Hydrodynamic Instability Experiments in High-Energy-Density Plasmas

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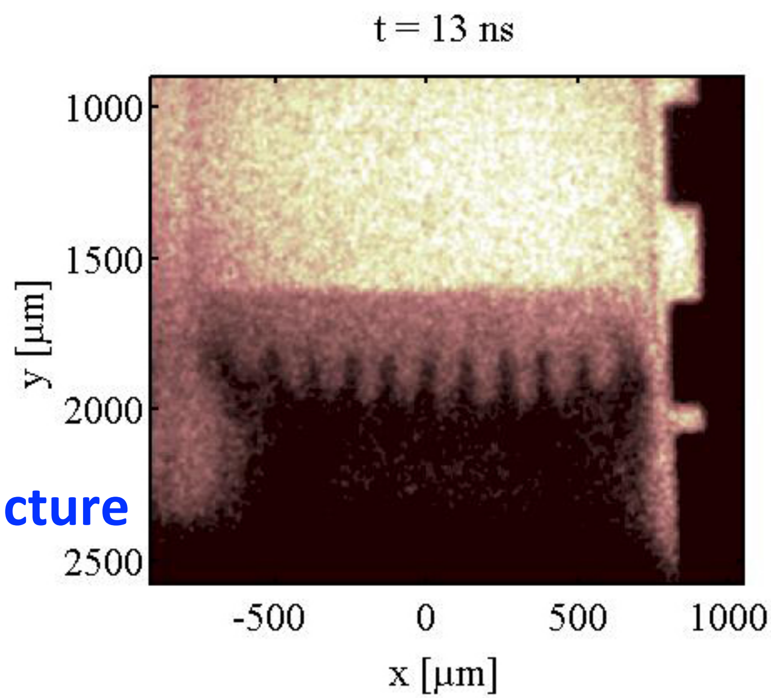
The Center for Laser Experimental Astrophysics Research studies high-energy-density phenomena that are relevant to astrophysics

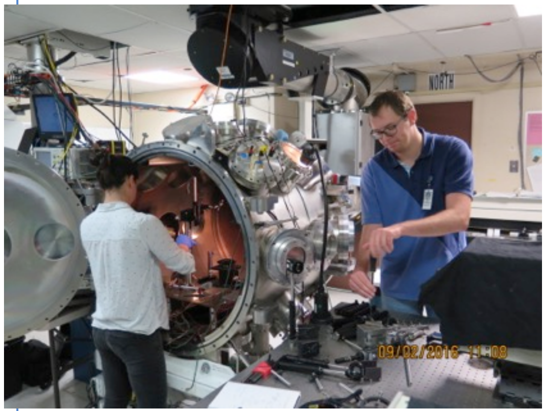
- **We advance fundamental understanding of HED dynamics relevant to astrophysics**
  - Radiation hydrodynamics
  - Complex HED hydrodynamics
  - Magnetized flowing plasma
- **While advancing the required infrastructure**
  - Computer simulation
  - Target fabrication
  - X-ray diagnostics
- **The ultimate goal of these activities is to train junior scientists**



X-ray radiography of a RT experiment at the National Ignition Facility with high energy fluxes

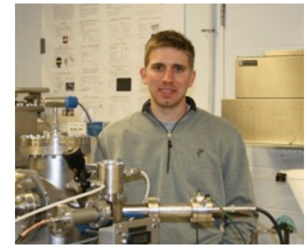
CLEAR team is oriented toward training students

- **Post Docs: Gray, Young**
- **Recent Grad students:**
  - Rasmus (LANL), Young (UM), Wan (LANL), MacDonald (UCB/LLNL), Fein (SNL)
- **Current Grad Students:**
  - Belancourt, Elgin, Levesque, VanDervort, Angulo, Lefevre, Coffing, Melean, (Ma, Cearly, Wadas)
  - Many undergrads (10)
- **We graduate about 1 – 2 students/year**
- **We have an excellent publication record!**
  - > 100 since 2009
  - ~12/year

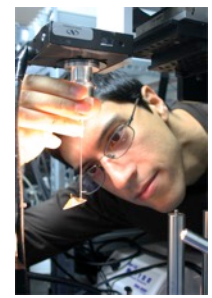


Our graduates have proven attractive to NNSA labs

- **Most of our students come through the UM Applied Physics Program**
  - Outstanding applicants; highly competitive
  - Diverse program – 30% women, 30% URM
  - Imes-Moore Fellowship (1st generation citizen, 1st generation college, financial hardship)
- **Since 2007 we have graduated 13 PhDs from CLEAR and its predecessors**
  - 8 went into the NNSA labs (3 LLNL, 3 LANL, 2 SNL)
  - 2 went into HEDP at SLAC and General Atomics
  - 2 remain in HEDP in universities
  - 2 went into industry



Harding, SNL



Di Stefano, LANL

Huntington, LLNL

CLEAR relies on experienced senior scientists with a breadth of experience

- **Faculty:**
  - Kuranz, Drake
- **Staff:**
  - Trantham, Klein, Gillespie

Kuranz

Drake

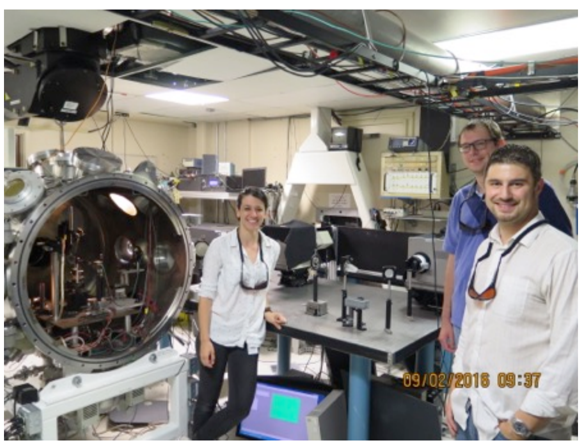
Klein

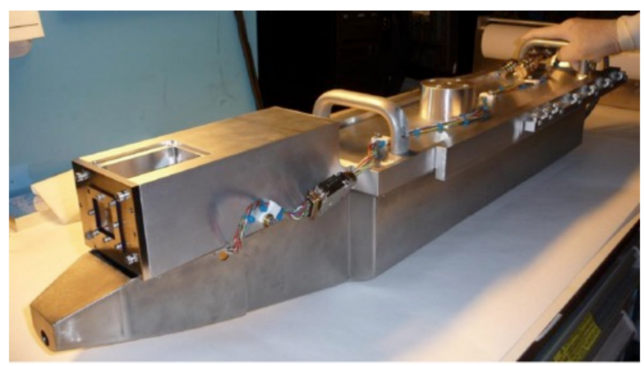
Trantham

- **Additional Faculty at UM:**
  - Johnsen (ME), McBride (NERS),
  - Willingale (EECS), Thomas (NERS)

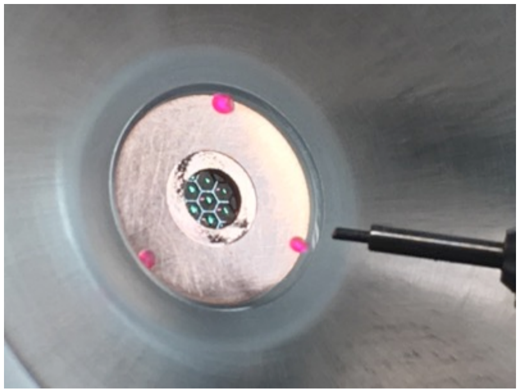
We experiment and collaborate at many HEDP facilities

Led by CLEAR:	Facility	Collaborative participation	Facility
Radiation Hydro	Omega	XRTS	Omega
Complex Hydro	Omega/NIF	LLNL Complex Hydro	Omega & NIF
Magnetized Flows	Omega/JLF	LANL Complex Hydro	Omega
Astrophysical Dust	Jupiter	Complex Hydro	LMJ
X-ray Thomson Scatt.	Omega/NIF	Radiative shocks	LMJ
		Magnetized Flows	LULI



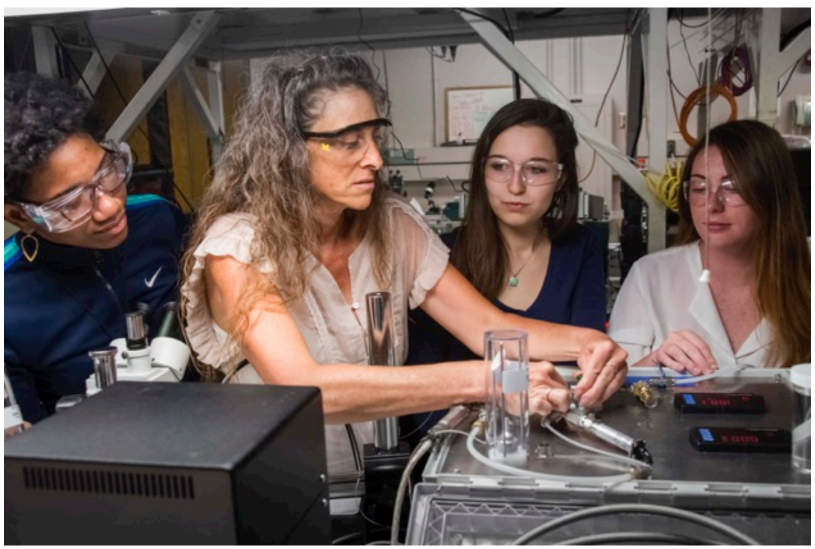


We have been fabricating targets for our experiments since 2004

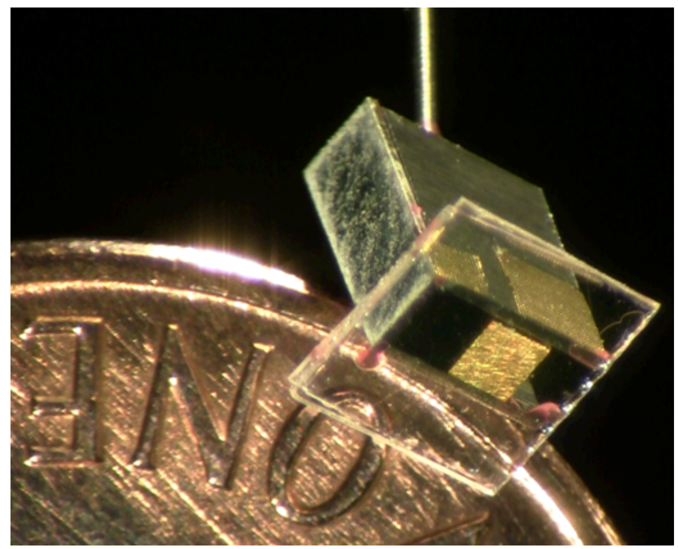


Components for photoionization front gas target

Some components are fabricated at General Atomics

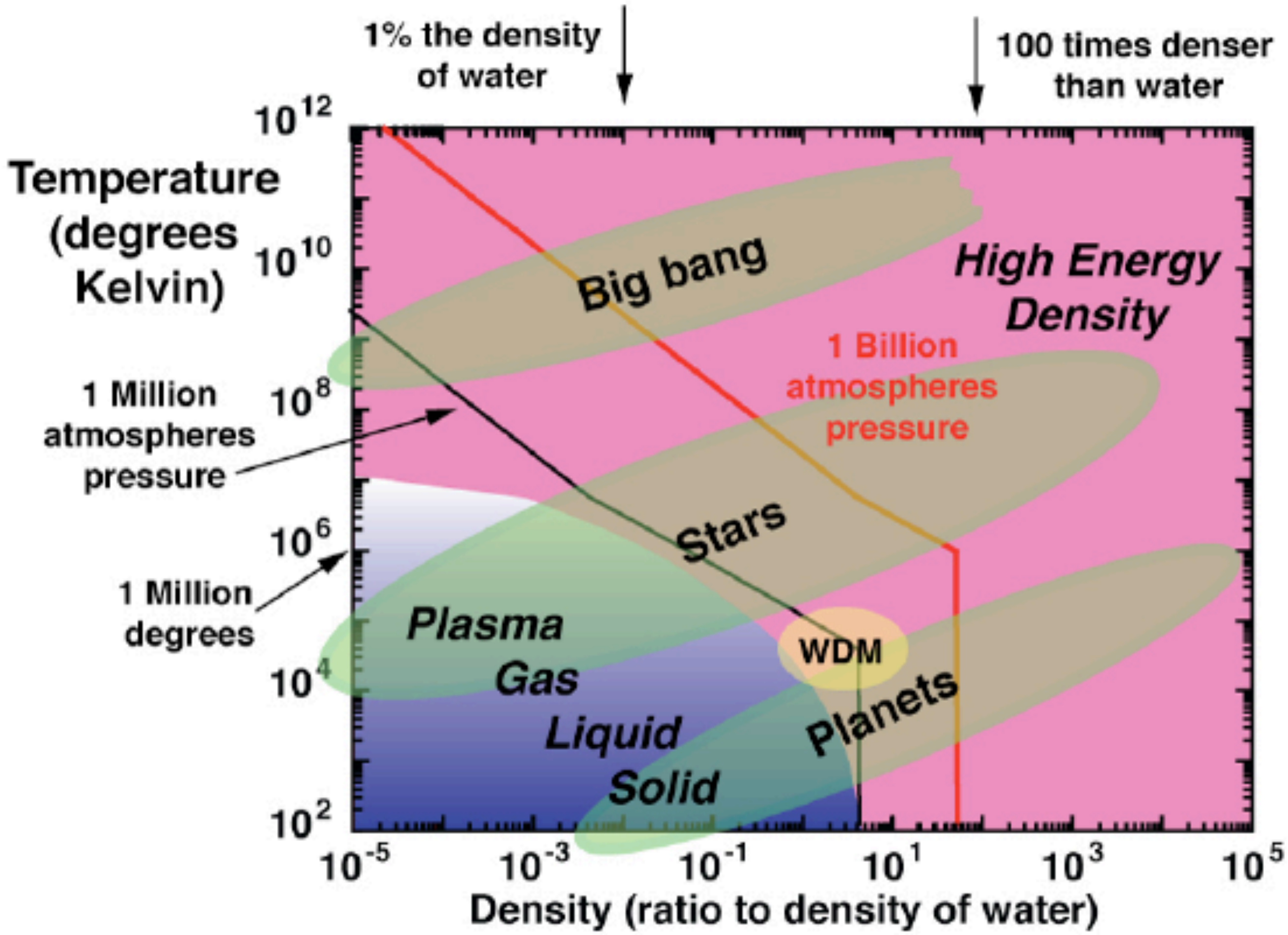


Sallee Klein and students gas filling targets at LLE



Omega-EP Kelvin Helmholtz target, Wan, Malamud

Where are these conditions found in nature?



R.P. Drake, *Physics Today*

Hydrodynamic fluids described by single-fluid Euler Equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\rho\left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v}\right) = -\nabla p$$

$$\frac{\partial p}{\partial t} - \gamma \frac{p}{\rho}\frac{\partial \rho}{\partial t} + \mathbf{v} \cdot \nabla p - \gamma \frac{p}{\rho} \mathbf{v} \cdot \nabla \rho = 0$$

- **See Ryutov et al. ApJ., 518, 821 (1999)**
  - **Supernova hydrodynamics, a young SNR, ring collision, and radiative SNRs**
- **See also Falize et al Astrophysics and Space Science 2009 and Cross et al Nature Communications 2016**

Euler Equations are invariant under transformation

If two systems are hydrodynamic and related by the transformation below then there is a direct correspondence between the two systems*

$$r_{SN} = a r_{lab} \qquad p_{SN} = c p_{lab}$$

$$\rho_{SN} = b \rho_{lab} \quad t_{SN} = a\sqrt{\frac{b}{c}}\, t_{lab}$$

	SN	lab
r	10^{11} cm	10^{2} μm
ρ	10^{-2} g/cc	1 g/cc
p	10 Mbar	1 Mbar
t	1000 s	10 ns

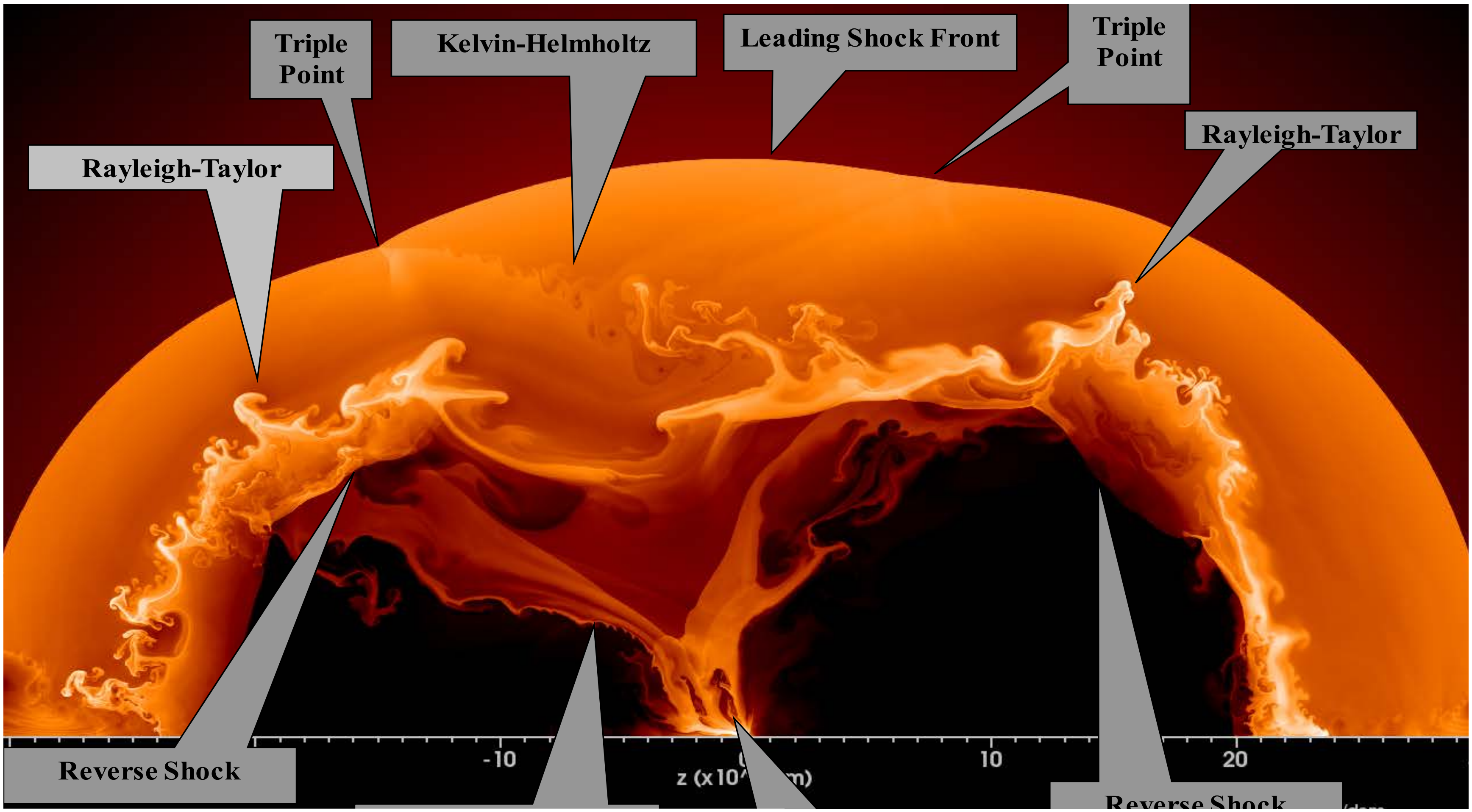
*Ryutov (1999)

Lab experiment must be in the same regime as astrophysical object

- System must be highly collisional, $\boldsymbol{\lambda_c << r}$
- Viscosity negligible, **Re >> 1**
- Heat conduction negligible, **Pe >> 1**
- Radiation flux negligible, $\mathbf{Pe_\gamma >> 1}$

	SN	lab
r/λ_c	10^6	10^4
Re	2.6×10^{10}	1.9×10^6
Pe	1.5×10^{12}	1.8×10^3
Pe_γ	2.6×10^5	…
τ_{BB}/τ_{hydro}	…	580

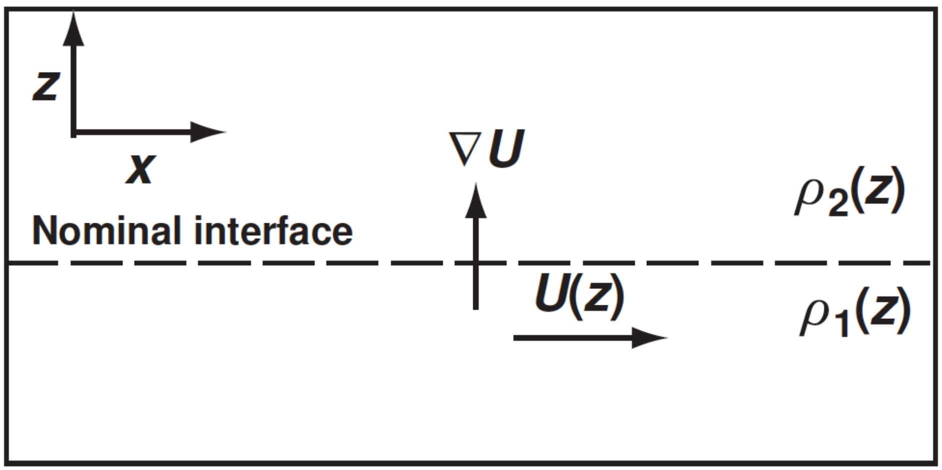
Hydrodynamics instabilities often occur in HED astrophysical systems



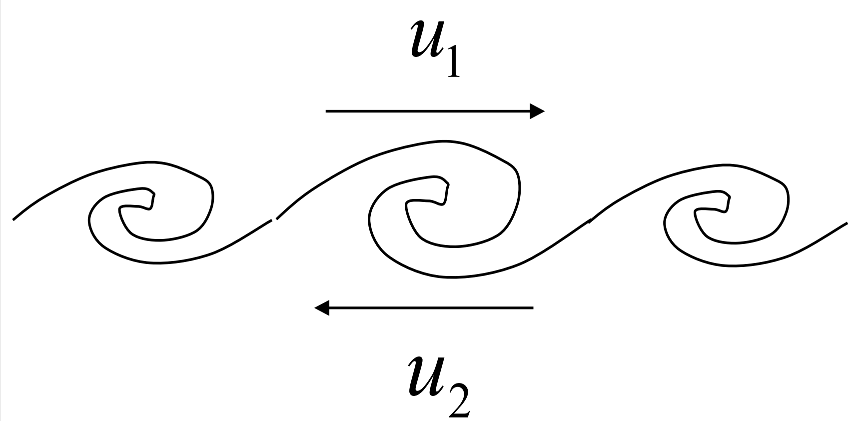
Ardent simulation from Tomek Plewa

Shear drives the Kelvin Helmholtz instability

Shear flow between two layers creates vorticity at the interface causing vortices to develop and grow



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

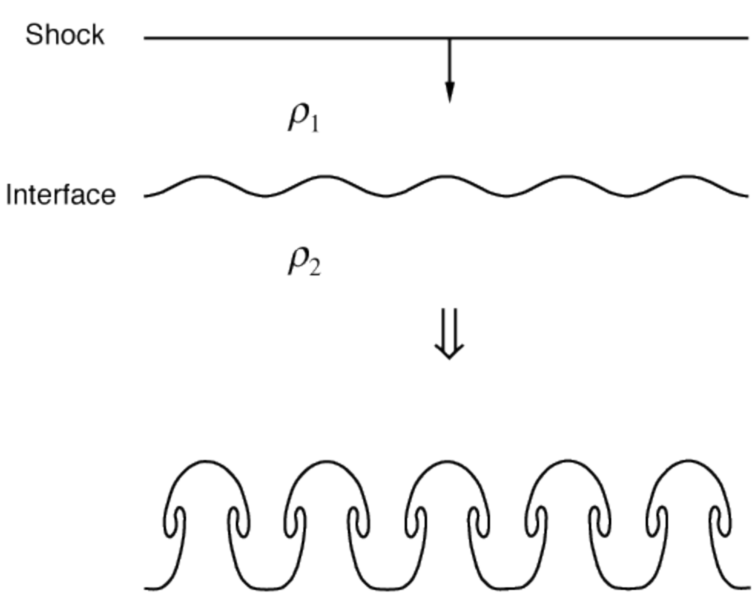


$$\gamma_{KH} = \frac{k(\Delta u)}{2}\sqrt{1 - A^2}$$

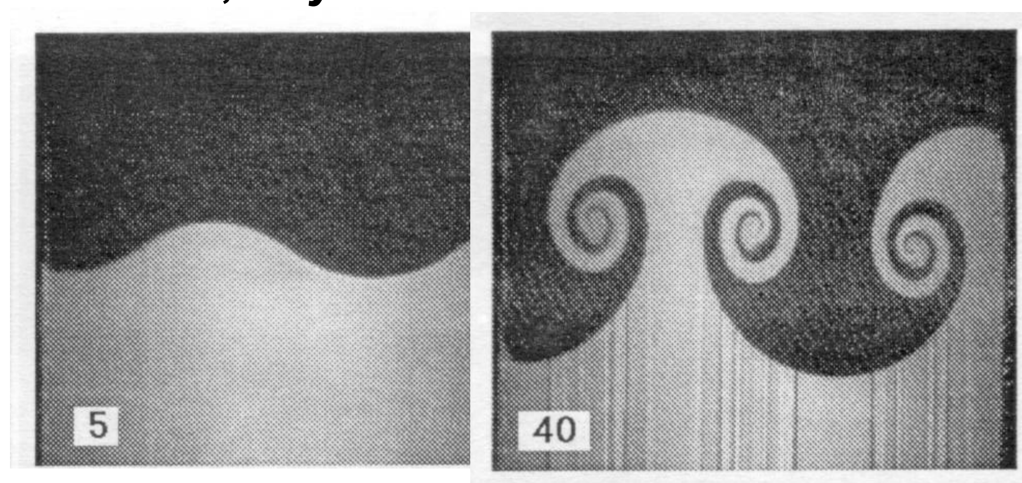
Vorticity drives the Richtmyer-Meshkov process

When a shock crosses a rippled interface, vorticity is deposited and causes the perturbation to grow

O. Schilling



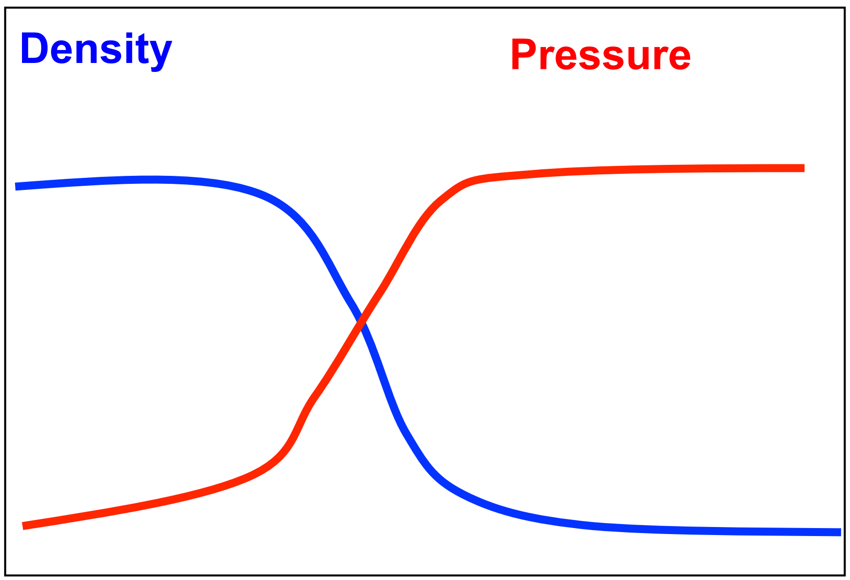
Jacobs, *Phys. Fluids* 2005



$$\frac{da_{RM}}{dt} = k u_{ps} A_{ps} a_{ps}$$

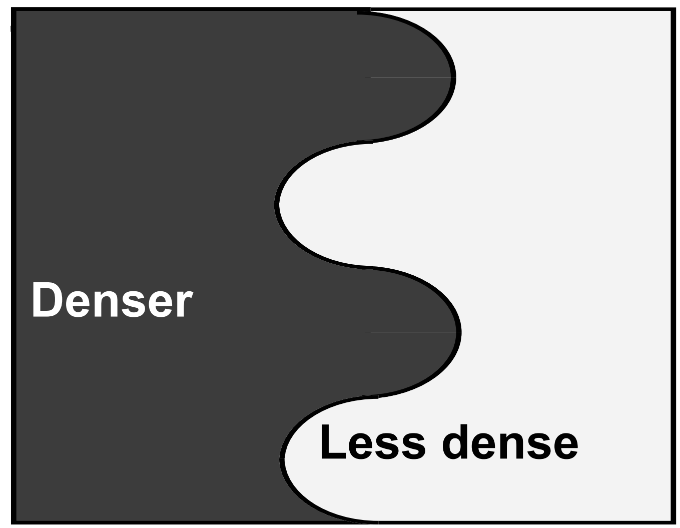
Buoyancy drives the Rayleigh Taylor instability

A blast wave crossing an interface with a drop in density, creates an opposing pressure and density gradient, and perturbations on the interface will grow



$$\nabla\rho \longrightarrow \quad \longleftarrow \nabla P$$

Acceleration $\longrightarrow$



$$\gamma_{RT} = \sqrt{Agk}$$

Benefits of performing hydrodynamic instability experiments using high-energy-density facilities

- **We use solid materials with known perturbations and density gradients**
- **"Drive" conditions (laser or pulsed power) can create different acceleration histories**
- **We can reach high *Re* = UL/ν and M = U/c_s**
- **We can explore radiative or magnetic effects**

Observation of Single-Mode, Kelvin-Helmholtz Instability in a Supersonic Flow

W. C. Wan,[1,*] G. Malamud,[1,2,†] A. Shimony,[2,3] C. A. Di Stefano,[1] M. R. Trantham,[1] S. R. Klein,[1] D. Shvarts,[1,2,3] C. C. Kuranz,[1] and R. P. Drake[1]

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[2]*Nuclear Research Center – Negev, Beer Sheva 84190, Israel*

[3]*Department of Physics, Ben Gurion University of the Negev, Beer Sheva 84190, Israel*

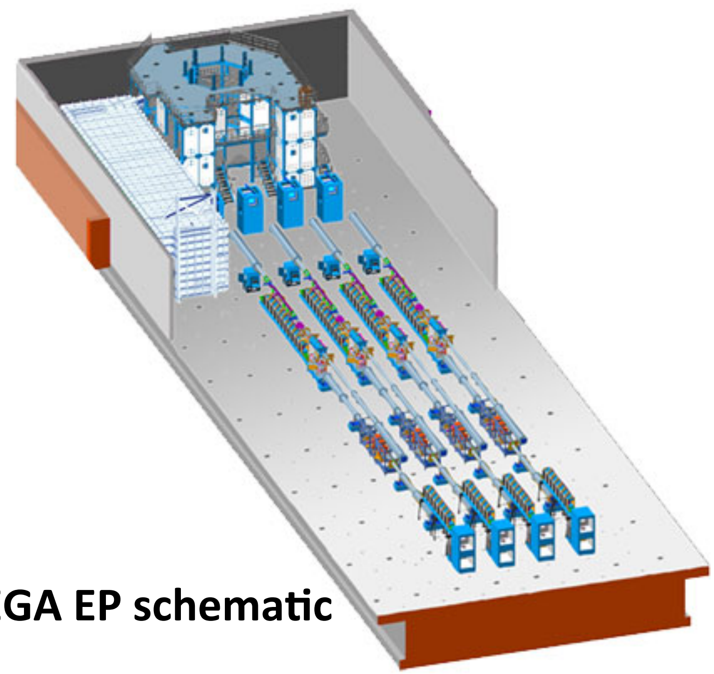
(Received 3 December 2014; revised manuscript received 12 June 2015; published 1 October 2015)

We report the first observation, in a supersonic flow, of the evolution of the Kelvin-Helmholtz instability from a single-mode initial condition. To obtain these data, we used a novel experimental system to produce a steady shock wave of unprecedented duration in a laser-driven experiment. The shocked, flowing material creates a shear layer between two plasmas at high energy density. We measured the resulting interface structure using radiography. Hydrodynamic simulations reproduce the large-scale structures very well and the medium-scale structures fairly well, and imply that we observed the expected reduction in growth rate for supersonic shear flow.

DOI: 10.1103/PhysRevLett.115.145001 PACS numbers: 52.35.Tc, 47.20.Ft, 47.40.Ki, 52.38.-r

Omega EP has 4 individual lasers

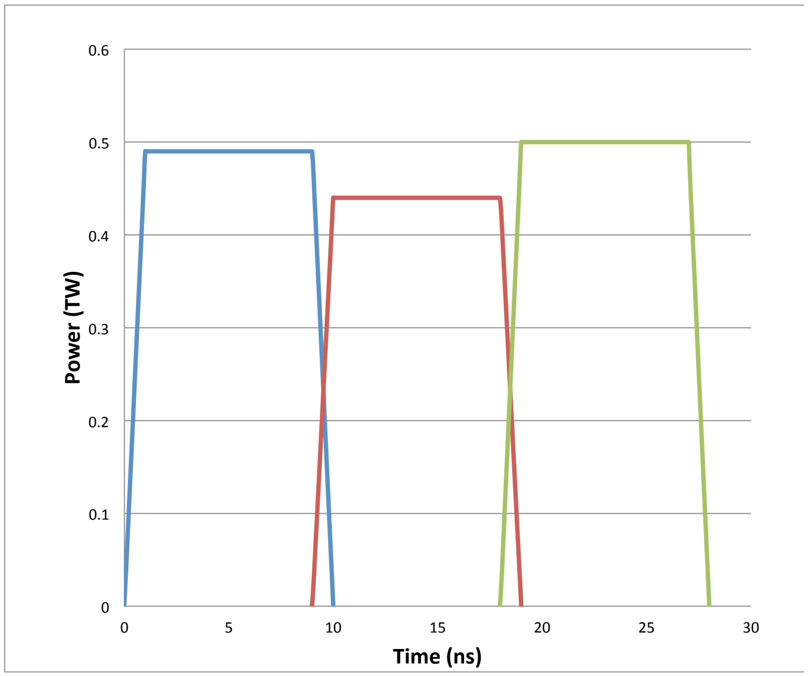
- 4 beams, 1 ps to 10 ns
- Can be sequentially fired

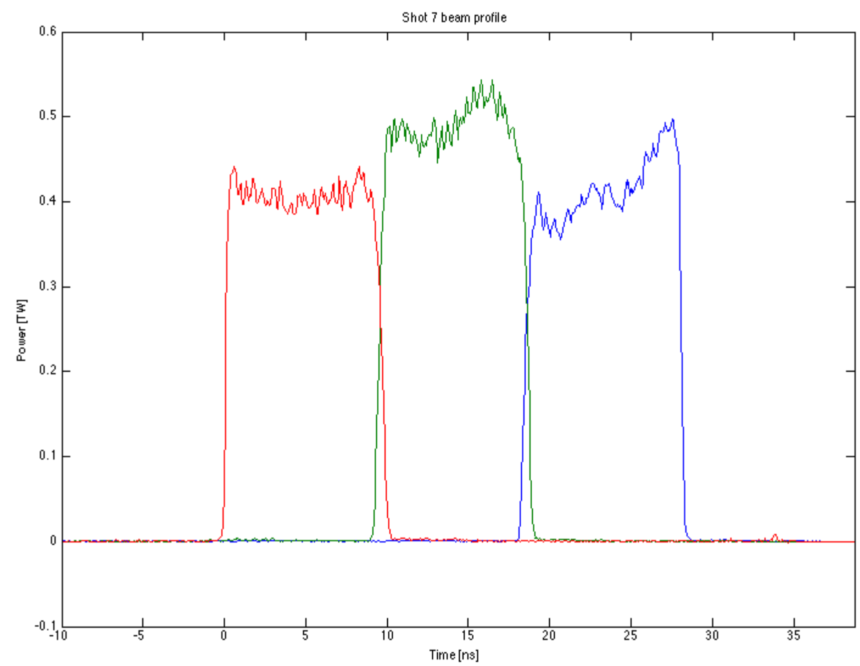


OMEGA EP schematic

OMEGA-EP beam amplifiers

We "stack" 3 beams in time to create a steady shock



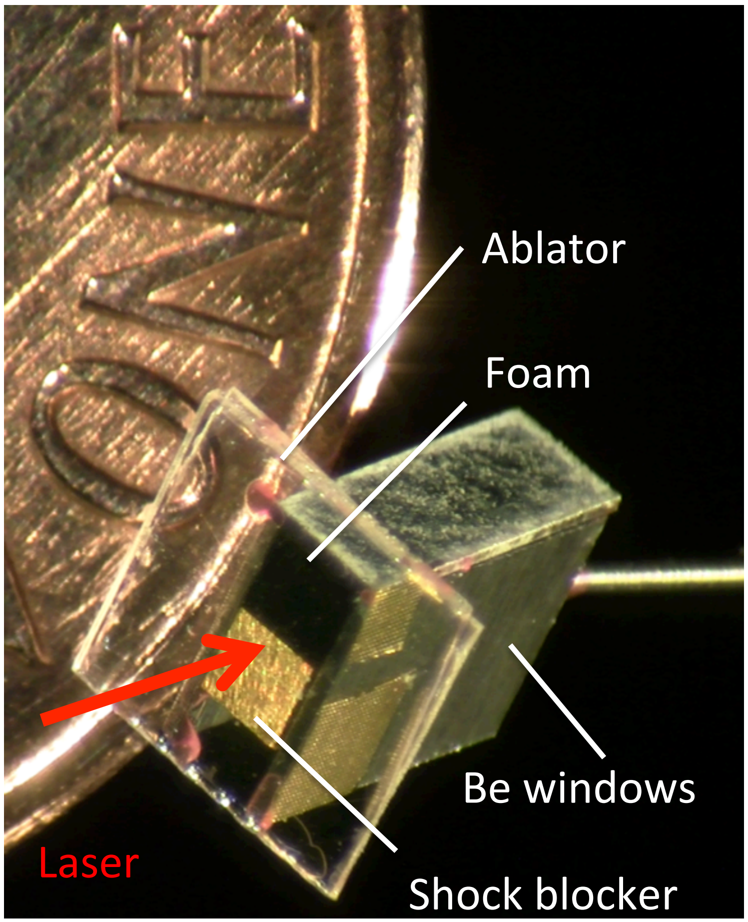


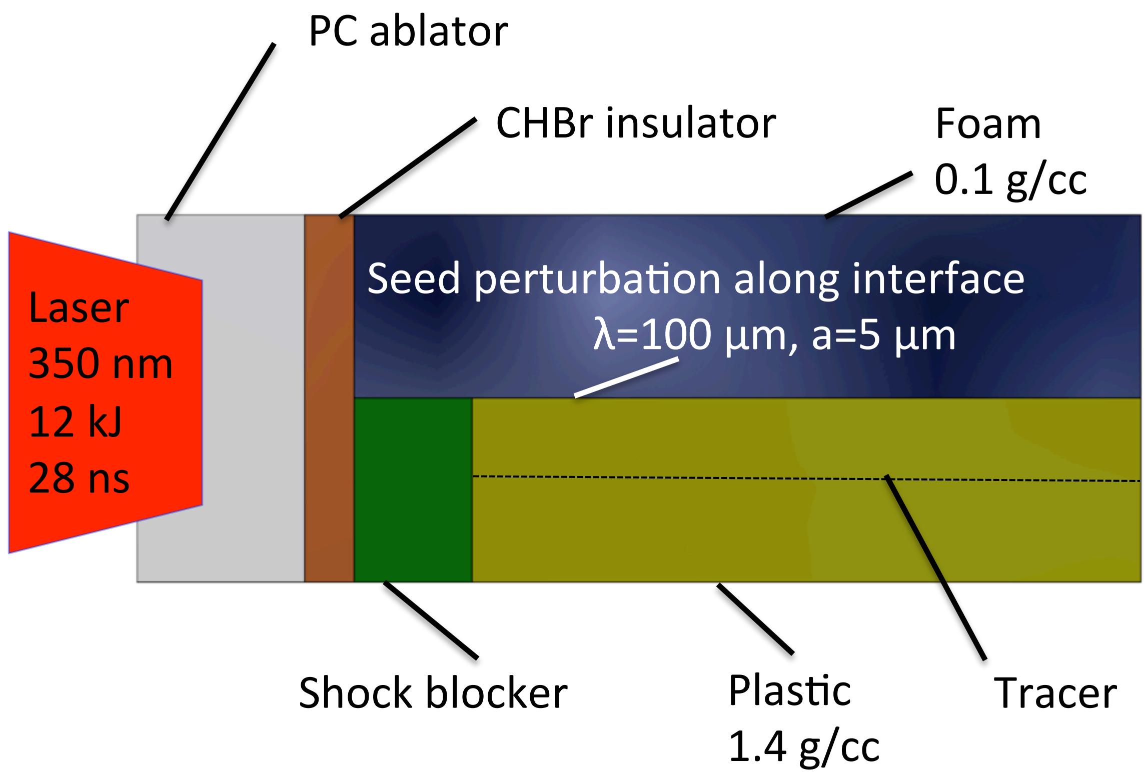
We stitch together 3, 10 ns beams for a ~27 ns pulse

Spherical Crystal Imager

C. Stoeckl, Review of Scientific Instruments, 2012

We aim to study the effects of compressibility on KH growth

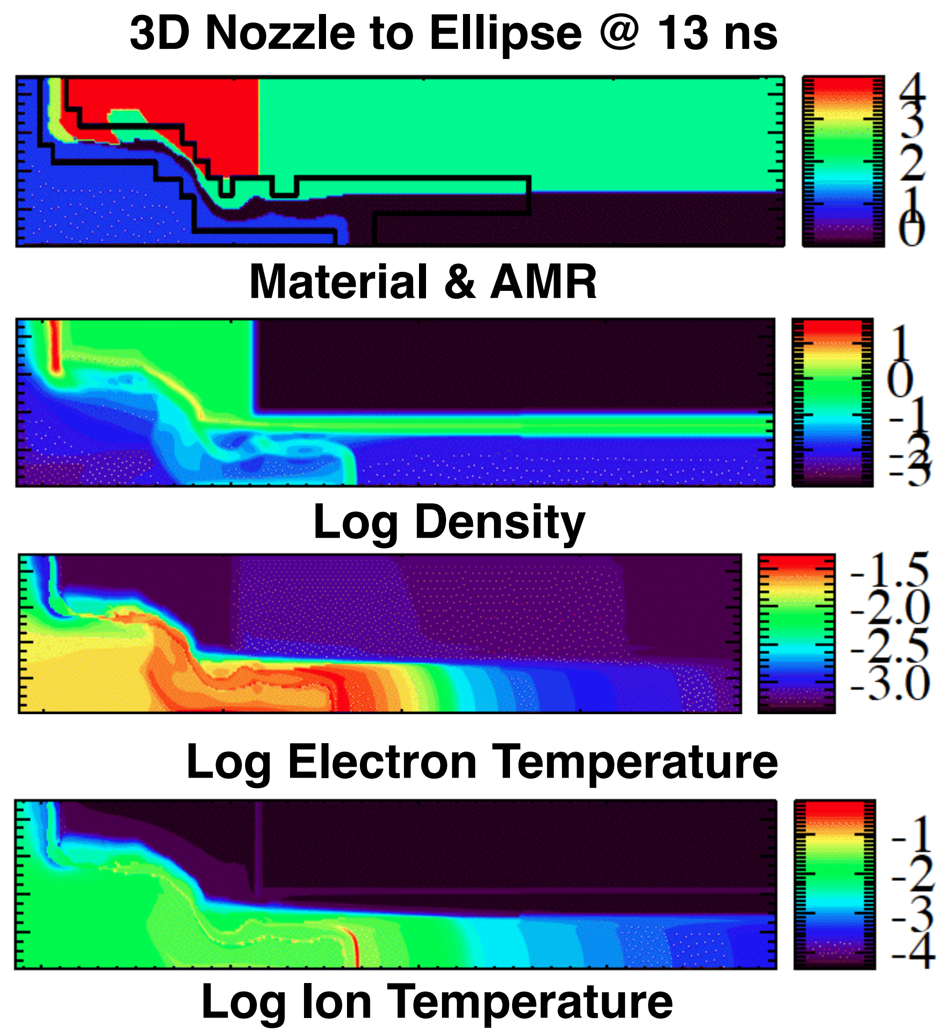




Grad student: Willow Wan
Design: Guy Malamud

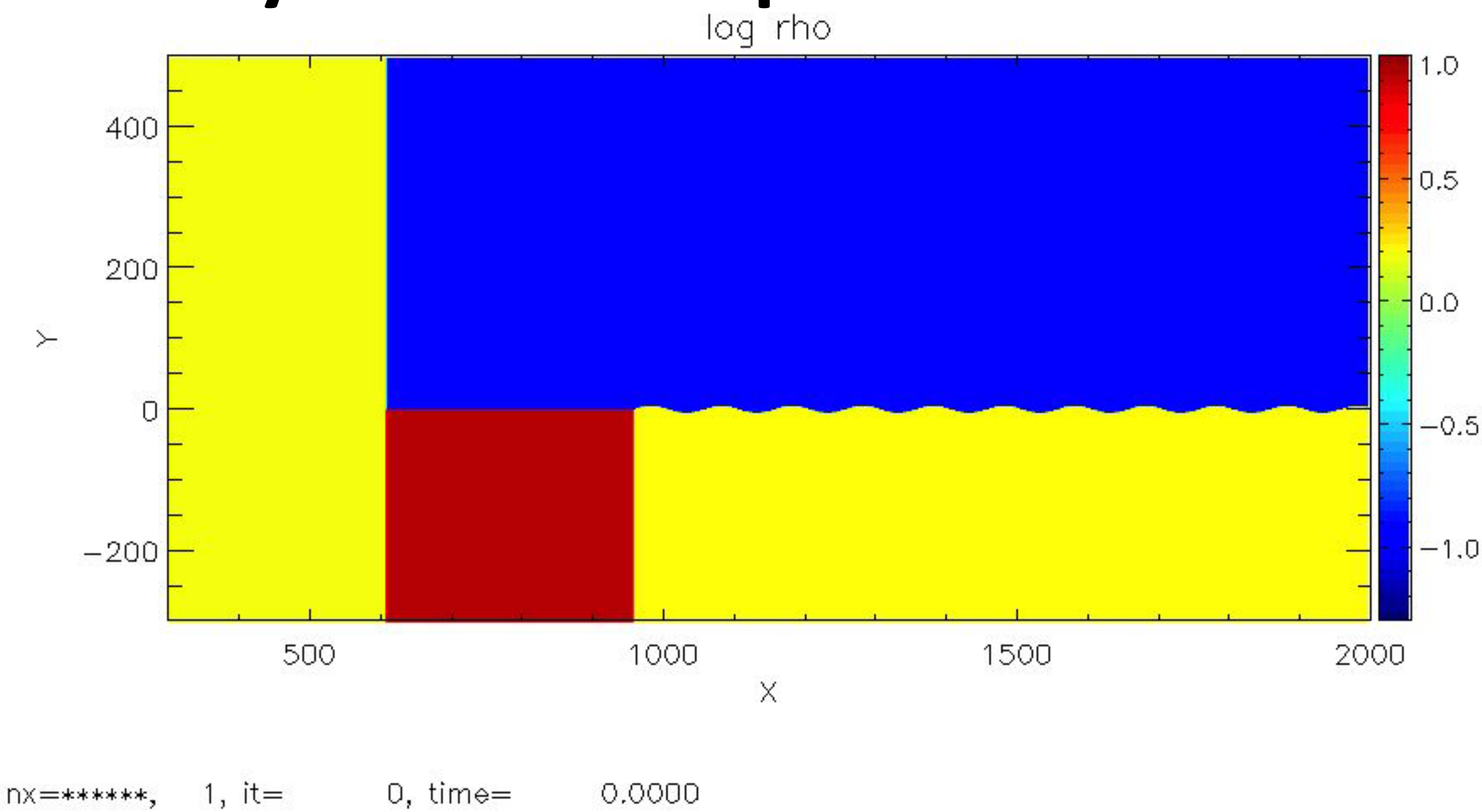
We modeled the experiment in CRASH, a radiation hydrodynamic code

- 1D, 2D or 3D
- Dynamic adaptive AMR
- Level set interfaces
- Self-consistent EOS and opacities
- Multigroup-diffusion radiation transport
- Electron physics and flux-limited electron heat conduction
- Laser package
  - 3D ray tracing for 2D or 3D runs

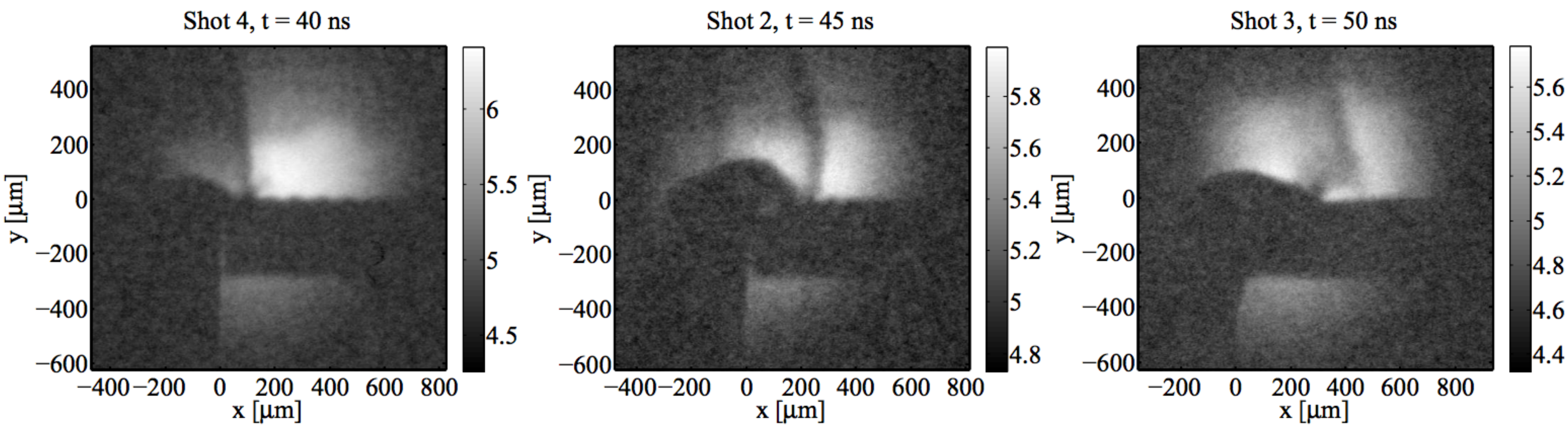


CRASH code: Van der Holst et al, Ap.J.S. 2011

CRASH has aided in the design and analysis of this experiments

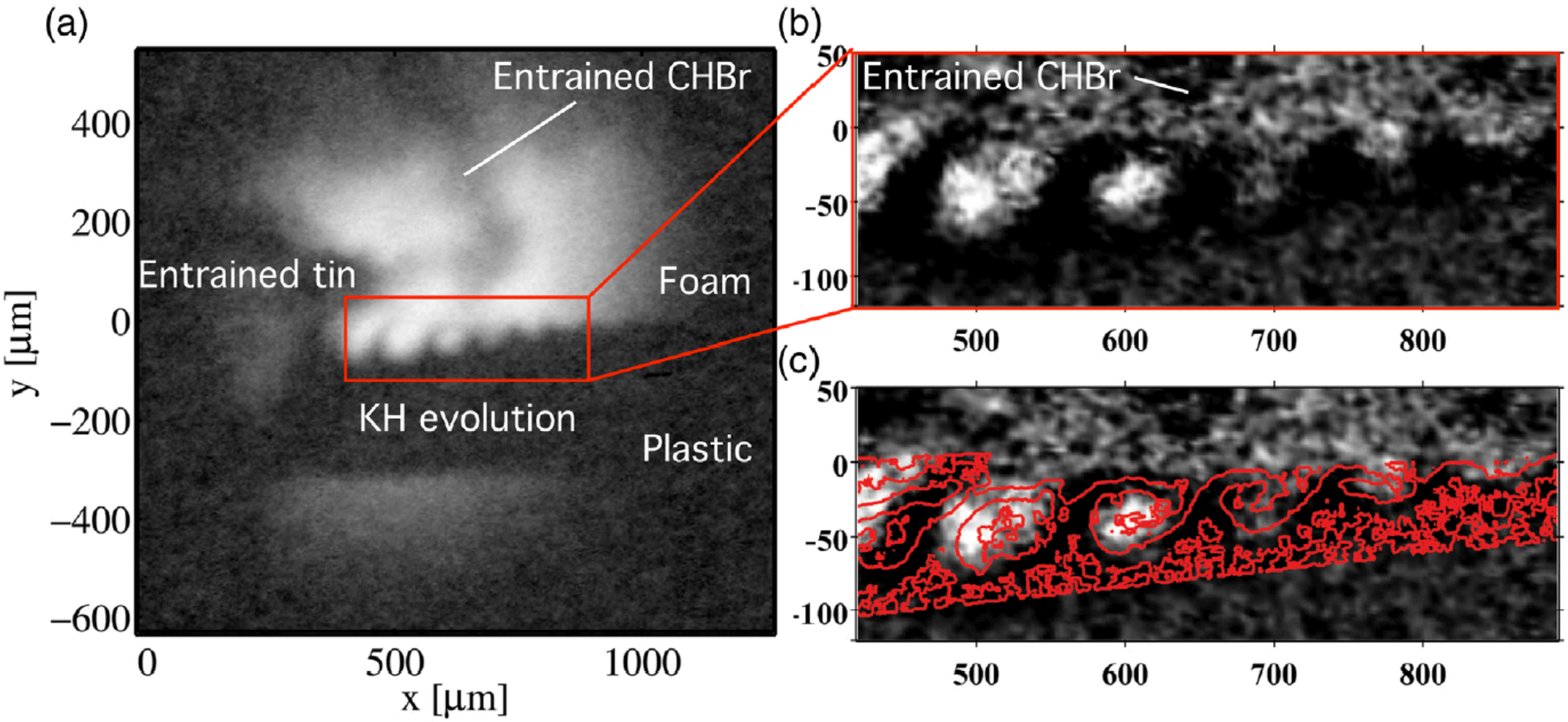


We use the Spherical Crystal Imaging diagnostic for high SNR radiographs



Wan, PoP, 2016

Post processing the images allows use to see small structures



Spherical Crystal Imaging diagnostic, C. Stoeckl et. al. *RSI* (2012)

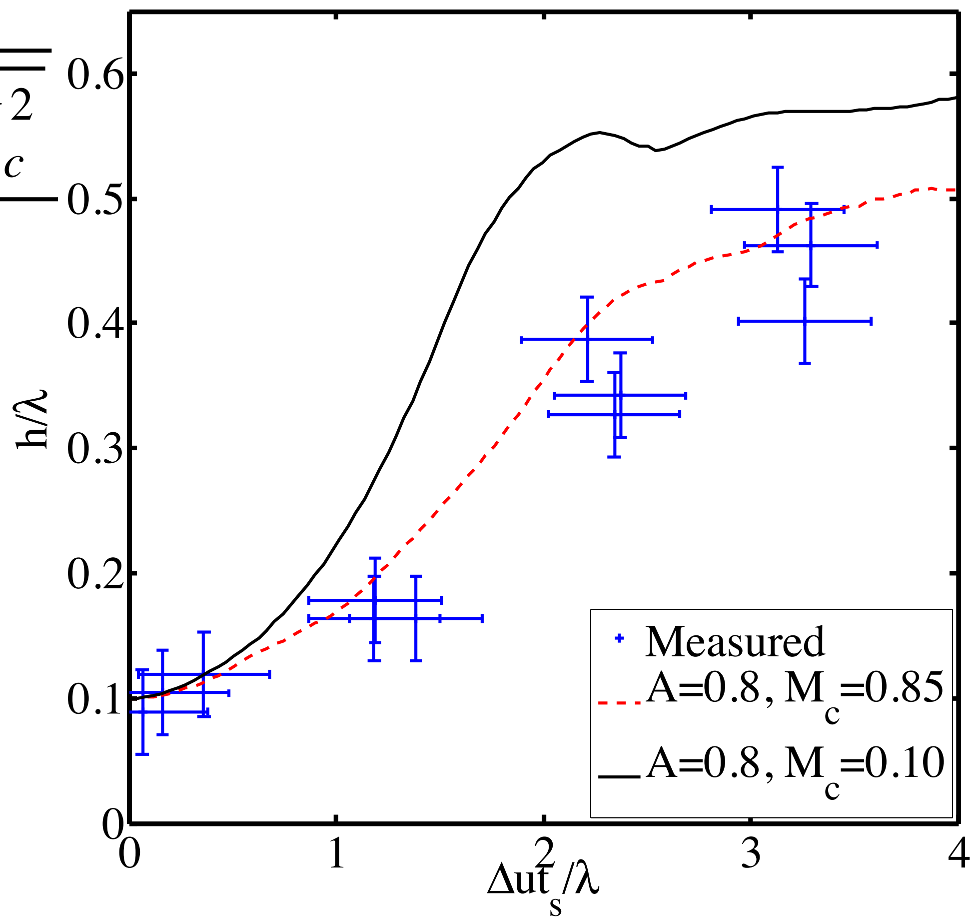
The data support an inhibited KH growth rate

$$\gamma = \gamma_{inc} \frac{\sqrt{-1 - M_c^2 + \sqrt{1 + 4M_c^2}}}{M_c}$$

γ	=	growth rate coefficient
γ_{inc}	=	incompressible growth rate coefficient
c	=	speed of sound
M_c	=	convective Mach number (supersonic at >0.5)

$$M_c = \frac{\Delta u}{c_1 + c_2}$$

Normalized data vs. shear flow simulations



Wan, PRL 2015

APPLIED PHYSICS LETTERS **106**, 114103 (2015)

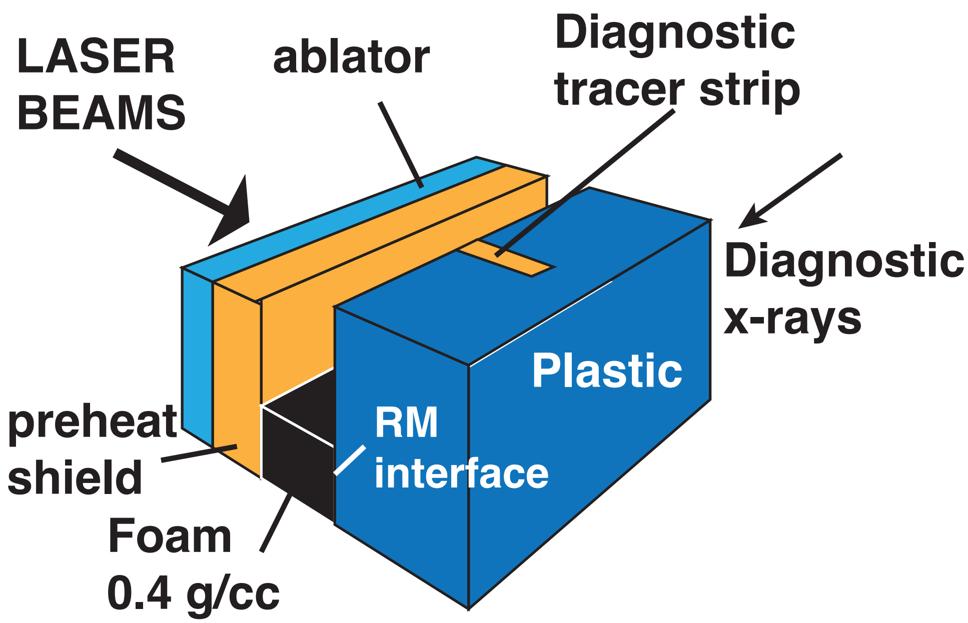
Richtmyer-Meshkov evolution under steady shock conditions in the high-energy-density regime

C. A. Di Stefano,[1,a)] G. Malamud,[1,2,a)] C. C. Kuranz,[1] S. R. Klein,[1] C. Stoeckl,[3] and R. P. Drake[1]
[1]*University of Michigan, Ann Arbor, Michigan 48109, USA*
[2]*Nuclear Research Center - Negev, Beer-Sheva 84190, Israel*
[3]*Laboratory for Laser Energetics, University of Rochester, Rochester, New York 14623, USA*

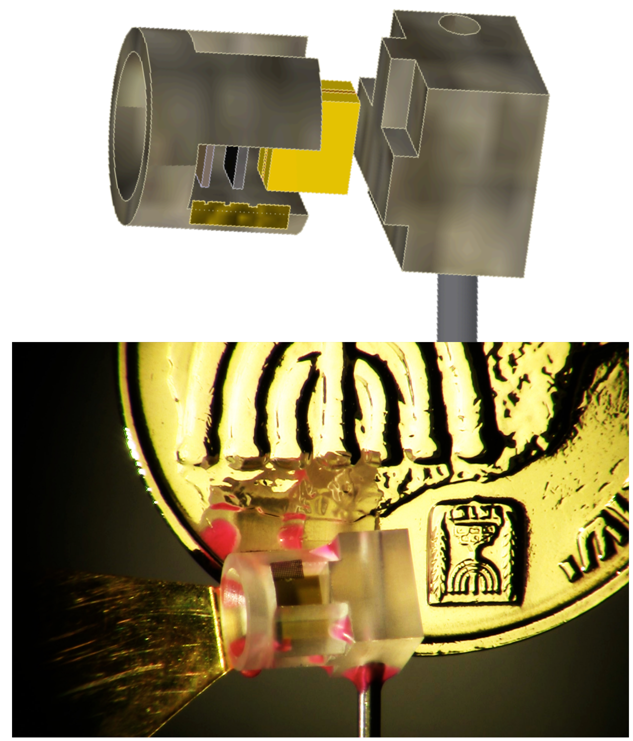
(Received 9 August 2014; accepted 8 March 2015; published online 17 March 2015)

This work presents direct experimental evidence of long-predicted nonlinear aspects of the Richtmyer-Meshkov process, in which new modes first arise from the coupling of initially-present modes, and in which shorter-wavelength modes are eventually overtaken by longer-wavelength modes. This is accomplished using a technique we developed employing a long driving laser pulse to create a strong (Mach ∼ 8) shock across a well-characterized material interface seeded by a two-mode sinusoidal perturbation. This technique further permits the shock to be sustained, without decay of the high-energy-density flow conditions, long enough for the system to evolve into the nonlinear phase. [http://dx.doi.org/10.1063/1.4915303]

We have performed the first HED "light-to-heavy" Richtmyer-Meshkov experiment



Design enables 20 ns constant shock on OMEGA EP

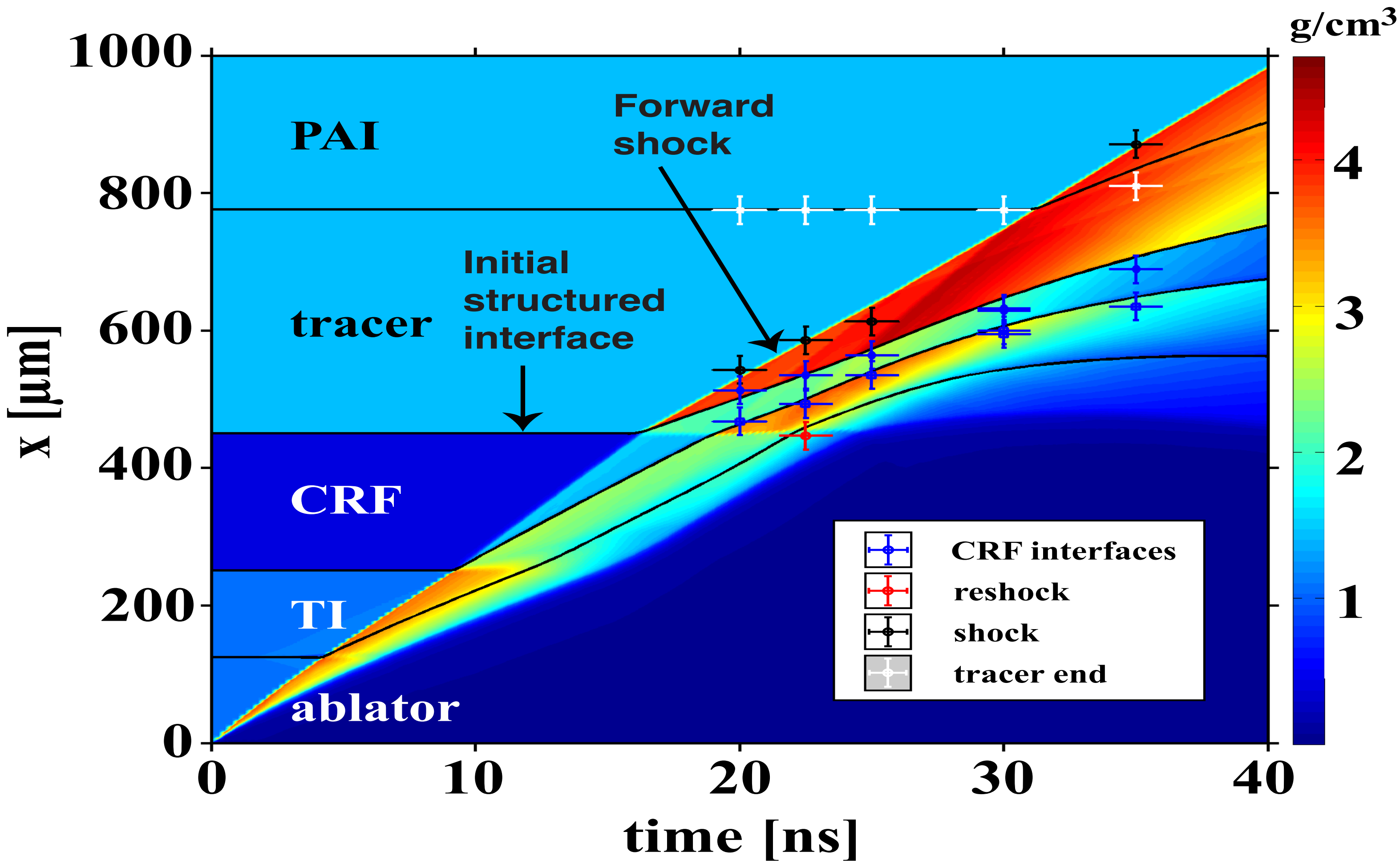


rendered draft (top)
actual target (bottom)

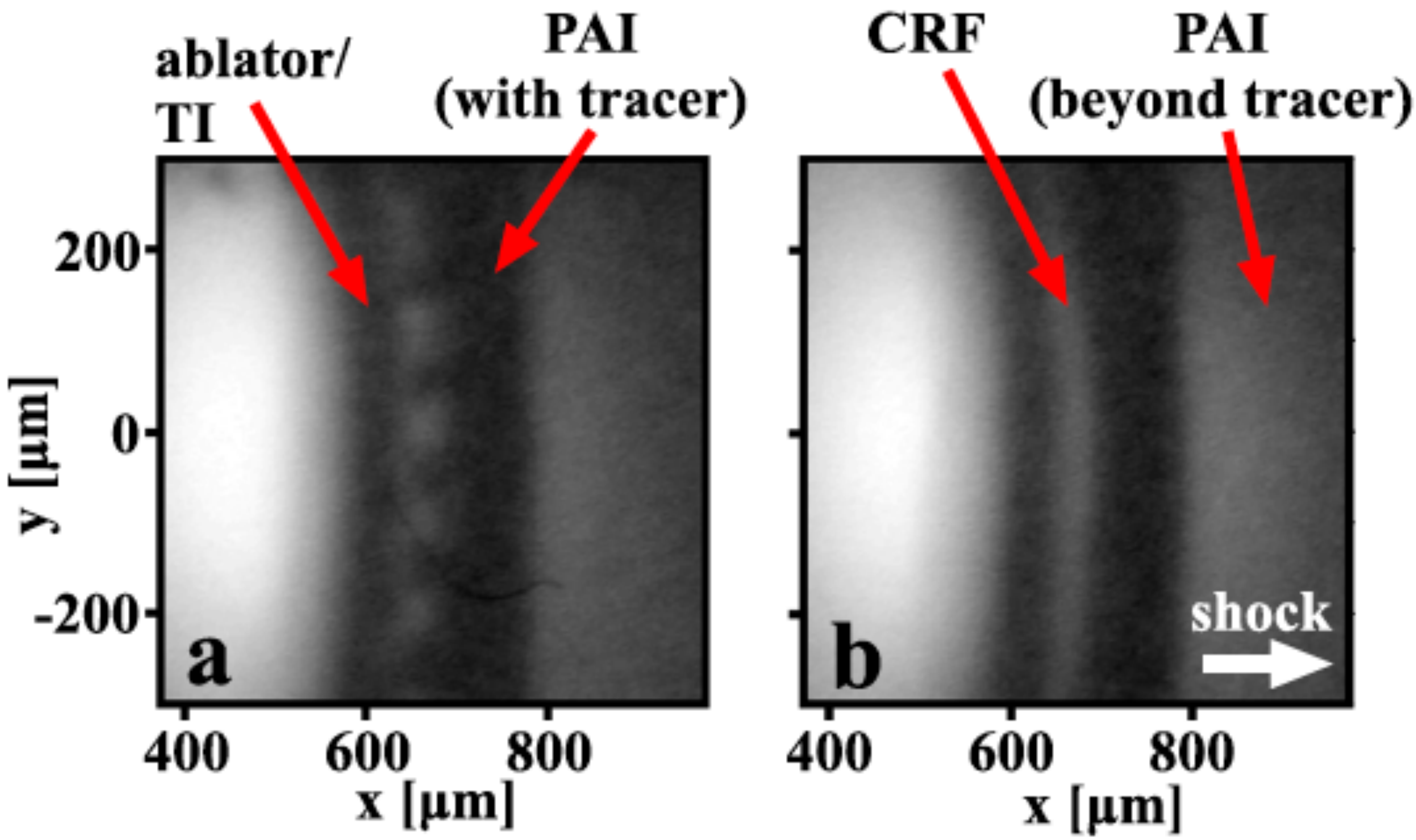
Grad student: Carlos Di Stefano
Design: Guy Malamud

Hyades aided in the RM experimental design

Data confirm the 1D hydro



We observed the RM unstable interface using spherical crystal imager (SCI)

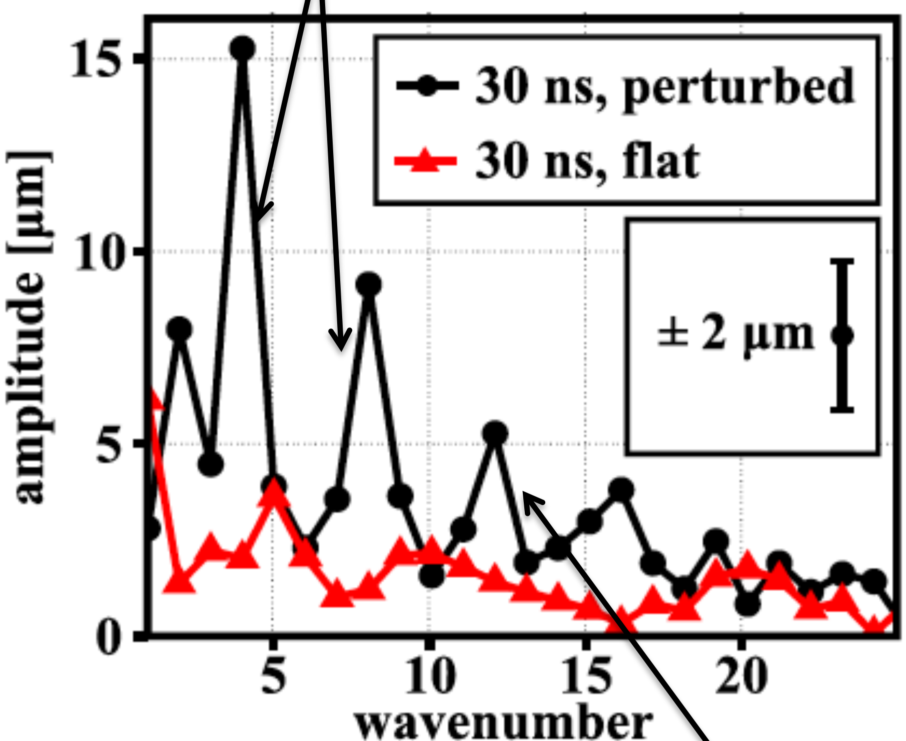


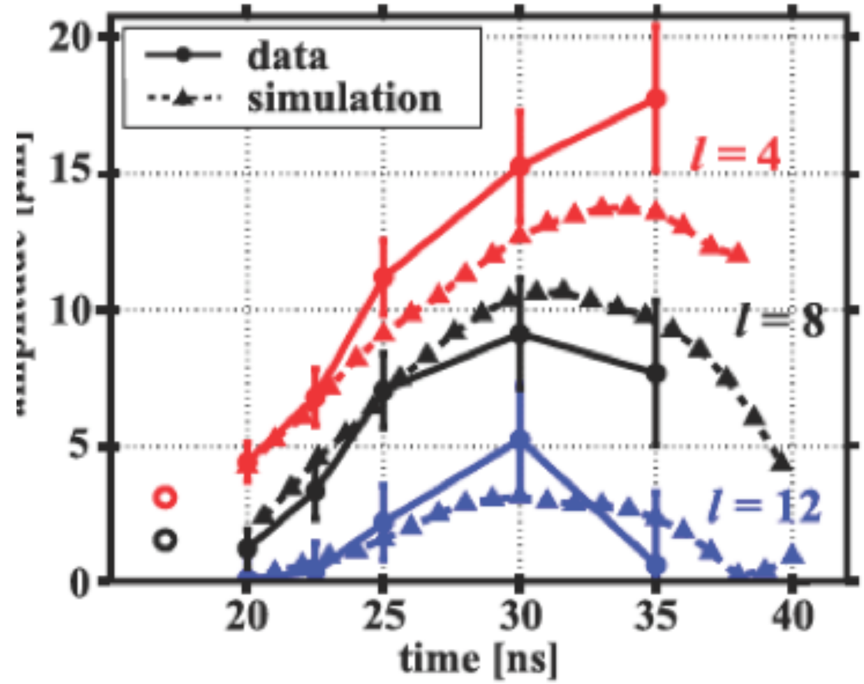
Rippled interface

Planar interface

We observed RM mode coupling

Seeded modes





Harmonic mode

Di Stefano, *Applied Physics Letters*, 2015

PHYSICS OF PLASMAS VOLUME 10, NUMBER 3 MARCH 2003

The time scale for the transition to turbulence in a high Reynolds number, accelerated flow

H. F. Robey, Ye Zhou, and A. C. Buckingham
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PHYSICS OF PLASMAS VOLUME 11, NUMBER 5 MAY 2004

Nonlinear mixing behavior of the three-dimensional Rayleigh–Taylor instability at a decelerating interface[a)]

R. P. Drake,[b)] D. R. Leibrandt, E. C. Harding, C. C. Kuranz, and M. A. Blackburn
University of Michigan, Atmospheric Oceanic and Space Sciences, 2455 Hayward Street, Ann Arbor, Michigan 48109-2143

H. F. Robey, B. A. Remington, M. J. Edwards, A. R. Miles, T. S. Perry,
R. J. Wallace,
Lawrence Liverm

J. P. Knauer
University of Roc

D. Arnett
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[DOI: 10.1063/

THE ASTROPHYSICAL JOURNAL, 696:749–759, 2009 May 1 doi:10.1088/0004-637X/696/1/749

TWO-DIMENSIONAL BLAST-WAVE-DRIVEN RAYLEIGH–TAYLOR INSTABILITY: EXPERIMENT AND SIMULATION

C. C. KURANZ[1], R. P.
A. R. MILES[2], T. S. PE

[2] Lawrence

[4] Departmer
5

This paper shows
two-dimensional i
Laser and use ~5 k
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the Richtmyer–M
into the nonlinear
in order to study
explosion phase o

Key words: hydro

Online-only mate

PHYSICS OF PLASMAS **17**, 052709 (2010)

Spike morphology in blast-wave-driven instability experiments

C. C. Kuranz,[1] R. P. Drake,[1] M. J. Grosskopf,[1] B. Fryxell,[1] A. Budde,[1] J. F. Hansen,[2] A. R. Miles,[2] T. Plewa,[3] N. Hearn,[4] and J. Knauer[5]
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[2]*Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, California 94550, USA*
[3]*Department of Scientific Computing, Florida State University, 400 Dirac Science Library, Tallahassee, Florida 32306, USA*
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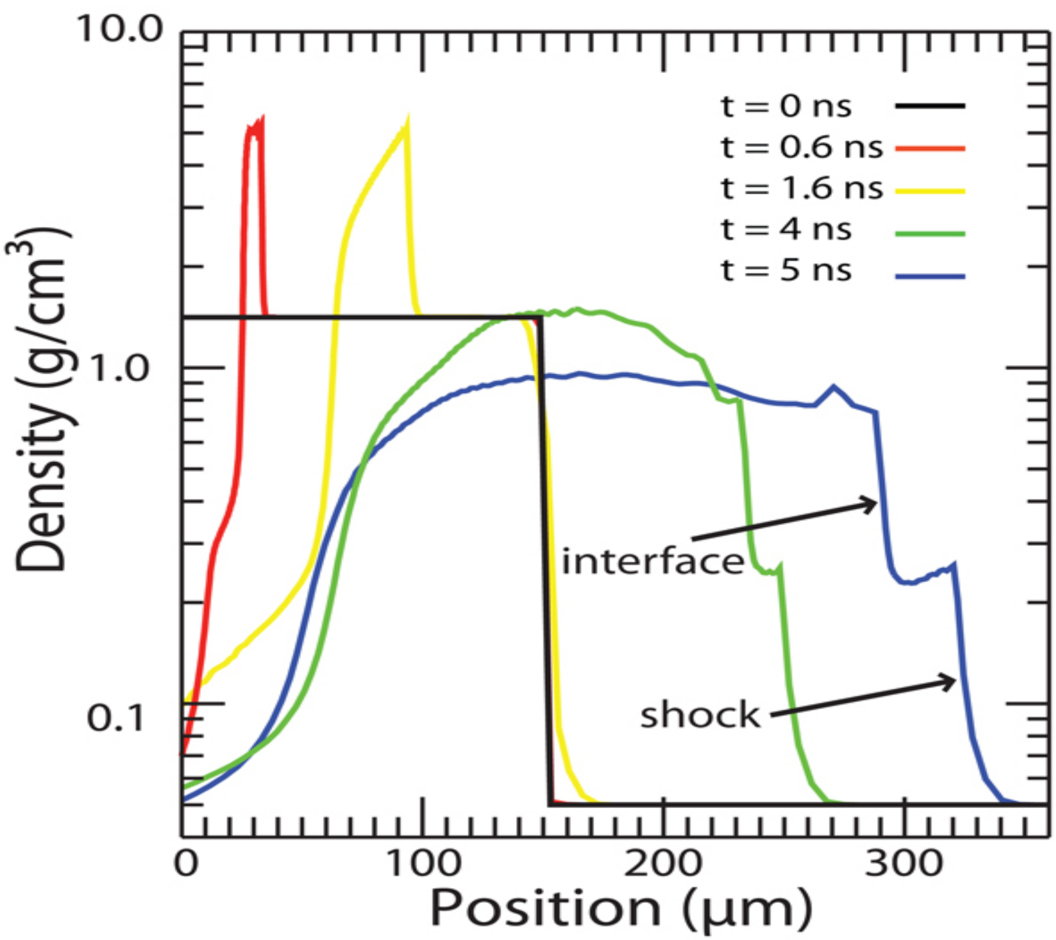
(Received 7 May 2009; accepted 19 February 2010; published online 27 May 2010)

The laboratory experiments described in the present paper observe the blast-wave-driven Rayleigh–Taylor instability with three-dimensional (3D) initial conditions. About 5 kJ of energy from the Omega laser creates conditions similar to those of the He–H interface during the explosion phase of a supernova. The experimental target is a 150 μm thick plastic disk followed by a low-density foam. The plastic piece has an embedded, 3D perturbation. The basic structure of the pattern is two orthogonal sine waves where each sine wave has an amplitude of 2.5 μm and a wavelength of 71 μm. In some experiments, an additional wavelength is added to explore the interaction of modes. In experiments with 3D initial conditions the spike morphology differs from what has been observed in other Rayleigh–Taylor experiments and simulations. Under certain conditions, experimental radiographs show some mass extending from the interface to the shock front. Current simulations show neither the spike morphology nor the spike penetration observed in the experiments. The amount of mass reaching the shock front is analyzed and potential causes for the spike morphology and the spikes reaching the shock are discussed. One such hypothesis is that these phenomena may be caused by magnetic pressure, generated by an azimuthal magnetic field produced by the plasma dynamics. © *2010 American Institute of Physics*. [doi:10.1063/1.3389135]

A planar blast is created in the experiment using a 1 ns laser pulse

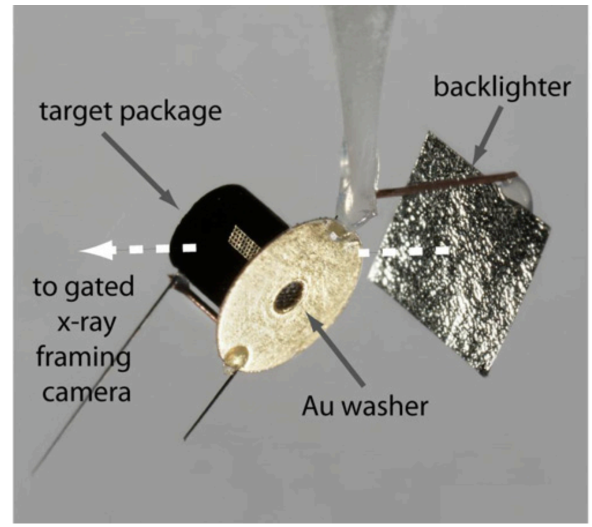


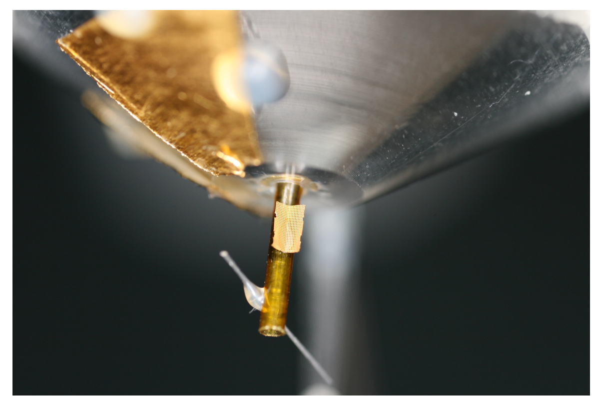
Key components of target

150 µm plastic (1.41 g/cc)

- **Tracer strip material: $C_{500}H_{457}Br_{43}$ (1.42 g/cc)**
- **Entire surface machined with seed perturbation**

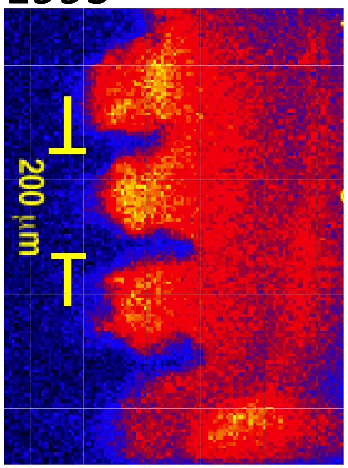
2-3 mm Carbonized Resorcinol Formaldehyde (CRF) foam (50 - 400 mg/cc)



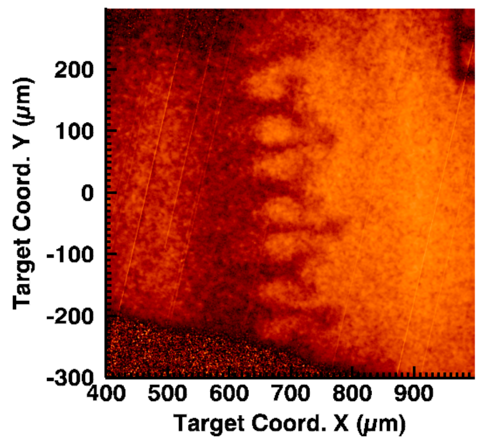


HED RT experiments have been performed on many laser facilities over the past 2 decades

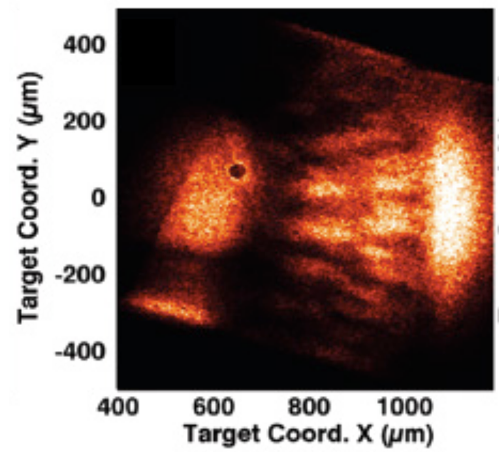
1995



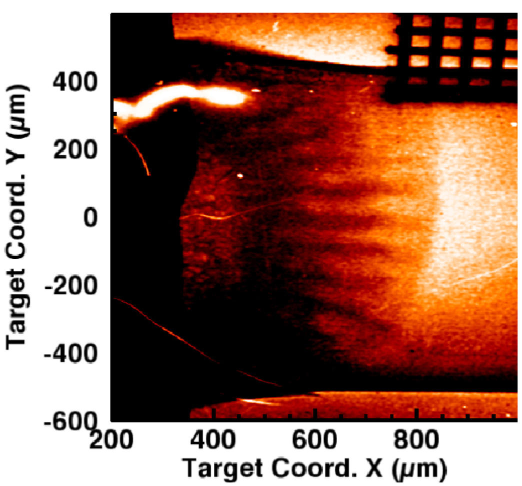
Late 90's



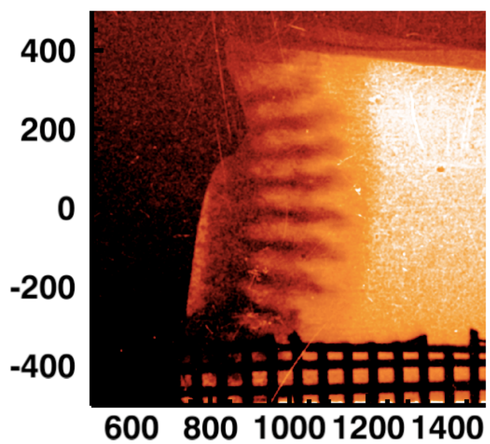
Early 2000



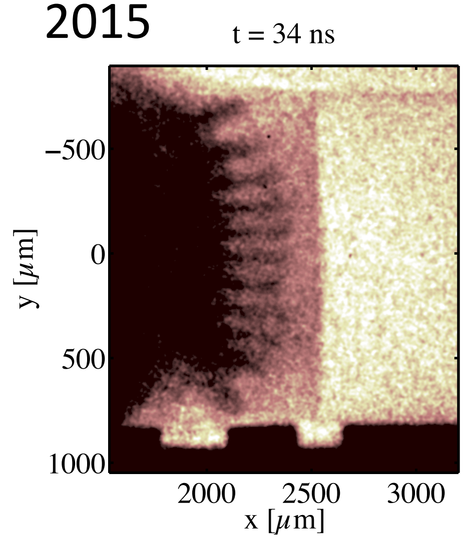
2004



2009



2015



Comparing data to the 2D and 3D buoyancy-drag model

An incompressible model for Rayleigh-Taylor mixing

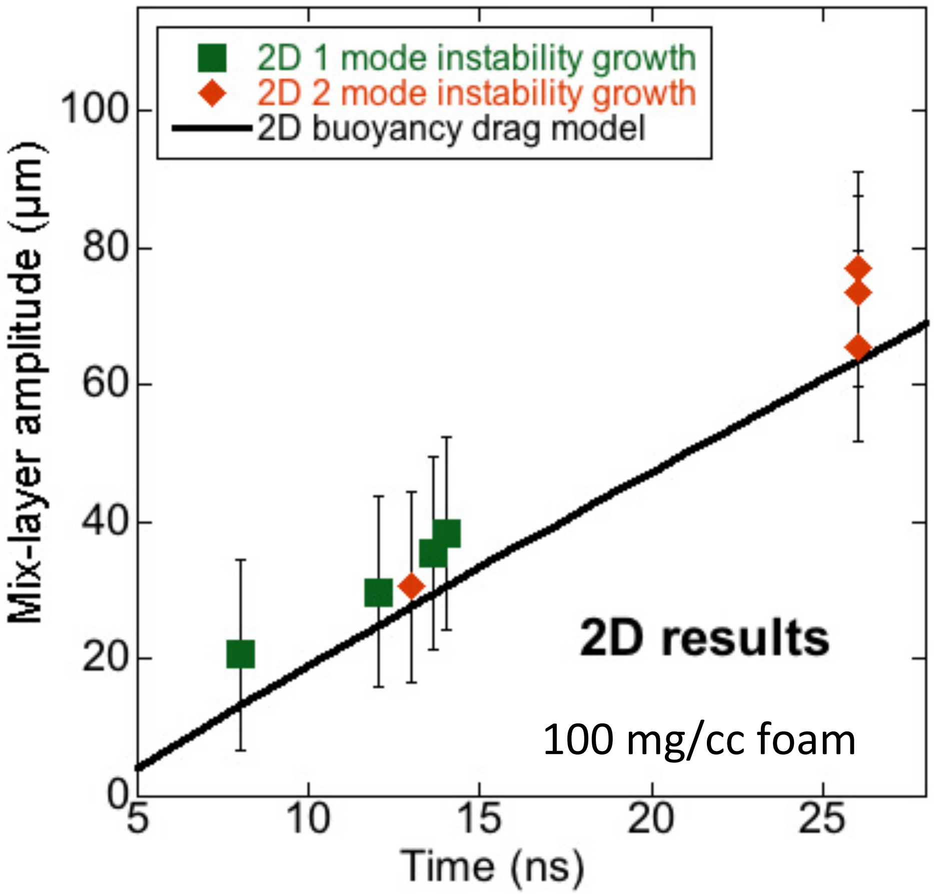
$$(\rho_1 + C_a \rho_2)\frac{du}{dt} = (\rho_2 - \rho_1)g - \frac{C_d}{L}\rho_2 u^2$$

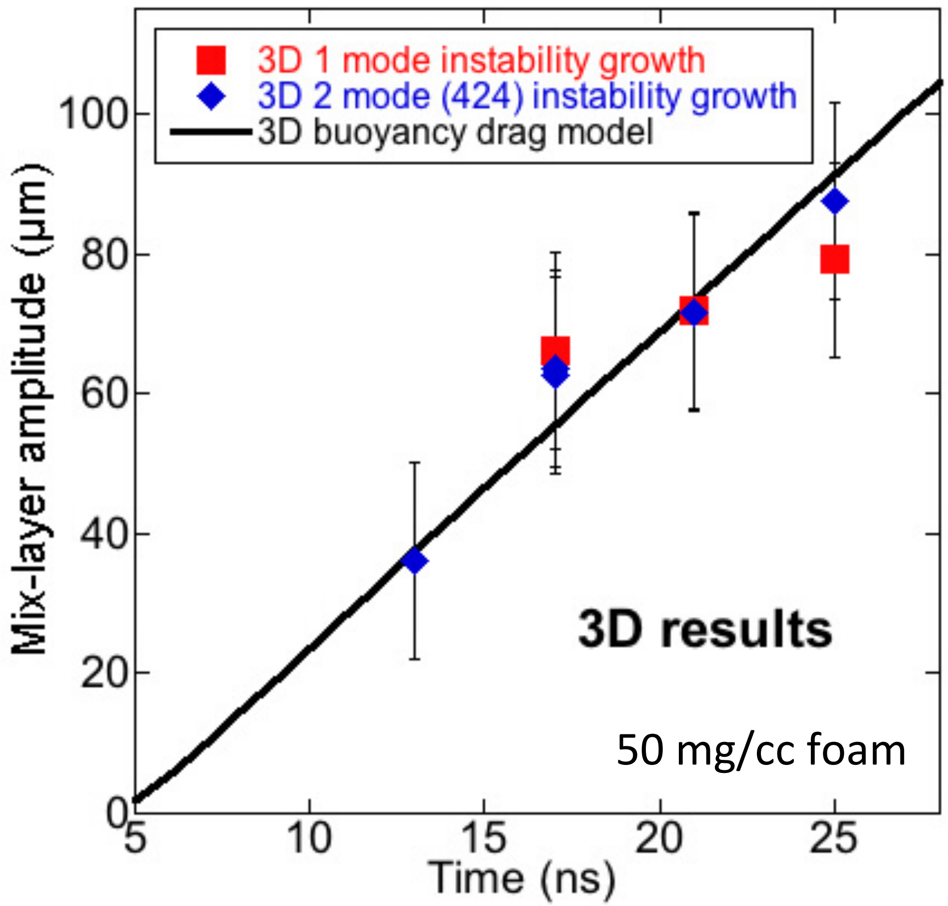
$$\text{2D:} \quad C_a = 2; \quad C_d = 6\pi$$

$$\text{3D:} \quad C_a = 1; \quad C_d = 2\pi$$

G. Dimonte, Phys. Plasmas 7 (6), 2255-2269 (2000)
D. Oron, Phys. Plasmas 8 (6), 2883-2890 (2001)

Once corrected for decompression data agree with buoyancy-drag model





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ARTICLE

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How high energy fluxes may affect Rayleigh–Taylor instability growth in young supernova remnants

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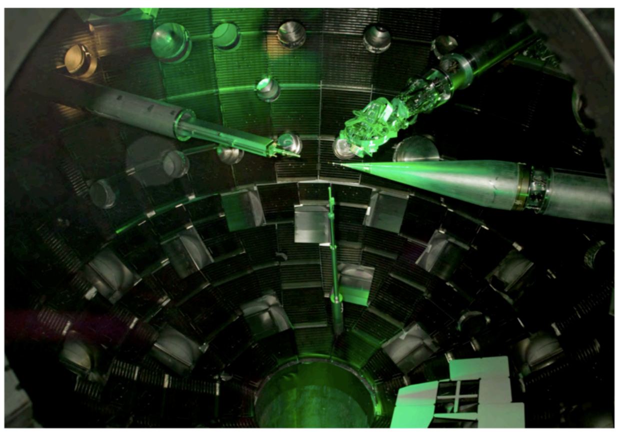
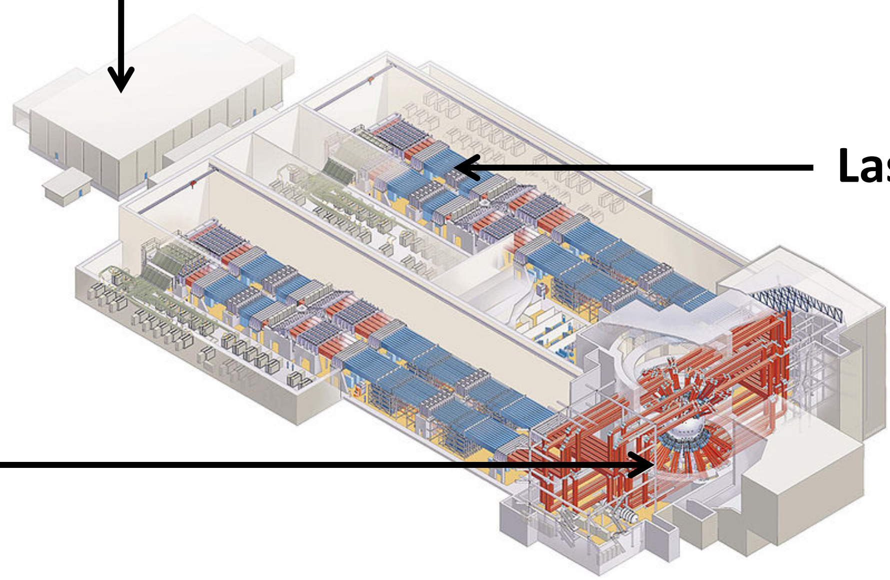
Energy-transport effects can alter the structure that develops as a supernova evolves into a supernova remnant. The Rayleigh–Taylor instability is thought to produce structure at the interface between the stellar ejecta and the circumstellar matter, based on simple models and hydrodynamic simulations. Here we report experimental results from the National Ignition Facility to explore how large energy fluxes, which are present in supernovae, affect this structure. We observed a reduction in Rayleigh–Taylor growth. In analyzing the comparison with supernova SN1993J, a Type II supernova, we found that the energy fluxes produced by heat conduction appear to be larger than the radiative energy fluxes, and large enough to have dramatic consequences. No reported astrophysical simulations have included radiation and heat conduction self-consistently in modeling supernova remnants and these dynamics should be noted in the understanding of young supernova remnants.

We performed these experiments at the National Ignition Facility

Control Rooms

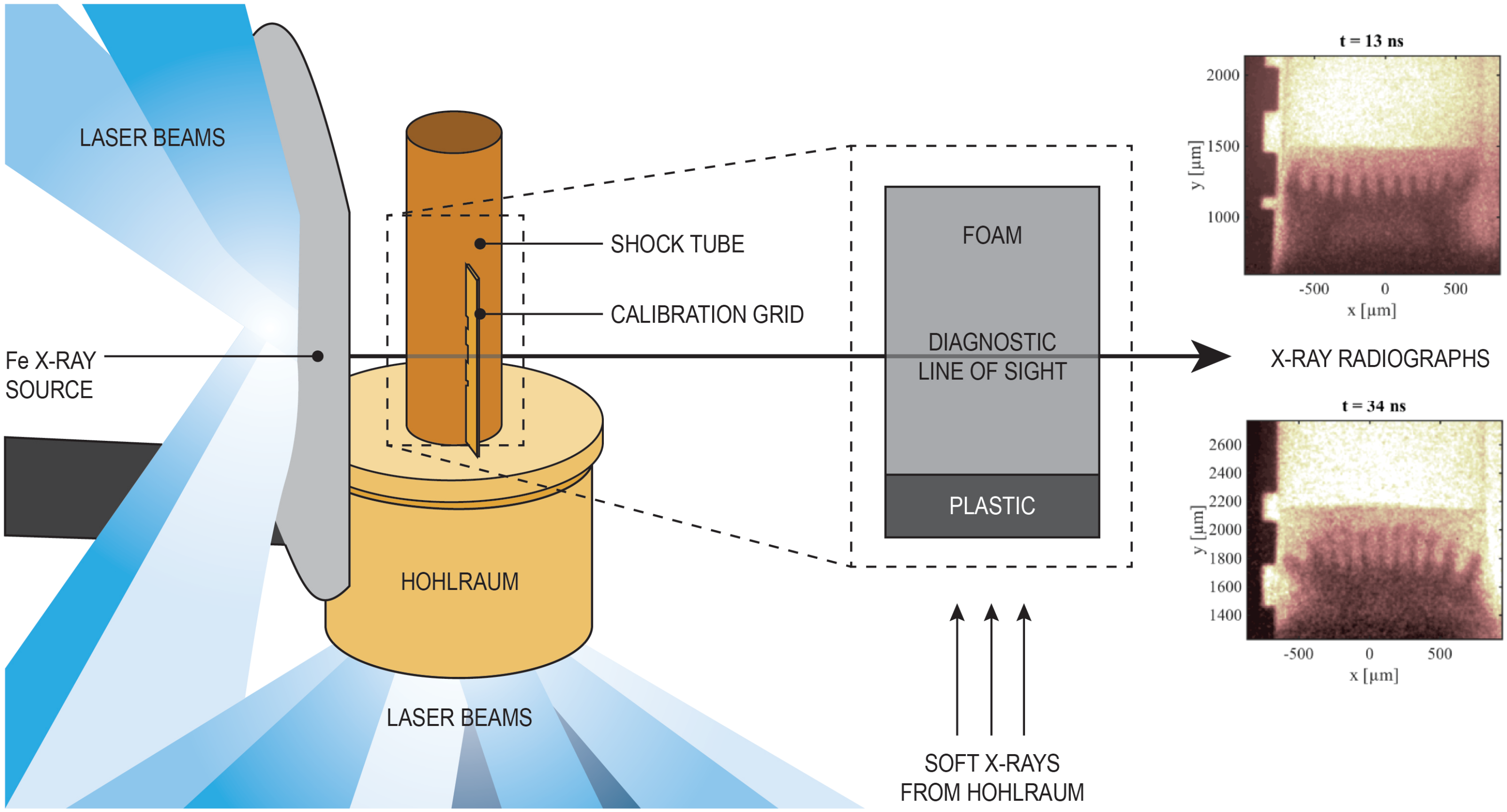


Target Chamber



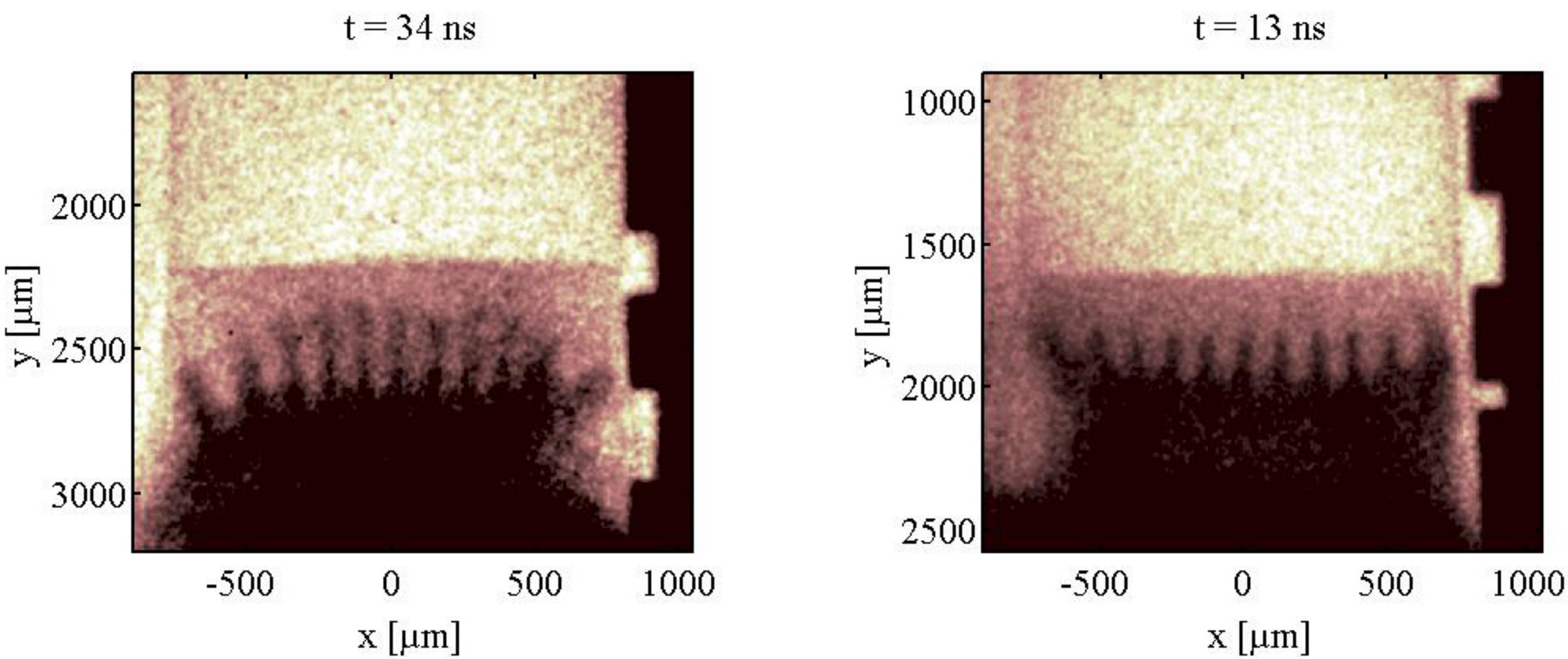
Laser Bays

We use to NIF drive a create a high- and low-energy flux in an RT unstable system



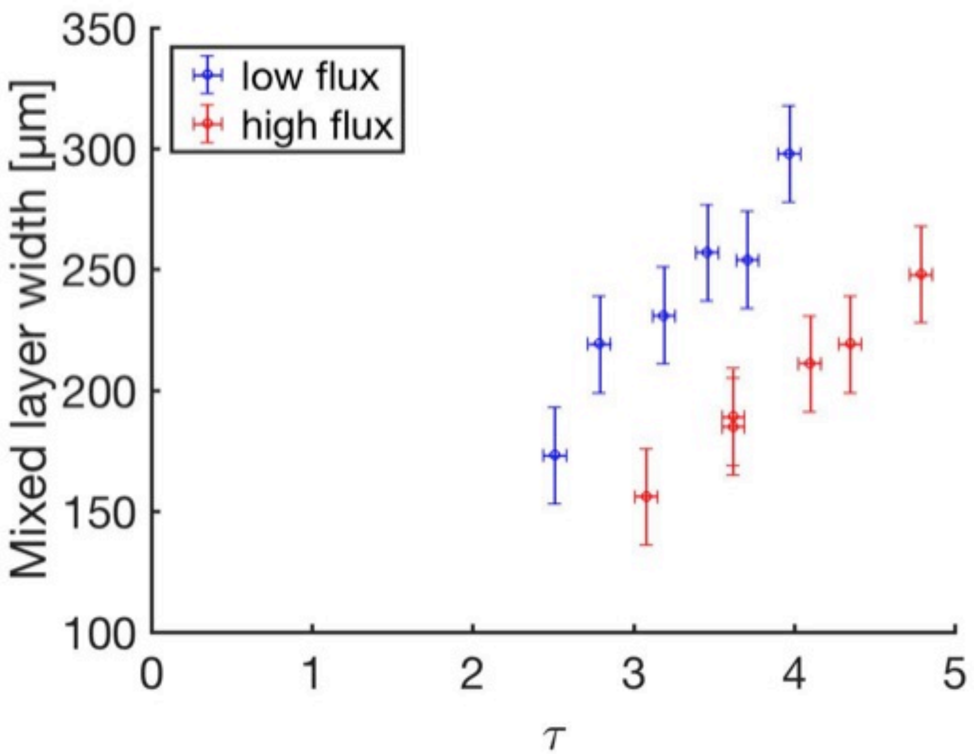
PI: Hye-Sook Park, Channing Huntington, Carolyn Kuranz, Aaron Miles, Forrest Doss, Kumar Raman

Typical data show qualitative and quantitative differences between cases



Low energy flux **High energy flux**

We must compare the RT growth of each case

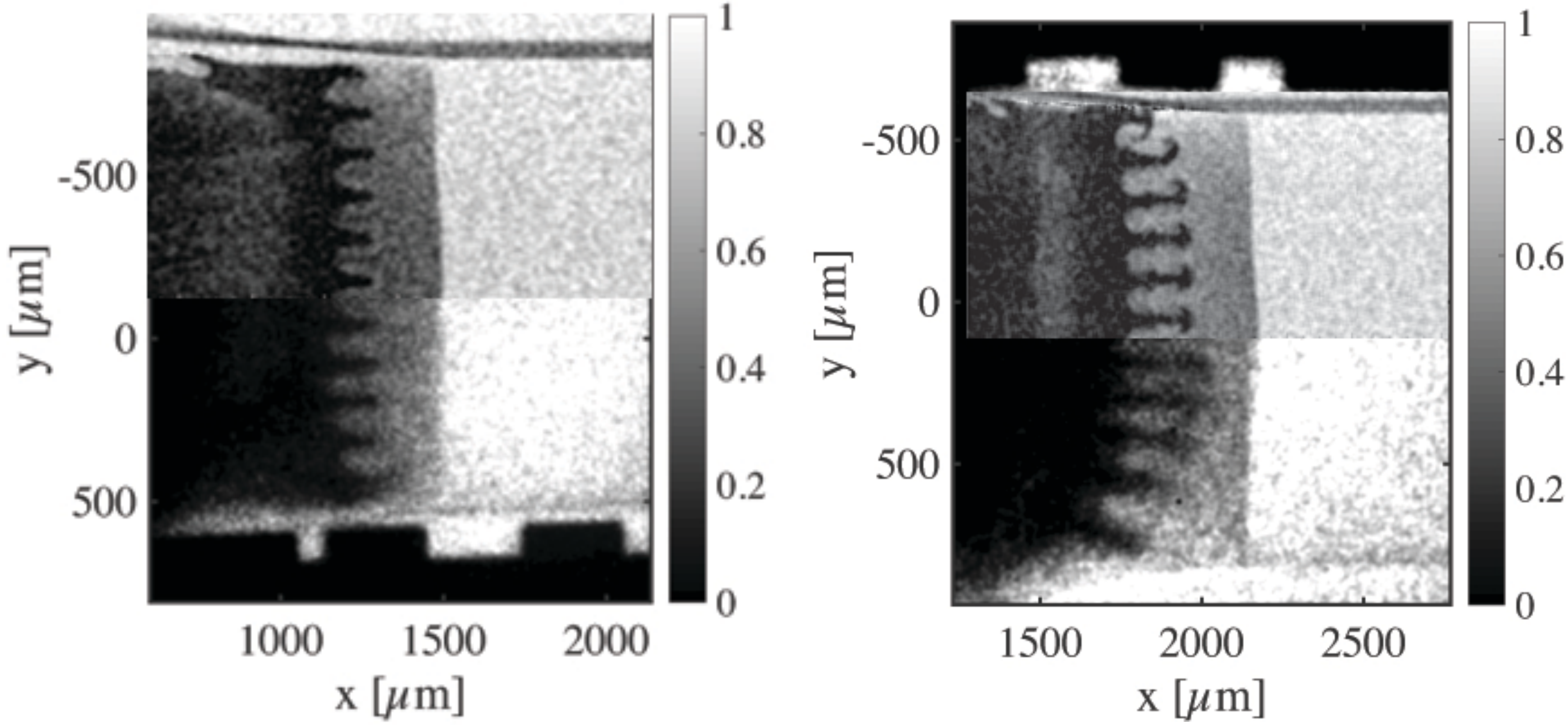


$$\tau = \int \gamma_{RT} dt$$

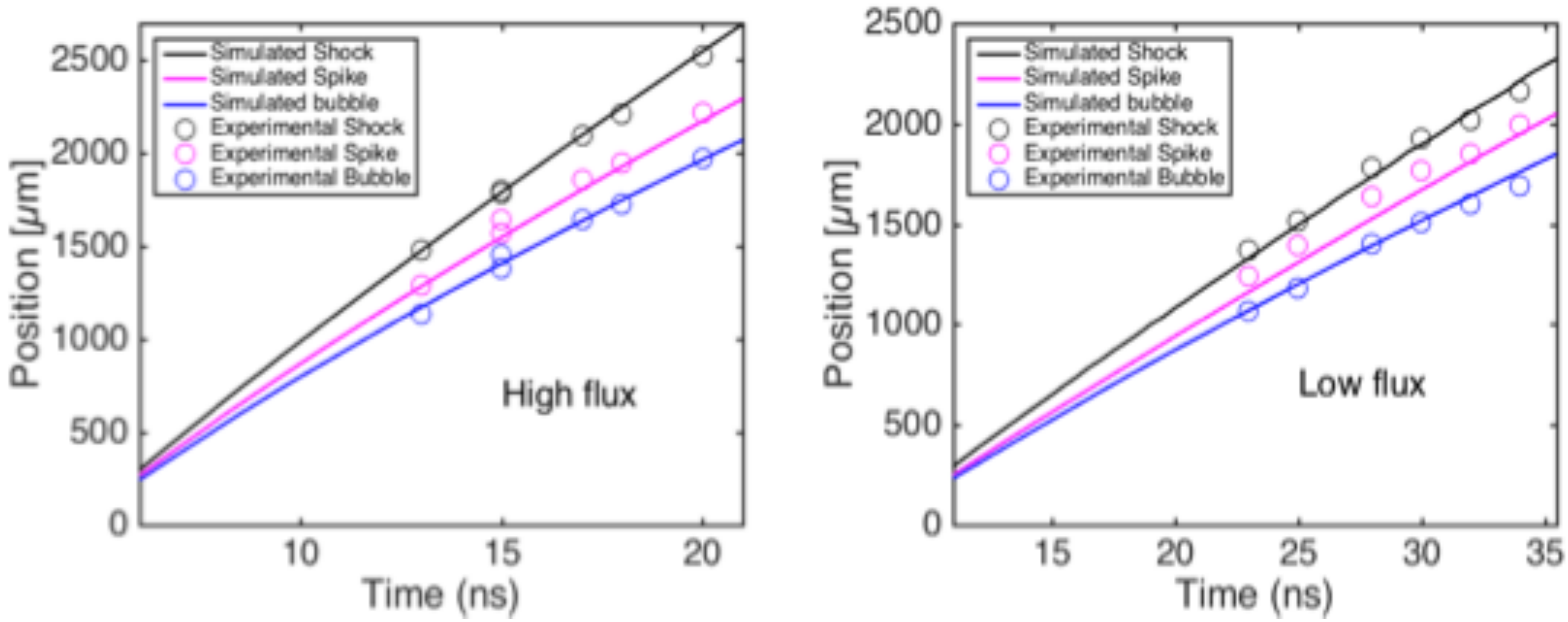
$$\gamma_{RT} = \sqrt{A(t)g(t)k}$$

A(t) is the Atwood number, g(t) is the acceleration and k is the wave number of the initial perturbation

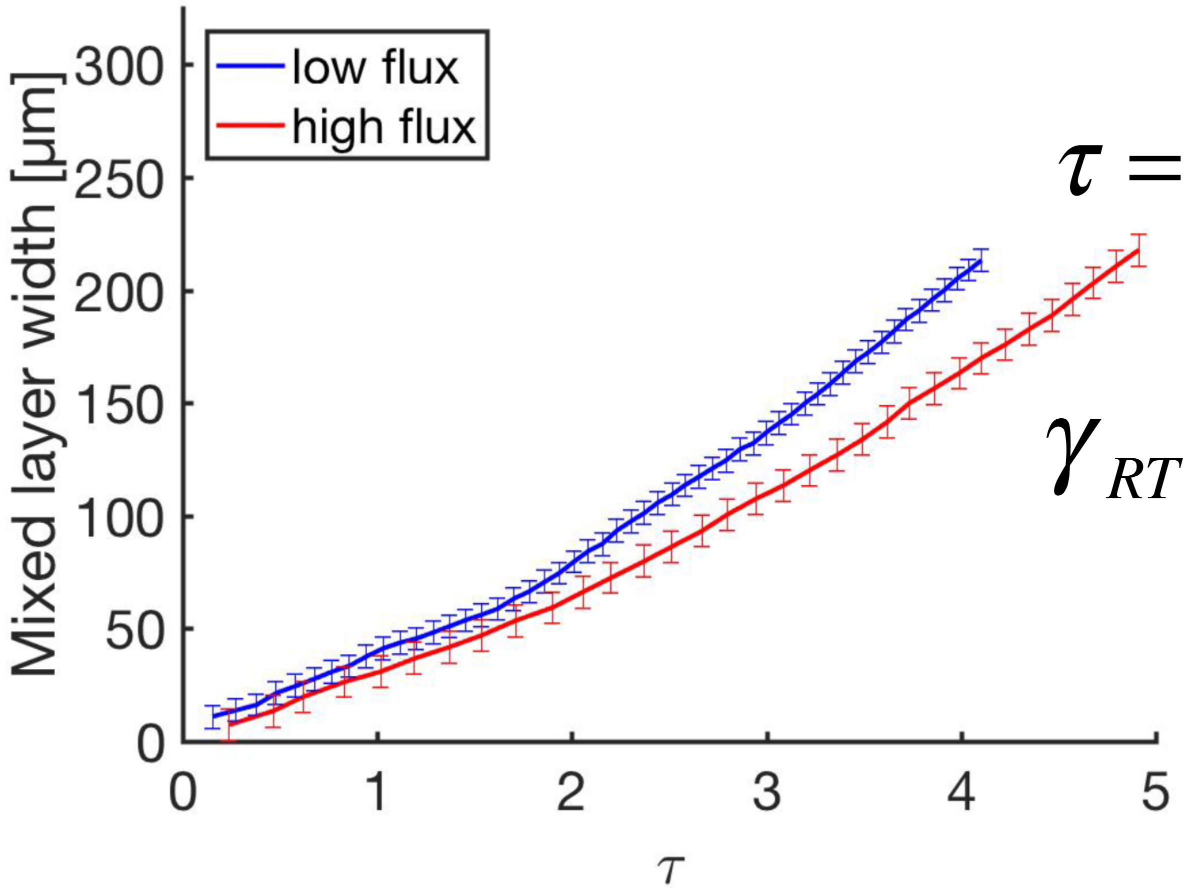
Experimental data and CRASH simulations are in good agreement



Experimental data and CRASH simulations are in good agreement



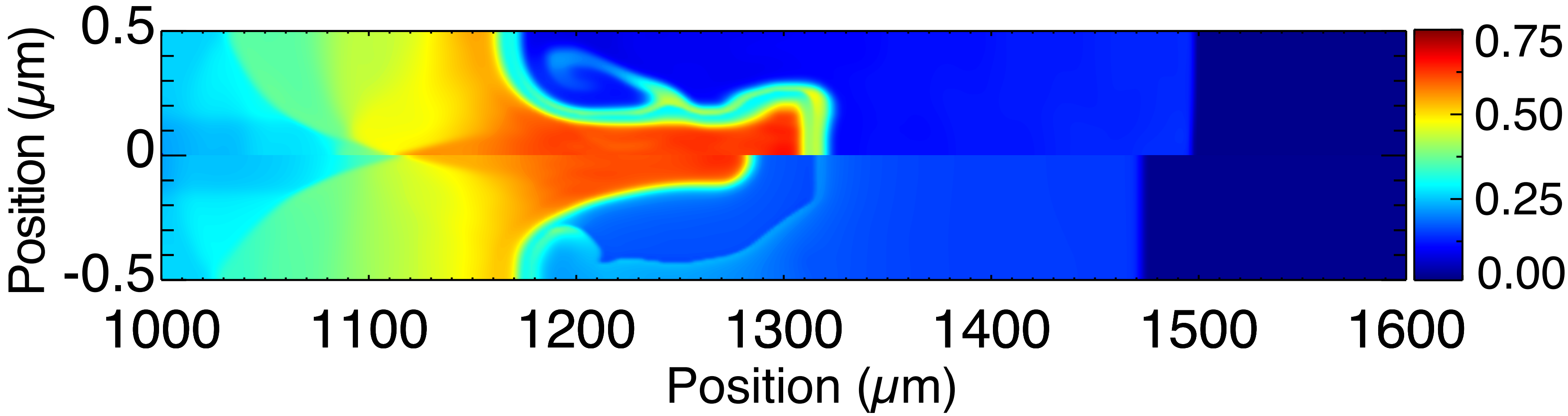
CRASH simulations also show a reduction in RT growth



$$\tau = \int \gamma_{RT} dt$$

$$\gamma_{RT} = \sqrt{A(t)g(t)k}$$

CRASH simulations also show a reduction in RT growth



Comparison of simulated nominal and reduced opacities

Astrophysical and experimental parameters

Scale Parameter	SN1993J	NIF experiment
Intershock distance L (cm)	$2.8 \times 10^{14} t_{yr}^{0.95}$	0.02
Shock separation speed U (cm/s)	$3.0 \times 10^{8} t_{yr}^{-0.046}$	6.8×10^{6}
Ejecta density at RS (g cm^{-3})	$3.4 \times 10^{-19} t_{yr}^{-1.6}$	0.026
SEL Density (g cm^{-3})	$1.4 \times 10^{-16} t_{yr}^{-1.6}$	0.5
SCSM Density (g cm^{-3})	$9 \times 10^{-19} t_{yr}^{-1.6}$	0.18
SEL Temperature (eV)	$3800 t_{yr}^{-0.092}$	20
SCSM Temperature (eV)	$7.8 \times 10^{5} t_{yr}^{-0.092}$	80
RS Velocity (km s^{-1})	$1.7 \times 10^{4} t_{tyr}^{-0.046}$	35
FS Velocity (km s^{-1})	$2 \times 10^{4} t_{tyr}^{-0.046}$	170
Z	1	2
A	1	20

Key dimensionless parameters

Dimensionless number	SN1993J	NIF experiment
λ_c/L	$\sim 10^{-4}$	$\sim 10^{-8}$
Re	$\sim 10^{6}$	$\sim 10^{7}$
Energy flux ratio R	$\sim 10^{3}$	~ 2

Both systems are highly collisional with negligible viscosity and energy fluxes due to radiation and heat conduction are higher or comparable to the mechanical energy flux

Heating is possible by radiation and electron heat conduction

$$F_{rad} = n_e n_i \Lambda D$$

Energy flux due to cooling by radiative losses from the shocked layer

$$Q_e = 0.1 n_e m_e v_{e,cs}^3$$

Electron heat flux, 10% the free-streaming heat flux

$$F_{mech} = \rho_{ej} v_{rs}^3$$

Mechanical energy flux driving the shock-heating of the shocked matter

n_e electron density

n_i ion density

Λ cooling function

D shocked layer thickness

m_e electron mass

$v_{e,cs}$ electron thermal velocity

ρ_{ej} ejecta density

v_{rs} reverse shock velocity

Radiative and heat conduction fluxes are large in SN1993J

Scale Parameter	SN1993J	NIF experiment
F_{mech} (ergs/cm^2/s)	$1.8 \times 10^5 t_{tyr}^{-1.76}$	2.8×10^{19}
F_{rad} (ergs/cm^2/s)	$3.6 \times 10^7 t_{tyr}^{-2.26}$	4.2×10^{19}
Q_e (ergs/cm^2/s)	$2.0 \times 10^8 t_{tyr}^{-1.76}$	1.7×10^{19}

$$R = \frac{Q_{ecs} + F_{rad}}{F_{mech}}$$

Energy flux ratio R	10^3	2

Conclusions

- **We create and observe the evolution of hydrodynamic instabilities in the HEDP regime**
- **We have observed the reduction in KH growth due to compressibility effects (Wan, *PRL* 2015)**
- **We have observed mode coupling in RM (Di Stefano, *APL* 2015)**
- **We have observed ablative stabilization of the RT instability (Kuranz, *Nature Communications* 2018)**
  - **Future work through NIF DS to measure temperature**