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Title: Exploring the Richtmyer-Meshkov instability in multiple fluid regimes

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Intended for: Talk at LANL, send out slides to those interested

Issued: 2018-05-24

Exploring the Richtmyer-Meshkov instability in multiple fluid regimes

Tiffany Desjardins

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Barbara DeVolder (XTD)

Elizabeth Merritt
Kirk Flippo
Tiffany Desjardins
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Thomas Day (MST-7)

The Extreme Fluids Team:

Gerardo Veliz
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Adam Martinez
Tiffany Desjardins
Kathy Prestridge (P-23)

The Extreme Fluids Team (pRad work):

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Levi Neukirch, Andy Saunders, Tamsen Schurman, Zhaowen Tang, Dale Tupa, Amy Tainter, Michael Martinez, Jason Medina (P-25)

John Wright, Frank Cherne, Brian Hollander (M-9)

Adam Pacheco, Mary Sandstrom, Wendy Vogan, Sam Vincent, Joel Heidemann (J-3)

Outline of Talk

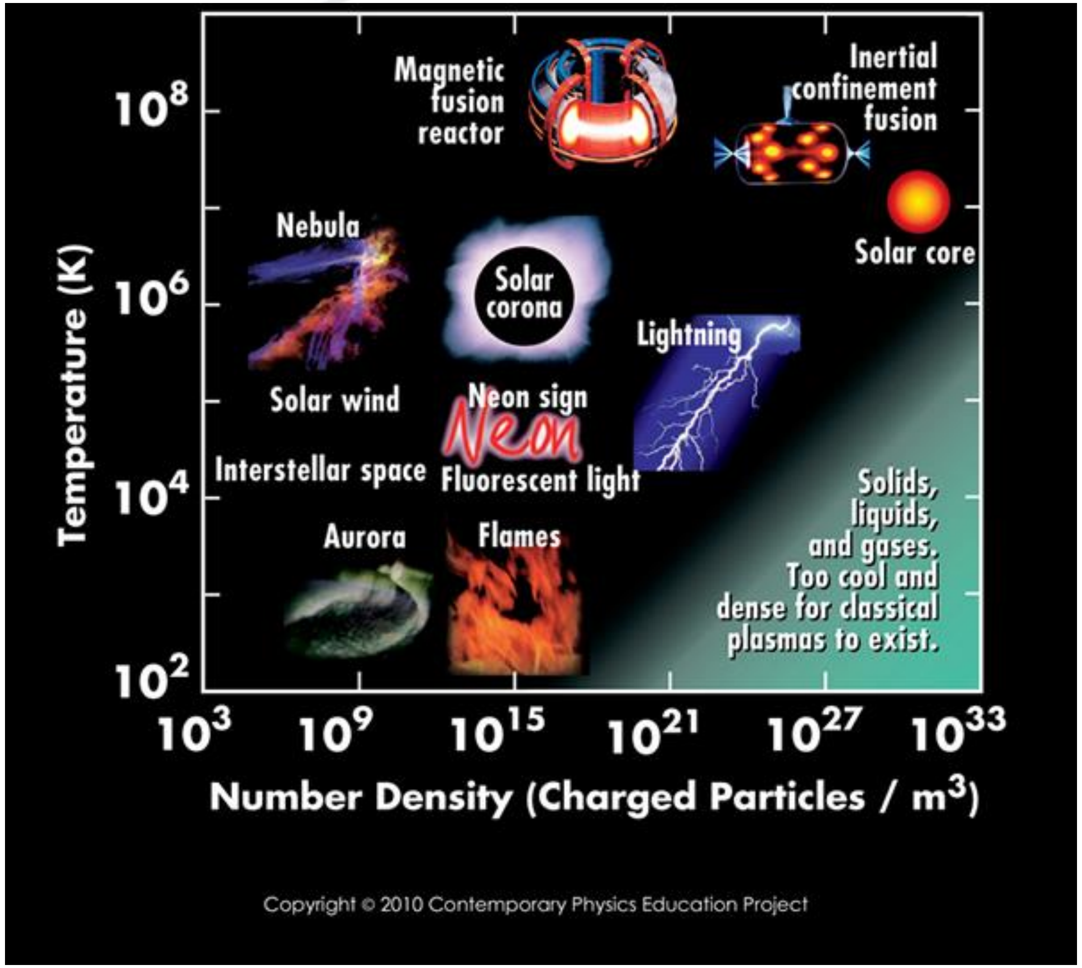
- Why are ‘fluids’ and shocks important?
- Brief overview of Shock Physics and RMI
- Experimental Facilities and measurements
- What we actually do with the data
- Summary

Why are ‘fluids’ and shocks important?

A fluid is defined as a substance whose shape is variable with applied pressure

Traditional fluid experiments take place in fluids or gases, which are limited to low energy density (LED) regimes

A plasma is an ionized gas consisting of positively charged ions and negatively charged electrons



Three criteria to be considered a plasma:

- The size of the plasma, L, must be larger than the Debye length:

$$L \gg \lambda_d = \left(\frac{\epsilon_0 k T_e}{n e^2}\right)^{1/2}$$ **(quasi-neutrality)**

- The number of particles in a Debye sphere must be much greater than 1

$$N_d = n\frac{4}{3}\pi\lambda_d^3 \gg 1$$ **(collectivity)**

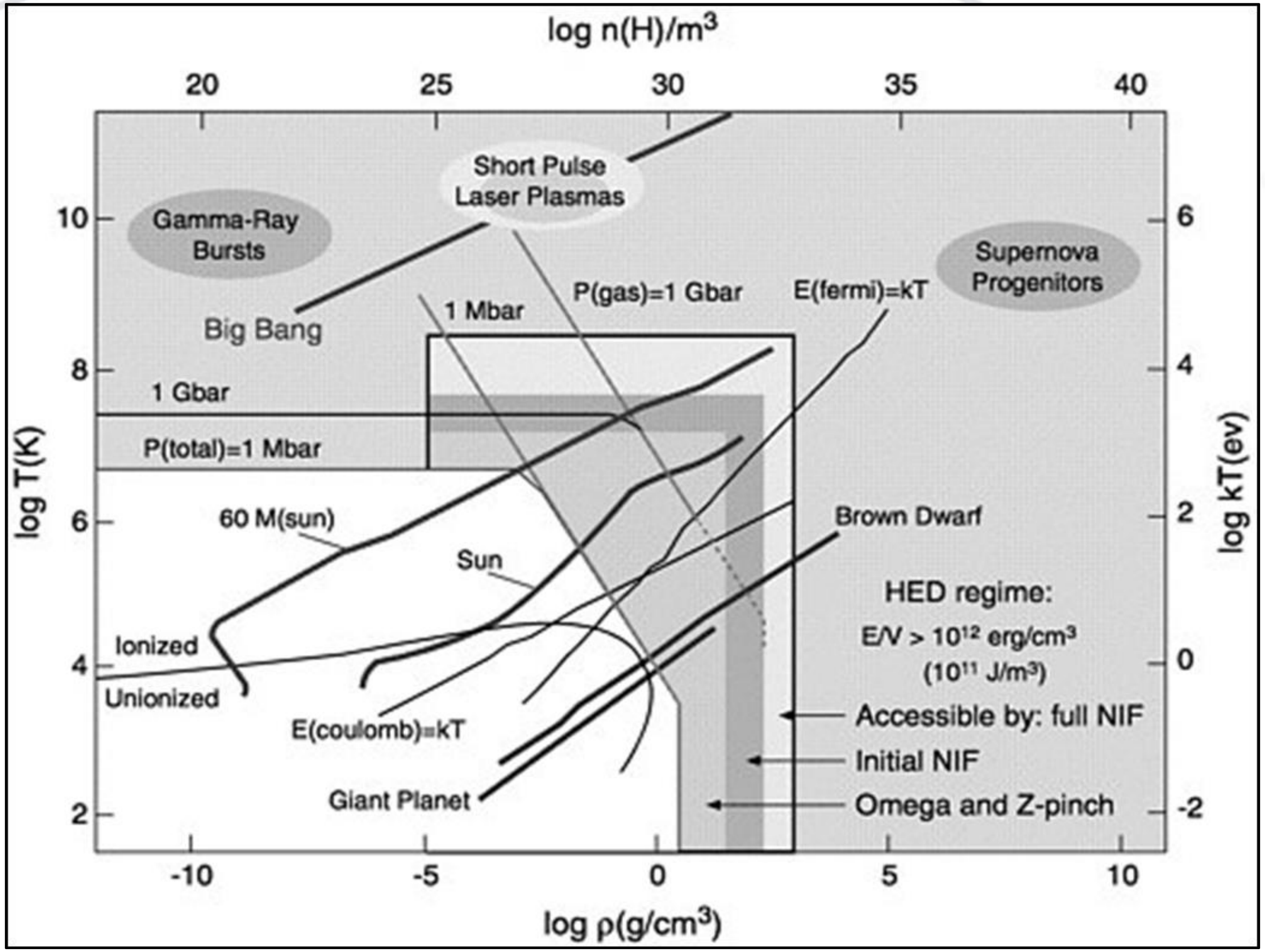
- Collisions must occur less frequently than typical plasma oscillations

$$\omega\tau > 1$$ **(collisionality)**

Plasmas are often treated as a fluid with additional affects, such as magnetic and electric fields

High-energy-density systems are defined as systems having pressures above 1 Mbar or energy densities above 100 GJ/m^3

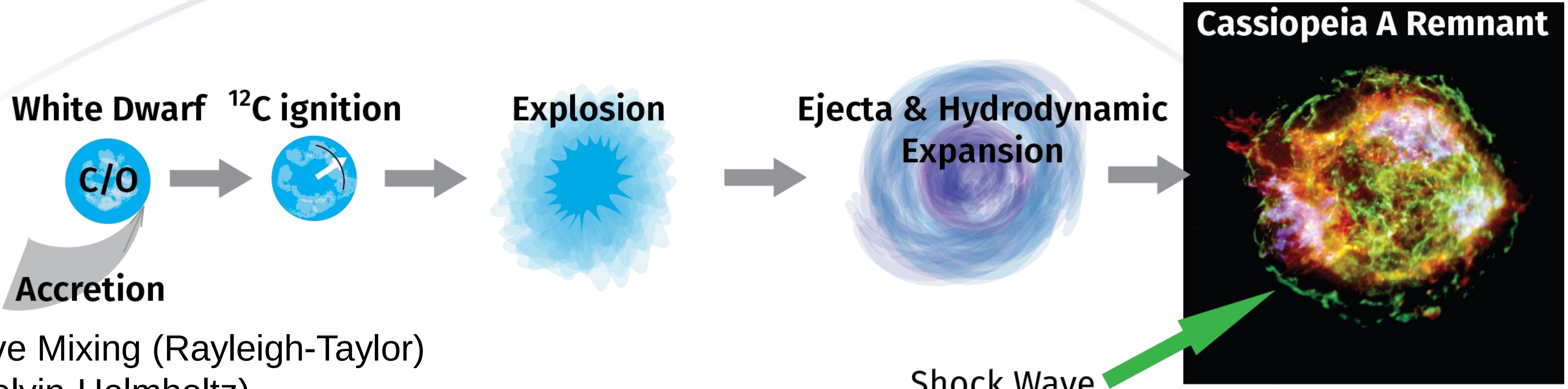
1 Mbar = 1 million atmospheres



R.P. Drake,
High-Energy-Density Physics

HED systems are technically a plasma, but are often treated and modeled as a traditional fluid

Type Ia supernovae are "standard candles" that help determine the age of the universe



10 light years diameter (10^{14} km)

Convective Mixing (Rayleigh-Taylor)
Shear (Kelvin-Helmholtz)
Shock-driven (Richtmyer-Meshkov)

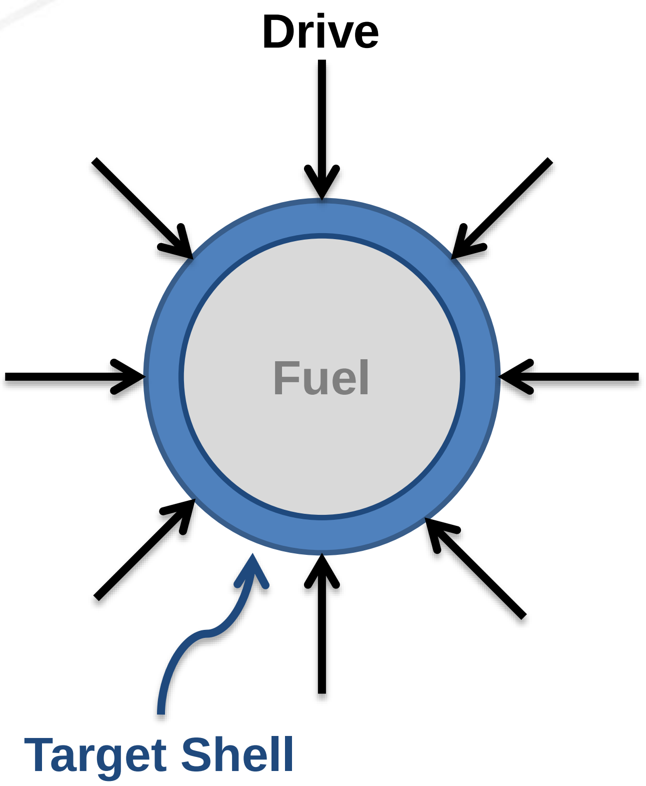
Instabilities are important in:

- Pre-ignition conditions
- Triggering ignition
- Final chemical structure

Image from NASA's Chandra X-Ray Observatory chandra.harvard.edu

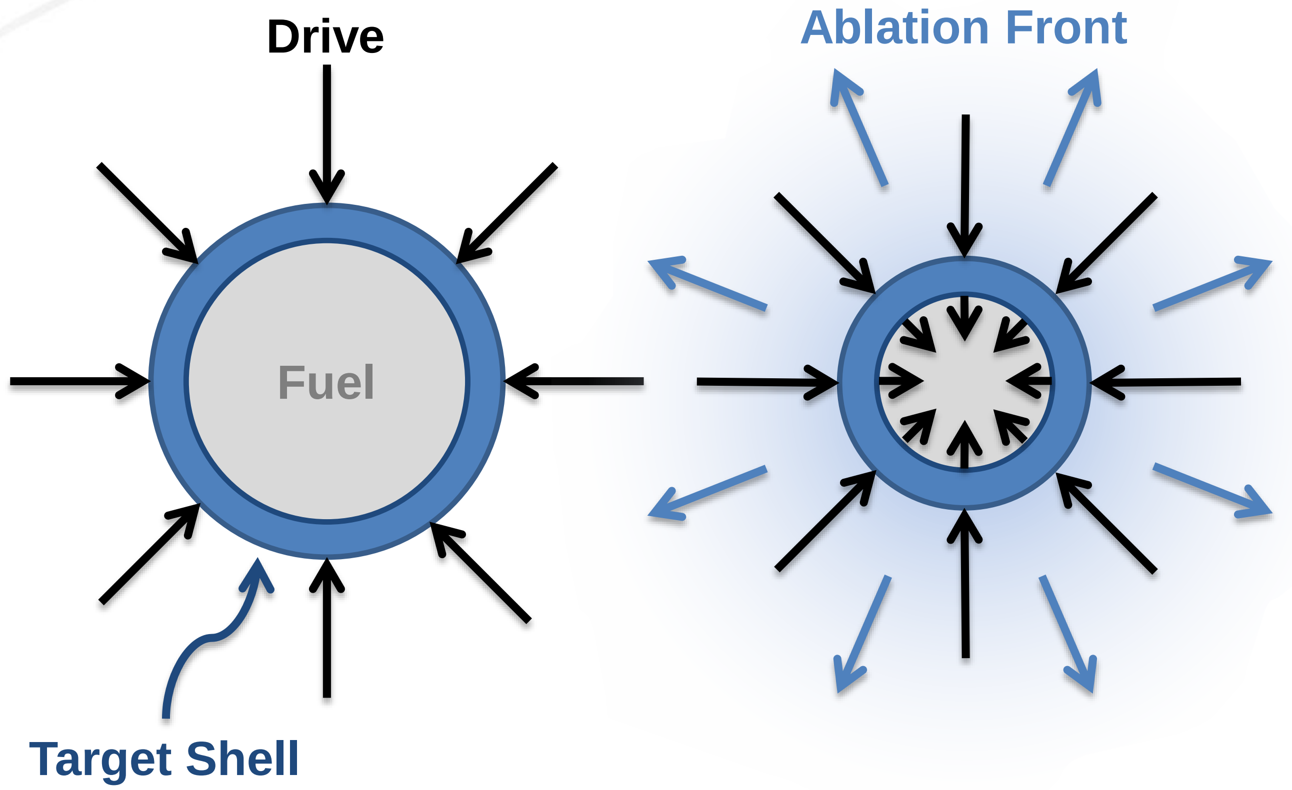
Slide courtesy of Kathy Prestridge

Inertial Confinement Fusion (ICF) seeks to use high power lasers to generate fusion by compressing DT fuel



Slide courtesy of
Elizabeth Merritt

Inertial Confinement Fusion (ICF) seeks to use high power lasers to generate fusion by compressing DT fuel



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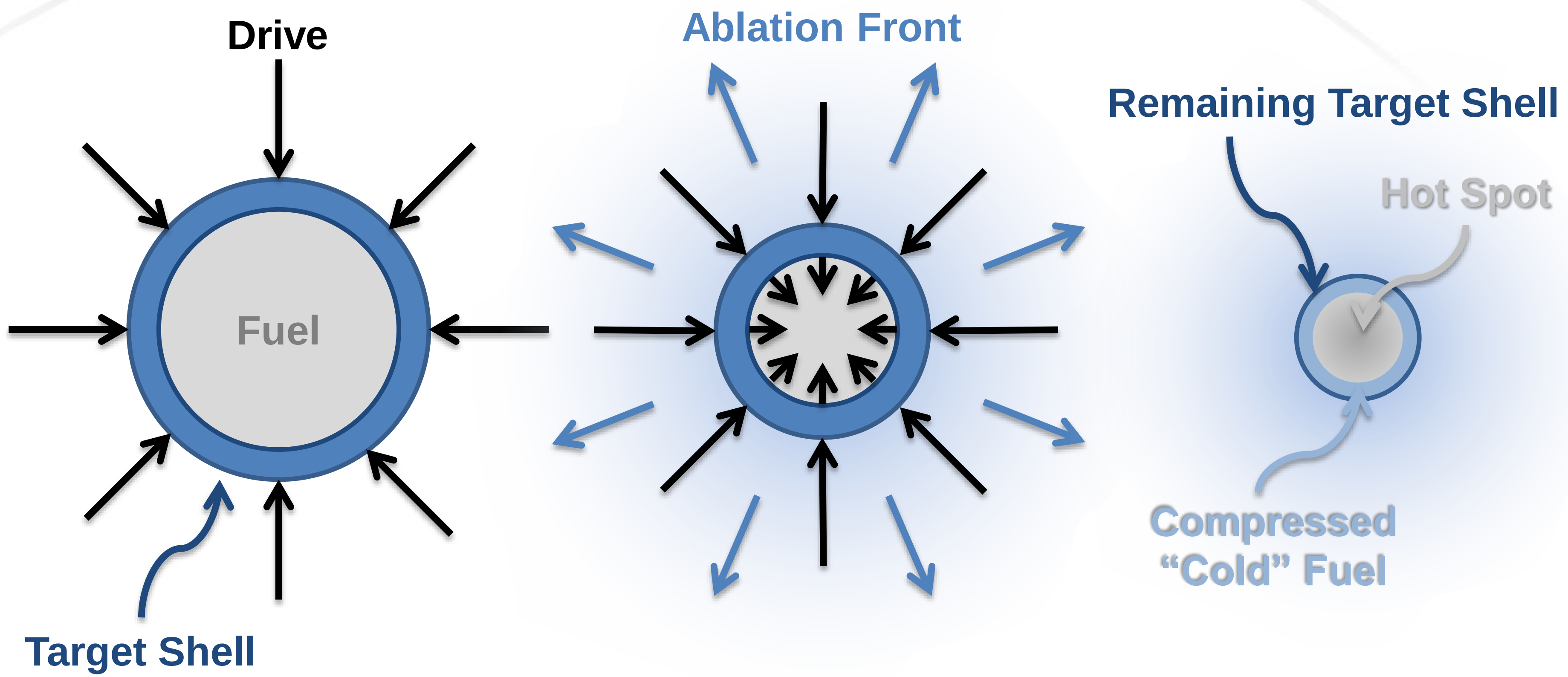
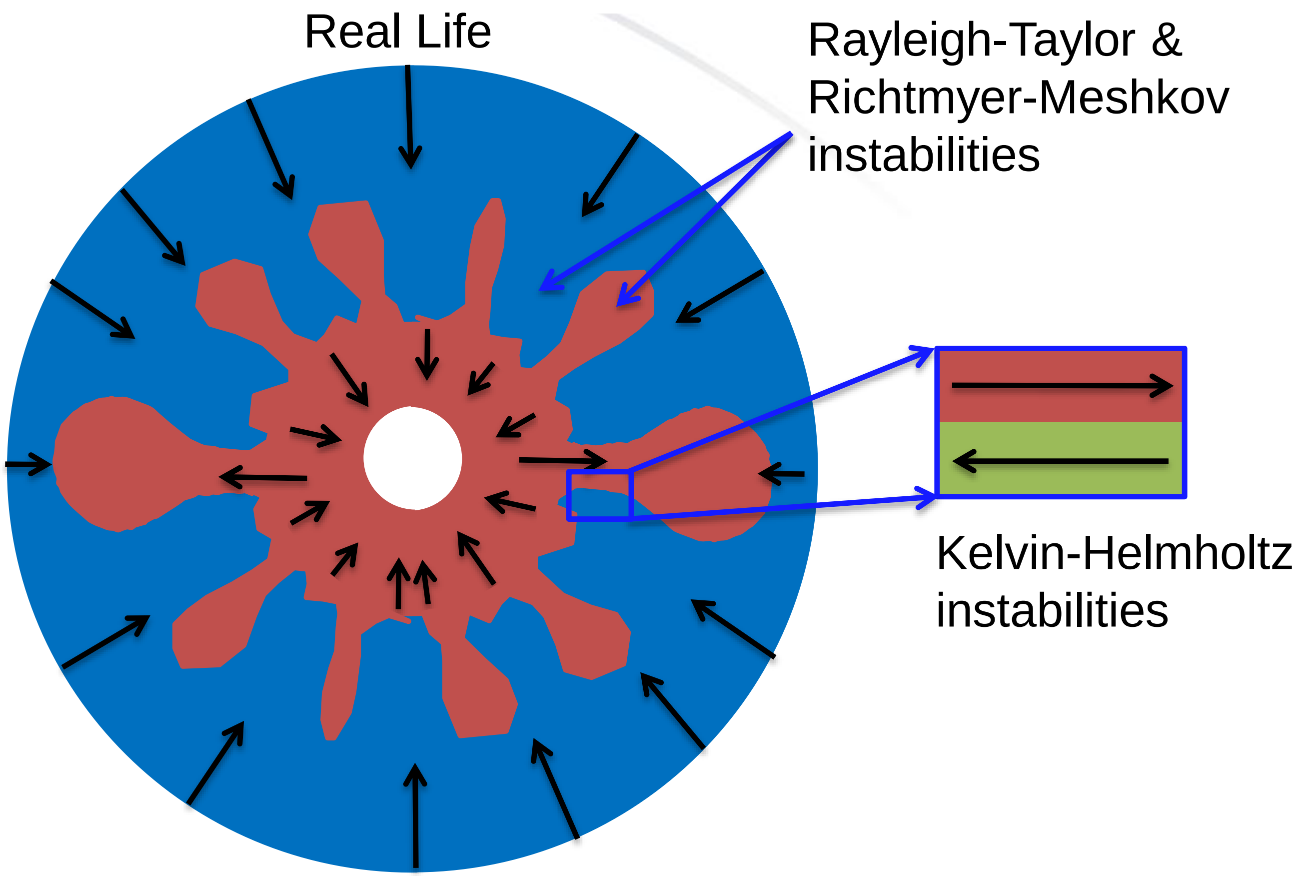


This is ideally how the process should work, but…

Slide courtesy of Elizabeth Merritt

ICF capsules are prone to instabilities at interfaces

- Different target layer densities
  - Rayleigh-Taylor
- Strong Shear flows
  - Kelvin-Helmoltz
- Multiple shocks
  - Richtmyer-Meshkov



Instabilities can mix ablator material into the fuel and degrade and/or prevent ignition

Slide courtesy of Kathy Prestridge and Elizabeth Merritt

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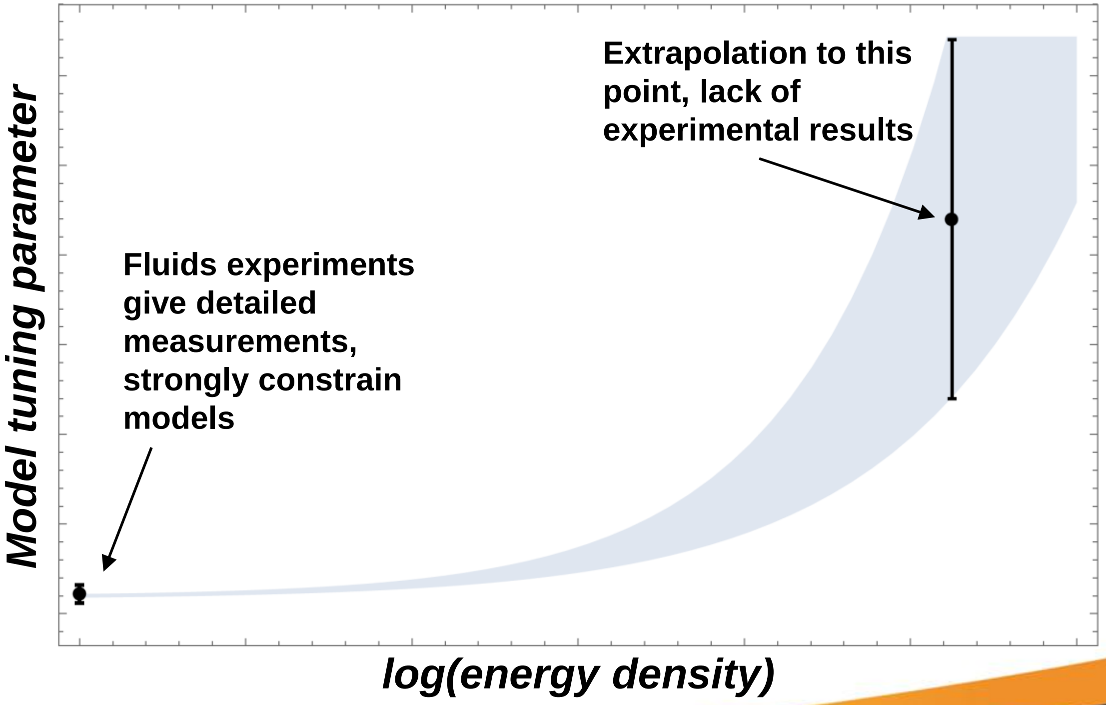
National labs are trying to extend low-energy density fluid experiments into the high-energy density regime

Experiments in the HED plasma regime are where fluid dynamics approximations may break down

Doss *et al*., *Phys. Plasmas* 20, 012707 (2013)
Doss *et al*., *Phys. Plasmas* 20, 122704 (2013)
Doss *et al*., *Phys. Plasmas* 23, 056303 (2015)
Flippo *et al*., *JPCS* 688, 012018 (2016)

- Relevant to mix in ICF capsules and astrophysics
- Used to benchmark hydrodynamics and advanced turbulence models
  - Widely benchmarked in low-energy-density (LED) fluid regimes e.g. aerospace
  - Do we need to include HED effects?



National labs are trying to extend low-energy density fluid experiments into the high-energy density regime

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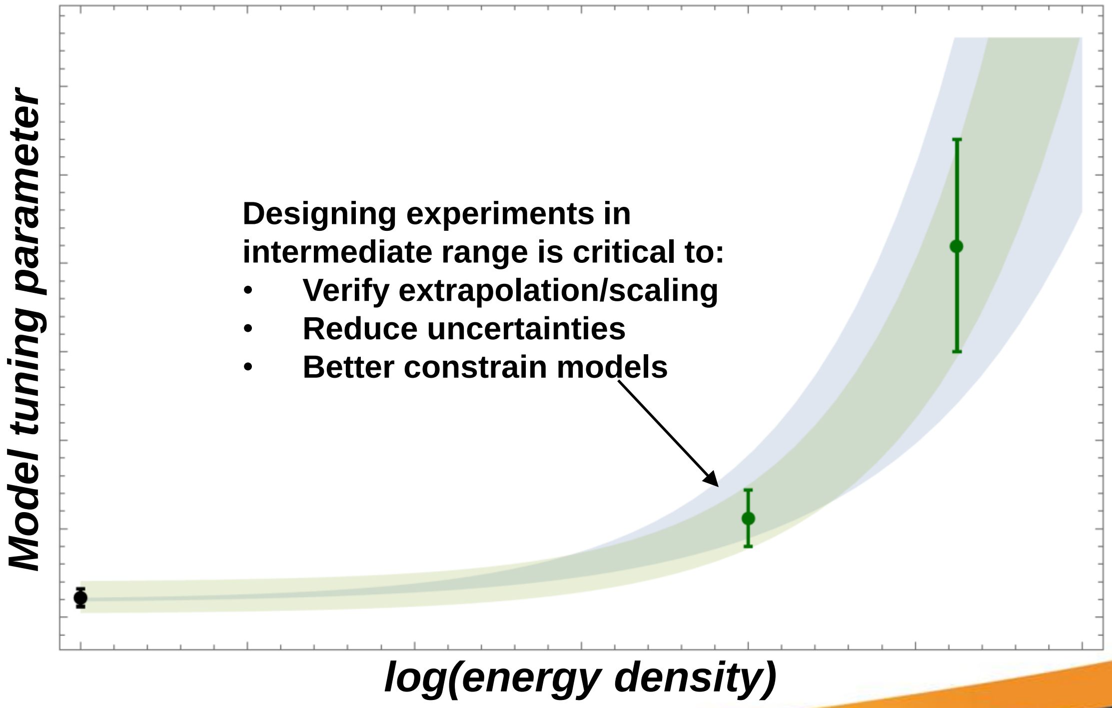
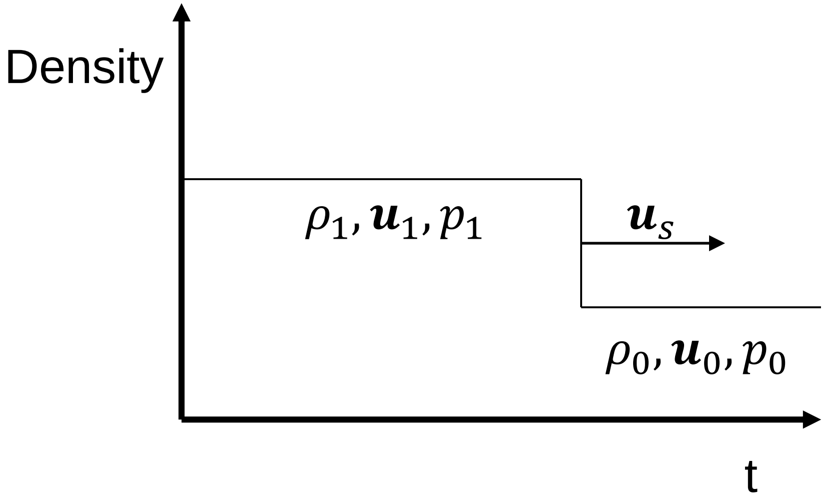


National labs are some of the only institutions extending hydrodynamics and turbulences models beyond LED regimes

Brief overview of Shock Physics and RMI

A shock wave may be considered as a moving front that exhibits a sharp discontinuity in fluid properties



Euler Conservation Laws:

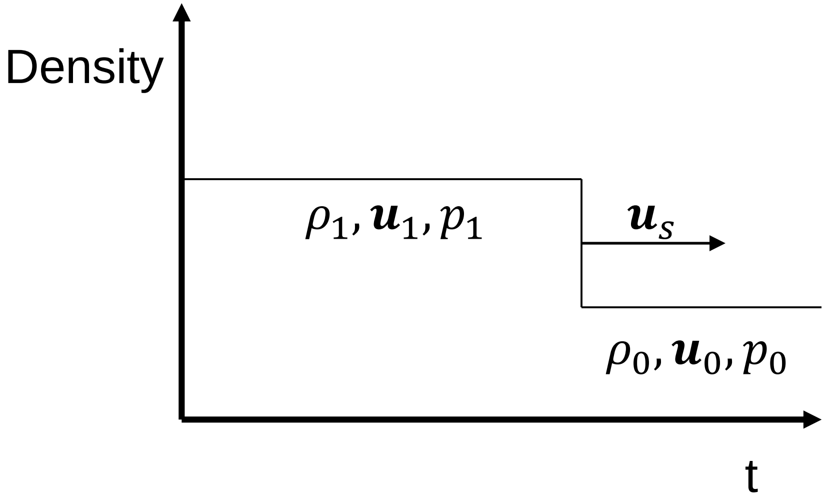
Continuity
$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \boldsymbol{u})$$

Momentum
$$\frac{\partial}{\partial t}(\rho \boldsymbol{u}) = -\nabla \cdot (\rho \boldsymbol{u}\boldsymbol{u}) - \nabla \mathrm{p}$$

Energy
$$\frac{\partial}{\partial t}\left(\frac{\rho u^2}{2} + \rho \epsilon\right) = -\nabla \cdot \left[\rho \boldsymbol{u}\left(\epsilon + \frac{u^2}{2}\right) + p\boldsymbol{u}\right]$$

Conservation laws must be obeyed, even with the presence of a discontinuity

In order to close the equations, an assumption has to be made about the relation between energy and pressure



Euler Conservation Laws:

Continuity $$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \boldsymbol{u})$$

Momentum $$\frac{\partial}{\partial t}(\rho \boldsymbol{u}) = -\nabla \cdot (\rho \boldsymbol{u}\boldsymbol{u}) - \nabla \mathrm{p}$$

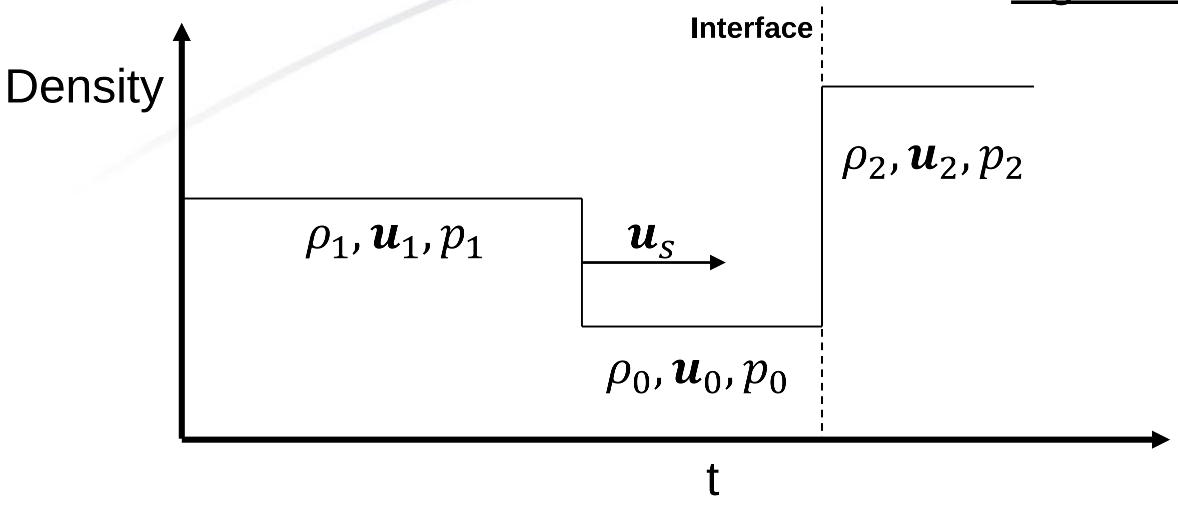
Energy $$\frac{\partial}{\partial t}\left(\frac{\rho u^2}{2} + \rho\epsilon\right) = -\nabla \cdot \left[\rho \boldsymbol{u}\left(\epsilon + \frac{u^2}{2}\right) + p\boldsymbol{u}\right]$$

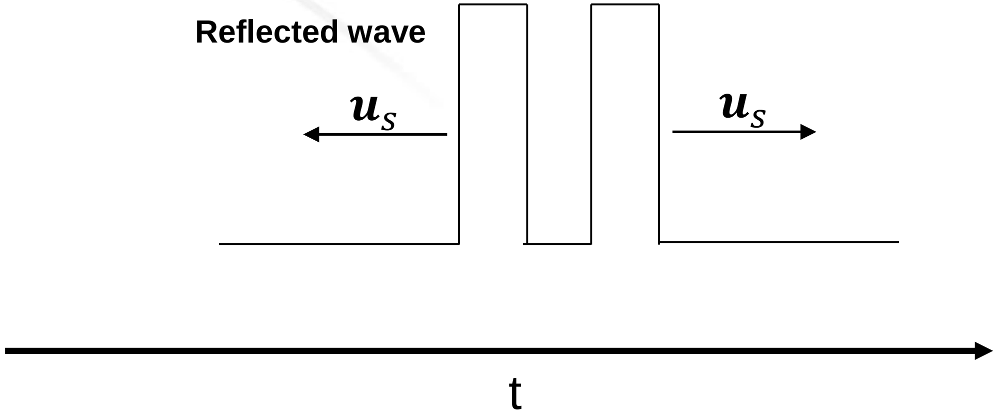
Polytropic gas $$\rho\epsilon = \frac{p}{\gamma - 1} \qquad \frac{p}{\rho^\gamma} = C$$

Shock waves are supersonic, which means the wave travels faster than information

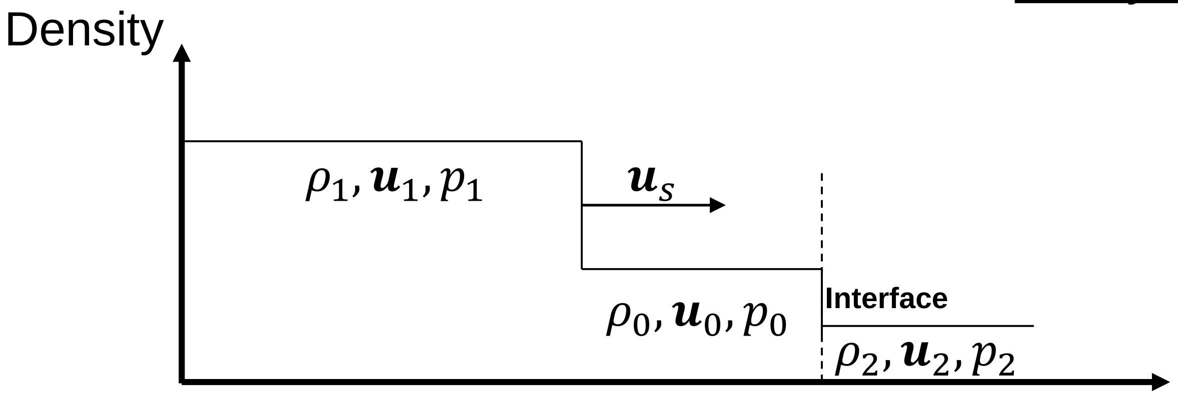
When a shock interacts with an interface, reflections and rarefactions can occur

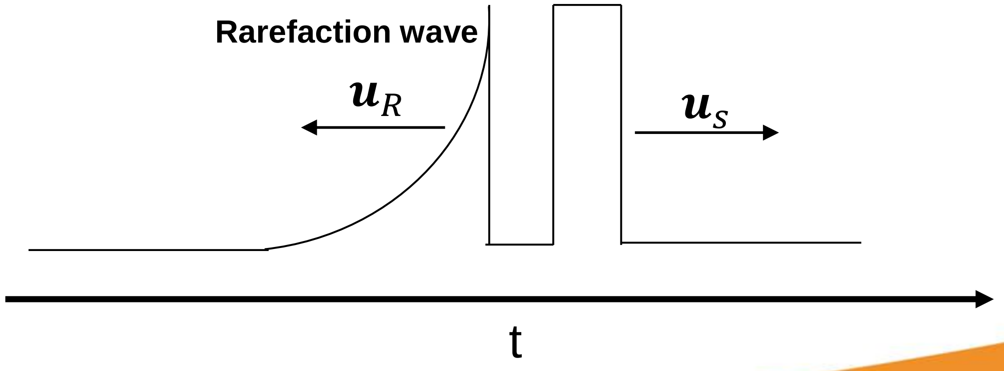
<u>Light material→ Heavy material</u>





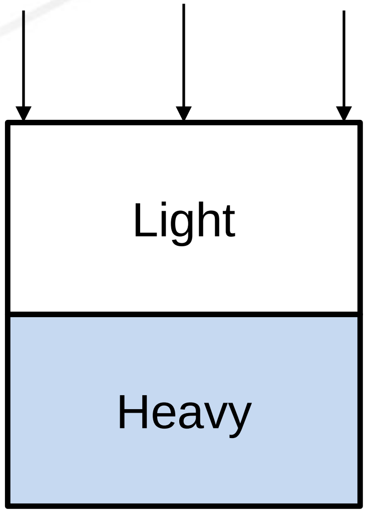
<u>Heavy material→ Light material</u>

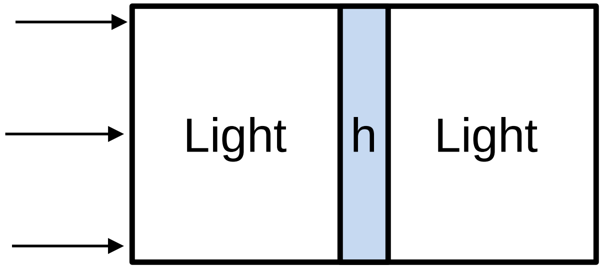


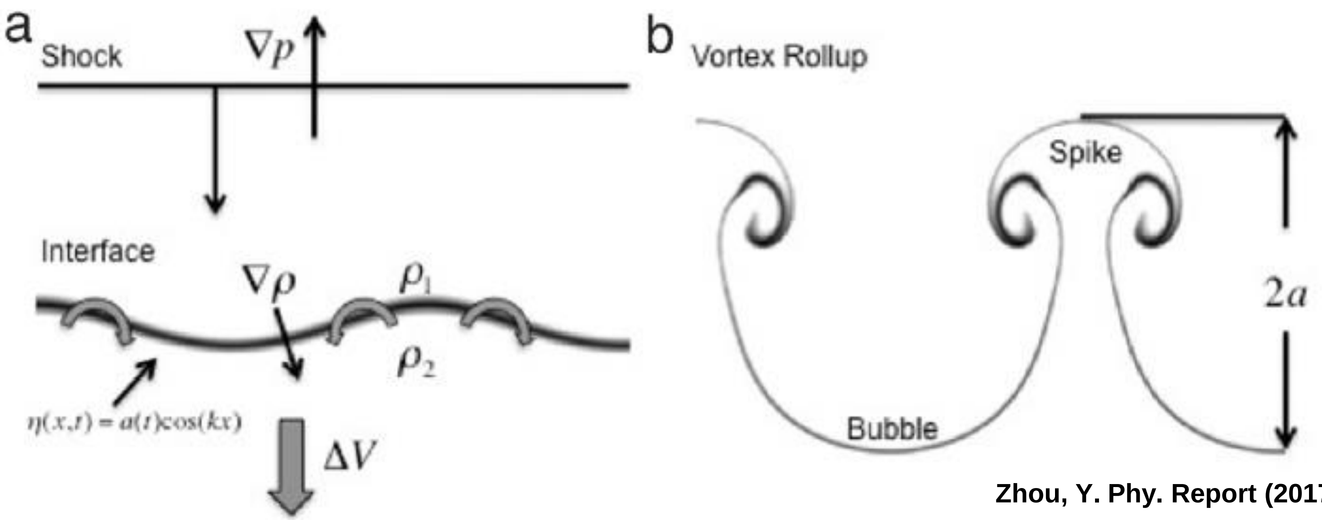


Shocks and rarefactions move material, which can change the material properties, generate new interfaces and give rise to instabilities.

The Richtmyer-Meshkov instability (RMI) is a shock driven instability at the interface of two disparate densities







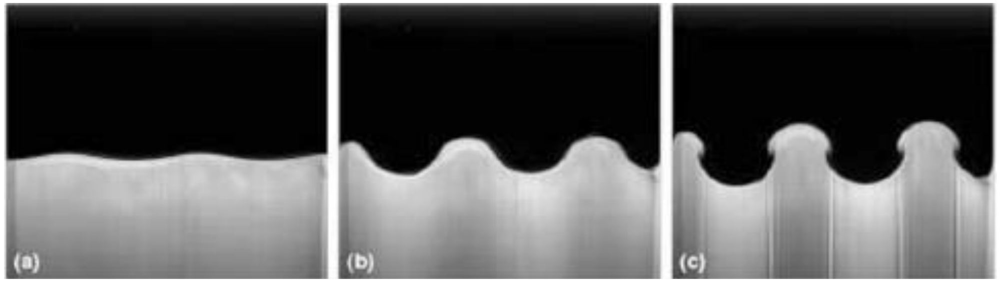
Zhou, Y. Phy. Report (2017)

$$\frac{D\omega}{Dt} = \underbrace{\frac{\nabla\rho \times \nabla p}{\rho^2}}_{\text{Baroclinic production}} + \underbrace{\omega \cdot \nabla \boldsymbol{u}}_{\text{Vortex stretching}} - \underbrace{\omega(\nabla \cdot \boldsymbol{u})}_{\text{Vortex dilation}}$$

Inviscid compressible vorticity equation

The deposition of baroclinic vorticity drives the RMI, which gives rise to bubbles and spikes that cause materials to mix

Initially, RMI growth is linear, but can quickly become nonlinear



Linear growth equation:

$$\frac{da(t)}{dt} = a_0 A k \Delta u$$

- Valid for $a_0 k \ll 1$
- a_0 and A may be pre-shock, post-shock or averaged values

Niederhaus and Jacobs (2003), J. Fluid Mech.

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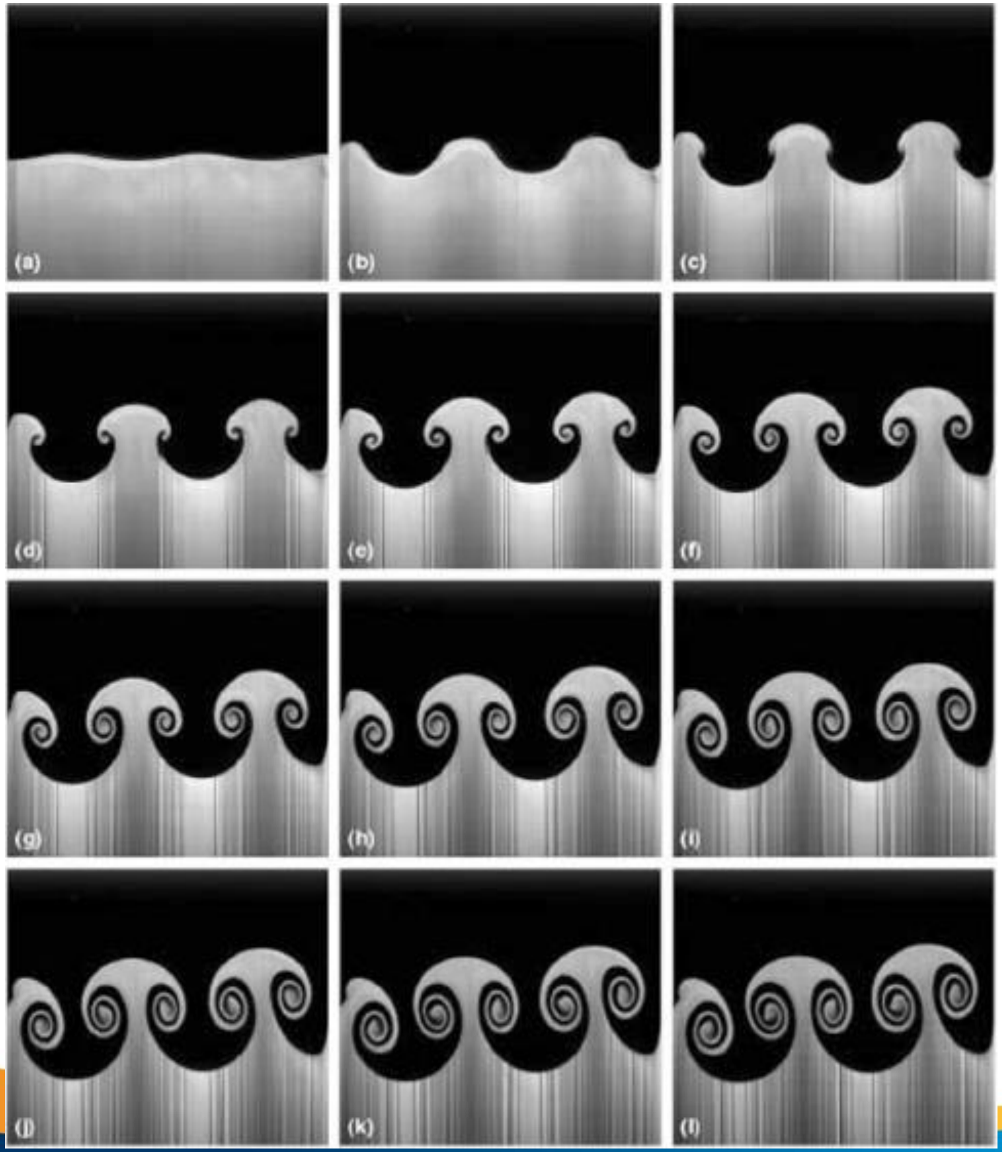


Niederhaus and Jacobs (2003), J. Fluid Mech.

Linear growth theory:

$$\frac{da(t)}{dt} = a_0 A k \Delta u$$

- Valid for $a_0 k \ll 1$
- a_0 and *A* may be pre-shock, post-shock or averaged values

Non-linear growth theory:

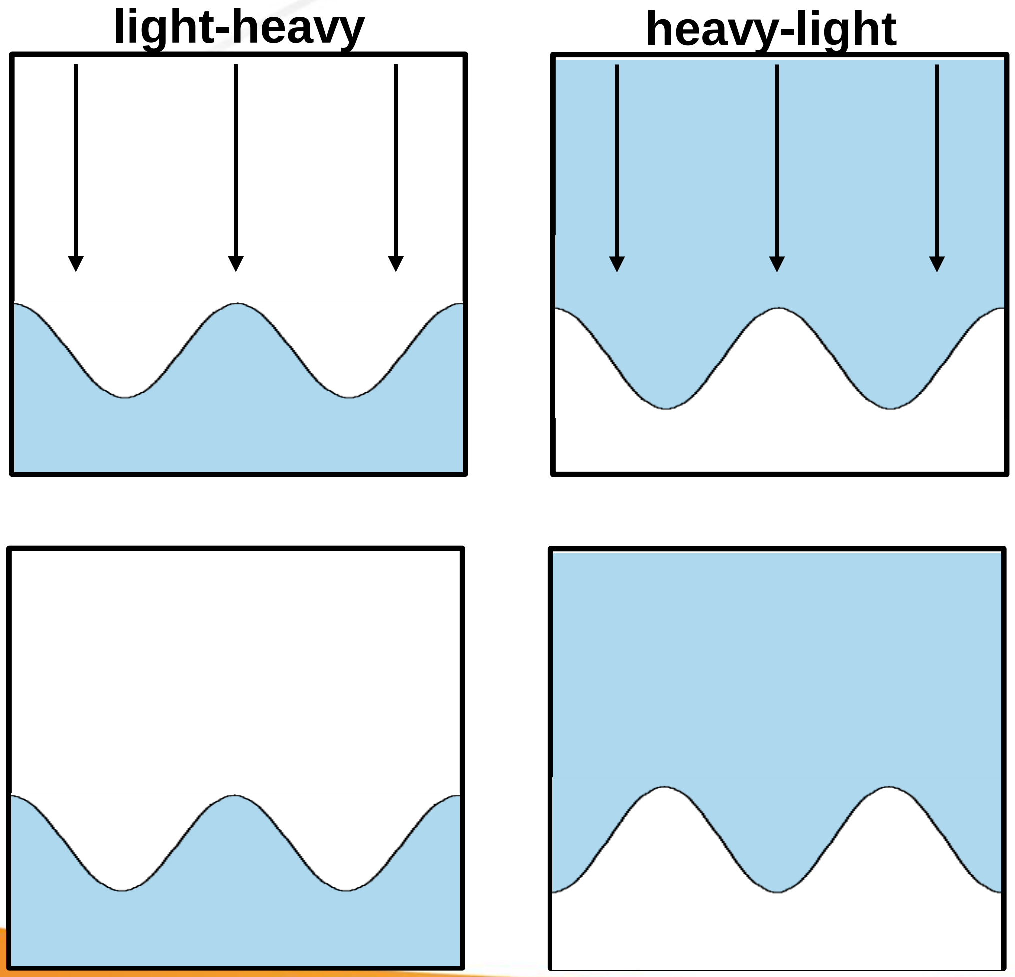
- There exist several formulations
- Bubble (+) and spike (-) growth handled separately
- Sadot *et al* (1998) found single formula to describe growth

$$u(t) = u_0 \frac{1 + u_0 k t}{1 + D_{b,s} t + E_{b,s} t^2}$$

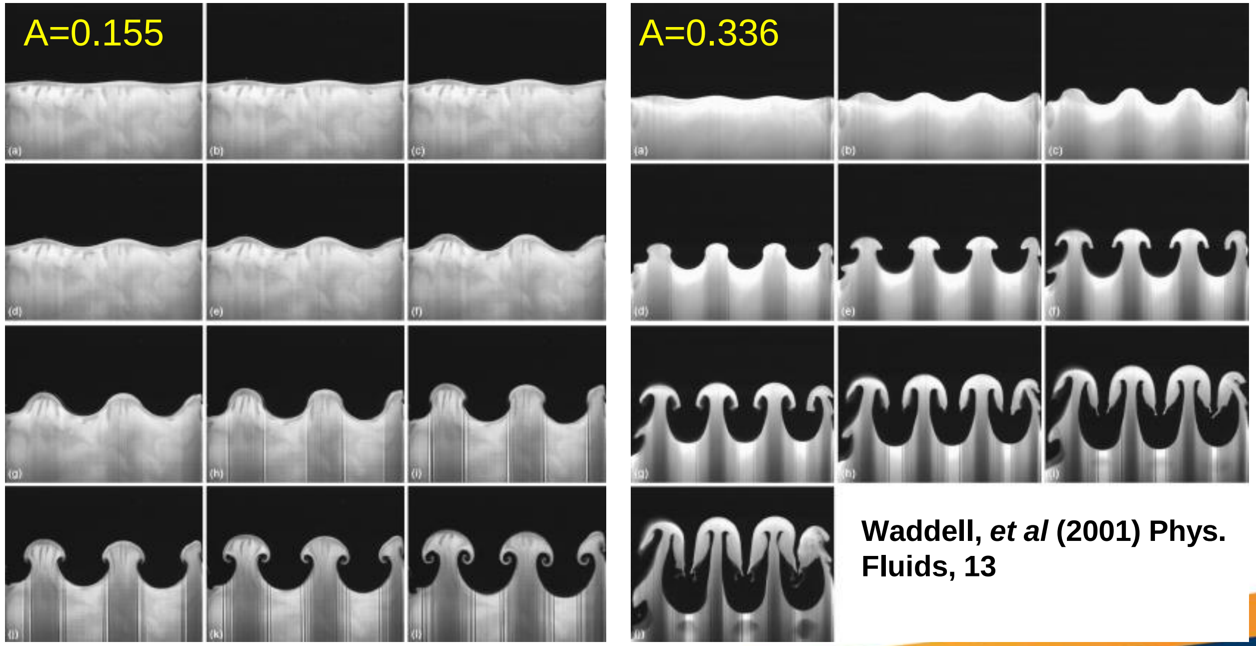
$$D_{b,s} = (1 \pm A) u_0 k \qquad E_{b,s} = \frac{1 \pm A}{1 + A} \frac{u_0^2 k^2}{2\pi C}$$

Equations shows that RMI growth is dependent on:

Atwood number can affect the phase of the RMI growth, as well as asymmetries in bubble to spike growth

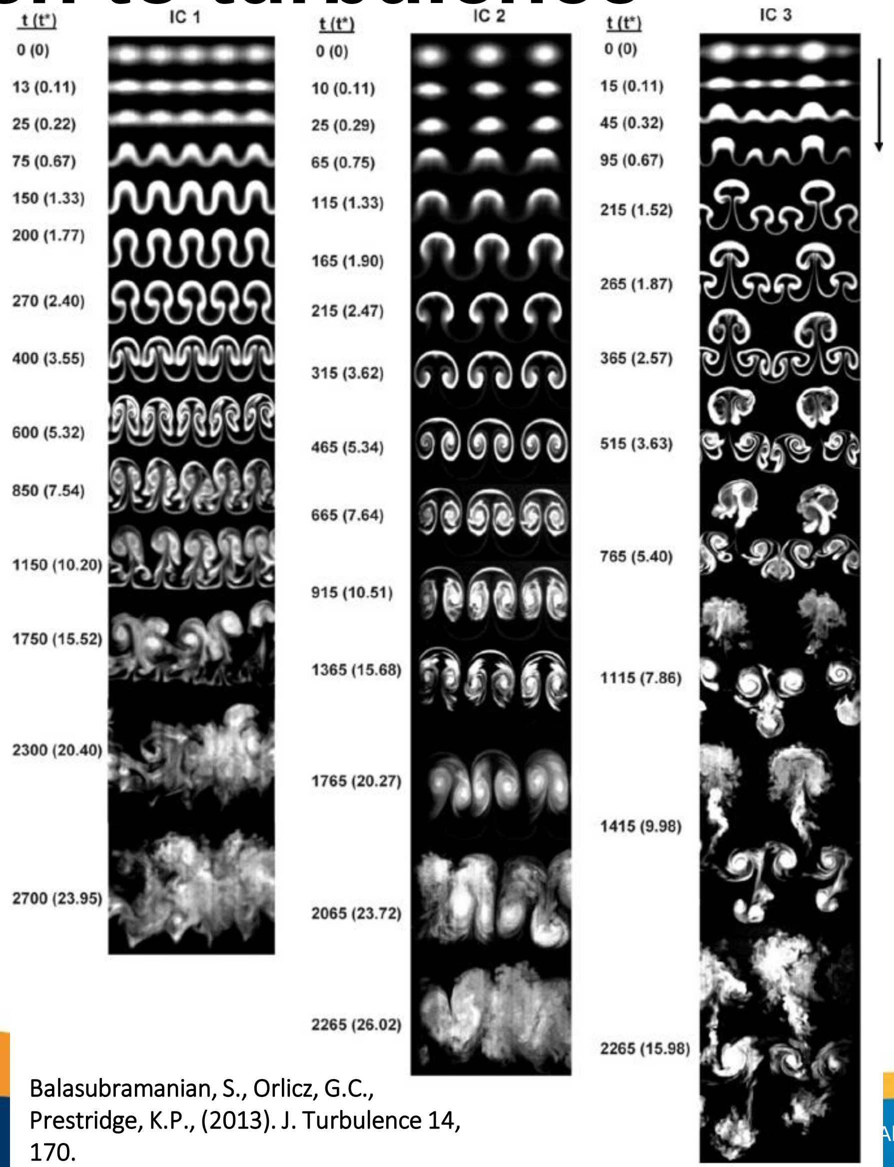


- Atwood number, *A*
  - $A = \frac{\rho_1 - \rho_2}{\rho_1 + \rho_2}$



Waddell, *et al* (2001) Phys. Fluids, 13

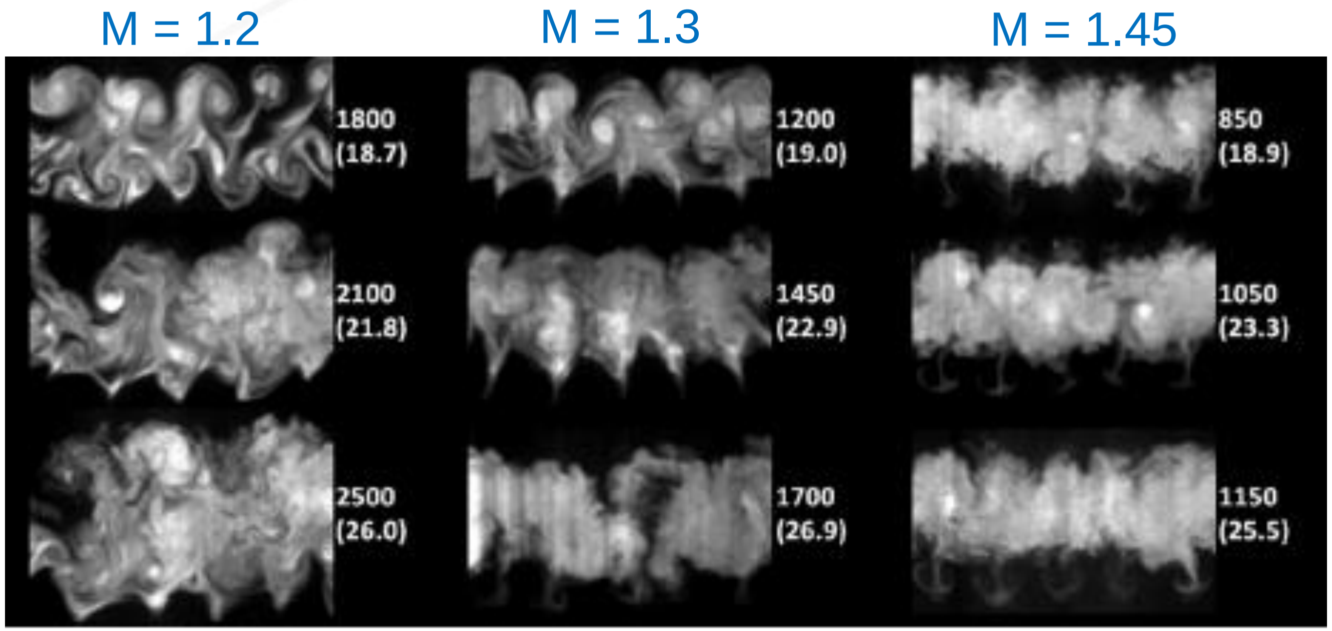
Initial conditions affect the rate at which the RMI transitions from linear to non-linear and even to turbulence



Balasubramanian, S., Orlicz, G.C., Prestridge, K.P., (2013). J. Turbulence 14, 170.

- Atwood number, *A*
  - $A = \frac{\rho_1 - \rho_2}{\rho_1 + \rho_2}$
- Initial condition at the interface
  - *k* = wavenumber
  - a_0 = *amplitude of perturbation*

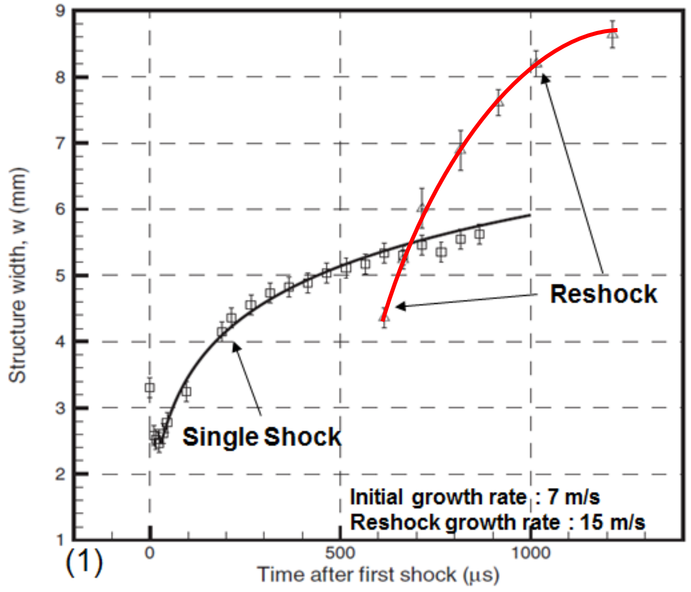
Mach number has a similar effect as initial conditions, and affects the growth and mixedness of the layer

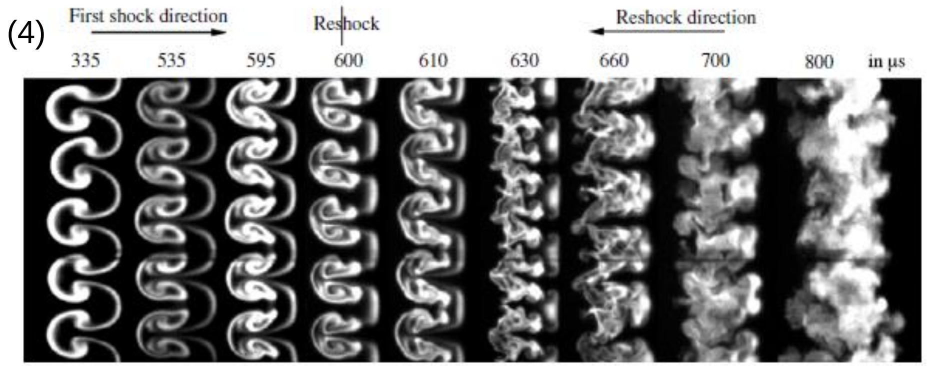


- Atwood number, *A*
  - $A = \frac{\rho_1 - \rho_2}{\rho_1 + \rho_2}$
- Initial condition at the interface
  - *k* = wavenumber
  - a_0 = *amplitude of perturbation*
- Mach number of the shock
  - $M = \frac{u}{c_s}, \ c_s = \sqrt{\frac{\gamma p_0}{\rho_0}}$
  - *M* < 1, subsonic
  - ***M* > 1, supersonic**

Orlicz, S. Balasubramanian, Prestridge (2013) *Phys. Fluids.*
Orlicz, S. Balasubramanian, Vorobieff, Prestridge (2015) *Phys. Fluids*

Fluid's experiments found that reshock increases instability growth rate and can lead to turbulence





- Without reshock, growth slows and stagnates
- With reshock, layer initially compresses before growing more quickly
- Growth after reshock dependent on:
  - Reshock Mach[2]
  - Growth/mix of layer at re-shock[3]
  - Atwood number
- Reshock has also been shown to drive RM turbulent[4,5]

Growing RMI can be re-shocked by reflected waves or rarefactions, changing the instability dynamics and leading to additional mixing

1. Balakumar, B. J., *et al*. Phys. Fluids 20 (2008)
2. Leinov, E., *et al*. J. Fluid Mech 626 (2009)
3. Balasubramanian, S. *et al*, Phys. Fluid 24 (2012)
4.Tomkins, C. D., *et al*. J. Fluid Mech. (2013) 735
5. Balakumar, B. J., *et al.* J. Fluid. Mech. 696 (2012)

Los Alamos NATIONAL LABORATORY EST. 1943

Experimental Facilities and Measurements

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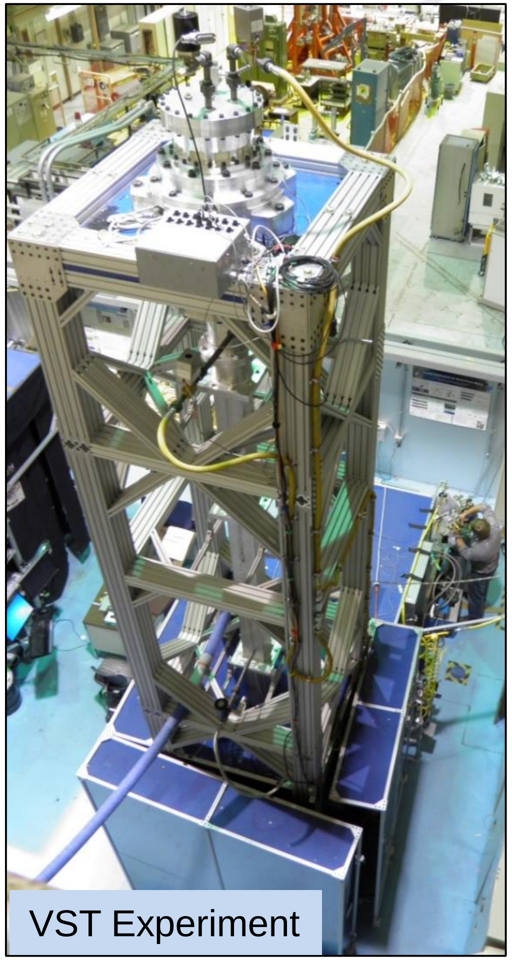
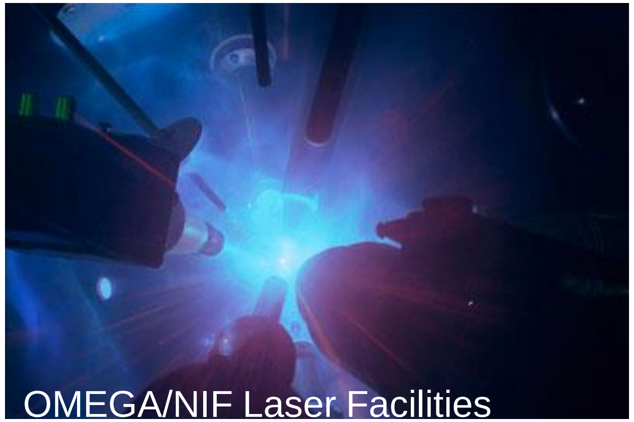
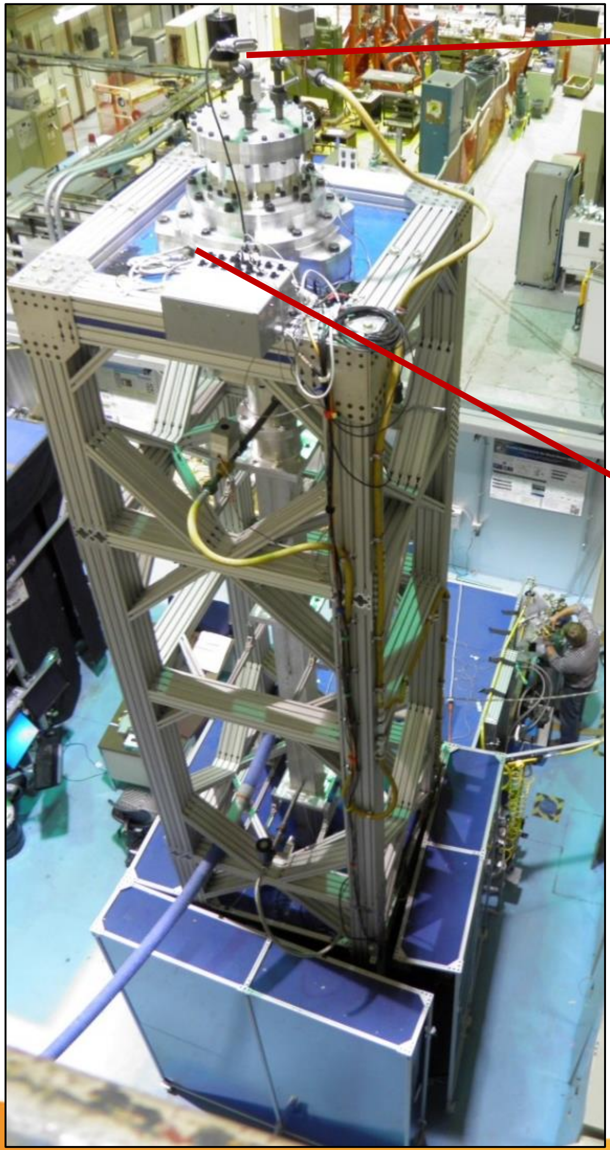
The Richtmyer-Meshkov instability is studied in multiple physical regimes at LANL

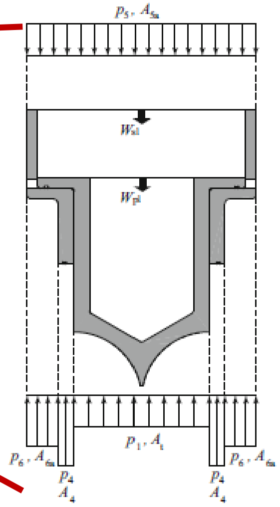


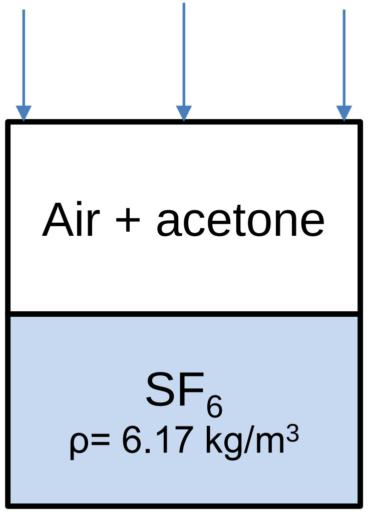


- **Vertical Shock Tube (VST):** Shocks gases, traditional fluid, Low Mach number
- **pRad:** Shocks gases, but at high Mach number
- **Mshock**: Shock plasmas

VST studies RMI mixing dependence on initial conditions and Mach number

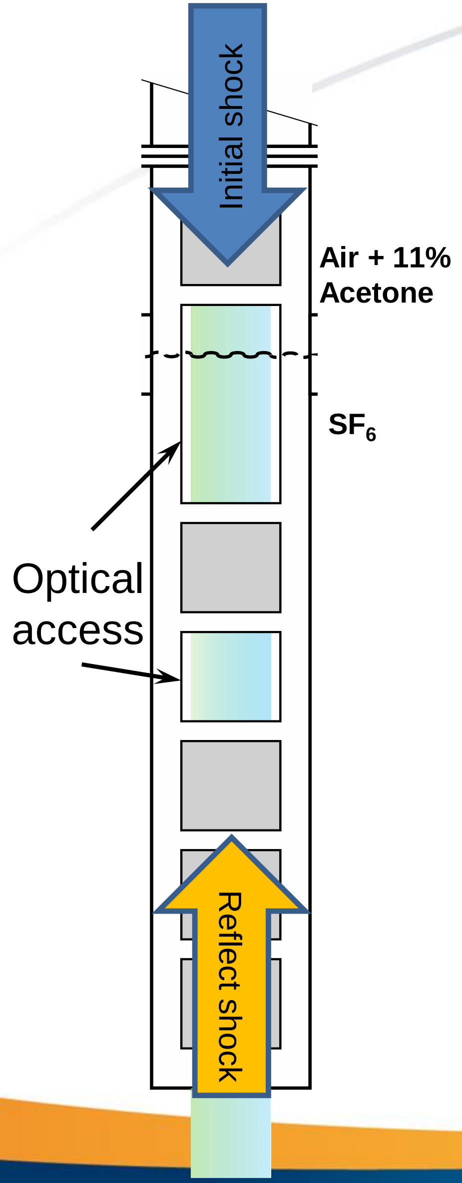




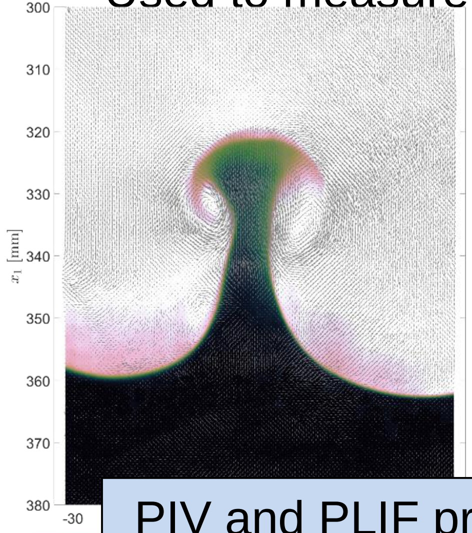


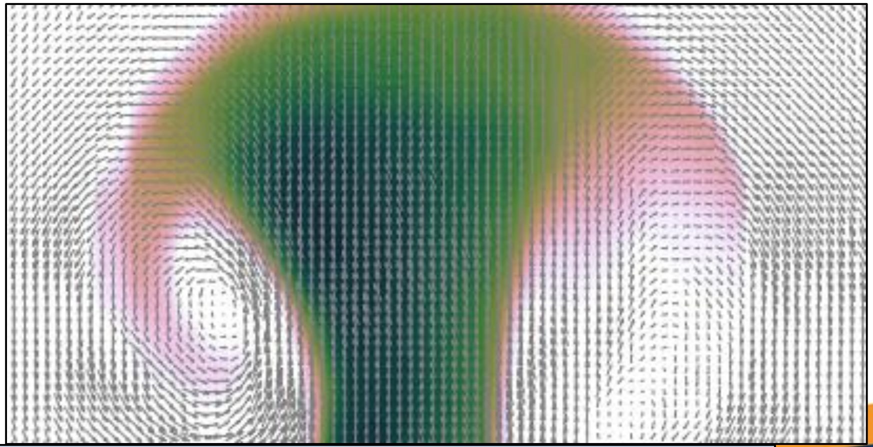
- Shock tube dimensions:
  - ~7 m tall shock tube
  - 5 x 5 inch rectangle
- Driven by piston
- Shock speeds:
  - M=1-1.5
  - New upgrades will allow M=2
- Shot rate
  - 20-30 shots/day
  - 2-4 images per shot
- Drives shocks with and in gases
  - Air
  - SF_6

Main diagnostics are PIV, PLIF and pressure transducers



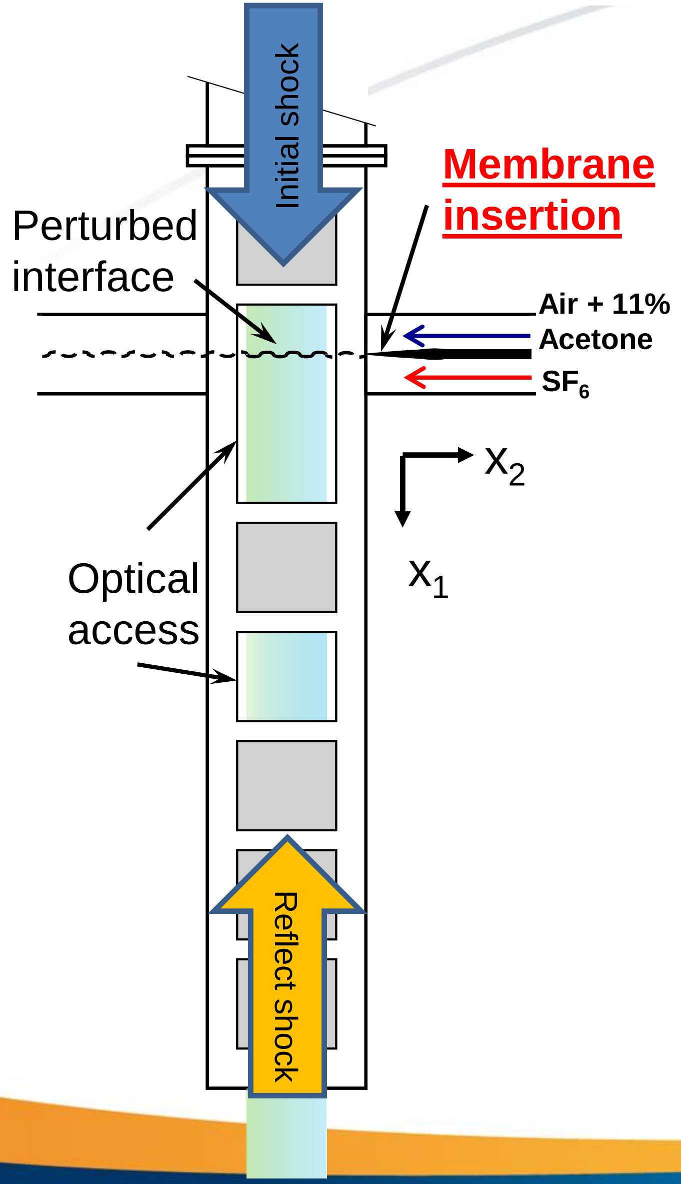
- PIV (Particle Image Velocimetry)
  - Seed particles (olive oil) scatter laser
  - Concurrent time images show changes due to flow
  - Measures velocity field
- Planar Laser-Induced Fluorescence (PLIF)
  - Sheet of laser light which illuminates tracer particles (acetone)
  - Measures concentration of particles
- Pressure transducers measure changes in pressure
  - Used to measure shock location and calculate shock speed



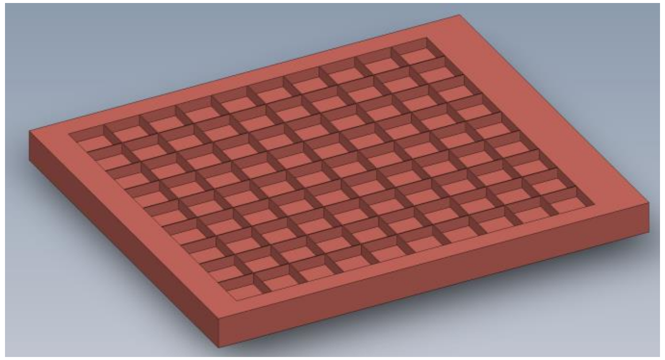


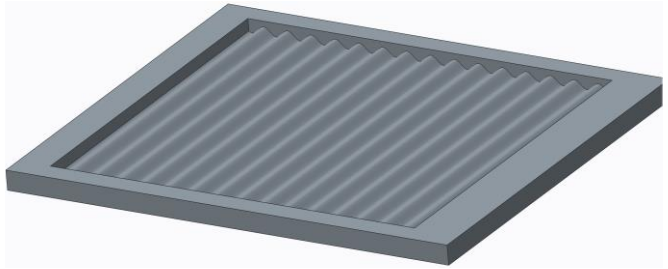
PIV and PLIF provide detailed measurements that can be used to highly constrain model

Generating repeatable initial conditions is difficult



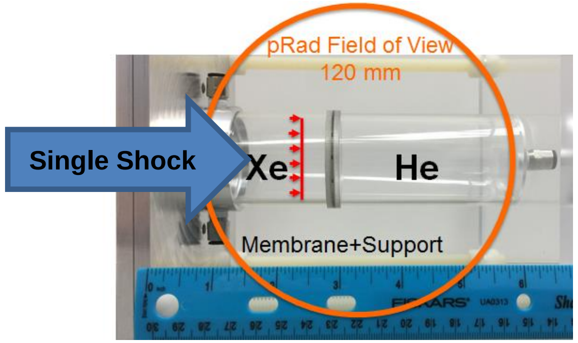
- Attempted to use a flapper plate with air and SF_6 feeding into chamber
  - Were able to set amplitude and frequency
  - Results were not reproducible
- Moving to membranes
  - How thin is thin enough?
  - How much does membrane breaking affect resulting instability?





Repeatable initial conditions are critical for achieving higher order statistics, while changing initial conditions are important for affecting the mix and testing models

pRad offers a chance to examine RMI under high Mach number with variable initial conditions

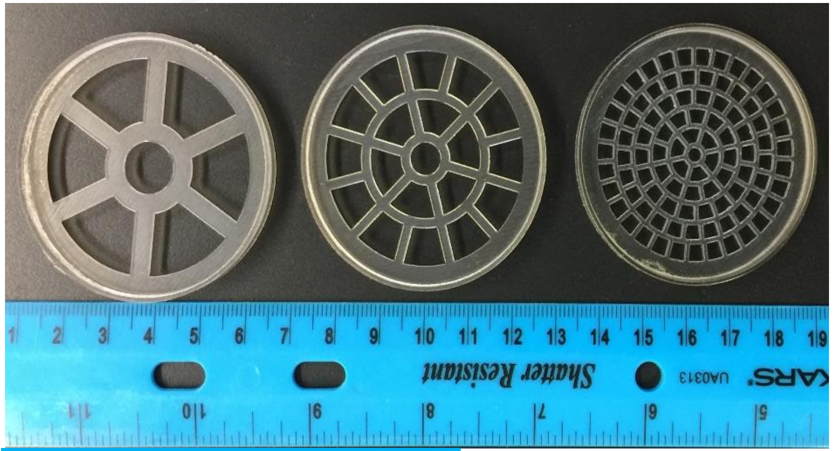


- Shock tube dimensions:
  - ~6 cm diameter
- Driven by powder gun
- Shock speeds:
  - M= 8-11
- Shot rate
  - 5-6 shots per year
  - ~30 images per shot
- Drives shocks in gases
  - Currently shock driven in Xenon
  - Interface separates from Helium

High Mach number tests our understanding of physics in a new regime and may provide a stepping stone to the HED/plasma regime

Proton radiography is used to image the mix width induced by various initial conditions

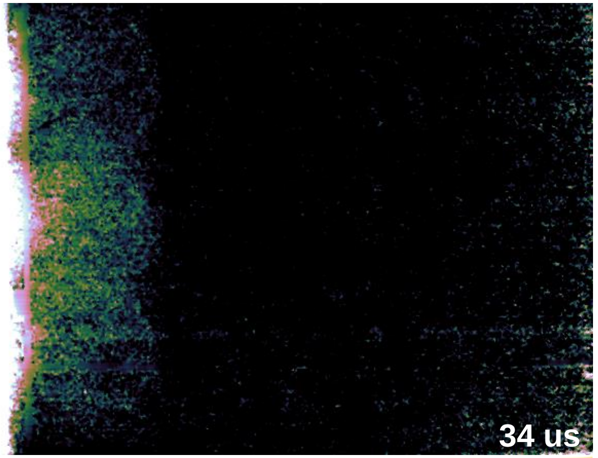
Shot # 680 679 677

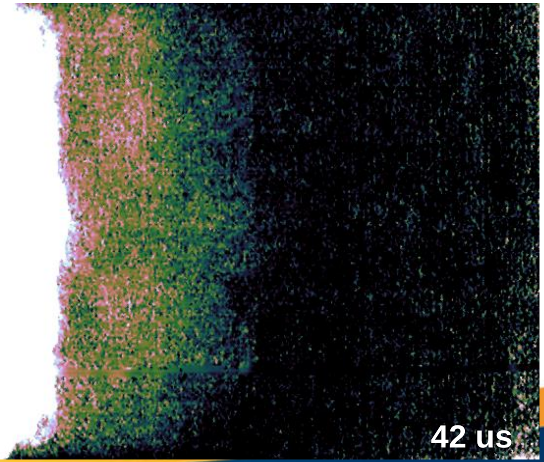


Aluminized Mylar membrane

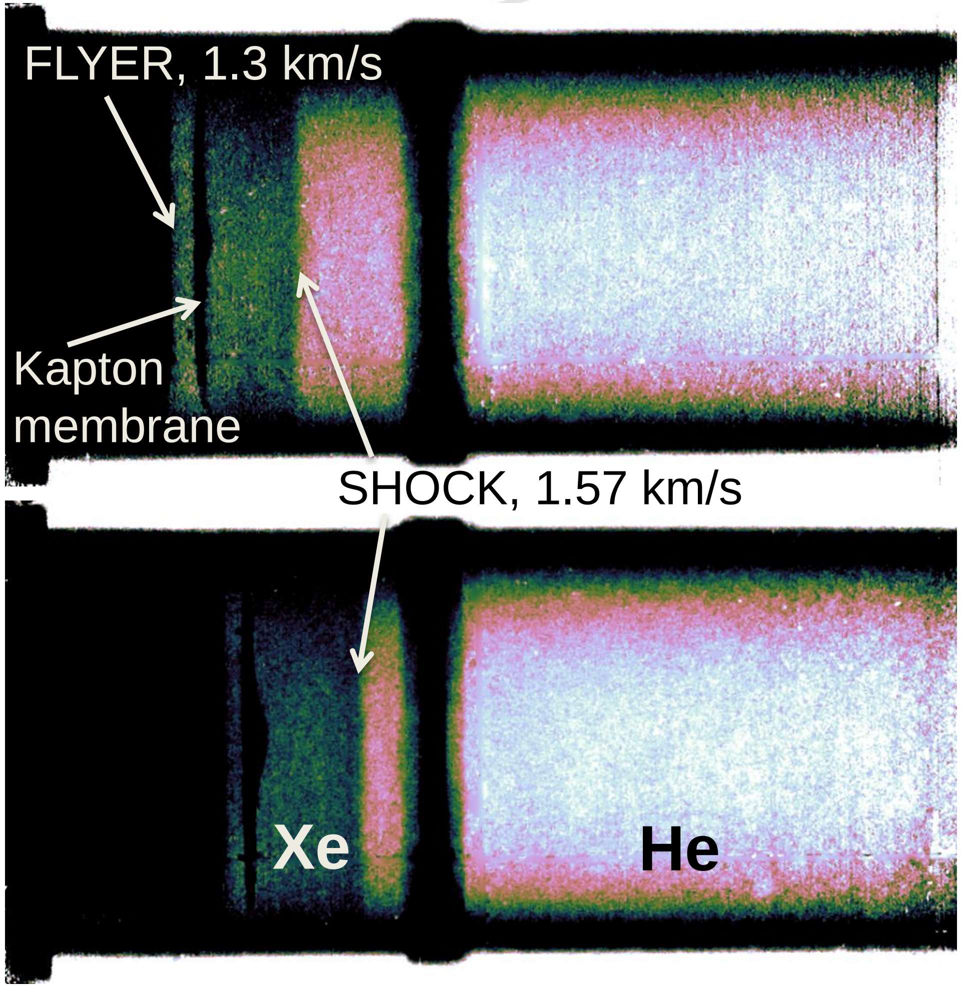
Goal: Measure time-dependent growth of Xe-He turbulent mixing region

- Protons are absorbed by the xenon, but pass through helium
  - Provides contrast imaging between two gases
  - Highlights regions of mixing
- Initial conditions are set by membrane
  - 3D printed
  - Covered with Aluminized Mylar

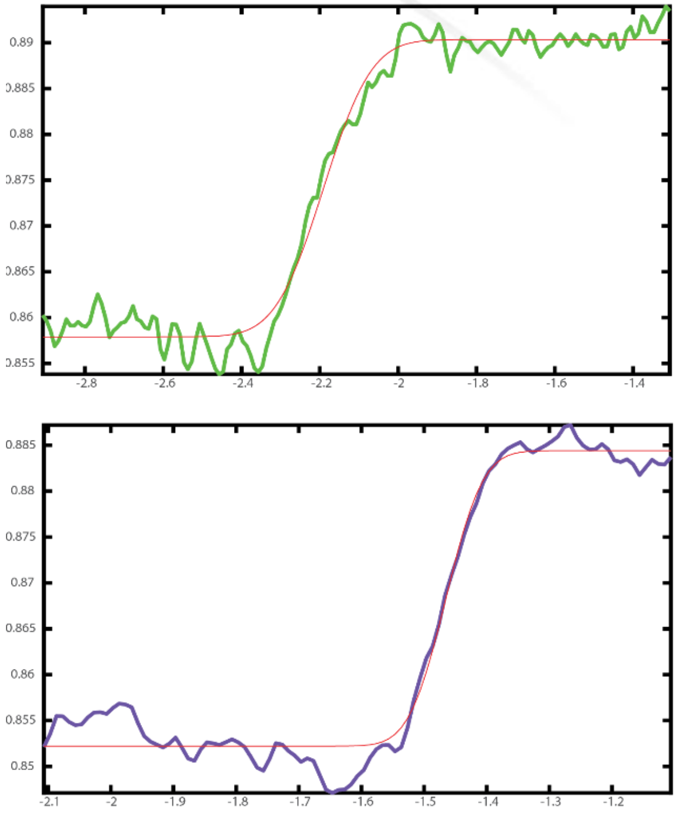




Proton Radiography (pRad) provides shock speed and density jump



Transmission lineouts to determine shock position & speed



$$\frac{\rho_2}{\rho_1} = \frac{(\gamma+1)M^2}{2+(\gamma-1)M^2}$$

$$\gamma = 1.651$$

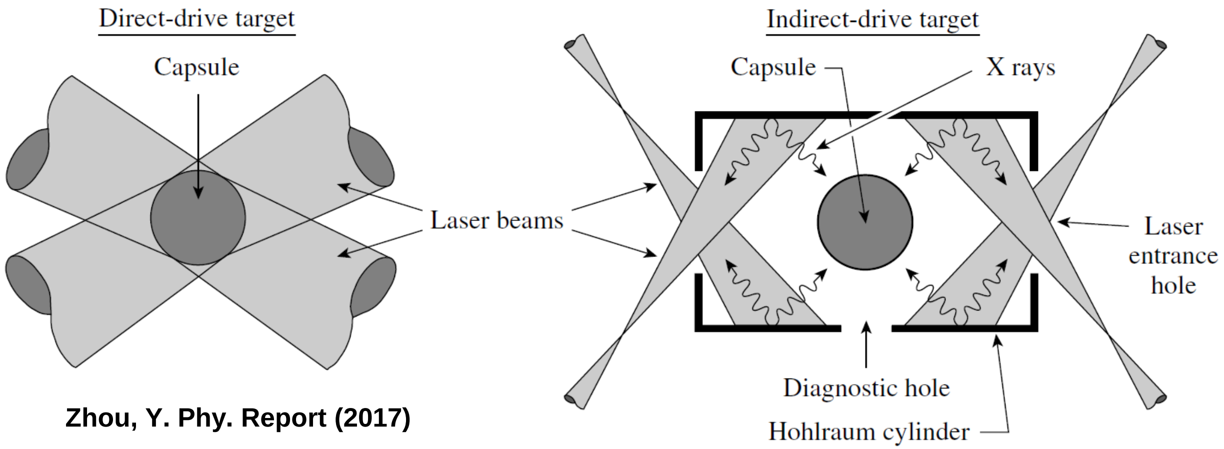
$$M = 8.78$$

$$\frac{\rho_2}{\rho_1} = 3.92$$

Δt = 5 µs. pRad pulse width=200 ns

Slide courtesy of Kathy Prestridge

HED physics uses high power lasers to drive shocks

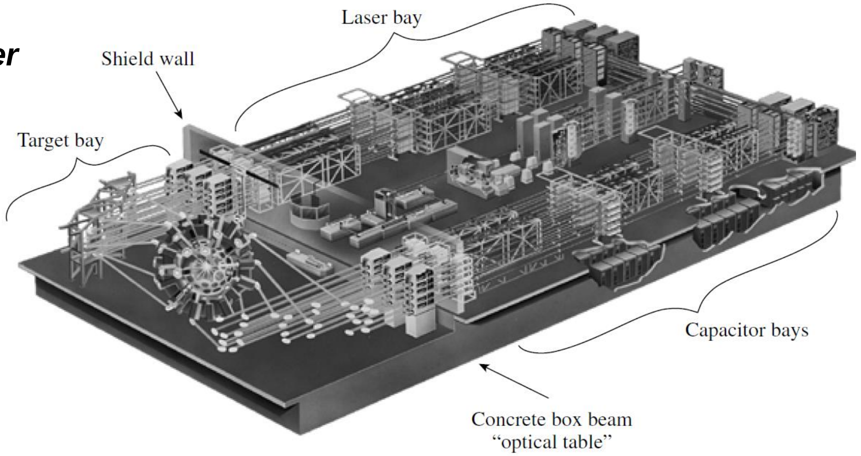


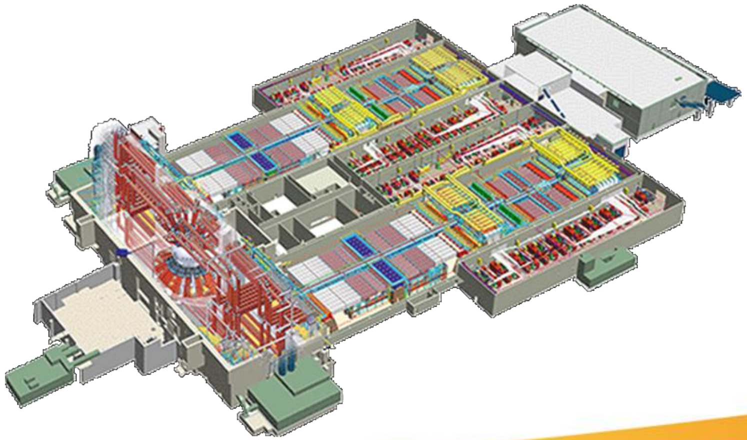
Zhou, Y. Phy. Report (2017)

OMEGA 60 uses direct drive to apply up to 30 kJ in a 1 ns pulse

NIF uses indirect drive with up to 192 laser to apply up to 2 MJ

www.lle.rochester.edu/



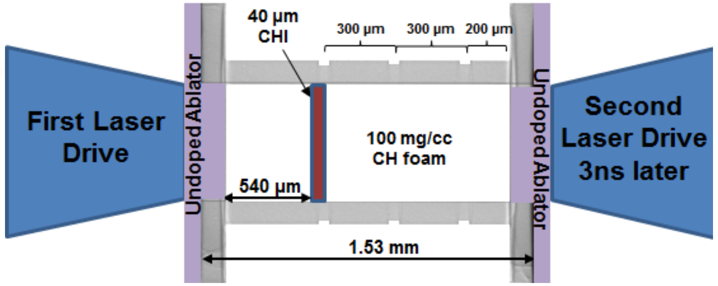


https://lasers.llnl.gov/about/what-is-nif

Mshock is studying the RMI in an HED physics regime

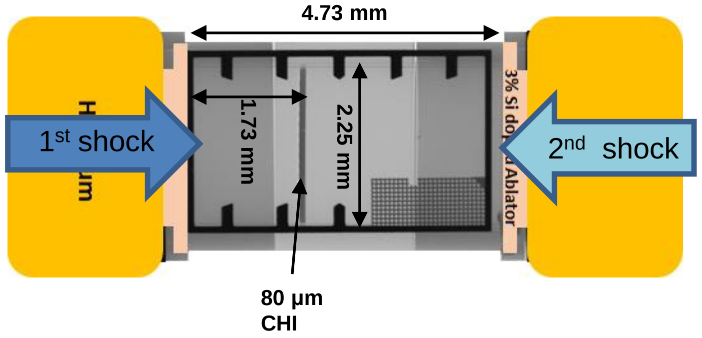
Typical OMEGA Setup

Experiment lasts ~16 ns



Current NIF Setup

Experiment lasts ~30 ns

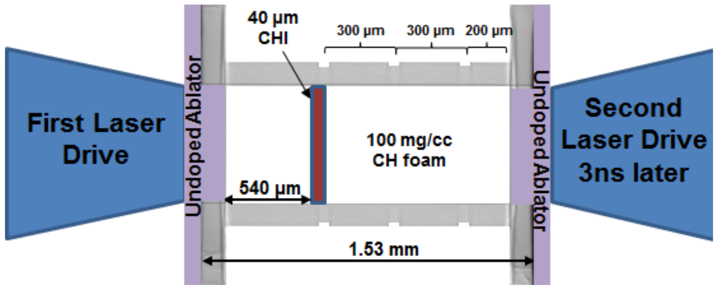


- Shock tube dimensions:
  - OMEGA: 0.5 mm diameter, 1.53 mm length
  - NIF: 2.25 mm, 4.73 mm length
- Driven two separate laser sources
  - High control of timing between shock and re-shock
- Shock speeds:
  - Mach number not well known (~10-20?)
- Shot rate
  - OMEGA:
    - 2-3 days/year,
      - 14 shots per day, 2 images each shot
    - Data low resolution
  - NIF:
    - 2-3 days/year,
      - 2-3 shots per day, 2 images per shot
    - Data high resolution
- Target begins as solid, laser drives turns into plasma

Mshock is studying the RMI in an HED physics regime with two shocks

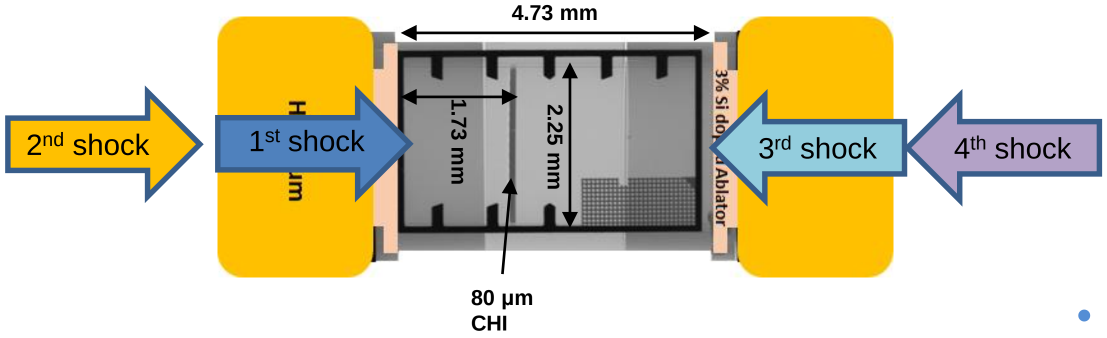
Typical OMEGA Setup

Experiment lasts ~16 ns



Future NIF Setup

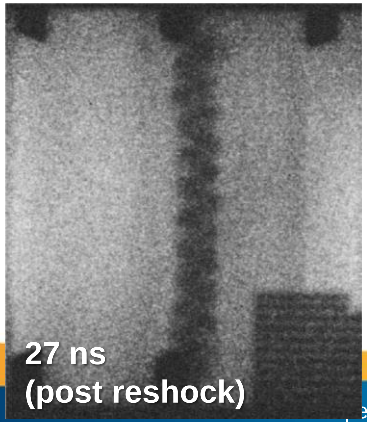
Experiment lasts ~30 ns



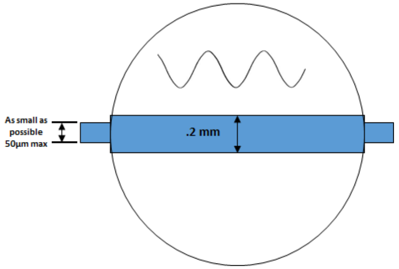
- Shock tube dimensions:
  - OMEGA: 0.5 mm diameter, 1.53 mm length
  - NIF: 2.25 mm, 4.73 mm length
- Driven two separate laser sources
  - High control of timing between shock and re-shock
- Shock speeds:
  - Mach number not well known
- Shot rate
  - OMEGA:
    - 2-3 days/year,
      - 14 shots per day, 2 images each shot
    - Data low resolution
  - NIF:
    - 2-3 days/year,
      - 2-3 shots per day, 2 images per shot
    - Data high resolution
- Target begins as solid, laser drives turns into plasma

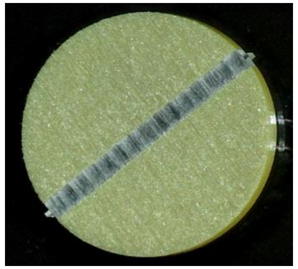
Future NIF setup plans to launch multiple shocks (2 per side) to re-shock growing layer multiple times, which has not been tested or compared with simulations

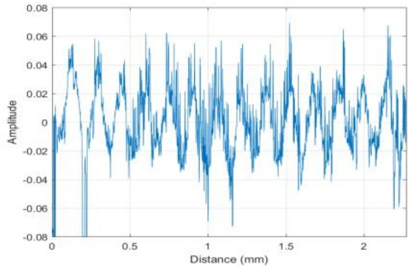
X-ray radiography is used to image the growth from initial conditions that are precision machined onto interface



- X-rays are generated from a laser source interacting with a backlighter material
- Initial conditions are machined onto the interface between low density foams
  - Exact characterization is completed before target completion
  - Can be affected by preheating of the layer

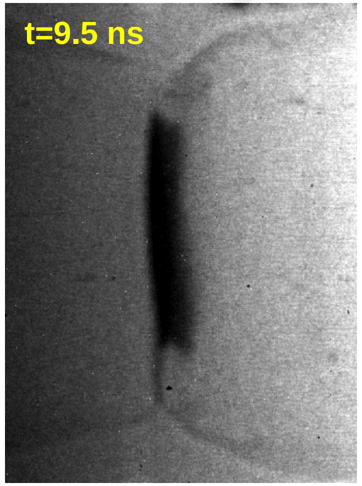


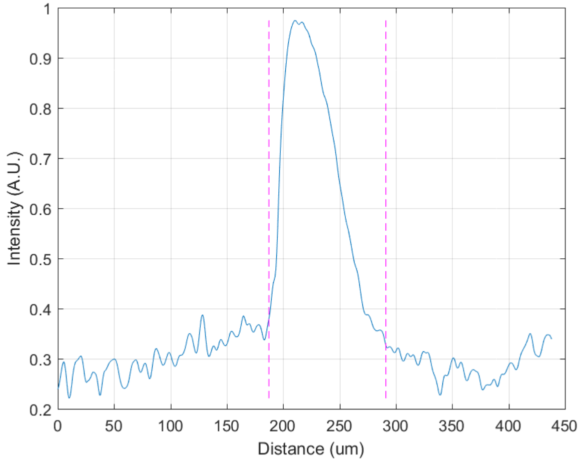




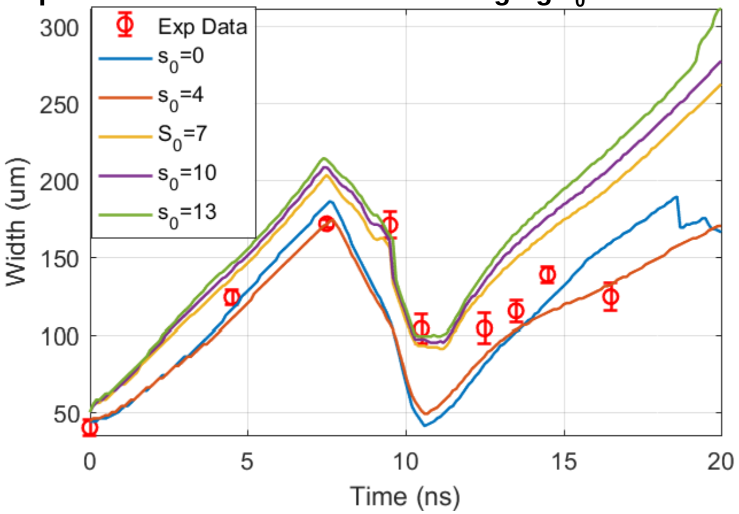
To improve feature resolution we utilize doping profiles to highlight mixing areas

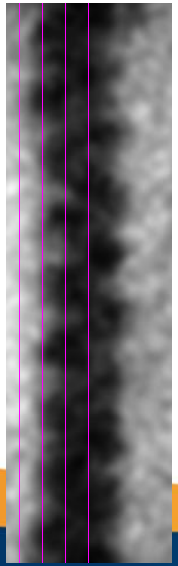
X-ray radiography gives measurements of the mix-width, but may also be able to give measure of the mixedness

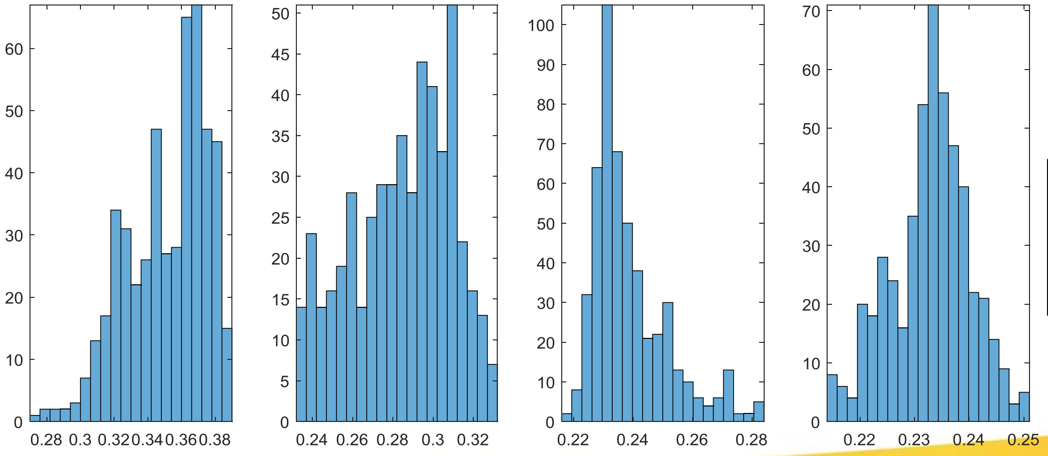




Comparison of simulation results changing s_0 initial condition







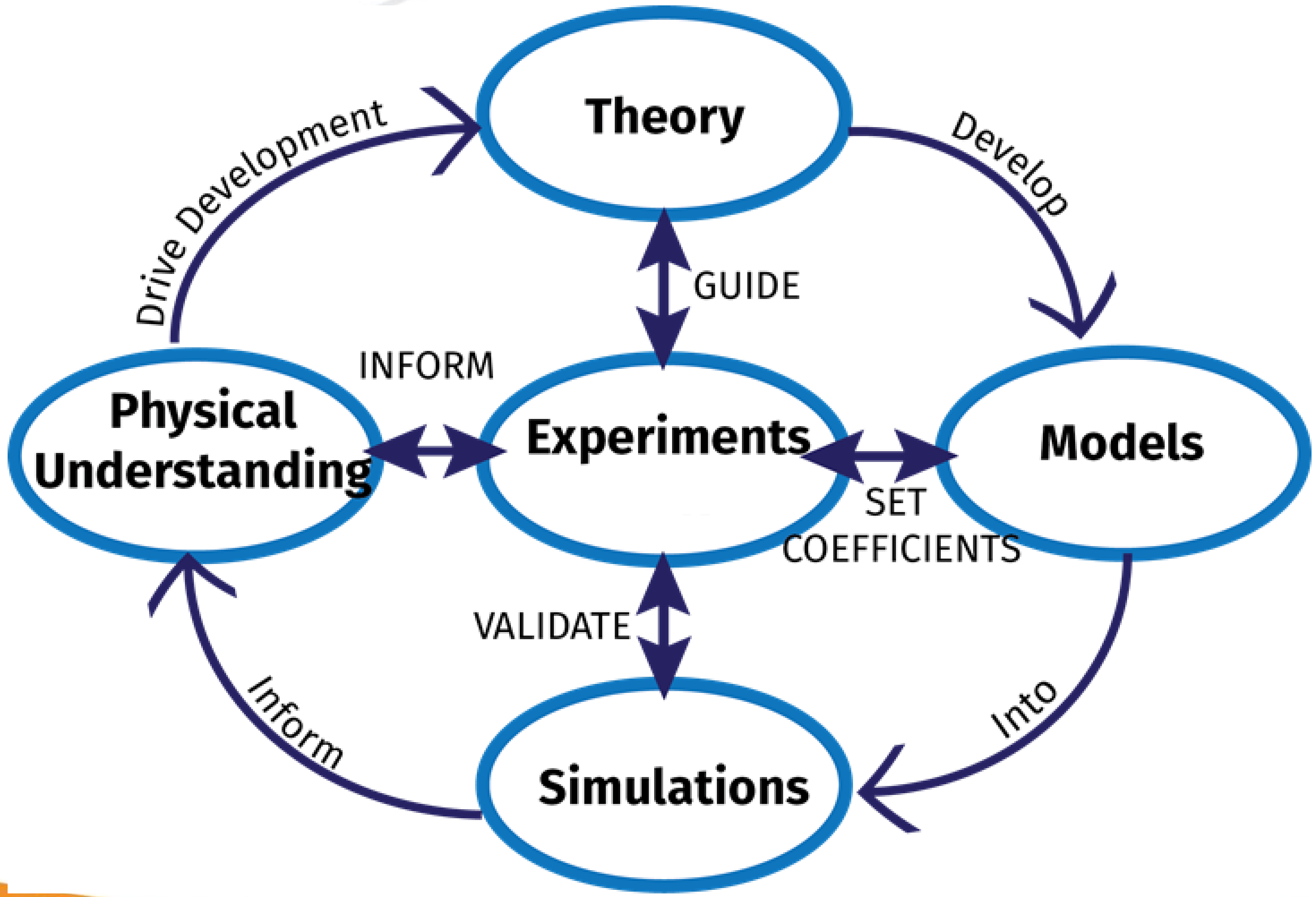
Variance in transmission may relate back to model parameters

These experiments test our understanding of hydrodynamics over a wide parameter range

	VST	pRAD	Mshock
Medium	Gas	Gas	Plasma
Shock tube dimensions	5 mm x 5 mm square 7m height	6 cm diameter 14 cm length	0.5 – 2.25 mm diameter 1.5 – 4.7 mm length
Time scale of experiment	10's of milliseconds	50-60 microseconds	15-30 nanoseconds
Driver	Piston	Powder Gun	Laser
Mach Number	1-2	8-11	~10-20 ?
Atwood Number	0.67	0.99	Variable
Measures	Velocity Field Concentration	Mix width	Mix Width Transmission→ Density?
Initial conditions	Difficult, membranes?	Uses membranes	Easily varied
Number of shocks	1 to 2 (reshock)	1 to 2 (reshock)	Current: 1 to 2 (reshock) Future: 2 to 4

What we actually do with the data

LANL has feedback system for developing fluid codes and mix-models



Using a mix-model simplifies the physics of 3D systems, while allowing additional physics of 1D and 2D systems to study turbulence

LANL has developed the sophisticated BHR mix-model implemented in the RAGE fluid code

Academia → 1970s

2 Eqn model (energy + scale)

Turbulence scale

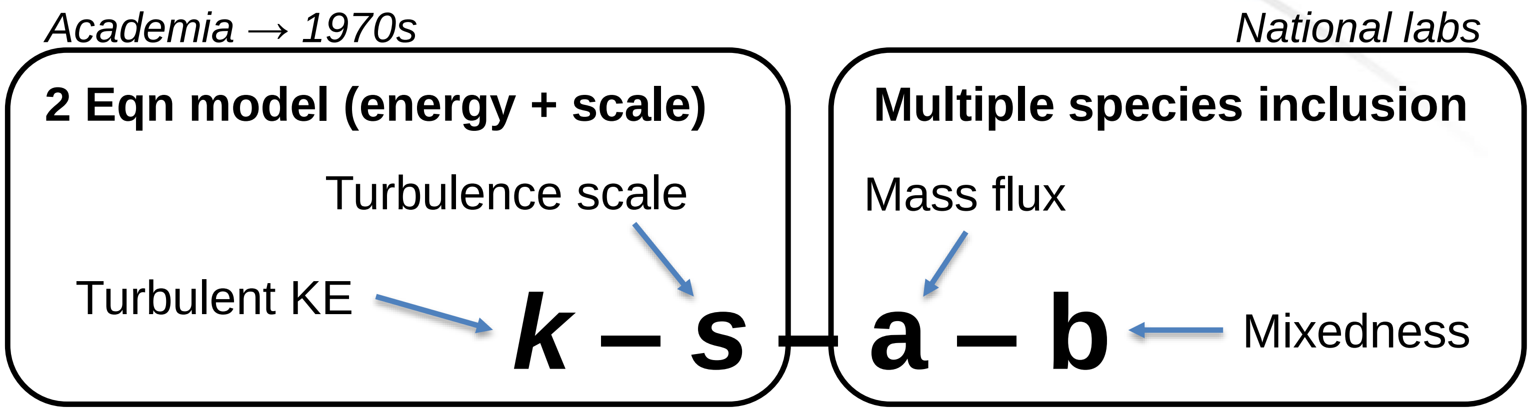
Turbulent KE

$$k - s$$

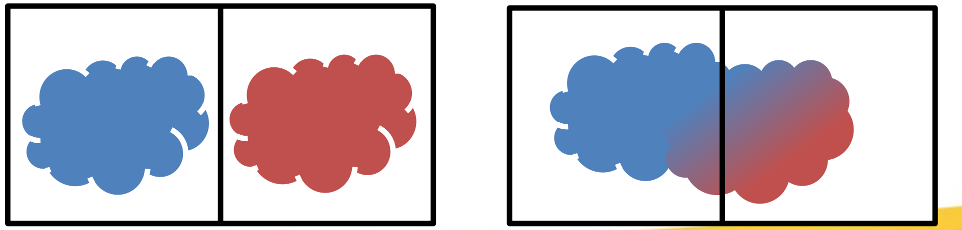
- Academia and industry use two equation model for *single species*
  - ***k*** describes location of energy
  - ***s*** describes size of material

Slide courtesy of Elizabeth Merritt

LANL has developed the sophisticated BHR mix-model implemented in the RAGE fluid code



- Academia and industry use two equation model for single material
  - ***k*** **–** location of energy
  - ***s*** **–** size of turbulence
- National labs have expanded model to include multi-species
  - ***a*** **–** movement of material
  - ***b*** **–** *mixedness*



Slide courtesy of Elizabeth Merritt

LANL has developed the sophisticated BHR mix-model implemented in the RAGE fluid code

Academia → 1970s

2 Eqn model (energy + scale)

Turbulence scale

Turbulent KE

$$\mathbf{k - s}$$

National labs

Multiple species inclusion

Mass flux

$$\mathbf{a - b}$$

Mixedness

BHR initialization parameters

$$k_0 - s_0$$

How do we best initialize the simulation to match experimental initial conditions?

Instability type

KH RT RM

Slide courtesy of Elizabeth Merritt

LANL has developed the sophisticated BHR mix-model implemented in the RAGE fluid code

Academia → 1970s

2 Eqn model (energy + scale)

Turbulence scale

Turbulent KE → $\boldsymbol{k - s}$

National labs

Multiple species inclusion

Mass flux

$\mathbf{a - b}$ ← Mixedness

BHR initialization parameters $k_0 - s_0$ →

How do we best initialize the simulation to match experimental initial conditions?

↓

Current methods require *tuning* parameters to match experimental conditions

Instability type KH RT RM

Slide courtesy of Elizabeth Merritt

LANL has developed the sophisticated BHR mix-model implemented in the RAGE fluid code

Los Alamos NATIONAL LABORATORY EST. 1943

Academia → 1970s

2 Eqn model (energy + scale)

Turbulence scale

Turbulent KE

***k* – s**

National labs

Multiple species inclusion

Mass flux

a – b

Mixedness

BHR initialization parameters

$k_0 - s_0$

Modal model

Instability type: KH, RT, RM

Experiment initial conditions/profiles

initialization parameters

Experiment input → Model input (predictive)

Slide courtesy of Elizabeth Merritt

LANL has developed the sophisticated BHR mix-model implemented in the RAGE fluid code

Los Alamos NATIONAL LABORATORY EST. 1943

BHR[3.1] evolves full Reynold's stress model

Turbulent kinetic energy

$$\frac{\partial(\bar{\rho}\tilde{R}_{ij})}{\partial t} + (\bar{\rho}\tilde{u}_k\tilde{R}_{ij})_{,k} = \overbrace{[a_i\bar{P}_{,j} + a_j\bar{P}_{,i}] - \bar{\rho}\left[\tilde{R}_{ik}\tilde{u}_{j,k} + \tilde{R}_{jk}\tilde{u}_{i,k}\right]}^{\text{Production}}$$
$$+ \underbrace{C_r\left(\frac{S}{\sqrt{K}}\bar{\rho}\tilde{R}_{kn}\tilde{R}_{ij,n}\right)_{,k}}_{\text{Diffusion}} - \underbrace{C_{r3}\bar{\rho}\frac{\sqrt{K}}{S}\left(\tilde{R}_{ij} - \frac{1}{3}\tilde{R}_{kk}\delta_{ij}\right)}_{\text{Return to Isotropy}}$$
$$- \overbrace{C_{r1}[a_i\bar{P}_{,j} + a_j\bar{P}_{,i}] + C_{r2}\bar{\rho}\left[\tilde{R}_{ik}\tilde{u}_{j,k} + \tilde{R}_{jk}\tilde{u}_{i,k}\right]}^{\text{Rapid Distortion}}$$
$$- \underbrace{C_{r2}\frac{2}{3}\bar{\rho}\tilde{R}_{mk}\tilde{u}_{m,k}\delta_{ij} + C_{r1}\frac{2}{3}a_k\bar{P}_{,k}\delta_{ij}}_{\text{Rapid Distortion}} - \underbrace{\bar{\rho}\frac{2}{3}\frac{K\sqrt{K}}{S}\delta_{ij}}_{\text{Dissipation}},$$

Turbulence scale

$$\frac{(\bar{\rho}S)}{\partial t} + (\bar{\rho}\tilde{u}_jS)_{,j} = \underbrace{-\frac{S}{K}\left(\frac{3}{2} - C_1\right)\bar{\rho}\tilde{R}_{ij}\tilde{u}_{i,j} + \frac{S}{K}\left(\frac{3}{2} - C_3\right)a_j\bar{P}_{,j} - \left(\frac{3}{2} - C_2\right)\bar{\rho}\sqrt{K}}_{\text{Net Production}} + \underbrace{C_s\left(\frac{S}{\sqrt{K}}\bar{\rho}\tilde{R}_{kn}S_{,n}\right)_{,k}}_{\text{Diffusion}}$$

Mass flux

$$\frac{\partial(\bar{\rho}a_i)}{\partial t} + (\bar{\rho}\tilde{u}_ka_i)_k = \underbrace{b\bar{P}_{,i} - \tilde{R}_{ik}\bar{\rho}_{,k} - \bar{\rho}a_k\tilde{u}_{i,k}}_{\text{Net Production}} + \underbrace{\bar{\rho}(a_ka_i)_{,k}}_{\text{Redistribution}} + \underbrace{\bar{\rho}C_a\left(\frac{S}{\sqrt{K}}\tilde{R}_{kn}a_{i,n}\right)_{,k}}_{\text{Diffusion}} - \underbrace{C_{a1}\bar{\rho}\frac{\sqrt{K}}{S}a_i}_{\text{Destruction}}$$

Mixedness

$$\frac{\partial(\bar{\rho}b)}{\partial t} + (\bar{\rho}b\tilde{u}_k)_{,k} = -\underbrace{2(b+1)a_k\bar{\rho}_{,k}}_{\text{Production}} + \underbrace{2\bar{\rho}a_kb_{,k}}_{\text{Redistribution}} + \underbrace{\bar{\rho}^2C_b\left(\frac{S}{\bar{\rho}\sqrt{K}}\tilde{R}_{mn}b_{,n}\right)_{,m}}_{\text{Diffusion}} - \underbrace{C_{b1}\bar{\rho}\frac{\sqrt{K}}{S}b}_{\text{Destruction}}$$

Besnard, Harlow, Rauenzahn "Conservation and transport properties of turbulence with large density variations LA-10911-MS

Schwarzkopf et al. *JoT* (2011), *Flow Turb. Comb* (2016)

NNSA National Nuclear Security Administration

Summary: LANL is in a unique position to perform scaled hydrodynamic experiments

- Fluid, HED and shock physics are important for:
  - understanding astrophysical phenomena and ICF
  - furthering our understanding of hydrodynamics
- There are multiple hydrodynamics experiments at LANL to investigate similar physics
  - Vertical Shock Tube
  - pRad
  - P-24 work at OMEGA and NIF
  - Horizontal shock tube (see talk by Ankur Bordoloi on June 20th)
- Future work will focus on:
  - generating scaled experiments
  - Comparisons with BHR
  - Comparisons with modal model

Thank you!