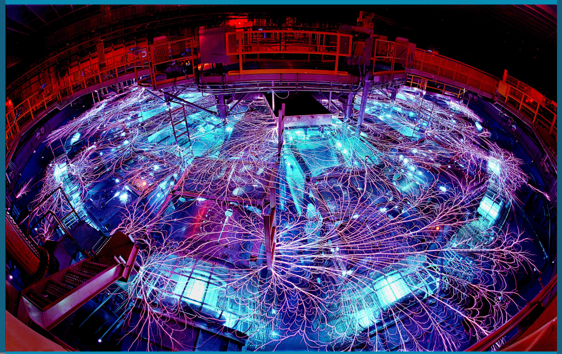
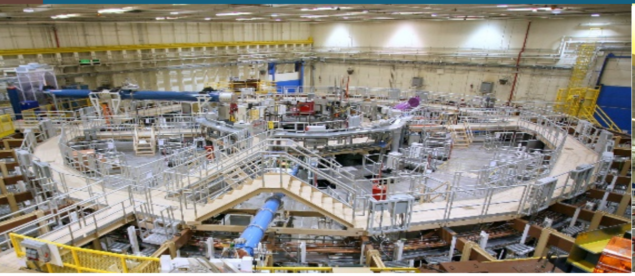
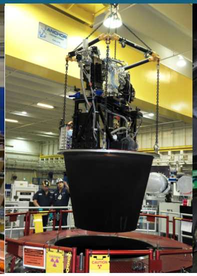
SAND2021-0603PE

Sandia National Laboratories

Material physics with pulsed power at Sandia







Presented by

Dr. Thomas R. Mattsson, Senior Manager 1640 and Deputy Executive for Assessment Science at Sandia National Laboratories

Los Alamos National Laboratory (LANL) Physics and Theoretical Division Colloquium, Los Alamos National Laboratory, January 21, 2021.

U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

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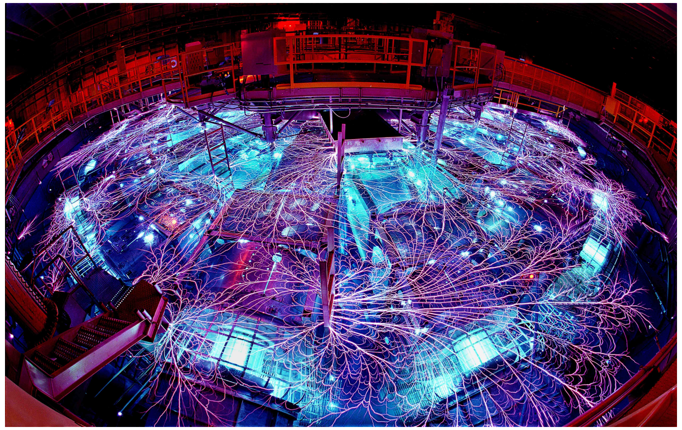
Outline

- Introduction
  - Magnetic pressure is pressure!
- Planetary science
  - Vaporization of iron (Harvard and UC Davis)
  - Metallization of hydrogen (Univ. of Rostock)
- Applications in material physics
  - Plutonium program on Z (LANL)
  - EOS of high explosives (LANL)
  - EOS of foams (LANL)
  - Tri-lab strength collaboration (LANL and LLNL)
  - Phase transitions – dynamic freezing of gallium (LLNL)
  - Phase transitions – dynamic freezing of cerium (LANL)
  - X-ray diffraction on Z and THOR
- Where material physics ends, dense plasma physics begins
  - Instability experiments (LANL)
  - Plasma transport / kinetic (LANL)
- Summary
  - Points of contact at Sandia



The Z-machine at Sandia

Thor center section

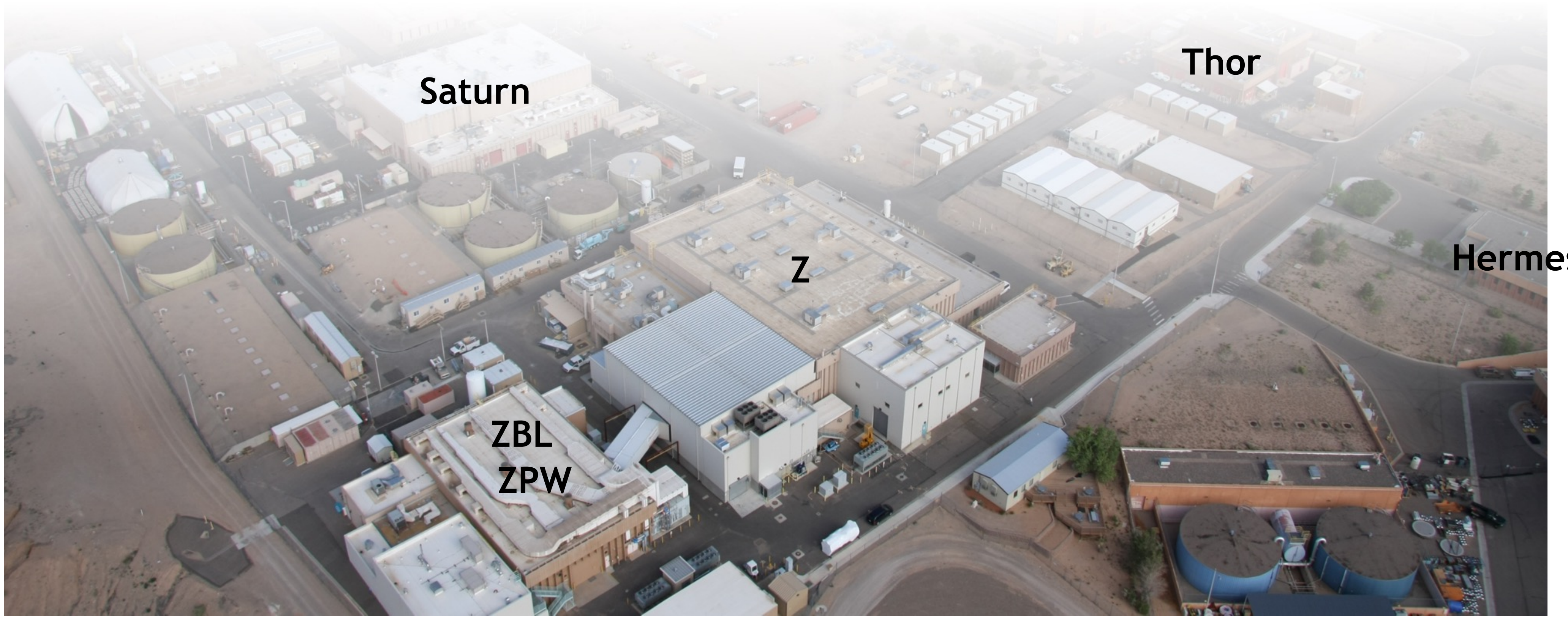
First Heilmeier questions for HED Material Physics at SNL

- What are you trying to do? Articulate your objectives using absolutely no jargon.
  - Create, diagnose, and model/simulate matter at extreme conditions – and do it with accuracy
- How is it done today, and what are the limits of current practice?
  - Gas guns are limited to shocks and – in comparison – low pressures
  - Lasers are limited to small samples and short time scales
- What is new in your approach and why do you think it will be successful?
  - Pulsed power can drive macroscopic samples for long times resulting in high accuracy
- Who cares? If you are successful, what difference will it make?
  - Provide data for materials like plutonium, deuterium, and more for stockpile stewardship
    - Improved and validated material models employed in multi-physics simulations that are ubiquitous in stockpile stewardship
  - High-quality data and models turn planetary physics quantitative
    - What causes the differences between Jupiter and Saturn?
    - How much of an asteroid is vaporized upon impact on the early Earth? – is that how the moon was formed?

George H. Heilmeier, a former DARPA director (1975-1977), crafted a set of questions known as the "Heilmeier Catechism" to help Agency officials think through and evaluate proposed research programs.

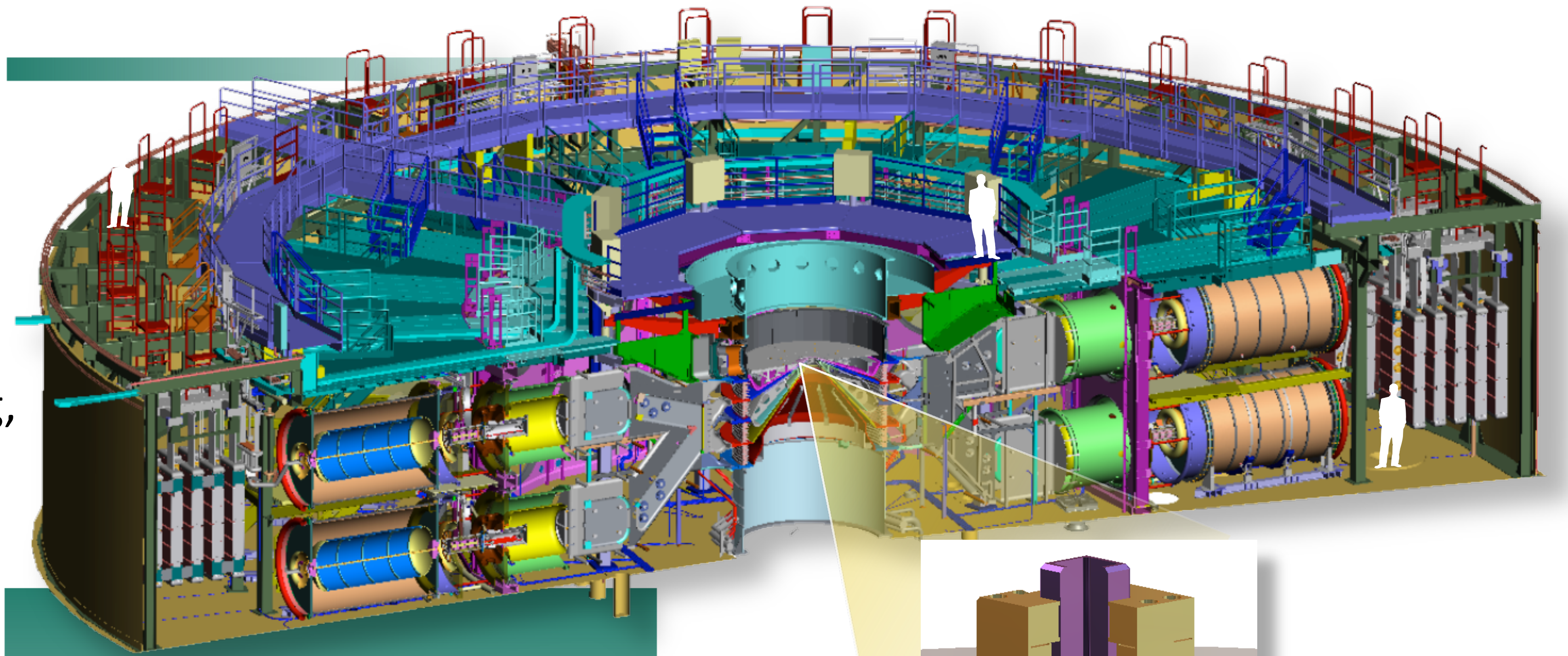
Tech Area IV at Sandia National Laboratories in Albuquerque is quite a neighborhood for HED Science

- Three of the largest fast pulsed power machines in the world
- One of the largest laser systems in the US

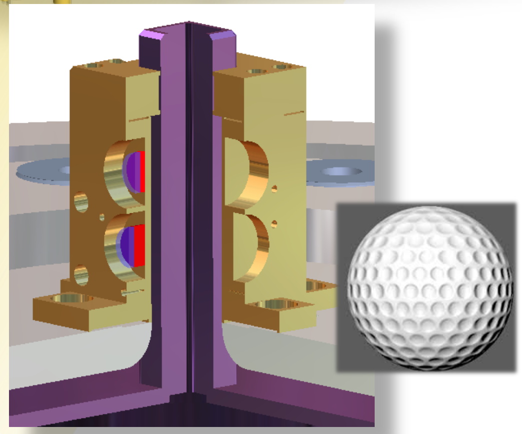


Sandia's Z Machine is a unique platform for multi-purpose research on high energy density (HED) environments

Team of teams:
Z operations, cryogenics, diagnostics, theory/ simulations, target design and -fabrication, engineering, and management.



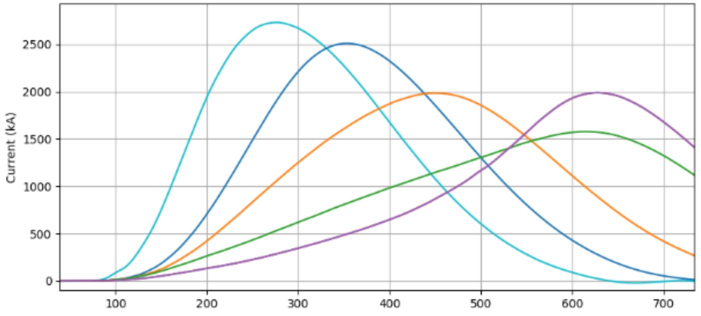
- Pulsed Power Technology
- Radiation Sources/-Physics
- Inertial Confinement Fusion
- Materials at high pressure/EOS

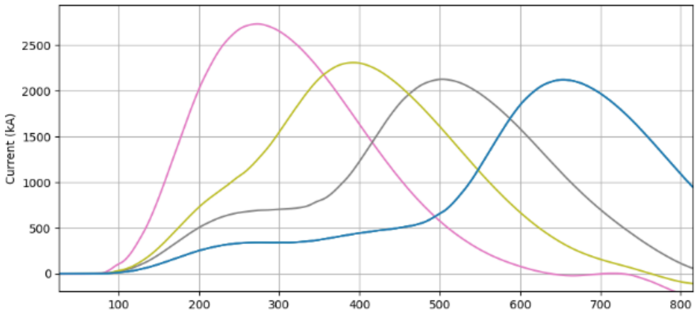


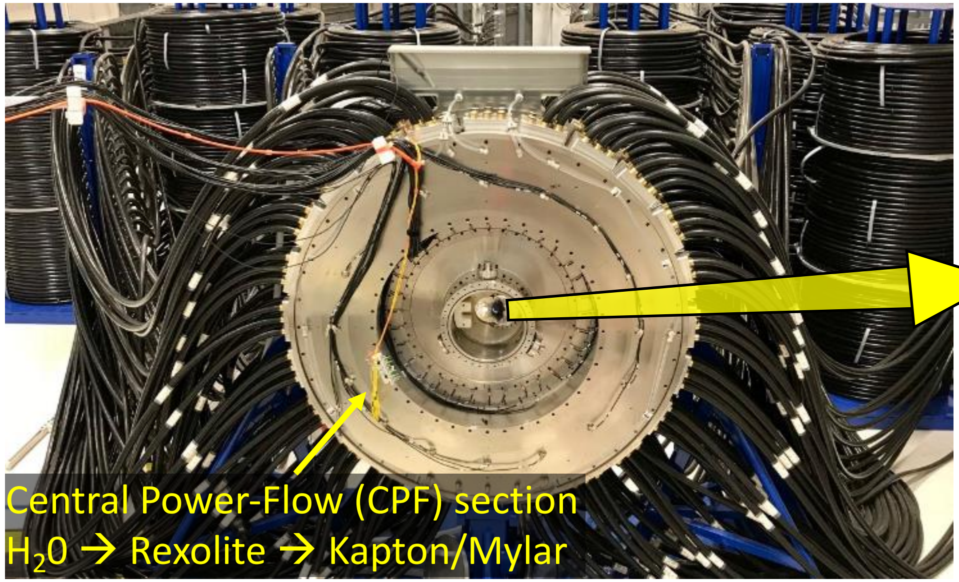
I ~ 26 MA,
τ ~100-1000 ns
X-ray power > 250 TW
X-ray energy > 2 MJ

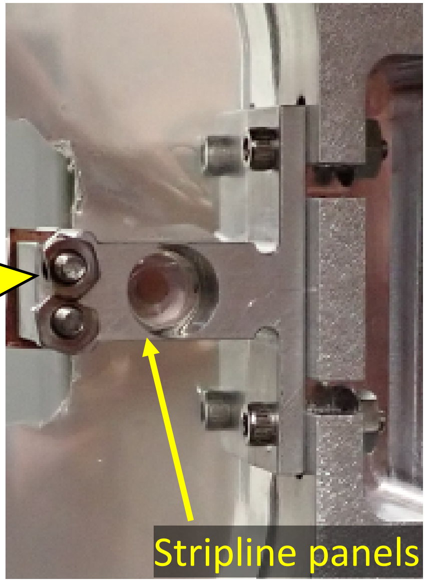
Thor is a ~2-MA pulsed-power machine at Sandia capable of a large range of pulse shapes for ramp loading of materials

- 64 “bricks” (2 capacitors + 1 switch) with 51 kJ energy at 90 kV
- 2.5 MA with ~150-ns rise time synchronous mode
- Independently trigger groups of 4 bricks up to 500 ns
- Peak stress in Al/Cu electrodes of 10-40 GPa at strain rates of $5\times10^{5}-10^{7}/s$
- Stripline targets with two identically-loaded samples or drive + sample
- We plan 100-150 shots during FY21



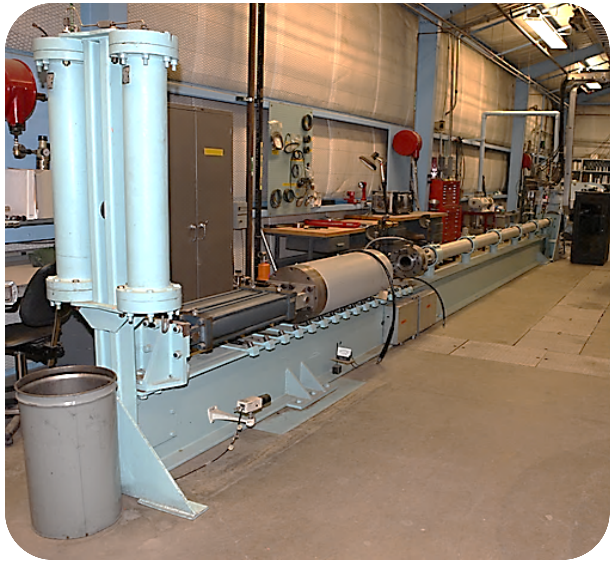




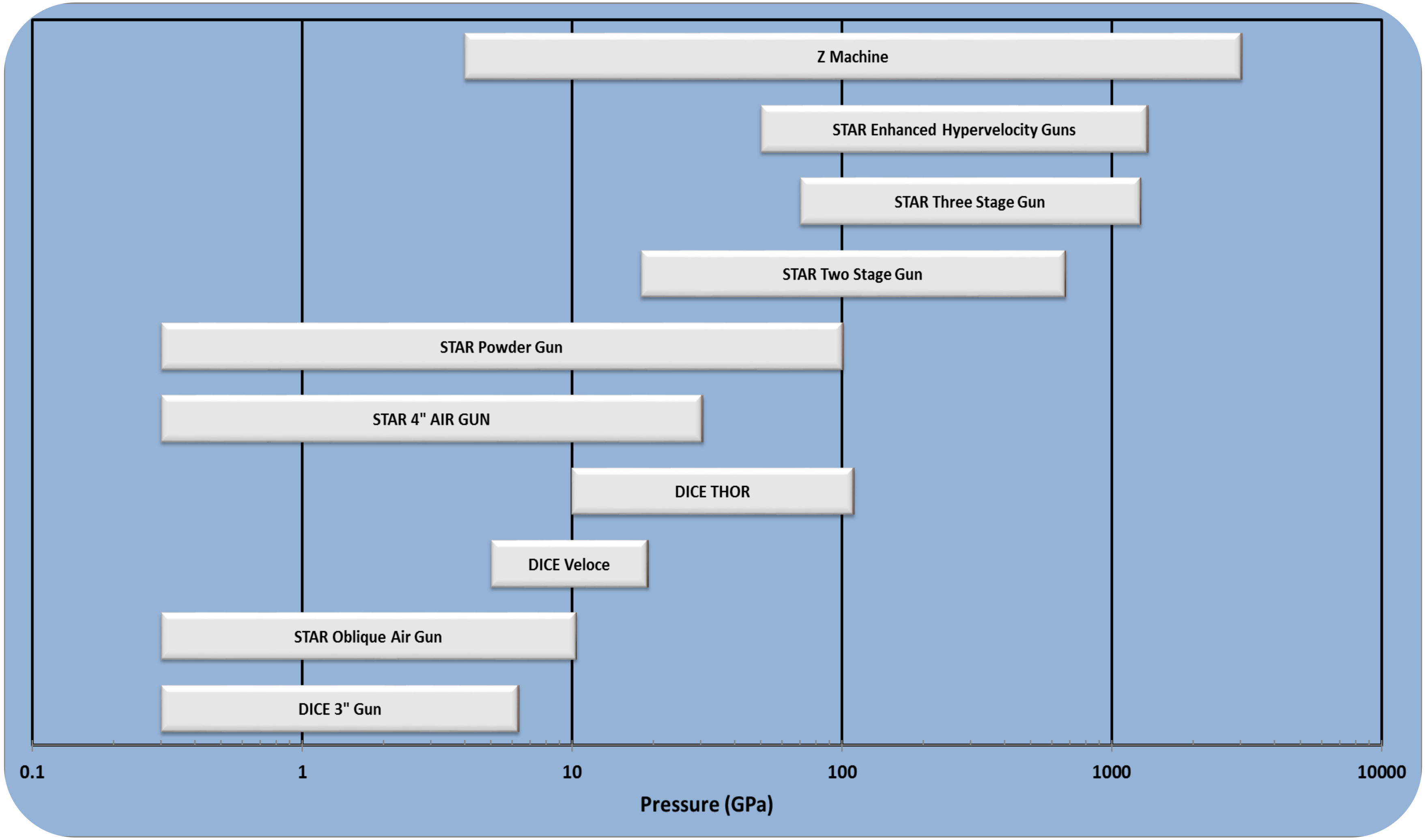


In addition to Z and Thor, we operate Veloce as well as multiple different launchers at the STAR and DICE facilities

STAR two stage gun



STAR air gun



STAR/DICE POCs: Gordon Leifeste, Bill Reinhart, Scott Alexander, and Steven Dean

MHD: currents and the corresponding magnetic fields create matter and radiation in extreme conditions

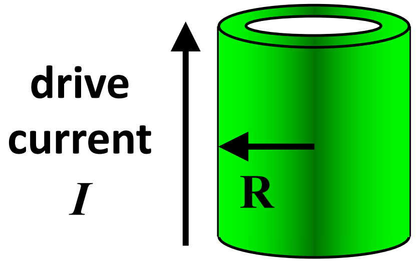
Current x magnetic field

Magnetic field as scalar pressure

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t}+(\mathbf{u}\cdot\nabla)\mathbf{u}\right)=\frac{\mathbf{J}\times\mathbf{B}}{c}-\nabla P\approx\frac{1}{4\pi}\mathbf{B}\bullet\nabla\mathbf{B}-\nabla\left(P+\frac{B^2}{8\pi}\right)$$

Pressure

velocity field



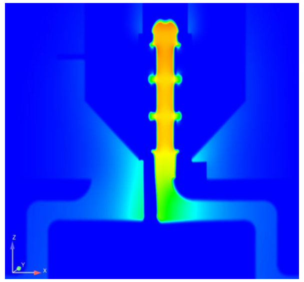
- 25 MA at 1cm radius is 1 Mbar
- 25 MA at 1mm radius is 100 Mbar

- Advantages with current drive
  - *Can create high pressures without making material hot*
  - Long time scales with control over the time history
  - mm to cm sized samples - large enough for real materials
  - 2 MJ energy to load of 20 MJ stored

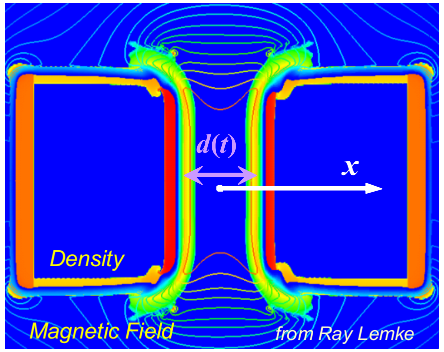
Integration of theory, computation, and experiments provide a broad perspective on HED physics

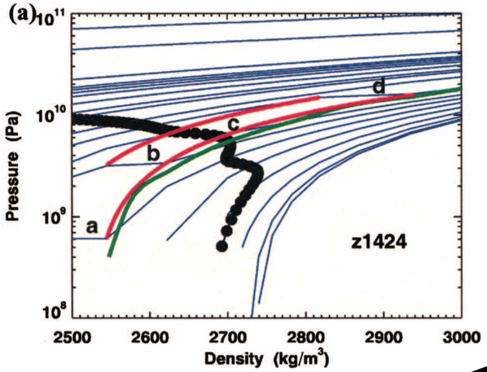
ALEGRA ... The Shock and Multiphysics Family of Codes

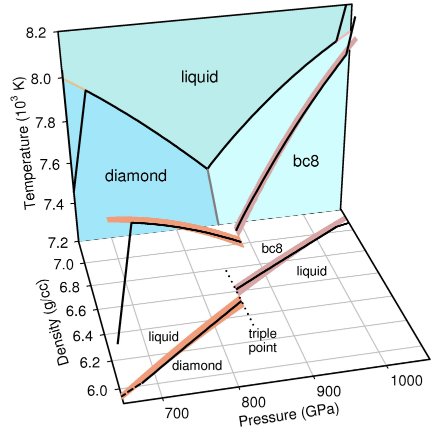
DAKOTA

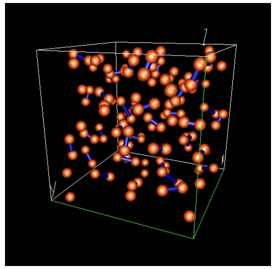


$$\sigma_{\mathbf{k}}(\omega)=\frac{2\pi e^2\hbar^2}{3m^2\omega\Omega}\sum_{\alpha=1}^{3}\sum_{j=1}^{N}\sum_{i=1}^{N}\left(F(\varepsilon_{i,\mathbf{k}})-F(\varepsilon_{j,\mathbf{k}})\right)\left|\left\langle\Psi_{j,\mathbf{k}}\left|\nabla_\alpha\right|\Psi_{i,\mathbf{k}}\right\rangle\right|^2\delta(\varepsilon_{j,\mathbf{k}}-\varepsilon_{i,\mathbf{k}}-\hbar\omega)$$

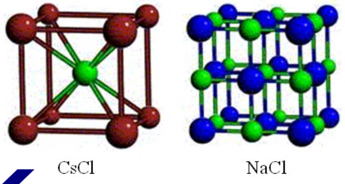




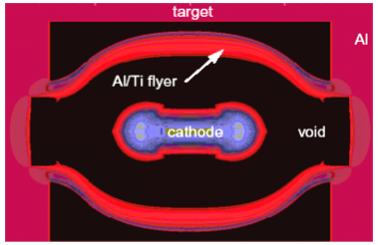


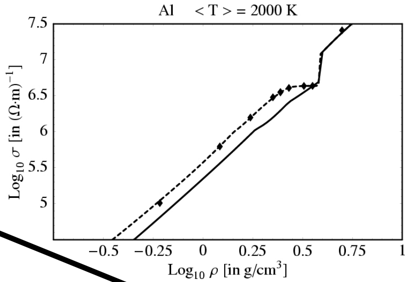


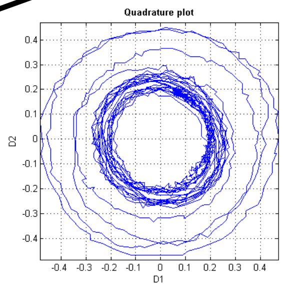
Vienna Ab-initio Simulation Package

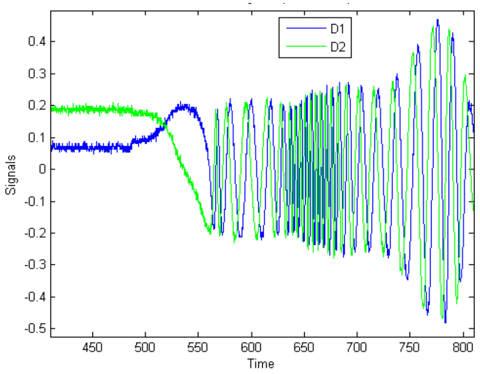


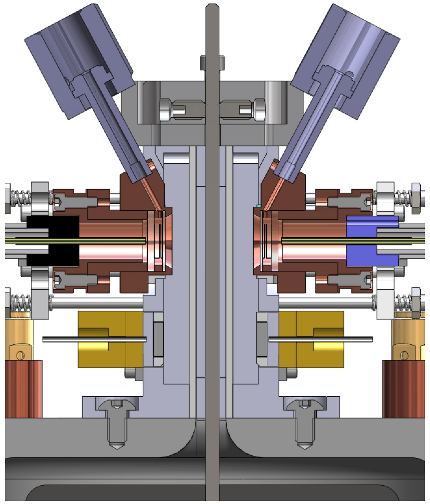
QMCPACK

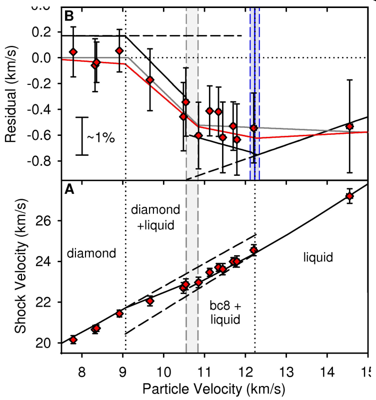


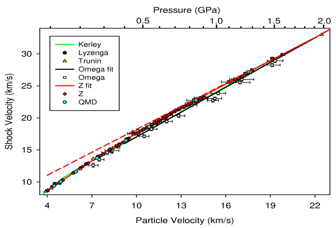




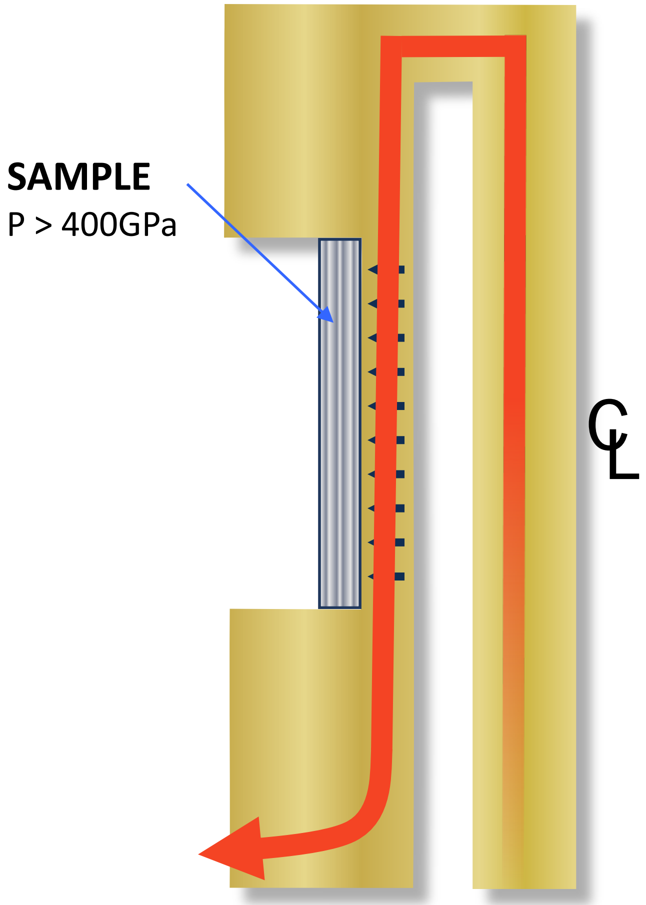




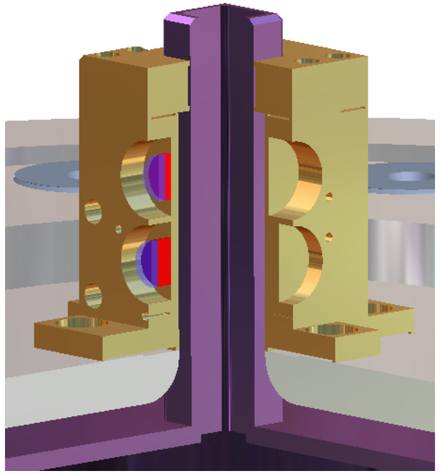


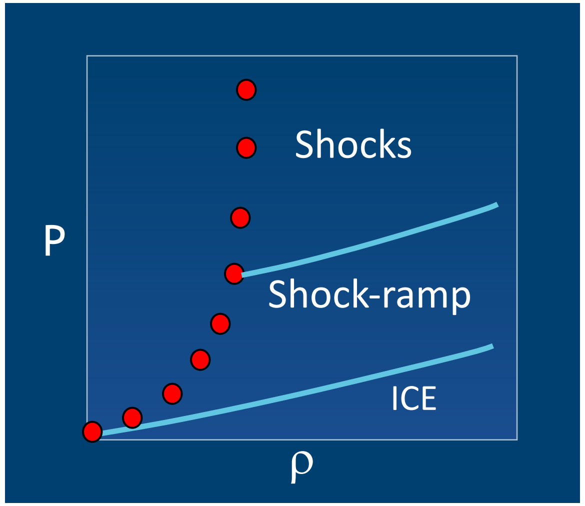


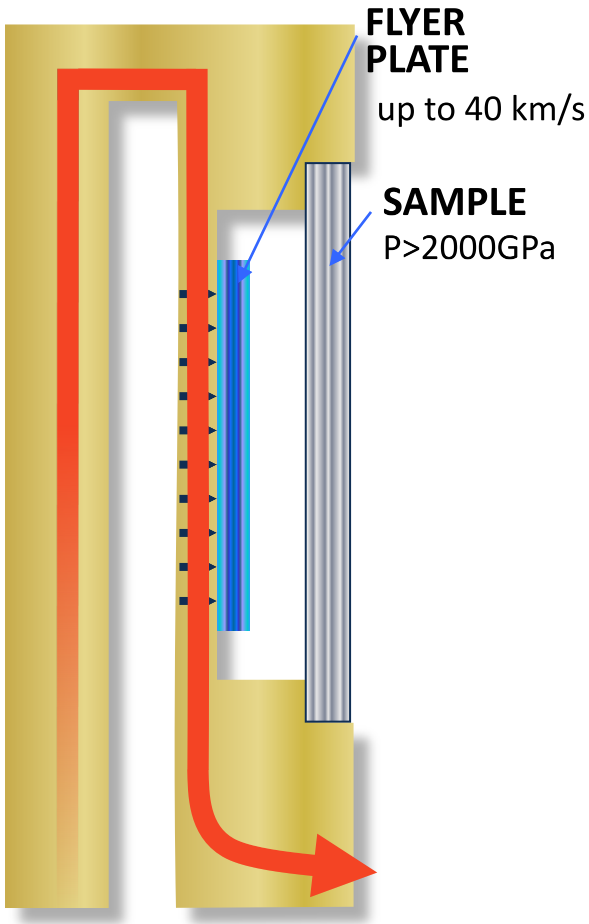
Isentropic compression and shock wave experiments map different regions of phase space



Isentropic Compression Experiments:
Gradual pressure rise in sample

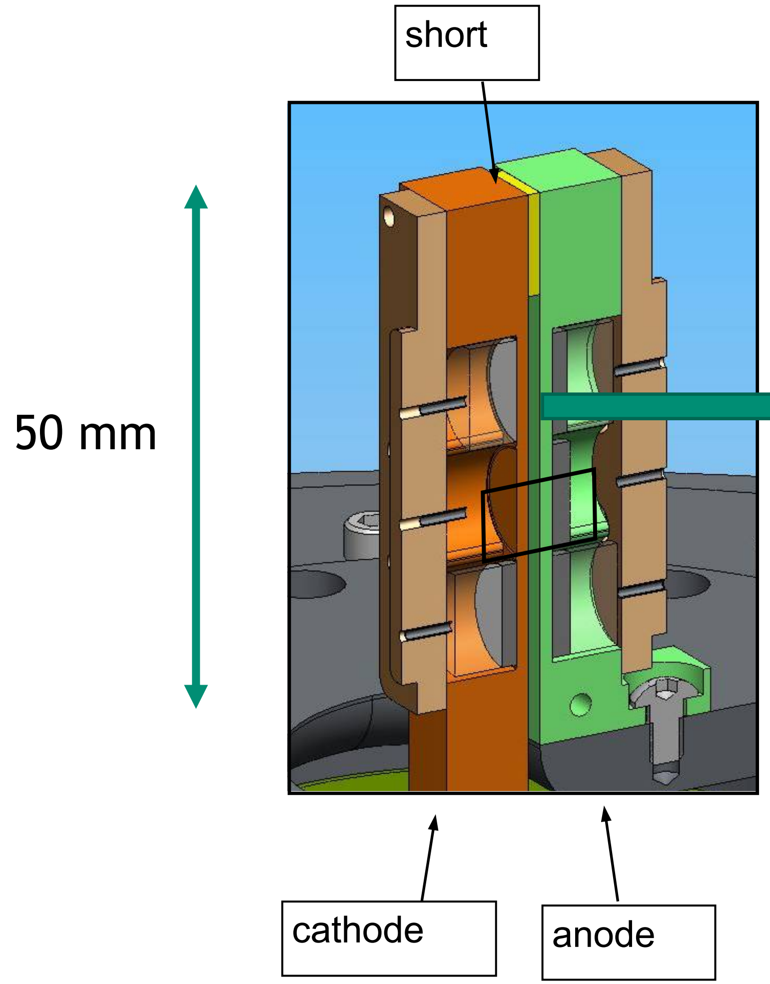


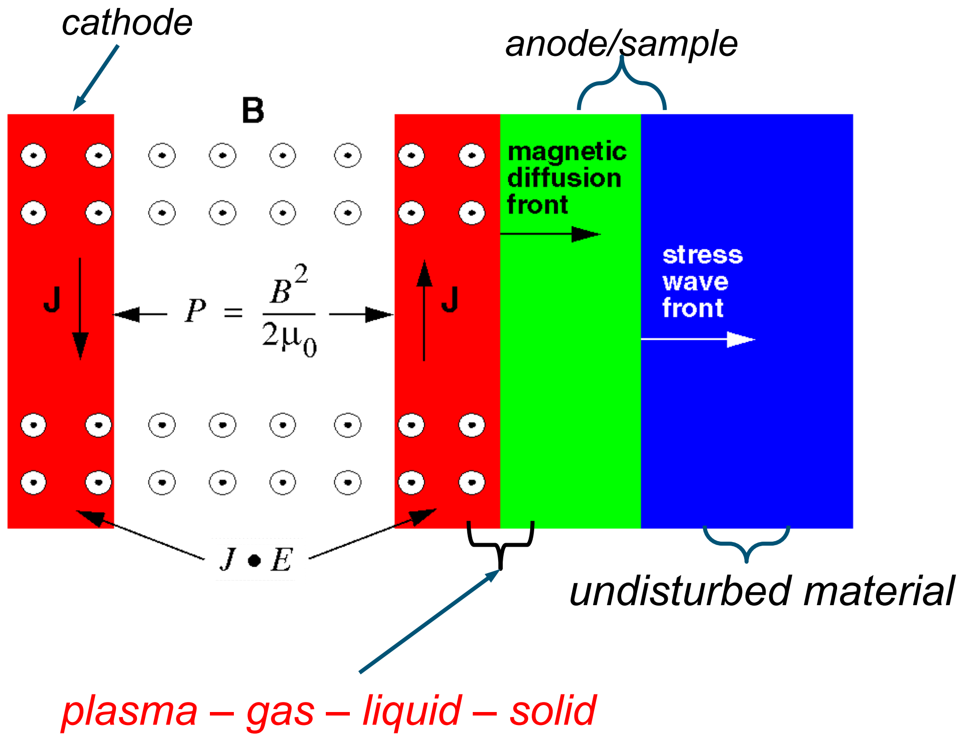




Shock Hugoniot Experiments:
Shock wave in sample on impact

How about the magnetic field? It moves slower than the stress wave



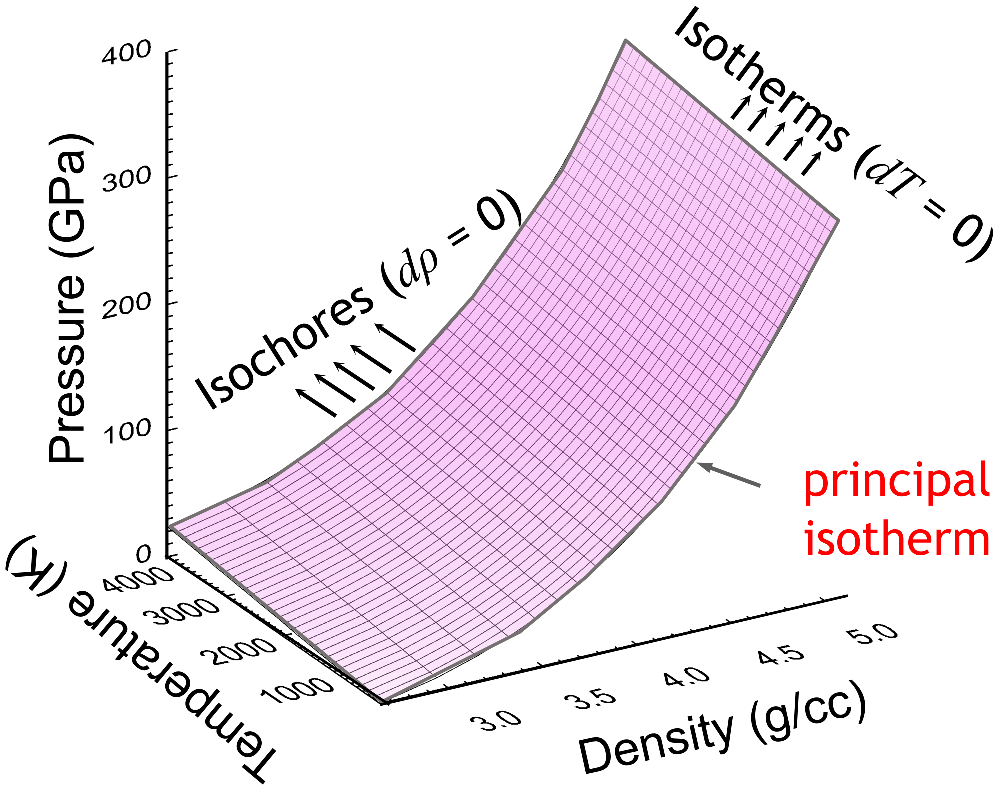


A fluke of nature – magnetic diffusion is slower than the stress wave

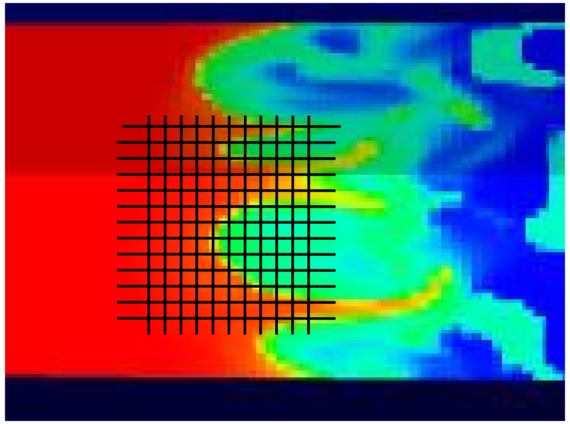
mm – sized samples are large enough to study many types of real materials like powders, foams, high explosives

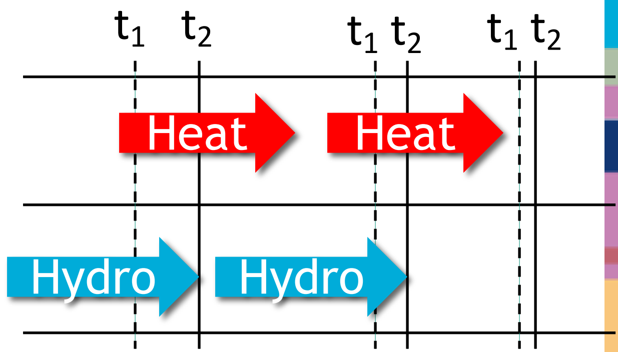
The Equation of State (EOS) governs the hydrodynamic motion and thermal evolution of a material

EOS – the relation between temperature, pressure, volume/density, and internal energy



J.-P. Davis





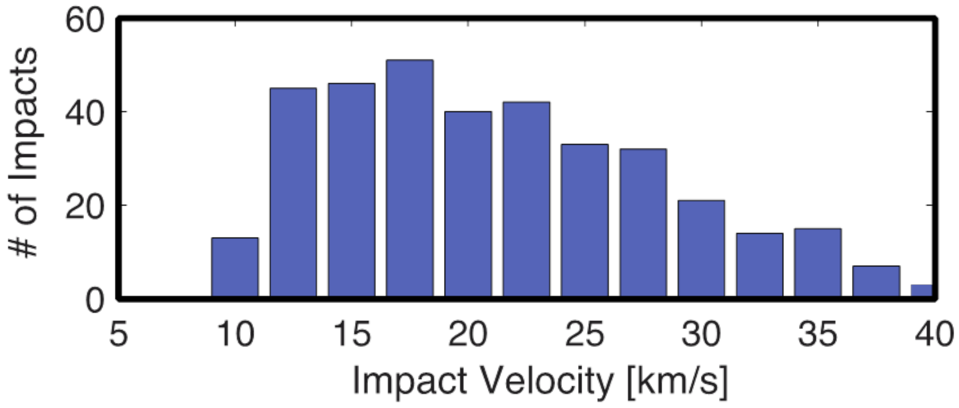
Material models rule the hydrodynamic- and thermal evolution in multi-physics simulations - how fast does an element heat up and change volume?

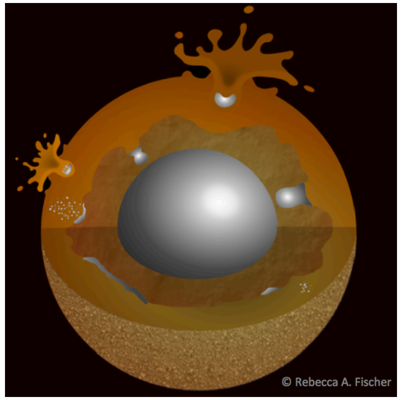
A simulation is never better than the material models it is based on.

Plots of density/pressure, pressure/ temperature, and even density/entropy for different materials

Vaporization a key mechanism during planet formation and -evolution

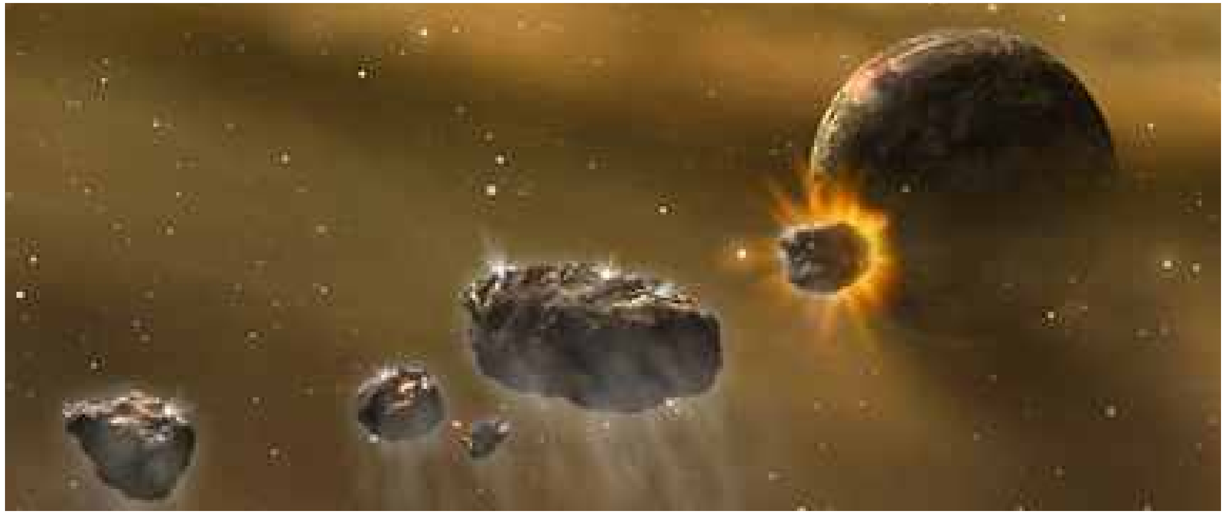
Simulations of planetary dynamics suggest high impact velocities





Fluid instabilities CAN NOT sufficiently mix the incoming iron cores to explain observed iron content in the mantel or the similarity in isotopics between the earth and the moon.

Large uncertainty in onset of vaporization



Does an iron meteor:

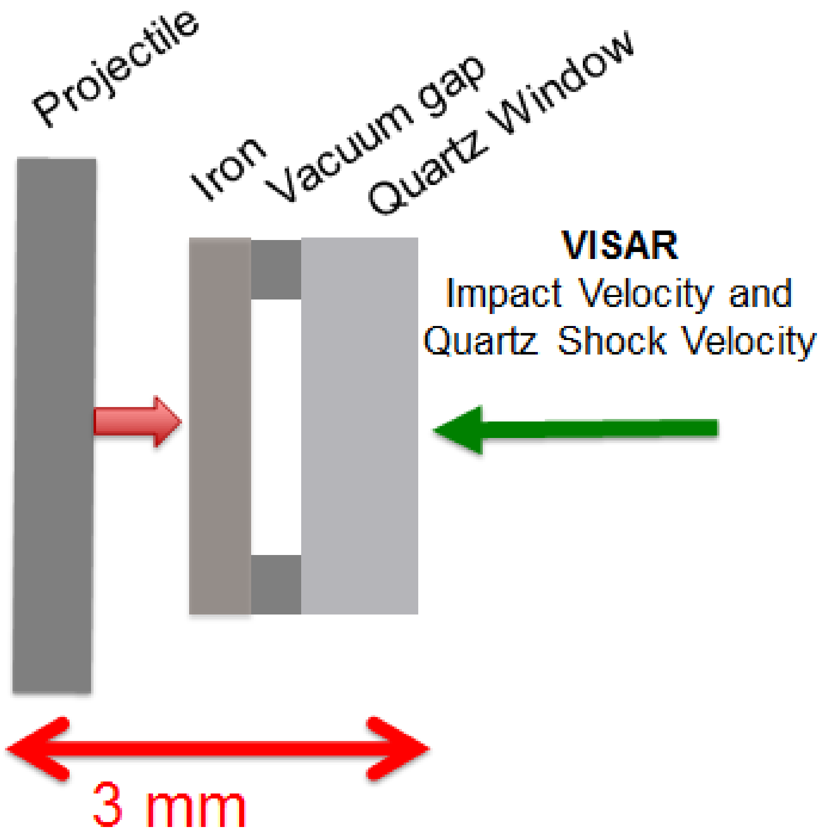
- plow into a planet as a bullet?
- splatter as a drop of rain?
- vaporize into a cloud of iron to return as iron rain?

The outcome depends on the HED properties of iron – particularly vaporization

N-body simulations from Raymond et al. 2009

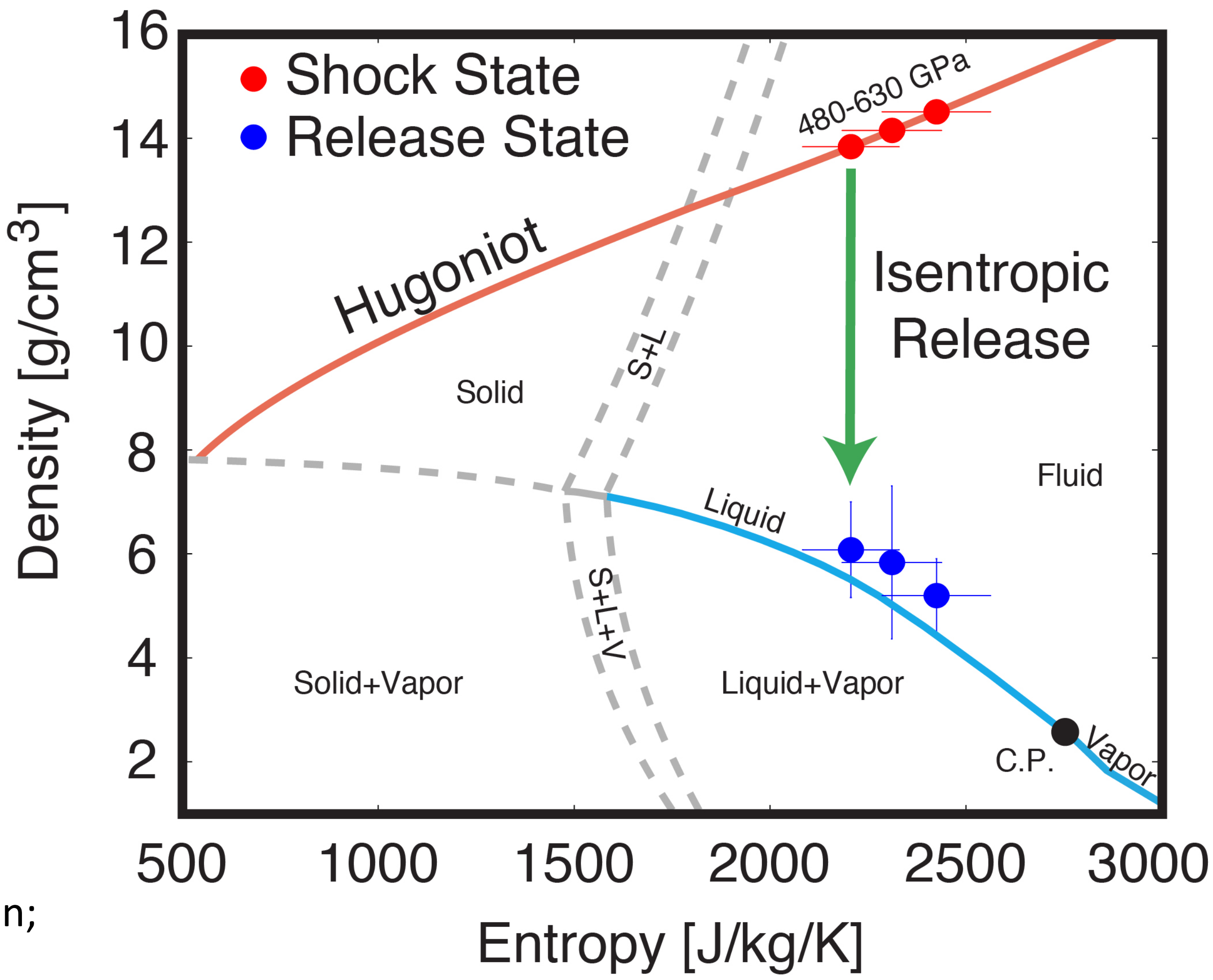
Vaporization by planet forming impacts can be studied on Z

- Flyer plates on Z can exceed 40 km/s
- Liquid-vapor dome located via shock-release experiments



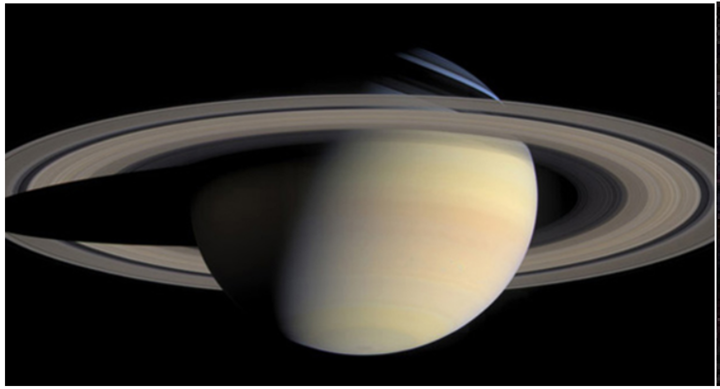
Kraus, Root, Lemke, Stewart, Jacobsen, and Mattsson; *Nature Geoscience* **8**, 269 (2015).

Iron Shock and Release Data



Observation of H2 metallization was needed to resolve a mystery

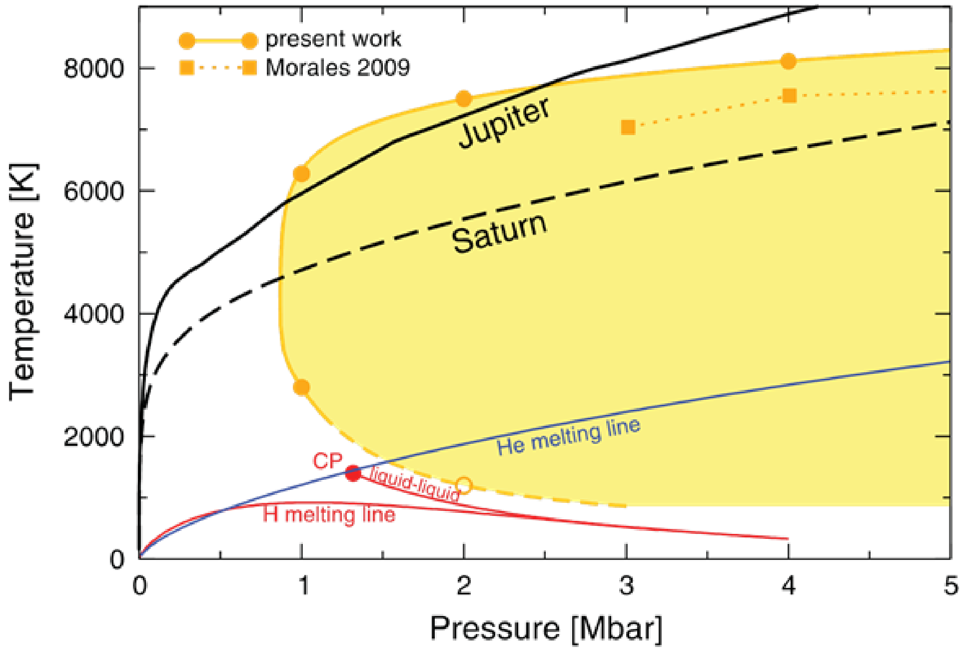
Why is Saturn hot?



- Planets cool with age
- Saturn is much hotter than would be expected for it’s age

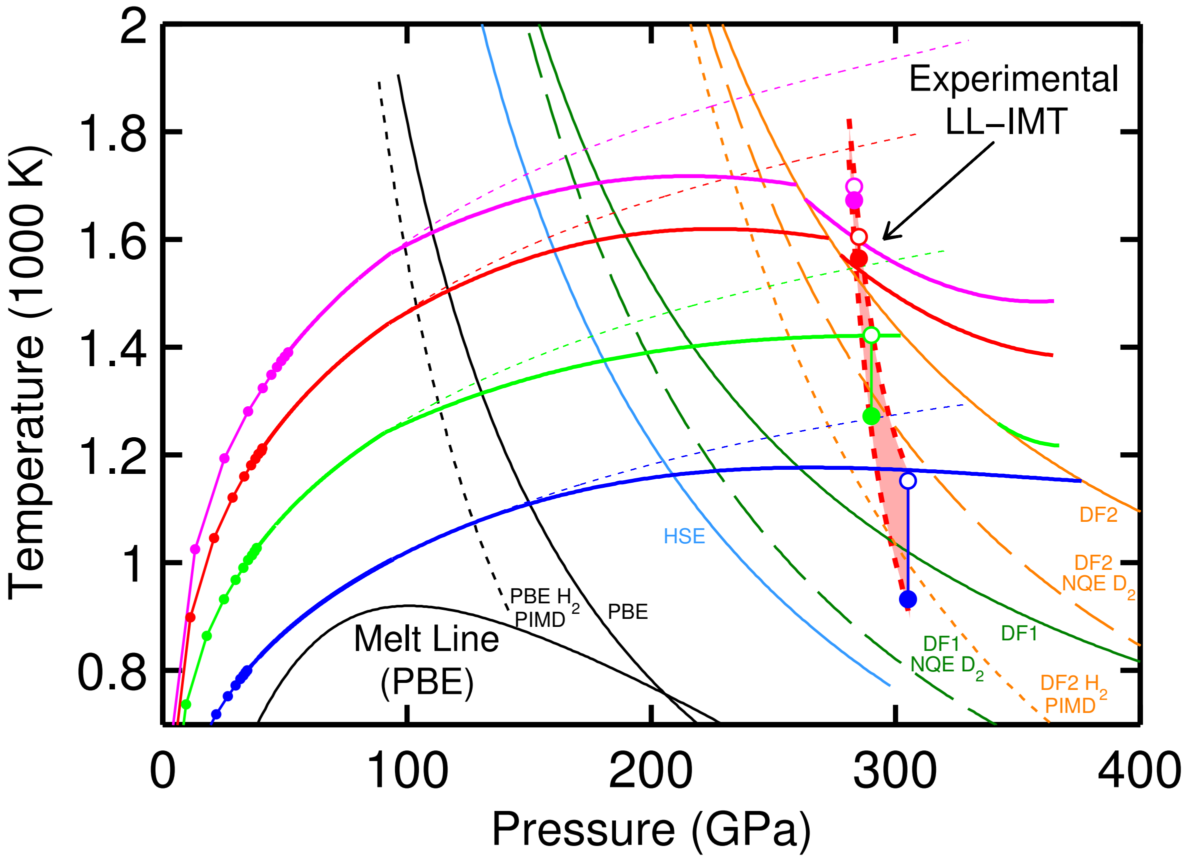
- *Two billion years problem using the same aging model as for Jupiter*

- Hydrogen metallization, Wigner(1935), is linked to H-He de-mixing
- Formation of helium rain would generate heat
- BUT - Jupiter would also have He rain and excess heat according to models at the time



W. Lorenzen, B. Holst, and R. Redmer, Phys. Rev. B 84, 235109 (2011)

Using shock-ramp loading on Z we located the metallization in deuterium to be a steep curve at 300 GPa



Insensitivity to T suggests this is a ρ-driven transition

- ρ at the transition is inferred to be ~2-2.1 g/cc in deuterium
- Qualitatively different transition than in shock experiments (T driven)

Broad team with expertise in diagnostics, pulse-shaping, experimental design, and first-principles simulations

Sandia and University of Rostock, Germany

M.D. Knudson, M.P. Desjarlais, A. Becker, R.W. Lemke, K.R. Cochrane, M.E. Savage, D.E. Bliss, T.R. Mattsson, and R. Redmer, Science **348** 1455, 26 June 2015.

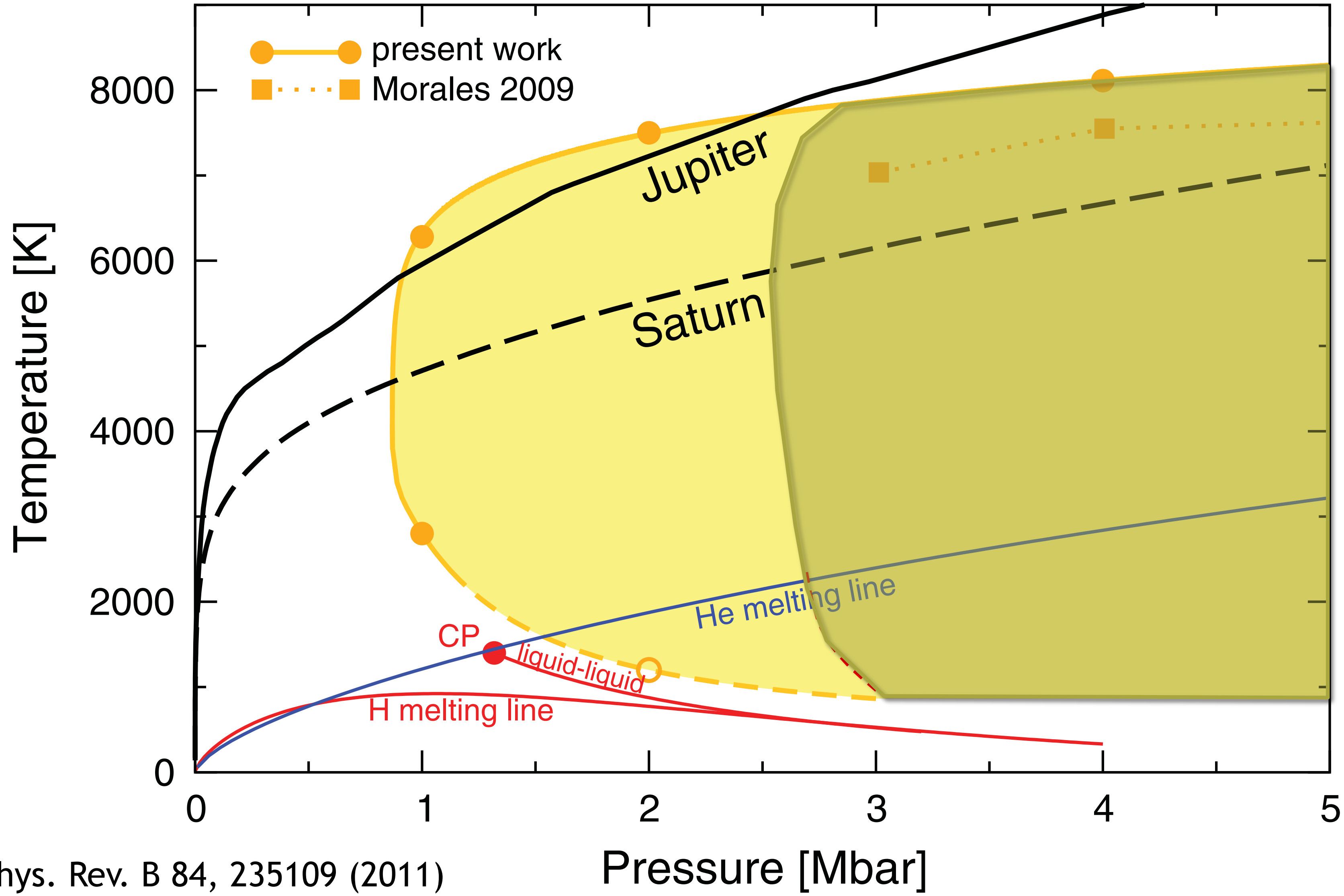
Recent analysis and comparison with Celliers et al Science **361**, 677 (2018). *Thermodynamics of the insulator-metal transition in dense liquid deuterium* M.P. Desjarlais, M.D. Knudson, and R. Redmer, PRB **101**, 104101 (2020).

We predicted the H-He demixing region to be shifted to higher pressure – possibly explaining the Jupiter/Saturn mystery

Quantitative knowledge of the behavior of matter under extreme conditions is crucial for improving our understanding of planetary physics

Mankovich and Fortney Ap. J. (2020)
https://doi.org/10.3847/1538-4357/ab6210

Evidence for a Dichotomy in the Interior Structures of Jupiter and Saturn from Helium Phase Separation



W. Lorenzen, B. Holst, and R. Redmer, Phys. Rev. B 84, 235109 (2011)

Strong and lasting partnership with LANL on plutonium experiments on Z

- Joint design, analysis, and decisions of experimental objectives to meet national needs – the present focus is on aging and production
- LANL produces, machines, measures, and mounts the Pu targets in load hardware delivered from Sandia
- The three pioneering experiments in 2006 were followed by increasingly advanced capabilities in drive and diagnostics
- Significant step in 2010 when Pu experiments were re-authorized after the Z refurbishment
- In 2020, the first “stripline” Pu experiment was executed on the machine, reaching record high pressure – with improved accuracy
- Executed more than 20 Pu experiments to date
- LANL team: Freibert, Moore, Dattelbaum, Tolar, Crockett, and others

The explosively driven containment system on Z makes plutonium experiments possible.

2018: The 22nd plutonium experiment compared 52.5-year-old stockpile Pu to samples made in 2012.

2019: Temperature was successfully measured in the 23rd, for the first time providing complete thermodynamic data under dynamic compression.

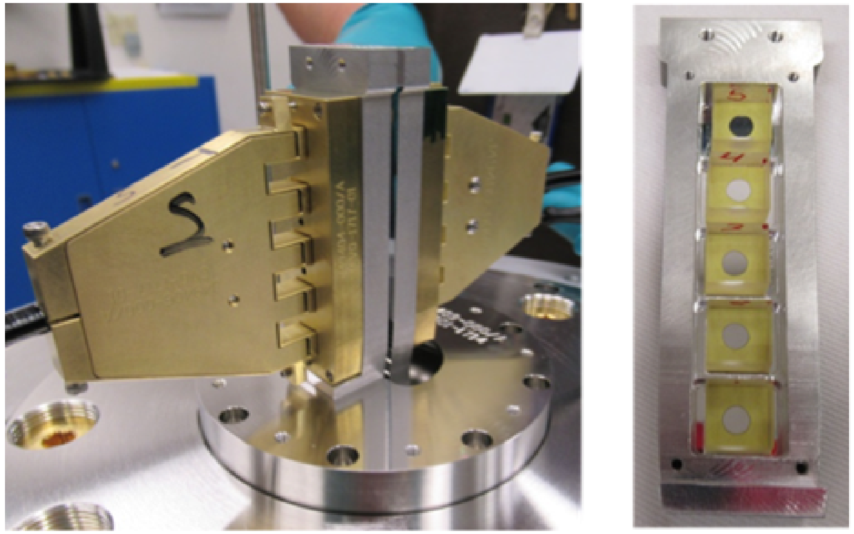
Study of Insensitive Secondary High Explosives on Z

Insensitive secondary high explosives are used in a variety of components

Understanding the response of the unreacted explosive at high pressures is critical for accurately determining the impulse they generate during detonation

Z machine is uniquely positioned to probe the high pressure thermodynamic response of explosive materials

- Shockless compression enables the achievement of high pressures in the explosive without inducing appreciable reaction
  - Related to the relatively low temperatures generated during shockless compression compared to shock compression
  - Enables measurement of the response of the unreacted explosive as apposed to the detonation products



Z3115 Load with Diagnostics Attached (Left) Along with the Anode Panel Containing 5 PBX 9502 Explosive samples (Right)

Paul Specht (SNL), Rick Gustavsen (LANL), Forrest Svingala (LANL), Malcolm Burns (LANL)

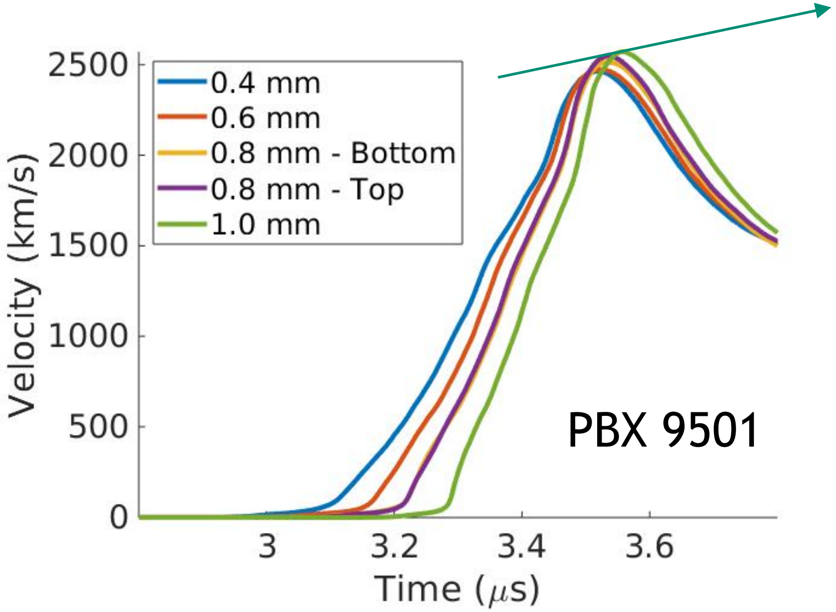
Study of Insensitive Secondary High Explosives on Z

Both PBX 9051 and PBX 9502 have been studied on the Z machine recently

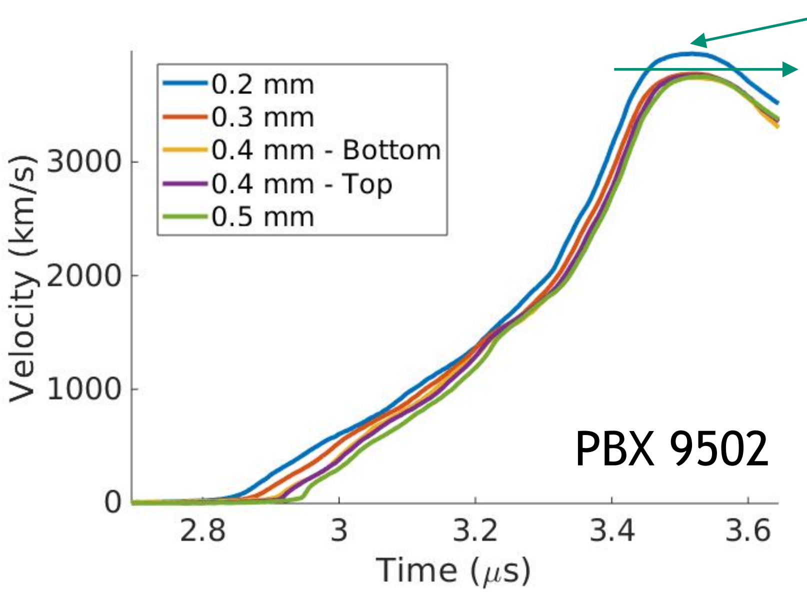
- One experiment PBX 9501
  - Evidence of reaction when approaching 50 GPa
- Three experiments on PBX 9502
  - No evidence of reaction to pressures approaching 1 Mbar
  - Comparisons between legacy and new production lots

Z is also approved for PBX 9503, Cyclotol, and Octol

These measurements are used to refine equation of state (EOS) models for the unreacted explosives for use in performance and safety assessments.



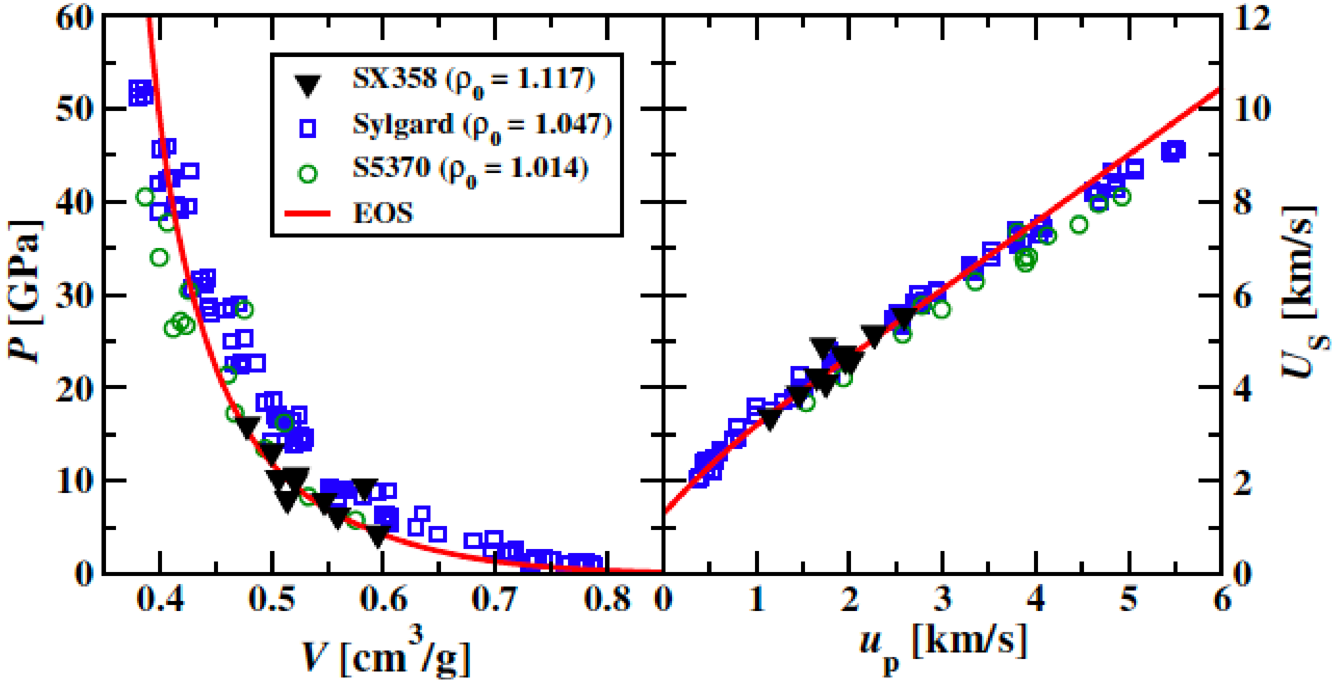
Increase in velocity with sample thickness indicates a chemical reaction is taking place



Larger velocity for the 0.2 mm thick sample results from a larger magnetic drive at the top of the panel

Z-machine experiments on SX358 Foam to validate product EOS

1.1 g/cc SX358



Z-machine providing new data at u_p>>6 km/s

3 Shots conducted on varying density SX358 foams at 8.85 km/s, 15.6 km/s, ~20 km/s.

The solid density dissociates into a product mixture at moderate pressures:

Fluids

Component	ΔH_f^0 [kJ/kg]	r_0 [Å]	ϵ/k_B [K]	α
CH_4	−4170.791061	4.22	184.5	13.0
CO	−4062.955188	3.55	155.0	12.0
CO_2	−8933.260319	4.0935	338.3	14.40
H_2	0	3.43	36.4	11.1
O_2	0	4.11	75.0	13.117
H_2O	−13262.13081	3.5	424	10.0
HCCH	9054.308569	4.41	250.0	13.0
HCO_2 H	−8234.583513	4.096	335	13.781
C	59667.80451	3.64	95.1	12.0

Solids

Component	ΔH_f^0 [kJ/kg]	B_0 [GPa]	$\frac{dB}{dP}$	Θ_D [K]	Γ
C (diamond)	201.898	432.4	3.793	1850	0.88
SiO_2	−13645.387	349.81	5.3	1210	1.22
SiC	−1784.359	221.0	3.91	1240	1.0

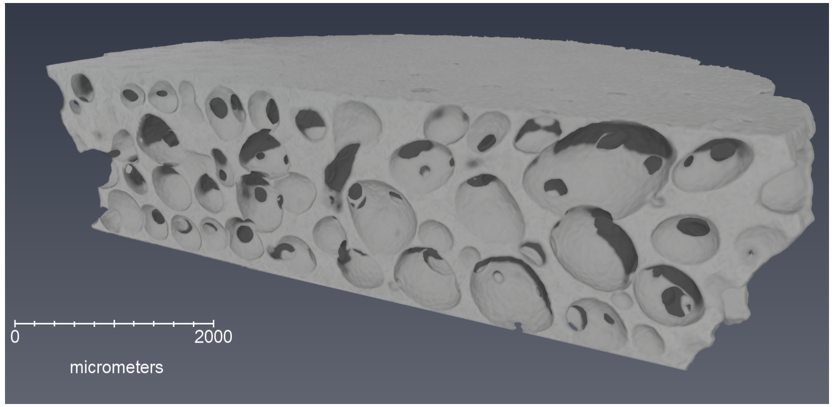
K. Maerzke, J. Lang, D. Dattelbaum, J. Coe et al.

- Experiments on SX358 foam samples at densities ranging from 0.41 – 1.1 g/cc are the first at impact velocities over 6 km/s.
- They are important for validating product EOS models – particularly in the expansion (anomalous) regime for foams, and at high pressures (e.g. average atom)

Brittany Branch (SNL), Chad McCoy (SNL), Dana Dattelbaum (LANL), Josh Coe (LANL)

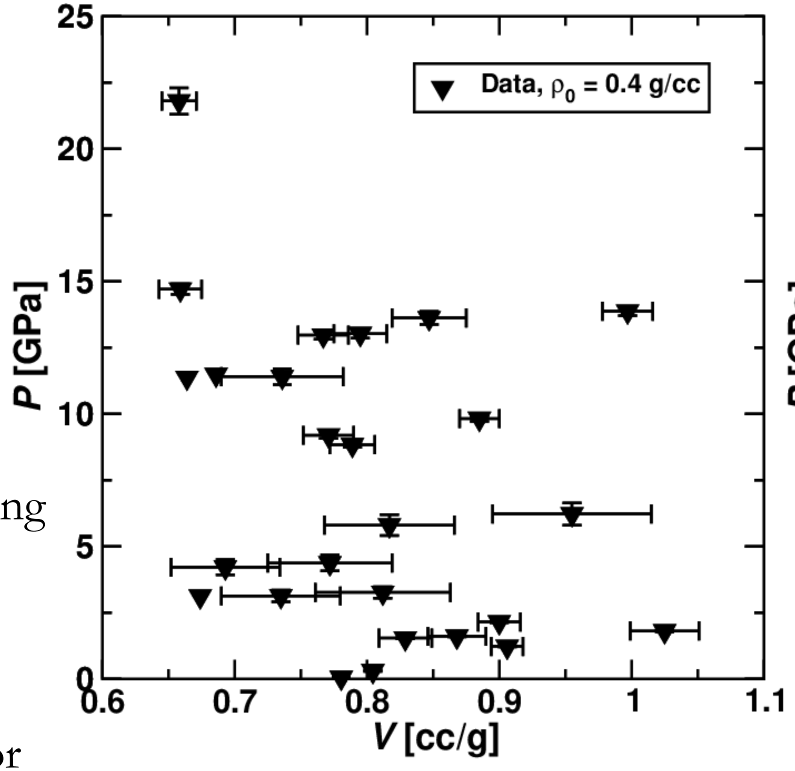
Z-machine experiments on SX358 Foam to validate product EOS

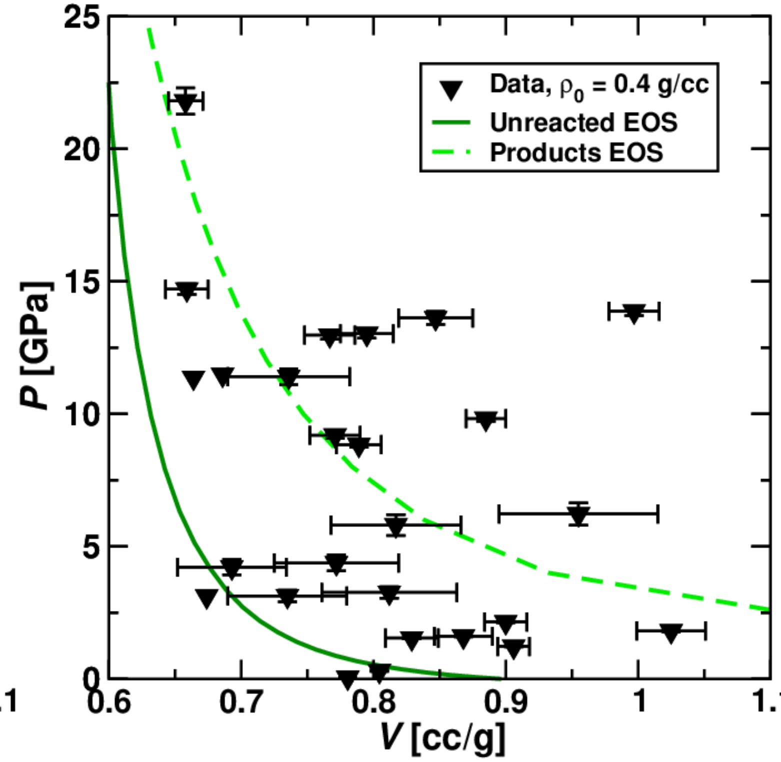
- **High temperatures cause polymers to chemically decompose**
  - Higher porosity foams produce higher temperatures during shock compression due to PV work
  - Leads to volume *expansion* in foams – **reactive anomalous compression**



- At low densities/high porosities, there is significant scatter in the measured data making modeling challenging – the behavior is anomalous
- The experiments at high pressures at the Z machine will help refine the product EOS for low to intermediate density foams

0.4 g/cc SX358

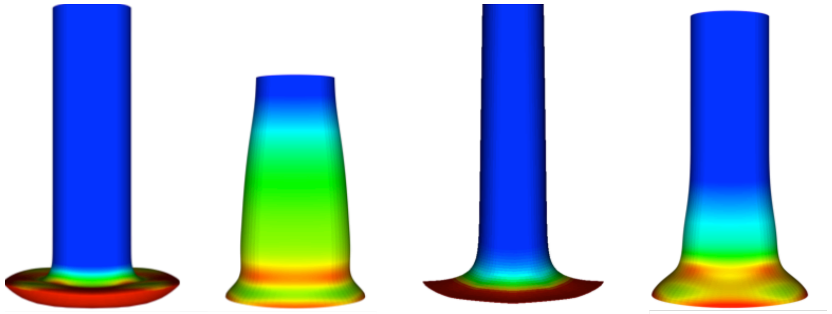




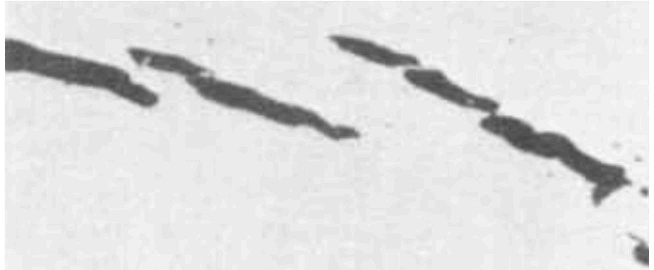
K. Maerzke, J. Lang, D. Dattelbaum, J. Coe et al.

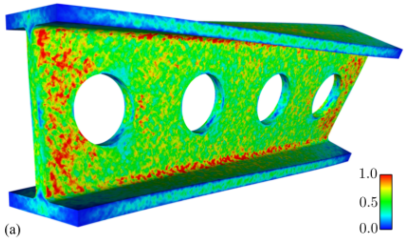
Future Work: Compare stochastic foams to AM foams!

Materials resist deformation – there is a need to measure strength

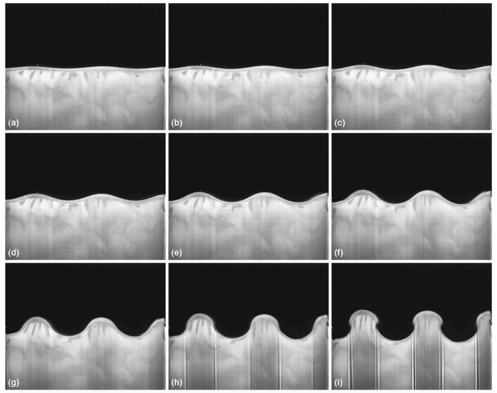


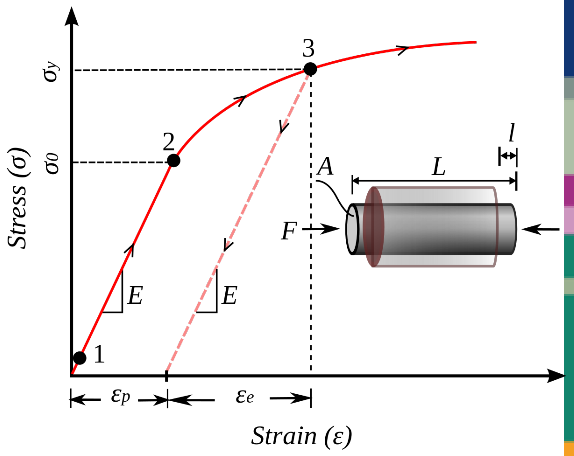
Strength is a measure of a material's ability to sustain an applied load without failure or irreversible deformation.





Equation of state (EOS) "only" controls compression:
EOS → controls volume compression
strength → controls deformability

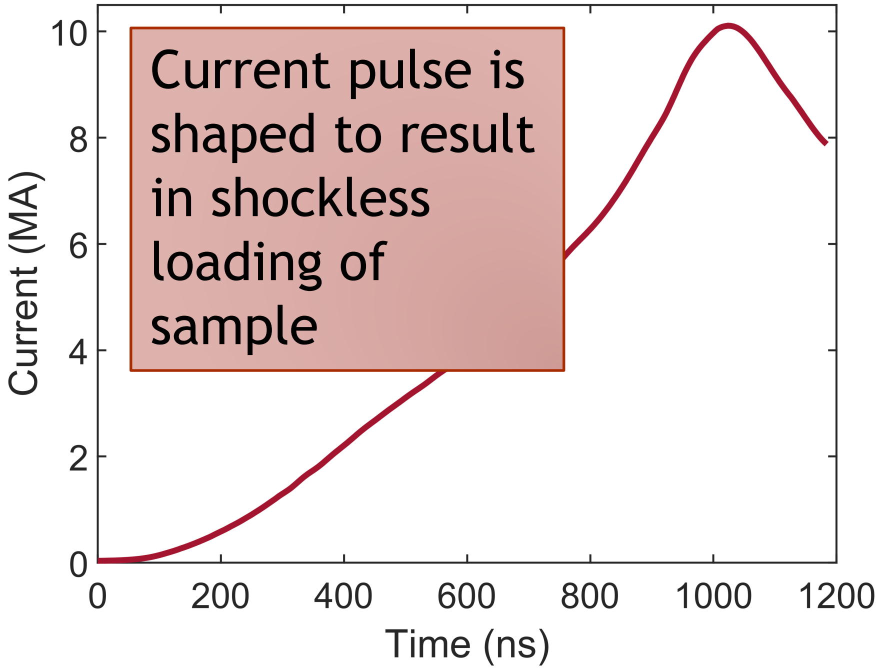


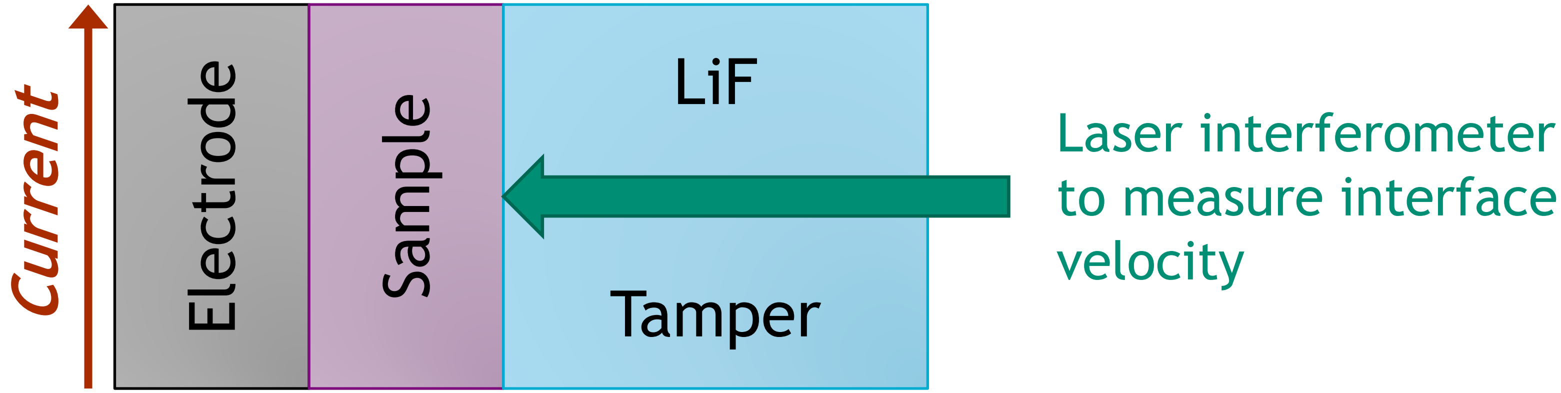


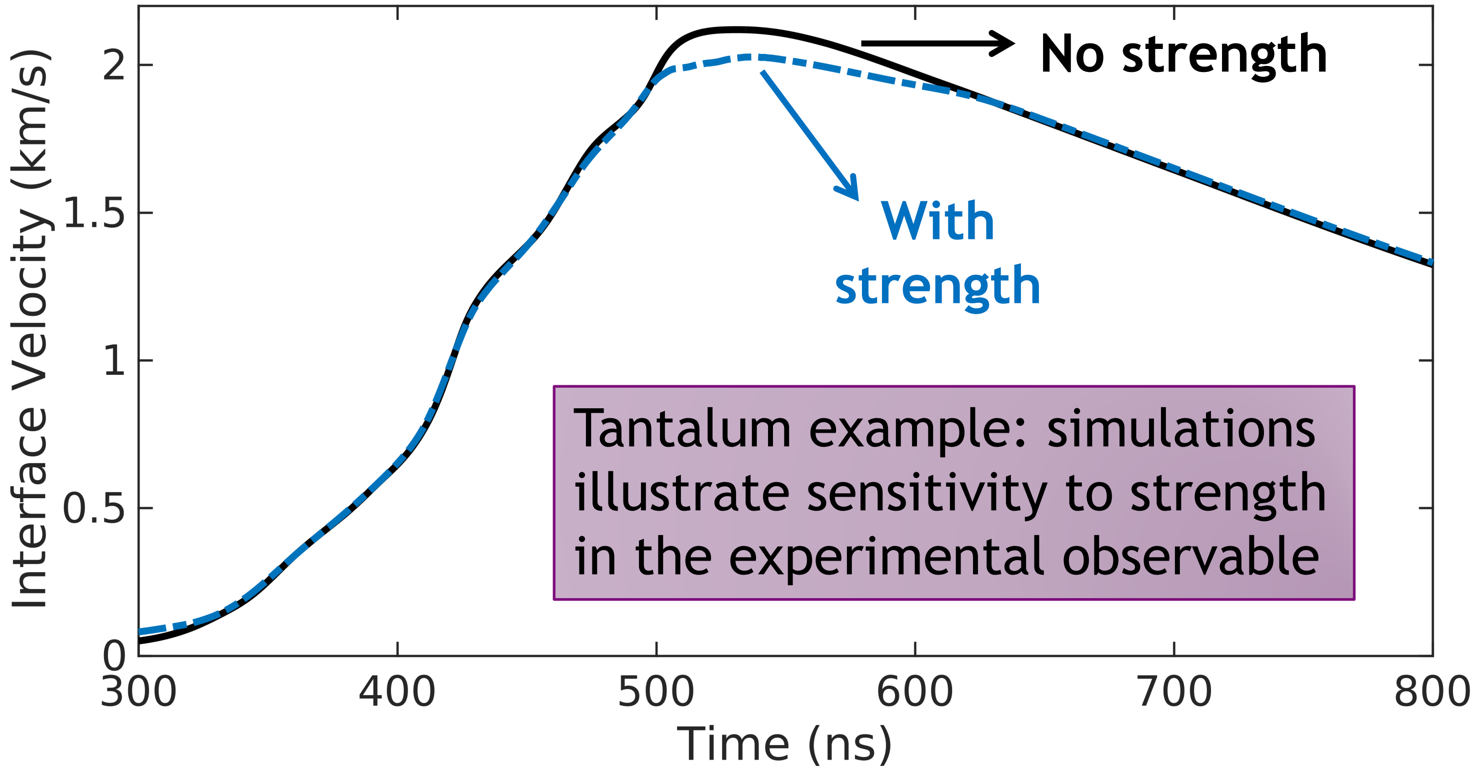
Strength response is "universal"
but the mechanisms are unique to each system.

In practice, in our simulation codes, strength is a model for deformability that augments the EOS model for compression

Strength at high pressures and low temperatures can be inferred from a shockless loading and unloading path



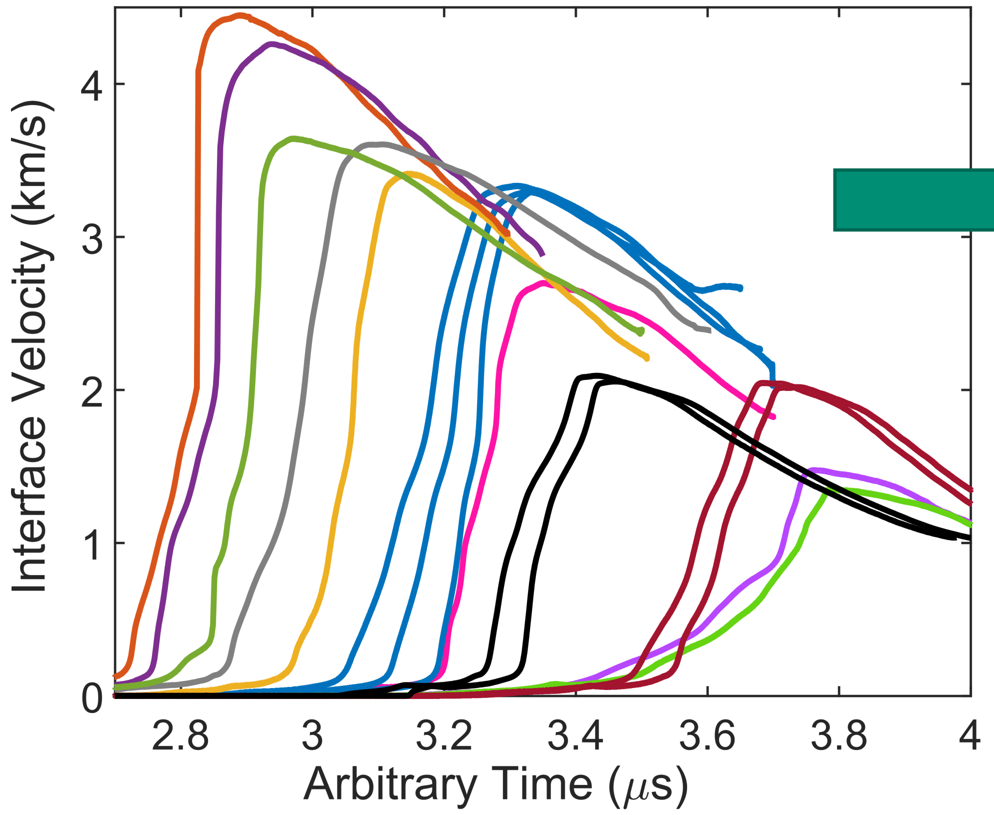




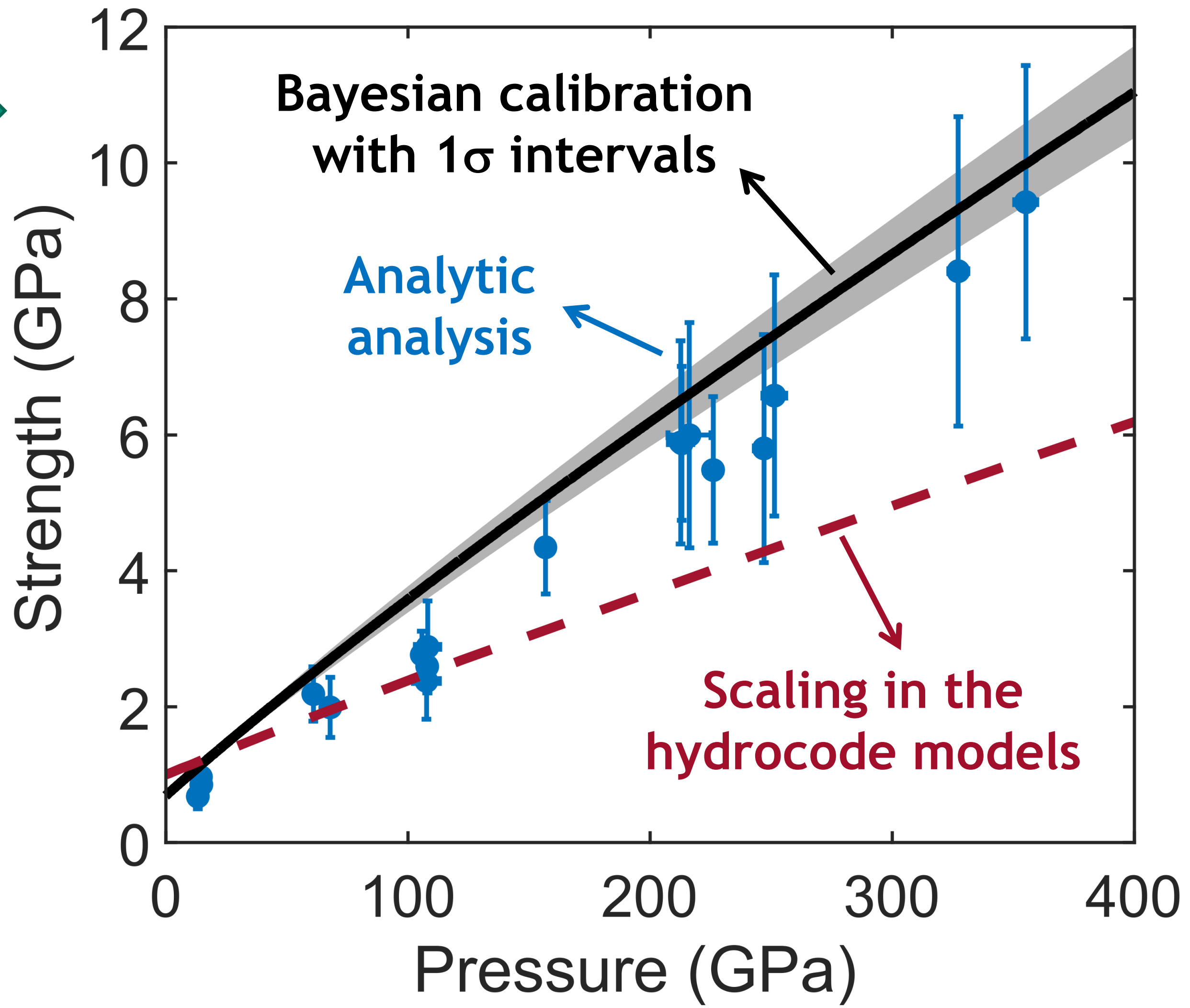
When the direction of the loading reverses the material undergoes an elastic-plastic transition.

- Measured velocities can be used to estimate the magnitude of the strength.

Data from Z suggests that tantalum has more strength than typical models predict

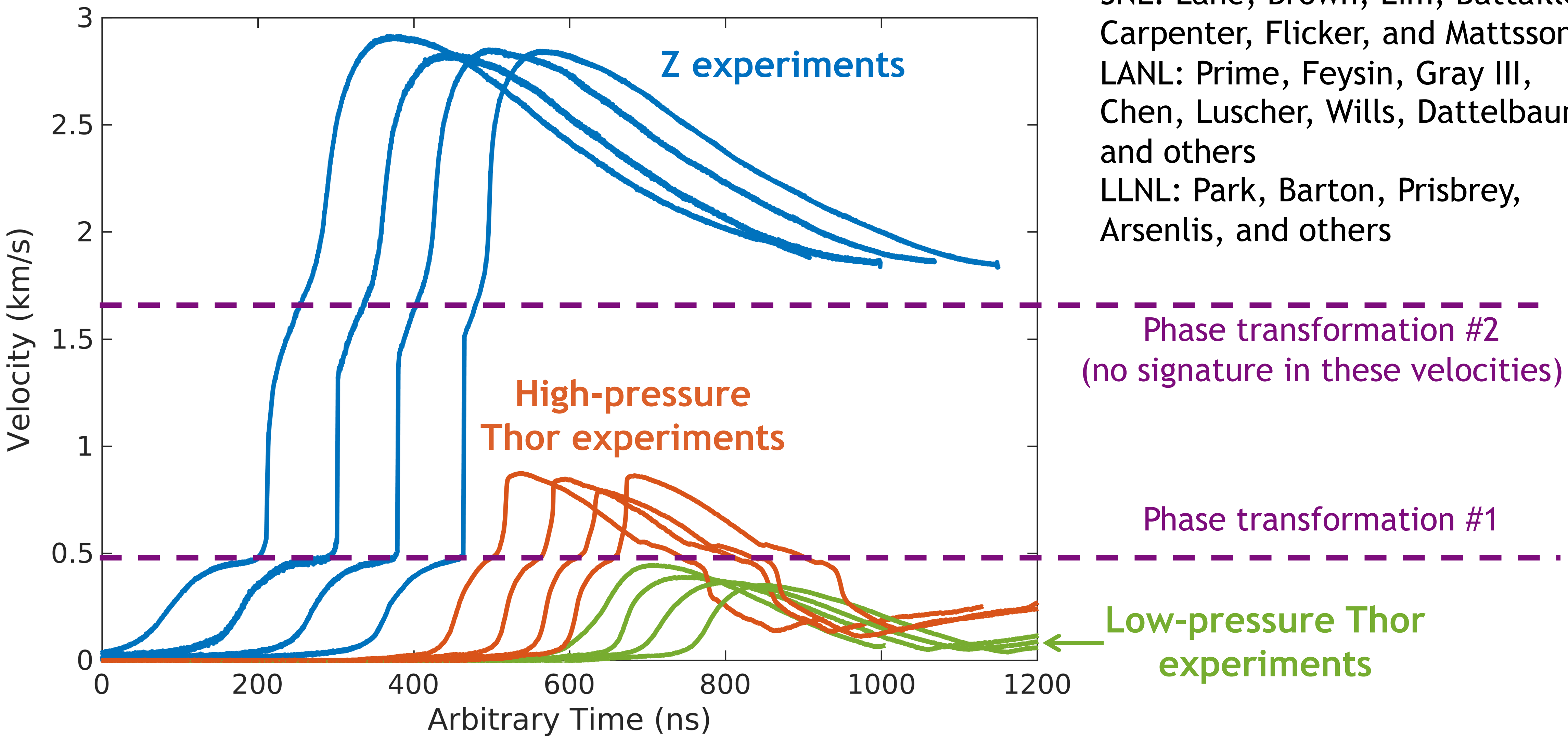


Two independent analysis techniques find too low pressure hardening in typical strength models



Part of a tri-lab (SNL, LANL, LLNL) collaboration examining multiple platforms to evaluate strength

Next step in the tri-lab collaboration: a series of experiments were conducted on Z and Thor exploring how strength couples with phase transformations in tin



SNL: Lane, Brown, Lim, Battaille, Carpenter, Flicker, and Mattsson
LANL: Prime, Feysin, Gray III, Chen, Luscher, Wills, Dattelbaum, and others
LLNL: Park, Barton, Prisbrey, Arsenlis, and others

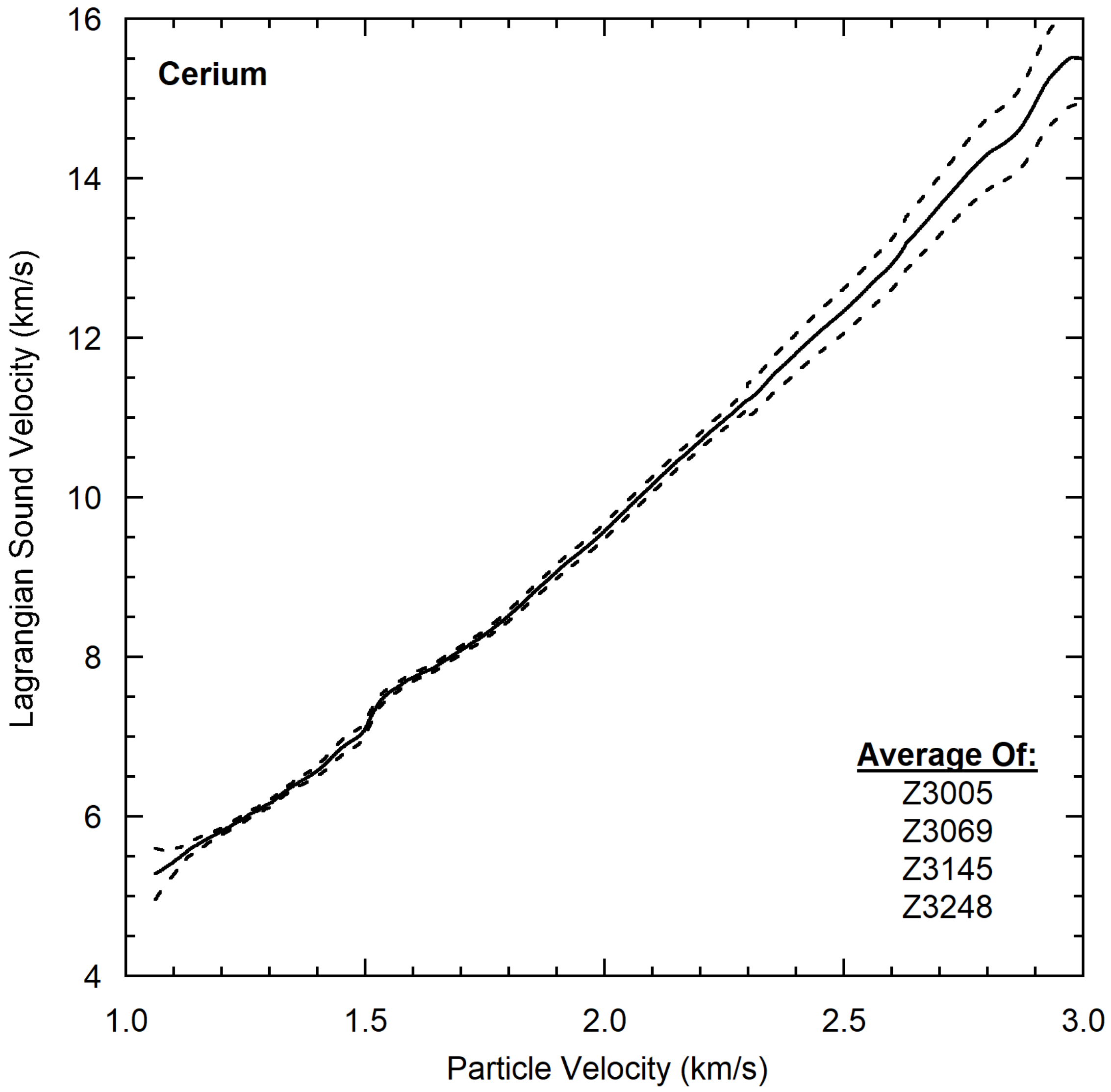
We performed shock-ramp experiments on Z to explore the freezing of liquid cerium under ramp compression

Cerium has a complex phase diagram – for example negative melt slope and a large volume change fcc-fcc (!) phase transition

Velocimetry shows no obvious “kink” in raw velocities on a single experiment

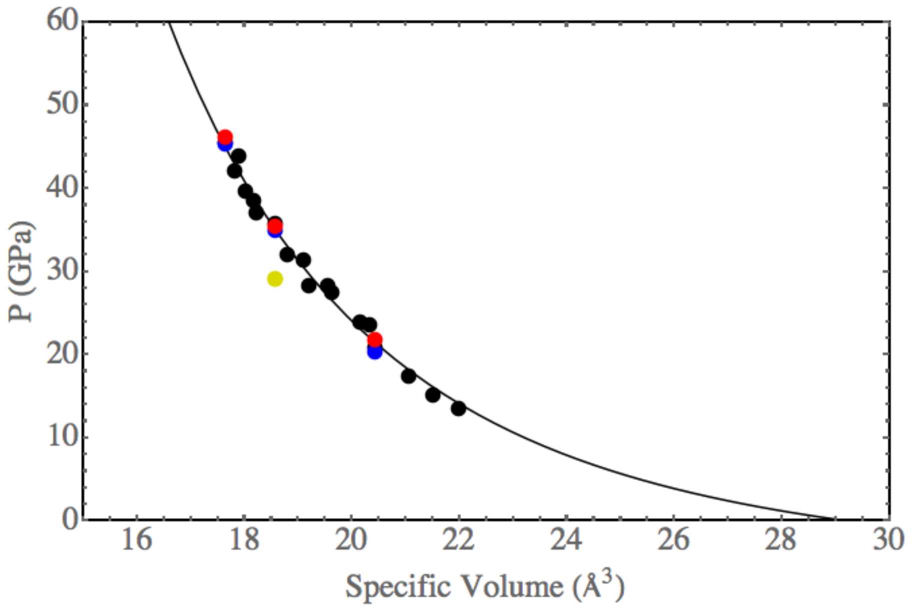
None of the sample pairs exhibit elastic behavior on initial loading from the starting shock state – *the cerium is shock melted.*

The averaged traces reveal the dynamic freezing of Ce



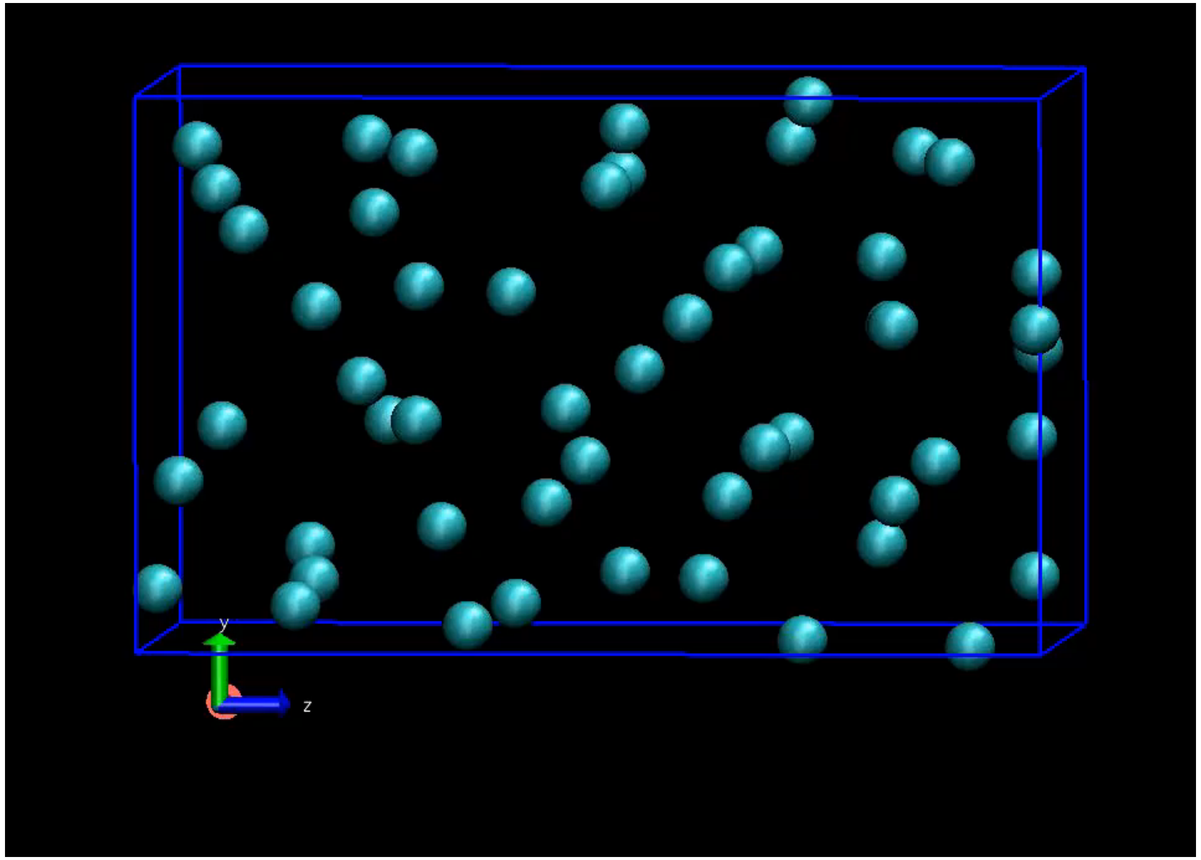
Compression-induced solidification of shock-melted cerium
C.T. Seagle, M.P. Desjarlais, A.J Porwitzky, and B.J. Jensen,
PRB **102**, 054102   Published: AUG 5 2020

Spontaneous Freezing was observed in the DFT-MD simulations at ~35 GPa



DFT with GGA+U gives good agreement with DAC data (Olsen, *et al.*, 1985) for ε-Ce

DFT GGA+U with 54 atoms, 12 electrons in the valence makes it computationally demanding



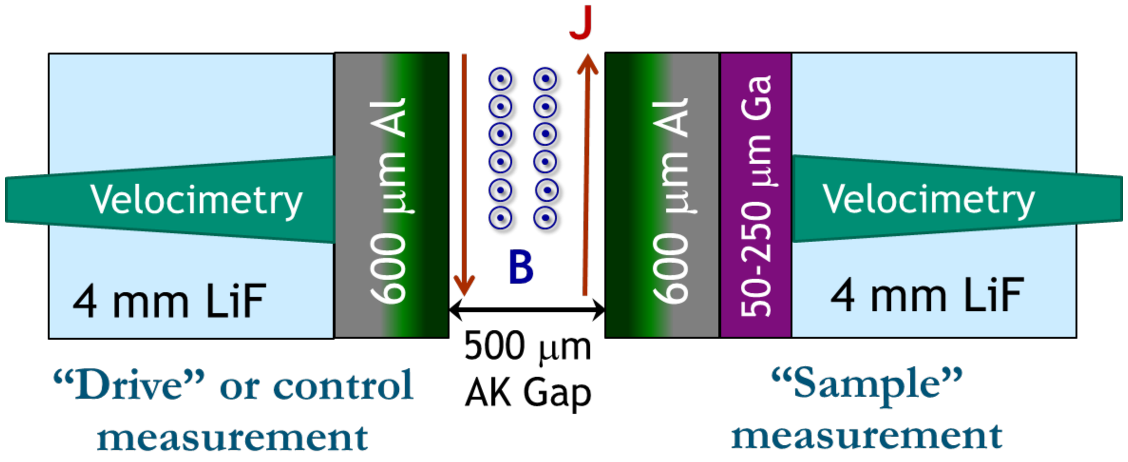
35 GPa, 11.8 g/cc, 1750K

The body centered tetragonal phase of ε-Ce emerges from the liquid.

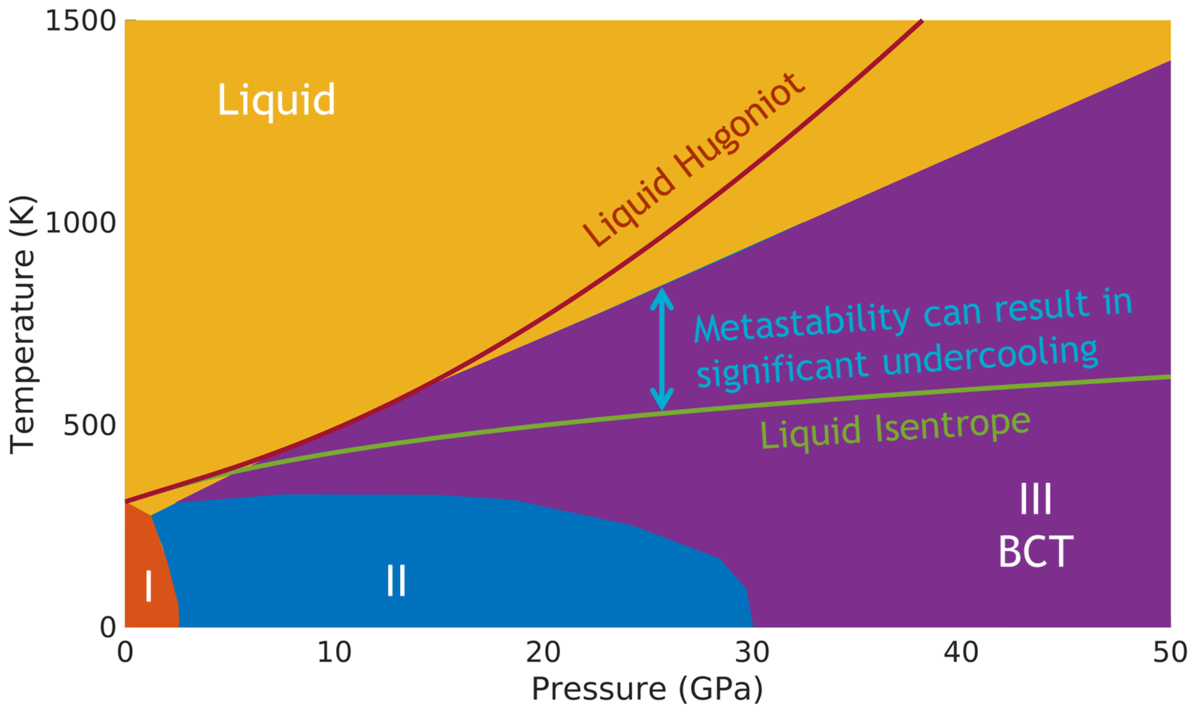
Gallium solidification experiments on Thor in collaboration with LLNL (J. Belof, P. Myint)

A thin liquid cell of Ga is driven quickly enough that a significant undercooling (ie. driving force for solidification) occurs.

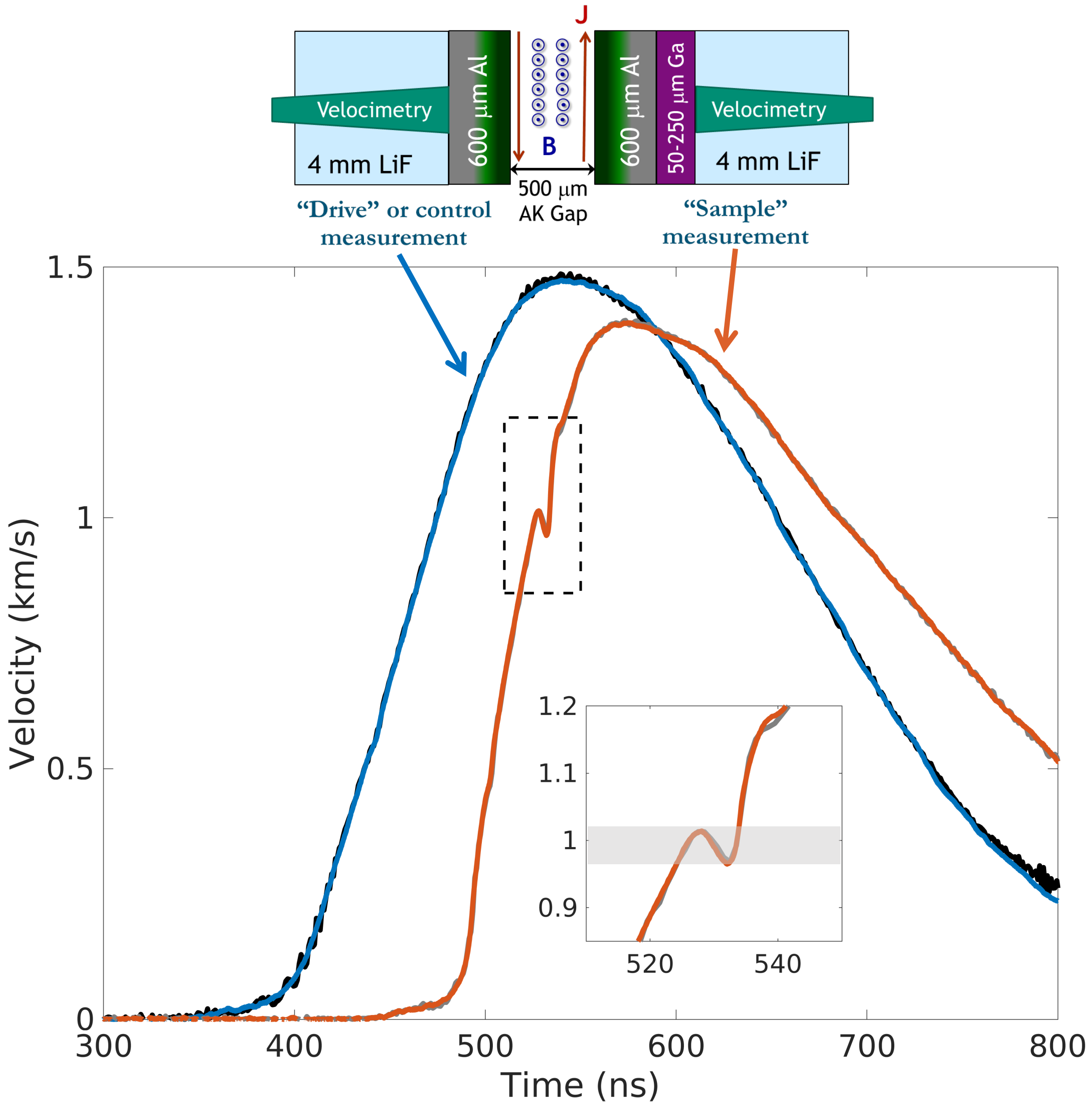
Question: does Ga solidify on the timescales of these dynamic loading conditions?



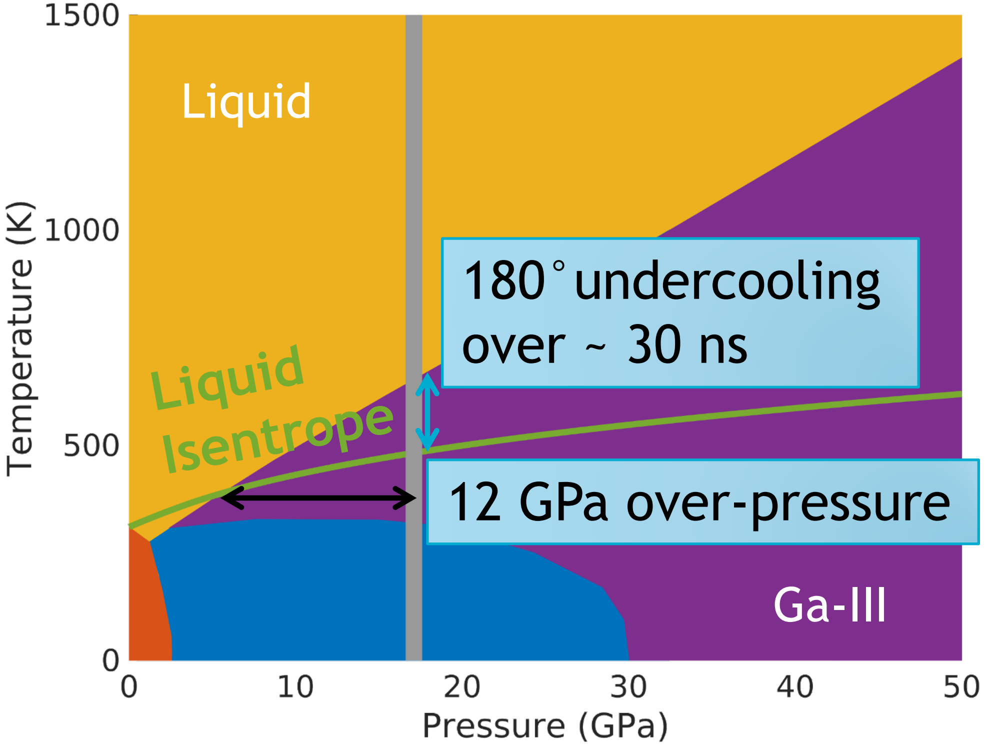
LANL Ga EOS, Crockett and Greeff (SCCM, 2009)



Typical measurements show a clear signature of solidification on nanosecond timescales



Observed solidification pressures are much higher than the equilibrium liquid boundary = significant kinetics

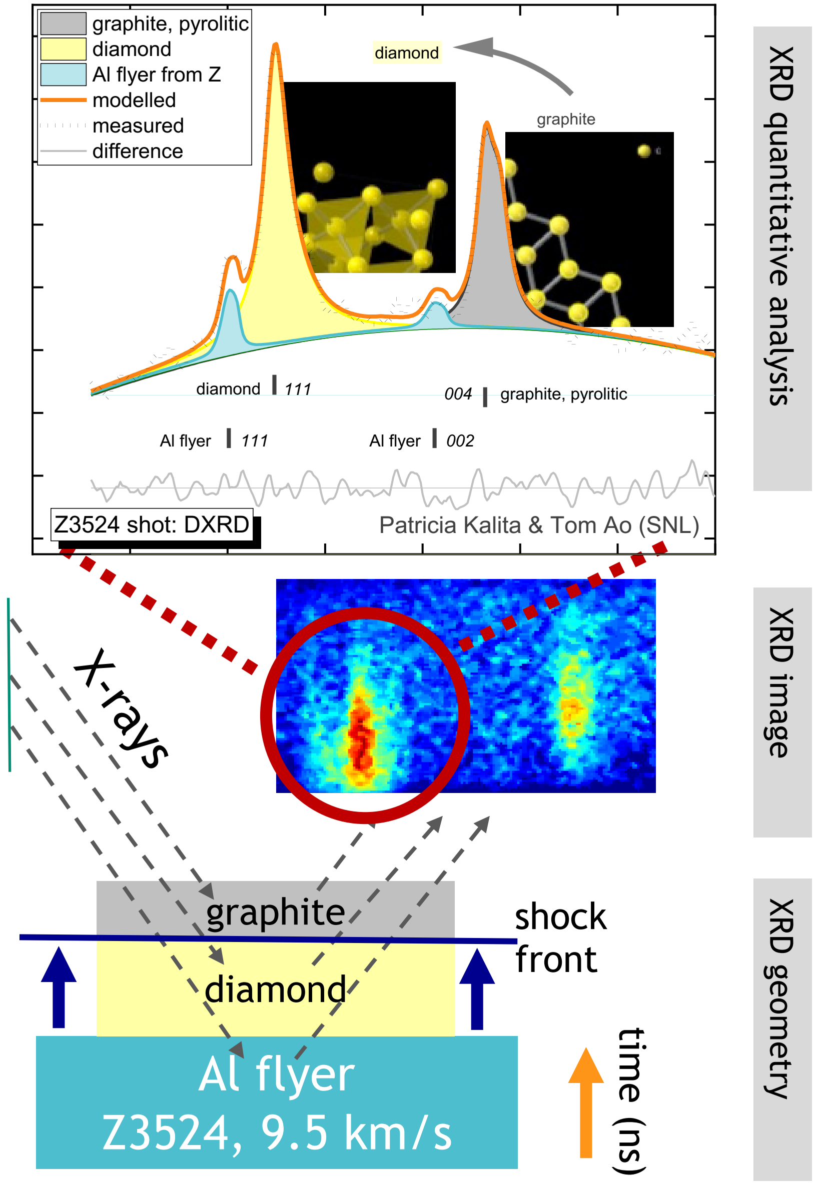


X-ray diffraction (XRD) on Z and Thor

- Implemented an XRD probe on Z for direct observation of phase transitions at atomic scale under extreme shock conditions.
- Used a spherical crystal diffraction imager (SCDI) to probe transformation of shock compressed carbon pyrolytic graphite into diamond.
- Second carbon/diamond shot with much improved signal/noise ratio and stronger XRD signal enables further specialized atomic-scale XRD analysis.
- Standing up XRD on Thor with recent first successful pattern

Answering questions about the dynamic behavior of materials at high pressure is a priority for Assessment Science Programs

SNL: Tom Ao and Patricia Kalita

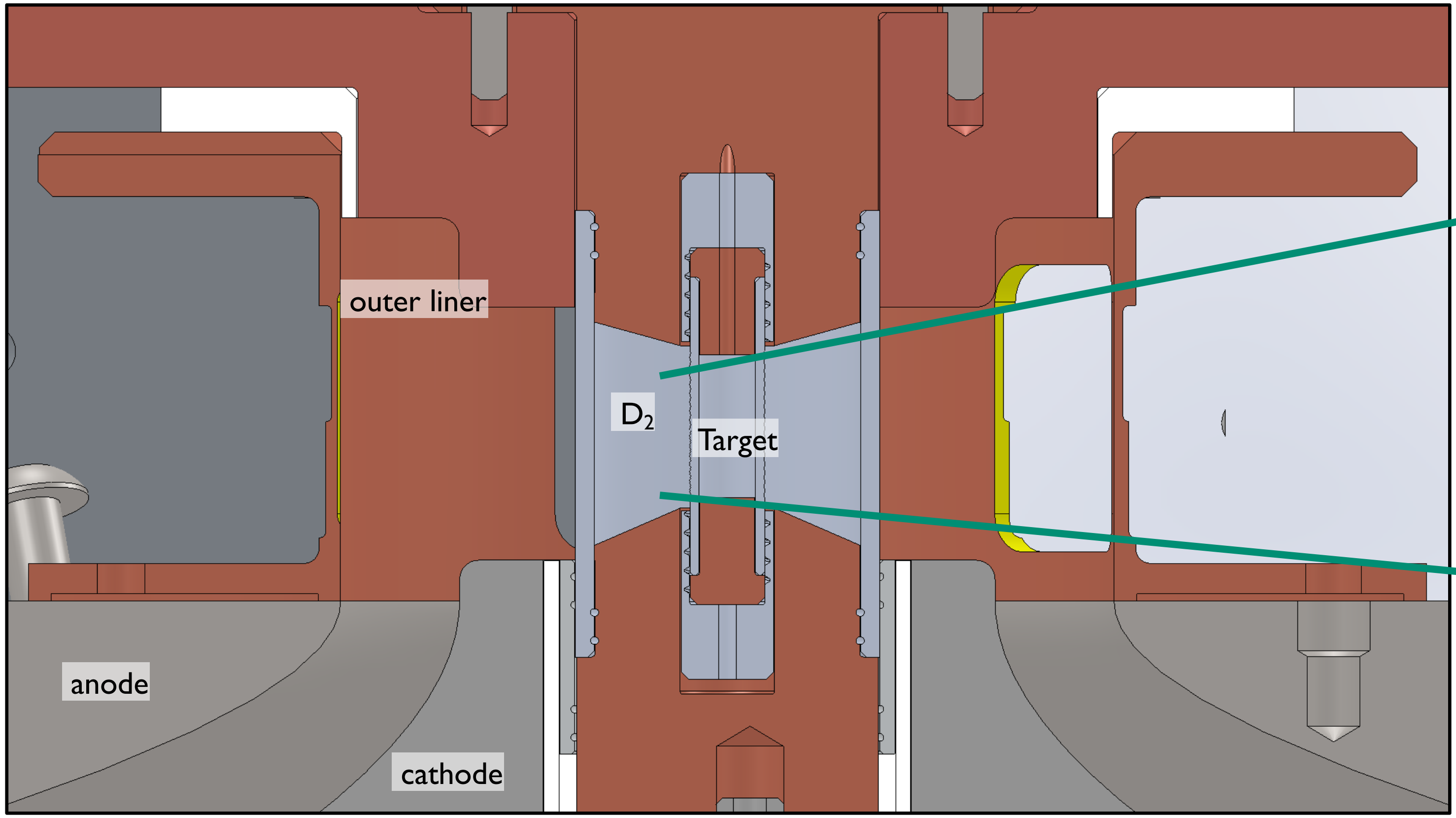


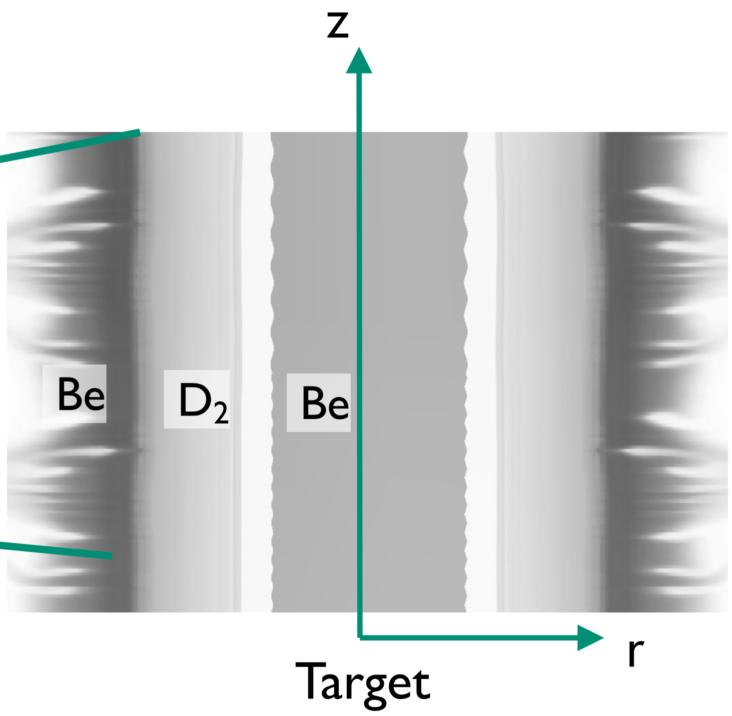
Dense plasma physics

LANL: Forrest Doss, Jeff Haack, James Langenbrunner, Tony Scannapieco, Igor Usov, Tana Morrow, Brian Albright, and Ray Tolar

SNL: Patrick Knapp, David Yager-Elorriaga, Kris Beckwith, Kyle Cochrane, Eric Harding, Nichelle Bennett Chris Jennings, Andrew Porwitzky, Clayton Myers, Matthew Martin, Daniel Ruiz, David Ampleford, Luke Shulenburger and Thomas Mattsson

We recently developed a platform to investigate instabilities





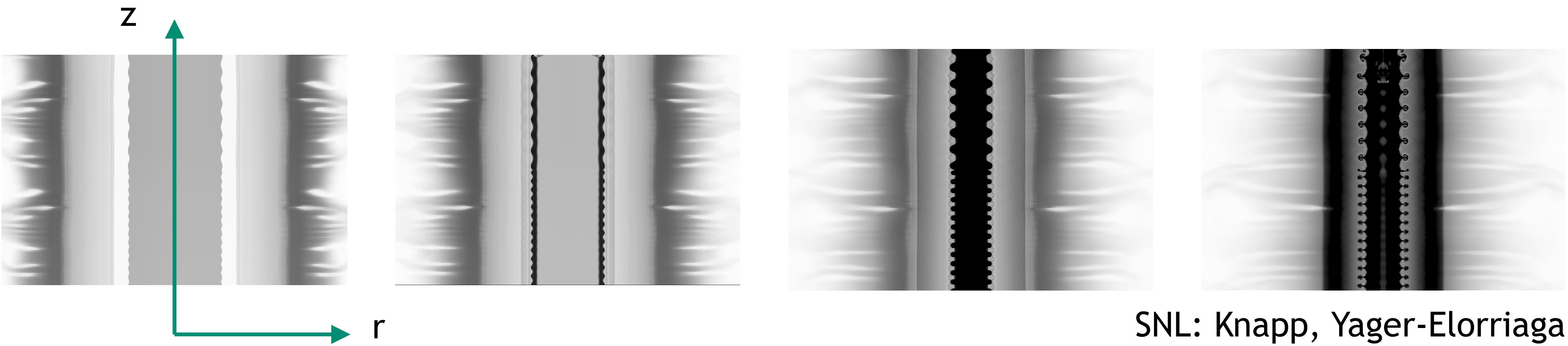
Synthetic radiograph

Beryllium cylindrical shell

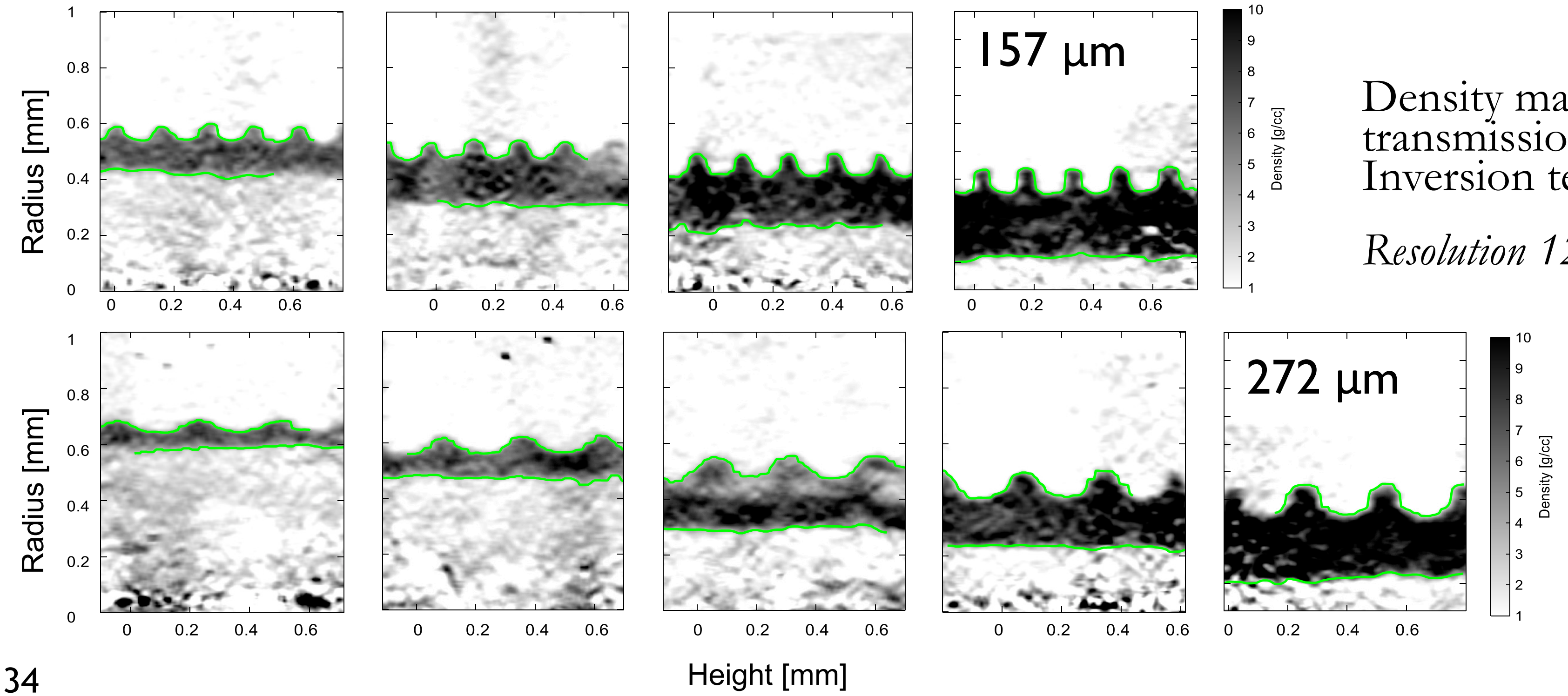
D2 liquid fill

Target on axis with perturbations

Convergent platform to investigate instability growth @ multi-Mbar pressure using radiography



SNL: Knapp, Yager-Elorriaga, et al
LANL: Doss

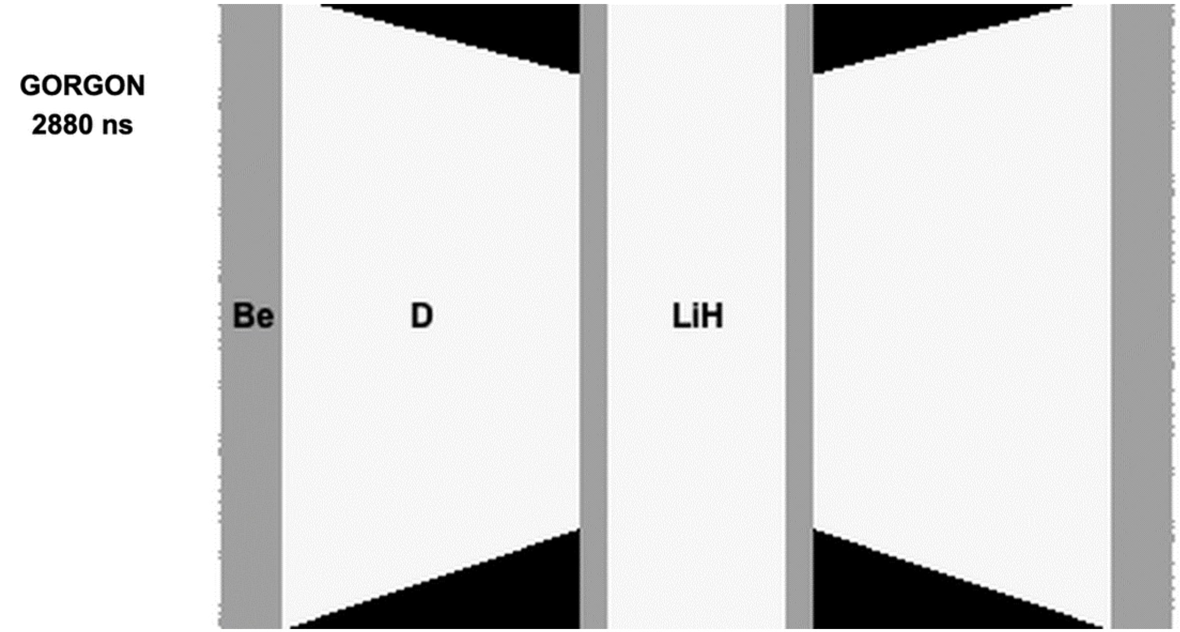


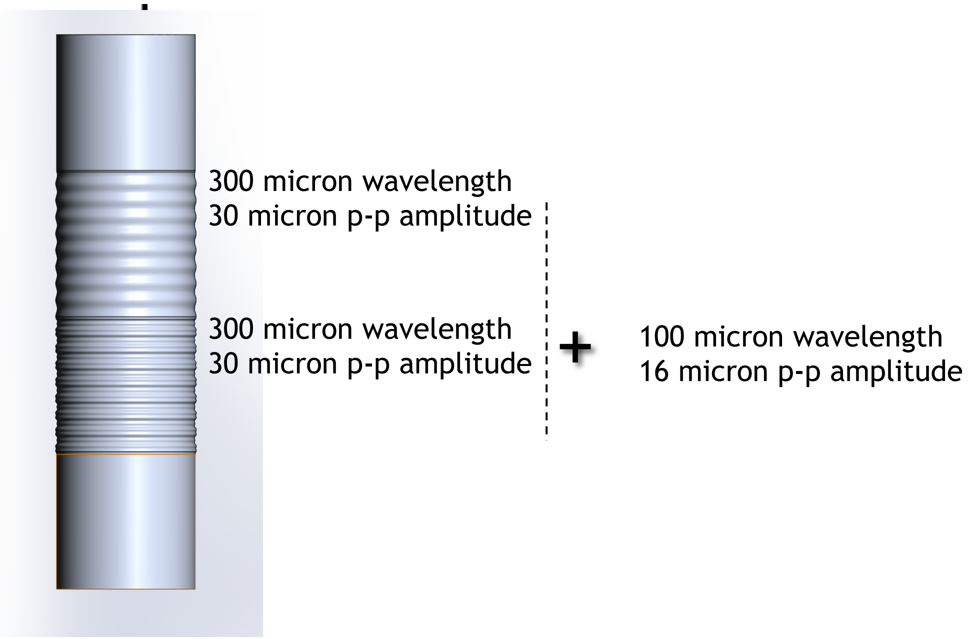
Density maps are obtained from transmission images using an Abel Inversion technique.

Resolution 12 µm with 4 × 12 mm FOV

A novel, magnetically driven convergent Richtmyer-Meshkov platform P. F. Knapp et. al. Phys. Plasmas **27**, 092707 (2020).

The first LANL designed SNL-fielded double-shell experiment was successfully executed in Oct 2020



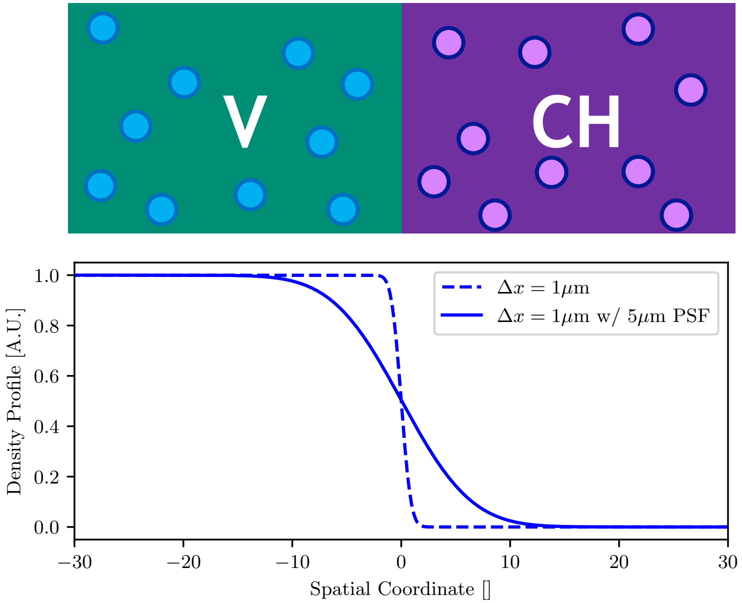


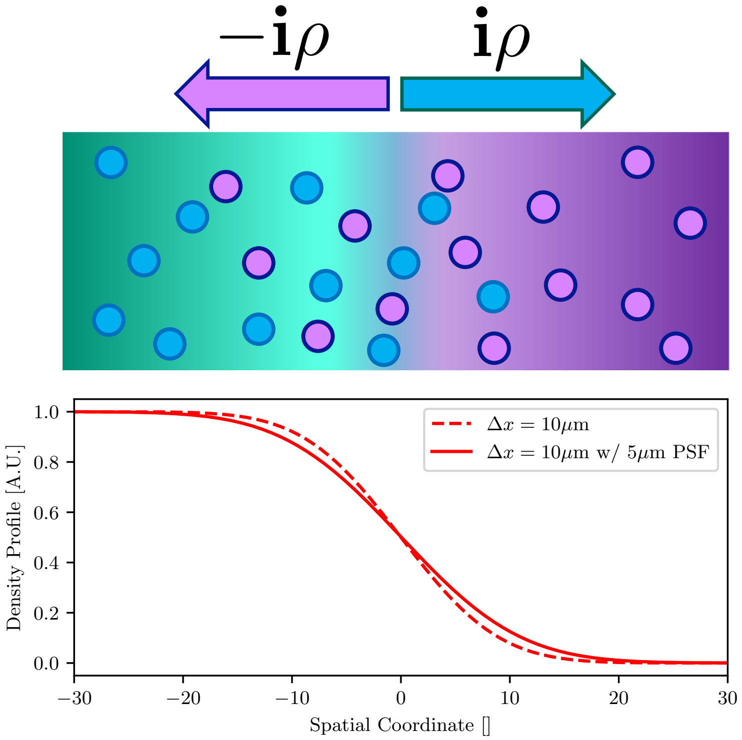
Gorgon MHD Simulation hand-off to xRage using the “RageRunner” interface

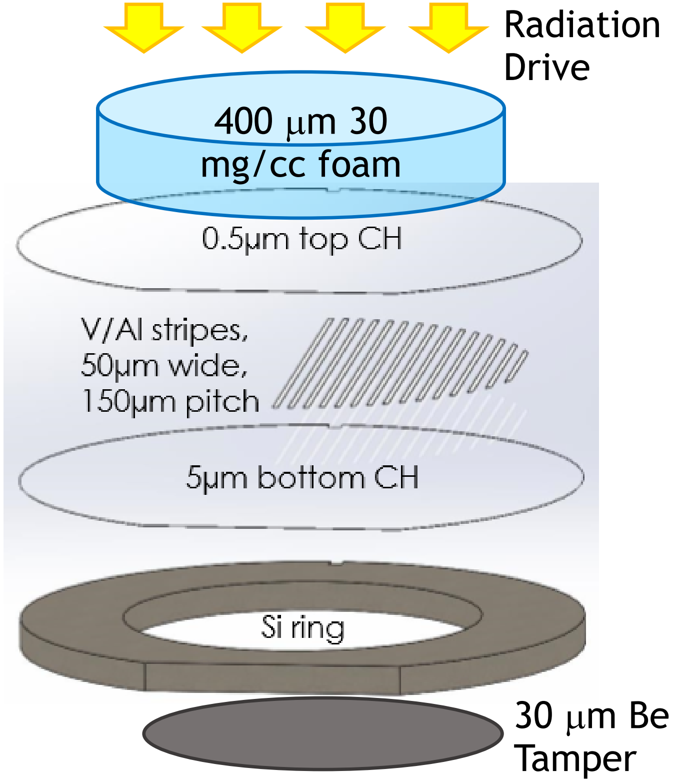
SNL: Patrick Knapp, David Yager-Elorriaga, et al
LANL: Forrest Doss

This LANL-designed, SNL-fielded experiment met its objective to demonstrate radiography on a platform for investigating feedthrough and other thin layer hydrodynamics. Data will inform models used in simulating the complex hydrodynamics often found in ICF environments.

Heating an initial interface will result in diffusion between species







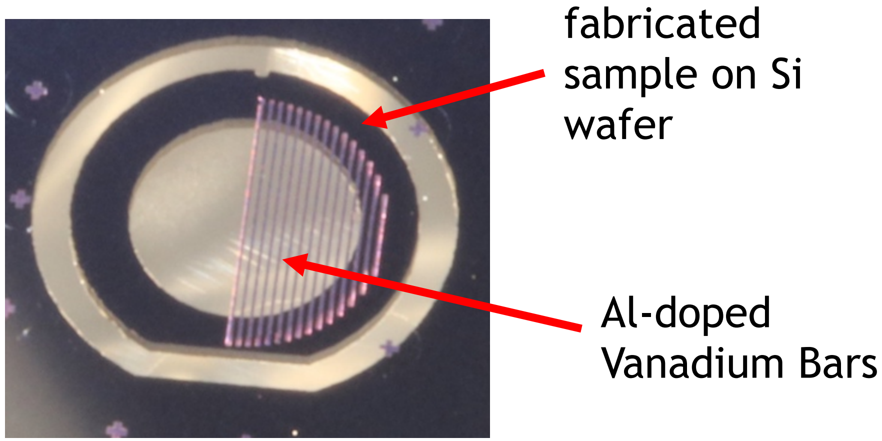
Calculations show the V region is heated to conditions where it is strongly coupled

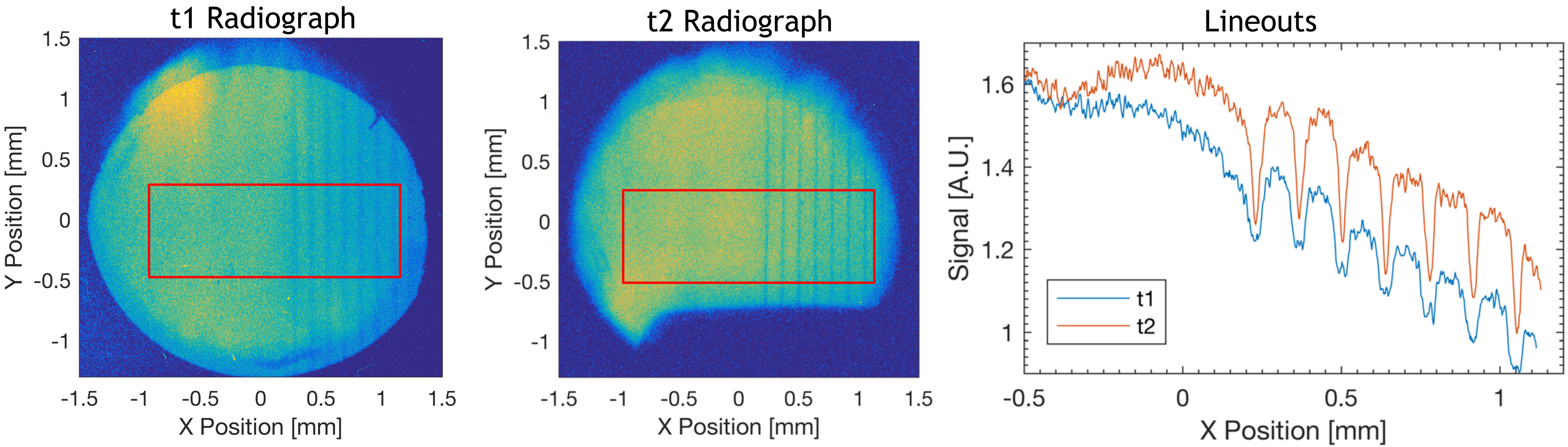
Kinetic calculations predict significant diffusion between the V and CH species and radiography can be used to measure it

The challenge lies is in minimizing hydrodynamic effects that could masquerade as diffusion

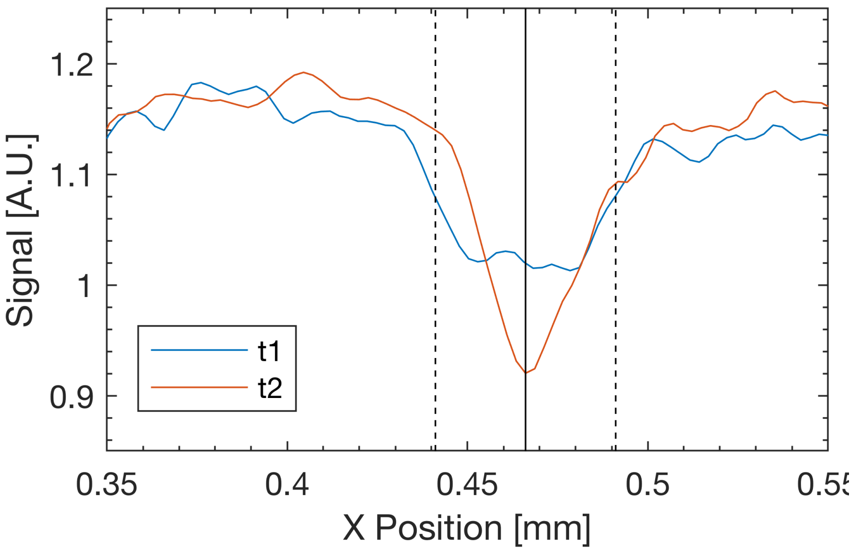
Shot z3220 was the first ever plasma transport experiments have been executed on Z demonstrating the feasibility of the proposed measurement

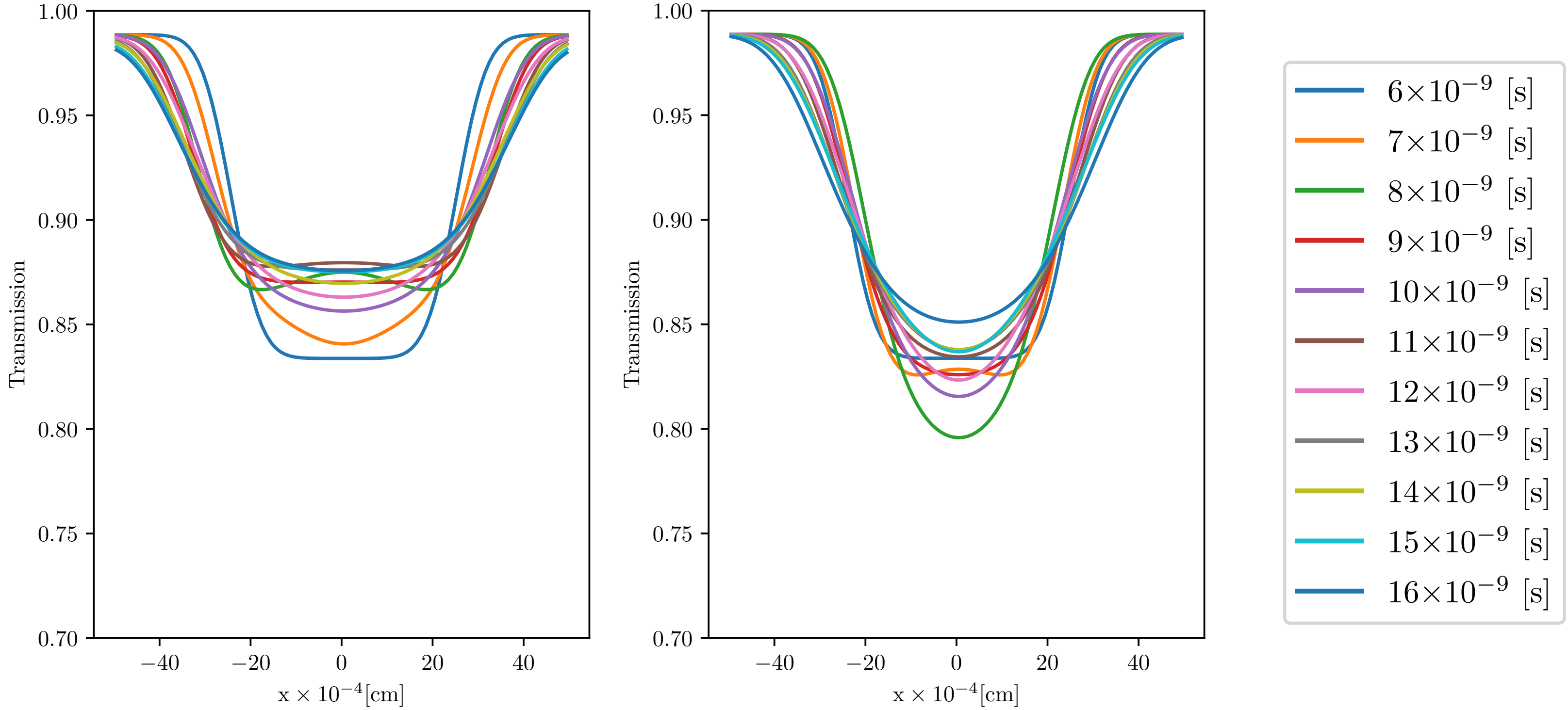
- Demonstrated usable contrast of the sample in the radiographs on shot z3220 (6.1 keV backlighter with detector placed at closer focal position)
- This represents the only useful data we have obtained to date





Kinetic Modeling of V/CH Interface: Synthetic Radiography

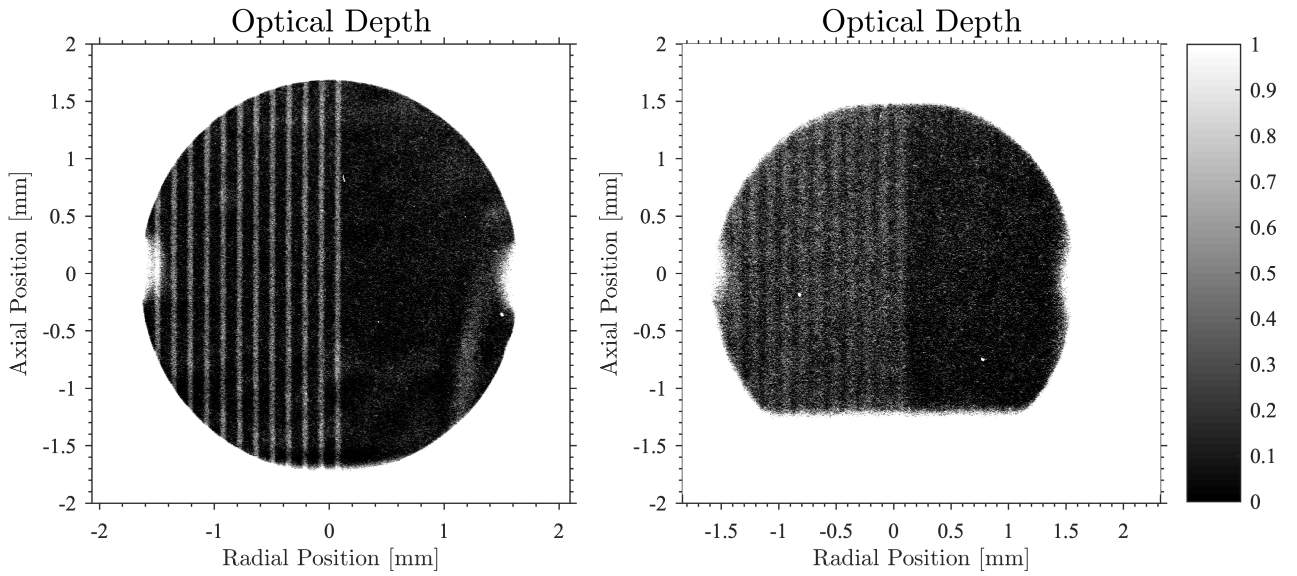


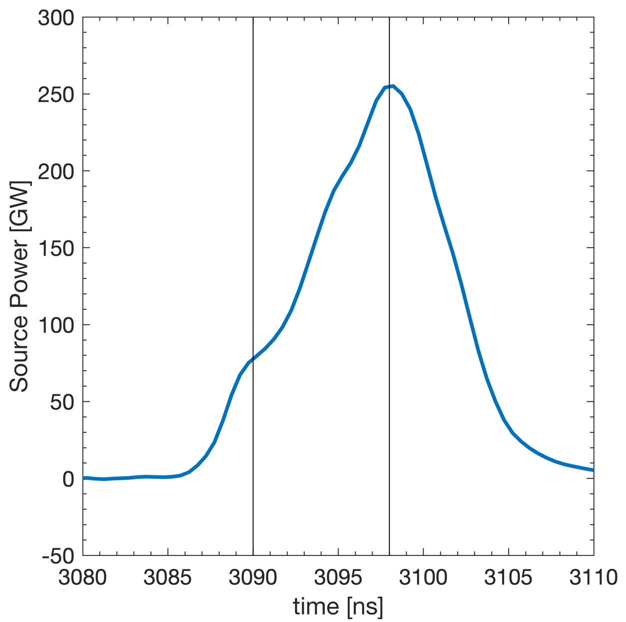


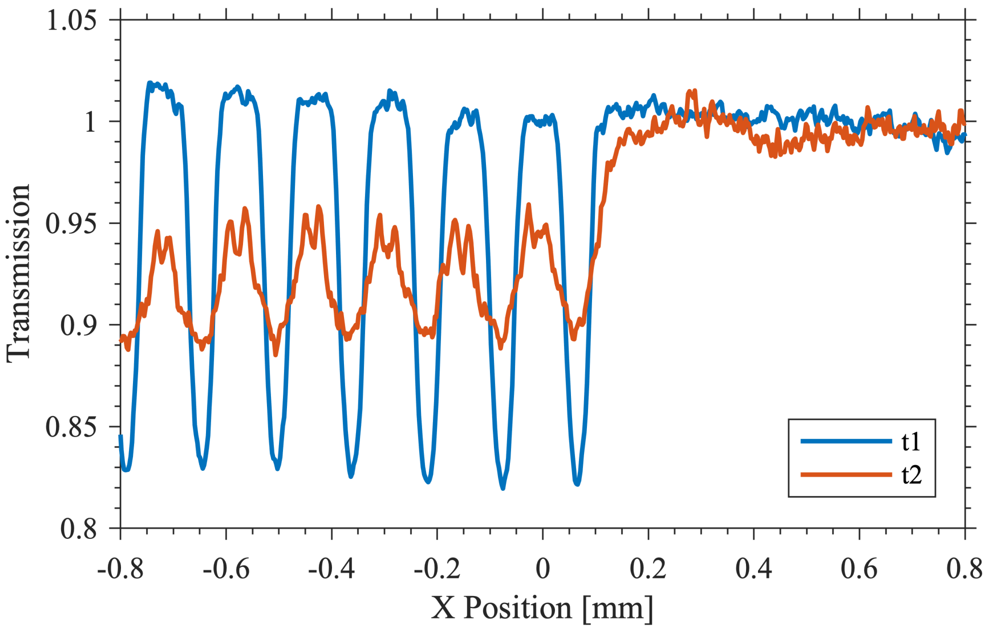
- Utilize electrostatic multi-species kinetic code to study plasma transport at CHO-V/Al interface
  - Thomas-Fermi Average Atom model for ionization state; Fermi-Dirac statistics for electrons
  - Comparing Temperature and momentum relaxation model for ion-ion collisions
- Simulation setup: V @90% solid density, 10% Al doping

- Ions initialized at 10eV
- Electrons temperature derived from 3 mg/cc rad hydro
- Synthetic radiography:
  - In temp. relaxation case Transmission profile deepens and narrows prior to 8 ns, then widens
  - In mom. Relaxation case, the profile always widens

Our first dataset obtained using the 8 keV x-ray source shows very promising results







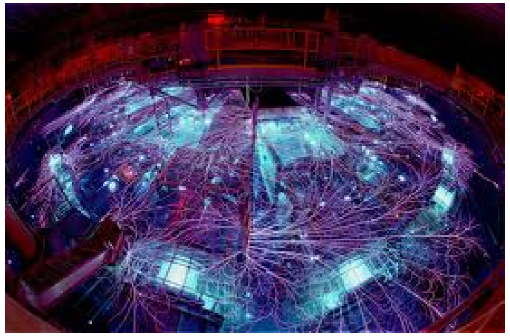
We have demonstrated that we can obtain radiographs in this environment sufficient to distinguish between competing models

Preliminary calculations show extremely uniform expansion with no instability development

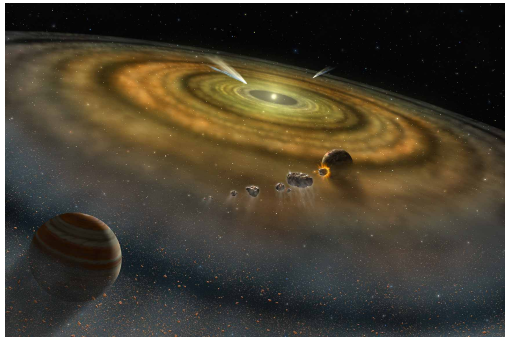
Temperature in the V layer is only ~5 eV

Current work is aimed at optimizing the x-ray source and sample to achieve the proper conditions

Pulsed power is well suited for HED science



- **The Z machine is great for Mbar material experiments**
  - Conditions at scale for planetary science and stockpile stewardship
  - Developing new capabilities in high-pressure platforms and diagnostics
    - *X-ray diffraction*
    - *Temperature measurements*
    - *New platform "tiny stripline" has reached 8 Mbar ramp pressure in Pt*
- **THOR is maturing as a production platform**
  - Ability to dial ramp rate
  - Developing x-ray diffraction with first successful shot 14 days ago
  - Low-cost and quick turnaround, can scan materials/ orientations/ etc
- **We reach interesting regimes and processes in dense plasmas**
  - Instabilities at multi-Mbar pressures
  - Plasma diffusion/kinetic effects
  - Spectroscopy, opacity, and of course ICF



- **Strong integration between experiments, theory, and simulations enhance the impact of the work**
  - From quantum mechanics to MHD via kinetic plasma simulations
- **Strong partnering with LANL and LLNL**
  - Aim to remain well aligned with the needs from the different National research programs

Points of contact at Sandia

• Dynamical Materials Properties	Chris Seagle
• Primary Assessment Technology	Luke Shulenburger
• STAR and DICE (w THOR)	Gordon Leifeste, Bill Reinhart, Scott Alexander, and Steven Dean
• X-ray diffraction	Tom Ao and Patricia Kalita
• Temperature measurements	Dan Dolan
• Z Fundamental Science Program	Marcus Knudson
• Strength and Bayesian analysis	Justin Brown
• EOS ramp experiments	Jean-Paul Davis
• EOS shock experiments	Brittany Branch, Paul Specht, Chad McCoy, Sakun Duwal
• Dense plasma physics	Patrick Knapp, David Yager-Elorriaga, Kris Beckwith
• EOS modeling	Kyle Cochrane
• DFT simulations	Joshua Townsend
• QMC theory and applications	Raymond Clay

Thomas Mattsson, trmatts@sandia.gov

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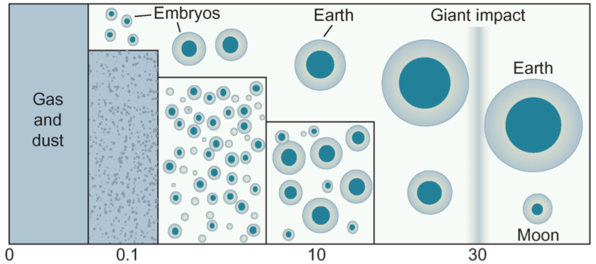
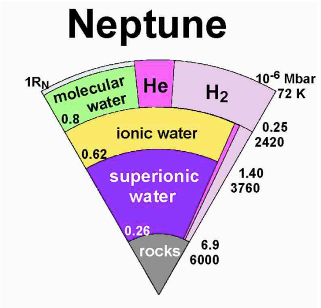
Extra material

Details on hydrogen, gallium, strength

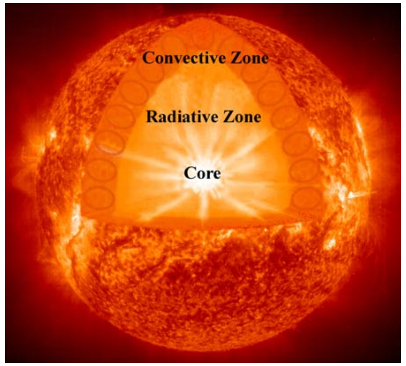
Z Fundamental Science Program is a growing community



Earth and super earths
Properties of minerals and metals



Jovian Planets
Water and hydrogen



Stellar physics
Fe opacity and H spectra

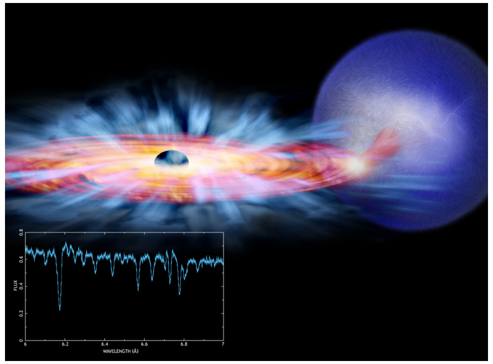


Photo-ionized plasmas
Range of ionization param. ξ

12+ students are currently involved

Resources over 10 years

- 115 dedicated ZFSP shots (5-7% of all Z shots)
- Ride-along experiments on Z program shots, guns, DICE, and THOR

Science with far-reaching impact

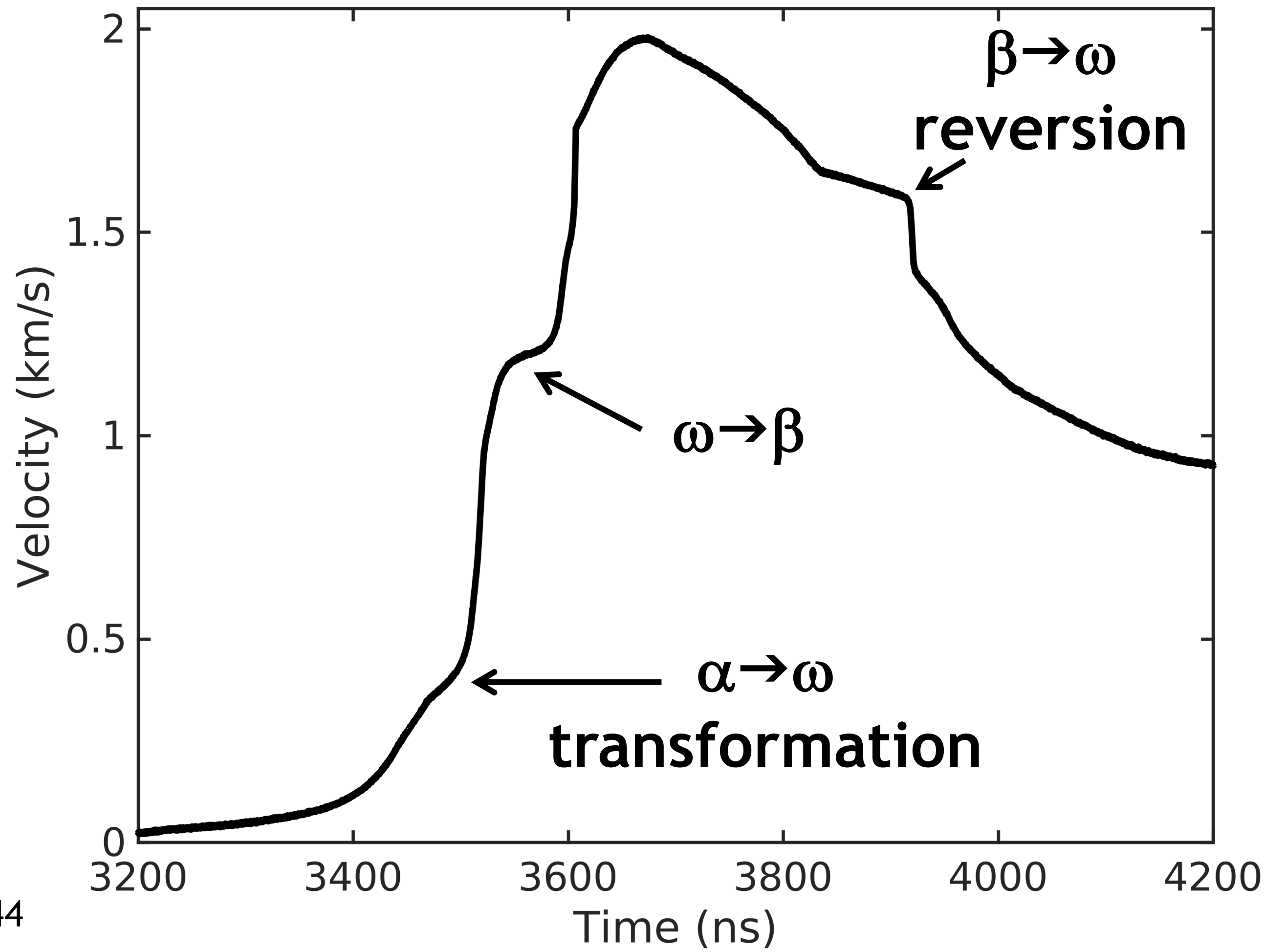
- Nature, Nature Geoscience, SCIENCE
- 7 Phys. Rev. Lett, 3+ Physics of Plasmas, 5+ Physical Review (A,B,E)
- More than 40 total peer reviewed publications and 10 conference proceedings
- 70+ invited presentations

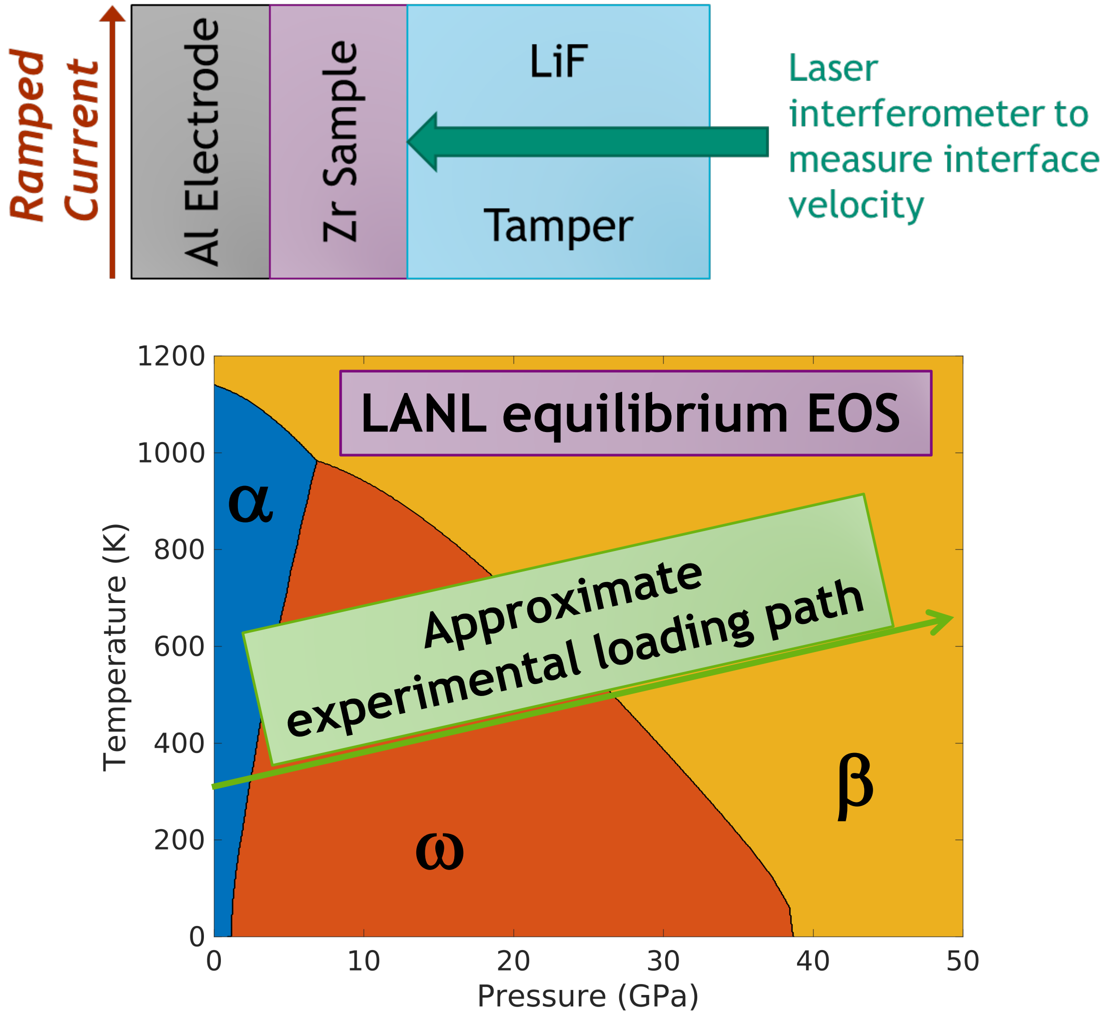
Popular outreach

- National Public Radio, “All things considered”, 2014
- Discover Magazine
  - Reportage 9/16/2012
  - *Iron rain #62 in top 100 Science stories in 2015*
- Albuquerque Journal Front Page 9/2017
- Twice local TV coverage on planetary science

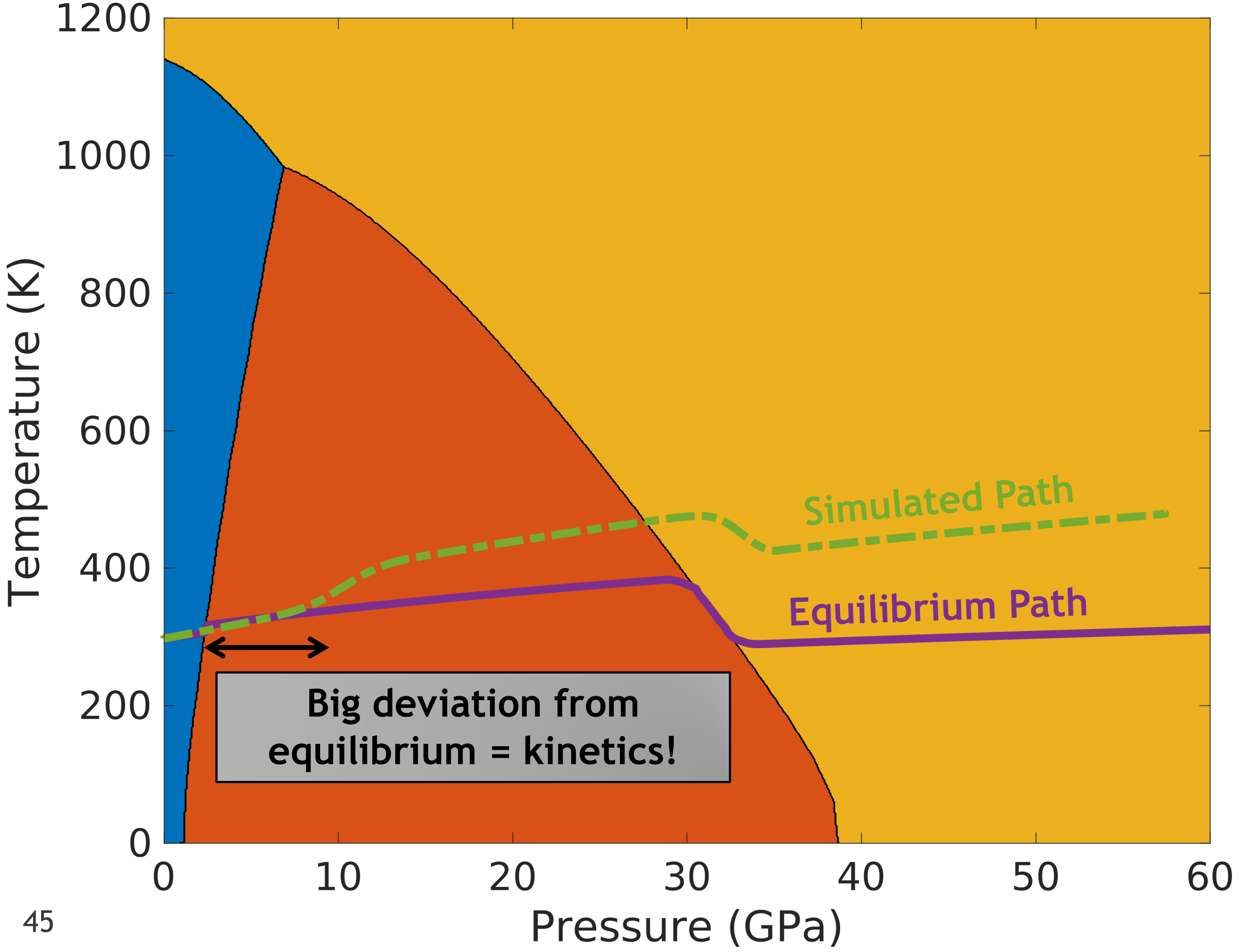
Experiments examining phase transitions in Zr were conducted in collaboration with LANL (C. Greeff)

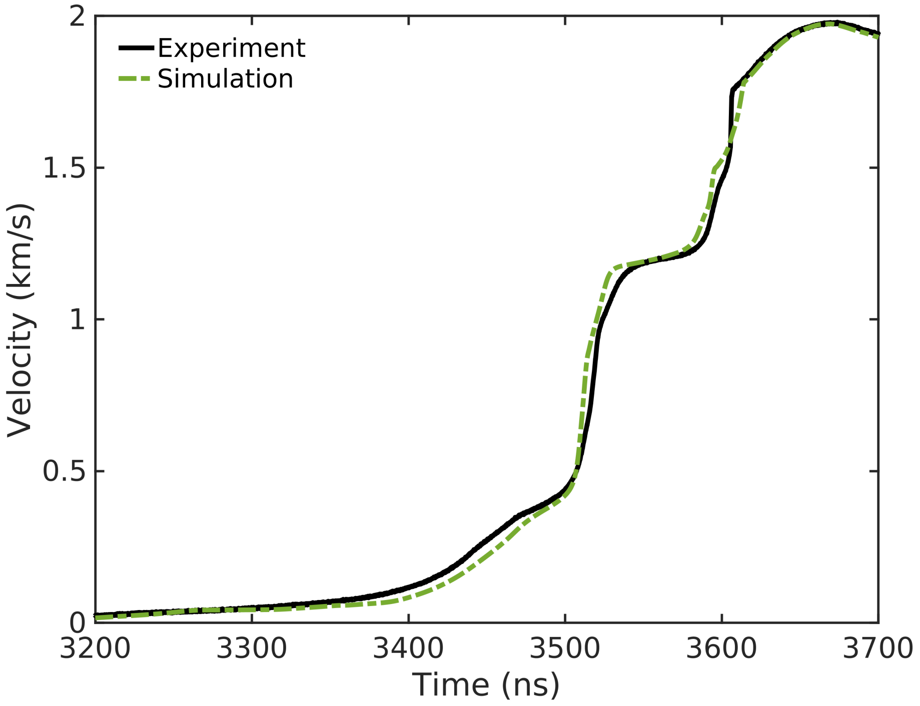
Principal of the experiment: when a ramp wave propagates through the Zr sample, kinks will appear in the measured interface velocity due to changes in wavespeed from the phase transitions





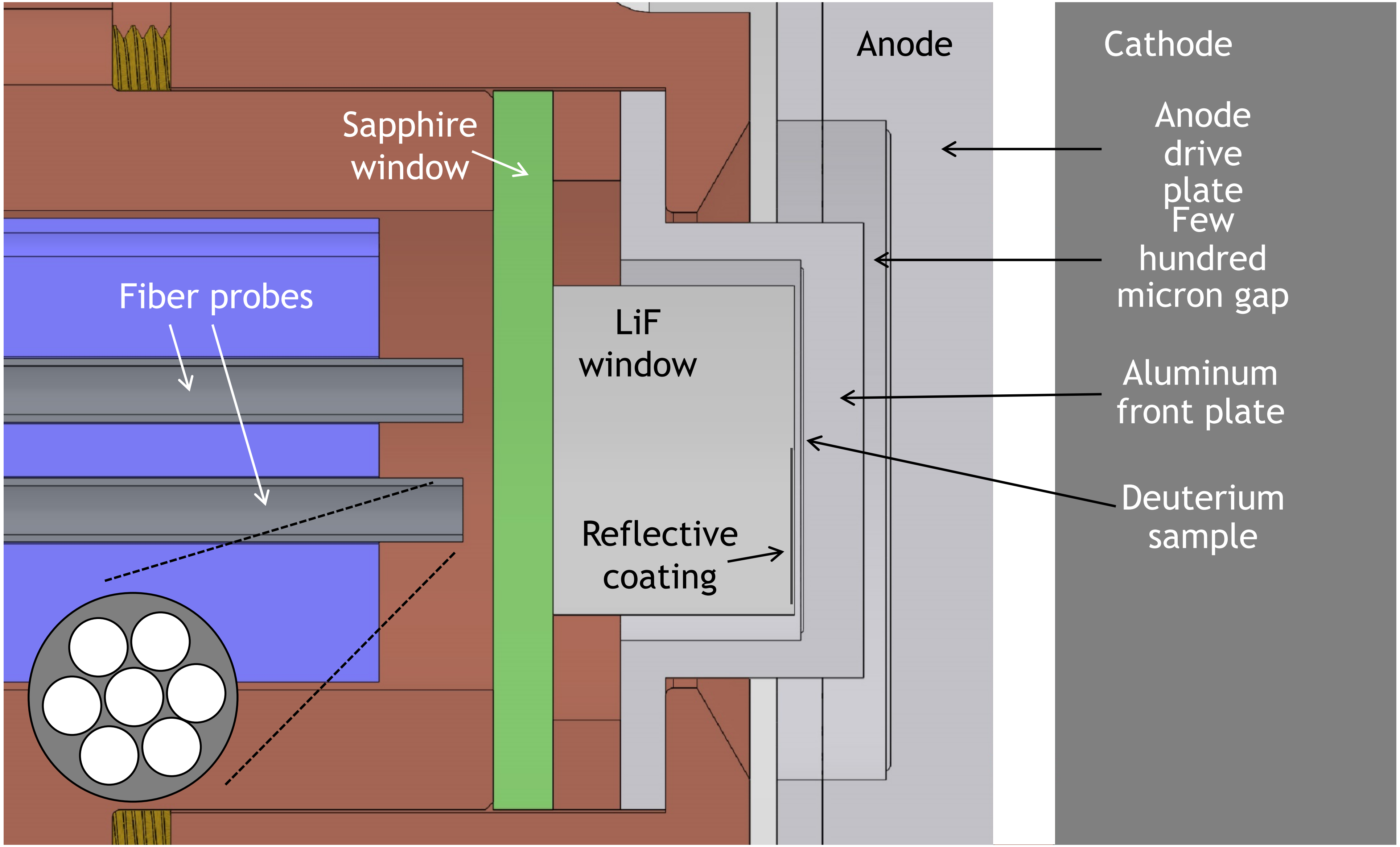
Forward simulations with a kinetics model are giving insights into the nature of these phase transitions





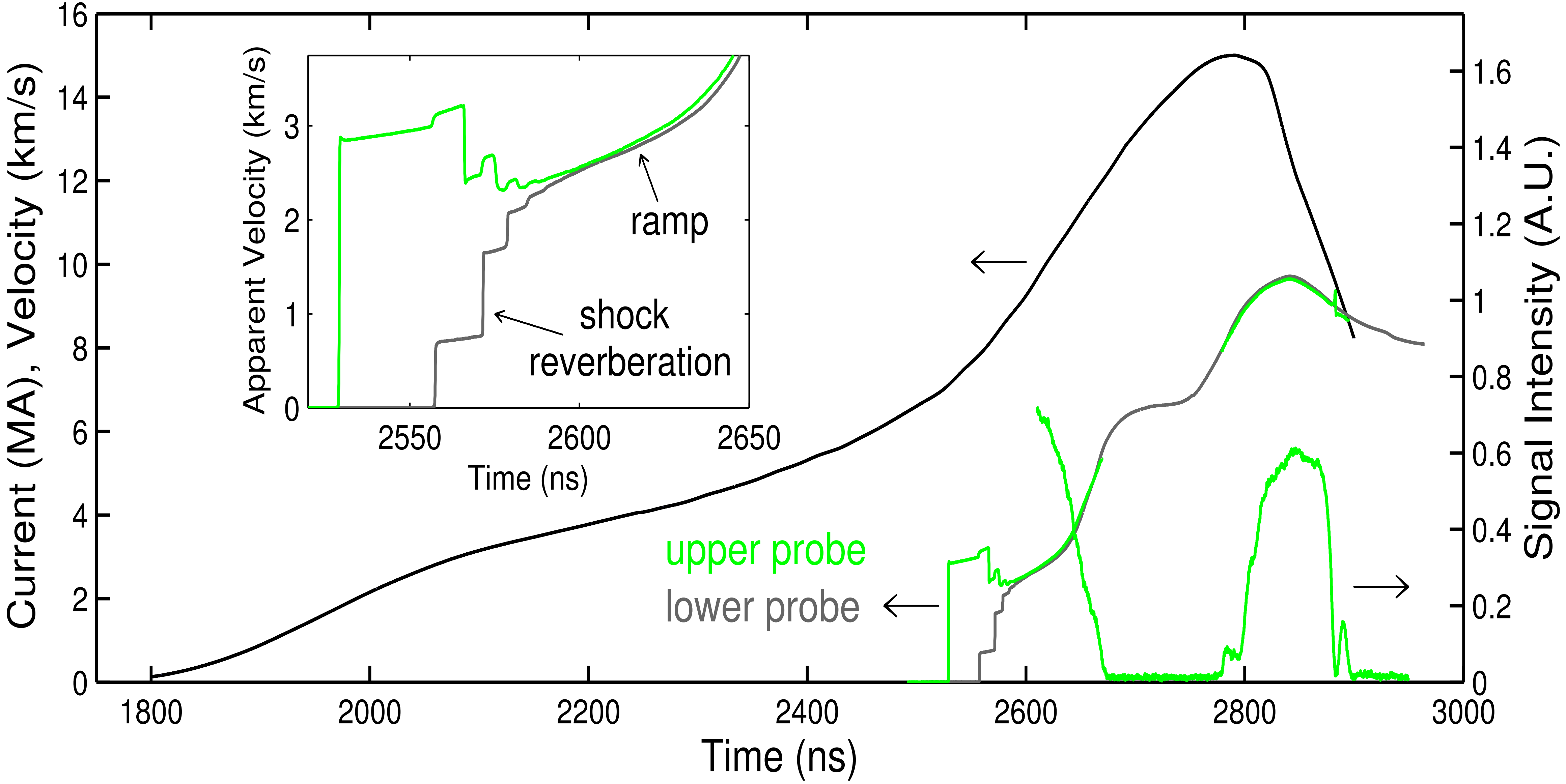
Not shown: we've also performed experiments with differences in impurities and starting temperature, both of which can significantly alter the kinetics of the phase transitions

Experimental configuration



Knudson, Desjarlais, Becker, Redmer, et al. Science 348, 1455 (2015)

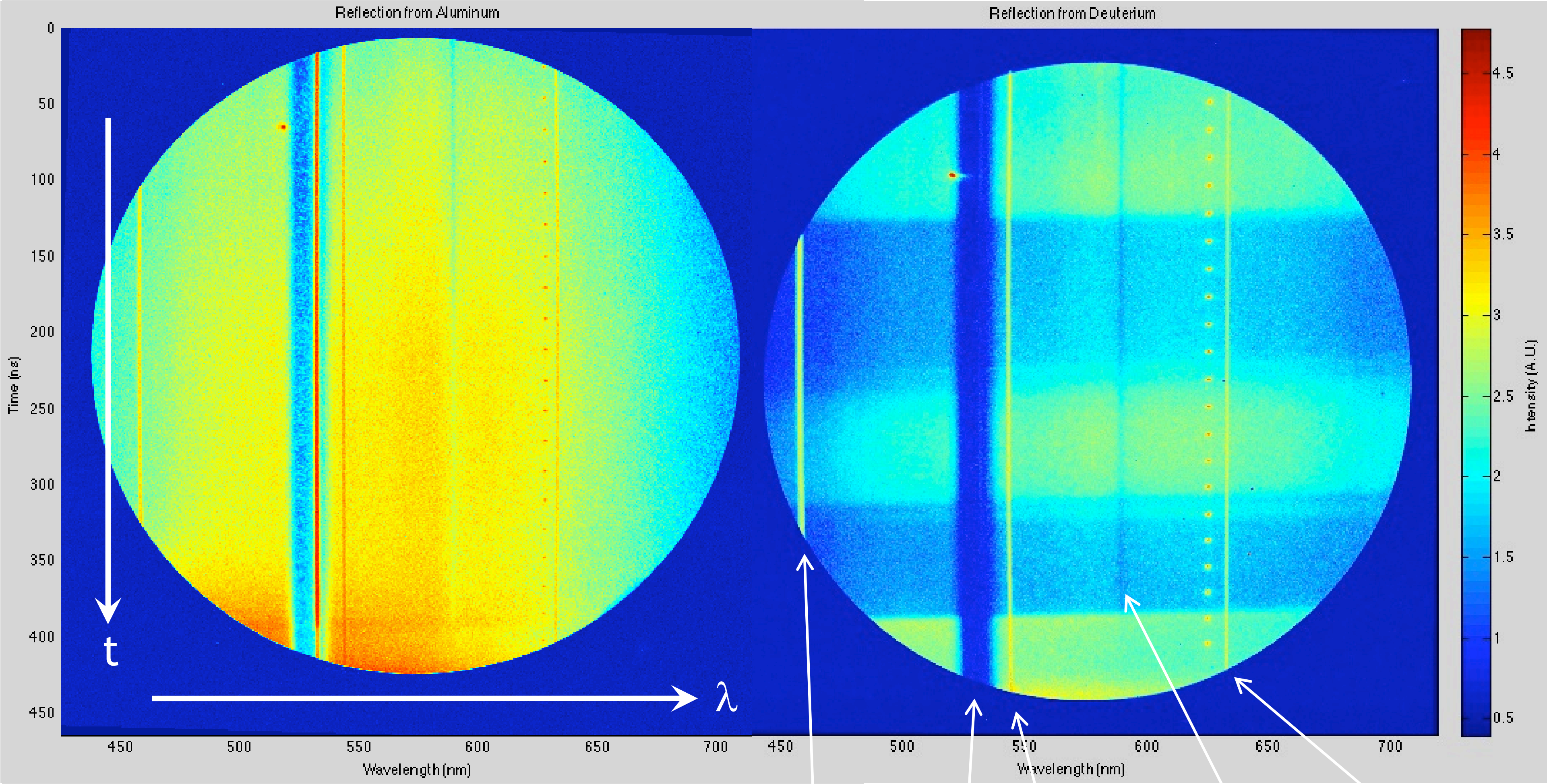
Representative data



Knudson, Desjarlais, Becker, Redmer, et al. Science 348, 1455 (2015)

Comparison of reflectivity from aluminum and deuterium

Reflection from aluminum coating | Reflection from deuterium



Wavelength range ~450-700 nm

457.9 nm | 532 / 543.5 nm | 589.3 nm | 633 nm

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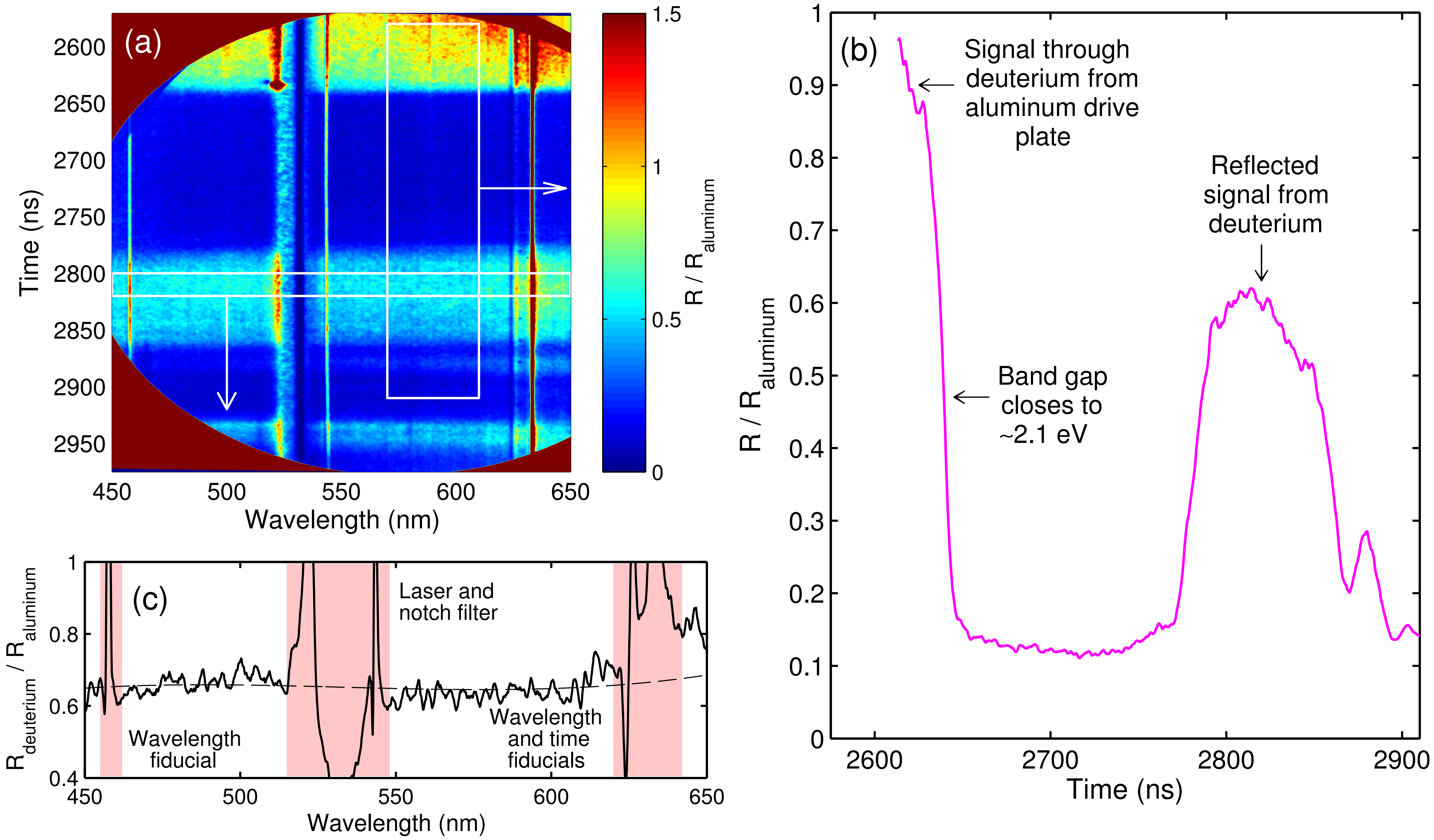
Wavelength dependence of reflectivity indicative of a metal

Shock-ramp



Knudson, Desjarlais, Becker, Redmer, et al. Science 348, 1455 (2015)

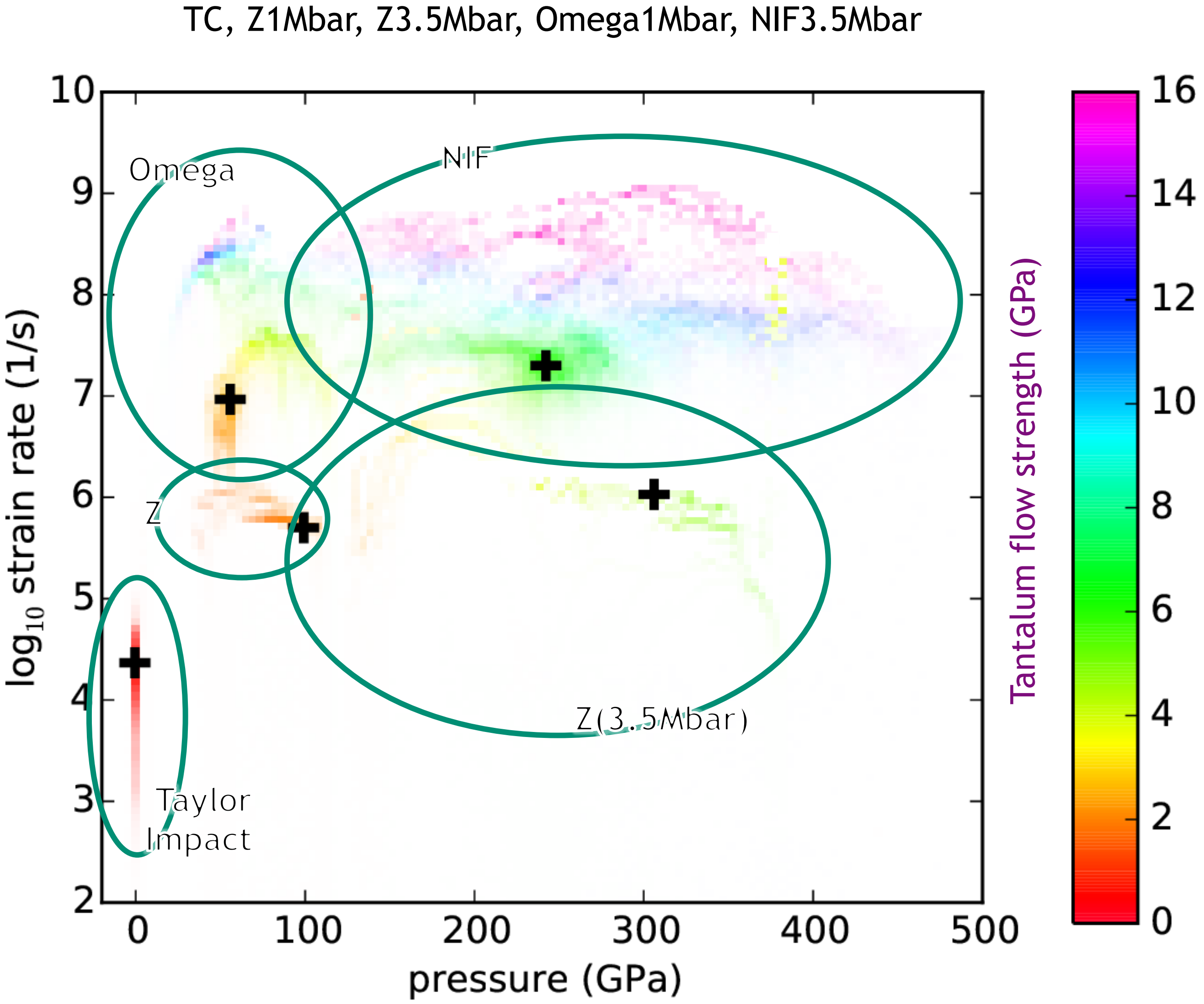
Combining platforms

Platform/ loading	Taylor Cylinder*	Gun (FS13) Shock-release	Gun (FS18) Shock-release	Z (2516)* Ramp Release	Omega* RT	Z (2488) Shock-Ramp Release	Z (3103)* Ramp Release	NIF* Ramp Release
Peak Pressure (GPa)	3	52	101	106	130	240	380	350
Sample Temperature (K)	305	700	1800	640	1200	900	1200	3800
strain rate (1/s)	$5x10^4$	$1x10^6$	$1x10^6$	$3x10^5$	$1x10^7$	$3x10^5$	$3x10^5$	$1x10^7$

Ambient melt temperature at 3290 K

Cross-platform trends: pressure, strain rate

- Overall trends make sense – strength increases with both pressure and rate
- Shows dependence on other quantities – and path dependence
- Strength isn't a single-value
- Different models are being used in these simulations of the experiments!



Strength in collaboration

Tightly integrating modeling with experiment across *platforms* is giving *invaluable* insight into the multivariate (pressure, strain rate, T) behavior of strength in extreme conditions

Each experimental platform provides unique capabilities in complimentary conditions

- **Taylor impact** measures of **large deformation** at low pressures and a focused range of strain rates
- **Z ramp-release** allows **precise strength extraction** at a given pressure but requires material release treatment in models for full mod-sim interpretation
- **NIF/Omega RT probes a large range of deformation conditions** in a single shot and reaches very high pressures. However, sensitivity to the surrounding target material requires further study

Modeling capability testing

- Sensitivity to the hydrocode can be controlled
- No single model appears to span low pressure/low strain rate and high pressure/high strain rate experiments