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Title: Dynamic experiments using IMPULSE at the Advanced Photon Source

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Dynamic Experiments using IMPULSE at the Advanced Photon Source

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The ability to examine the dynamic response of materials at extreme conditions requires diagnostics that can provide real-time, *in situ,* spatially resolved measurements at the appropriate length scales. Recent advances in synchrotron sources and diagnostics coupled to dynamic loading platforms are transforming the dynamic compression field to allow for such investigations. In the current work, recent experimental efforts on the IMPULSE capability at the Advanced Photon Source (Argonne, IL) will be highlighted to describe the development of the capability and its use to examine phenomena including jet-formation in metals, compaction, crack formation and propagation, and material strength and failure. These experimental results have relied in part on: 1) the development of a robust optically multiplexed intensified detector configuration to obtain the first "shock-movies" and 2) gun system improvements to better synchronize the impact event with the 60-ps width X-ray bunch. The IMPULSE capability is expected to continue to reveal novel phenomena for materials subjected to high strain rate loading while developing the required knowledge base to ensure success for future facilities including the Dynamic Compression Sector at the Advanced Photon Source and LANL's MaRIE.

70 YEARS OF CREATING TOMORROW

Los Alamos NATIONAL LABORATORY

Dynamic Experiments using IMPULSE at the Advanced Photon Source

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UNCLASSIFIED

Outline

- WX-9 Shock and Detonation Physics Group - Our mission and Capabilities
- Basic Shock physics experiments
- Development of the IMPULSE capability at Advanced Photon Source (APS)
  - Gun system development
  - Multi-frame Phase Contrast Imaging (MPCI) system to obtain shock movies
- Example dynamic experiments using single bunch X-ray MPCI
  - Jet formation in cerium to examine strength
  - Cracking in materials
  - New experiments in progress
- Single photon bunch Laue X-ray diffraction development
- The new Dynamic Compression Sector (DCS) at the APS
- Summary

Experimental activities in Shock and Detonation Physics at Los Alamos enable realistic simulations of our stockpile.

The Shock and Detonation Physics Group is involved in:
Fundamental Experiments, Material Characterization, Diagnostic Development, Integrated Experiments, New model development

Fundamental Experiments

↓

Development of Physics-based models

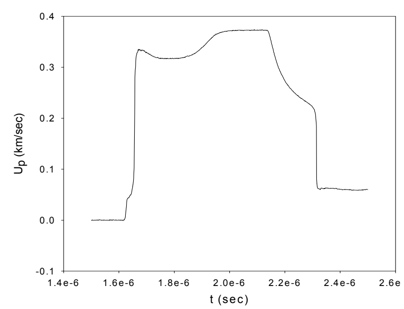
↓

Validation of models & Hydrocode calculations (Fundamental & Integrated Exp.)

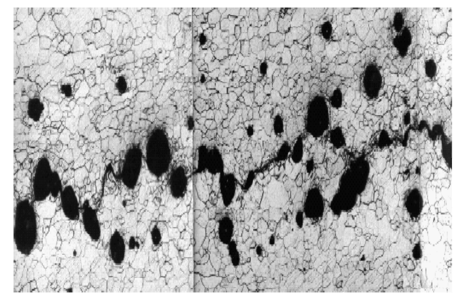
↓

Simulations of Integrated systems

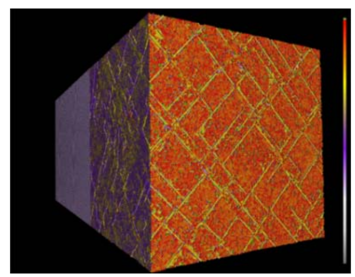
Continuum Data



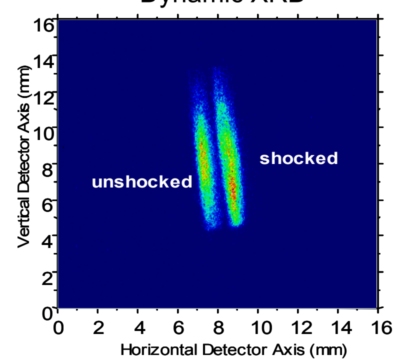
Meso-scale – Shock Recovery



Atomistic Calculations



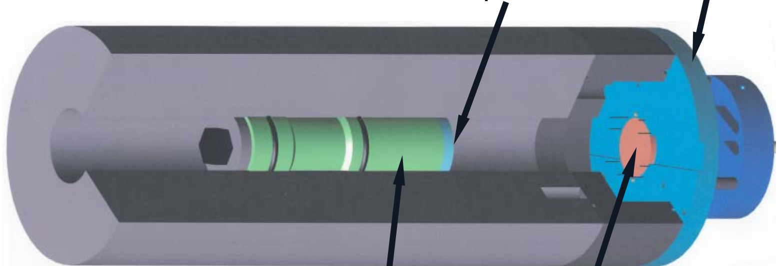
Dynamic XRD



Underlying Research theme is "Materials Properties under Extreme Conditions"

Dynamic Compression Capabilities in WX-9

- Gun systems (Single/Two stage gun systems, powder/gas)
- Firing Sites (explosive drive, large flyer plates)
- Laser drive Experiments
- Platforms at Advanced light sources (LCLS, NSLS, APS, etc.)
- Collaborations at other domestic/international facilities
- Diamond anvil cell

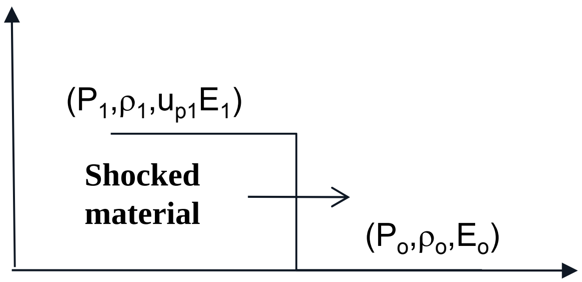



Outdoor 90-mm Gun Experiment

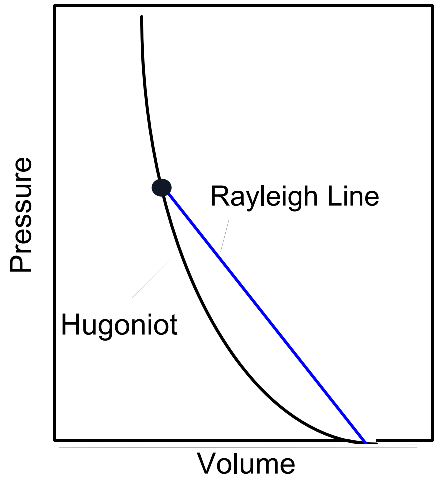

Explosively Driven Impact Experiment

Basic shock wave physics

Schematic of simple shock compression



Hugoniot Curve



Rankine-Hugoniot Jump Conditions

Mass $$\rho_1 = \rho_0 \frac{U_s}{U_s - u_p}$$

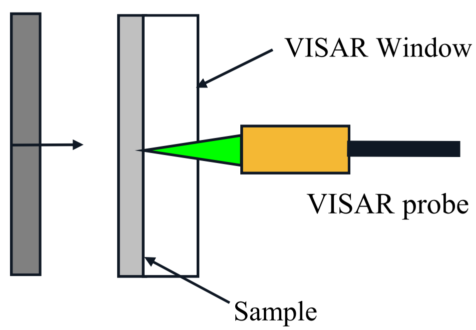
Momentum $$P_1 = P_0 + \rho_0 U_s u_p$$

Energy $$E_1 = E_0 + \frac{1}{2}(P_1 + P_0)(V_0 - V_1)$$

- The final stress (P), density (ρ), particle velocity (u_p), shock velocity (U_s), and energy (E) are obtained from the Rankine-Hugoniot Jump Conditions when two of these quantities are measured experimentally (typically U_s and u_p)
- Hugoniot is the locus of all end-states achieved through shock-wave loading (single-jump)
- Multiple experiments are required to construct the Hugoniot

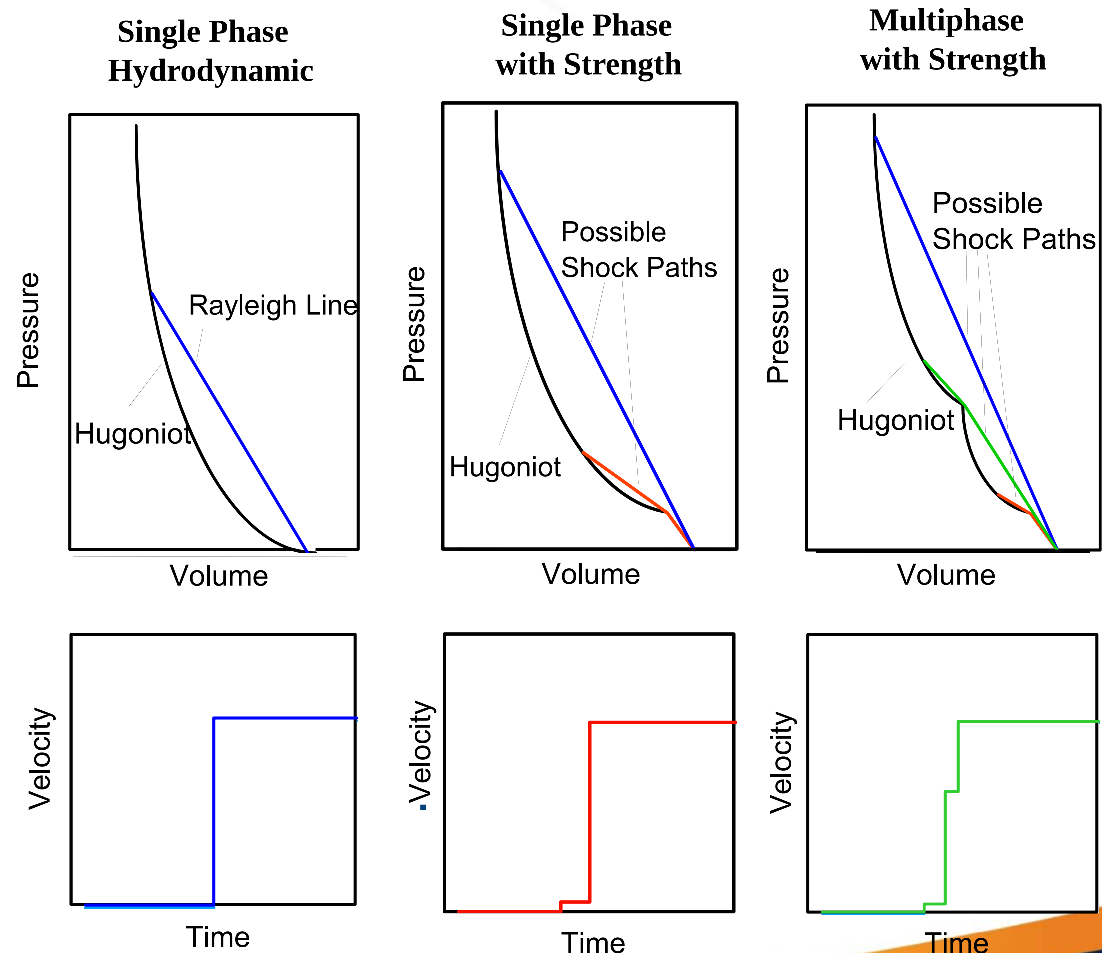
Traditional shock wave experiments monitor wave profiles and propagation to understand material response with pressure

Transmission Experimental Configuration



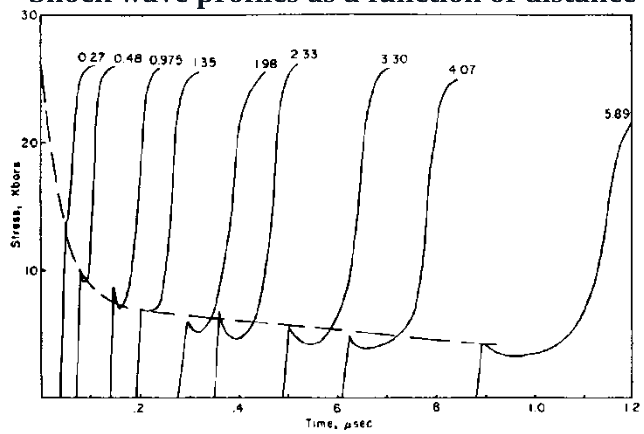
- Methods have been successful in examining numerous phenomena including phase transitions, EOS, kinetics, and strength

- Measurement is a convolution of wave propagation with the material response - Average over the bulk

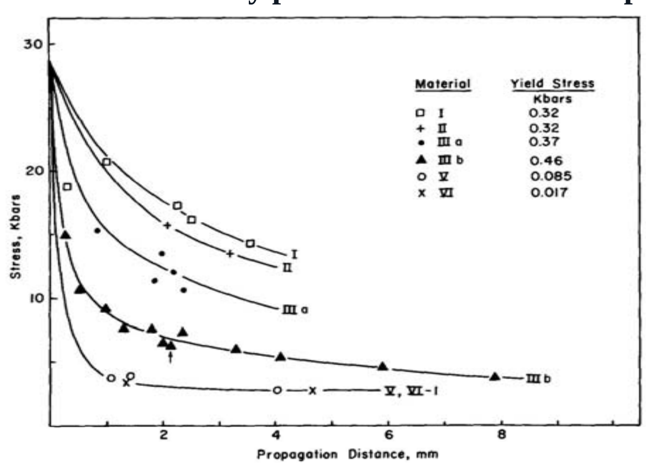


Traditional measurements have been used for decades to examine materials at extremes

Shock wave profiles as a function of distance

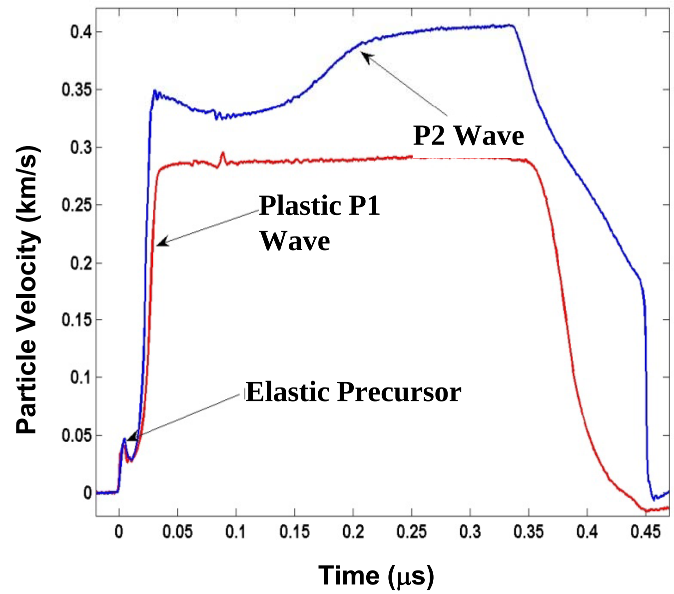


Elastic wave decay paths for various LiF samples



[J. R. Asay, et. al., J. Appl. Phys. 43, 2132 (1972)]

Wave profiles in iron showing
The well known α–ε transition at 13 GPa

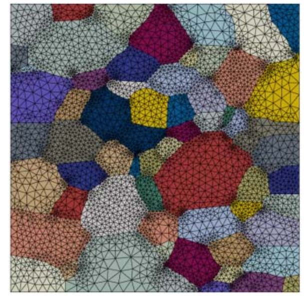


- Elastic-plastic deformation
- Phase transitions & kinetics
- Material strength
- Equation-of-state
- Compaction , Etc.

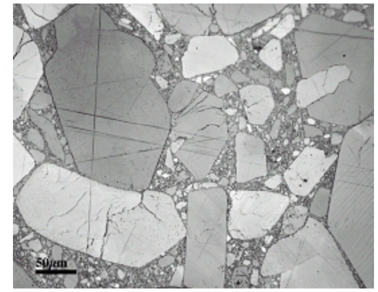
Experiments are needed that provide real-time, in-situ, spatially resolved measurements on relevant length and timescales

- Traditional shock wave diagnostics (VISAR, PDV) provide indirect information about the underlying microscopic mechanisms governing material response
- Diagnostics such as phase contrast imaging (PCI) and X-ray diffraction available at synchrotron sources offer unique opportunities for high-resolution spatially resolved measurements.
- Develop a mobile plate impact facility for use at synchrotron sources and to perform PCI and XRD measurements on dynamically compressed materials
- Impact experiments at the synchrotron are challenging (synchronization, short-lived dynamic states, etc.)
- Previous efforts at the APS by WSU and LANL have set the stage for synchrotron experiments.

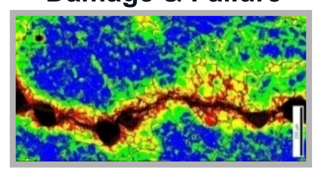
Real, Complex Materials



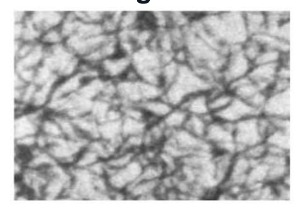
Plastic Bonded Explosive



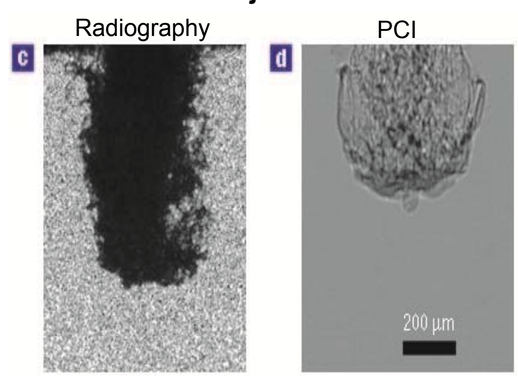
Damage & Failure



Freezing of Water

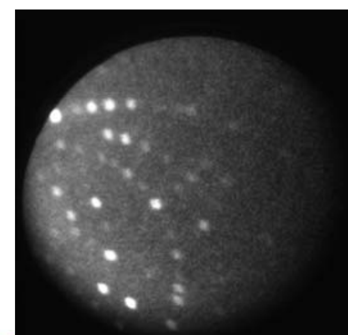


Fuel Injector Flow



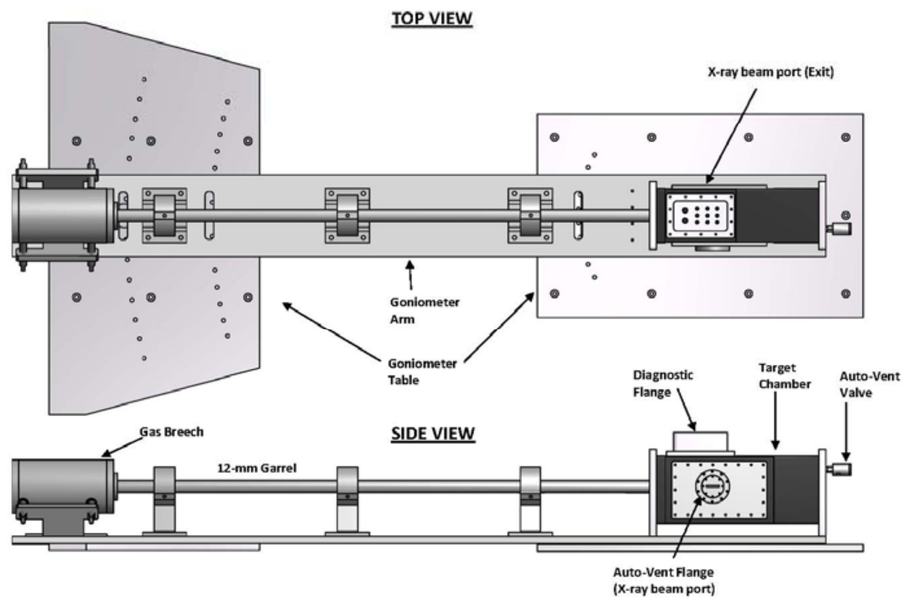
Y. Wang, X. Liu, et al. Nature Physics Vol. 4, p. 305 (2008)

X-ray Diffraction Pattern



A mobile 12.6 mm Launcher System has been developed for use at APS
IMPULSE = IMPact system for ULtrafast Synchrotron Experiments

- Standard wrap-around breech design with a 12.6 mm diameter projectile (50 caliber) with velocities up to 1 km/s
- Complete engineering analysis performed by R. Valdiviez (LANL) on the launcher (breech/barrel), target chamber, and support structure
- Side ports on the target chamber allow the x-rays to enter/exit. Target chamber qualified for up to 750 mg HE
- System can rotate to accommodate various experimental configurations and mobile to allow easy insertion in/out of the beam
- System remotely operated from outside the hutch and mobile



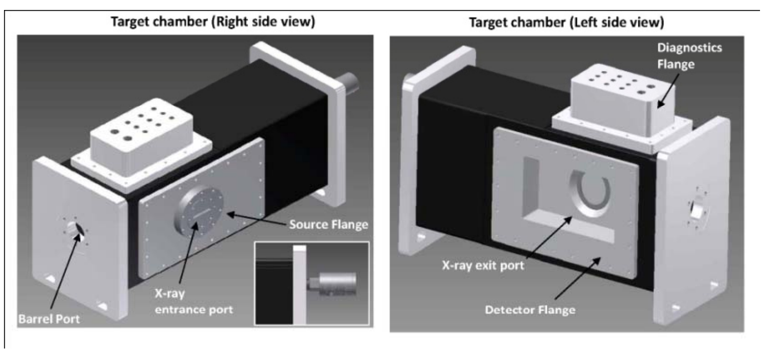
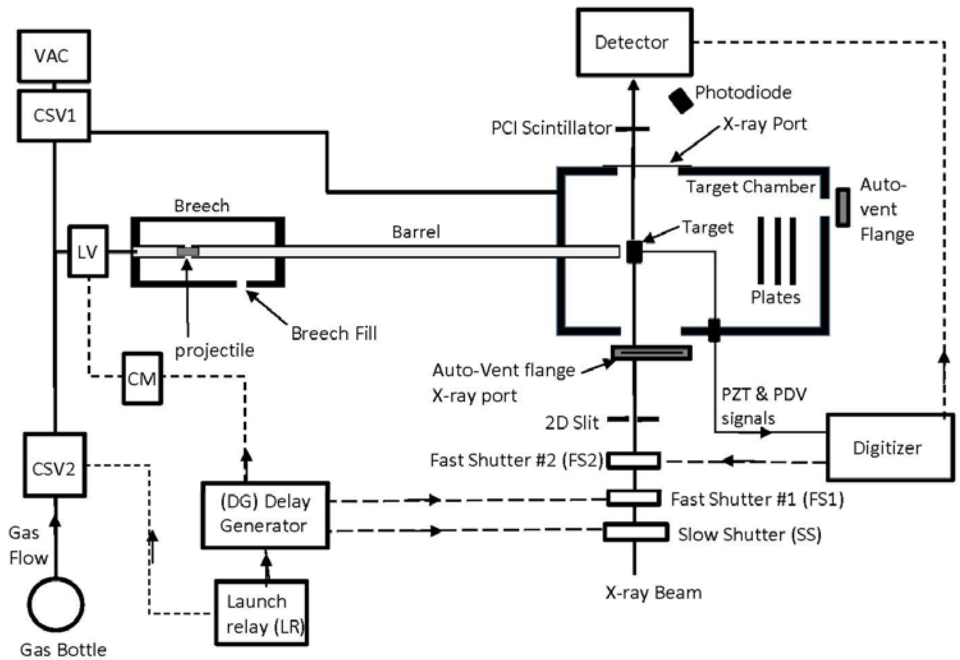


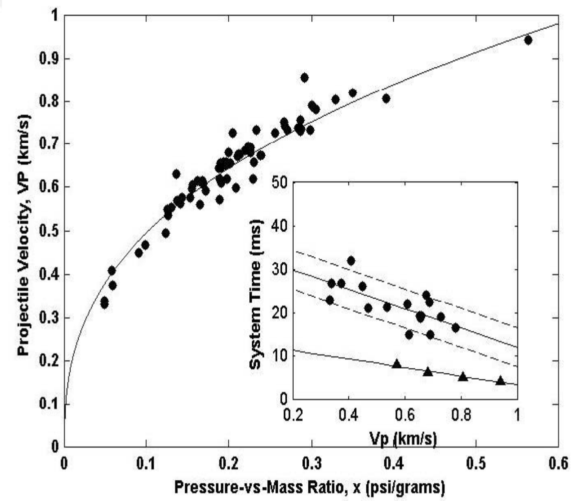
Photo of the Advanced Photon Source (Argonne, IL)

Gun located at Sector 32

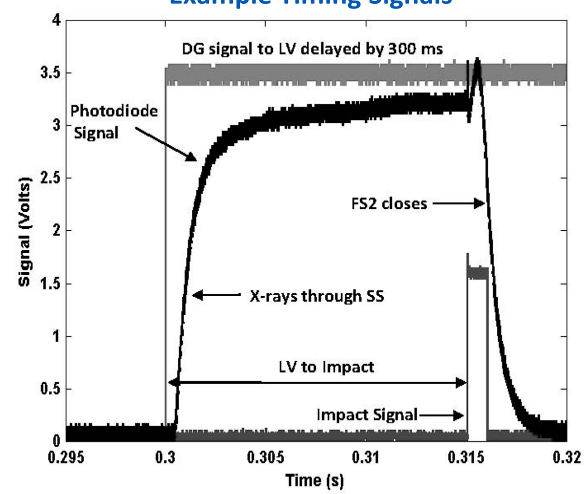
Synchronization is a key challenge: Gun system time reduced by an order of magnitude to improve synchronization of the impact event and detectors with X-ray bunch



Gun Performance Curves

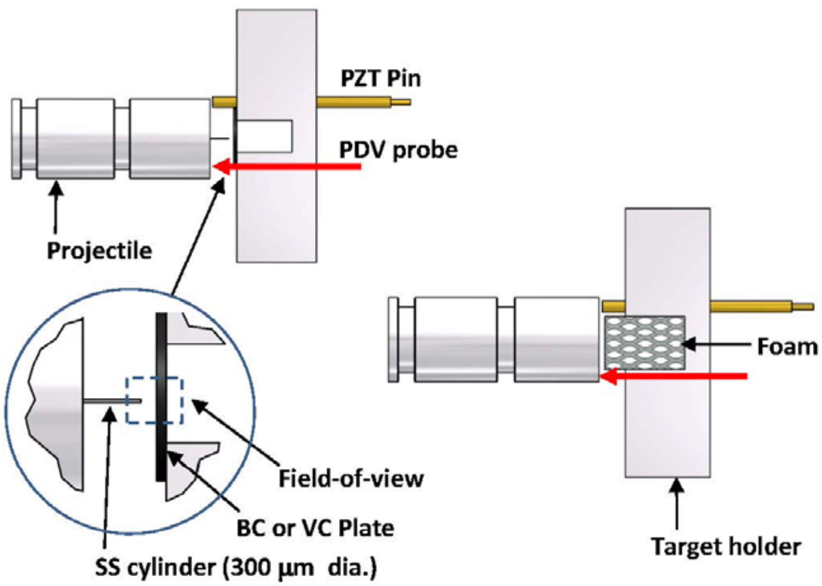


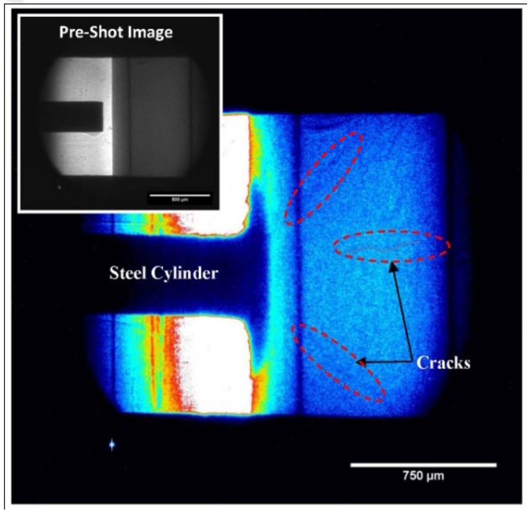
Example Timing Signals

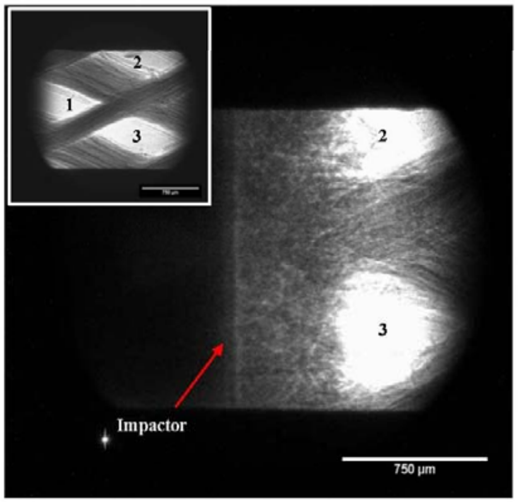


- New fast valve installed and tested to reduce system time
- Better synchronization minimizes the sample/component exposure
- System time and jitter reduced from 190±50 to 20±4 ms

In October 2011, we successfully performed the first dynamic experiments at APS on IMPULSE imaging materials using a single 80-ps X-ray bunch



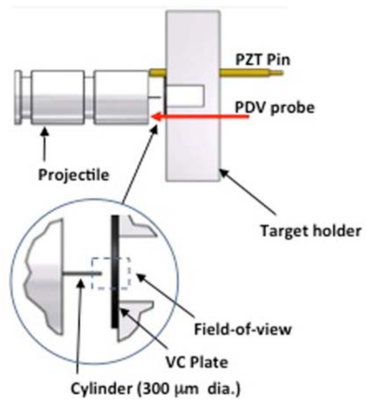




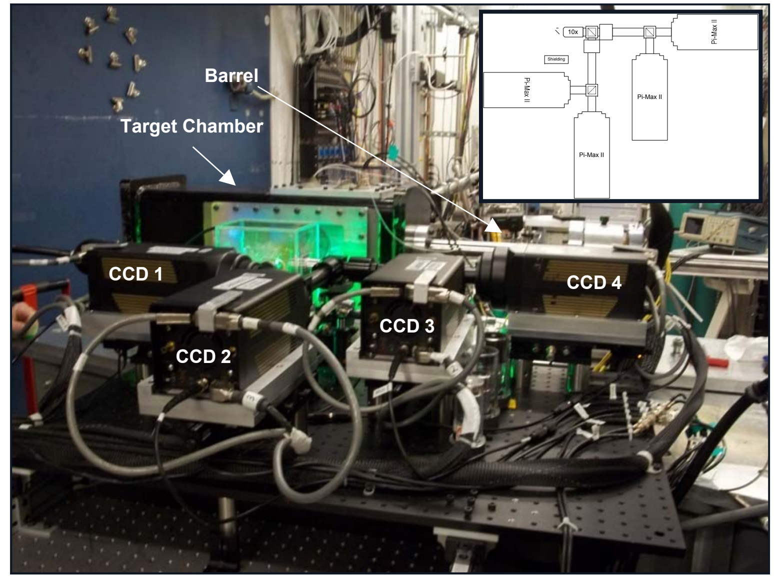
- Applications include: study of material failure, crack nucleation/growth, high strain-rate Taylor impact, void nucleation or collapse; compression of low density materials, etc

We recently developed a multi-frame ICCD system that was used to obtain "shock-movies" using PCI at the Advanced Photon Source

- Test experiment consists of a 300-μm cylinder impacting a VC plate
- Cracks clearly visible with latest detector system
- Systematic crack dynamic studies in progress (imaging dynamics of a single crack)
- Resolution estimated at 1 μm



IMPULSE experimental Configuration with 4-frame detector system



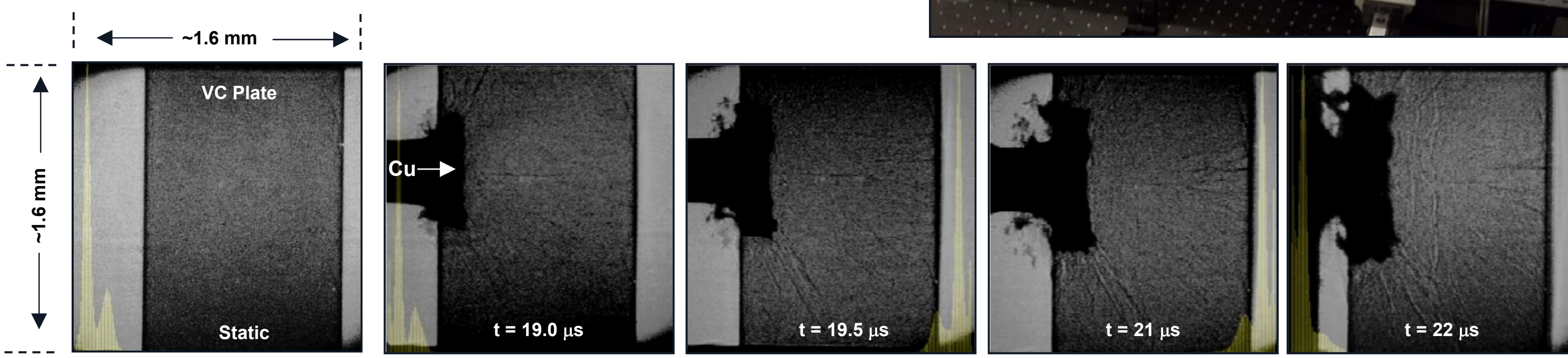
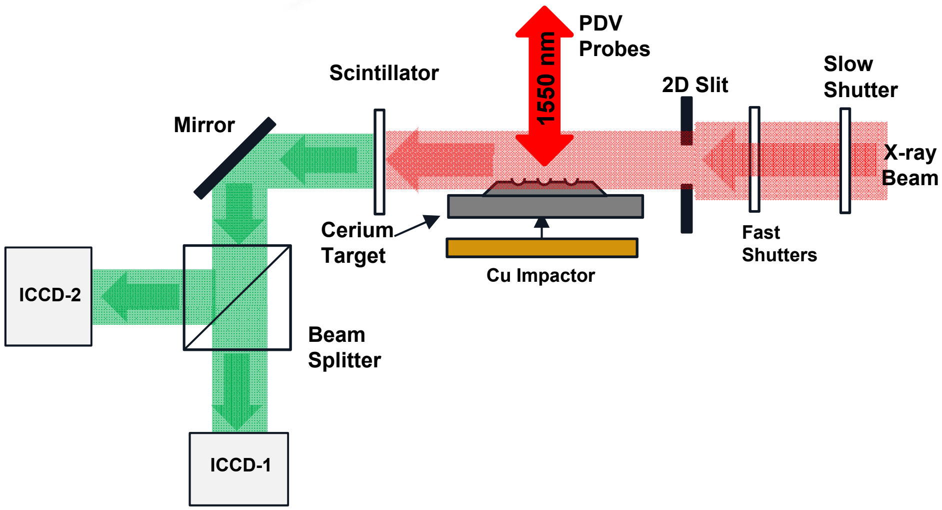


Fig. 1. Test experiment using the new 4-frame detector system to image the Impact of a 300-micron Cu cylinder onto a vitreous carbon plate to image crack formation (raw images). Times shown are referenced to a pre-impact trigger pin. CCDs can be gated and triggered independently on the nanosecond timescale

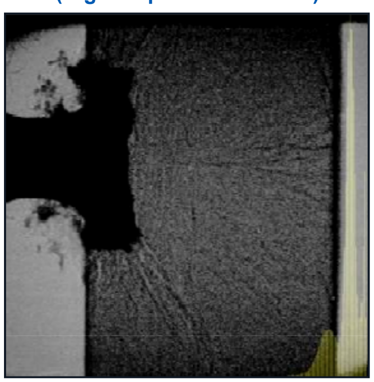
Numerous dynamic experiments have been performed at APS on IMPULSE imaging materials using a single 80-ps X-ray bunch

Experimental Configuration for Phase Contrast Imaging on IMPULSE

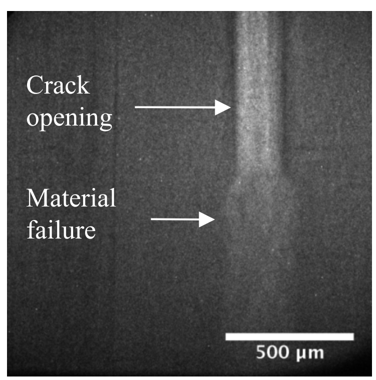


Experiments	Potential applications
PCI, Tylenol and Cerium jets	Jets, ejecta, flow and instability growth; material strength
PCI, steel plunger impact	Ballistics; high strain-rate Taylor impact; cracking; penetration; failure; dynamic friction
PCI, dynamic compression of microlattice foam	Void nucleation or collapse; compression of low density materials including plastic/metallic foams and gels; low-Z materials; equation of state
PCI, compaction of borosillicate glass beads	Compression of porous and granular materials; hotspots; powder reactions
Laue diffraction, Fe [100]	Phase changes; plasticity; concurrent diffraction and PCI measurements.

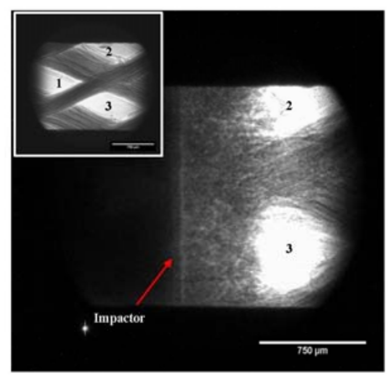
Taylor Impact – Cracking (Higher spatial resolution)



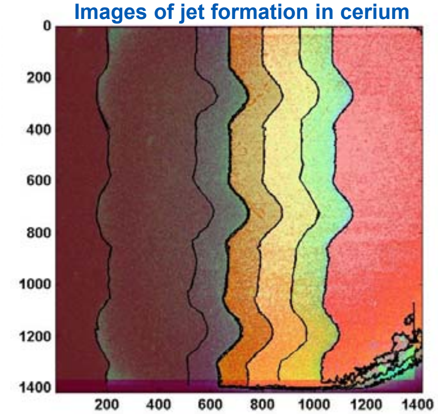
Crack Dynamics



Compression of engineered structures – MicroLattice Foam

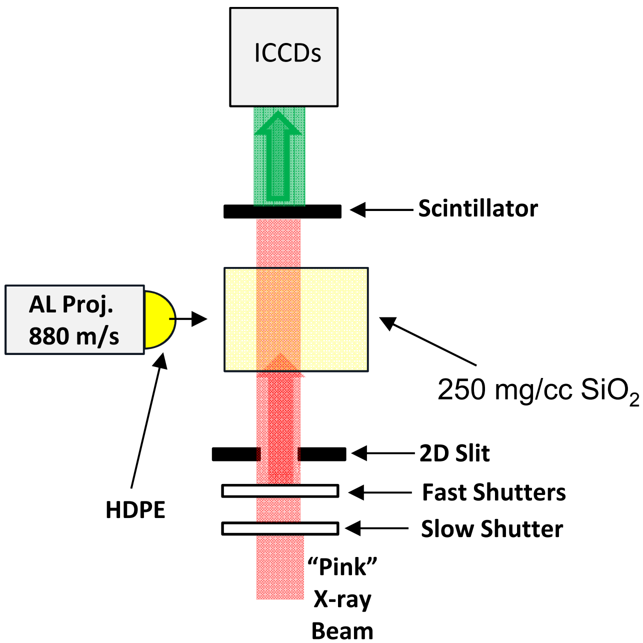


Rictmyer-Meshkov Intability Images of jet formation in cerium

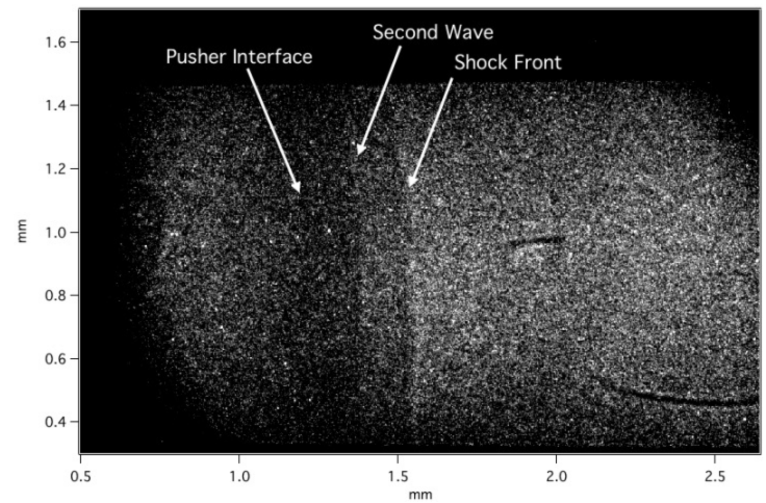


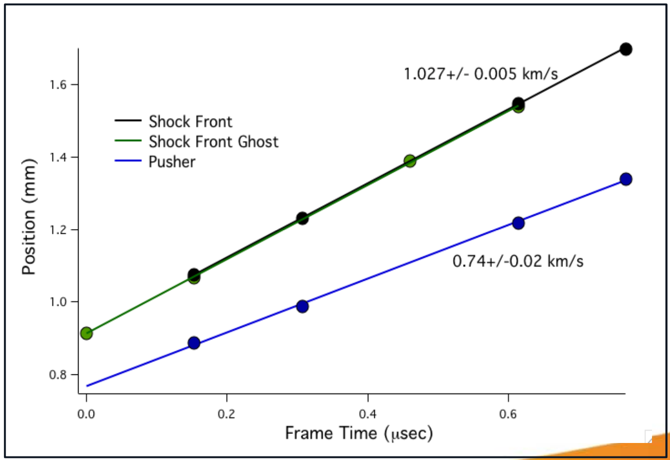
Impact of Aerogels: PCI used to observe in-situ motion of shock front

Experimental Configuration



Dynamic MPCI on Shocked Aerogel

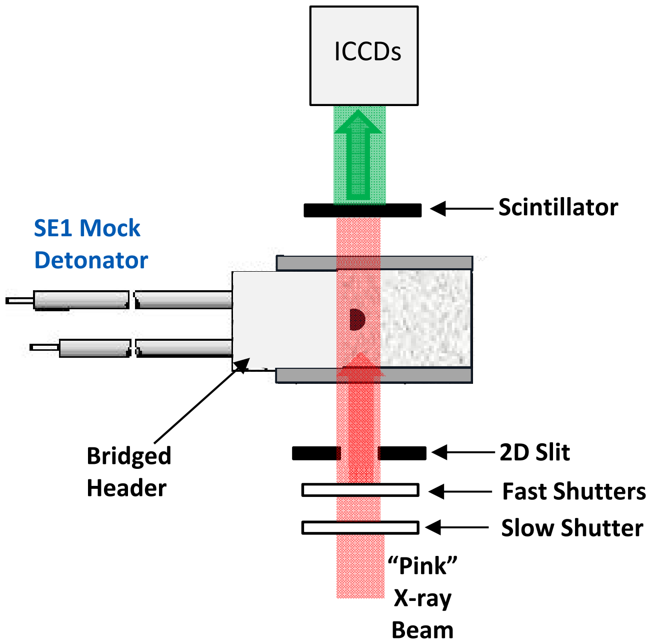




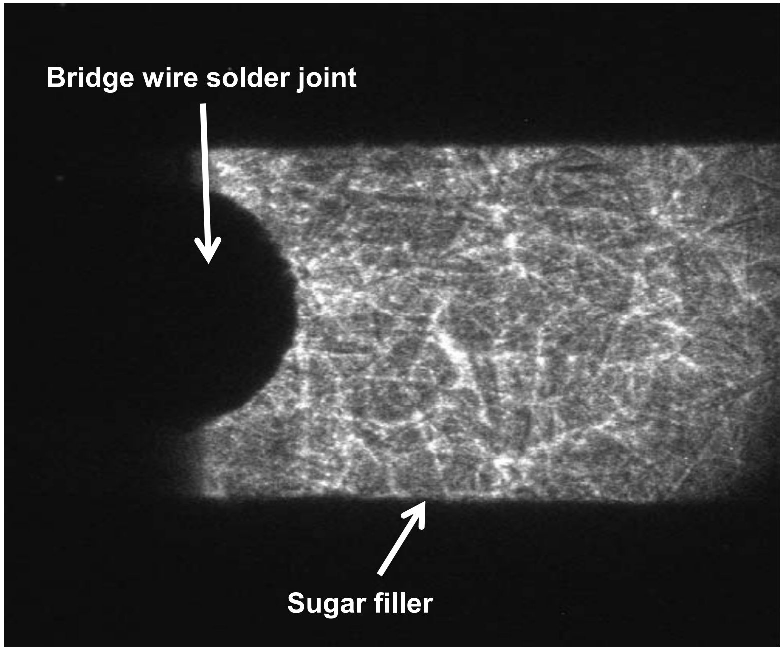
- First proof-of-concept experiment successful
- Images obtained of shock moving through aerogel
- Data provided accurate estimate of in situ shock velocity

Using PCI to examine in-situ detonator dynamics

Experimental Configuration



Static PCI Test Image on a mock SE1 Detonator



- Static PCI testing has demonstrated feasibility of single photon bunch images
- Goal: observe bridge wire explosion and subsequent dynamics leading to detonation
- Fireset/CDU ready for delivery to APS
- Dynamic experiments planned for February

Outline

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- Basic Shock physics experiments
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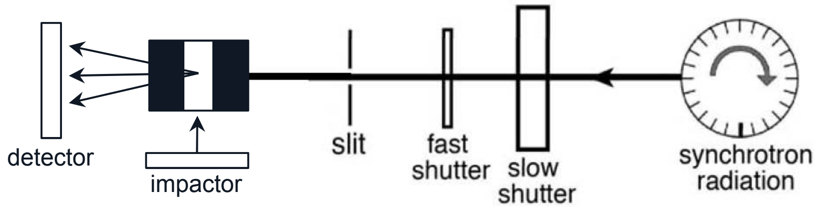
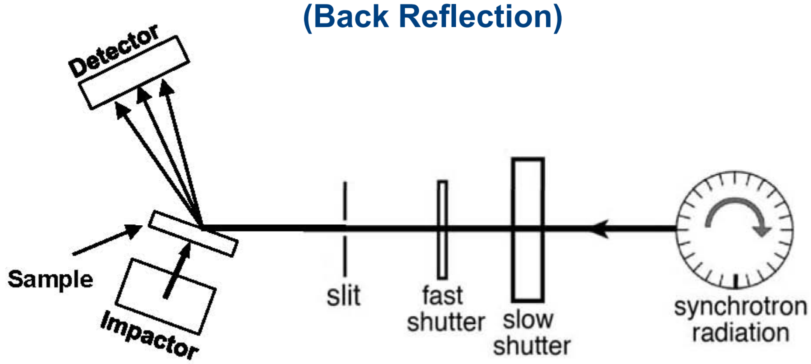
  - Gun system development
  - Multi-frame Phase Contrast Imaging (MPCI) system to obtain shock movies
- Example dynamic experiments using single bunch X-ray MPCI
  - Jet formation in cerium to examine strength
  - Cracking in materials
  - New experiments in progress
- ***Single photon bunch Laue X-ray diffraction development***
- The new Dynamic Compression Sector (DCS) at the APS
- Summary

Initial efforts to obtain single-bunch X-ray diffraction to examine atomic structure and microstructure promising

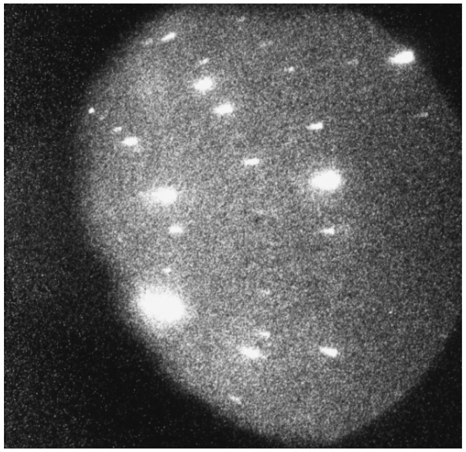
Dynamic Laue Diffraction Experiment Configuration (Transmission)



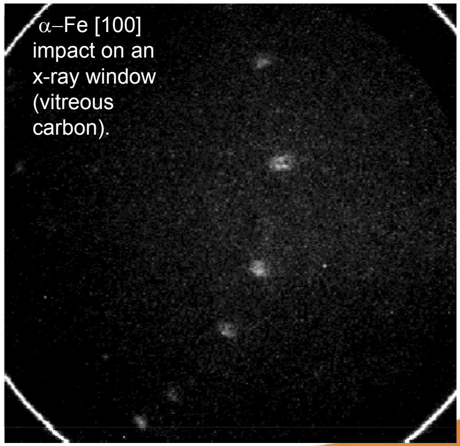
Dynamic Laue Diffraction Experiment Configuration (Back Reflection)



Diffraction from Tylenol using the fiber optic taper

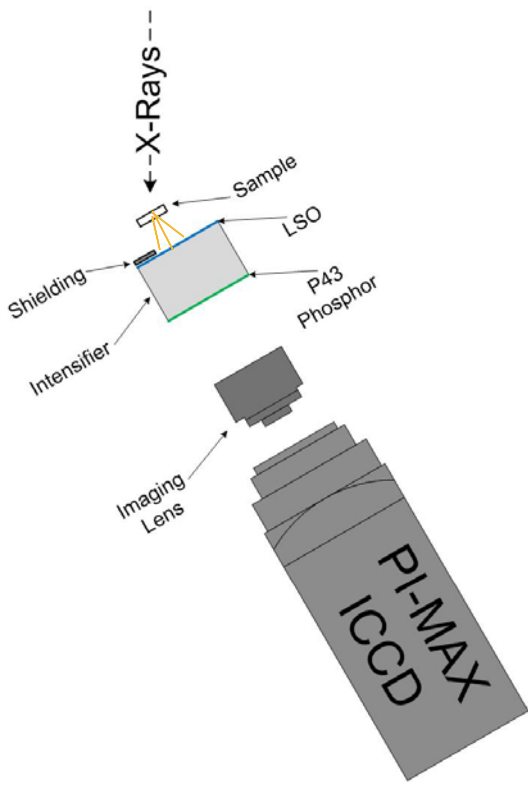


Data from the first dynamic Laue Diffraction experiment

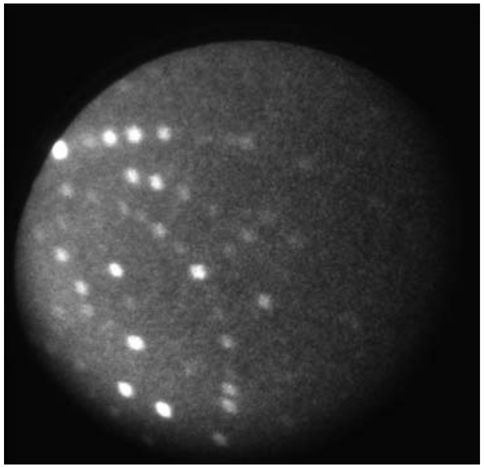


Single-photon bunch Laue diffraction (Transmission) achieved using a second image intensifier near the target

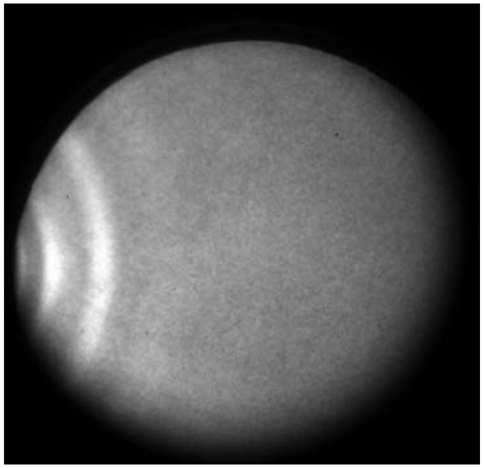
Dynamic Laue Diffraction Experiment Configuration (Transmission)



Static Single-bunch Laue XRD (Tylenol)



Static Single-bunch Laue XRD (Steel)

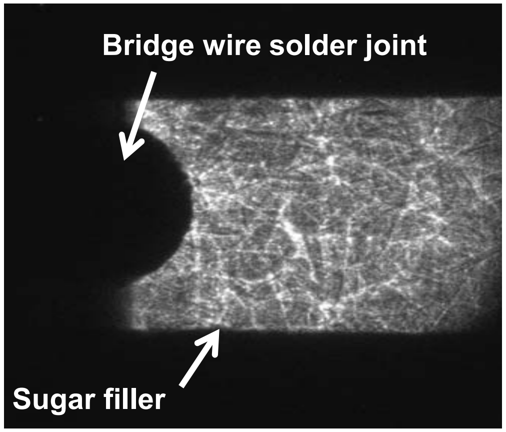


- Single-bunch Laue XRD is now possible using existing capabilities. We expect significant improvement with the Dynamic Compression Sector at APS
- Efforts are underway to use high energy X-rays (50-120 KeV) at Sector 1 of the APS for PCI and XRD

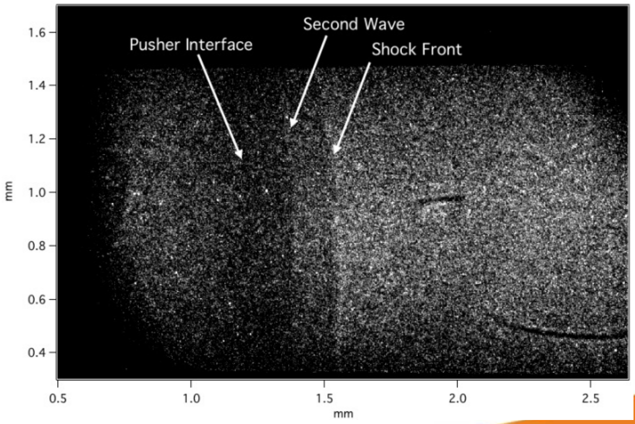
Summary of IMPULSE efforts

- In 10 months, the team developed a mobile gun system for synchrotron experiments - Installed system into experimental hutch (Sector 32 ID-B) at APS.
- First experimental series conducted in October 2011 to obtain dynamic images using PCI with a single 80-ps X-ray packet synchronized to the event.
- Shock-movies (4-frames) achieved using new optically multiplexed ICCD system for Multiframe PCI (MPCI)
- Engineering and system design continues: Improved gun system timing, new target designs, explosive capabilities, higher velocities, explosive vessel
- Over 200 experiments conducted to examine a wide variety of phenomena (jet-formation, compaction, crack dynamics, hole/void collapse, compression of engineered materials, etc.)
- XRD methods in development including the use of high energy (50-130 KeV) X-rays at APS Sector 1. Theoretical tools to aid in experiment setup, design, and nalysis

PCI (static) Test Image on an EBW

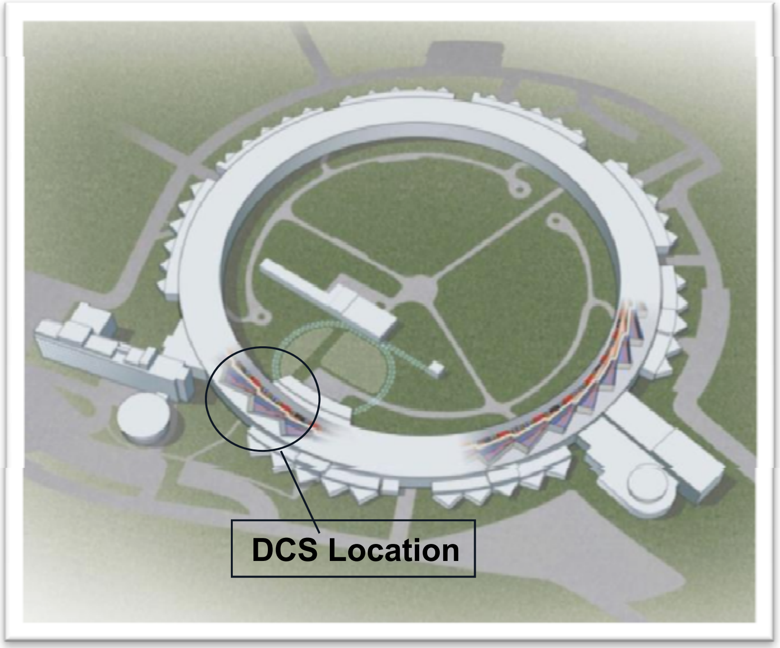


Dynamic MPCI on Shocked Aerogel



What is the dynamic compression sector?

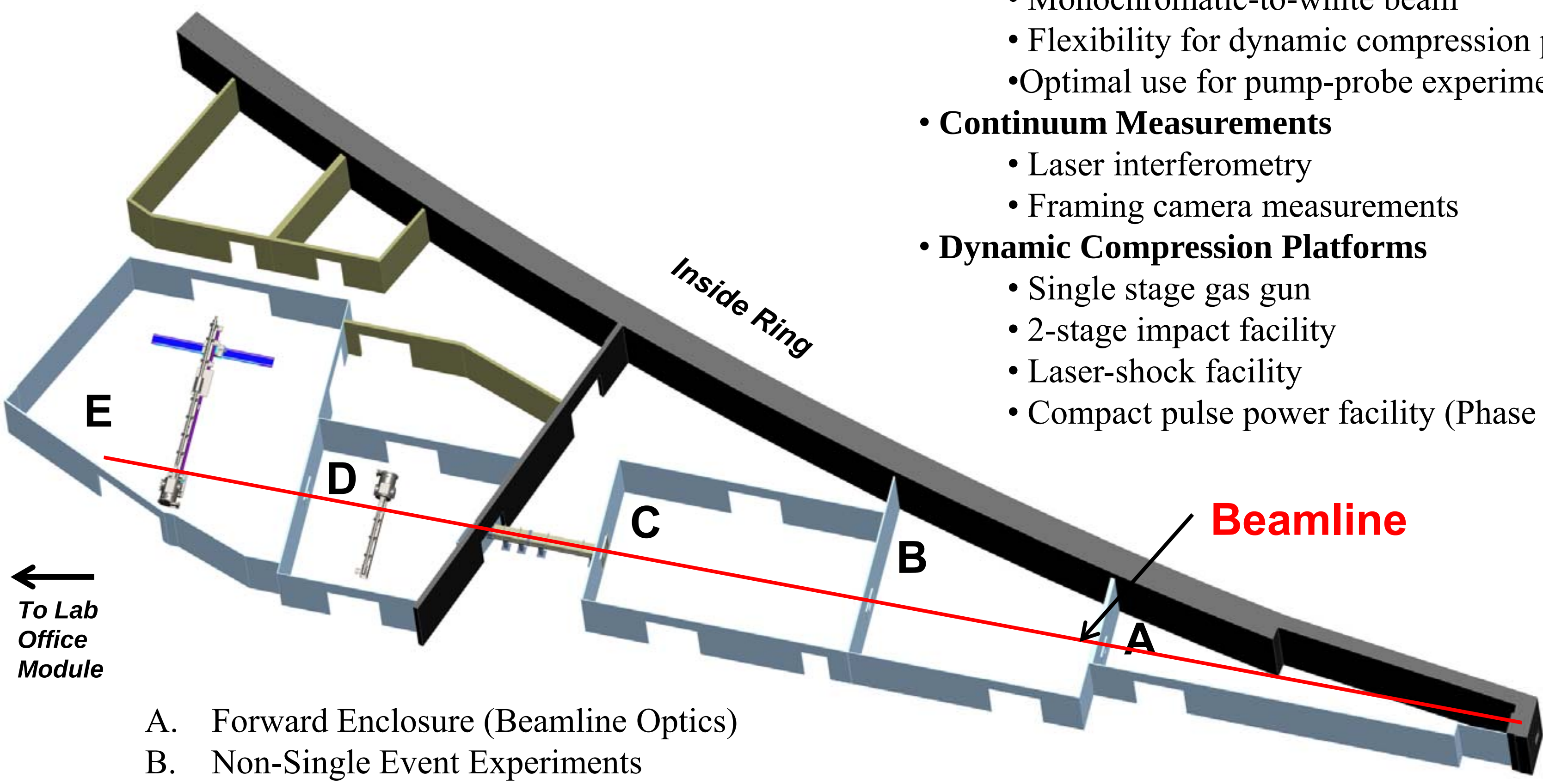
- A DOE/NNSA sponsored user facility dedicated to dynamic compression of condensed matter
- User facility designed to optimally link dynamic compression platforms to a dedicated synchrotron beam line
- Need to examine time-dependent changes under dynamic compression
  - Peak stress (~5 GPa to well over 200 GPa)
  - Time durations (ns to ms)
- Focus on time-resolved, in-situ diffraction and imaging measurements; simultaneous continuum measurements
- Project lead by WSU in collaboration with NNSA labs



New paradigm to understand dynamic compression of materials at multiple length scales

DCS Layout

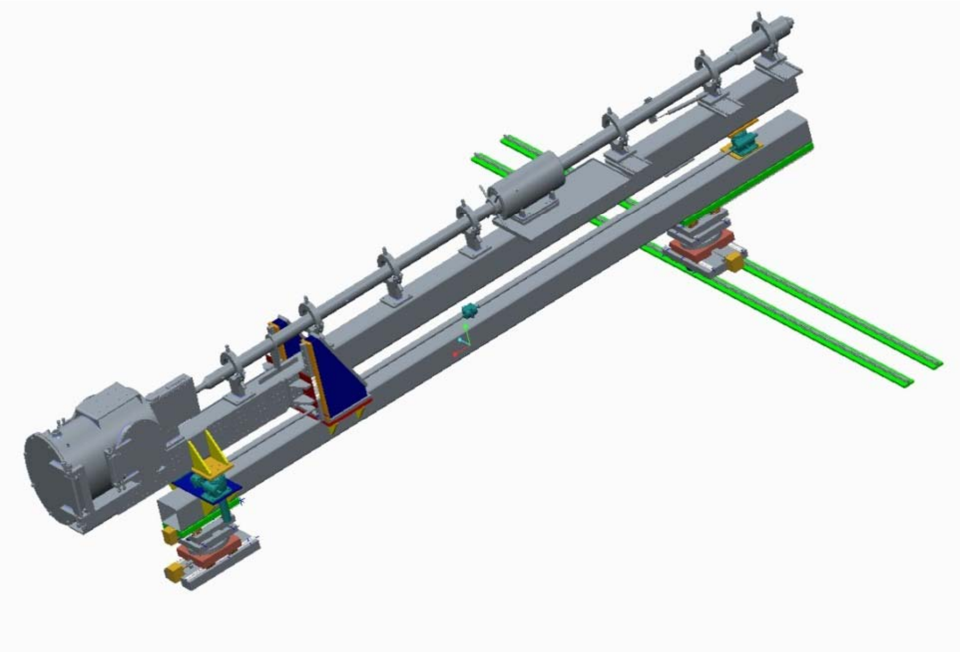
- **Focus on X-ray Diffraction and Imaging**
  - Monochromatic-to-white beam
  - Flexibility for dynamic compression platforms
  - Optimal use for pump-probe experiments
- **Continuum Measurements**
  - Laser interferometry
  - Framing camera measurements
- **Dynamic Compression Platforms**
  - Single stage gas gun
  - 2-stage impact facility
  - Laser-shock facility
  - Compact pulse power facility (Phase II)



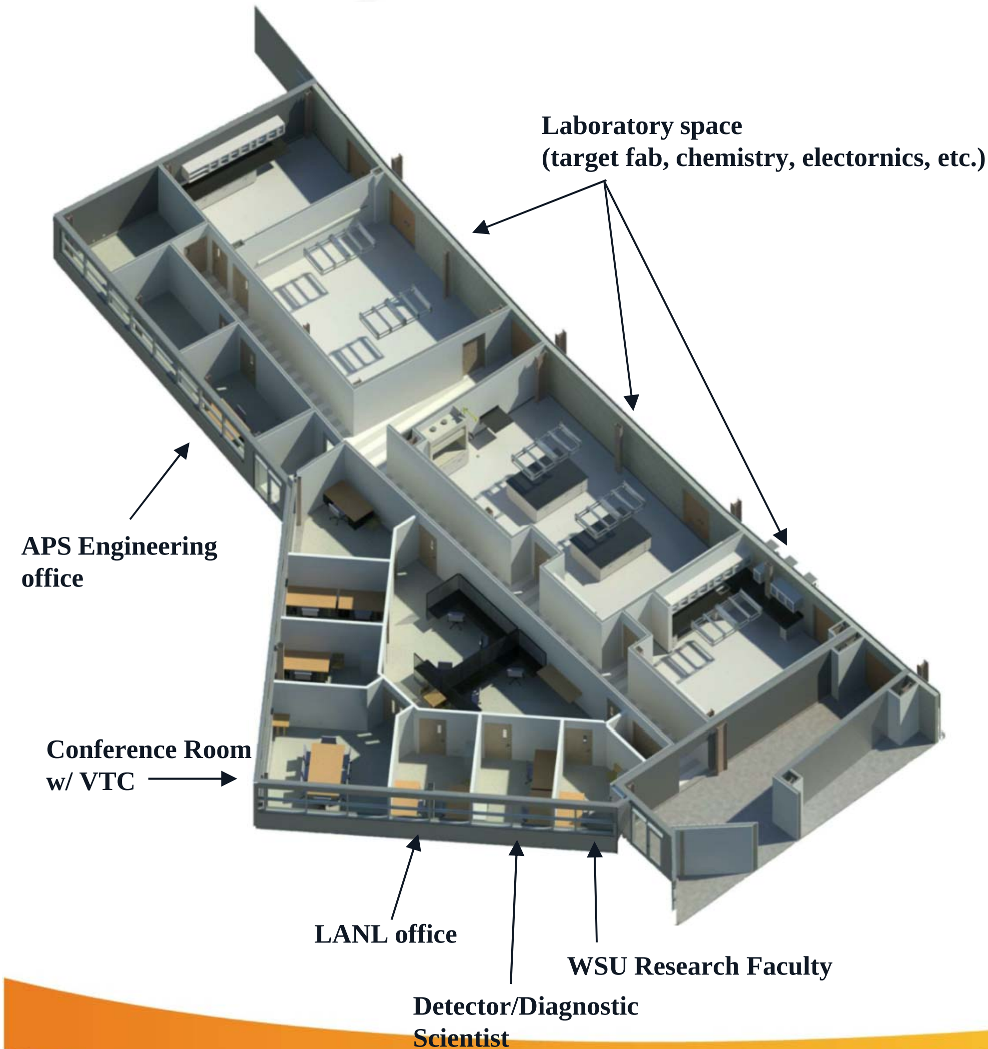
A. Forward Enclosure (Beamline Optics)
B. Non-Single Event Experiments
C. Laser Shock
D. Impact Facilities – Single Stage Launcher
E. Impact Facilities – 2 Stage Launcher

Sector 35 dynamic capabilities – Available in fall 2014

- Single stage light gas gun (0.1 to 1 km/s)
  - 1 liter breech; 10 Ksi maximum pressure
  - ½-in bore; 5 gram projectile
- Powder gun (0.1 to 2/km/s)
  - Utilizes the SSGG launch tube
  - ½-in bore, 5-gram projectile mass
- 2-stage light gas gun (1.5 to >5 km/s)
  - ½-in bore, 5 gram projectile
  - Drive gas: hydrogen, helium, or nitrogen
  - Powder gun compatible
- IMPULSE capability will be available in the Sector 35-B in February 2014



Lab Office Modules (LOM) – Completed

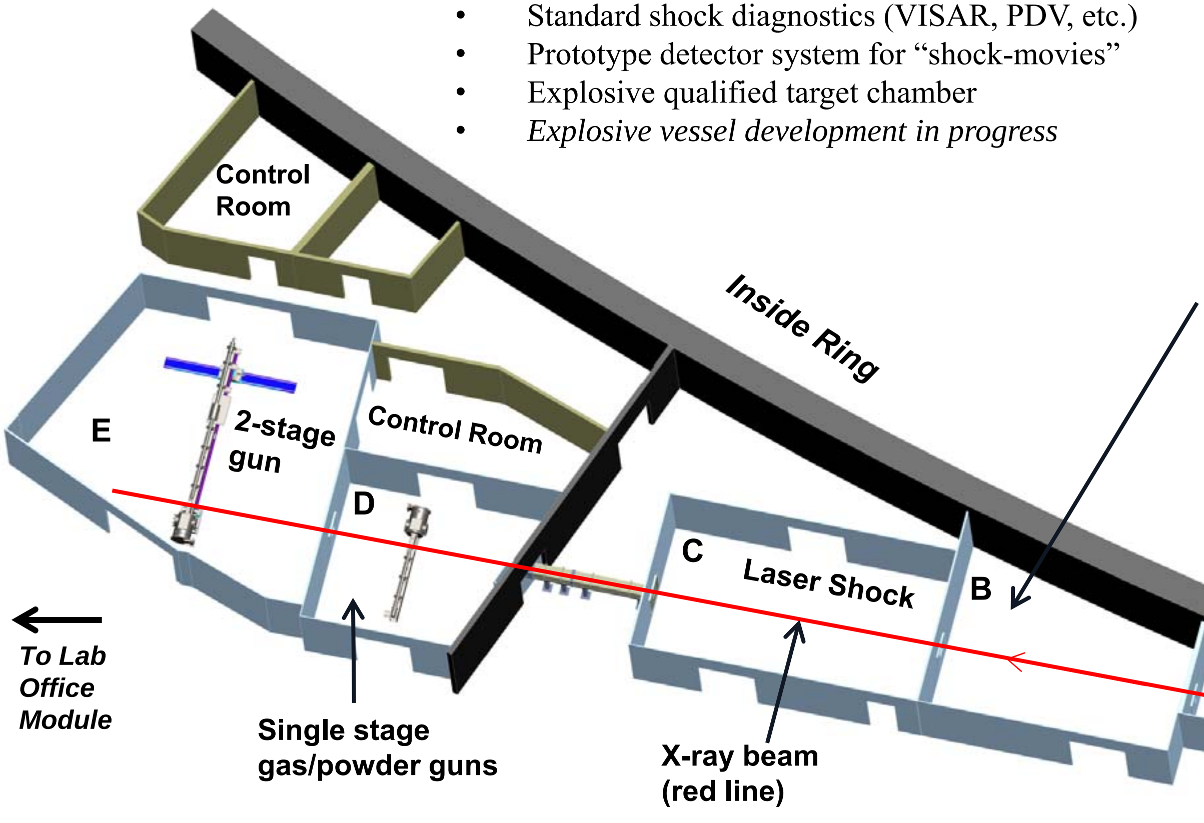


In January 2014, IMPULSE will occupy the Sector 35-B hutch at the Dynamic Compression Sector – An NNSA funded facility at Argonne's Advanced Photon Source

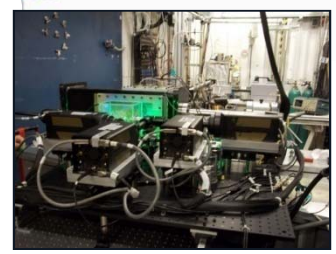
IMPULSE Capabilities

- Existing gun on new remotely operated table
- Standard shock diagnostics (VISAR, PDV, etc.)
- Prototype detector system for "shock-movies"
- Explosive qualified target chamber
- *Explosive vessel development in progress*

DCS layout



IMPULSE System



4-frame Detector System

PDV & Diagnostics

IMPULSE efforts are the first step toward development of the Dynamic Compression Sector and LANL's MaRIE

- The Dynamic Compression Sector is currently in development and will include multiple dynamic loading platforms coupled to the X-ray beam

- DCS is a stepping stone toward LANL's MaRIE concept which is a proposed facility that will couple dynamic compression platforms to multiple diagnostic beams (XFEL, electron beam, proton beam, neutron beam)

- The IMPULSE project has developed the foundation required to ensure success of proposed signature facilities such as DCS and MaRIE
  - Platform development (synchronization, target design, etc.)
  - Detection system development – "Shock Movies" using X-ray diagnostics
  - *Development of the user knowledge base needed for participation in DCS and MaRIE*

Questions?

IMPULSE Team, Participants, and Collaborators:

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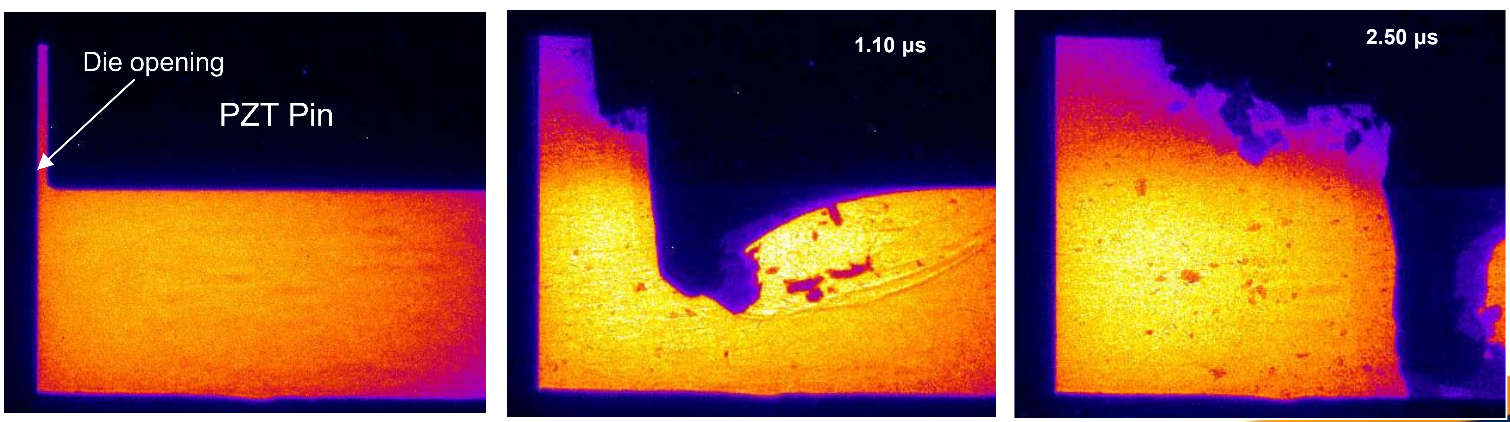
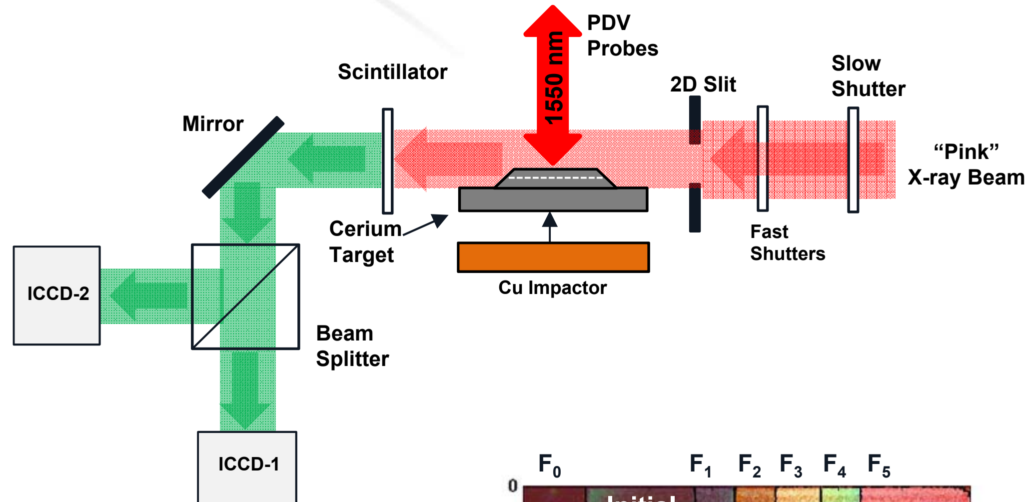
Impact of a PZT pin by a high-velocity extruding polymer

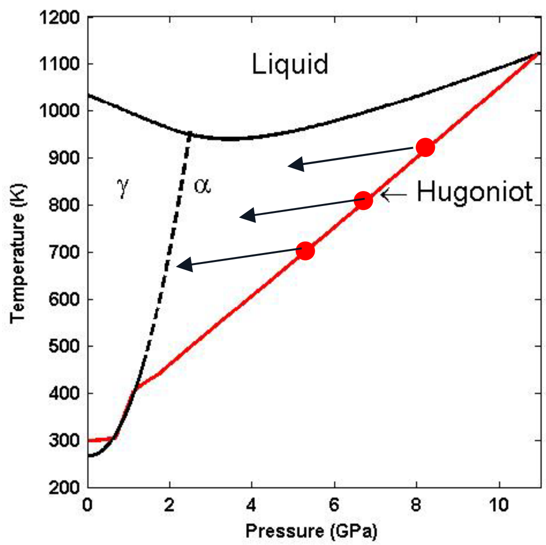


MPCI on IMPULSE used the RMI method to examine jet-formation following a shock-induced phase transition (Jensen, Cherne, Dimonte, Prime, etc.)

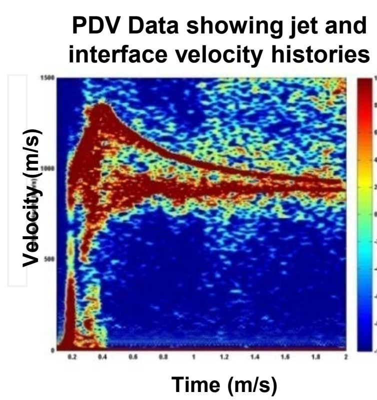
- RMI method based on the work by Dimonte et al used to infer yield stress for copper [PRL107 (2011) 264502]
- Experiments performed from 50-80 kbar from the solid α-phase up toward the melt transition

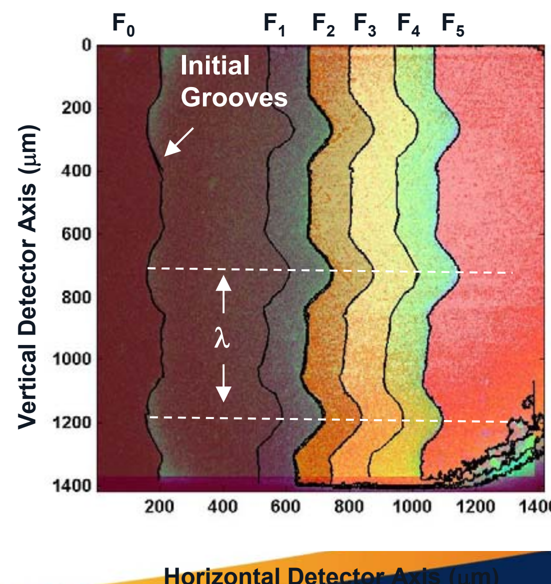


Phase Diagram For Ce (LANL MEOS)



PDV Data showing jet and interface velocity histories

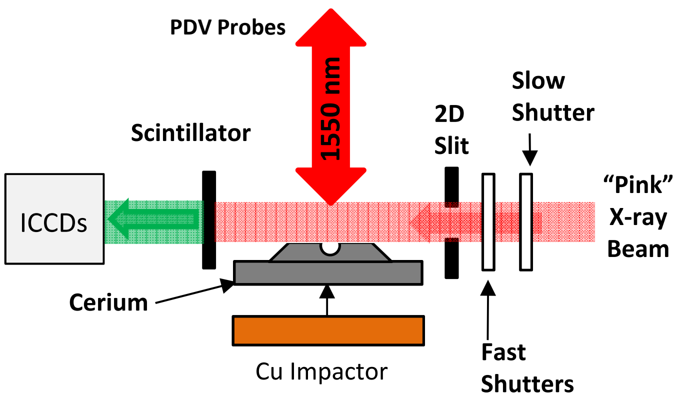




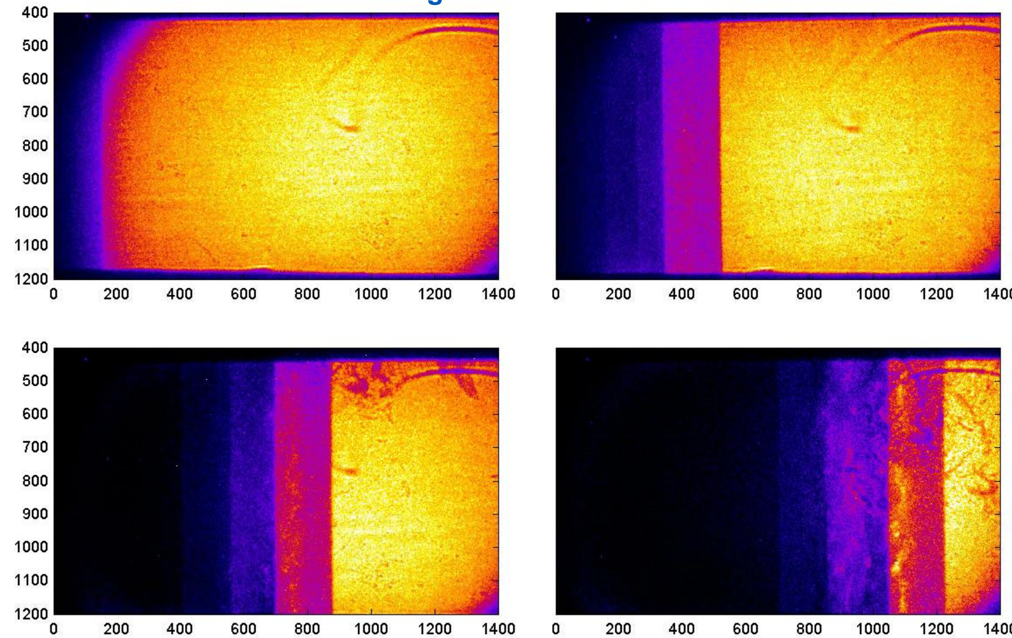
Ce RMI experiments reveal incipient jet breakup at the micron length scale

(Hammerberg, Preston, Cherne, et al.)

Experimental Configuration



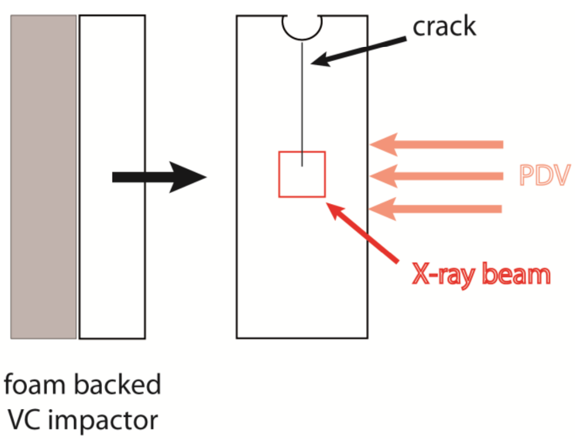
PCI images of Jet formation



- PCI used to examine jet evolution from a single groove to examine incipient breakup
- Data shows void growth/coalescence with micron resolution; data will be used to test available models
- Additional experiments planned for October run including larger grain samples

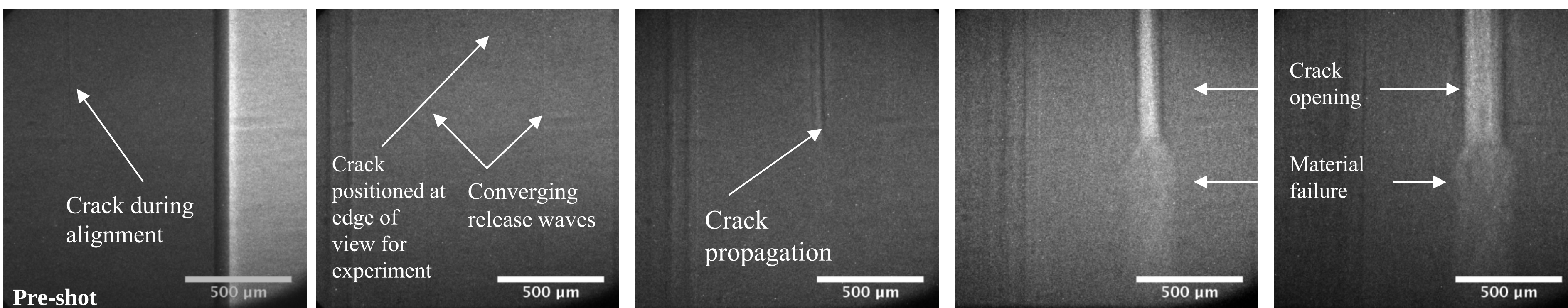
First in situ observation of crack dynamics and damage evolution observed using MPCI at IMPULSE (Ramos, Chang, Yeager, et al.)

Simplified geometry for dynamic stress intensity factor measurements in plane strain



- Multiple frame PCI has sufficient temporal, spatial, and density resolution for resolving physical and density interfaces and diffuse material failure during 1-D plane wave propagation
- Direct observation of release waves and heterogeneity behind the front
  - 80 ps X-ray exposure
  - 1-2 μm spatial resolution
  - $2.0\% \leq \Delta\rho/\rho_0 \leq 7.0\%$, $\rho_0 = 1.5$ g/cc
  - Demonstrates we can see wave fronts associated with structural transitions and resulting heterogeneity

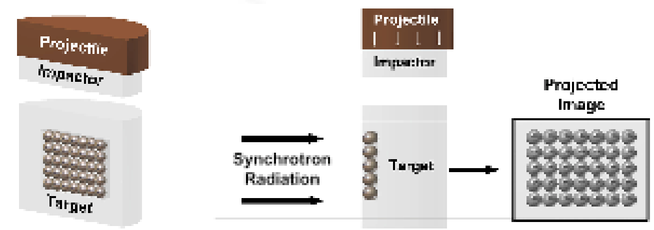
Crack propagation and material failure observed directly in vitreous carbon using MPCI

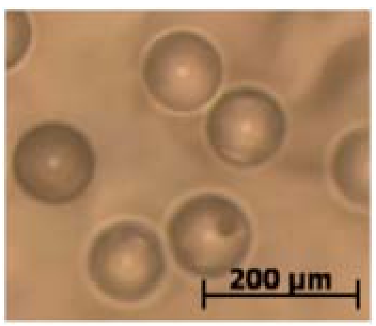


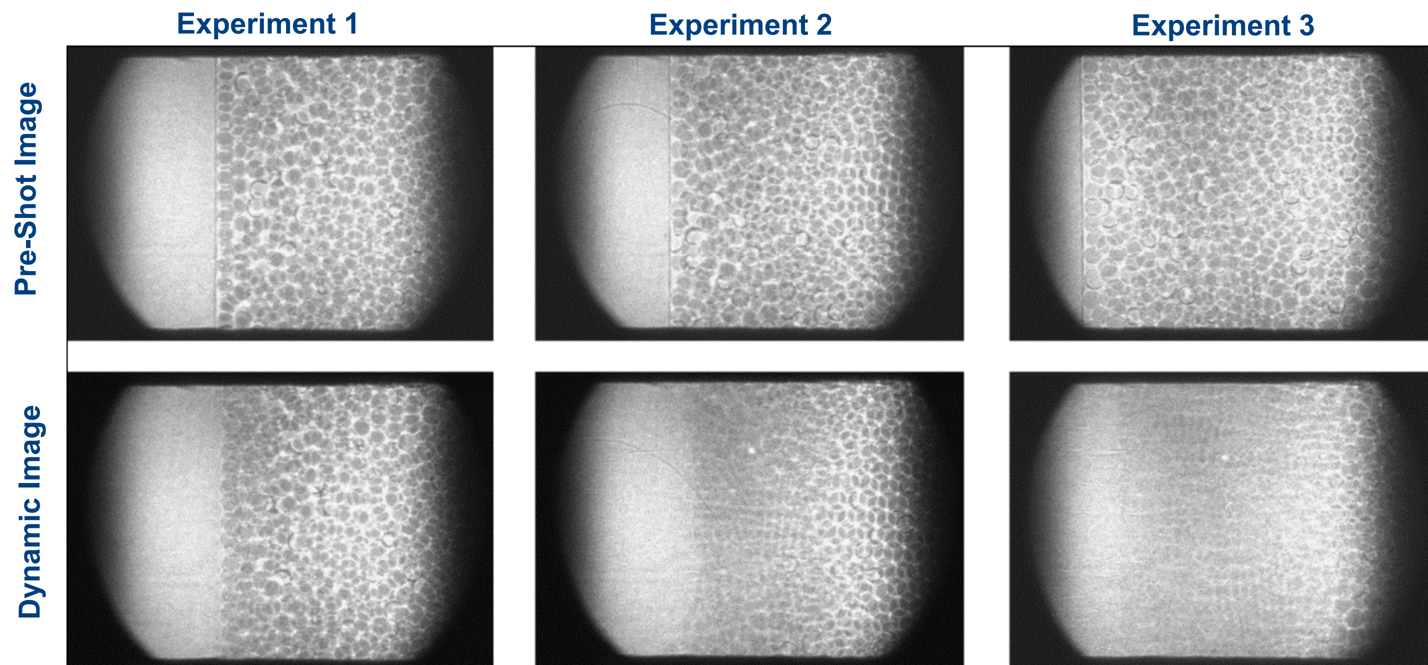
PCI captures progression of dynamic densification through an idealized system on boro-silicate glass spheres for real-time validation of compaction models (w/ D.A. Fredenburg)

As part of a larger effort to build physically based compaction models that incorporate particle-level deformation and fracture behavior for brittle materials, an idealized system of boro-silicate glass spheres is under investigation *(Fredenburg, Agnew Fellowship)*

Spheres are nominally 106 μm ± 6% in diameter







Impact Velocity ~750 m/s
150 ns delay between images

150 ns delay → **~300 ns delay**