Deconstructing Integrated High Energy Density Physics Experiments into Fundamental Models for Validation

Los Alamos
NATIONAL LABORATORY
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MIPSE seminar
Ann Arbor, MI

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Goals for the talk

- **Communicate the excitement of big science**
  - What are some of the big questions?
- **Advertise the LANL ICF/HED program, i.e. recruitment**
- **Provide a strategic program view for the work and how we use the data**

This work represents a large group of people across multiple programs!

One focus of LANL's high energy density physics effort is mix and burn during the stagnation phase of ICF implosions

- Inertial Confinement Fusion is a grand challenge in big science requiring a large mix of skills that includes participants both nationally and internationally
- While considerable progress has been made towards ignition, challenges remain which require improved implosion performance or larger capsules
- The largest looming questions are, “Is ignition on NIF possible?” and “What is required to achieve ignition?”
- LANL is strategically focuses on the understanding the evolution of hydrodynamics and burn physics for implosions using novel platforms and focused experiments for code validation
- The program looks to bring in capabilities that can improve our ability to quantify and validate our understanding

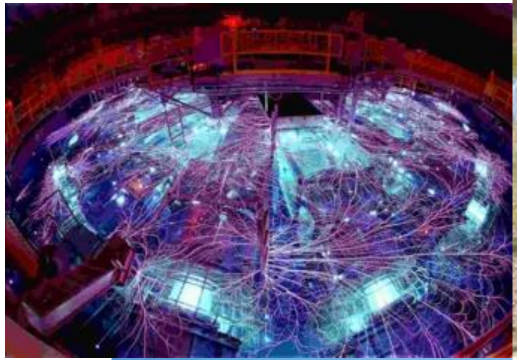
Big science requires large cutting edge facilities, a diverse work force, and large budgets

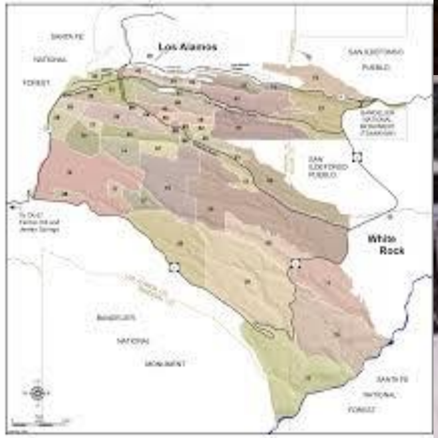
- ***Big staffs*: Grand challenges require cutting edge technology and a large diverse workforce to solve a collection or problems including scientists, engineers, technicians, and skilled crafts.

- ***Big machines*: Generating extreme conditions requires enormous energy or spatial scales to reach such conditions such as large pulsed power storage or long path length for particle acceleration

- ***Big laboratories*: Supporting activities with respect to R&D and specialized production drive the need for large laboratories.

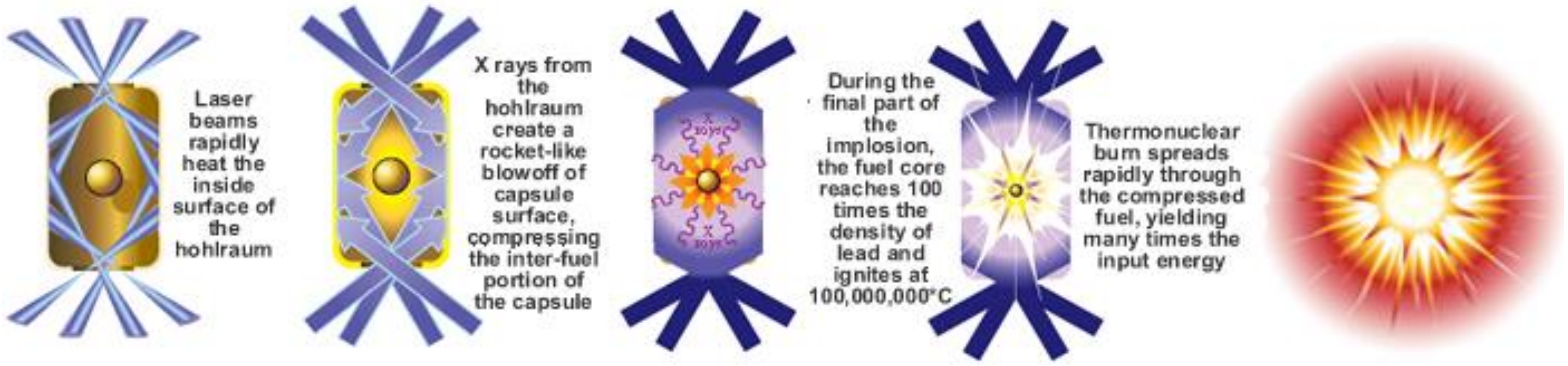
- ***Big budgets*: The combination of the requirements to achieve grand challenges leads to large budgets





Academic and industrial partners provide vital cost effective support

Indirect Drive Inertial Confinement Fusion converts laser light to x rays using high-Z material driving a Deuterium-Tritium filled capsule to fusion conditions



Many pieces of physics and engineering must come together to achieve ICF

Hohlraum

Peak laser Intensities

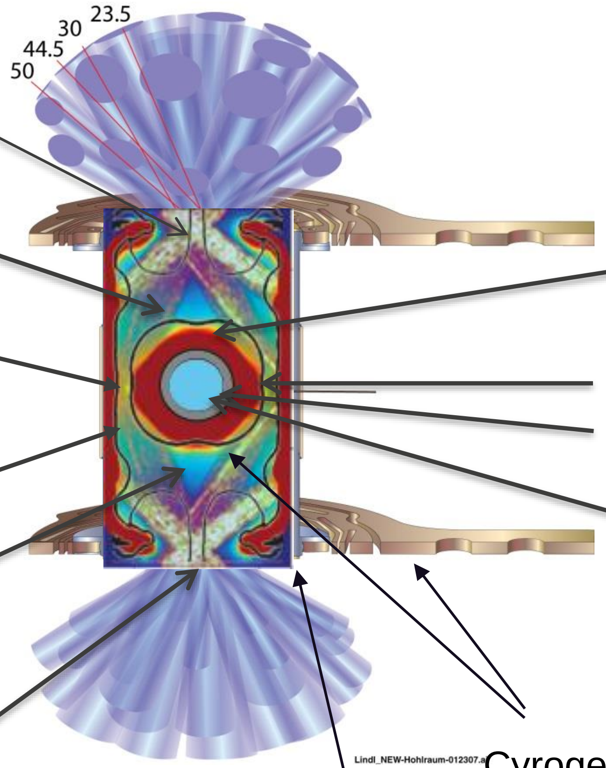
Gas fill species and optimum density

compressed between wall and ablator blowoff (SRS)

Be ablator blowoff (SBS)

Hot Electrons

Cross beam energy transfer



Hydrodynamic Instabilities

Tent/ fill tube defect hydro

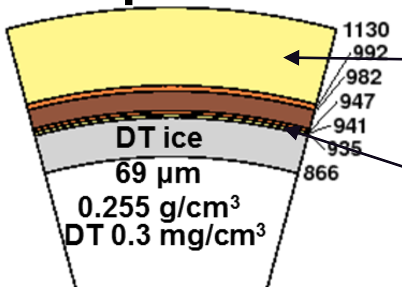
implosion symmetry

Fuel Adiabat

Cyrogenics

Precision Engineering

Capsule

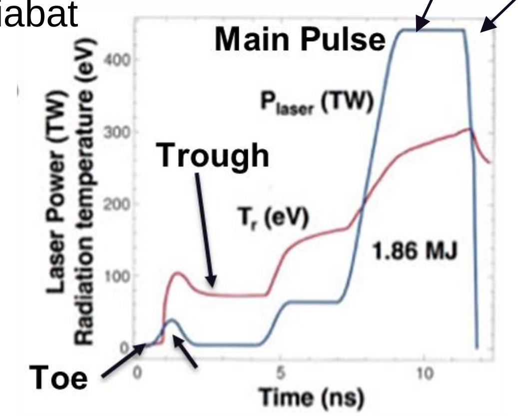


Material Science
EOS/Opacity

Manufacturing

Laser pulse shaping

Power balance



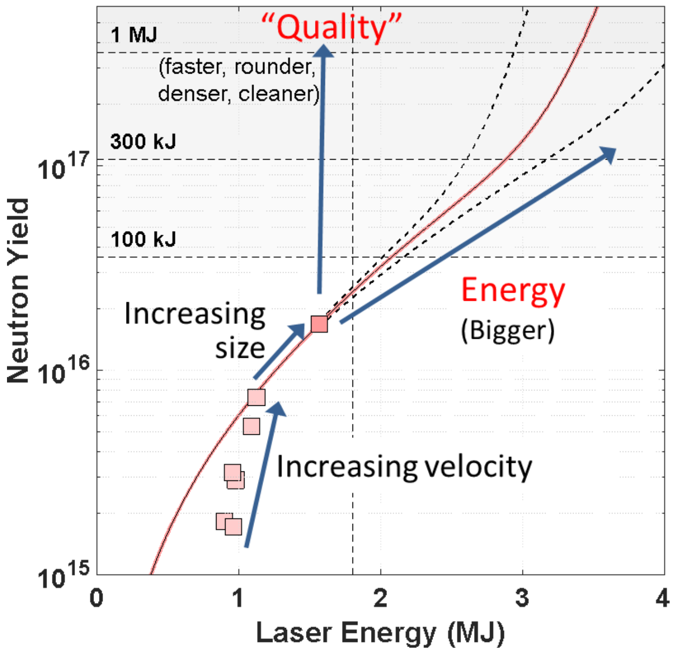
Adiabat:
α = DT ice internal energy/ Fermi energy @ 1000 g/cc

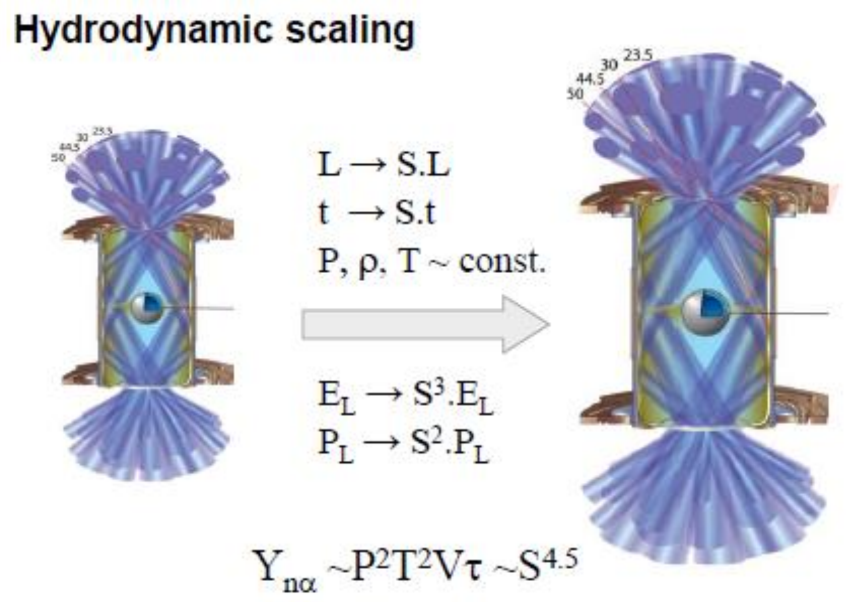
Diagnostics
Computation

A large pool of expertise is critical for advancing ICF

What will it take to achieve ignition in the laboratory? Can this be done with NIF?

Can we credibly scale to ignition?





Not all physics scales linearly with size:

- Radiation
- Heat conduction
- LPI
- Instability seeds/Richtmyer-Meshkov

No alpha

$$Yield \sim \textbf{Scale}^{4.5} \times \underbrace{P_{Ablation}^{4/5}\ \frac{Velocity^8}{Adiabat^2}}_{1D} \times \underbrace{[Mix < 1]\ [Shape < 1]}_{3D}$$

How well do we understand the physics for current targets?

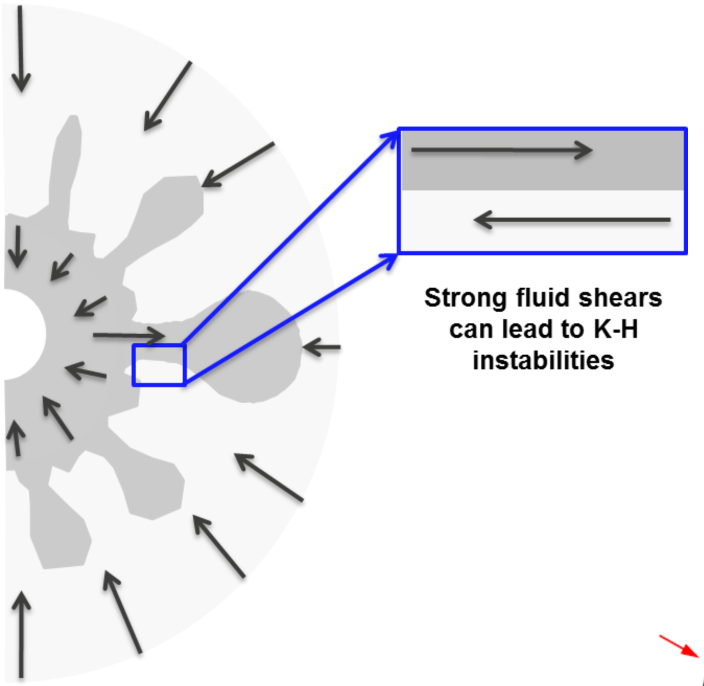
How do we build credibility for our scaling predictions?

There are several guidelines that need to be true to trust our predictions:

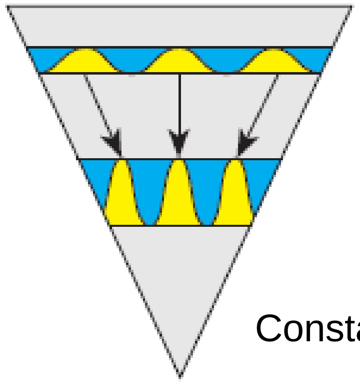
- the calibration and validation of the embedded models is sufficient to give confidence in the prediction;
- the embedded models are being used within their domain of applicability;
- the resulting prediction with its uncertainties is sufficient for the purpose for which the prediction is being made

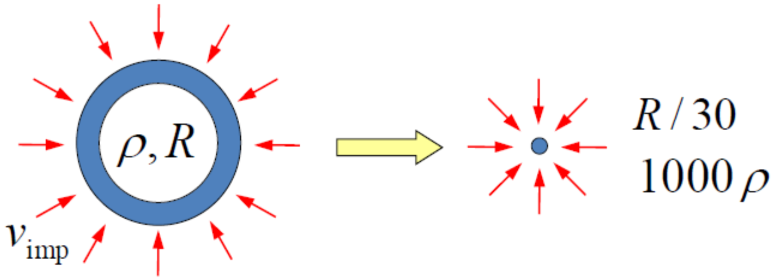
ICF implosions are inherently hydrodynamically unstable!

- **Different target layer densities**
  - Rayleigh-Taylor
- **Strong Shear flows**
  - Kelvin-Helmoltz
- **Multiple shocks**
  - Richtmyer-Meshkov
- **Models for burn in the presence of mix**
  - burn model



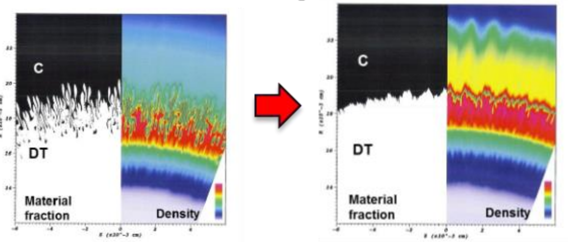
Convergence Amplified perturbations





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

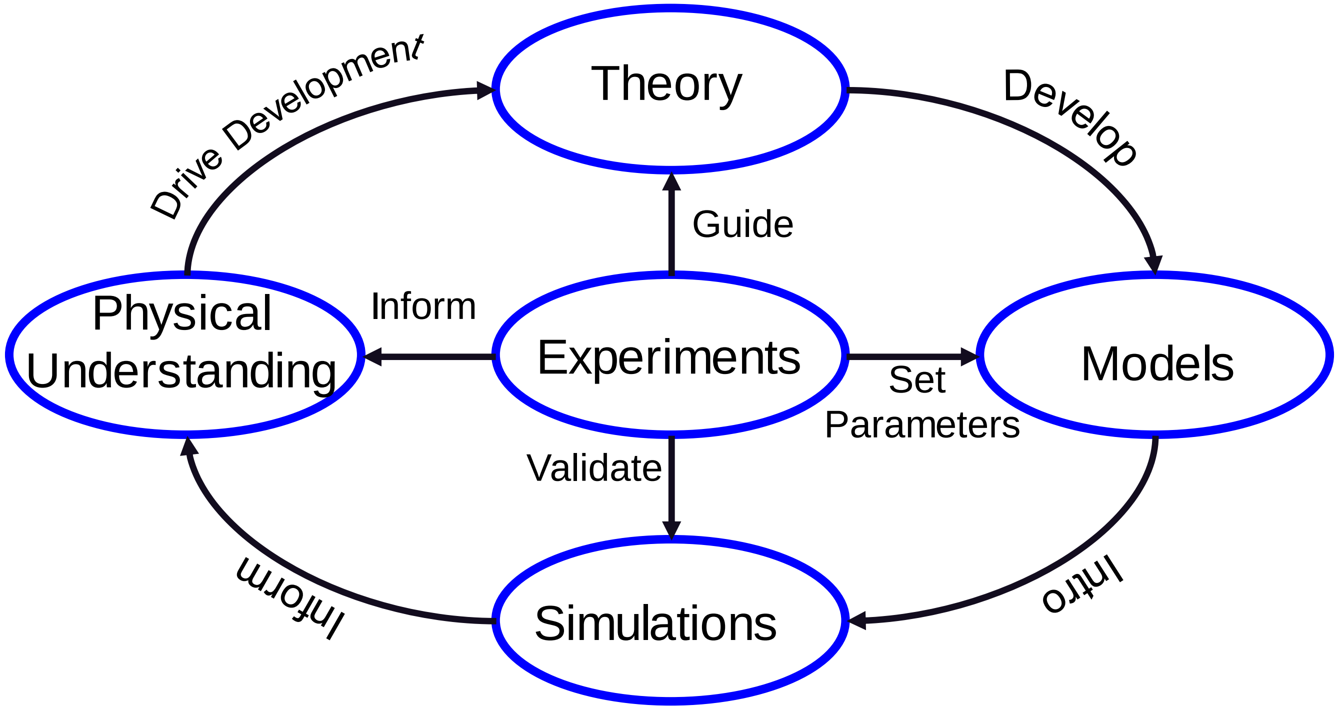
Interface mixing can affect compression



burn fraction

$$f = 1 - \frac{n_{\text{final}}}{n_{\text{init}}} = \frac{\rho R}{\rho R + 8 m_i c_s / \langle \sigma v \rangle} \cong \frac{\rho R}{\rho R + 6\ \text{g/cm}^2}, \quad T_i = 30\ \text{keV}$$

Advancing our predictive capability requires strong partnerships between theory, computation, and experiment



Experiments:

- Discover
- Validate
- Calibrate

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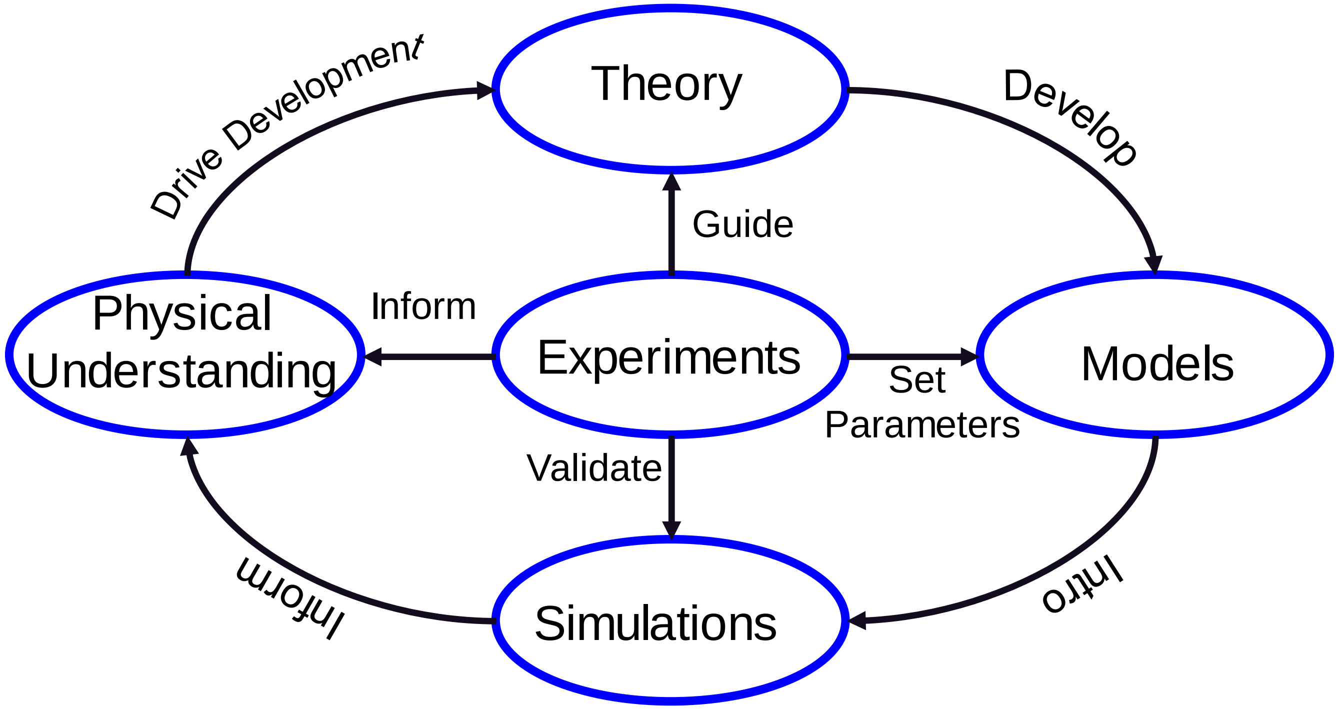


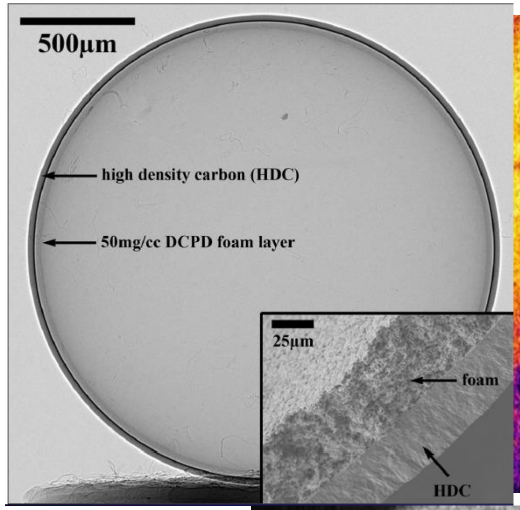
Experiments:
- Discover
- Validate
- Calibrate

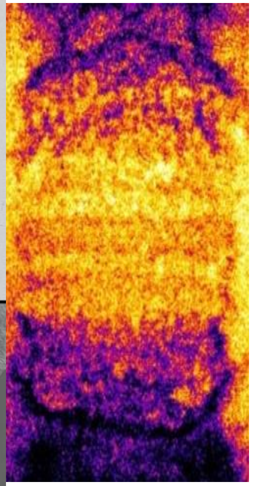
It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with *experiment*, it's wrong. --Richard Feynman

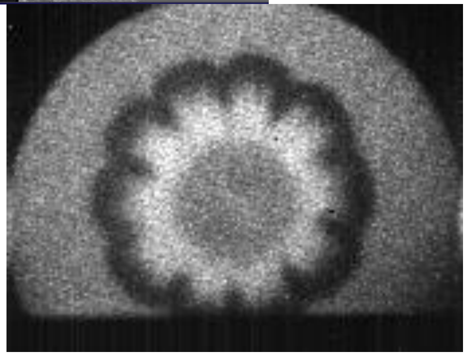
A principle focus of LANL HEDP program is mix and burning plasmas to validate models for ICF implosions

This is accomplished using three threads:

- **Novel implosion platforms to inform performance**
  - Reduced convergence wetted foam targets
  - Double Shell targets
- **Focused experiments for validation**
  - Hydrodynamic mix
    - *Shear driven hydrodynamic instabilities*
    - *Mod Con*
    - *Oblique shock*
    - *Cylinder*
  - Burn model
    - **PDF burn model**
  - Non-hydrodynamic
    - **Kinetic Plasma Effects**
- **Burning Plasma Diagnostics**
  - Neutron imaging, Reaction History, Radio-Chemistry
- **Developing UQ tools**
  - Bayesian Inference Engine

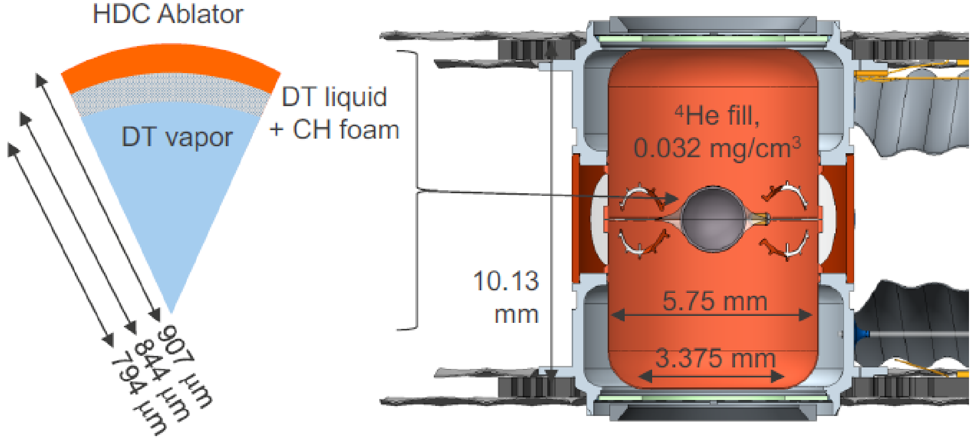






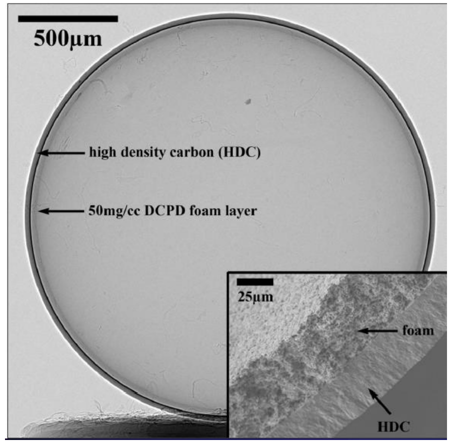
LANL developed a novel implosion platform to provide insight into the effect of convergence on performance

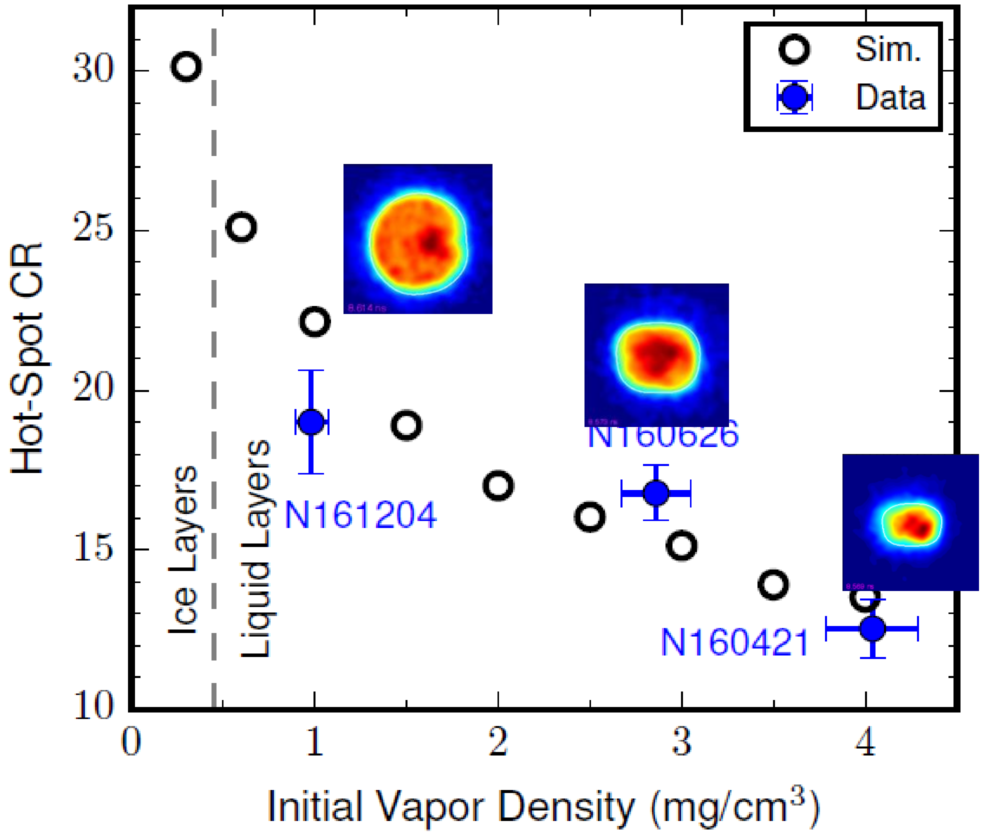
CH foam-lined HDC capsule | **Au near-vacuum hohlraum**



DT liquid = 0.22 g/cm^3
CH foam = 0.035 g/cm^3
DT vapor = 0.6 – 4.0 mg/cm^3

T_{cryo} = 20 – 26 °K



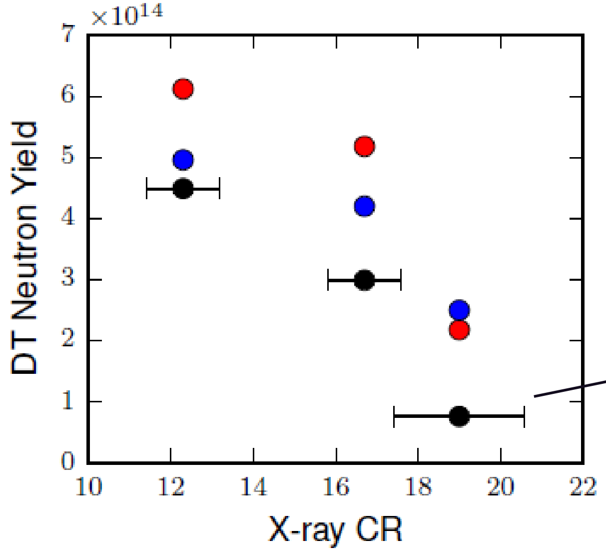


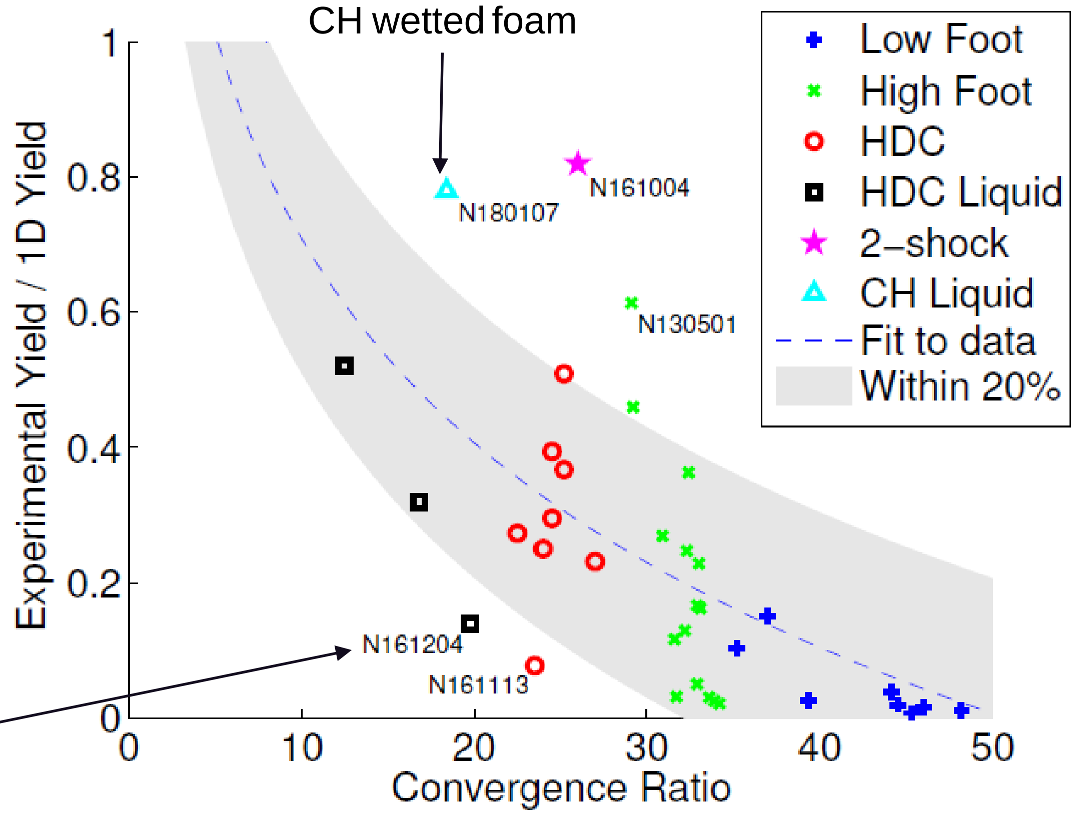
R. E. Olson *et al.* Phys. Rev. Lett. 117, 245001 (2016)
A. B. Zylstra *et al.* Physics of Plasmas 25 056304 (2018)

Convergence adjusted through changes only to target fielding temperature

A comprehensive look at ICF DT layered implosion data shows performance degradation with respect to convergence

- 1D simulations quantify idealized capsule performance with no impact of asymmetries
- Convergence ratio is one important factor impacting implosion stability





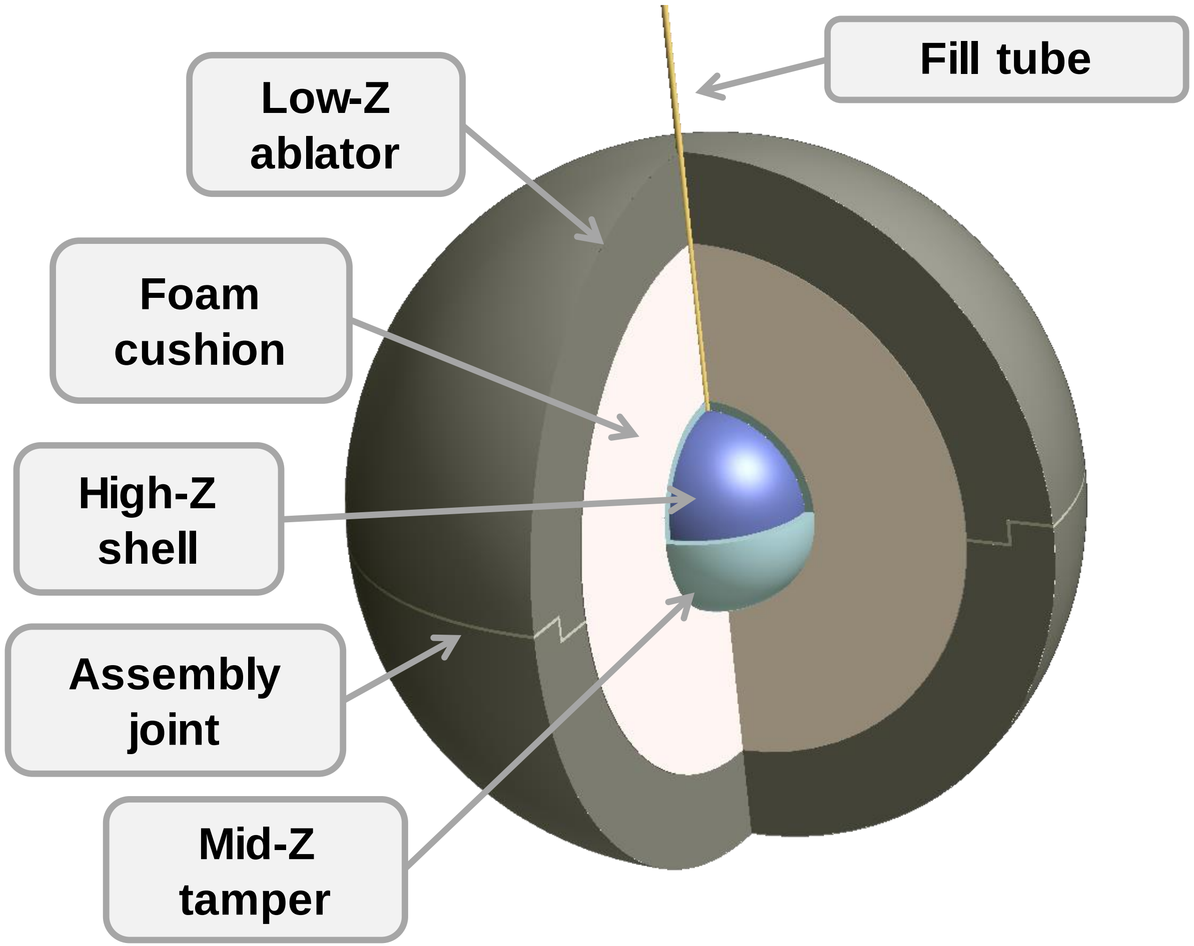
Thanks to S. MacLaren & P. Patel for ice layer data

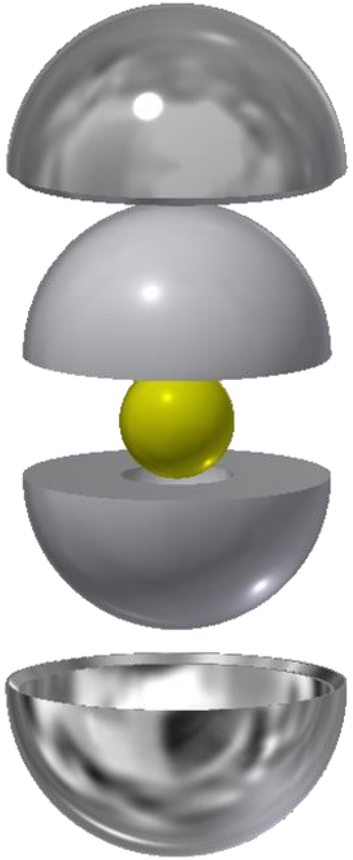
Low Foot: Landen et al., PoP 18:051002, 2011; High Foot: Park et al., PRL 112:055001, 2014; HDC: Le Pape et al., PRL 2018; HDC Liquid: Zylstra et al., PoP 25:056304, 2018; 2-shock: MacLaren et al., PoP 25:056311, 2018; CH Liquid: Haines et al., submitted, 2018

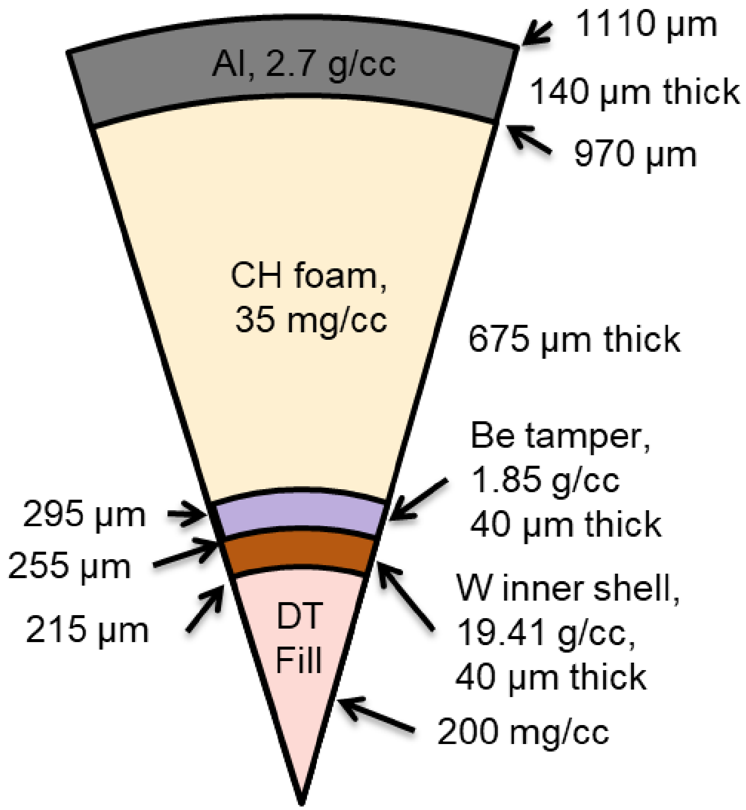
B. Haines, et al submitted to PoP (2018)

Convergence amplifies perturbations!

Double-Shells provide a low fuel convergence implosion option



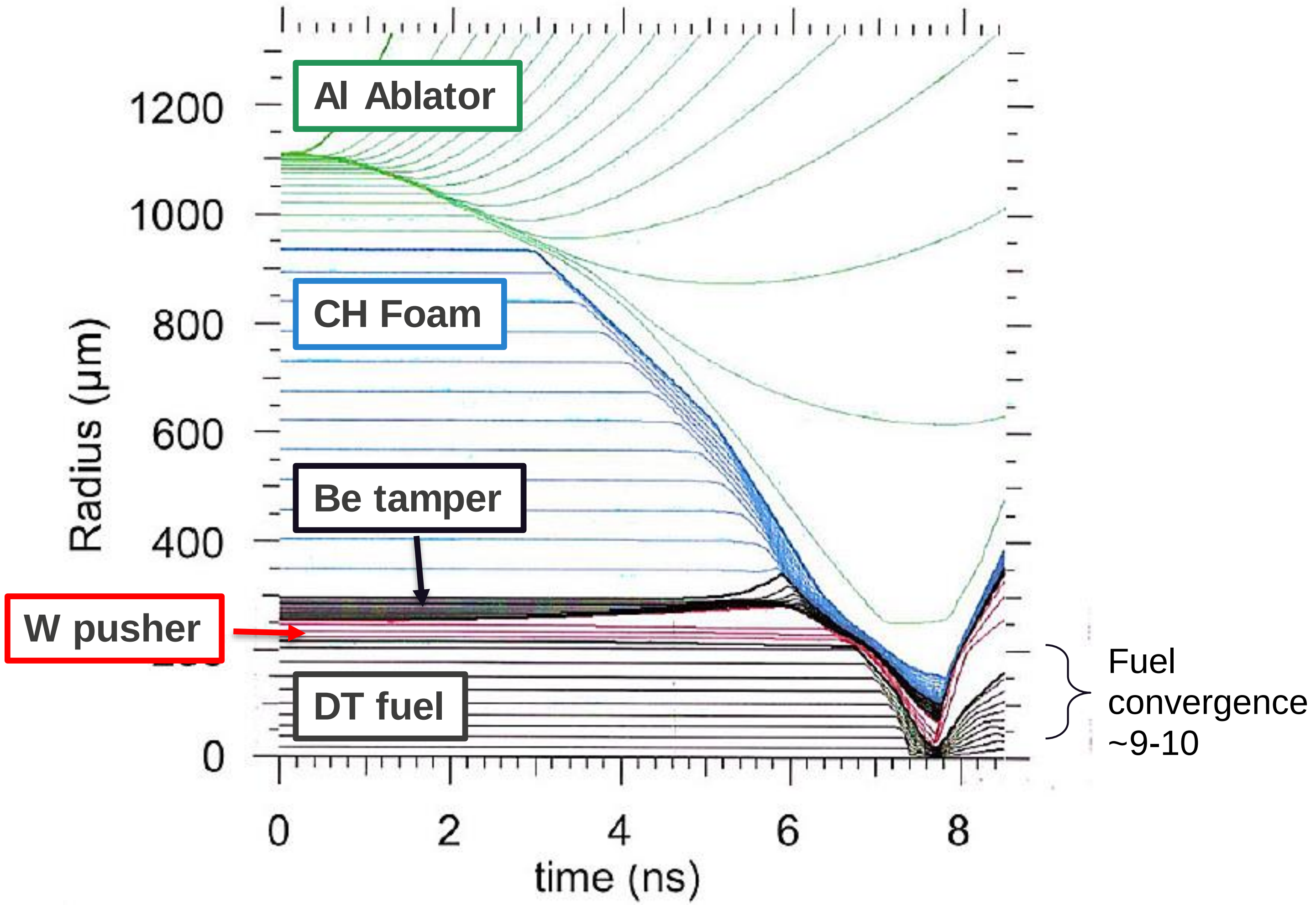




The Double-Shell capsule design trades “convergence” for engineering

Montgomery *et al.*, *Phys. Plasmas* (2018)

Can we characterize Double-Shells well enough to inform our mix and burn models for ICF implosions?



- High-Z pusher (inner shell) has higher initial ρR, so it need less compression to achieve necessary kinetic energy $\frac{1}{2}\rho v^2$
- This leads to several benefits of a high-z pusher:
  - *Lower fuel convergence/compression*
  - *Radiation Trapping*
  - *Reduced Implosion speed*
  - *Lower Ignition temperature*
- Trade-off is engineering challenges
- Open question is whether or not the inner shell converge is not affected by outer shell parameters

The Double-Shell capsule design is an alternative and complimentary approach to reaching burn

Montgomery *et al.*, *Phys. Plasmas* (2018)

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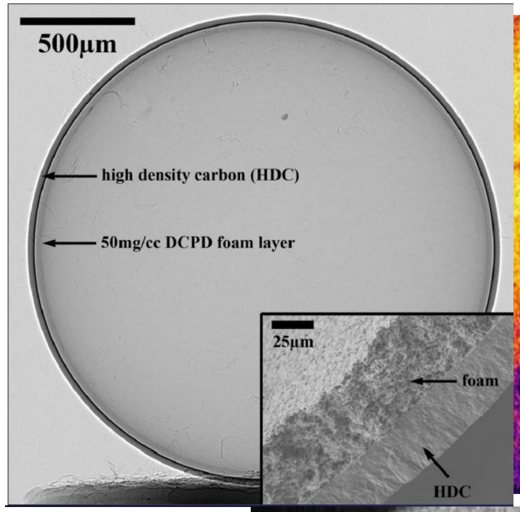
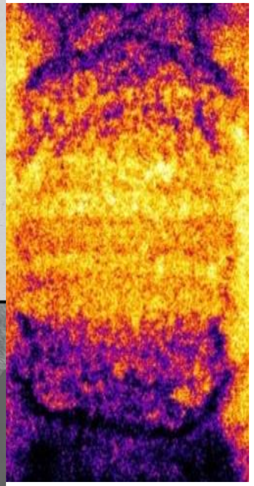
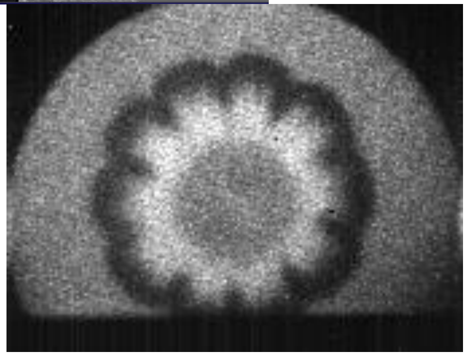
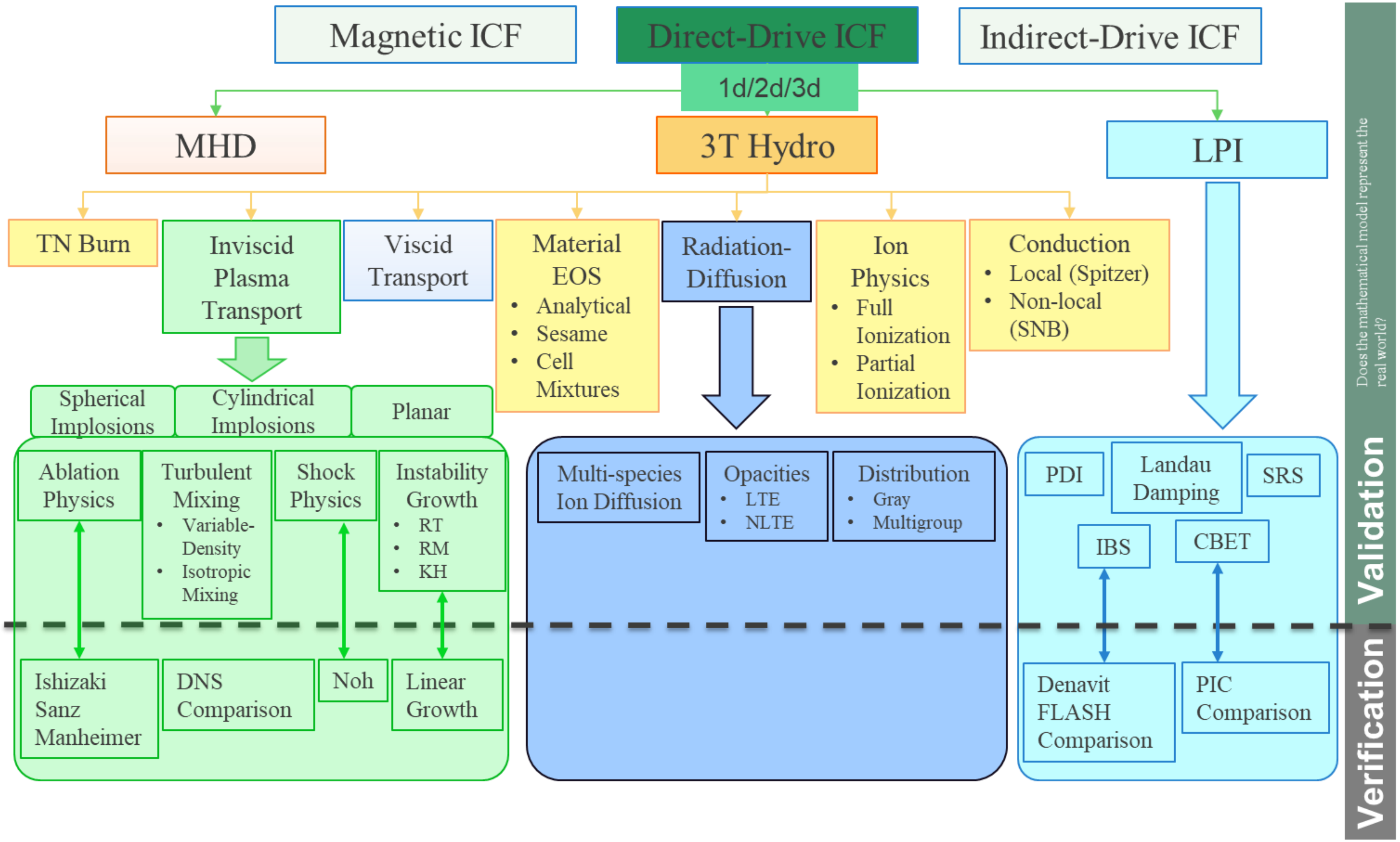


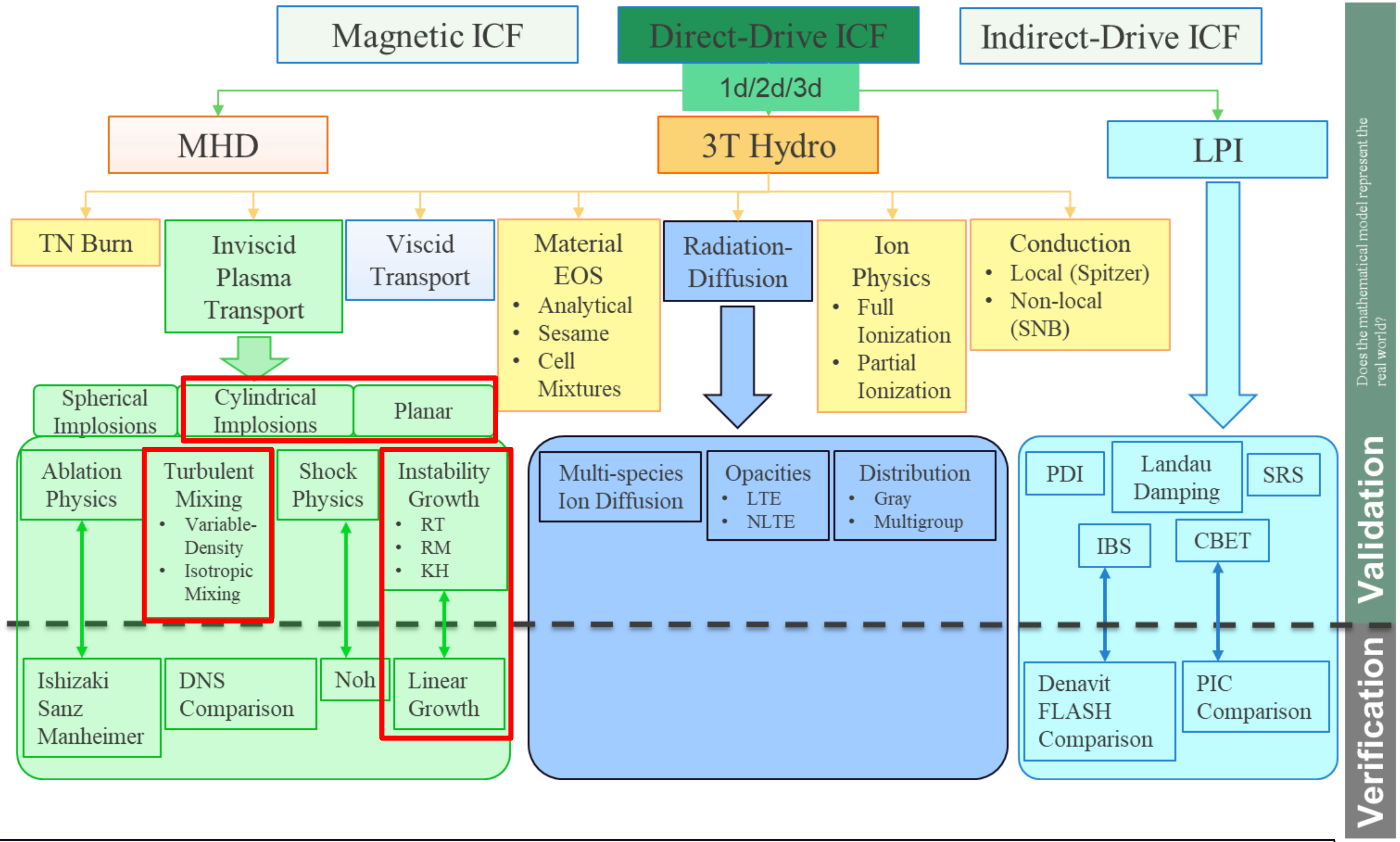




The simulations codes have a complex interplay of physics models



Our mix and burn experiments are designed to validate models in our codes



Validation requires a suite of data covering a range of conditions

Our HEDP experiments are focused on validating the LANL four equation turbulent mix model BHR used in our ICF simulations

k **Turbulent kinetic energy**

$$\frac{D\rho k}{Dt} = a_i \frac{\partial P}{\partial x_i} - R_{ij}\frac{\partial u_i}{\partial x_j} - \rho \frac{k^{3/2}}{s} + \text{diffusion}$$

s **Turbulence scale**

$$\frac{D\rho s}{Dt} = \frac{s}{k}\left[\left(\frac{3}{2} - c_4\right) a_i \frac{\partial P}{\partial x_i} - \left(\frac{3}{2} - c_1\right) R_{ij}\frac{\partial u_i}{\partial x_j}\right]$$

$$-c_3 \rho s \frac{\partial u_i}{\partial x_i} - \left(\frac{3}{2} - c_2\right)\rho k^{1/2} + \text{diffusion}$$

a **Mass flux**

$$\frac{D\rho a_i}{Dt} = b\frac{\partial P}{\partial x_i} - \frac{R_{ij}}{\rho}\frac{\partial \rho}{\partial x_j} - c_a \rho a_i \frac{k^{1/2}}{s} + \text{diffusion}$$

b **Mixedness**

$$\frac{D\rho b}{Dt} = 2\rho a_i \frac{\partial b}{\partial x_i} - 2(b+1)a_i\frac{\partial \rho}{\partial x_i} - c_b \rho b \frac{k^{1/2}}{s} + \text{diffusion}$$

Relevant Terms and Coefficients

- **Reshock**
- **Shear**
- **Compression**

A focus of our HED hydro-instability program is to test the BHR mix model by examining its performance in the HED regime

Academia → 1970s for fluid flows

National labs

2 Eqn model (energy + scale)

Turbulence scale

Turbulent KE

Multiple species inclusion

Mass flux

Mixedness

$$\boldsymbol{k - s - a - b}$$

BHR initialization parameters

$$k_0 - s_0$$

Modal model

Instability type KH RT RM

Experiment initial conditions/profiles

initialization parameters

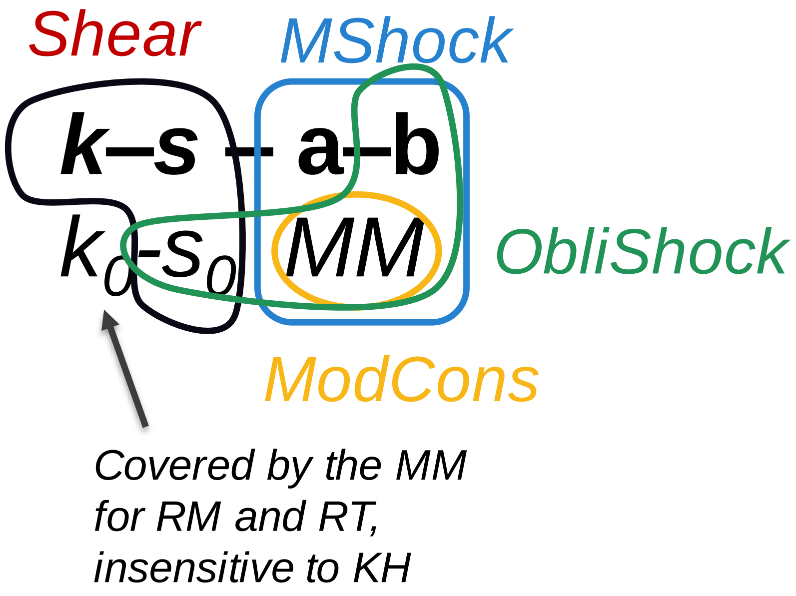
Experiment input → Model input (predictive)

Tuning

Experiment output → Model input (not predictive)

Our suite of HED hydro-instability projects form a complementary coverage of the parameters of the BHR mix

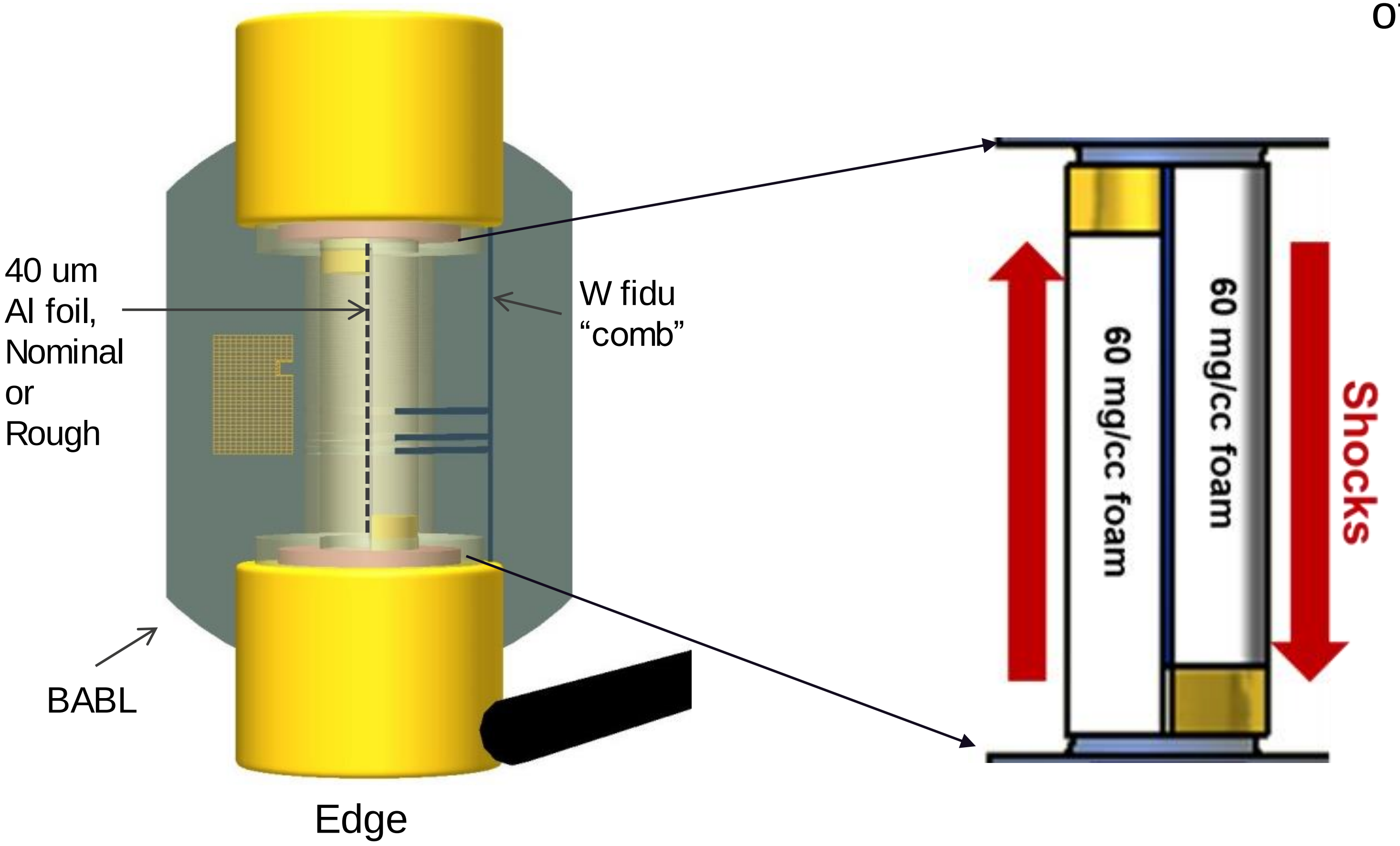
- Counter-propagating Shear (Shear)
  - *Kelvin-Helmholtz (KH) instability*
  - *Atwood numbers*
  - *Surface perturbations*
- Multi-Shock (Mshock)
  - *Richtmyer-Meshkov (RM) instability*
  - *Thin layer feed-through*
  - *Multi-directional shock effects*
- Modal Initial Conditions (ModCons)
  - *RM and Rayleigh-Taylor (RT) instability*
  - *Early-time evolution*
- Oblique Shock (ObliShock)
  - *Mixed KH & RM & RT*
- Cylinders
  - *Introduces convergence effects on above*

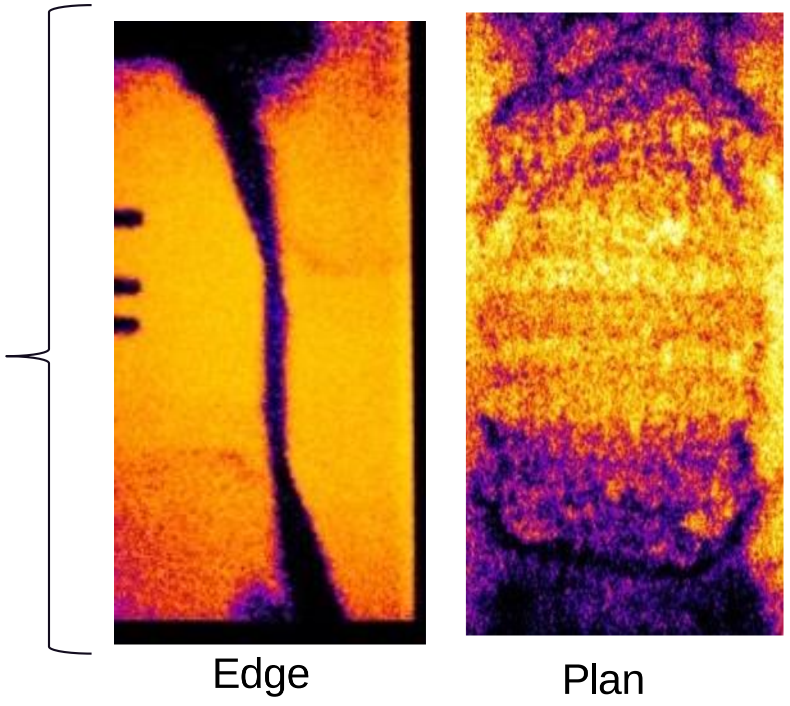


We have developed a counter-propagating shear platform to investigate multi-mode Kelvin-Helmholtz instabilities and the transition to turbulence

Radiation driven shock tube platform

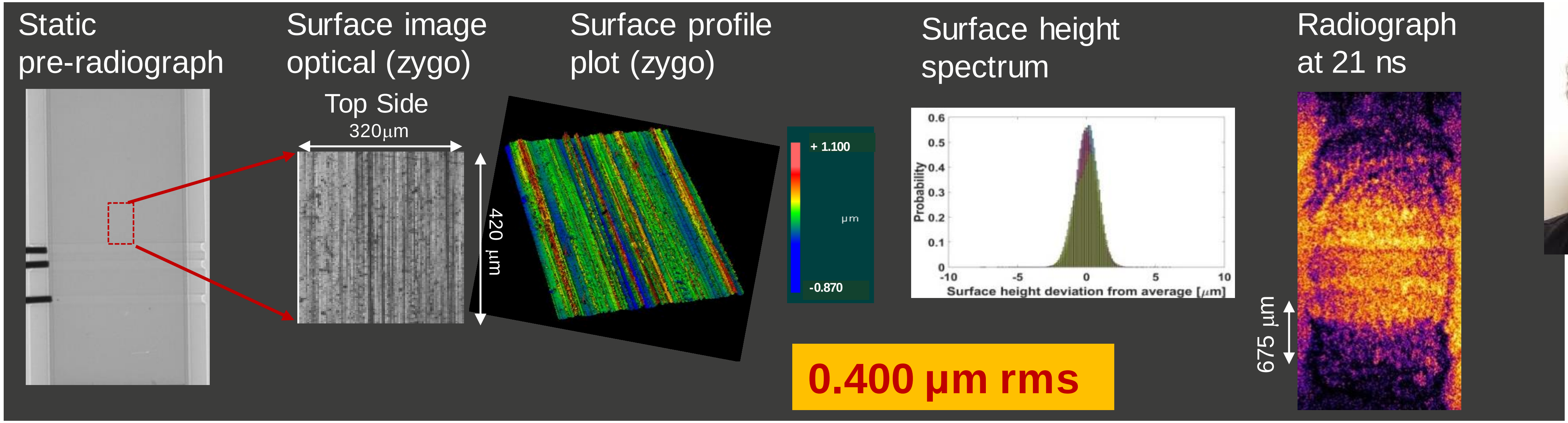
The tracer layer is imaged using 130 kJ of laser light onto the BALB foil, producing ~7kJ of x-rays

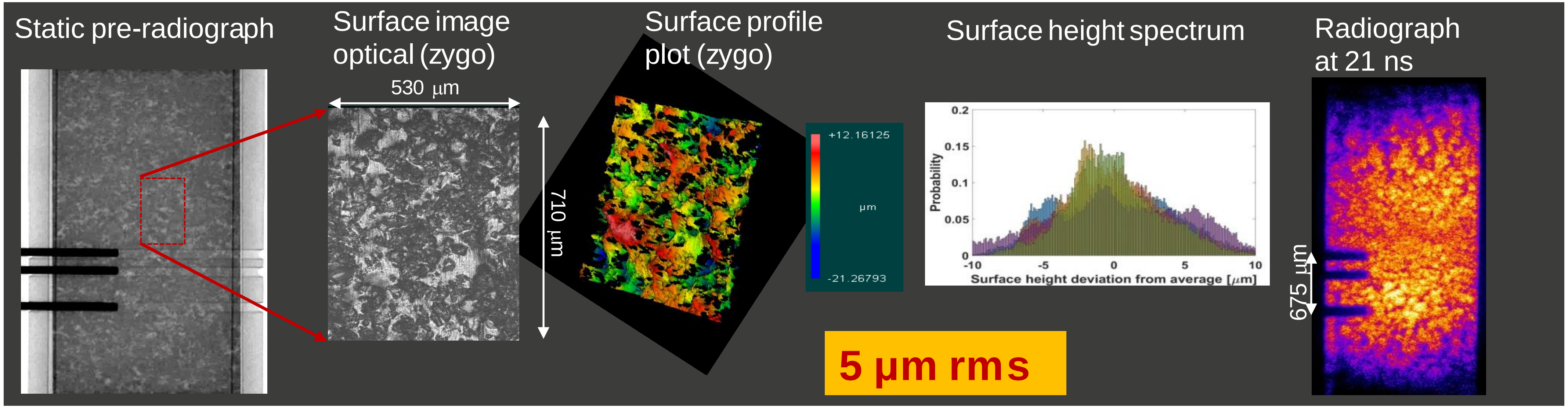




K. A. Flippo et al. *Rev. Sci. Inst.* **85**, 093501 (2014)

HED experiments enable control over interface initial conditions not possible in standard low energy density fluid mixing experiments

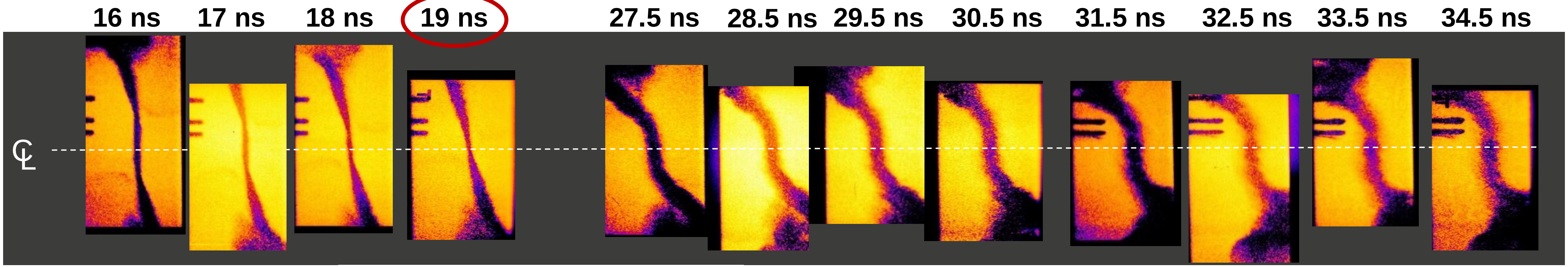


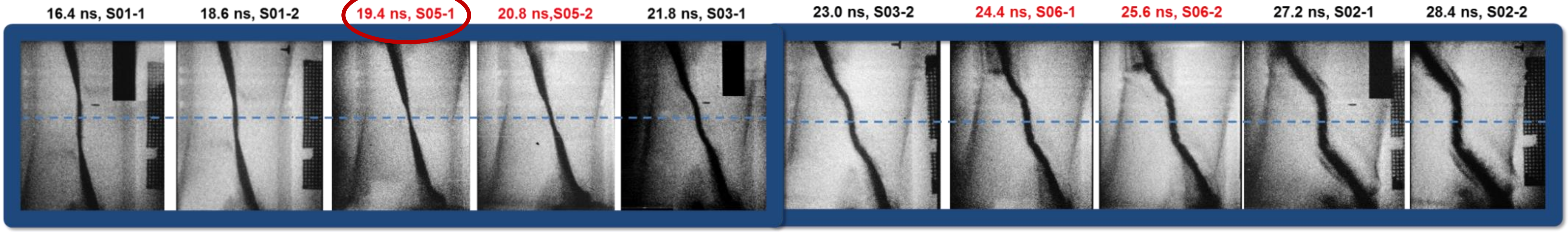


Kirk Flippo
Univ. of
Michigan

High quality experiments show the effect of initial conditions on the growth of the mixing region

Roughened Al 40 µm foil





Nominal Al 40 µm foil

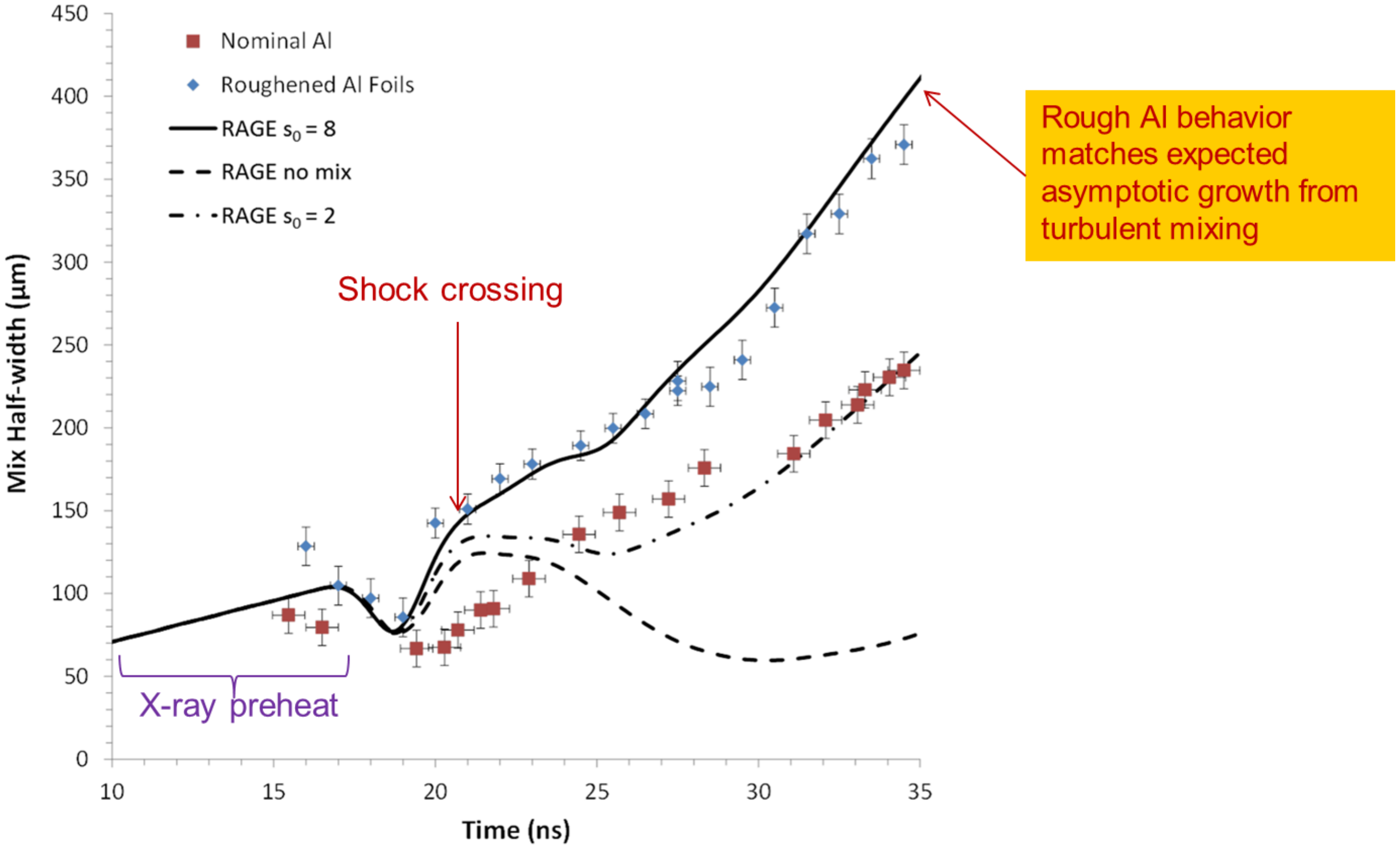
K. A. Flippo, F. W. Doss, J. L. Kline, et al. "Late-time mixing sensitivity to initial broadband surface roughness in high-energy-density shear layers," *Phys. Rev. Lett.* (accepted, in press)

NIF laser reproducibility enables high quality long data sequences built from multiple shots

Experiments show good agreement with simulations with key choices by the designer

There is still work to improve the BHR:

- So typically used as a free variable
- The BHR mix model is turned on during the simulations with designer's best feeling
- We are developing a modal initialization model which would be initialize at the beginning of the simulations

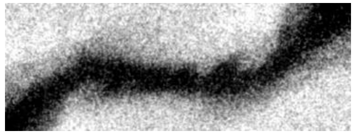


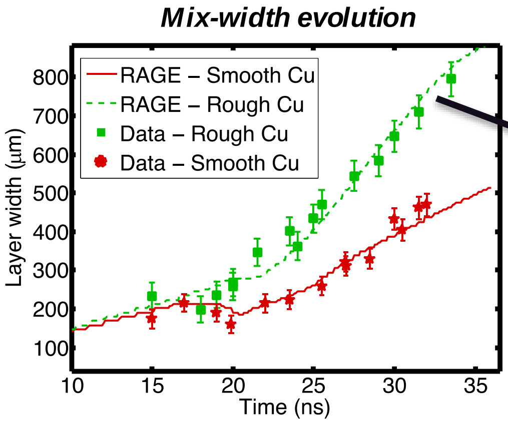
Comparisons of the mix widths between experiments and simulations while useful is not very constraining for models and more informative

The ensemble of radiography data gives a direct comparison between model and experimental turbulent kinetic energy

Model

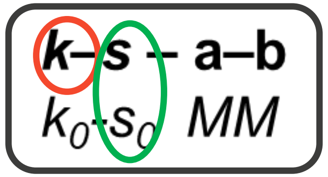
Measure mix width
→ tune s_0 → simulate *k*

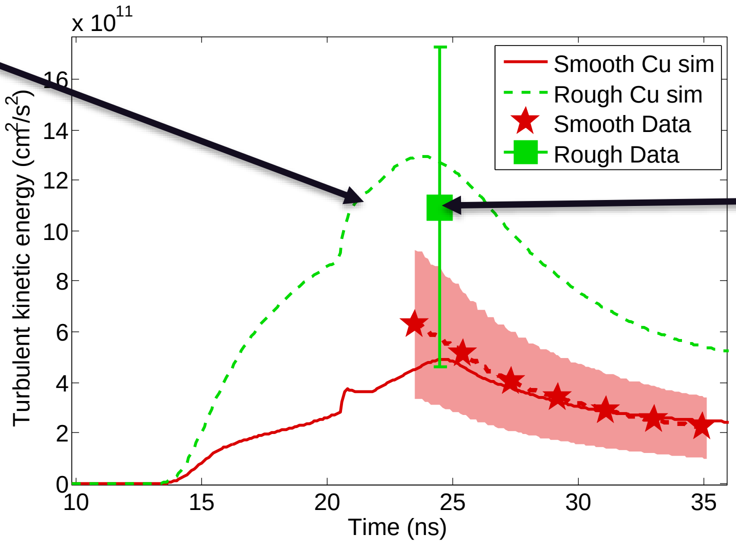




s_o increases with increasing surface roughness

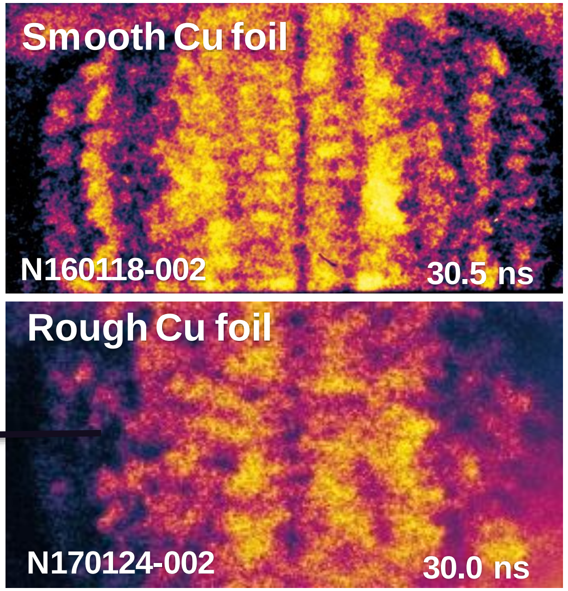
Doss et al,. Submitted to PRE (2018)





Analytic

Measure roller and rib growth
→ calculate *k*



Single data point w/ large error bars due to lack of rib evolution
→ *ongoing analysis development*

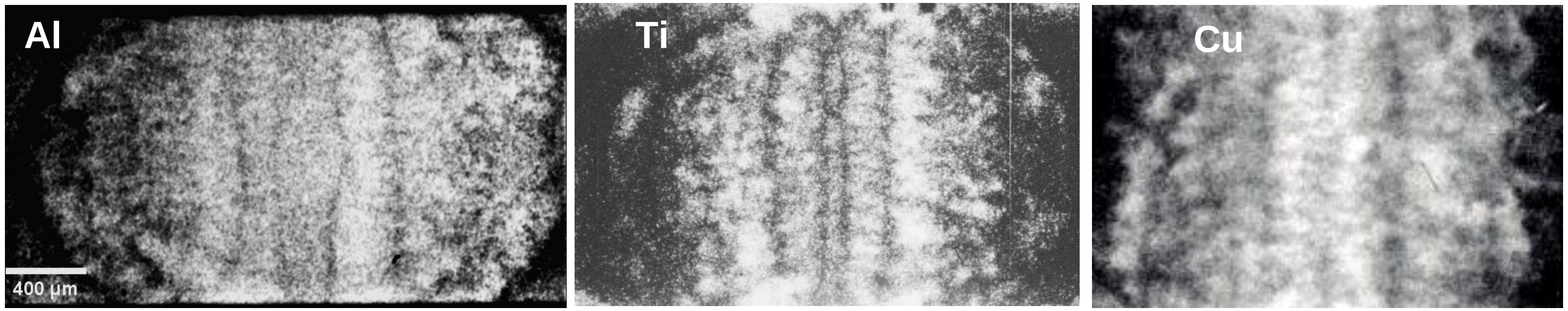
Forrest Doss

The roller and rib growth rates can be used to calculate the specific turbulent kinetic (kTKE) energy in the system, which is consistent with the RAGE & BHR models

Energy ratios in our HED experiment follow root-density Atwood scaling (roughly) from canonical fluid experiments

Ratios of TKE cancel out systematic modeling uncertainties, making error smaller than it might naively appear

Papamoshcou & Roshko, *JFM* **197** 453 (1988)
Dimotakis, "Entrainment into a Fully Developed, Two-Dimensional Shear Layer" AIAA-84-0368 (1984)



TKE (cm/s)^2	1.1e12 ± 6e11	4.5e11 ± 2e11	3e11 ± 6e11

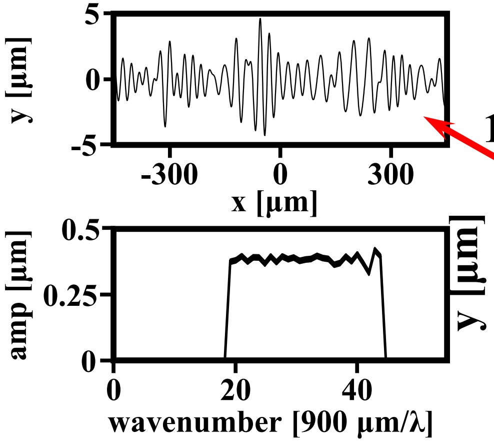
Al/Ti = 1.5 +- 0.6
("should be" 1.3)

Ti/Cu = 1.73 +- 0.5
("should be" 1.4)

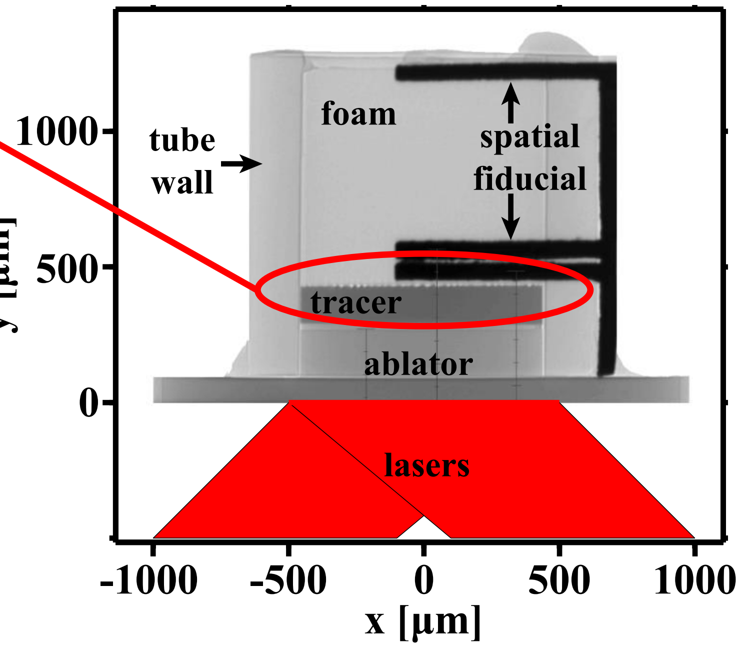
If our calculated TKE did not follows hydrodynamic scaling laws, that would indicated that our HED experiments were outside the regime of model applicability

The modal conditions (ModCon) experiments are designs to validate our modal model used to evolve the mix problem from simulation initiation

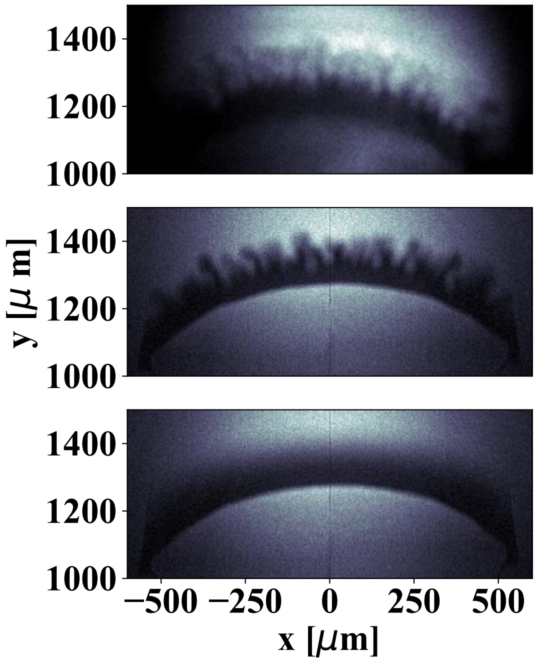
Initial perturbation



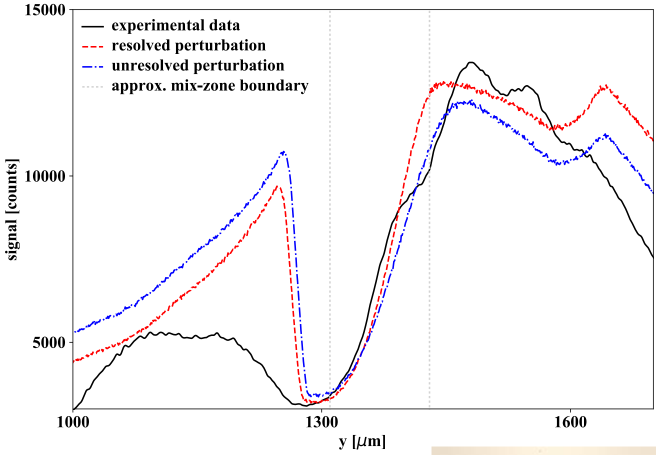
Pre-shot image



Experiment and simulation



Interface width



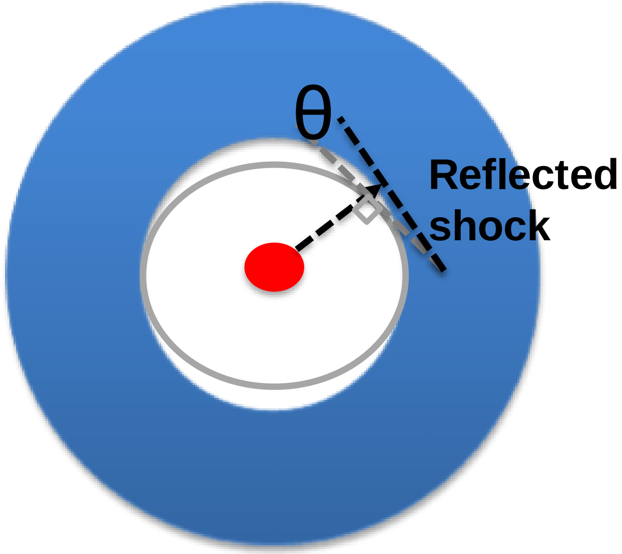
Carlos De Stefano

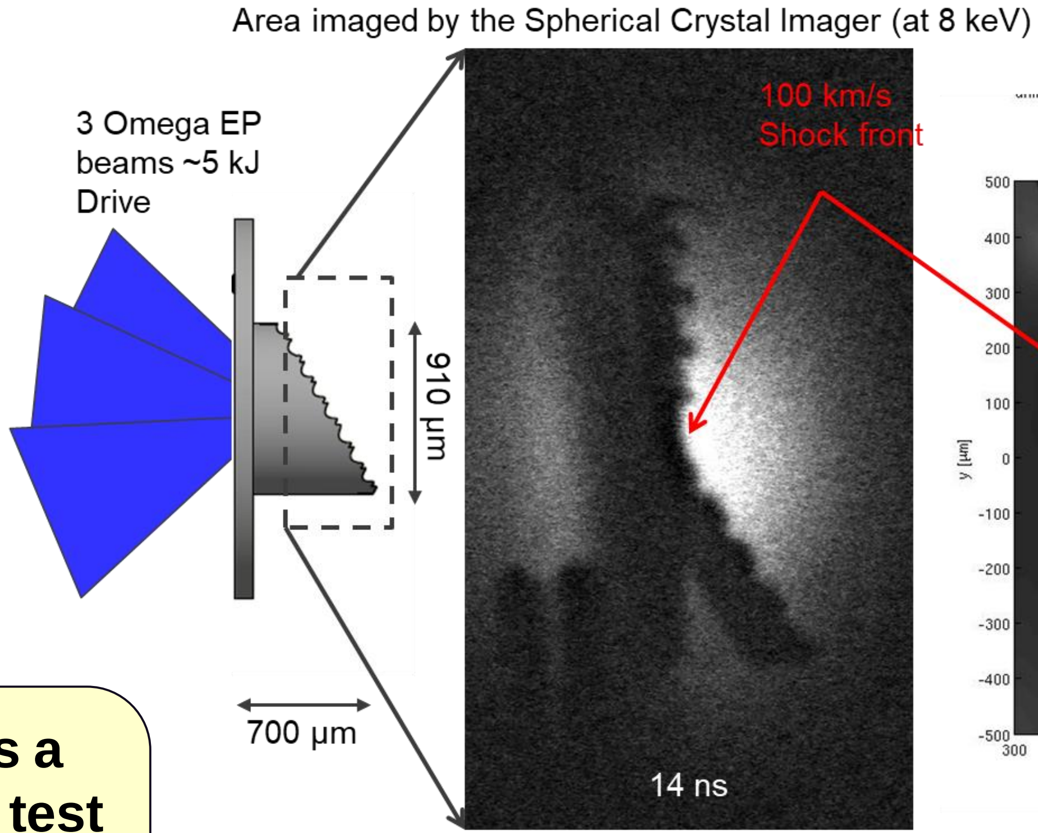
1. C. A. Di Stefano, *et al.* Phys. Plasmas 2017
2. B. Rollin and M. Andrews, *J. Turbulence*, 2013
3. G. Malamud, *et al. HEDP*, 2013

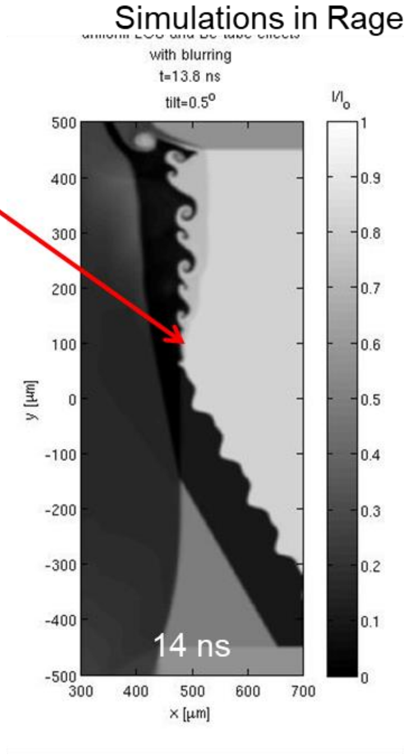
This type of perturbation is relevant to initialization schemes for hydrodynamic mixing (e.g. modal model)[3].

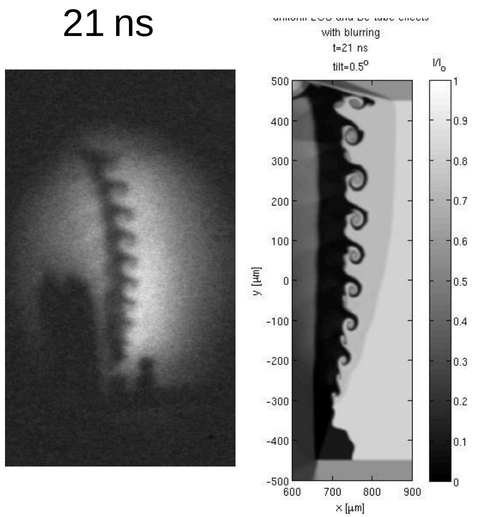
The Oblique Shock Campaign seeks to understand the interplay between Kelvin-Helmholtz and Rayleigh-Taylor instabilities on mixing in an HED environment

Asymmetric capsule drive can generate oblique shocks at interfaces





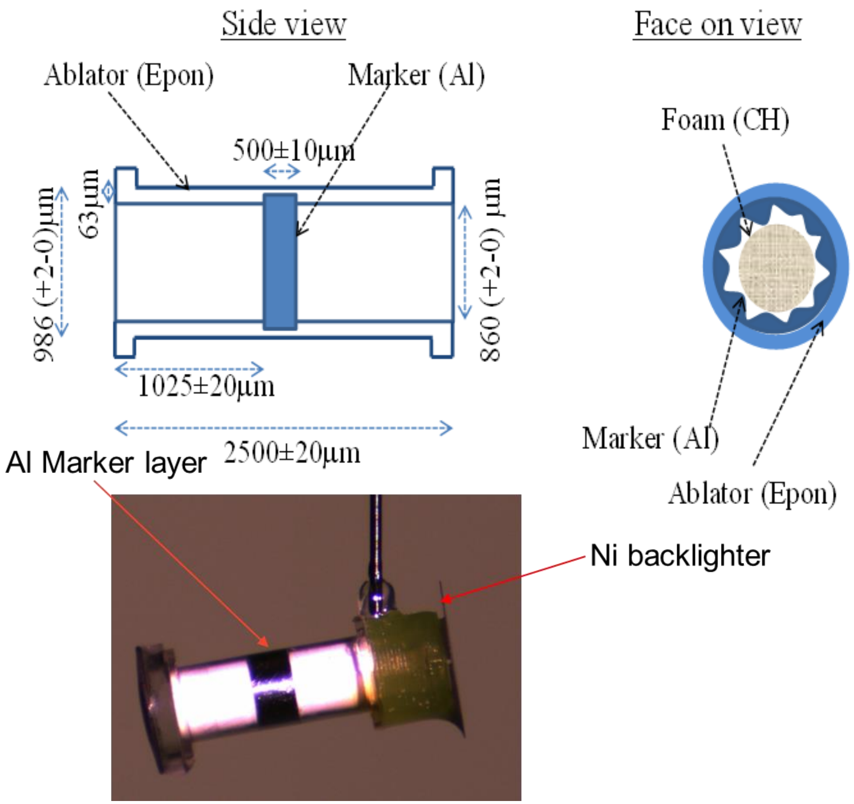


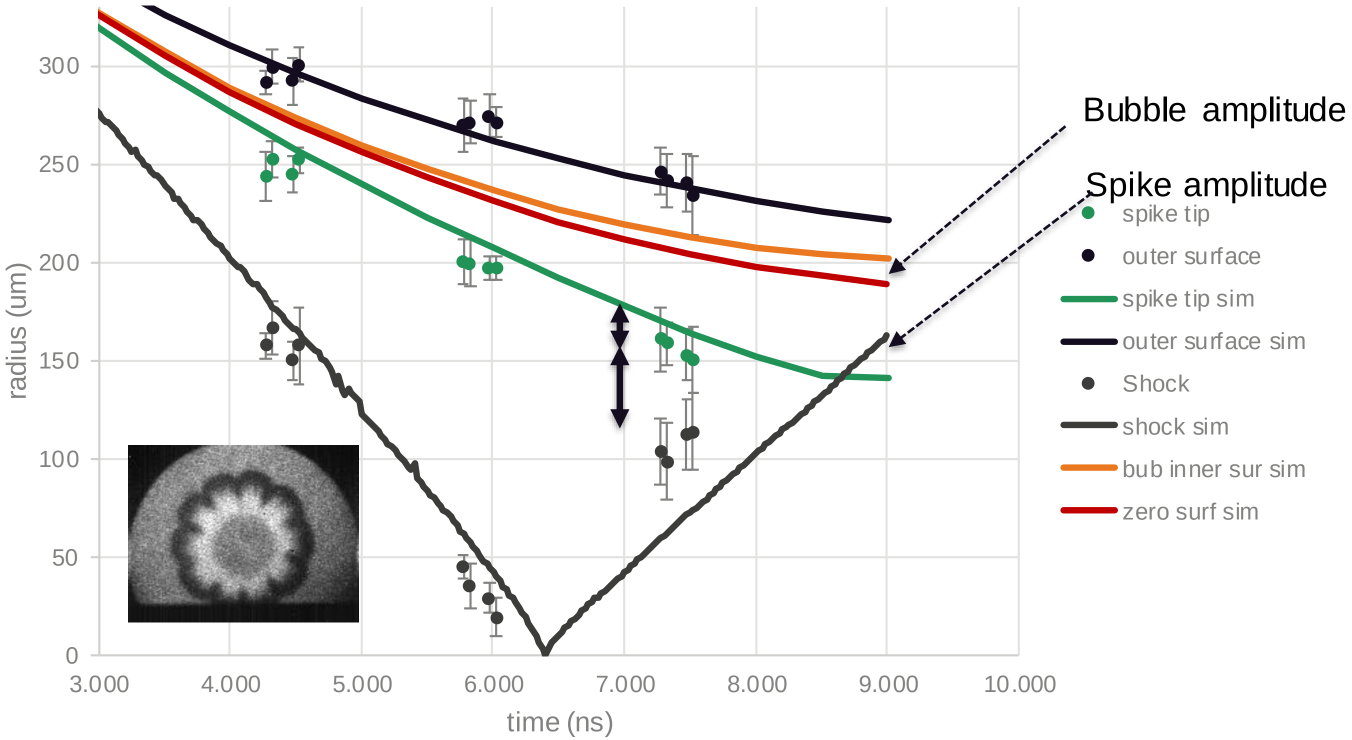


Alex Rasmus

Oblique shock provides a multi-physics integrated test for our models related to a potential technical issues for ICF implosions

We are re-establishing a cylindrical implosion platform to validate our hydrodynamics in convergent geometries

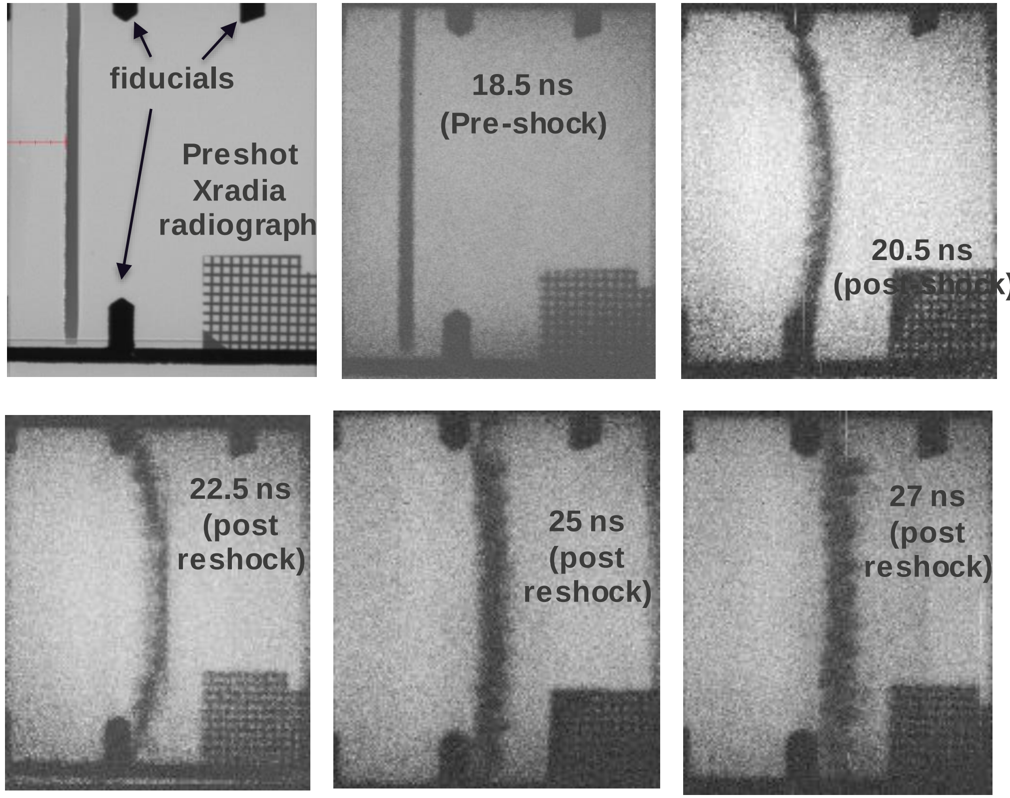




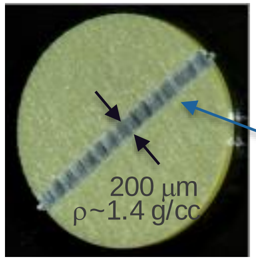
Cylindrical implosions enable direct diagnostic access to instability growth in convergent geometry. Convergent geometry adds:

- Compressibility
- Changing wave lengths
- Different Atwood numbers for bubbles an spikes

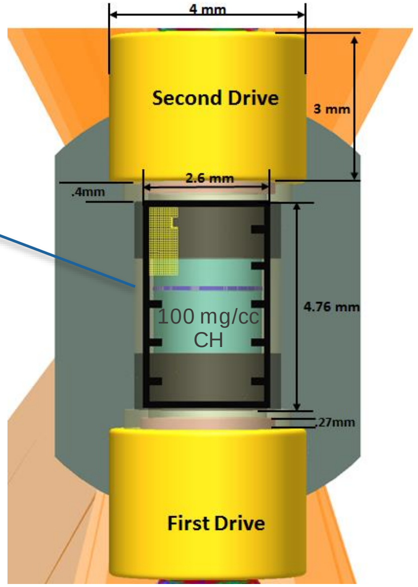
The MShock Campaign examines RM instability growth with multiple shocks with multiple interfaces



Radiograph data shows growth of high density layer, and features of the seeded mode

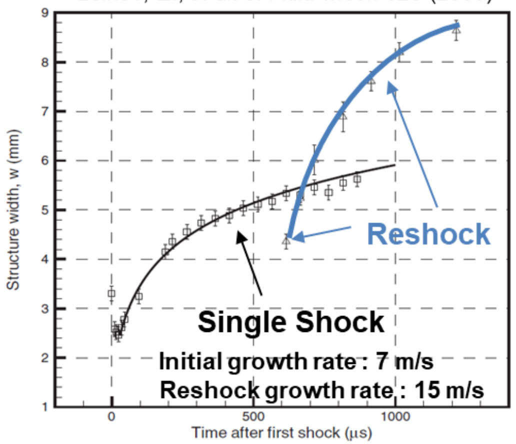


Plastic disk with 80 x 200 μm thick CHI tracer layer



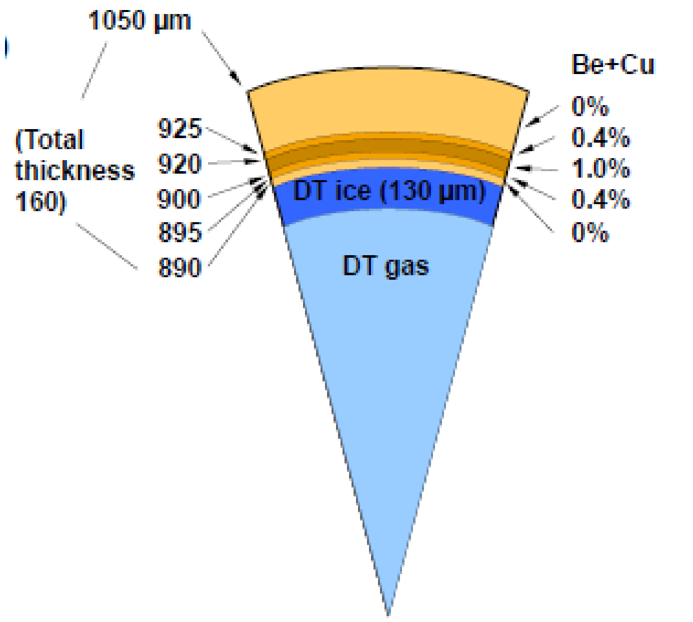
Fluid Reshock Experiments

Leinov, E., *et al*. J. Fluid Mech 626 (2009)



Grades dopant Ignition designs have multiple interfaces near ice layer

Be HF capsule



[1] Simakov *et al*. PoP **21**, 022701 (2014).
[2] Yi, *et al*. PoP (2014).

One advantage to the national lab is working closely with partners working in different regimes on the same problems

Turbulent Mixing Tunnel:
Open-circuit wind tunnel

Measurements:

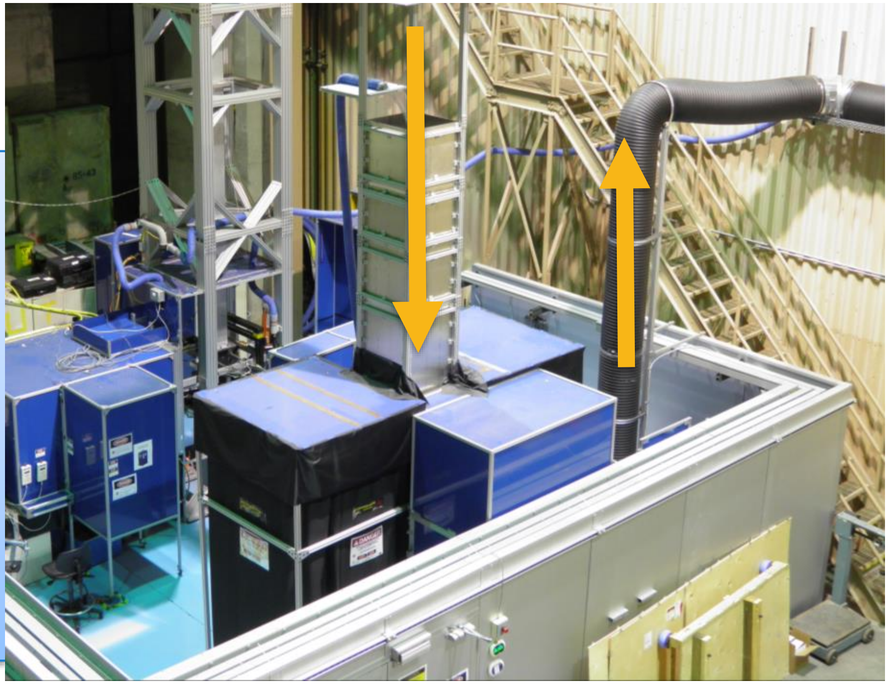
10,000 velocity & density fields of the flow per station

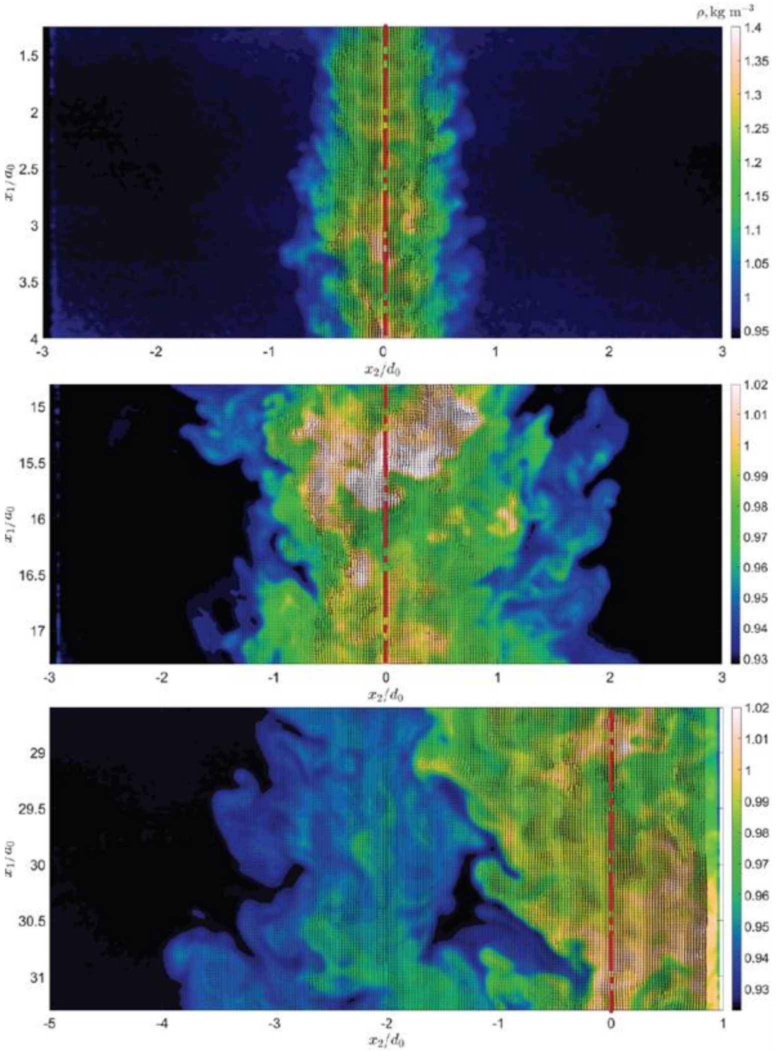
Jet conditions:

Re = 20,000

At = 0.1, 0.6

M = .09, .02

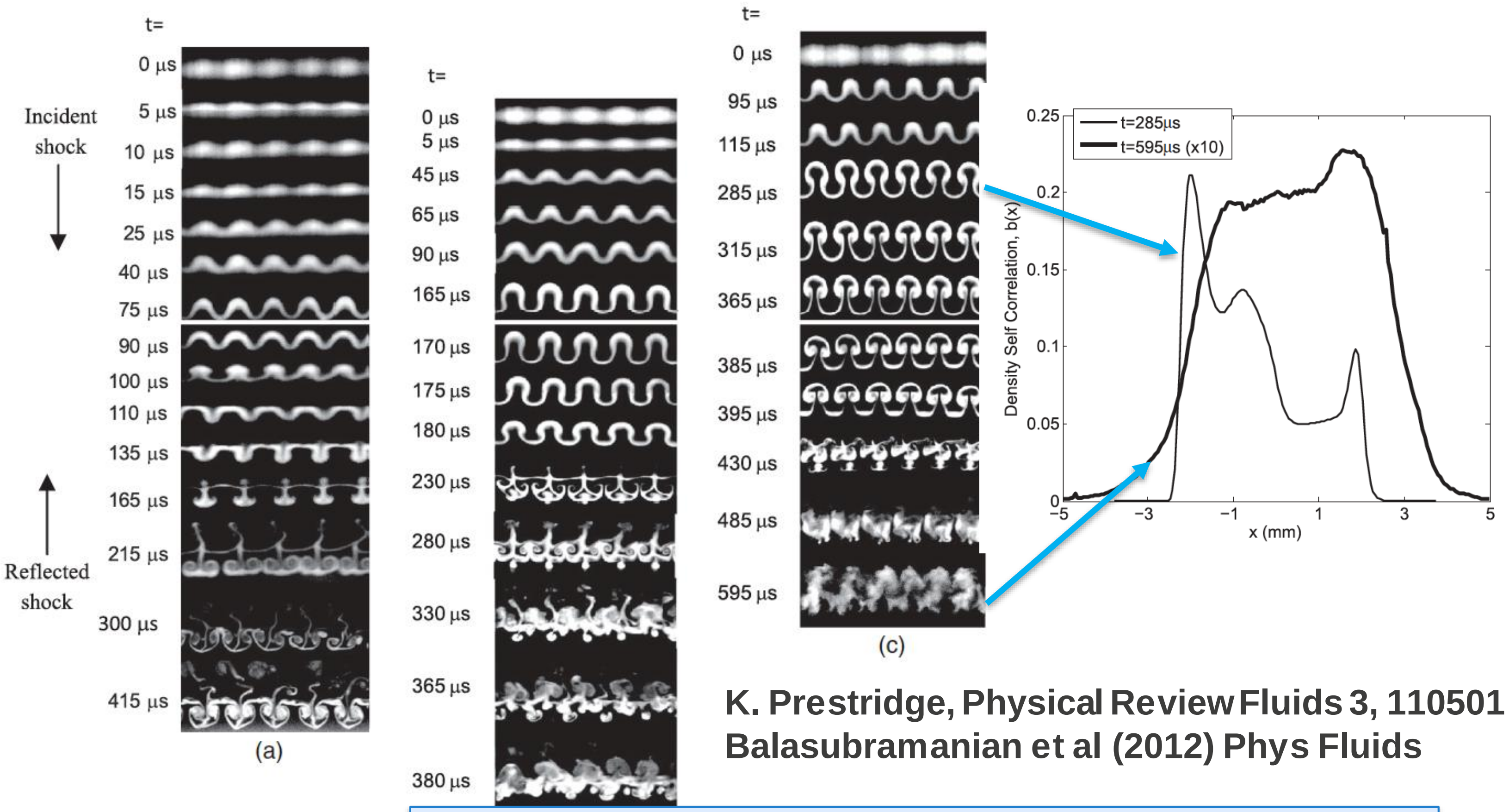




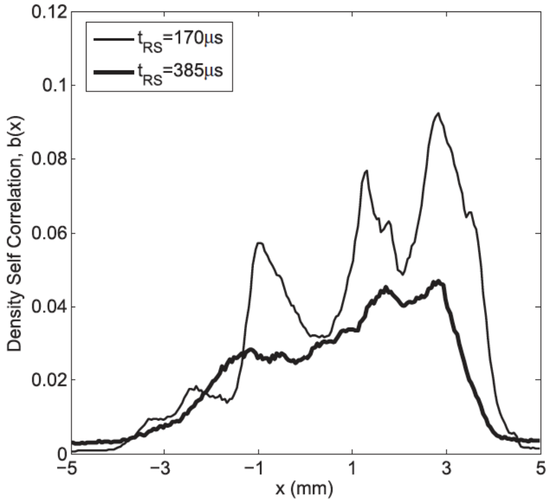
EXTREME FLUIDS

extremefluids.lanl.gov

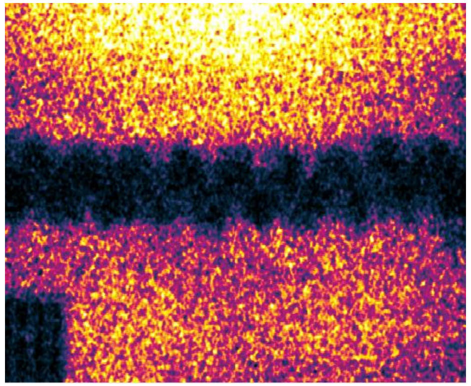
Mshock platform is duplicating gas curtain experiments in different flow conditions



Later reshock results in enhanced mixing



K. Prestridge, Physical Review Fluids 3, 110501 (2018)
Balasubramanian et al (2012) Phys Fluids



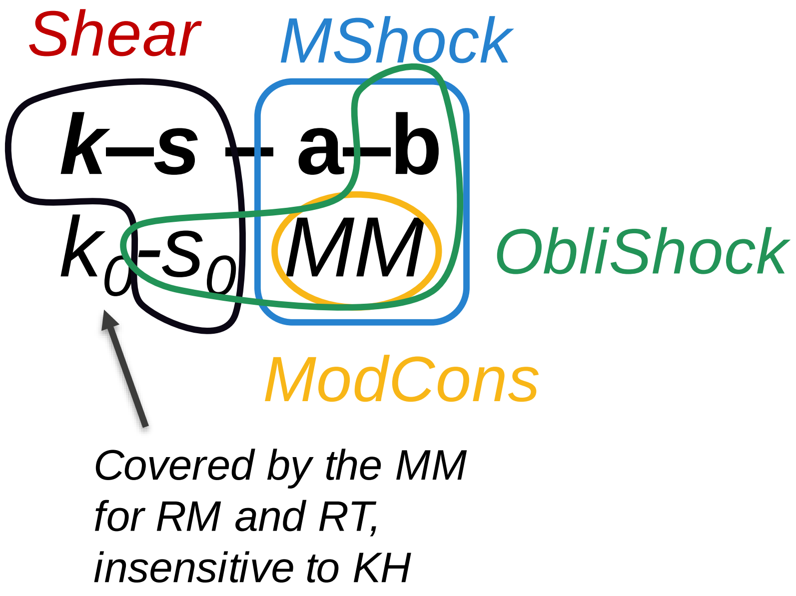
Mshock is an extension of fluid experiments and should be able to detect similar features in *b*

EXTREME FLUIDS

extremefluids.lanl.gov

Our suite of HED hydro-instability projects form a complementary coverage of the parameters of the BHR mix model

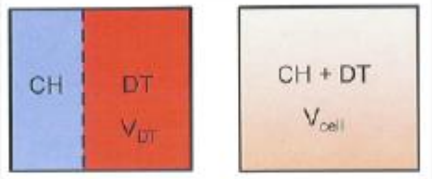
- Counter-propagating Shear (Shear)
  - *Kelvin-Helmholtz (KH) instability*
  - *Atwood numbers*
  - *Surface perturbations*
- Multi-Shock (Mshock)
  - *Richtmyer-Meshkov (RM) instability*
  - *Thin layer feed-through*
  - *Multi-directional shock effects*
- Modal Initial Conditions (ModCons)
  - *RM and Rayleigh-Taylor (RT) instability*
  - *Early-time evolution*
- Oblique Shock (ObliShock)
  - *Mixed KH & RM & RT*
- Cylinders
  - *Introduces convergence effects on above*



We are developing models that utilize the BHR mix model to advance mix morphology in terms of a distribution function to modify reactivity

Simulations: fusion burn is modeled through a reaction rated equation which can be modified by mix

$$\dot{N}_{DT} = \frac{N_D N_T}{V} \langle \sigma v \rangle (T_i)$$



Limiting cases of mixed cell

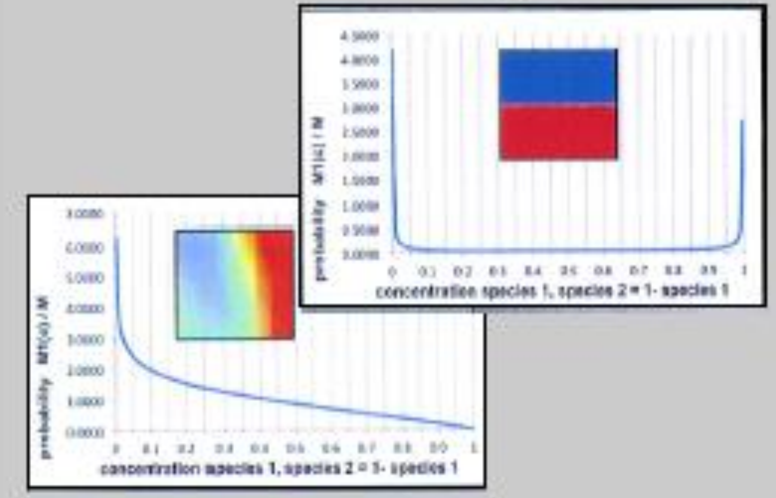
- BHR: time evolution and distribution of mix based on Reynold's Averaged Navier-Stokes (RANS) Equations
- Flow decomposed into average and fluctuating components
- Ensemble averaged equations provides mean motion of flow
- PDF: physical representation of unresolved cell morphology

t>0

Unresolved cell structure that might be computed from DNS

Beta Probability Distribution Function

$$p(c) = \frac{c^{\alpha-1}(1-c)^{\beta-1}}{B(\alpha,\beta)}, \quad B(\alpha,\beta) = \int_0^1 dc\, c^{\alpha-1}(1-c)^{\beta-1}$$



BHR: concentration c, and density self correlation b

→ PDF: p(c), fraction of cell (by mass) at concentration c

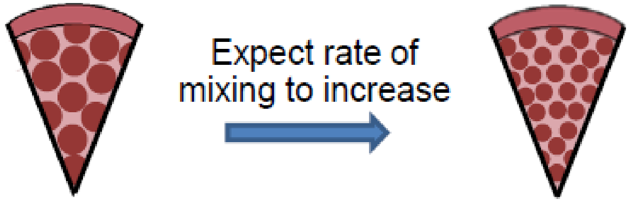
→ Reaction Rate equation

Burn and mix are interdependent, experiments to test fidelity of approach cannot separate the two

reference

We have developed experiments that attempt to control the mix morphology

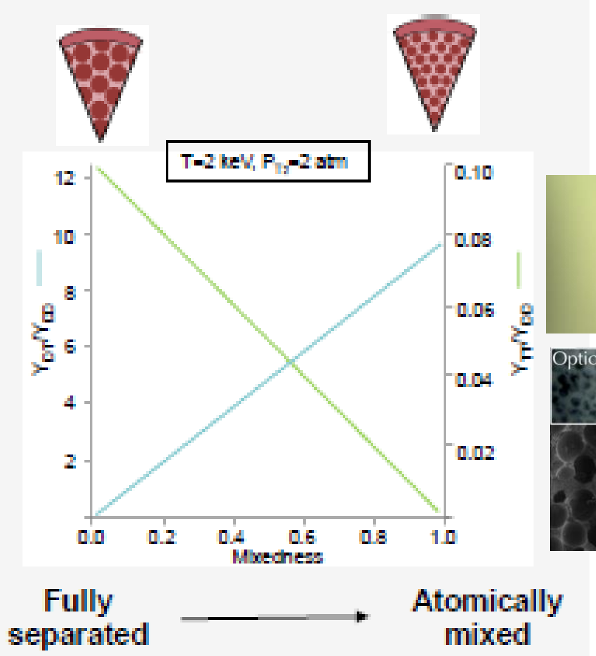
- Measured yields are indicative of how well the D and T species atomically mix
- How fast D and T components mix depends on the initial pore size, distribution, foam density and gas pressure



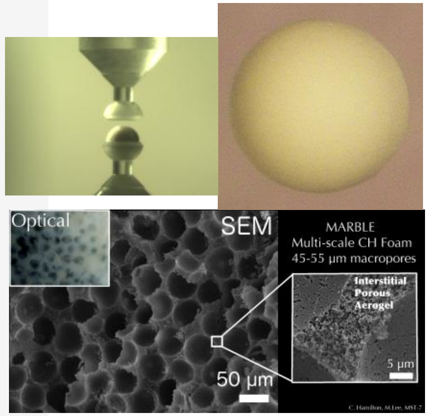
- Initial pore sizes estimated at ~ 100 μm

  Based on assumption of shock-driven variable density isotropic turbulent decay
- Key measurement: yield ratio

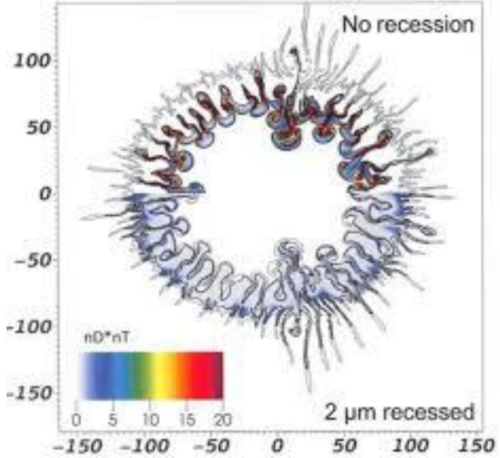
  Eliminates need to know detailed information on ion temperature
- Multi-D simulations incorporating a foam model indicated differences in DT yield will be observed



Extent to which D and T are mixed



Typical separated reactants mix experiment



J. Pino et al, PRL (2015)

A principle focus of LANL HEDP program is mix and burning plasmas to validate models for ICF implosions

This is accomplished using three threads:

- **Novel implosion platforms to inform performance**
  - Reduced convergence wetted foam targets
  - Double Shell targets
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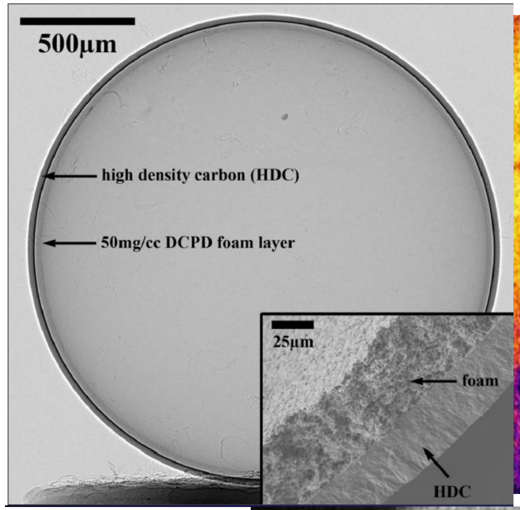
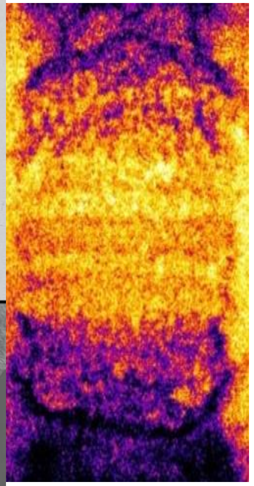
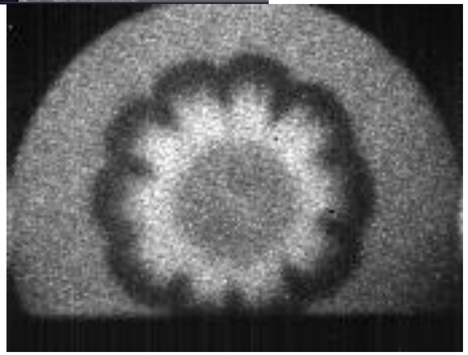
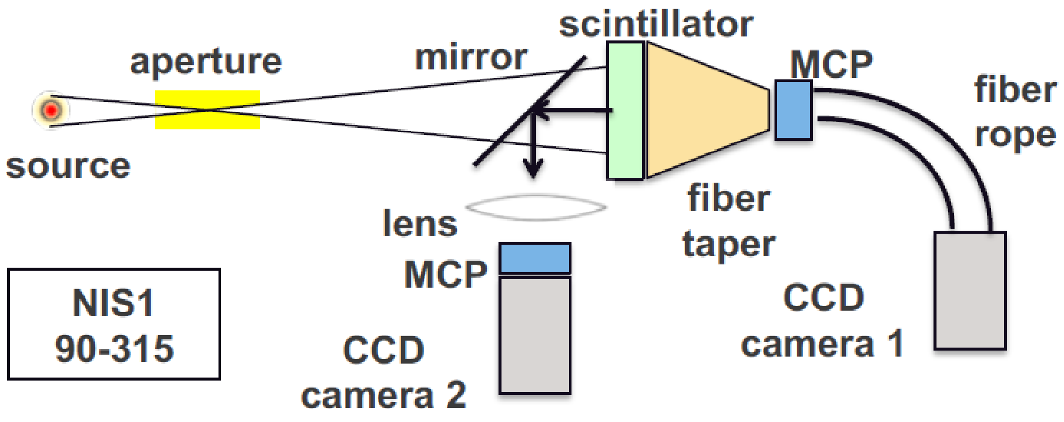
  - Bayesian Inference Engine

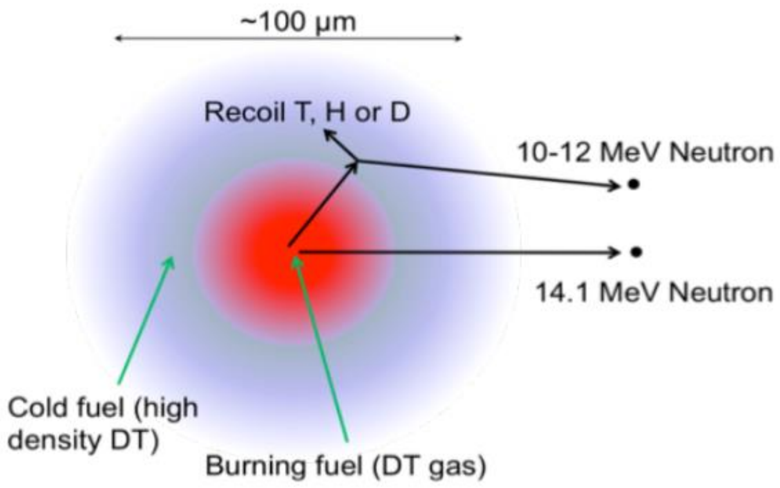


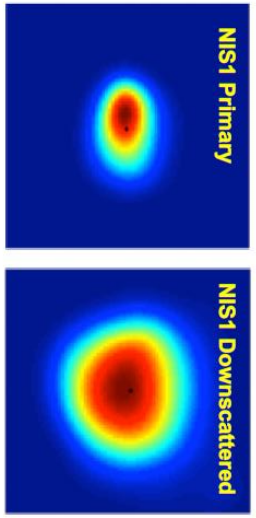


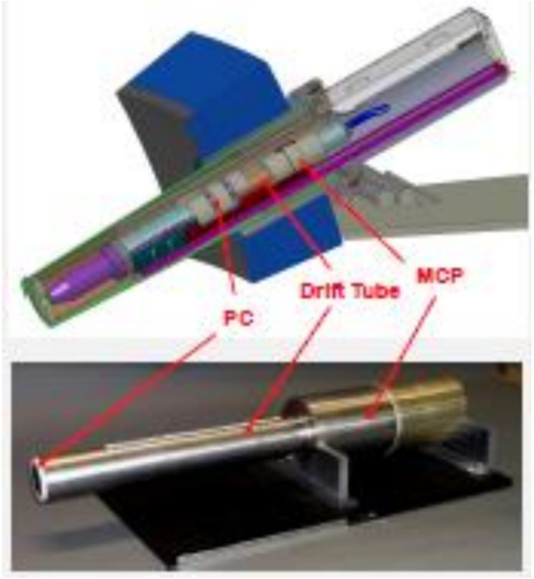


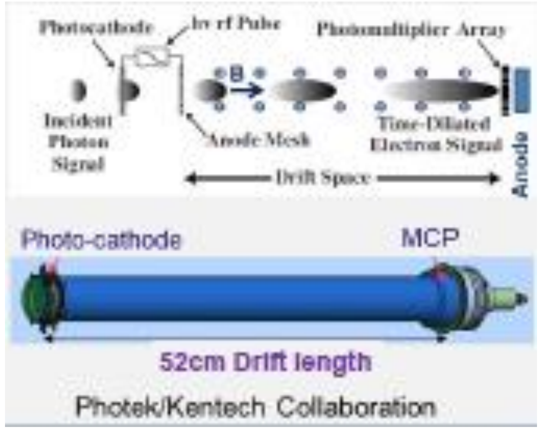
Investigating burning plasmas requires high quality nuclear diagnostics

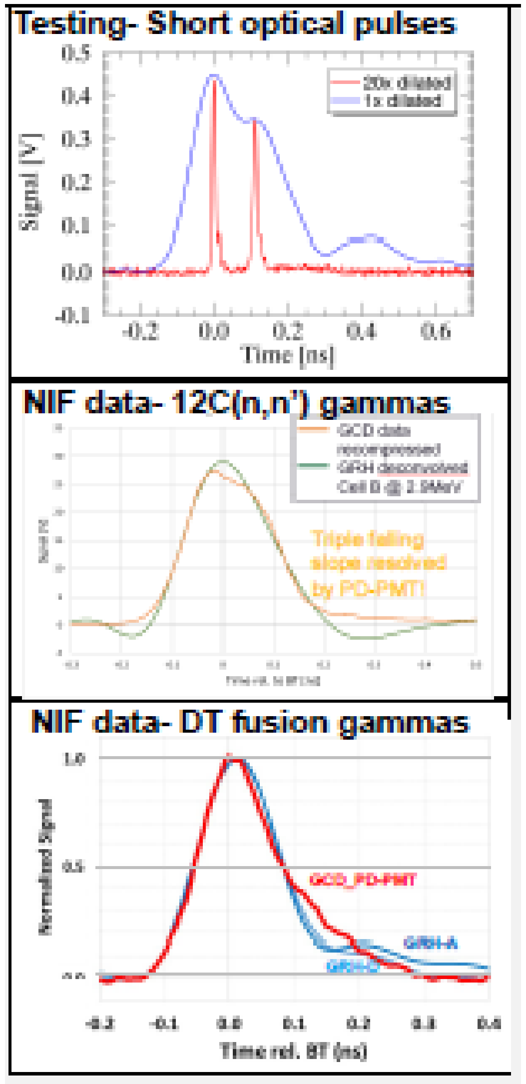






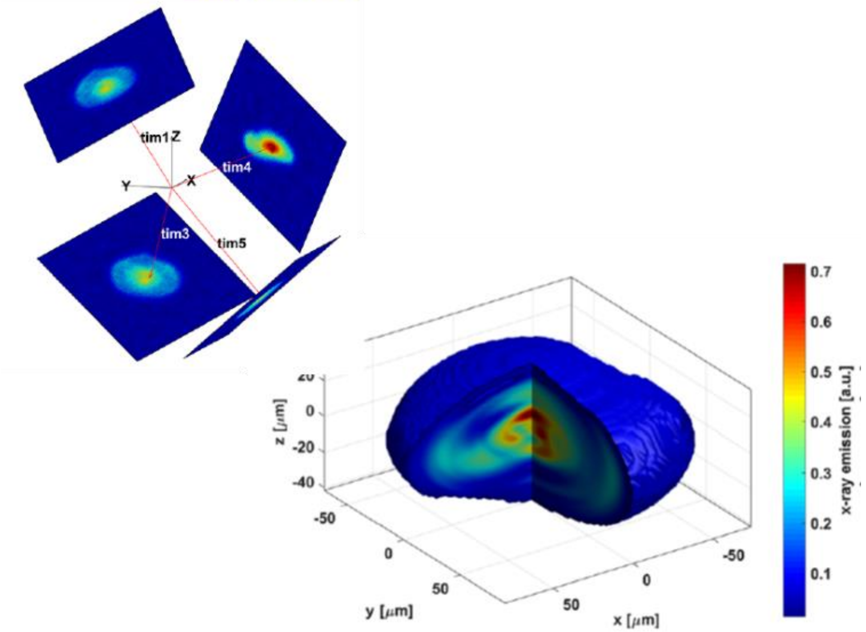




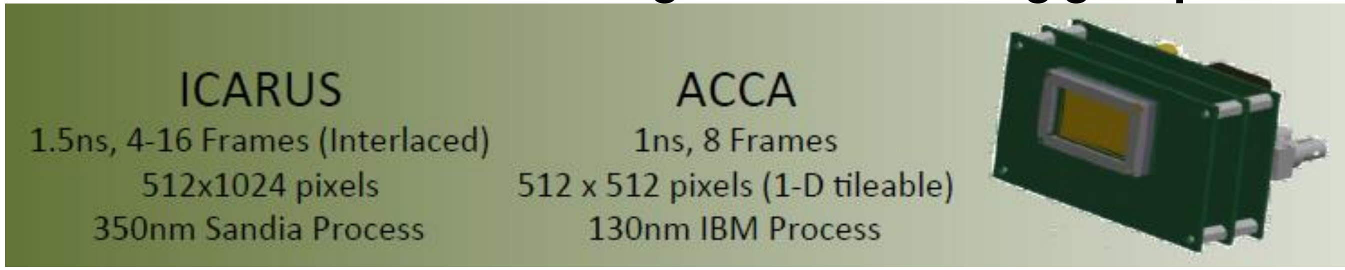


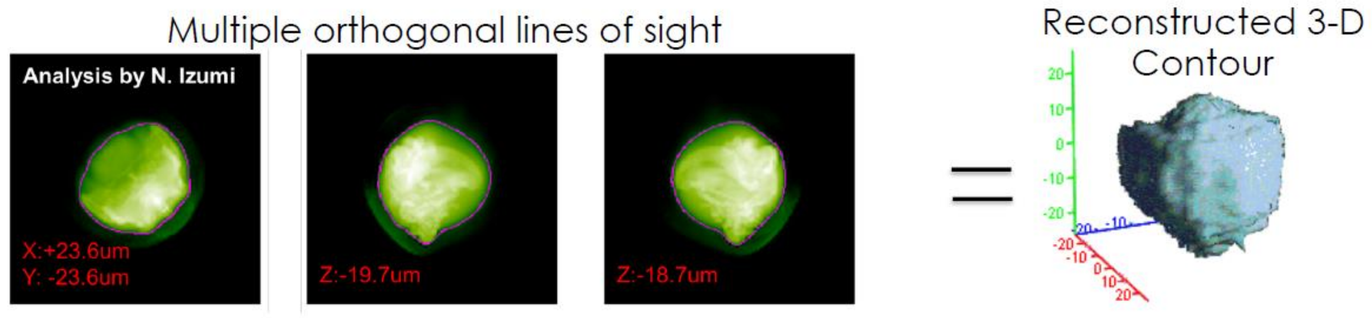
Development of 3D measurement capabilities is an important thrust since even experiments with a symmetry axis are often 3D

Experiments are 3D!



National Diagnostics Working group

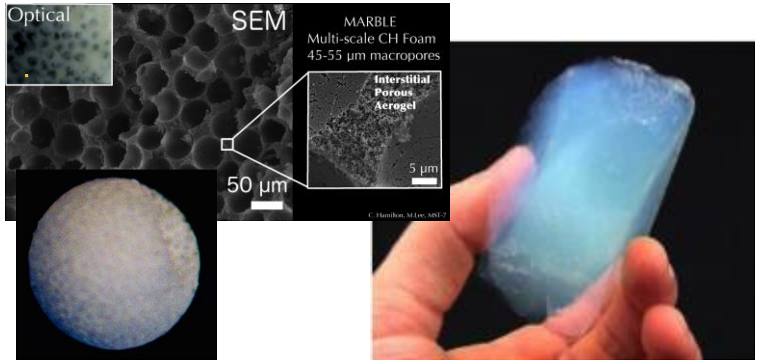




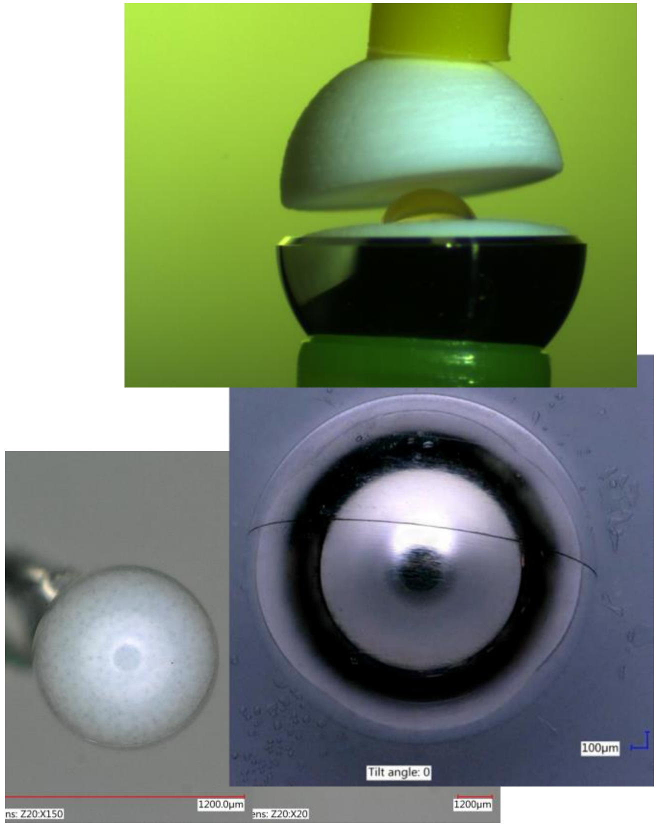
*Izumi (LLNL) et al.

LANL Target Fabrication Capabilities Include Foam Synthesis & Coatings, Micro-Machining, Precision Assembly and Characterization

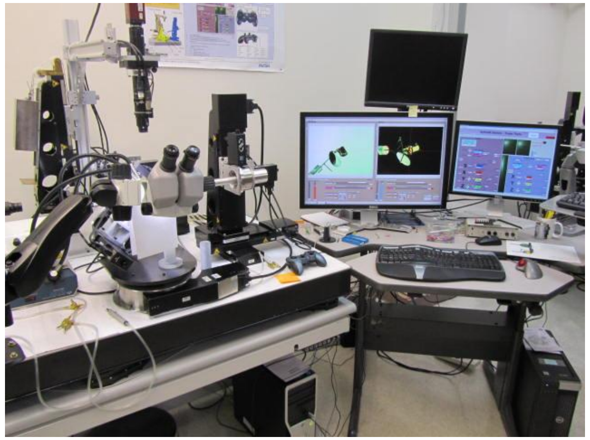
Many of our experiments require highly specialized Foams



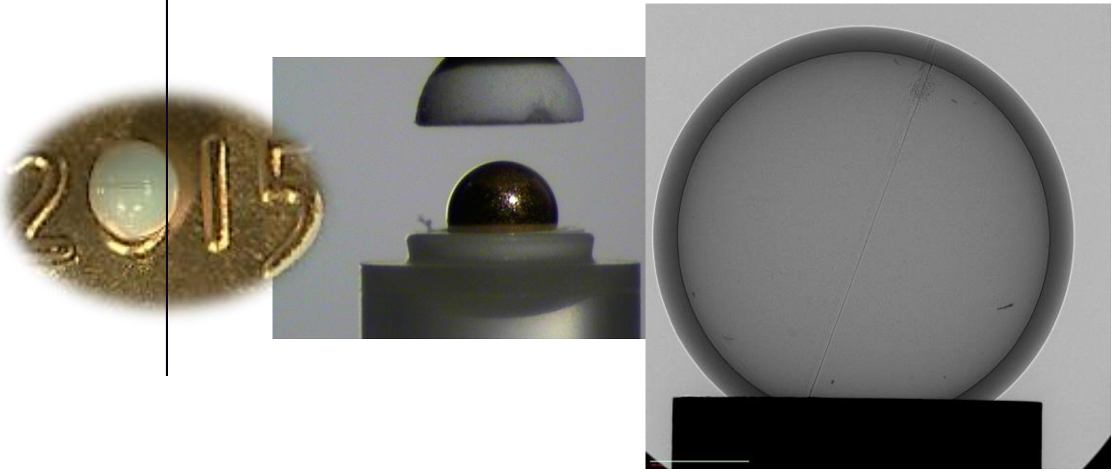
Micro-Machining of mm scale parts to um precision



Precision Assembly is critical for all targets, particularly ones of greater complexity



Double-Shell targets require Characterization of centering, density and voids



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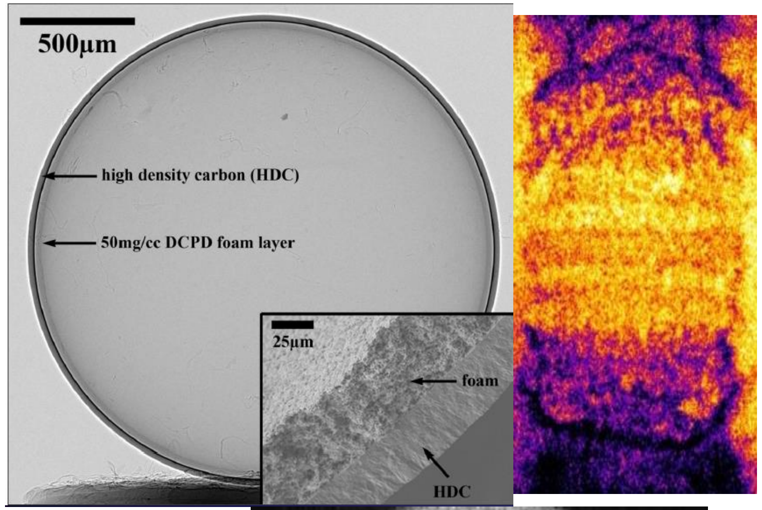
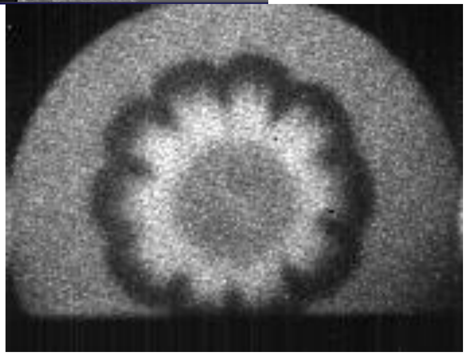
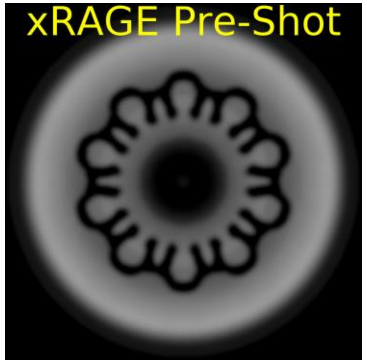
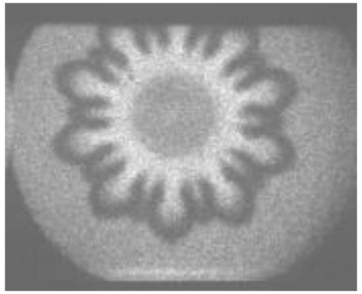
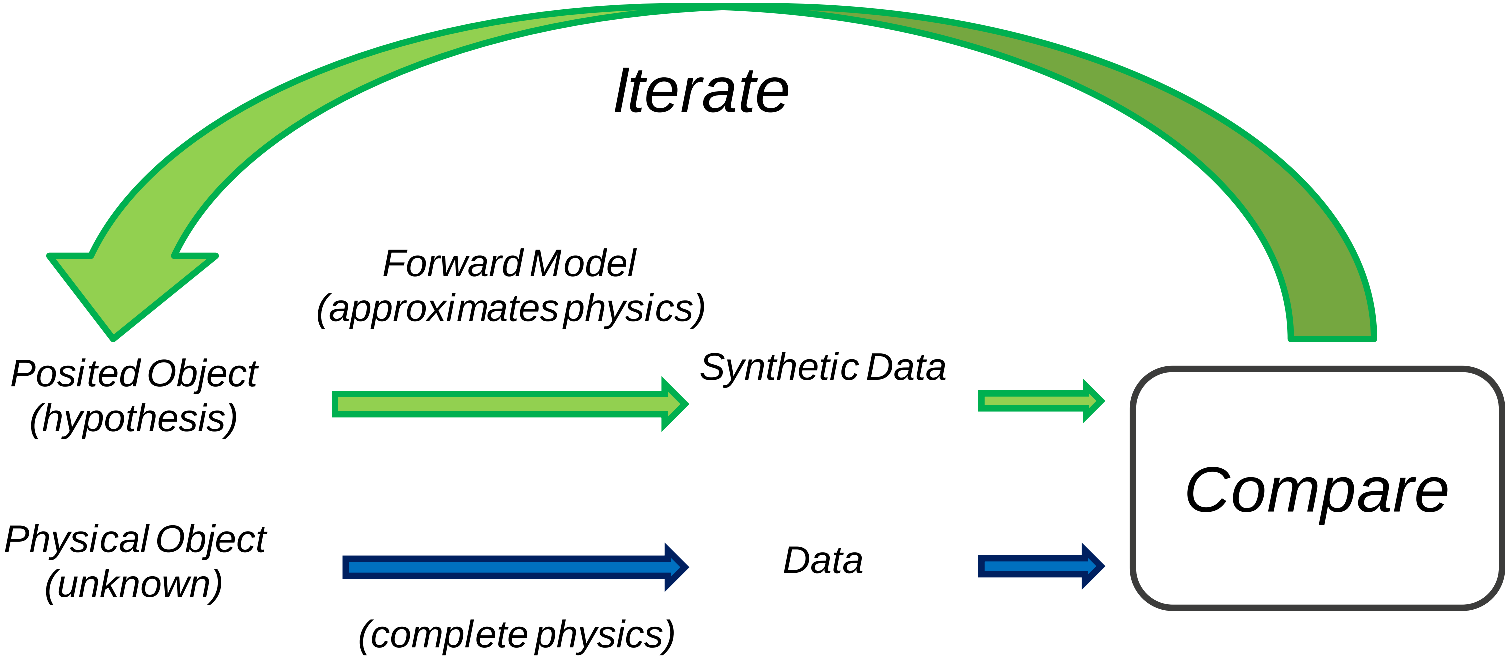




We are developing more Quantitative Statistical Inference (QSI) methods for uncertainty quantification

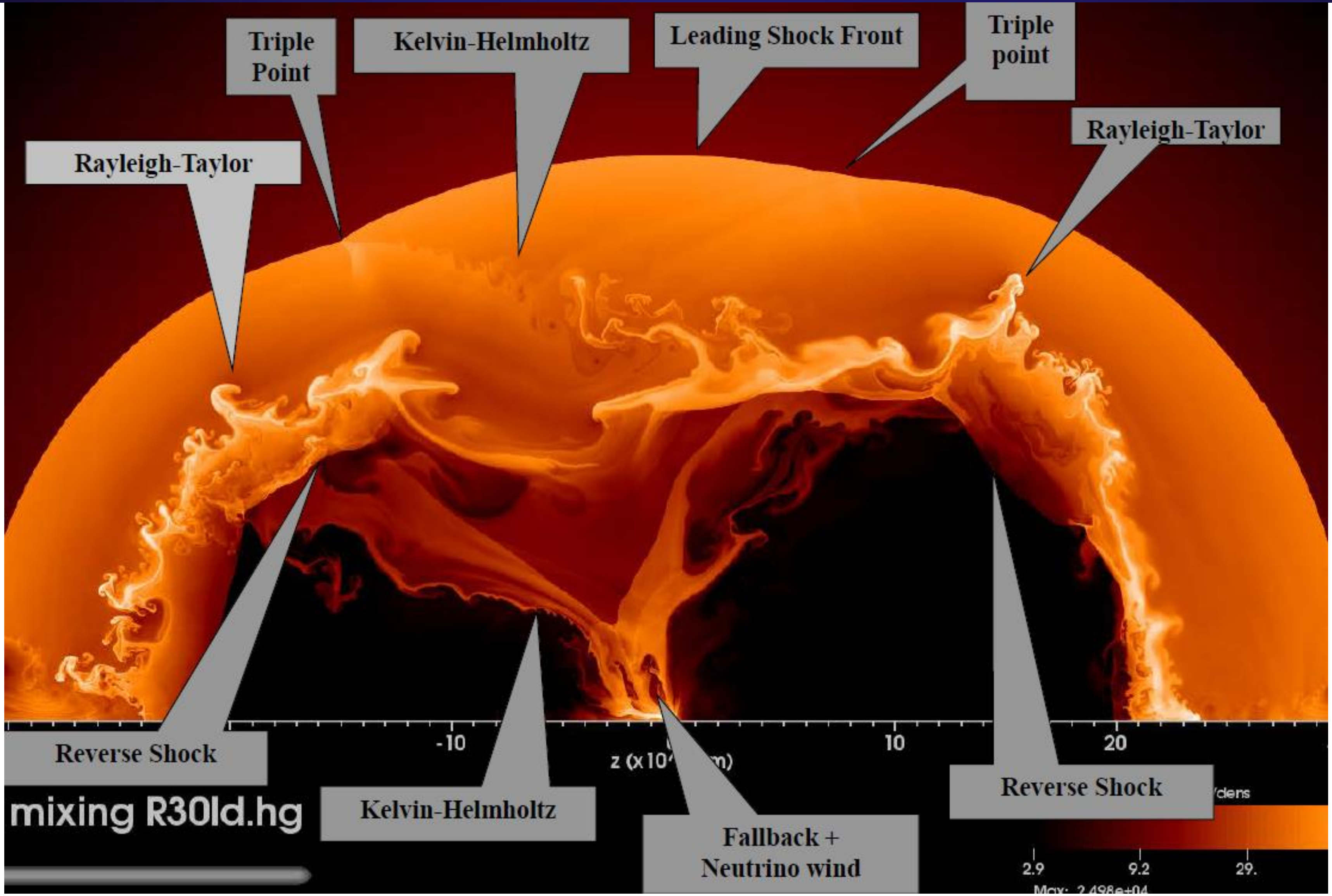






An iterative method of solving the inverse problem;
the best available deterministic solution is often a starting point

The work shown here is applicable to other areas of physics (Plewa)



What is the future:

HED experiments to become more integrated in fluids understanding how plasmas change the dynamics

- Quantitative evaluation of mix and transition to turbulence:
  - *3D characterization*
  - *Multiple frames for the same experiment to capture 3D evolution*
  - *diffusion*

Investigating burning plasma:

- Kinetics
- Interplay of mix in the presence of burn

Applications of ignition:

- Nucleosynthesis
- Nuclear physics
- Nuclear cross sections for burning plasmas

Turbulence is the most important unsolved problem of classical physics.
— Richard P. Feynman

"I would ask God two questions: 'Why quantum mechanics, and why turbulence. I think he will have answer for the former.'" W. Heisenberg or Horace Lamb

One focus of LANL's high energy density physics effort is mix and burn during the stagnation phase of ICF implosions

- Inertial Confinement Fusion is a grand challenge in big science requiring a large mix of skills that includes participants both nationally and internationally
- While considerable progress has been made towards ignition, challenges remain which require improved implosion performance or larger capsules
- The largest looming questions are, "Is ignition on NIF possible?" and "What is required to achieve ignition?"
- LANL is strategically focuses on the understanding the evolution of hydrodynamics and burn physics for implosions using novel platforms and focused experiments for code validation
- The program looks to bring in capabilities that can improve our ability to quantify and validate our understanding

Los Alamos
NATIONAL LABORATORY
EST. 1943