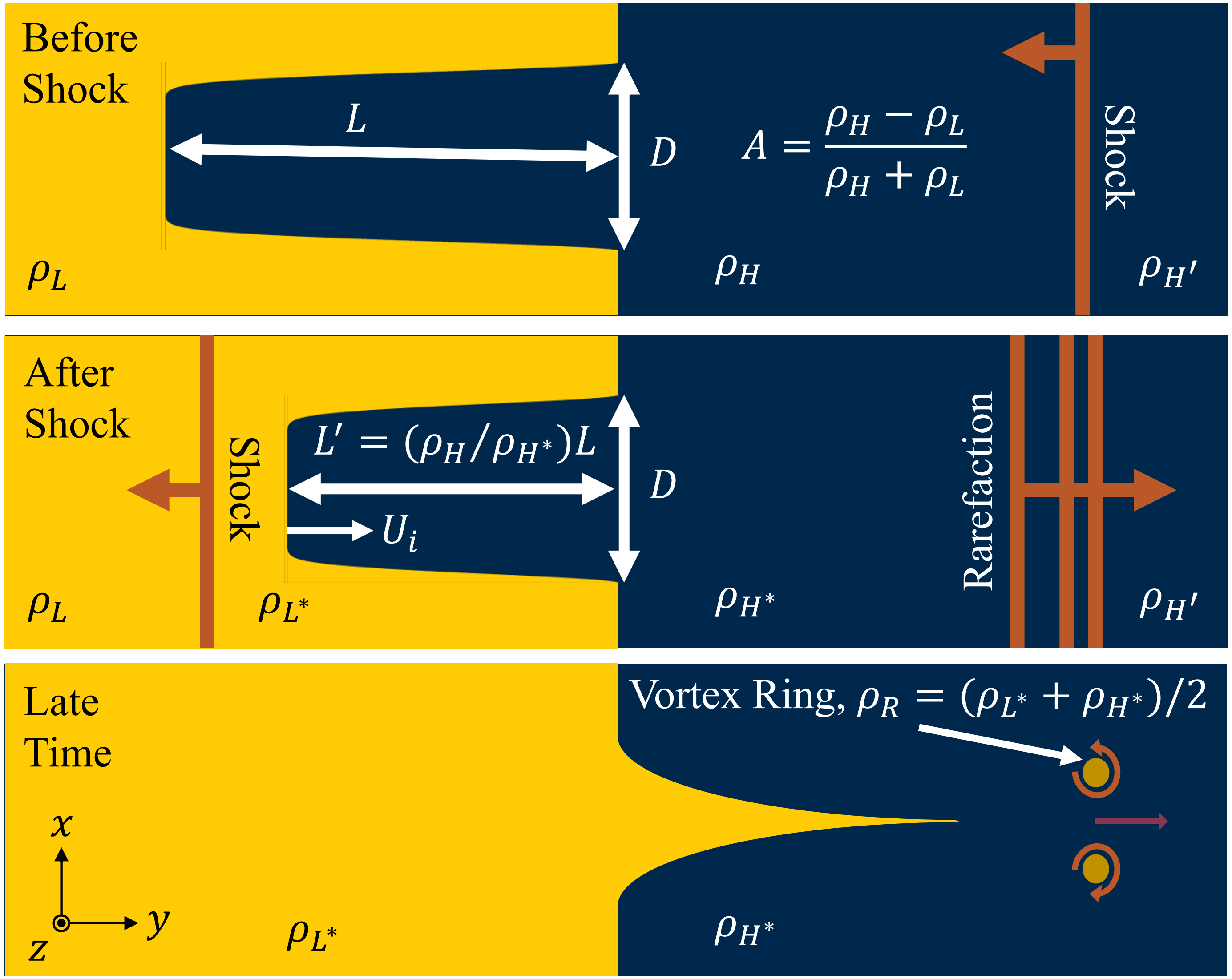




$$\frac{L}{D} = \sqrt{\frac{\pi}{2}}\, I_N^{\frac{1}{2}} \Gamma_N^{\frac{3}{2}}\, E_N^{-1} \qquad \frac{L}{D} = \sqrt{\frac{\pi}{2}}\, I_N^{-\frac{1}{2}} \Gamma_N^{\frac{3}{2}}\, U_N^{-1}$$

$$3.0 \leq \left(\frac{L}{D}\right)_{sat} \leq 4.6$$

We modify the classical theory for vortex ring scaling by considering the strength of the shock and the interfacial Atwood number.



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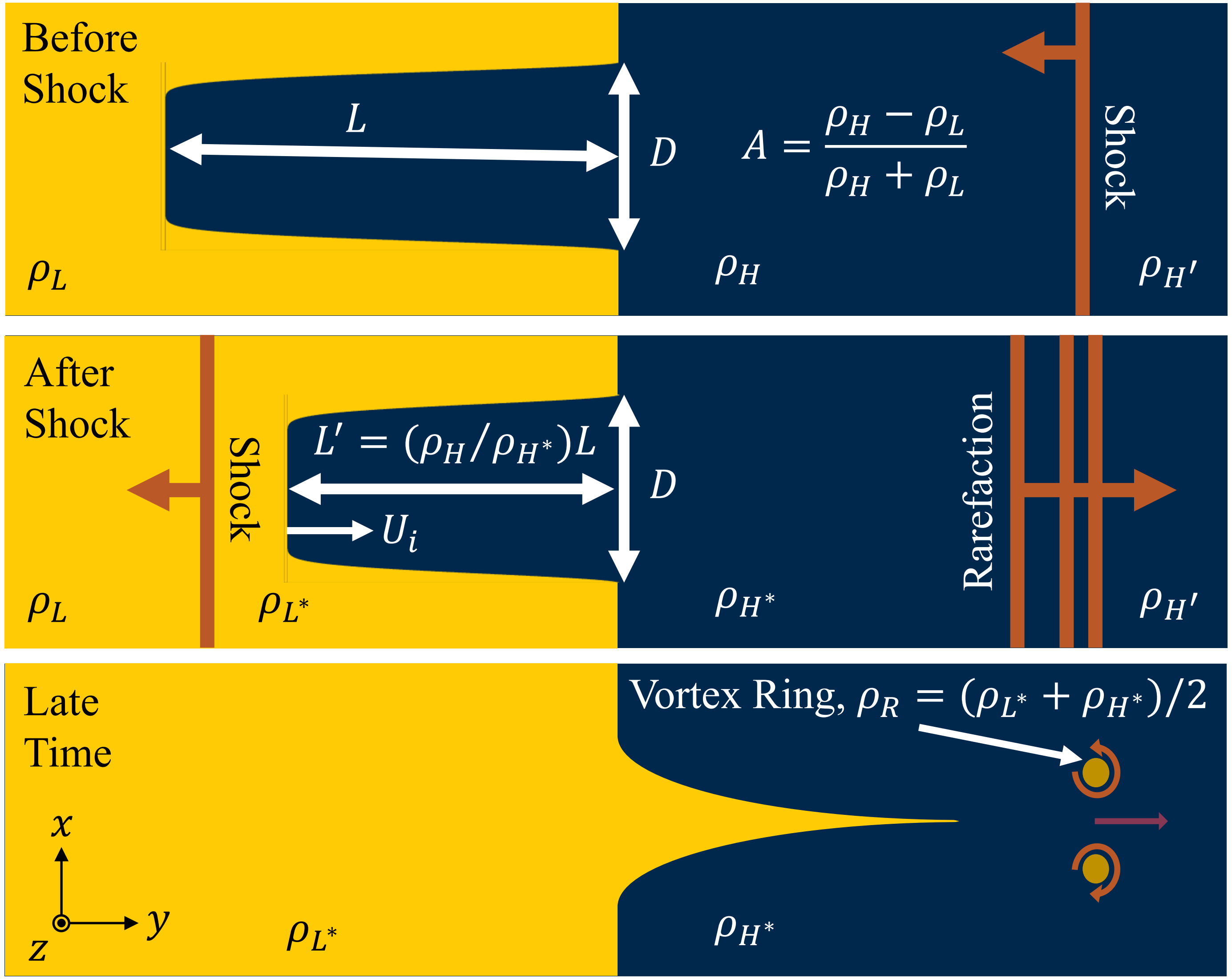


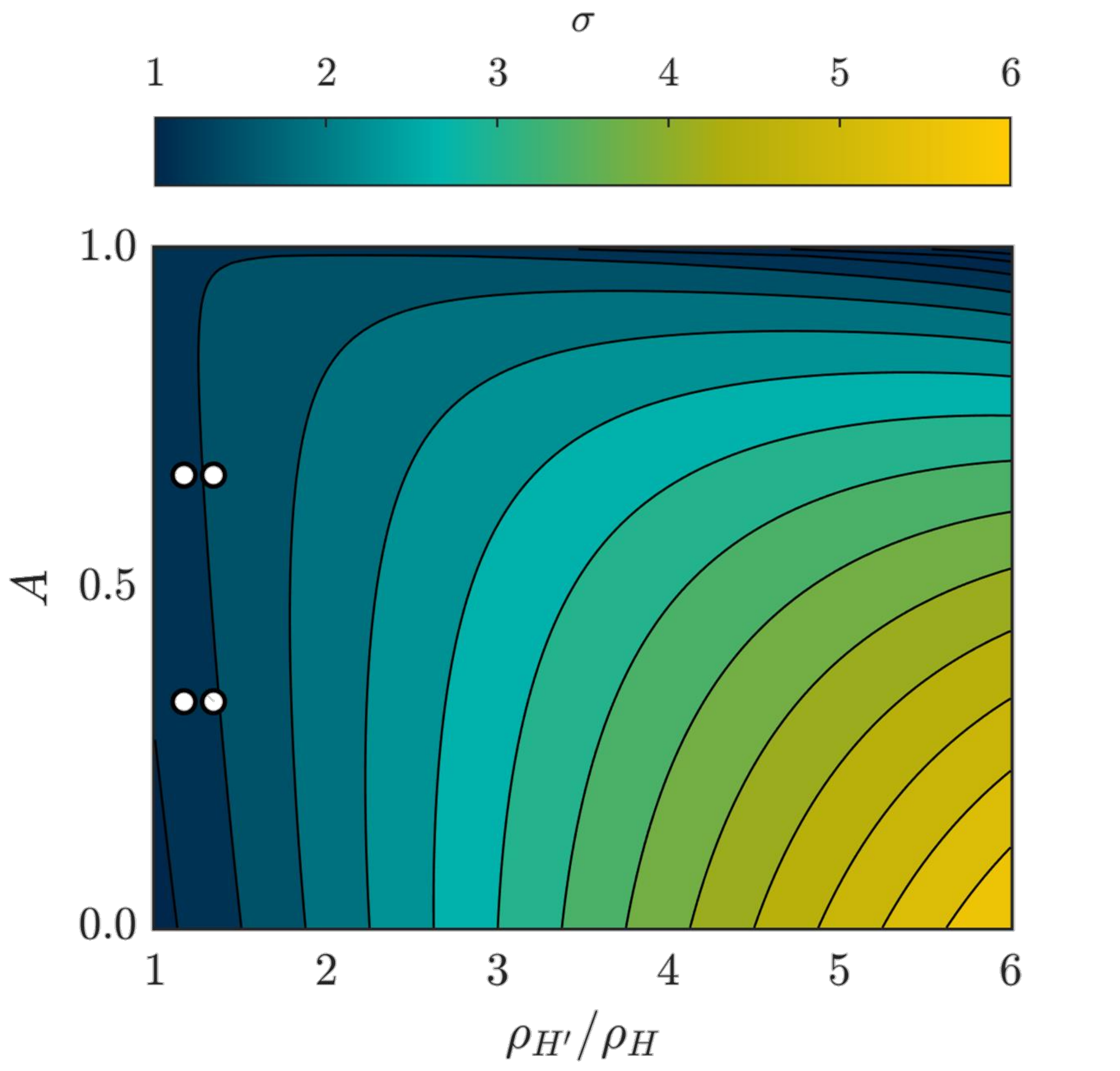
Slug Flow	Norbury Vortex Ring
$E = \boldsymbol{\rho_H} \frac{1}{8} \pi D^2 L U_i^2$	$E = \frac{(\boldsymbol{\rho_{L^*}} + \boldsymbol{\rho_{H^*}})}{\mathbf{2}} (\Omega \alpha l)^2 l^3 E_N$
$\Gamma = \frac{\boldsymbol{\rho_H}}{\boldsymbol{\rho_{H^*}}} \frac{1}{2} L U_i$	$\Gamma = (\Omega \alpha l) l \Gamma_N$
$I = \boldsymbol{\rho_H} \frac{1}{4} \pi D^2 L U_i$	$I = \frac{(\boldsymbol{\rho_{L^*}} + \boldsymbol{\rho_{H^*}})}{\mathbf{2}} (\Omega \alpha l) l^3 I_N$
$U_{tr} = \frac{\partial E}{\partial I} = \frac{1}{2} U_i$	$U_{tr} = (\Omega \alpha l) U_N$

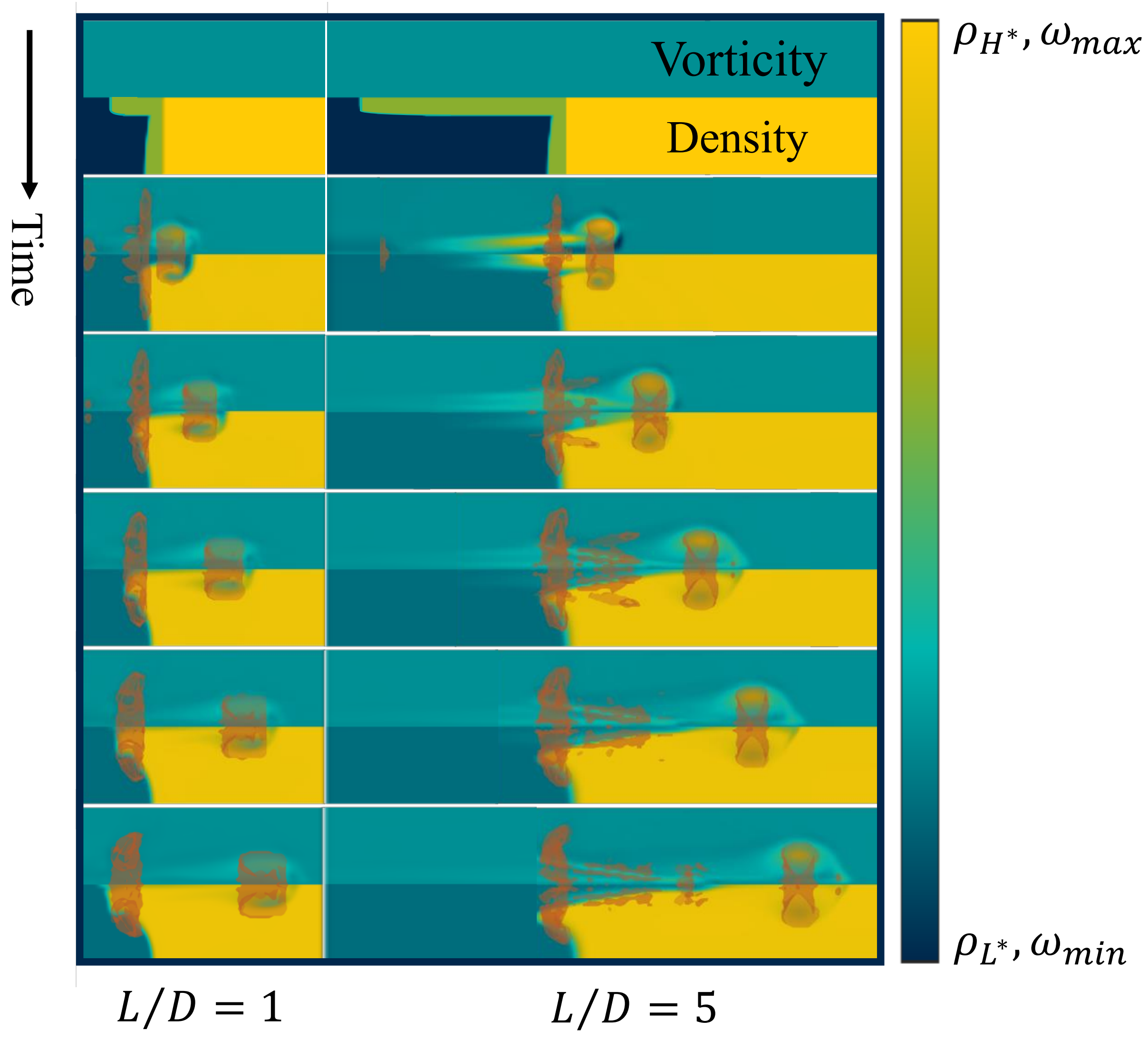
$$\left(\frac{L}{D}\right)_{sat,\,RMI} = \sigma \left(\frac{L}{D}\right)_{sat,\,Class}$$

$$\sigma = \sqrt{\frac{2\rho_{H^*}}{\rho_{L^*} + \rho_{H^*}} \frac{\rho_{H^*}}{\rho_H}} = f(\rho_{H'}/\rho_H, A)$$

Multifluid Compression

The model predicts an augmented formation number, and simulations show many formation number signatures.





Simulations verify that our model captures the augmented formation number scaling of vortex rings ejected from shock-accelerated interfaces.

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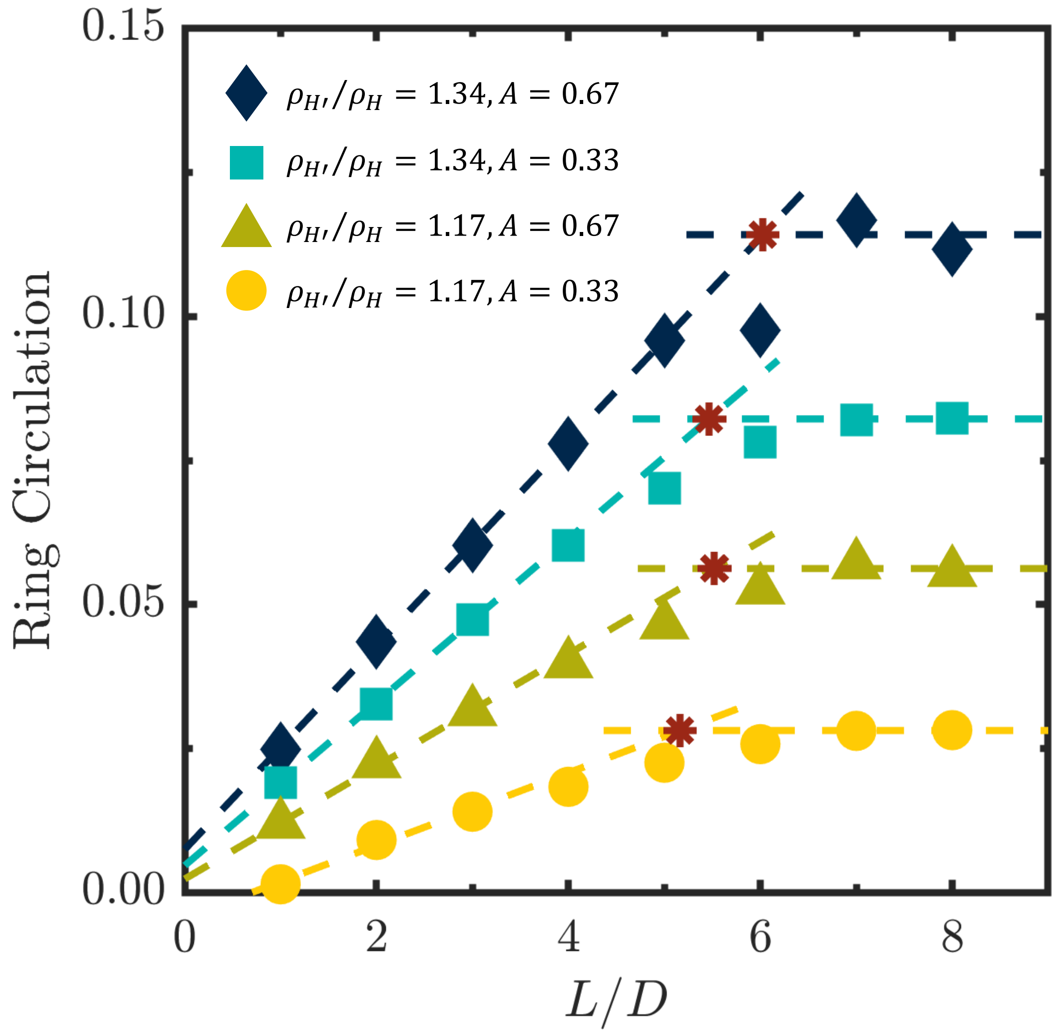

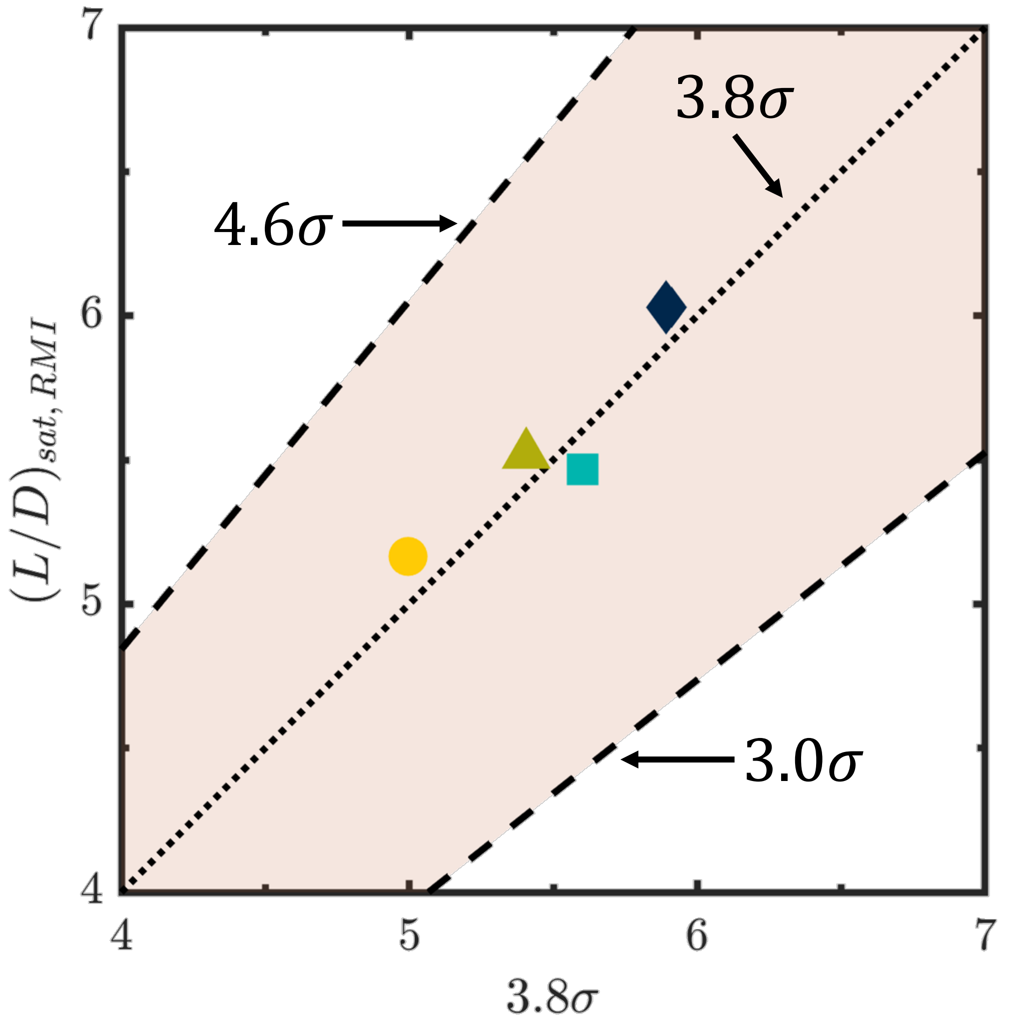

Summary

1. Shock waves occur in a wide range of engineering and scientific contexts including laser experiments, astrophysics, and inertial confinement fusion (ICF).
2. High-powered lasers can drive strong waves in materials, enabling their study in extreme pressure environments. We developed a method for further strengthening such shocks.
3. Shocked interfaces mix via the Richtmyer-Meshkov instability (RMI), possibly leading to the escape of high-vorticity ejecta with important implications for turbulent transitions.

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