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Title: HED Hydrodynamics Instability and Turbulence Campaigns

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Los Alamos
NATIONAL LABORATORY

HED Hydrodynamics Instability and Turbulence Campaigns

Elizabeth Merritt
Applied and Fundamental Physics, P-2

May 3rd, 2021

The HED hydro capability is supported by a team across multiple divisions at LANL

Design
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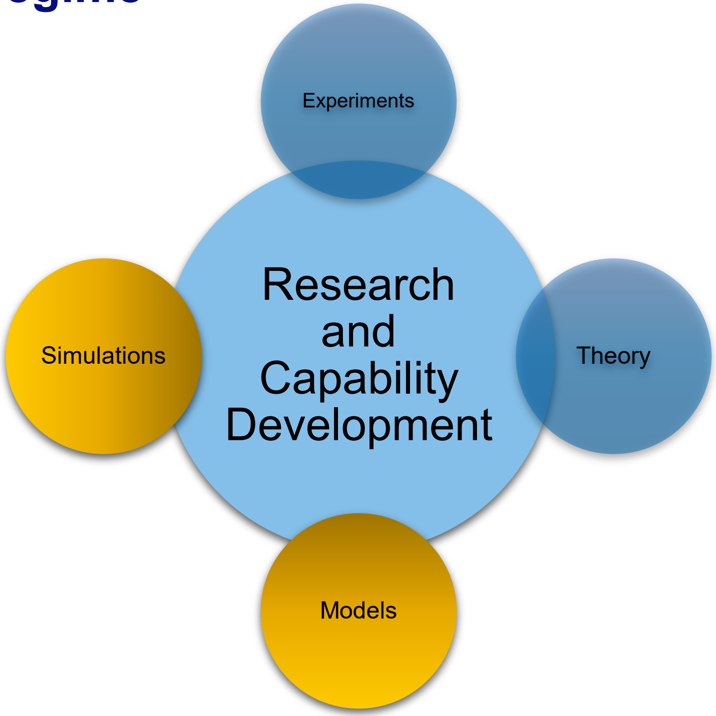
previously
Tiffany Desjardins P-2 (w/ VST)

We are funded mainly by Science Campaigns 4 and 10.

The high-energy-density (HED) hydro-instability program is extending instability and turbulence experiments into the HED regime

In the HED plasma regime fluid dynamics approximations may break down

- 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 some of the only institutions extending hydrodynamics and turbulence models beyond LED density regimes

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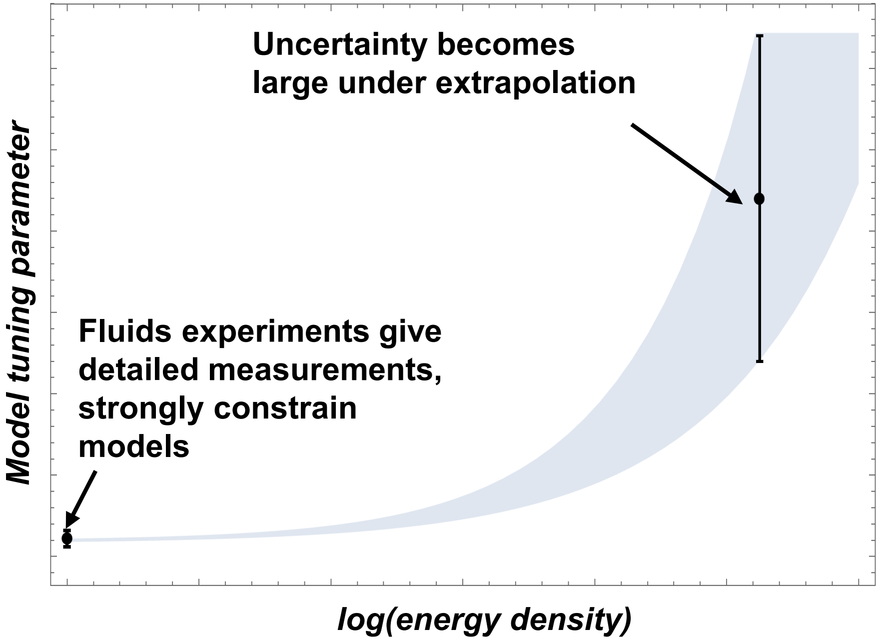

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A focus of the LANL HED hydro-instability program is to test applicability and performance of our BHR mix model outside fluid parameter space

BHR is currently a two-length scale turbulence model* implemented in our xRAGE hydrocode

2 length scale model (energy + scale)

Reynold's Stress Tensor → $\mathbf{R_{ij}}$ - $\mathbf{s_D}$ - $\mathbf{s_T}$

Decay scale → $\mathbf{s_D}$

Transport scale → $\mathbf{s_T}$

Multiple species inclusion

Mass flux → $\mathbf{a_i}$ – $\mathbf{b}$

Density-specific-volume covariance (Mixedness) → $\mathbf{b}$

*Schwarzkopf *et al*. Flow Turbulence Combust 96 (2016)

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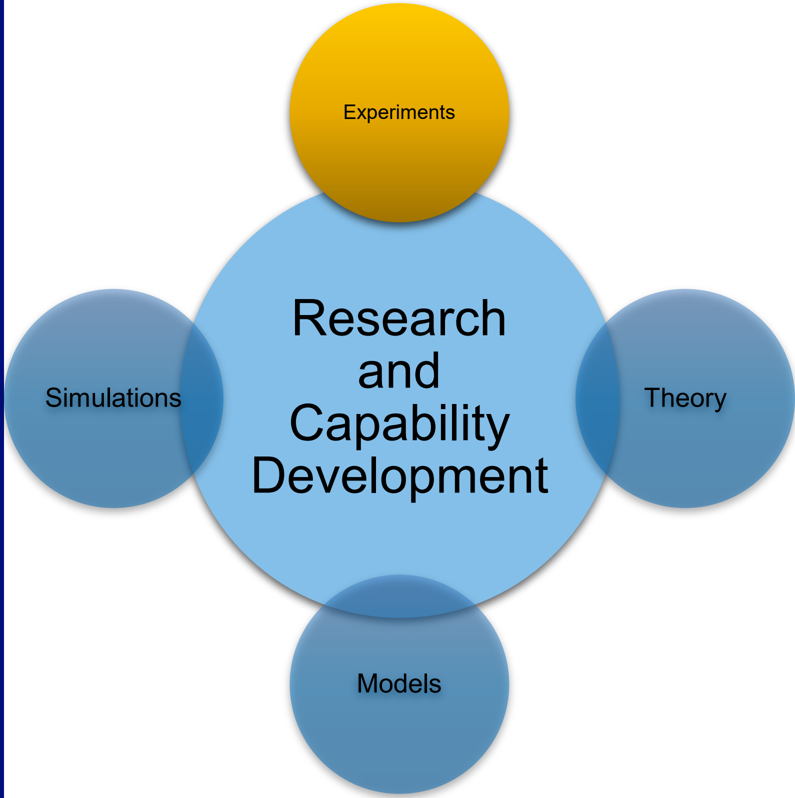
$$a_i - b$$

The more physics we preserve in our models, the higher the burden of validation the model requires

***Schwarzkopf *et al*. Flow Turbulence Combust 96 (2016)**

The LANL HED hydrodynamics program is designed to start with the simplest cases of isolated mixing physics, and build towards fielding and understanding more complex systems for comparison to our models



The LANL RT/RM experiment suite is designed to isolate the contributions of individual physics as we build to complex systems

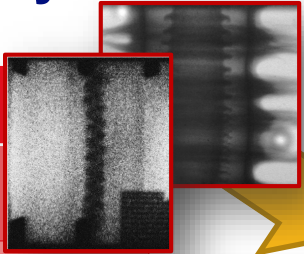
ModCons

- 1 shock
- 1-interface

Examine linear phase RM + RT growth for comparison to the Modal Model

Add interfaces

Mshock (Multi-interface)

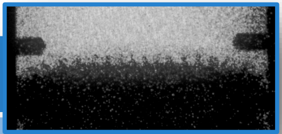


- ≤ 2 shocks from opposite directions
- 2-interfaces

Examine the interface coupling/feedthrough on instability growth under shock and reshock conditions

Add shocks

Mshock (Multiple Shock)



- ≤ 2 shocks from same direction
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- 1-interface

Examine interface growth and transition to turbulence of a single interface (no feedthrough effects) with two successive shock from the same direction, and reshock from the opposite direction.

Mshock (multi-shock & multi-interface)

- ≤ 2 shocks from same direction
- ≤ 2 shocks from the opposite direction
- 2-interfaces

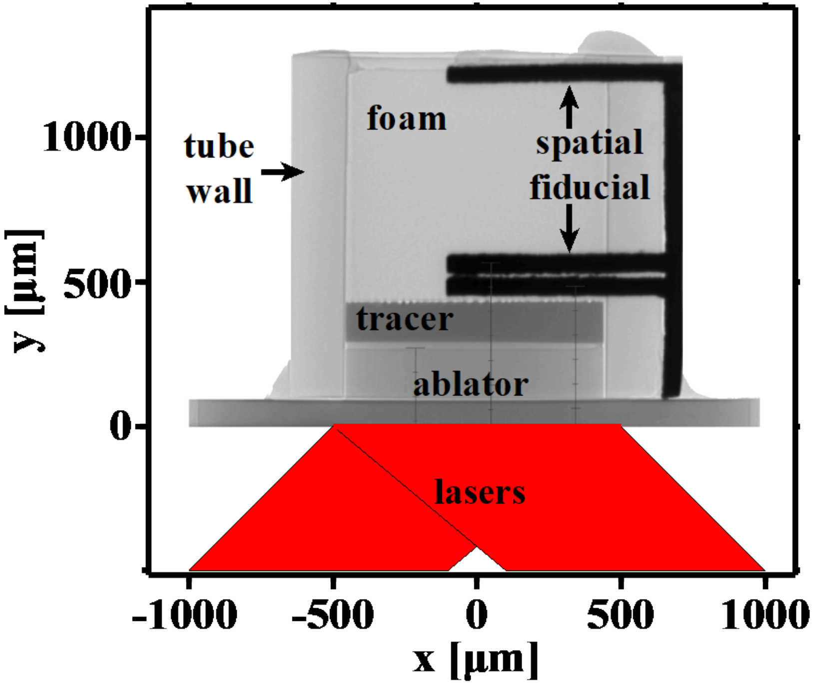
Add interface-coupling/feedthrough effects back into the study.

The LANL RT/RM experiment suite is designed to isolate the contributions of individual physics as we build to complex systems

Complementary to the VST LED work on the Modal Model

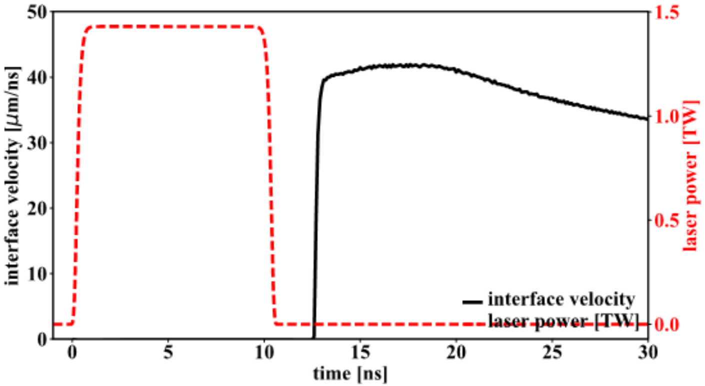
ModCons
• 1 shock • 1-interface
Examine linear phase RM + RT growth for comparison to the Modal Model

Many of our HED experiments use planar interfaces so we can more easily diagnose and understand the complex dynamics of perturbation growth and transition to turbulence



Our simplest experiment (ModCons) focuses on ensuring we can calculate the evolution of complex, multi-mode surface profiles correctly including fine-feature growth and mode coupling

A_t~0.67 (postshock)
P~13.5 Mbar (plastic), 2.1 Mbar (foam)



C.A. Di Stefano et al., *Phys. Plasmas* **24**, 052101 (2017)
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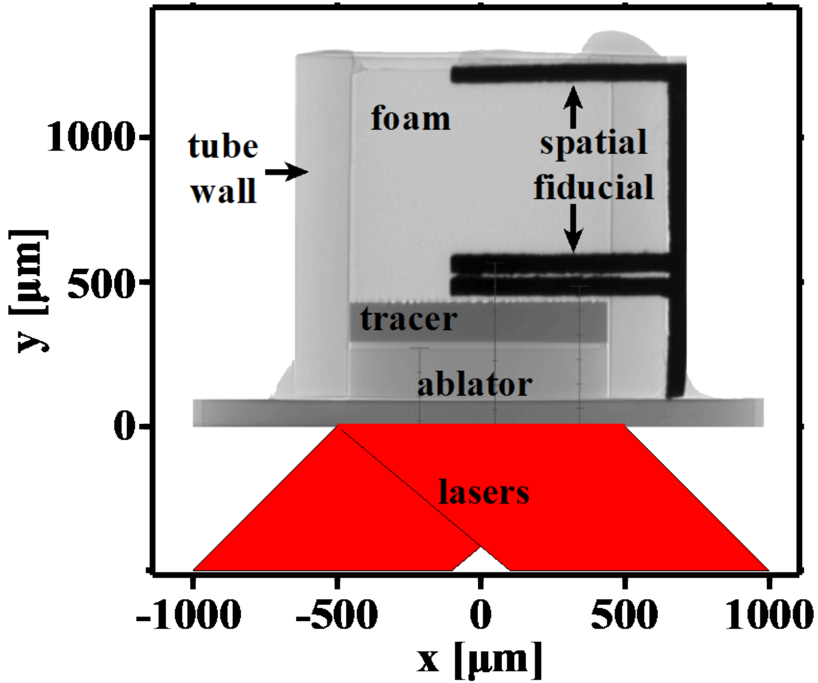

C.A. Di Stefano et al., *Phys. Plasmas* **24**, 052101 (2017)
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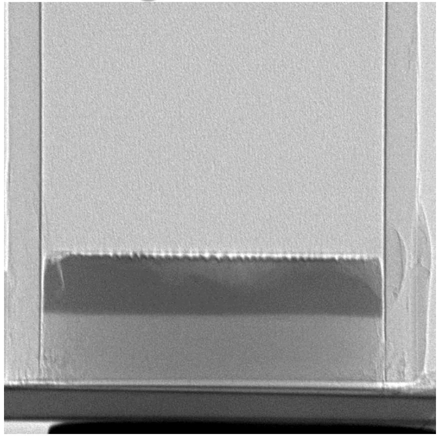
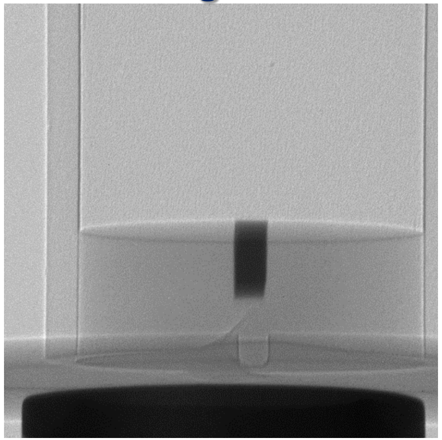
Localized doping increases fine-feature resolution

Diagnostic view



Edge-on



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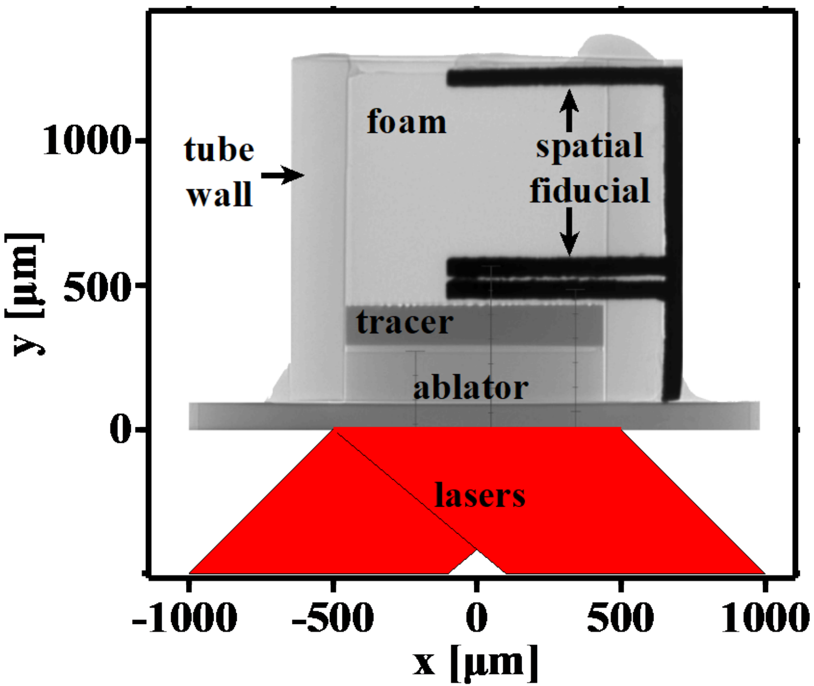
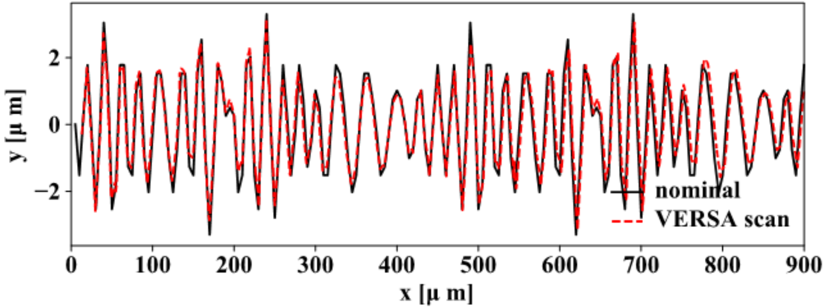
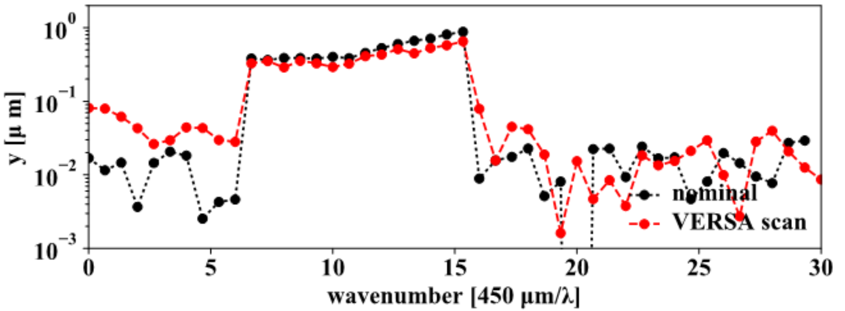


We can machine extremely complicated and precise interface profiles

Requested vs delivered surface profile



Requested vs delivered spectrum



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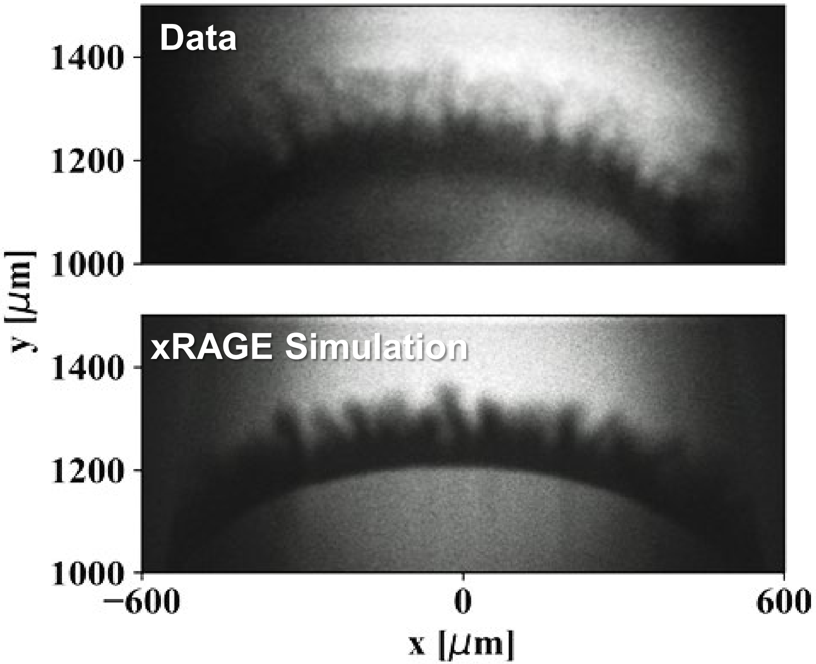
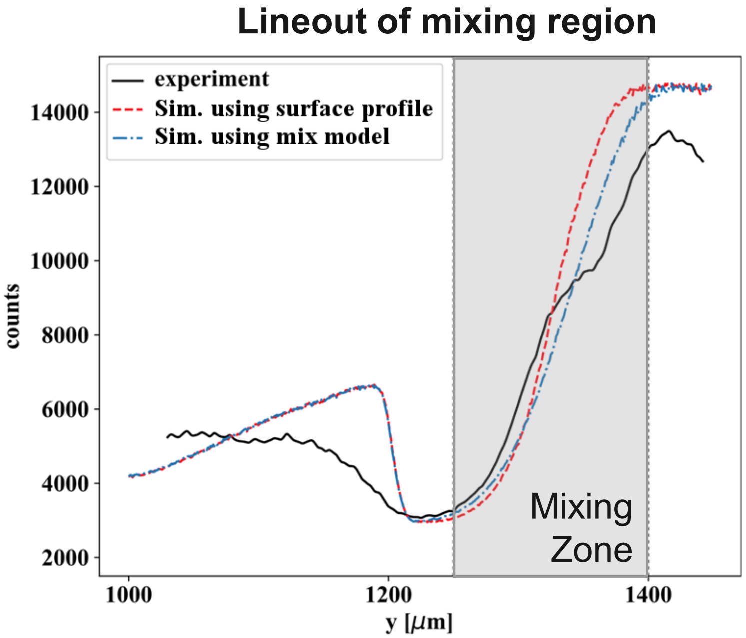
Traditionally we image the interface evolution and compare the 1D growth to our instability and turbulence models, in order to check if the models can capture the simplest mix metrics





Simulated 1D growth from two different model initializations shows reasonable agreement with experiment even with multimode initial conditions, giving us confidence in our model performance

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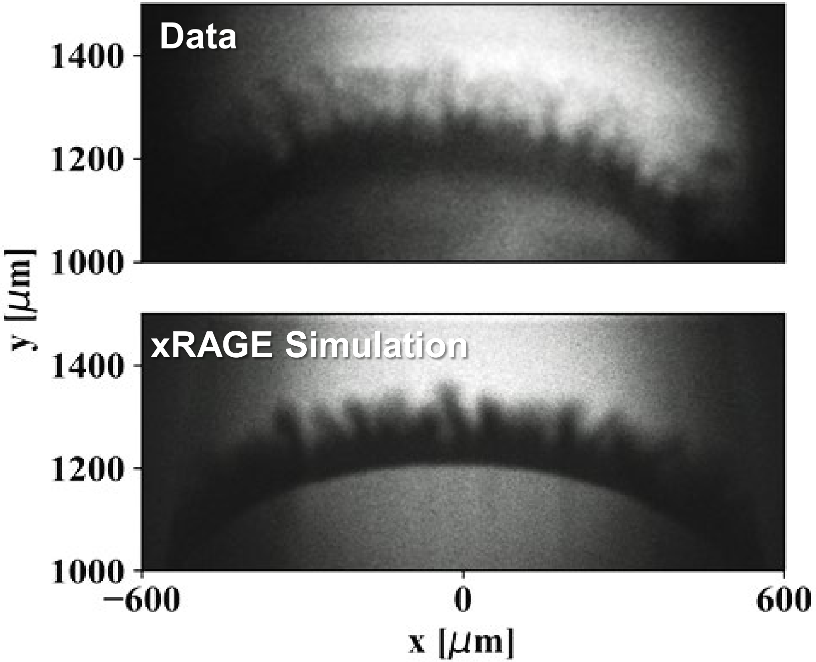
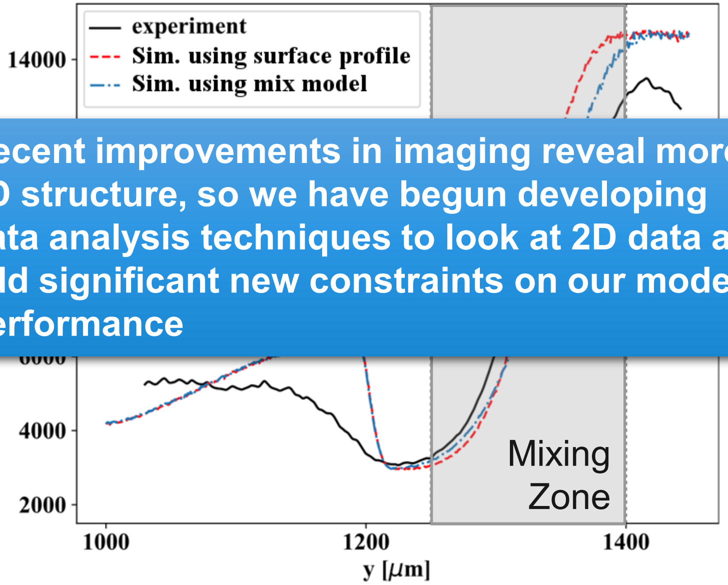


Lineout of mixing region



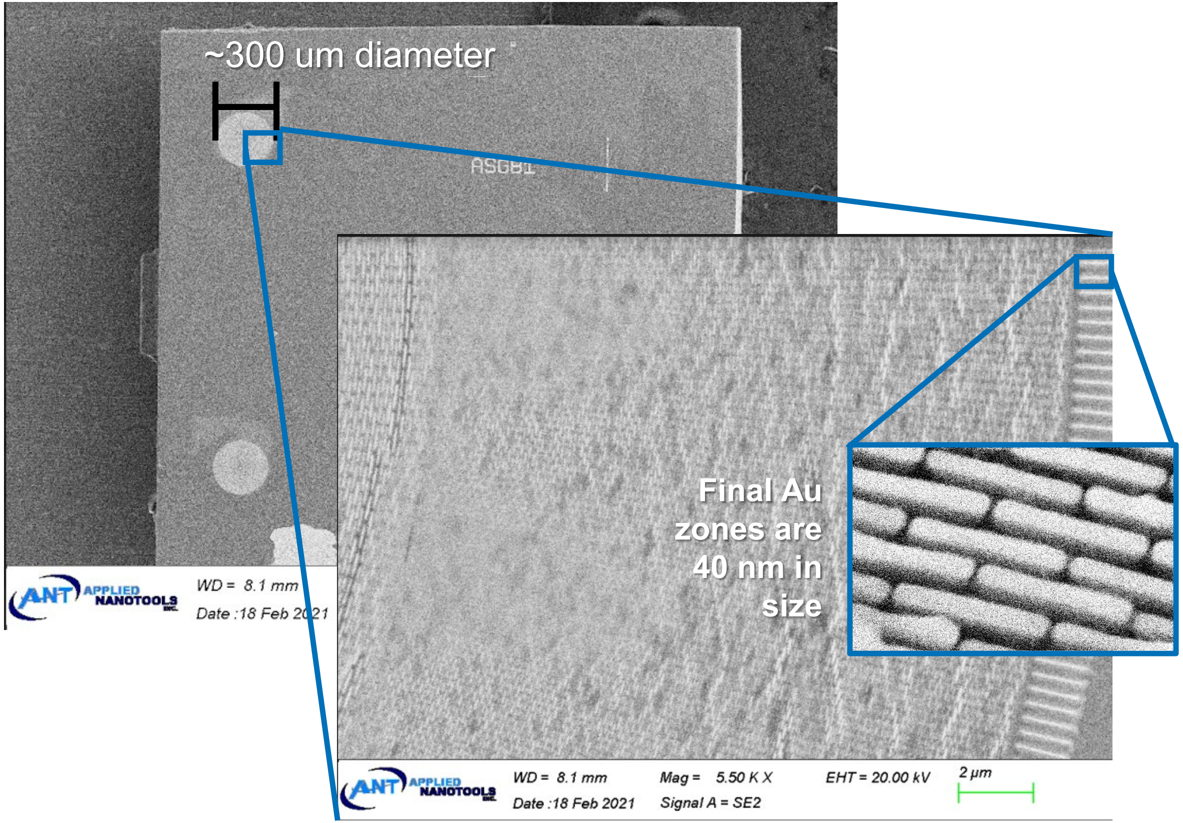
Recent improvements in imaging reveal more 2D structure, so we have begun developing data analysis techniques to look at 2D data and add significant new constraints on our model performance

Simulated 1D growth from two different model initializations shows reasonable agreement with experiment even with multimode initial conditions, giving us confidence in our model performance

Di Stefano *et al.*, *Phys. Plasmas* (2017)

LANL is developing higher-resolution imaging with X-ray Fresnel Zone Plates for our specifics needs on Omega and NIF

- Designed for x-ray through-put at 25x magnification with a **2-3 micron resolution** with a short working distance (higher flux).
- **Detailed forward model** under development (Sam Myren & Ben Tobias)
  - Model and verify performance objectives
  - **Design future improvements**
- Test in June on Omega



Slide courtesy of K. Flippo

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- **Detail** under Myren
  - M pe
  - **De im**
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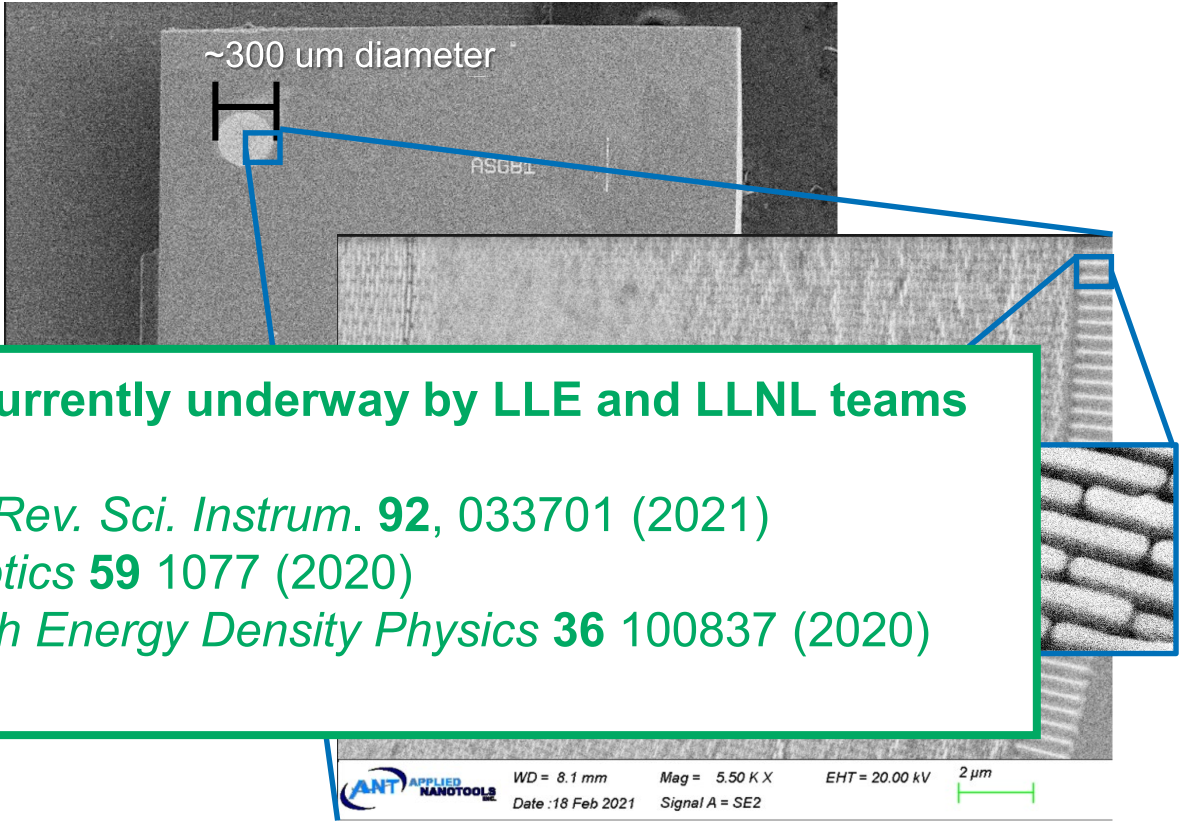

Based on work currently underway by LLE and LLNL teams

F. J. Marshall et al., *Rev. Sci. Instrum*. **92**, 033701 (2021)
A. Do et al., *App. Optics* **59** 1077 (2020)
K. Matsuo et al., *High Energy Density Physics* **36** 100837 (2020)

Slide courtesy of K. Flippo

The LANL RT/RM experiment suite is designed to isolate the contributions of individual physics as we build to complex systems

Add interfaces

ModCons

- 1 shock
- 1-interface

Examine linear phase RM + RT growth for comparison to the Modal Model

Mshock (Multi-interface)

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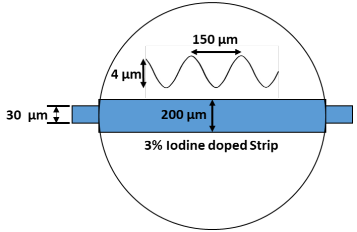
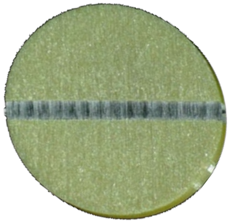
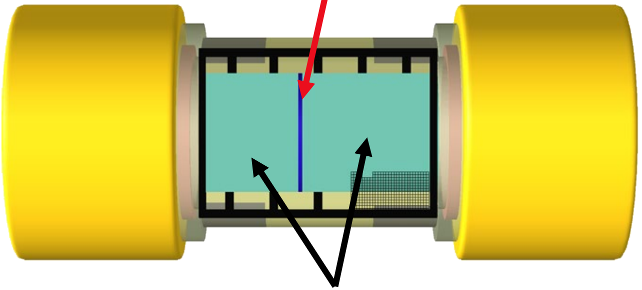
Perturbed CH layer (1.4 g/cc)
w/ CHI strip doping similar to ModCons







Low-density CH foam (100 mg/cc)

T.R Desjardins et al., *HEDP* **33**, 100705 (2019)

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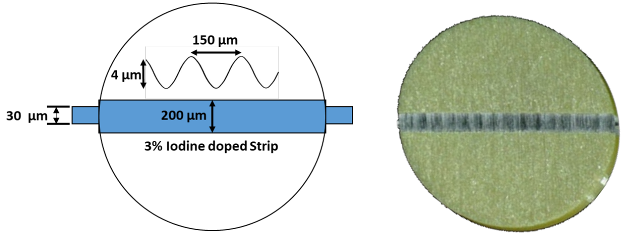

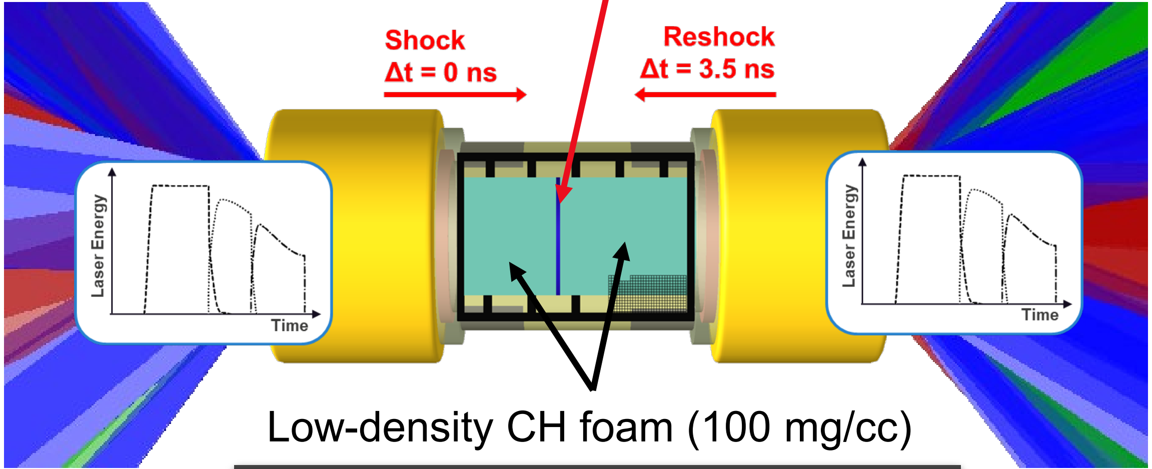

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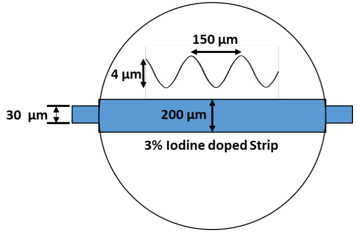
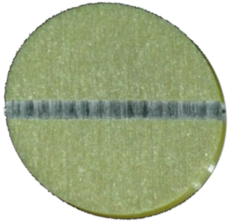
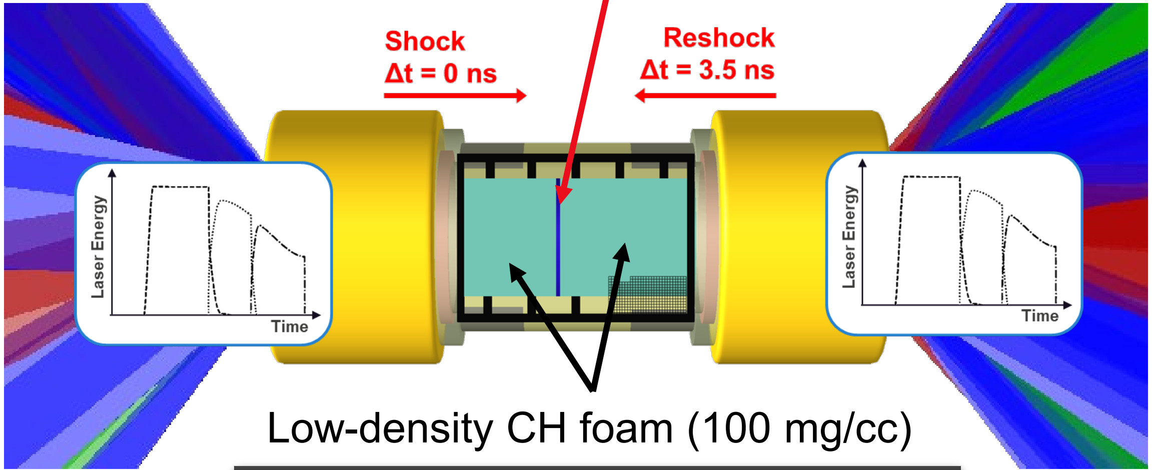




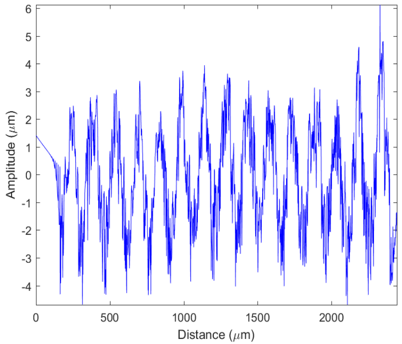


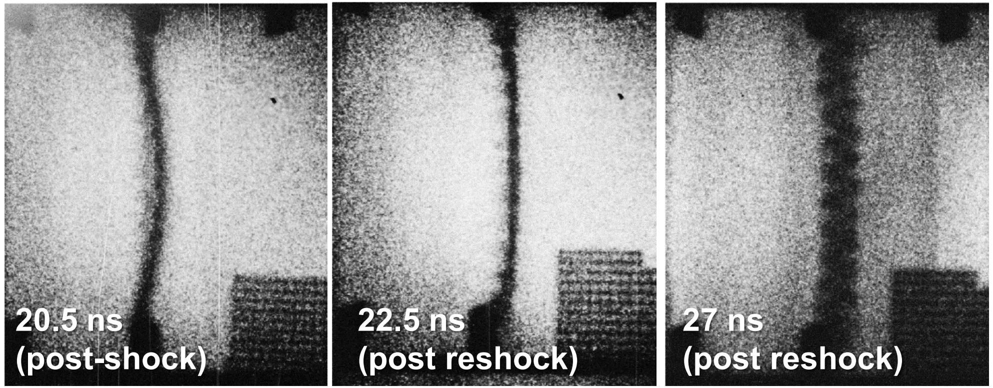
Early-time data looks at 2-interfaces w/ 1 shock

T.R Desjardins et al., *HEDP* **33**, 100705 (2019)

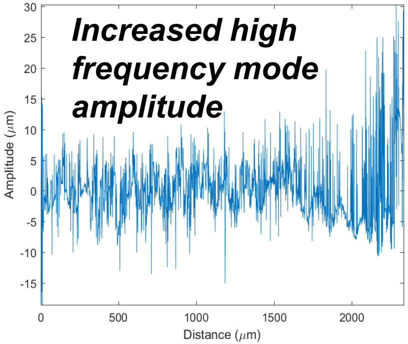
Thin-layer Mshock experiments show the ability to alter the large-scale instability growth by varying the small-scale initial conditions

Low-noise surface profile

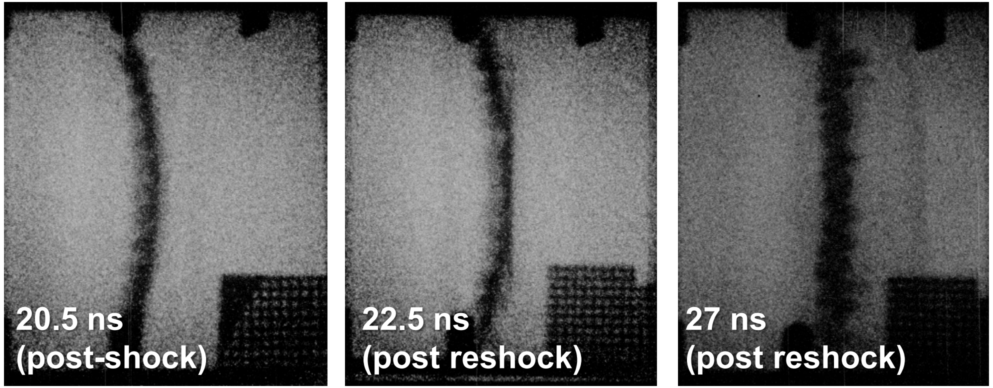




For our model to be applicable, it must be able to mimic this sensitivity to initial conditions



High-noise surface profile



We use these experiments to study BHR/Modal Model initialization schemes with combinations of large and small scale modes

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Add interfaces

Mshock (Multi-interface)

- ≤ 2 shocks fr
- 2-interfaces

Examine the inte
instability growth under shock and reshock
conditions

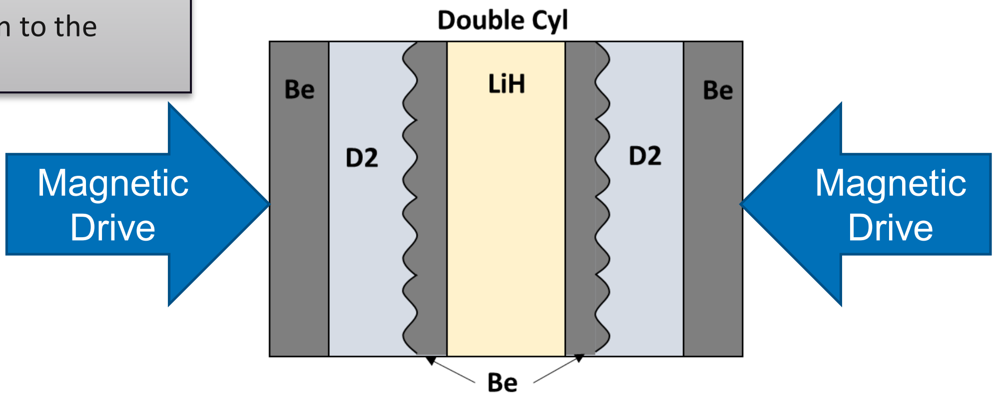
In collaboration with Sandia
Design: Forrest Doss (LANL)
Experiment: David Yager-Elorriaga (SNL)

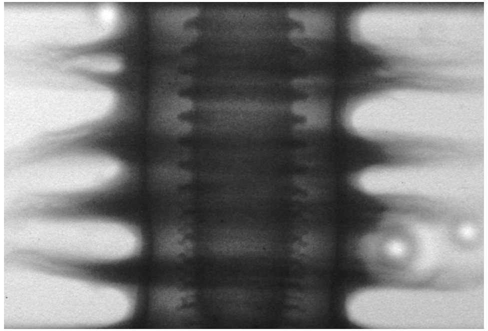
ModCons

- 1 shock
- 1-interface

Examine linear phase RM + RT growth for comparison to the Modal Model

We have also just begun a longer-growth time thin-layer experiment on Z at Sandia





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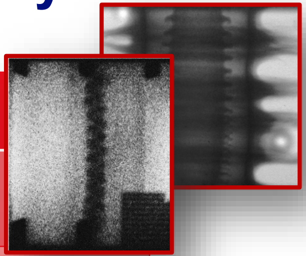

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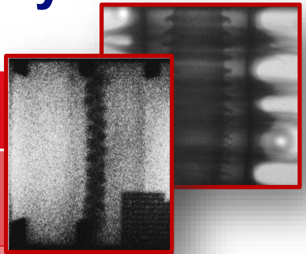

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LLNL Reshock* examines 1-interface w/ reshock

*Nagel *et al.*, Phys. Plasmas 24, 072704 (2017)

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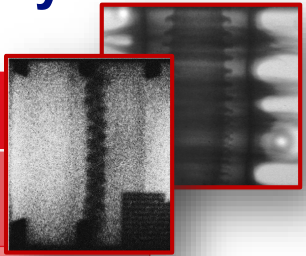

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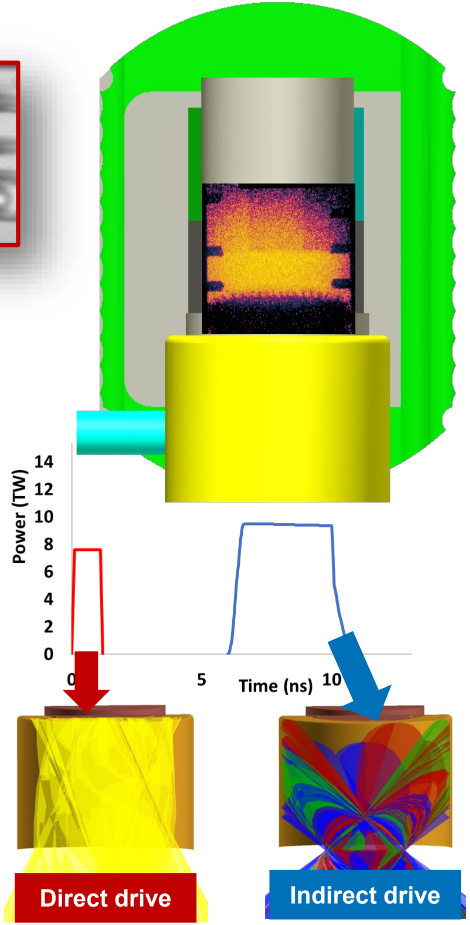
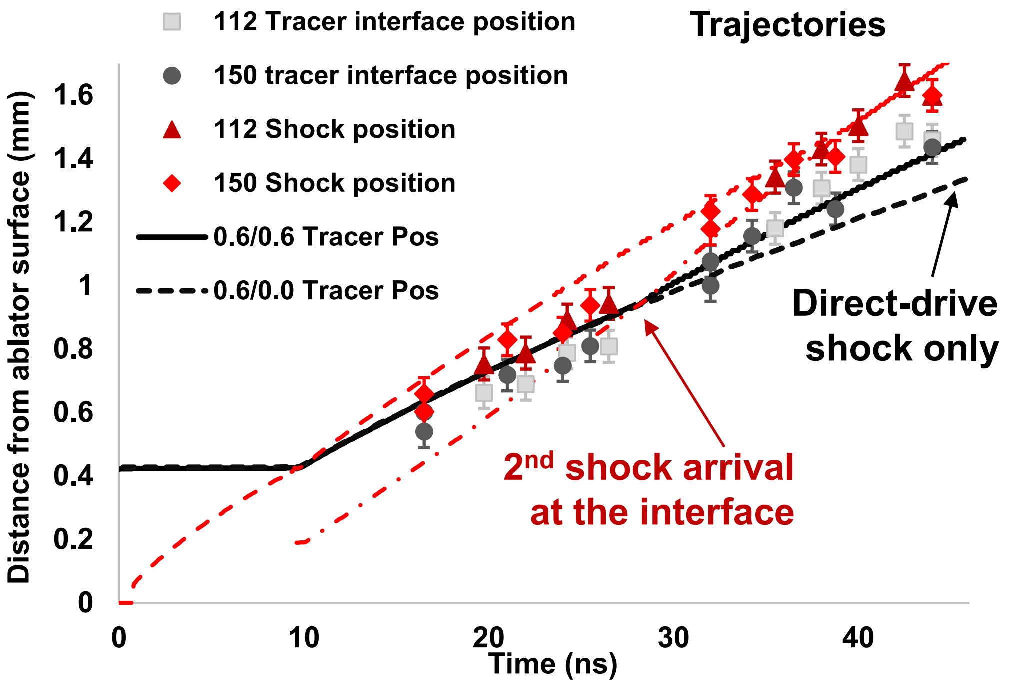


NIF Mshock experiments have shown the ability to create successive shocks, and the trajectory data is helping us refine our drive simulation capability w/ the laser package in xRAGE

With drive multipliers we are able to reasonably match the perturbed interface location, 2nd shock arrival, and shock location in the experiment

- Comparing drive tuning to physics models available in xRAGE to identify the source of drive degradation
  - CBET, non-local conduction, radiation diffusion, etc.

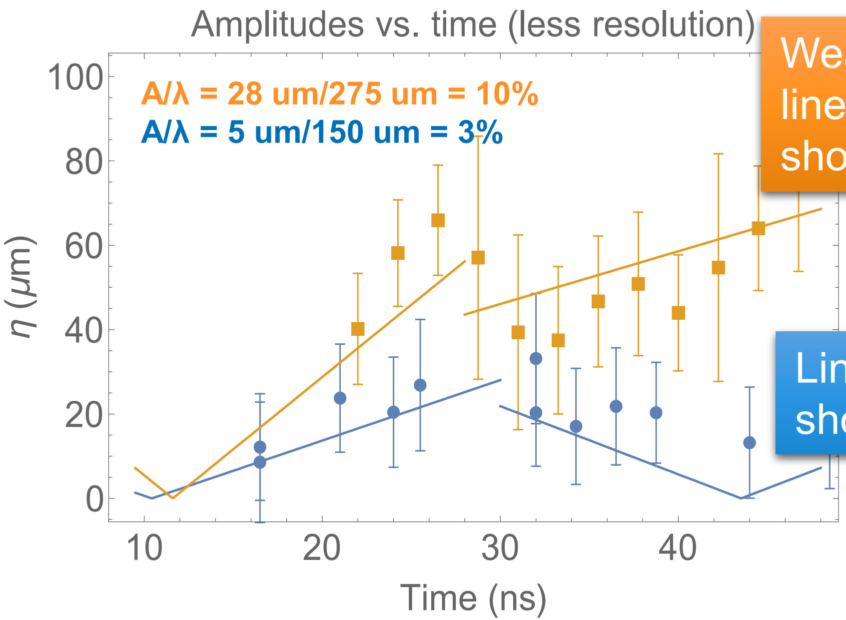
- We are also conducting code cross comparisons between xRAGE and HYDRA (LLNL)



See poster by C. Di Stefano

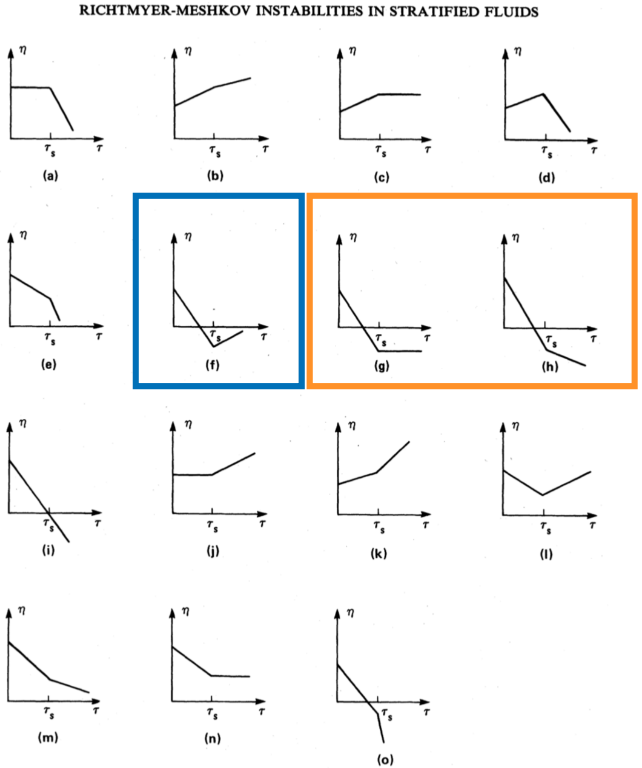
Successive shock experiments demonstrated the ability to vary the growth of a single-mode interface growth post-2nd shock based on interface linearity

Ideal theory* predicts 15 perturbation growth cases for a single mode under successive shocks



Weakly non-linear at 2nd shock arrival

Linear at 2nd shock arrival



The next step is to extend these studies into multi-mode regime for applicability to our turbulent mix model

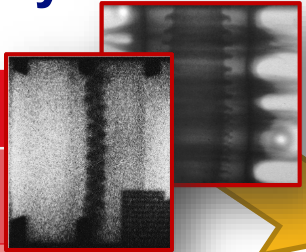
*Mikaelian, *PRA* 1985

The LANL RT/RM experiment suite is designed to isolate the contributions of individual physics as we build to complex systems

Add interfaces

Mshock (Multi-interface)

- ≤ 2 shocks from opposite directions
- 2-interfaces



Examine the interface coupling/feedthrough on instability growth under shock and reshock conditions

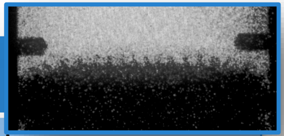
ModCons

- 1 shock
- 1-interface

Examine linear phase RM + RT growth for comparison to the Modal Model

Add shocks

Mshock (Multiple Shock)



- ≤ 2 shocks from same direction
- ≤ 2 shocks from the opposite direction
- 1-interface

Examine interface growth and transition to turbulence of a single interface (no feedthrough effects) with two successive shock from the same direction, and reshock from the opposite direction.

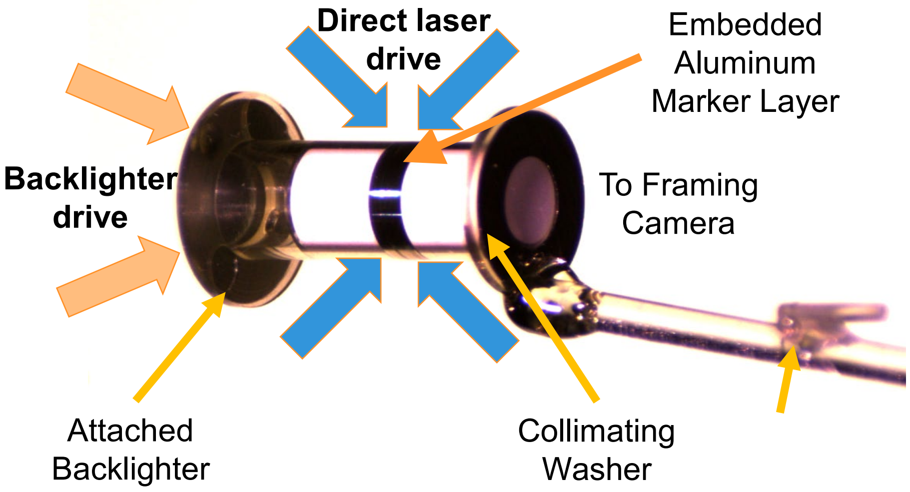
Mshock (multi-shock & multi-interface)

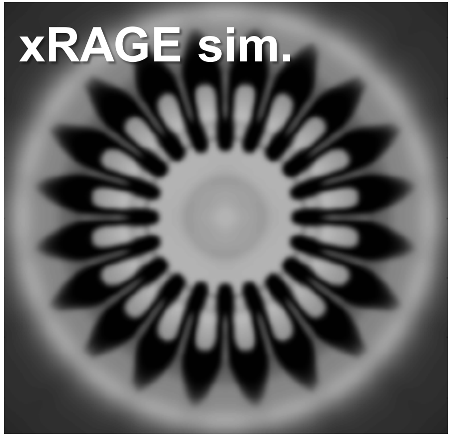
- ≤ 2 shocks from same direction
- ≤ 2 shocks from the opposite direction
- 2-interfaces

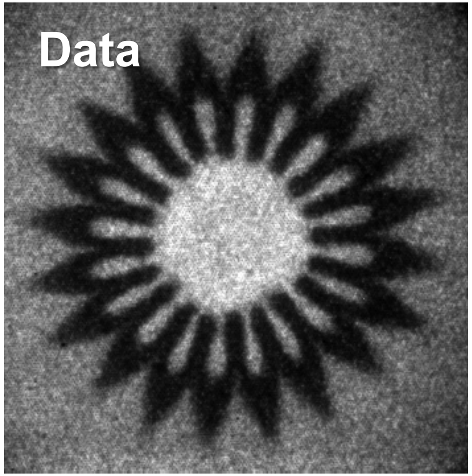
Add interface-coupling/feedthrough effects back into the study.

In addition to the planar RT/RM experiment suite, we are developing cylindrically imploding experiments to study the same physics with convergence effects

CylDRT Platform on Omega & NIF





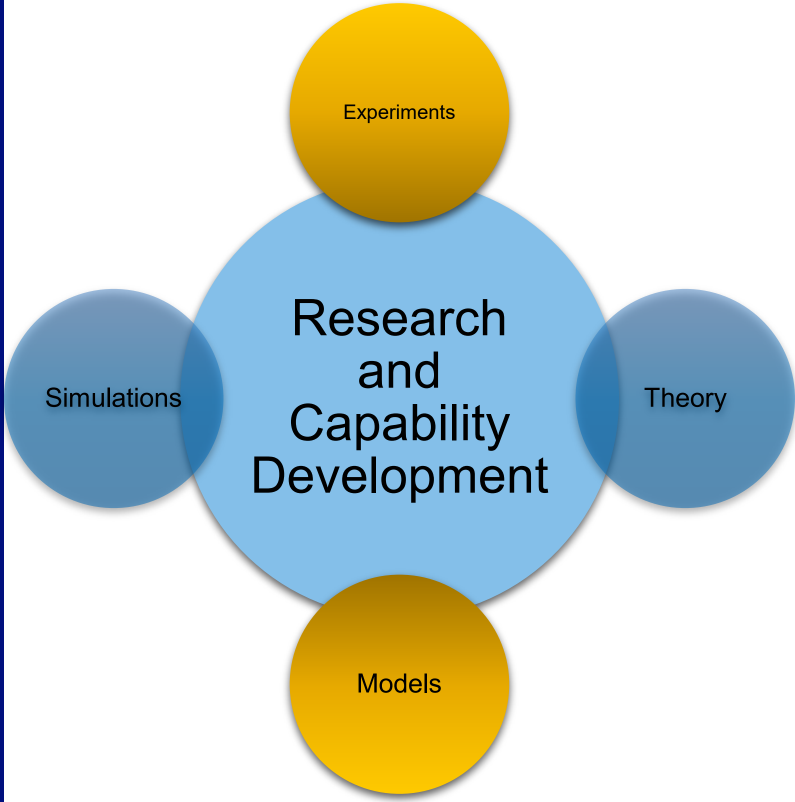


Current experiments have demonstrated feasibility at CR~ 5, and are pushing toward CR~10 (similar to Double Shells)

J. P. Sauppe et al. *Phys. Rev. Lett.* **124**, 185003 (2020)
S. Palaniyappan et al. *Phys. Plasmas* **27**, 042708 (2020)
J. P. Sauppe et al. *High Eng. Dens. Phys.* **36**, 100831 (2020)

Slide courtesy of J.P. Sauppe

Since all our platforms use radiography as our main diagnostic, we can use similar data analysis techniques across all experiments to extract metrics for comparison to our models



Recent improvements in imaging allow us to develop more sophisticated 1D & 2D data analysis to add significant new constraints on our model performance

1D Data Analysis

- Interface trajectory
  - Constrains simulated shock parameters for instability initial conditions
  - Used in development of laser drive simulation capability, e.g. the DRACO laser package in xRAGE **(see Di Stefano poster)**
- Mix-width
  - Single-mode perturbation growth tests 0th order applicability of analytical and computational model in HED
  - Multi-mode perturbation growth tests 1D turbulent mix model applicability and performance in HED

2D Data Analysis

- Interface spectral analysis
  - Test how well models handle mode-coupling in multi-mode systems
  - Measure mode feed-through in multi-layer systems
- ‘b’ analysis (density fluctuation analysis)
  - Use quantitative radiography to measure density fluctuations and calculate profiles of approximate model parameter *b*
  - Test BHR performance in HED, for multiple BHR initialization schemes, for b time-evolution on a surface and across a thin layer

We are implementing techniques like forward modeling, Bayesian inference, and machine learning

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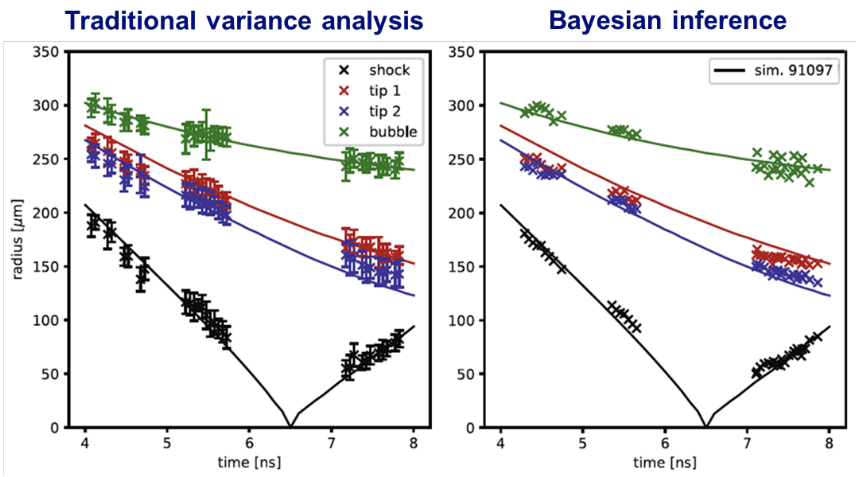

B. Tobias et al., *HEDP* **37**, 100879 (2020)

on a surface and across a thin layer

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1D

- In
  -
  -
- M
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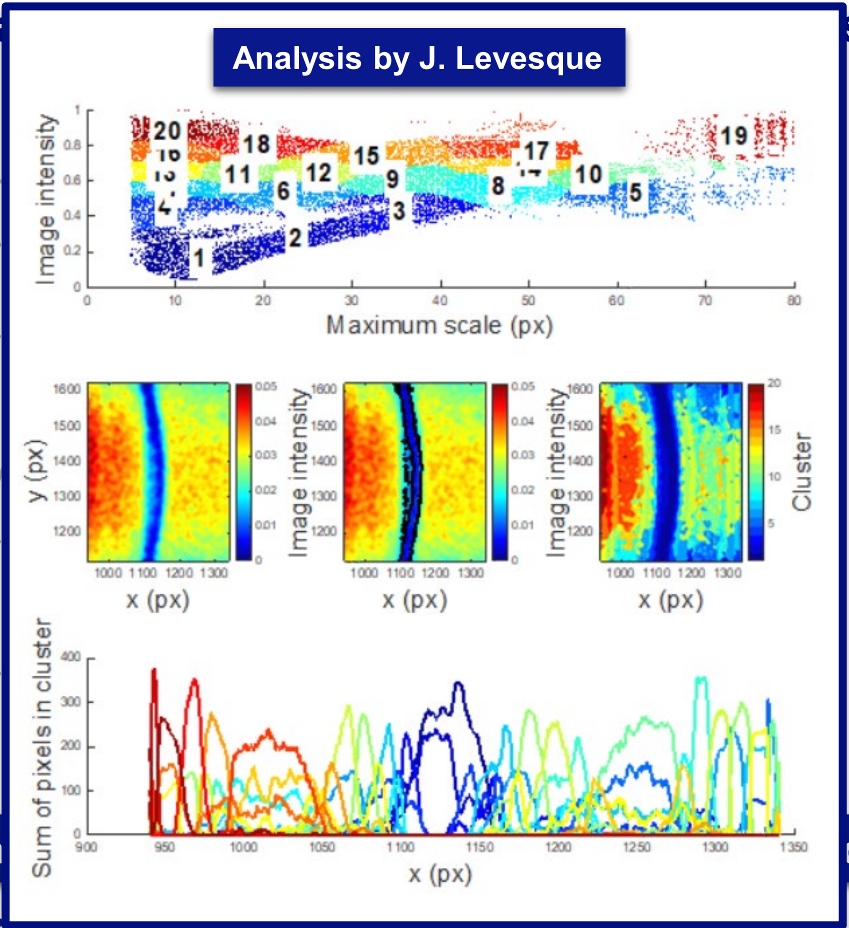

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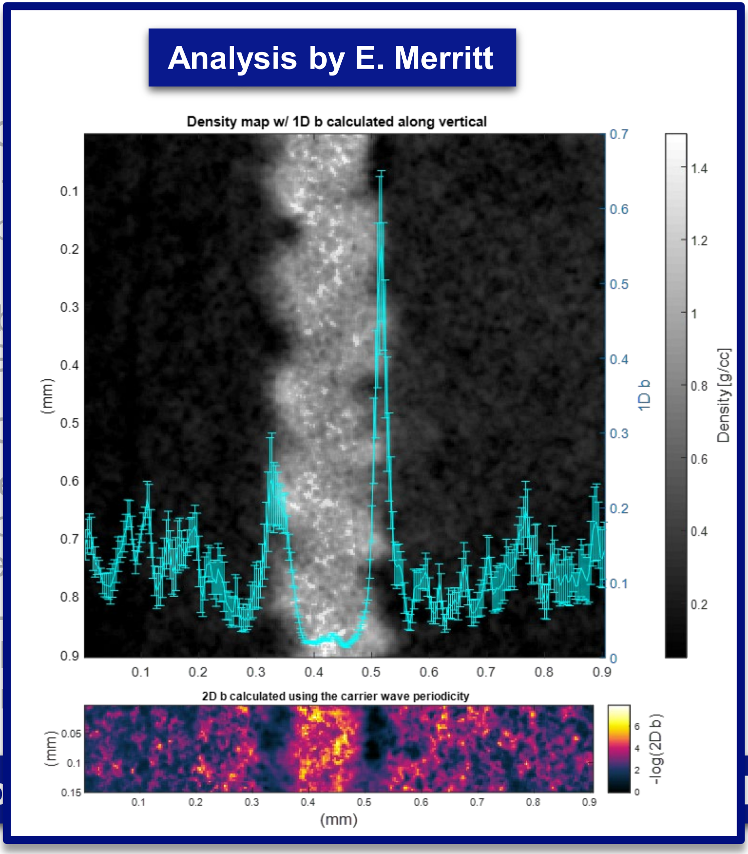
1D Data

- Interfac
  - Cons
    instab
  - Used
    capab
    xRAG
- Mix-wid
  - Singl
    applic
    mode
  - Multi-
    turbul
    perfor



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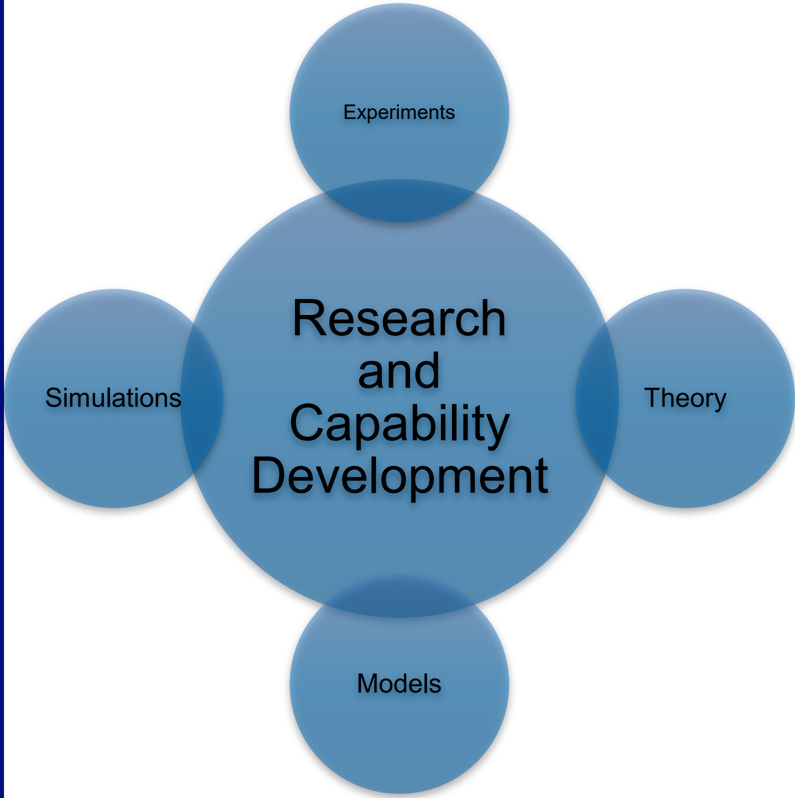
The high-energy-density (HED) hydro-instability program is extending instability and turbulence experiments into the HED regime

- A focus of the LANL HED hydro-instability program is to test applicability and performance of our BHR mix model outside fluid parameter space
- The LANL HED hydrodynamics program is designed to start with the simplest cases of isolated physics, and build towards fielding and understanding more complex systems for comparison to our models
- We currently have a suite of platforms designed to test RM growth under both single- and multiple-interface and shock conditions
- We are taking advantage of imaging improvement and developing a suite of new data analysis techniques to extract new 1D and 2D metrics for constraining our models

Thank you!


Experiments
Simulations
Research and Capability Development
Theory
Models

We also maintain collaborations with universities and other national labs across the country

- LLNL: Alex Do, Bernard Koziozieмski, Sabrina Nagel
- General Atomics: Mario Manuel, Reny R Paguio, Kurt Tomlinson
- Sandia: David A Yager-Elorriaga, Patrick F Knapp, Chris Jennings, Gabriel A Shipley, Andrew J Porwitzky, Daniel E Ruiz, Matt R Martin, Carlos Aragon
- UMich: Carolyn Kuranz, Eric Johnsen, Sallee Klein, with students Sam Pellone, Codie Fiedler-Kawaguchi, Kwyntero Kelso
- Virginia Tech: Bhuvana Srinivasan, Dave Higdon and student Nomita Vazirani
- University of Rochester: Petros Tzeferacos, Y.-C. Lu
- University of Alberta: Amina Hussein
- University of California, Irvine: Franklin Dollar
- LLE: Fredrick Marshall, J. J. Ruby, Dan Haberberger, Christian Stoeckl, Jonathan Peebles
- IAEC-NNRC: Assaf Shimony, Guy Malamud

A focus of the LANL HED hydro-instability program is to test applicability and performance of our BHR mix model outside fluid parameter space

BHR is currently a two-length scale turbulence model* implemented in our xRAGE hydrocode

2 length scale model (energy + scale)

Decay scale

Transport scale

Reynold's Stress Tensor

Multiple species inclusion

Mass flux

Density-specific-volume covariance (...ness)

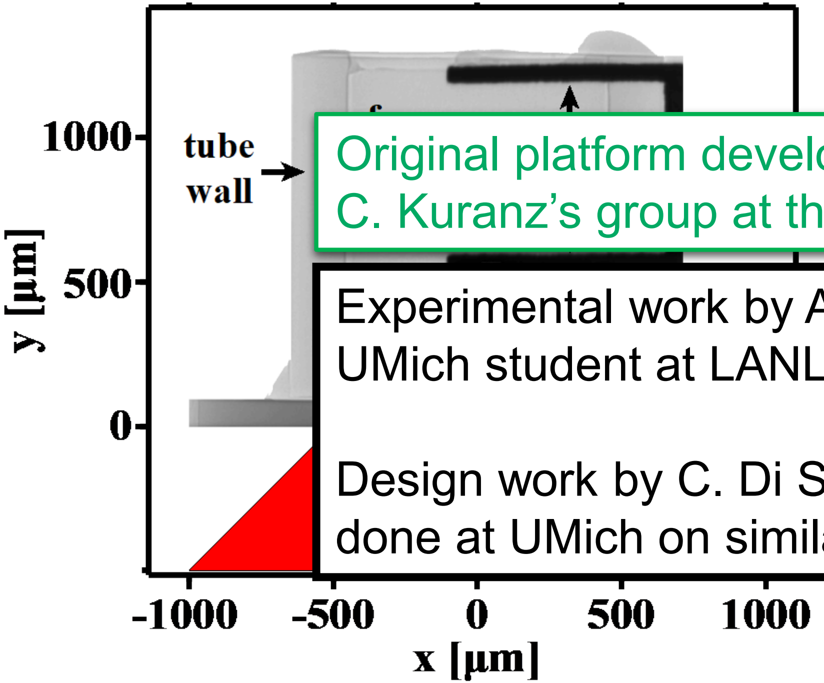
$$\mathbf{k_{ij} - L_D - L_T \quad a_i}$$

LLNL has also implemented a variable-density two-length-scale k-l-a model

Morgan *et al*, Phys. Rev E **97**, 013104 (2018)

***Schwarzkopf *et al*. Flow Turbulence Combust 96 (2016)**

Many of our HED experiments use planar interfaces so we can more easily diagnose and understand the complex dynamics of perturbation growth and transition to turbulence

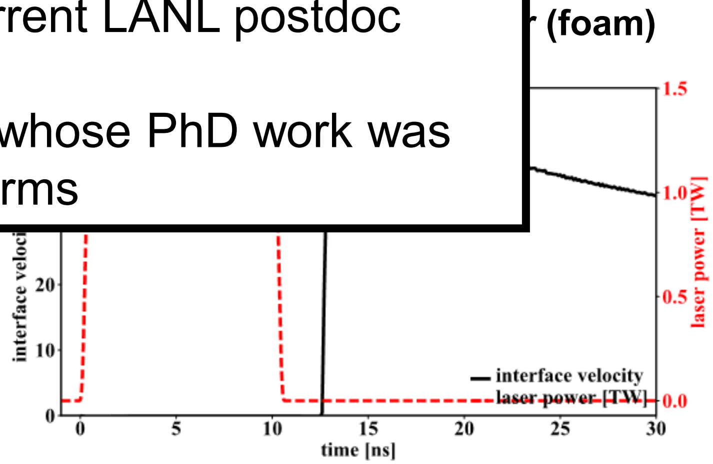


Our simplest experiment (ModCons) focuses on
ensuring we can calculate the evolution of
ofiles correctly
mode coupling

Original platform development in collaboration with C. Kuranz's group at the University of Michigan

Experimental work by A. Rasmus, while both a former UMich student at LANL and current LANL postdoc

Design work by C. Di Stefano, whose PhD work was done at UMich on similar platforms

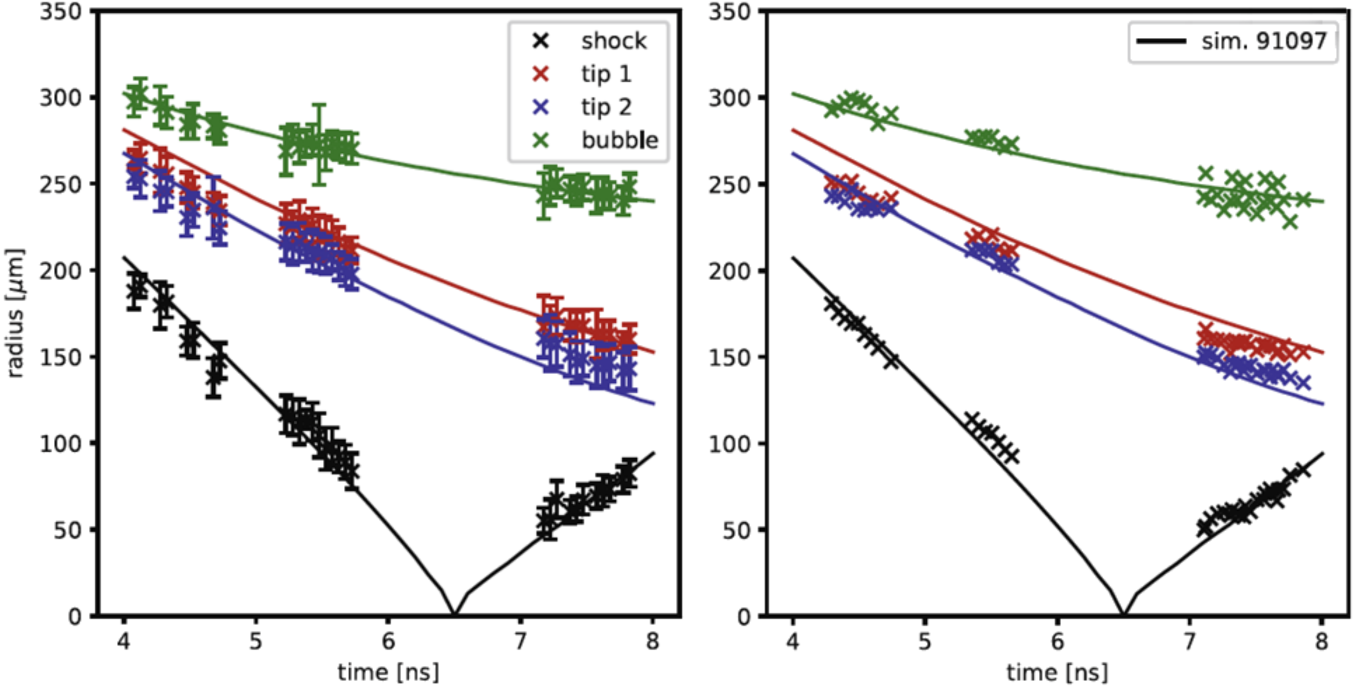


C.A. Di Stefano et al., *Phys. Plasmas* **24**, 052101 (2017)
C.A. Di Stefano et al., *Phys. Plasmas* **26**, 052708 (2019)

Bayesian methods have already improved mix-width quantification and reduction of uncertainty for our cylindrical implosion work

- Iterative forward modeling of radiographic scenes
- Self-consistent inferences of magnification, layer position, velocity and width
- Development of tools that allow time-dependent constraints and hydrodynamically consistent inferences

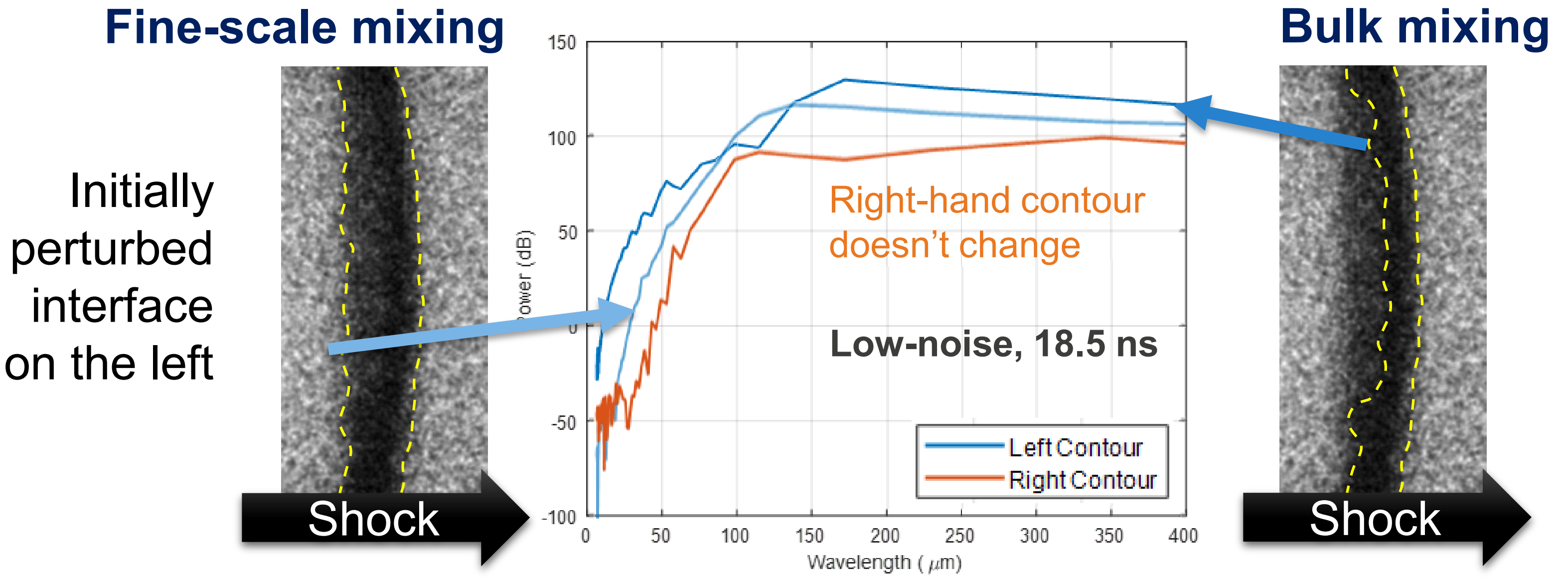
Traditional variance analysis | **Bayesian inference**



B. Tobias et al., *HEDP* **37**, 100879 (2020)

Slide courtesy of B. Tobias

In mixing layers with significant density gradients, where we choose a to draw a contour will effect what information about mix we capture

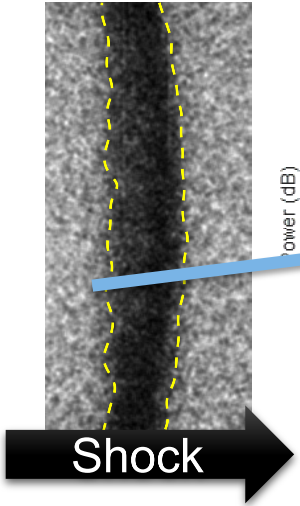


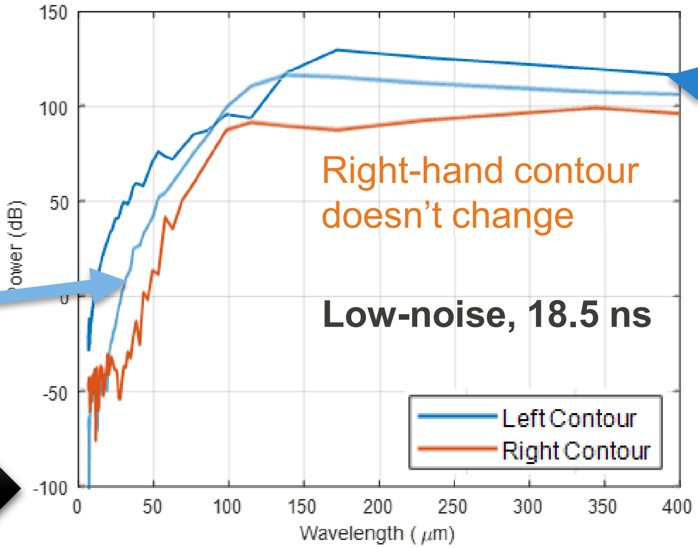
Analysis by T. Desjardins

In mixing layers with significant density gradients, where we choose a to draw a contour will effect what information about mix we capture

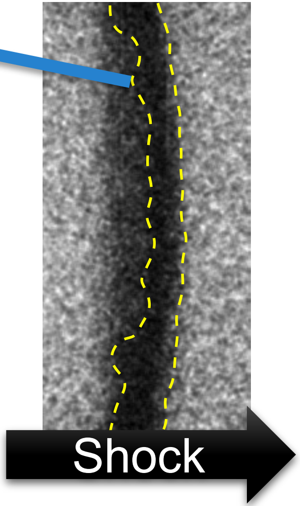
Fine-scale mixing

Initially perturbed interface on the left





Bulk mixing

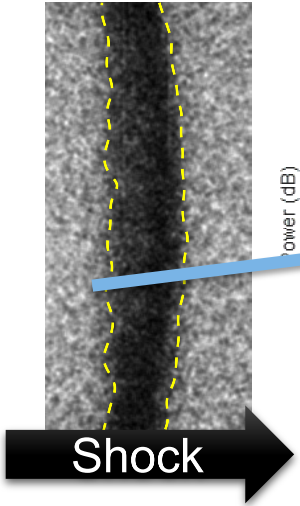


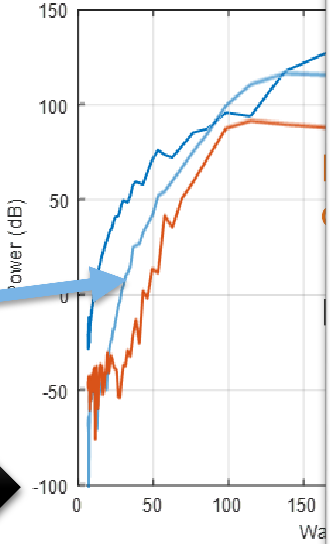
Former postdoc, now staff working on the VST
Analysis by T. Desjardins

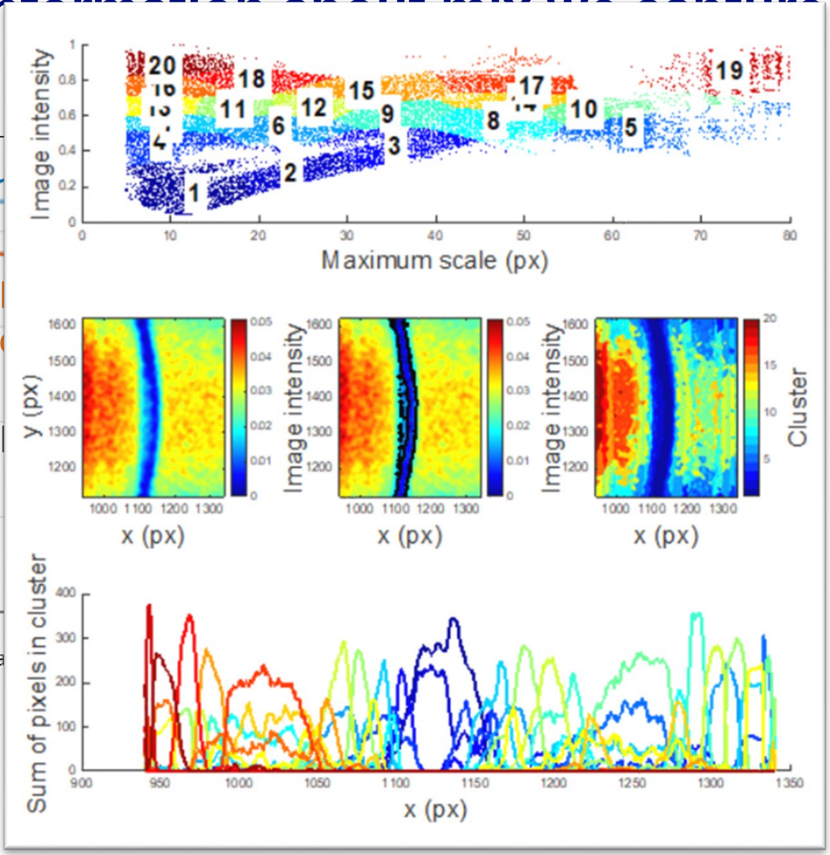
In mixing layers with significant density gradients, where we choose a to draw a contour will effect what in

Fine-scale mixing

Initially perturbed interface on the left





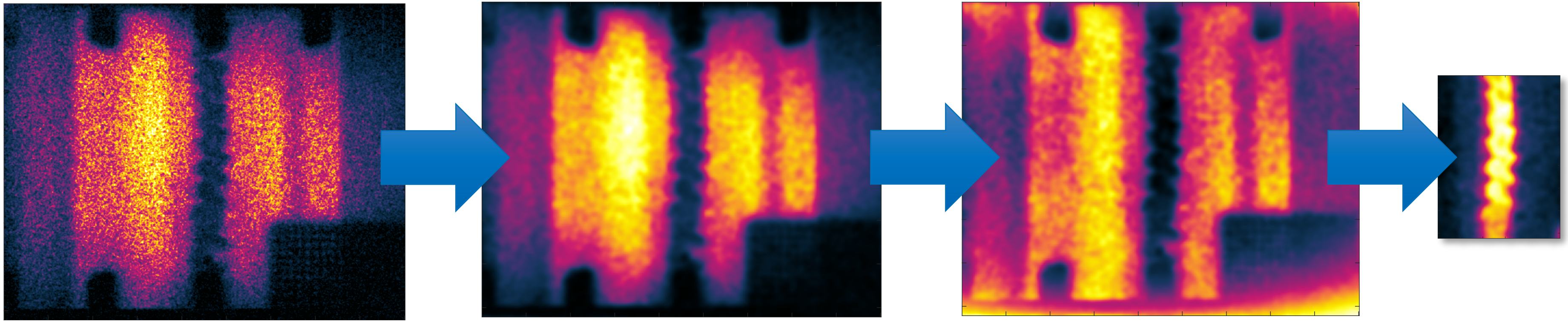


We are pursuing machine learning techniques for identifying different density mixing regions in our data for spectral analysis

Analysis by J. Levesque

The challenges of extracting ‘b’ (density fluctuations) are converting image intensity to material density, and removing diagnostic artifacts

Initial image → (Remove noise) → Denoised image → (Remove diagnostic artifacts) → Flattened image → (Calibrate to known transmission fiducial) → Transmission map → (Use information about material geometry and opacities) → Density map



Based on method from Kurien *et al.*, Physica D 405,132354 (2020)

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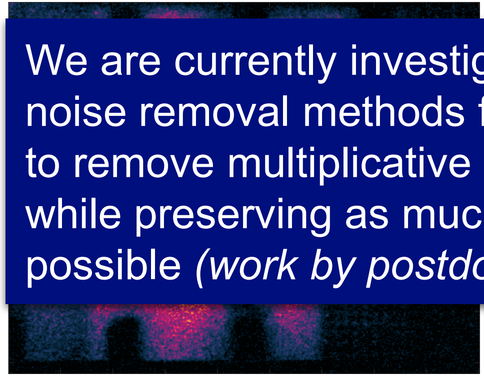

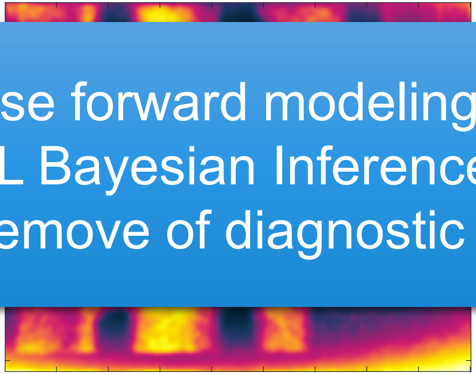

We are currently investigating modern noise removal methods from other fields to remove multiplicative image noise while preserving as much information as possible *(work by postdoc J. Levesque)*

We can use forward modeling tools, like the LANL Bayesian Inference Engine, to the remove of diagnostic artifacts

Based on method from Kurien *et al.*, Physica D 405,132354 (2020)

Measuring the *b* profiles gives a multiple comparison metrics for assessing model performance

- Width of the profile
  - Analogue to traditional ‘mix’ width
- Amplitude of the profile
- Shape of the profile
  - # of peaks
  - Peak symmetry/asymmetry
  - Valley depth and breadth