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Title: The Little Things that Matter:Detonation Manipulation through Sub-Critical Diameter Structure in High Explosives.

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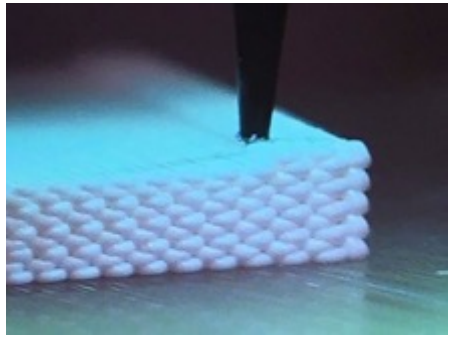
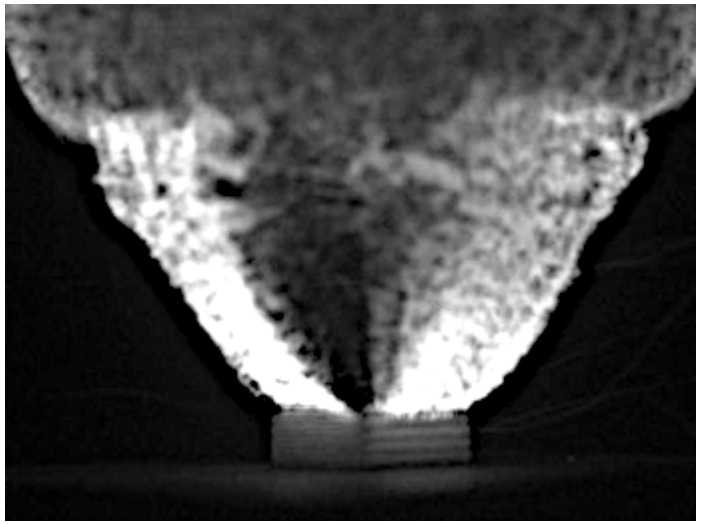
The Little Things that Matter:

Detonation Manipulation through Sub-Critical Diameter Structure in High Explosives.

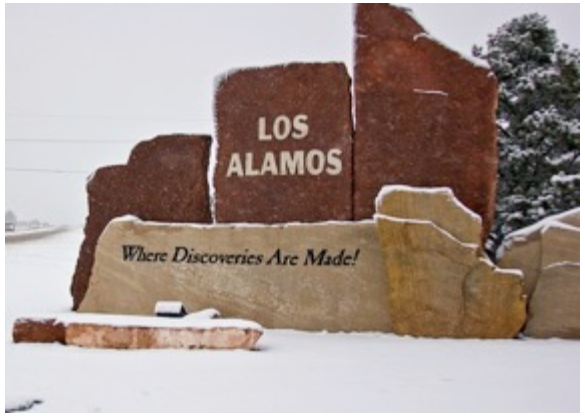




Alexander Mueller

Texas Tech University

March 28th, 2019.



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discover LDRD

NNSA National Nuclear Security Administration

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Outline

- **Introduction**
  - Team.
  - Methods.
  - Why AM?
- **Results**
  - Structurally Modified Shock Interaction .
  - Structure Length Scales Available.
  - Anisotropic Detonation – Prediction and Measurement.
  - Observation of Mechanism.
  - Manifestation in Mushroom Tests.
- **Summary**

Participants

- **Alex Mueller (PI)**
  - Andrew Schmalzer
  - Michelle Espy
  - Joe Lichthardt
  - Markus Hehlen
  - Elizabeth Francois
  - Renita Walzel (GS)

Instrumentation and Characterization

- **Bryce Tappan (co-PI)**
  - Ruillian Wu
  - Virginia Manner
  - Phil Leonard
  - Thuy-Ai Nguyen (PD)

Synthesis and formulation

- **Dana Dattelbaum (co-PI)**
  - Patrick Bowden
  - Larry Hill

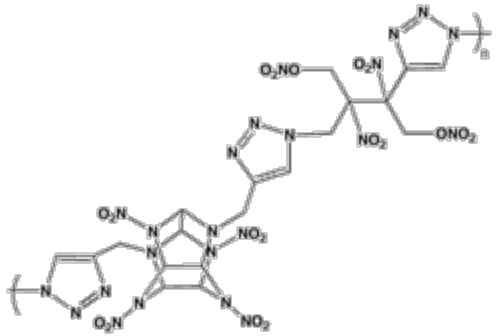
HE Physics

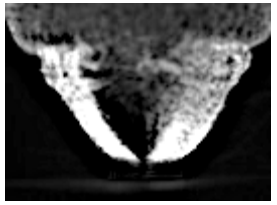
- **Brad Clements (co-PI)**
  - Ralph Menikoff
  - Axinte Ionita

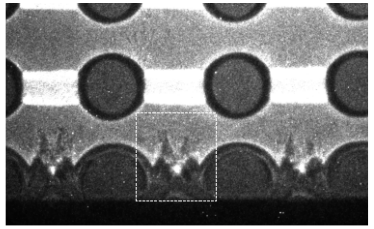
Modeling

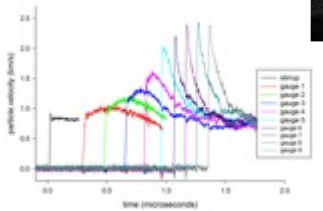
Project Overview

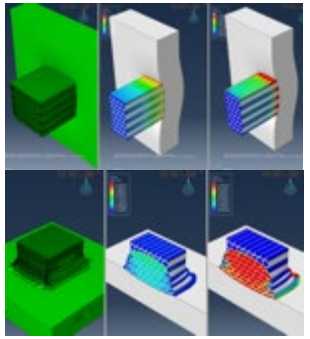
Synthesis	Fabrication & Characterization	In situ Dynamics	Propagation

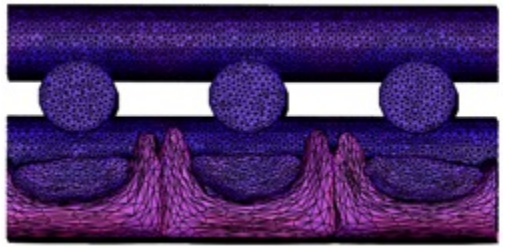


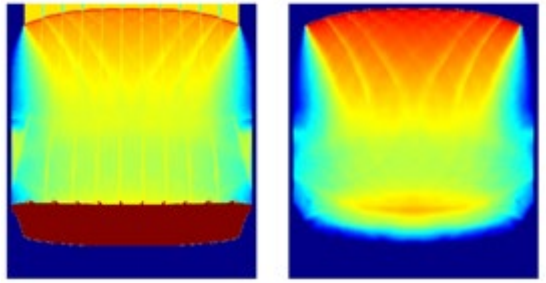








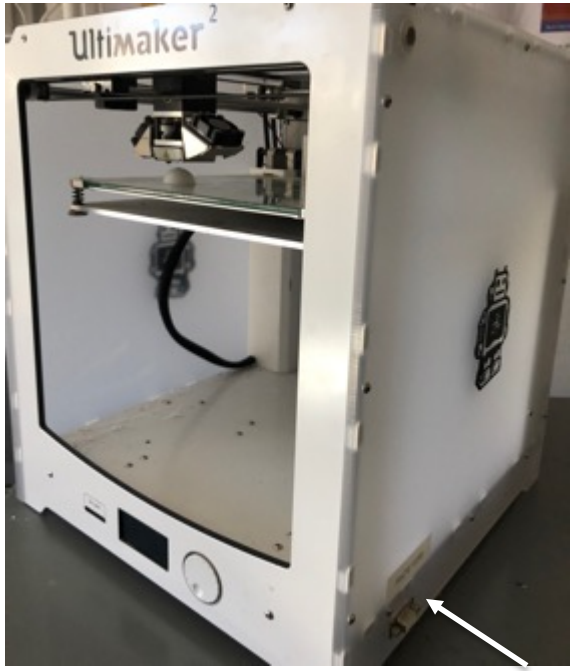




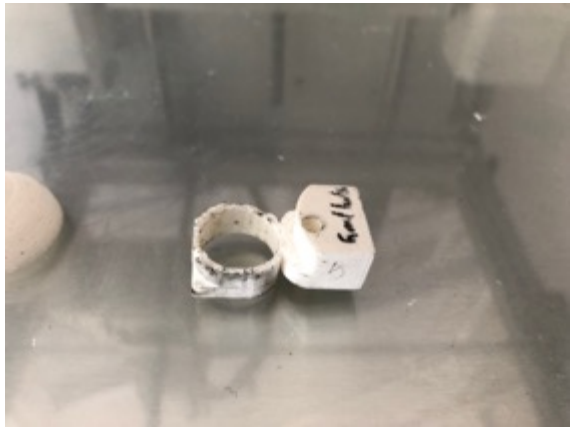
Model construction	Structure design Finite element analysis (FEA)	reactive burn modeling

Humble Origins

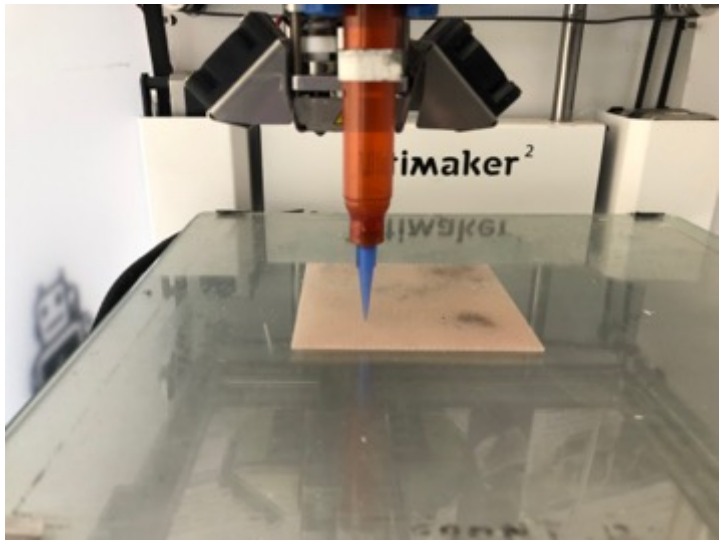
- **Ultimaker 2 modifications:**
  - True to Self-Replicating mantra of hobbyist AM community
  - Hobby machines = Arduino or Rasberry pi controllers. =Hackable!



DB15 connector to interface to Arduino board.

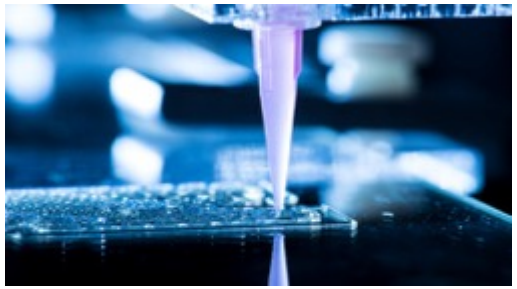


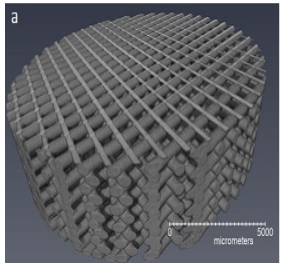
Syringe holder printed using Ultimaker 2.

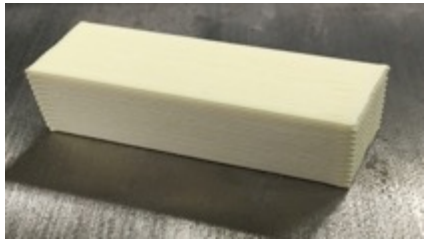


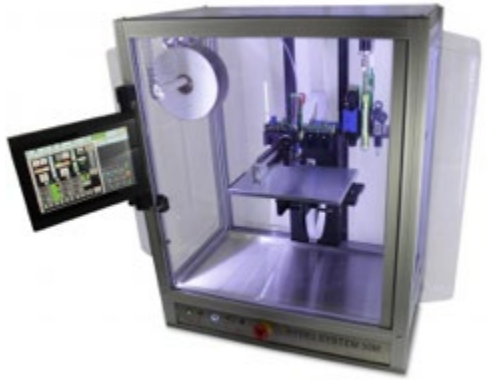
Silicone lattice printed using modified Ultimaker 2.

Concept Progression









Silicone lattice printed using ~$2000 in equipment and materials.

→

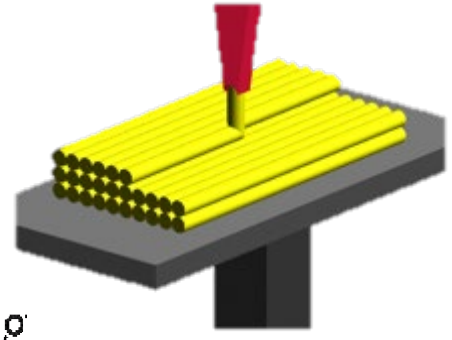
Generates interest in developing methods and assessing the safety of AMHE. ($5k instrument)

→

Leads to $5M program to study structure in HE.

AM Methods that touch on our Project

- **Extrusion methods:**
  - DIW: AMX 7001: Main experimental body of work.
    - HMX based @ 70 wt%, allowing use of down to 400 µm nozzle.
    - Introduction of UV Curing functionality immediate setting yielded very precise shape control in part development.
    - Fast UV cure, allowed thinning the binder system – dropping viscosity.
    - Pneumatic extrusion.
  - FDM: AMX 7002.
    - Direct Displacement
    - Thermal extrusion.



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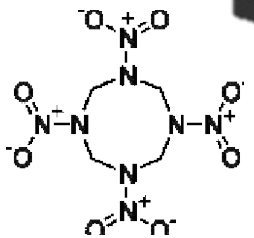
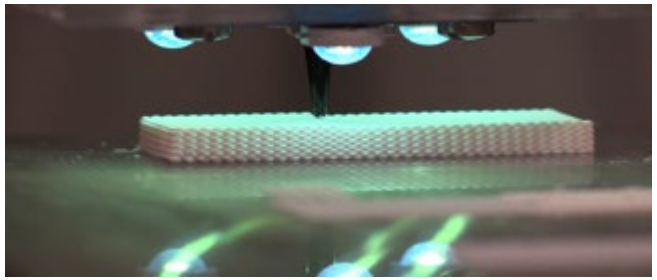
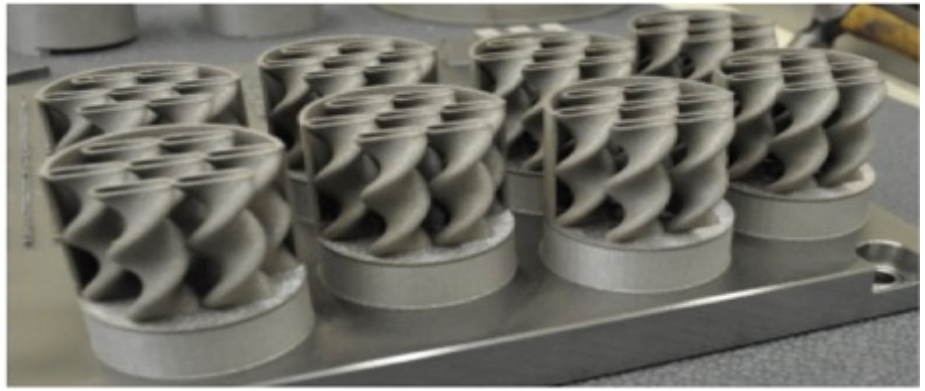
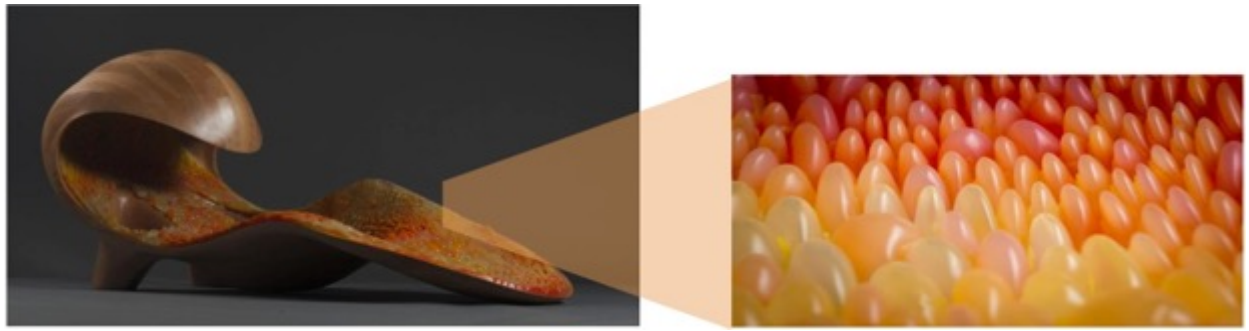




New Functionality Through AM

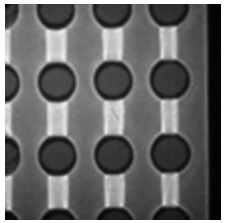
- **AM allows the fabrication of products with controlled internal structure, enabling:**
  - High Strength to weight ratios.
  - Tuned COG (mass mocks).
  - Superior heat transfer characteristics.
  - Tunable acoustic properties.
  - Designed mechanical properties.
  - Designed failure mode.
- **As voxel resolution improves, so will the possibilities:**
  - Designed thermal transfer paths.
  - Frequency transmission / isolation.



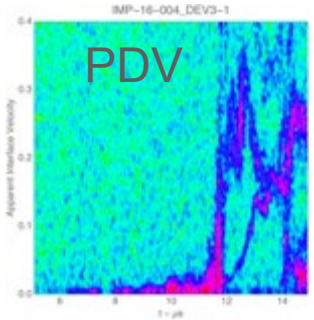


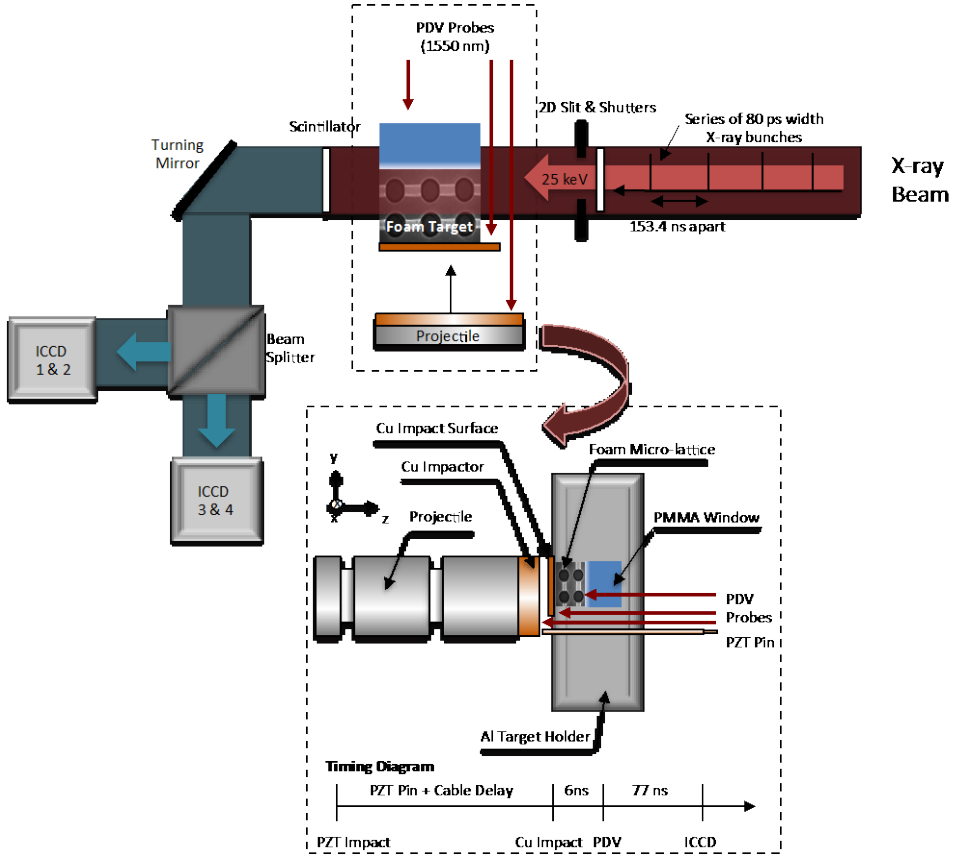
IMPULSE / DCS Experiment

The Dynamic Compression Sector (DCS) is a DOE/NNSA sponsored facility dedicated to dynamic compression experiments using X-rays

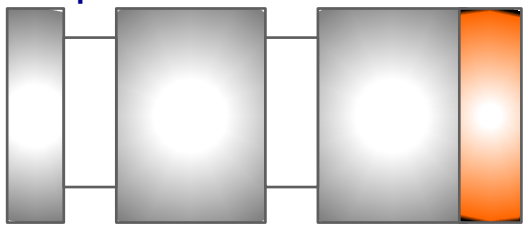


U_s U_p - PCI

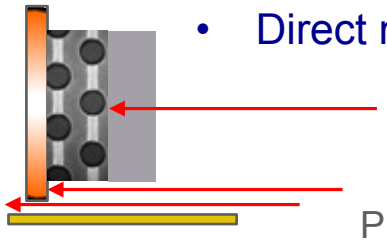




Experimental detail



Cu flyer



- Direct measurement of U_s, u_p

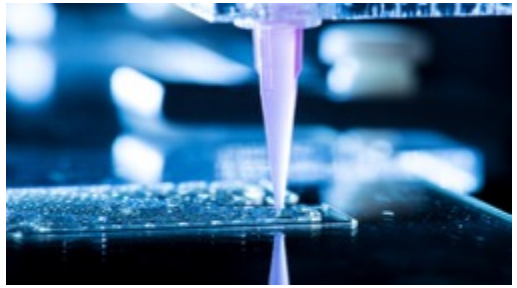
PDV 3 (foam/PMMA)

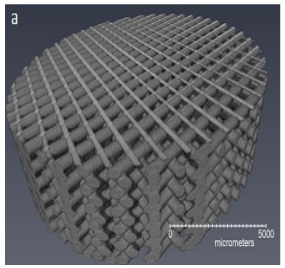
PDV 2 (Cu/PMMA)

PDV 1 (projectile)

Pulse frequency	Pulse duration	8 frames/shot	Areal density resolution	Spatial resolution	Temporal resolution	HE mass limit
154 ns	80 ps	2 images/camera with 4 cameras	~ 20%	2-4 micron	70-100 ns	3 g (soon 15g)

Shock wave modulation through microstructure

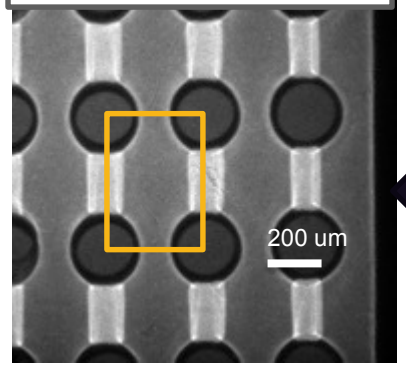




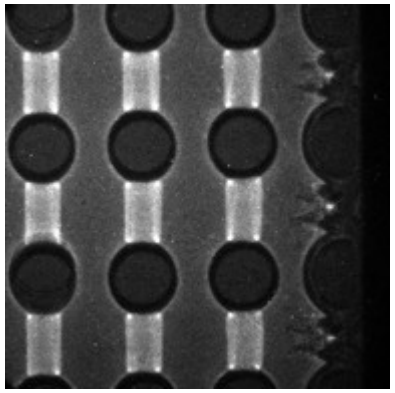
X-ray computed tomography

- Direct Ink Write (DIW)
- Dow Corning SE1700 polydimethylsiloxane
- 11 layers with filament spacing of ~440 μm

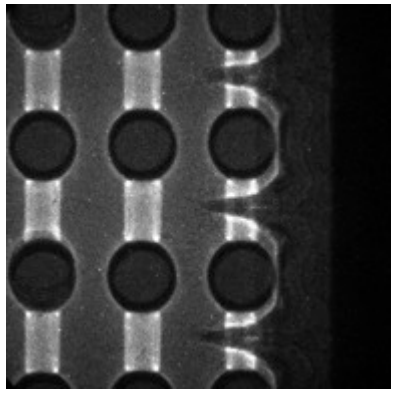
Simple Cubic



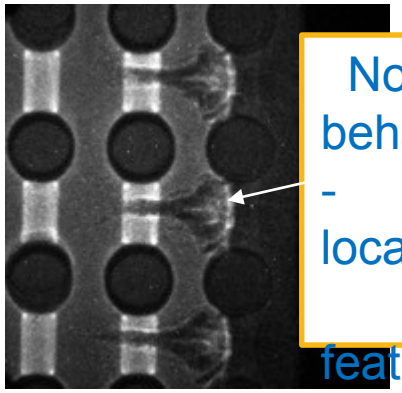
static



4.815 ❍s



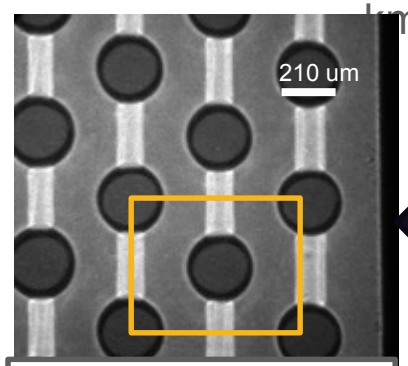
4.967 ❍s



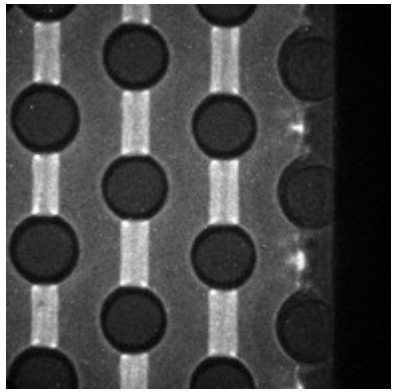
5.131 ❍s

Novel behavior - localized features form

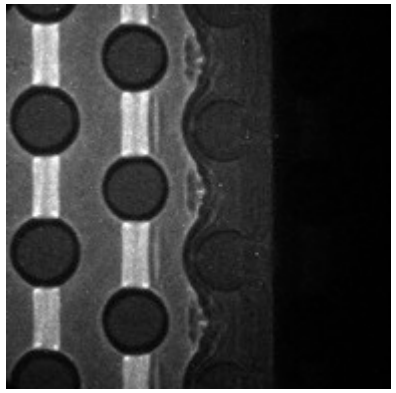
0.720 km/s



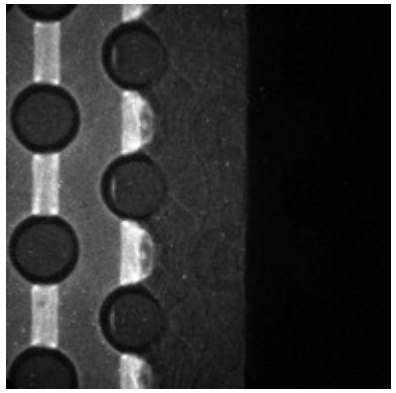
Face-centered Tetragonal



8.295 ❍s



8.458 ❍s

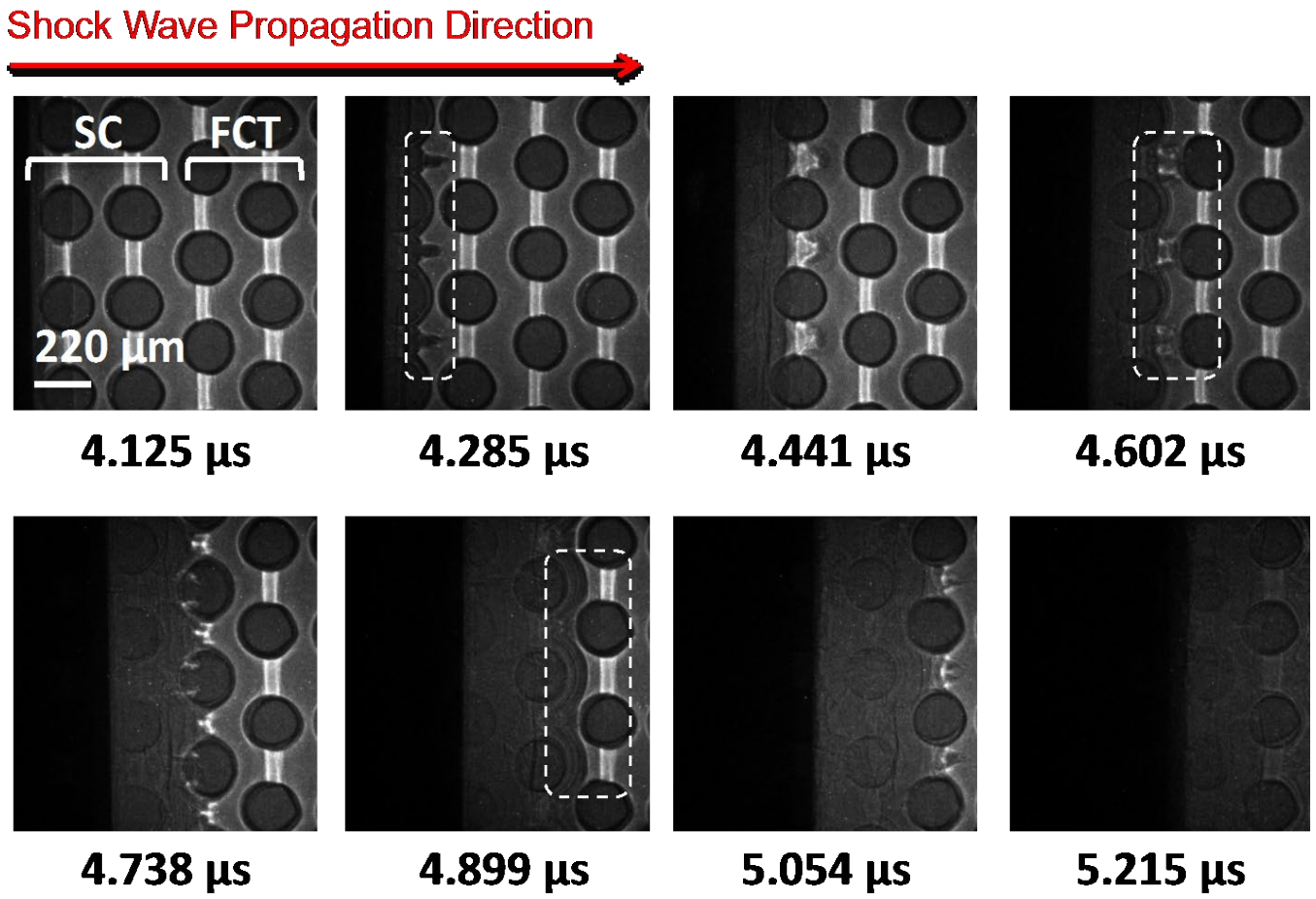


8.765 ❍s

Observed jetting is strongly dependent on initial shock strength and AM structure

Grading Shock Flow through Structure.

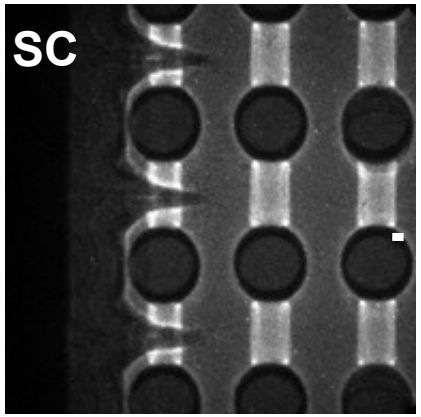
Take advantage of the flexibility that AM offers!

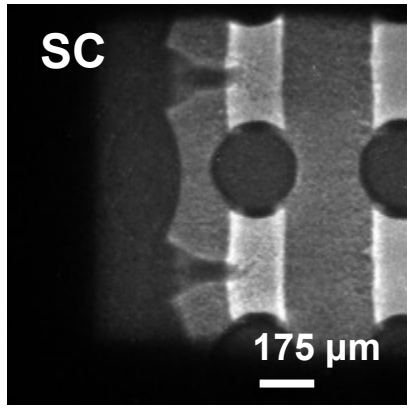


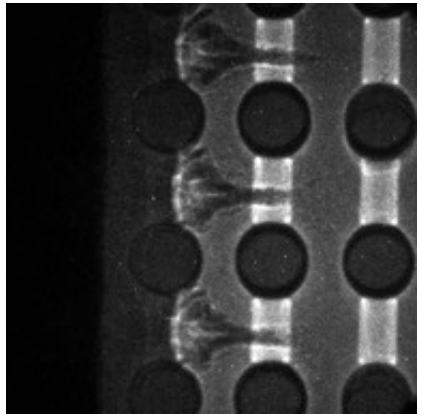
Shock Interaction in AMX Structures.

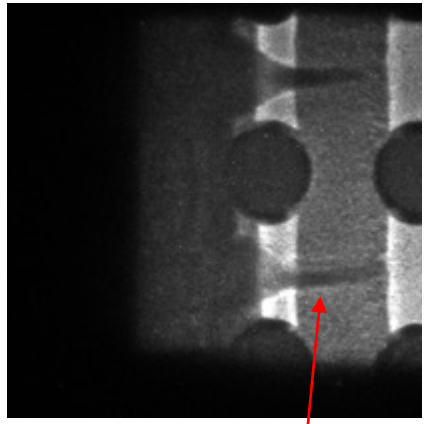
SE1700

AMX-HE

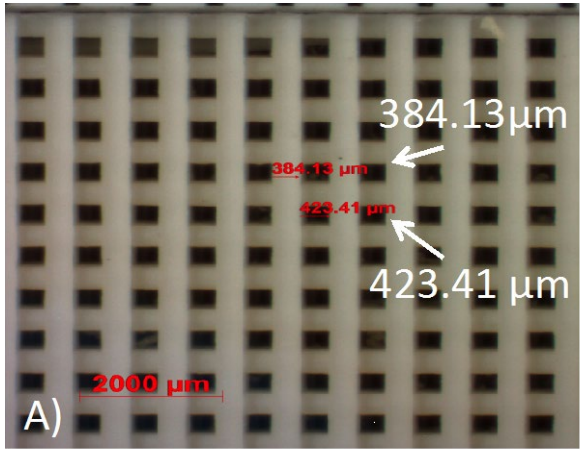


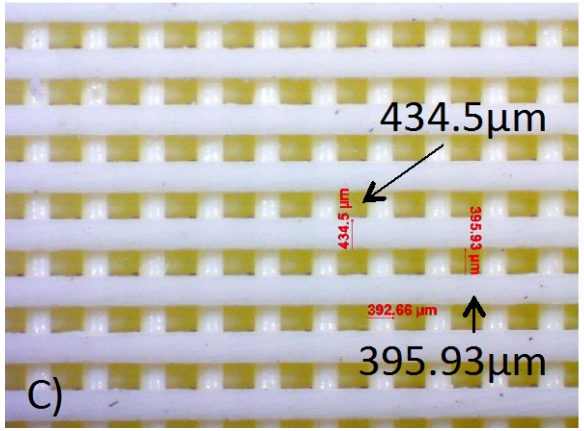


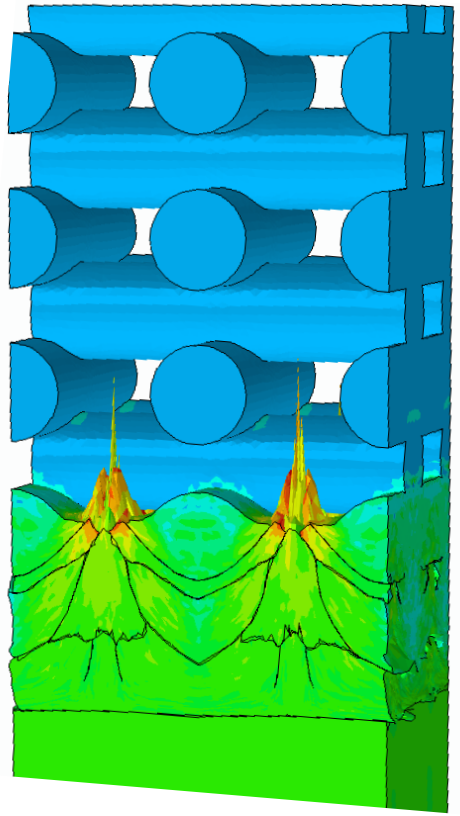




Observed jetting AMX structure



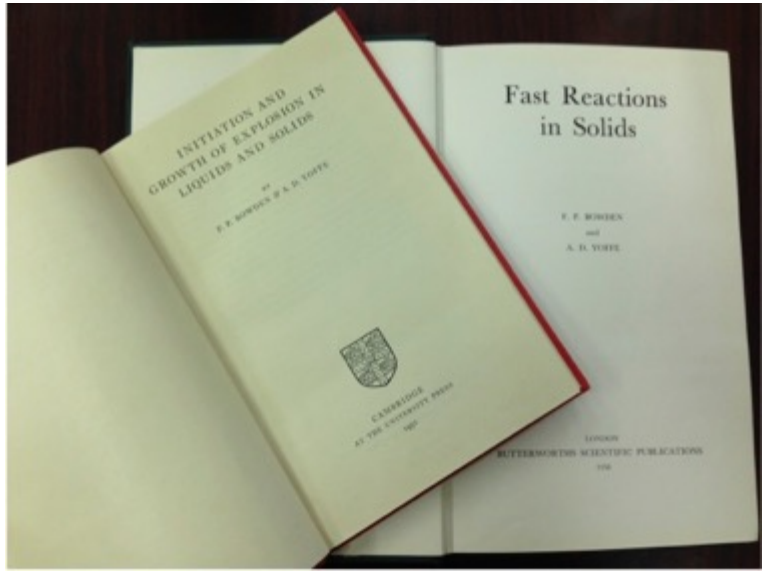


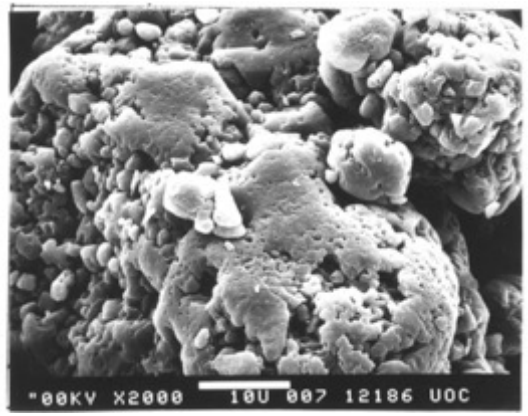


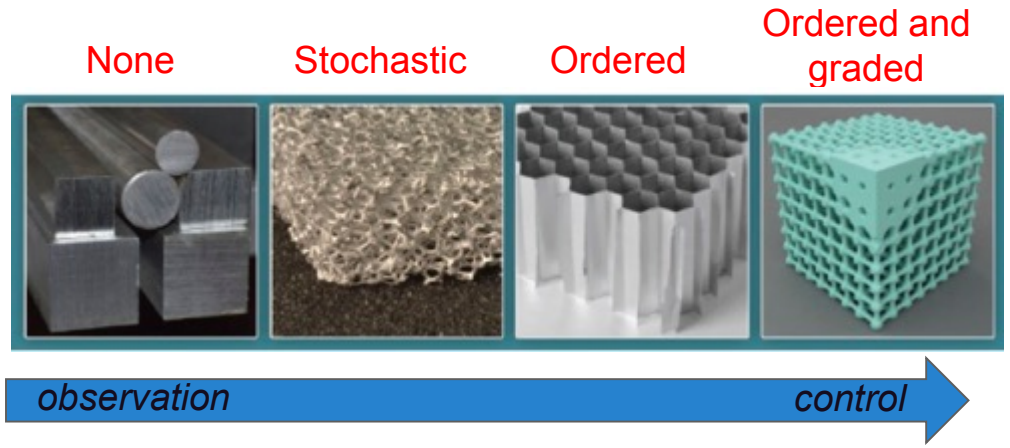
LANL HE mechanical model (called MATCH) finds jet formation in high binder content explosives but not in brittle explosives.

Role of Structure in HE

- **Shock initiation and reactive burn in high explosives (HE) are strongly controlled by structural defects at the mesoscale (porosity, grain boundaries, defects).**
  - "Hotspots".
  - Well known since pre-WWI.
- **Current fabrication methods for HE do not allow for the systematic introduction of structure.**
  - Difficult to study effects of features.
    - Elegant experiments have developed understanding of interaction lengths.
      - Engelke, Sheffield, LANL.
      - Dattelbaum et al. ; 2010.
  - *Impossible to exploit or tailor.*

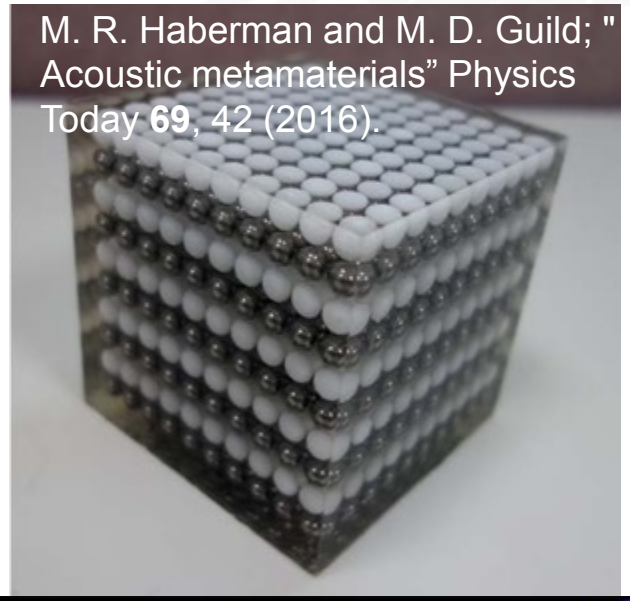




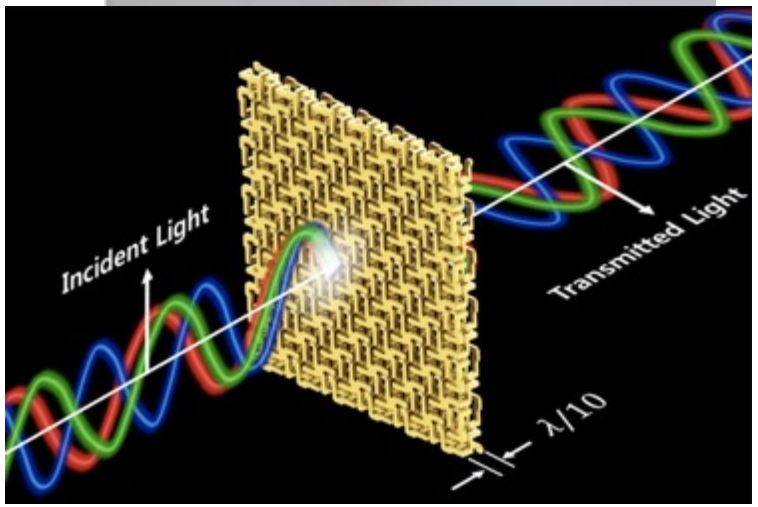


Scaled Analogies “dopants” vs. “metamaterials”

- **Hotspots are caused by voids or grit at the sub to 10’s of µm scale.**
  - Nearest neighbor interactions cause growth to detonation.
  - Relative Size and Function analogy: Dopants in SC.
- **Metamaterials: Manipulation of waves using sub-wavelength structure.**
  - Manipulation of wave interactions through index and absorption changes at periodicities of wavelengths.
    - Waveguides, evanescent wave interactions.
    - Optical: 100’s of nm, Acoustic : mm’s.
    - HE: Reaction Zone Length scales: 10’s to 100’s of µm.

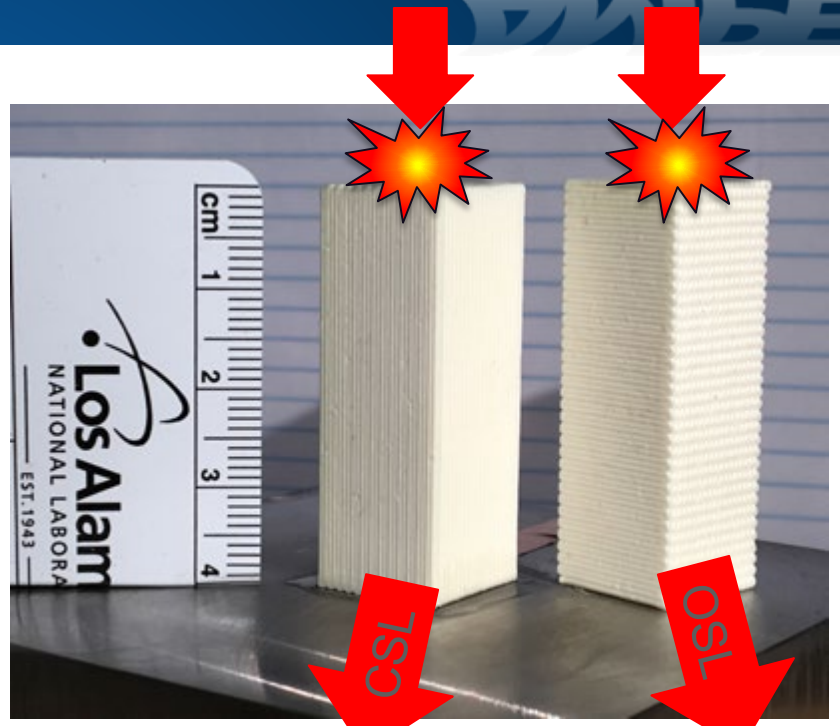


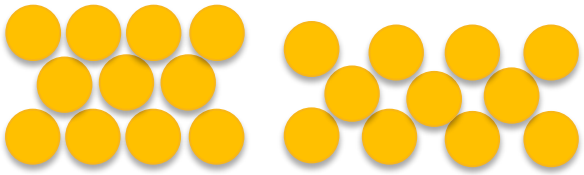
M. R. Haberman and M. D. Guild; " Acoustic metamaterials” Physics Today **69**, 42 (2016).

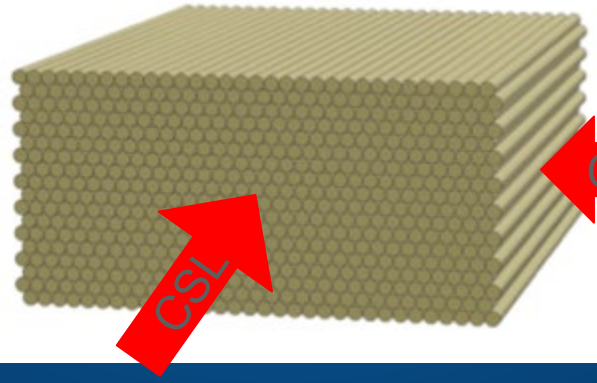


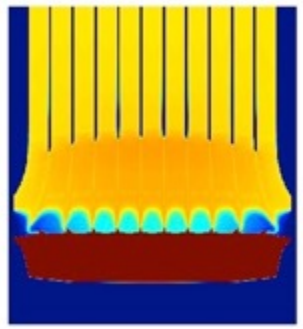
Structural Anisotropy.

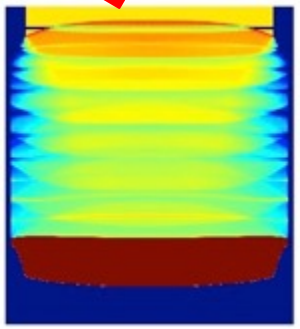
- **Structurally Anisotropic HE samples allows for directionally selective propagation of preceding shock wave.**
  - "Stacked Logs" = hcp arrays with varying r/a spacing.
    - Orthogonal (OSL) and Co-linear (CSL) directions.
    - r/a spacing allows for controlled introduction of gaps up to filament diameter.
  - SURF model includes shock desensitization parameters.
    - Sub mm-printing scales allows for continuum model.
    - Dimensions scaled to show effects in 9501.
    - Informed by 9501 EOS- true calibration recently achieved.
  - Predicted anisotropic detonation behavior.







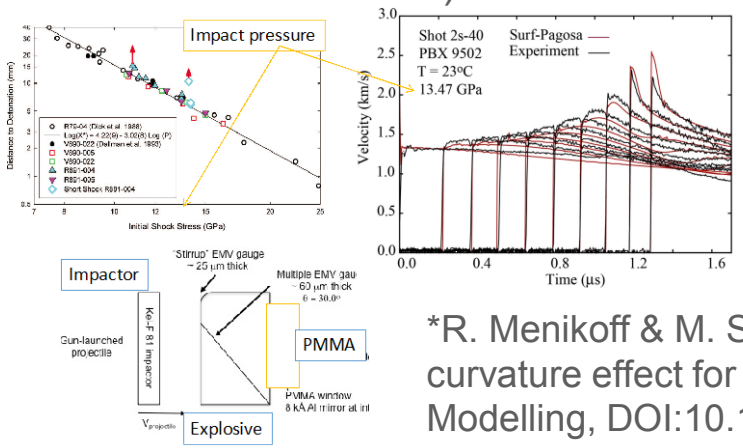




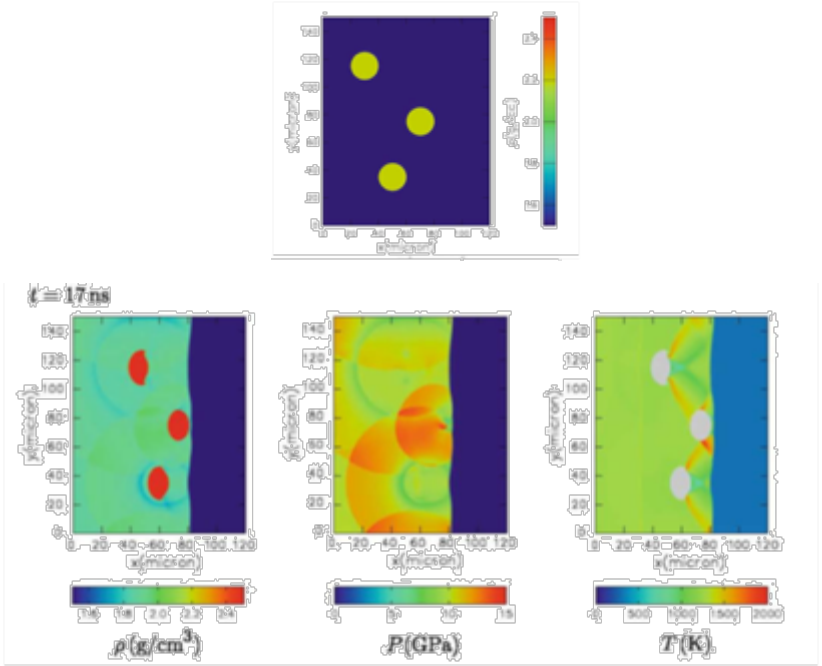
SURF- Hot Spot Based Model Captures Structured HE Behavior.

SURF: LANL reactive burn model developed by Menikoff and Shaw.

- Model is a function of the scaled reactive variable (s) and lead shock strength (P_s).
  - s=function of hot spot density.
  - d/dt s = f(P_s)
- Understanding how energy localization couples to burn provides explanation of interactions.
- SURF is suitable for high velocity impact, where Shock-to-Detonation (SDT) is likely.
  - captures the details of the build up to detonation, not just the pop plot.
- SURF captures *short shocks, shock desensitization* and *dead zones.* (This is critical for AM simulations!)

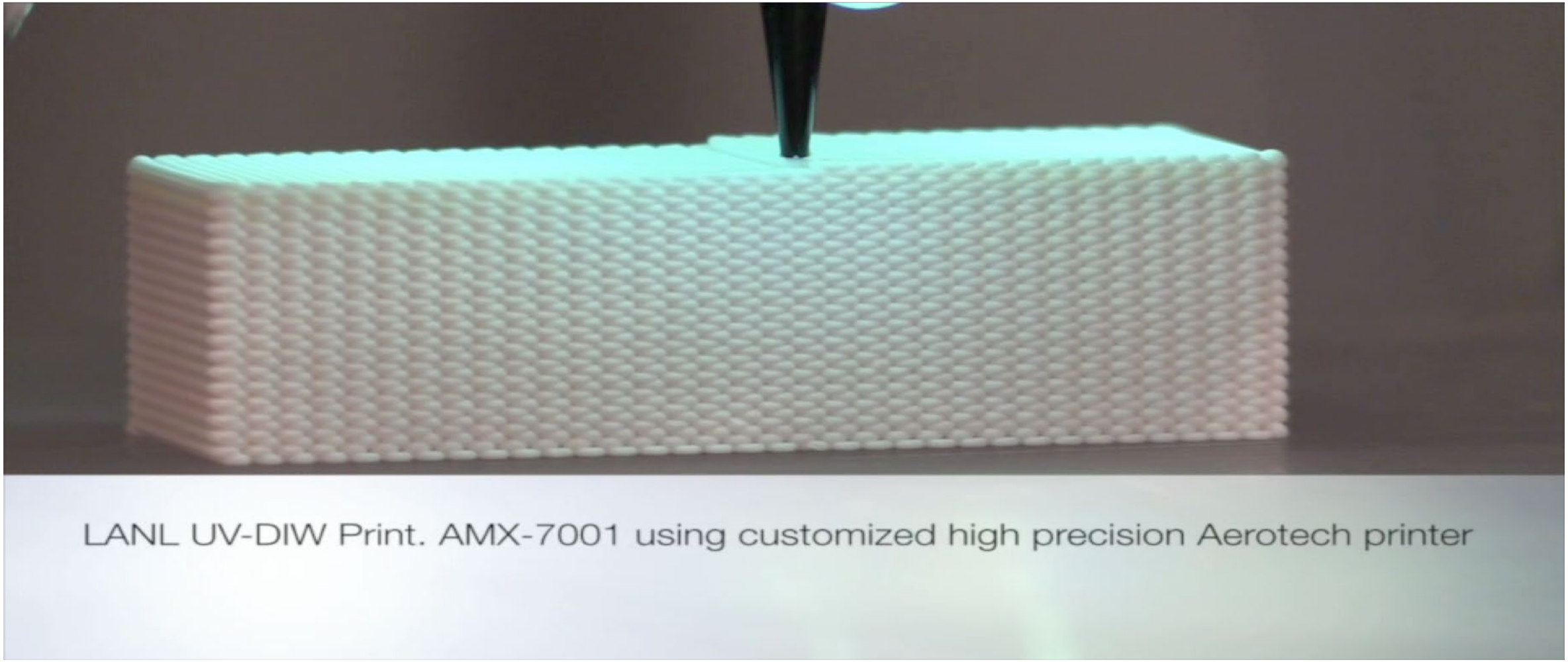


*R. Menikoff & M. S. Shaw (2012): The SURF model and the curvature effect for PBX 9502, Combustion Theory and Modelling, DOI:10.1080/13647830.2012.713994



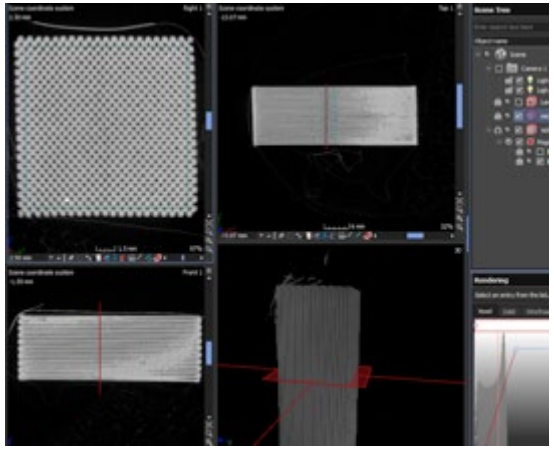
XRAGE simulations of 20 um features shown above at t=0, are theorized to result in shock reflections from the impurities, resulting in "hot spots" and thermal localization from which chemistry initiates.

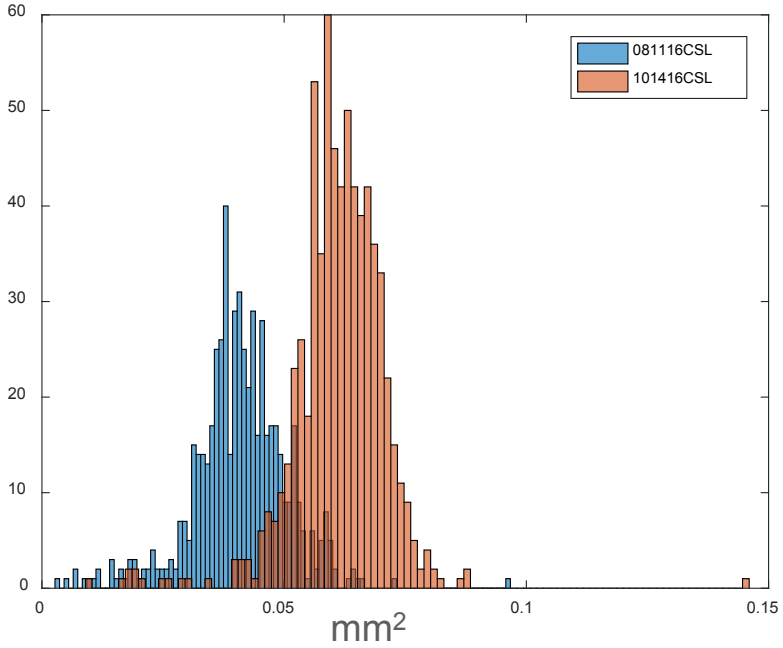
LANL Precision Printing with UV-DIW feedstock.



High Explosive AM instrumentation Progress

- **DIW using new UV-DIW feedstock AMX 7001 produced series of anisotropic samples.**
  - Allows builds of tall parts while avoiding their collapse under material weight.
  - Highly crystal loaded extrudable formulation.
- **Fabrication only possible by AM methods.**
  - Over 3000 elements per part.
    - Every part analyzed by X-ray computed tomography.
  - Aerotech custom high precision motion stage with in-house constructed extruder.

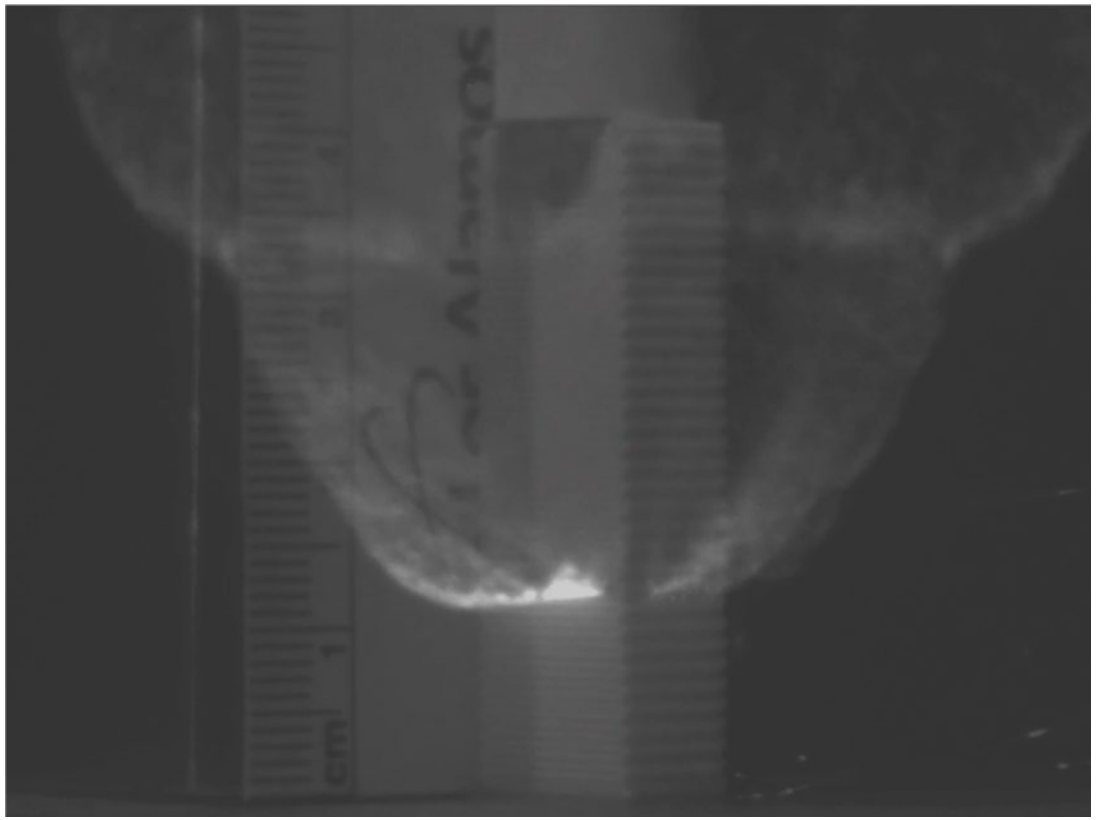


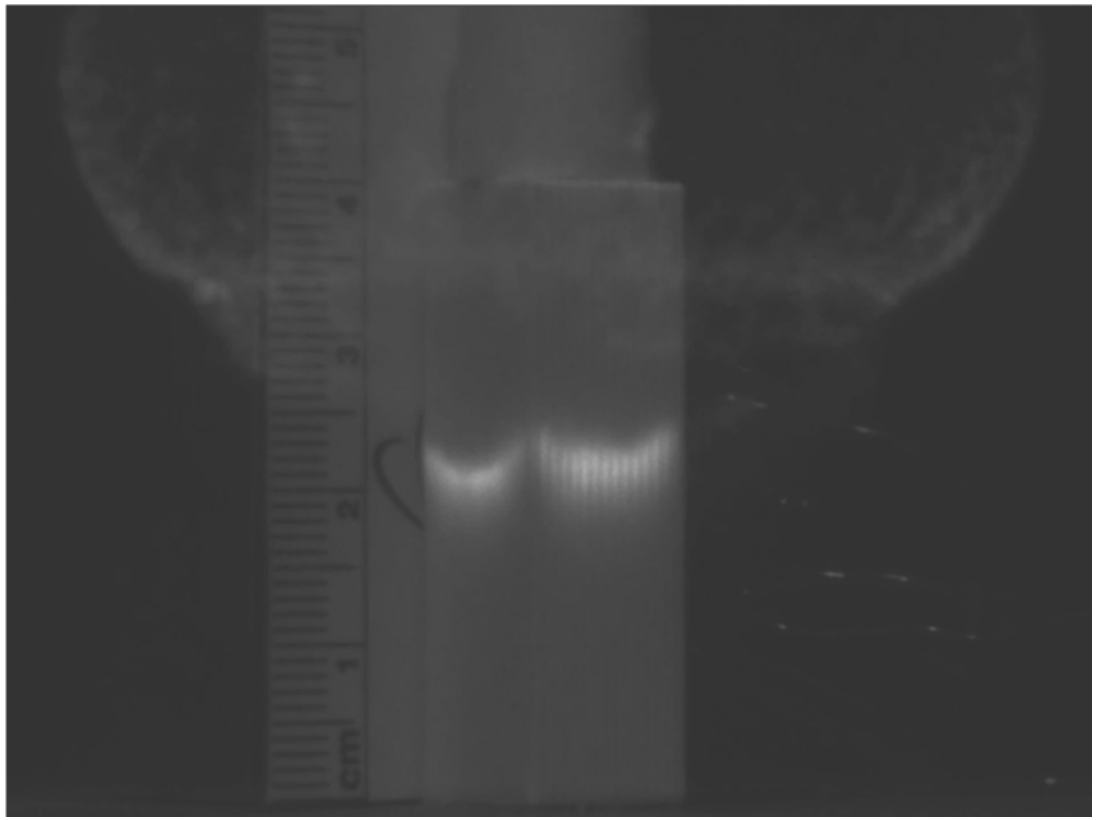


Distribution of the projected area of voids in a 2D slice of the x-ray CT.

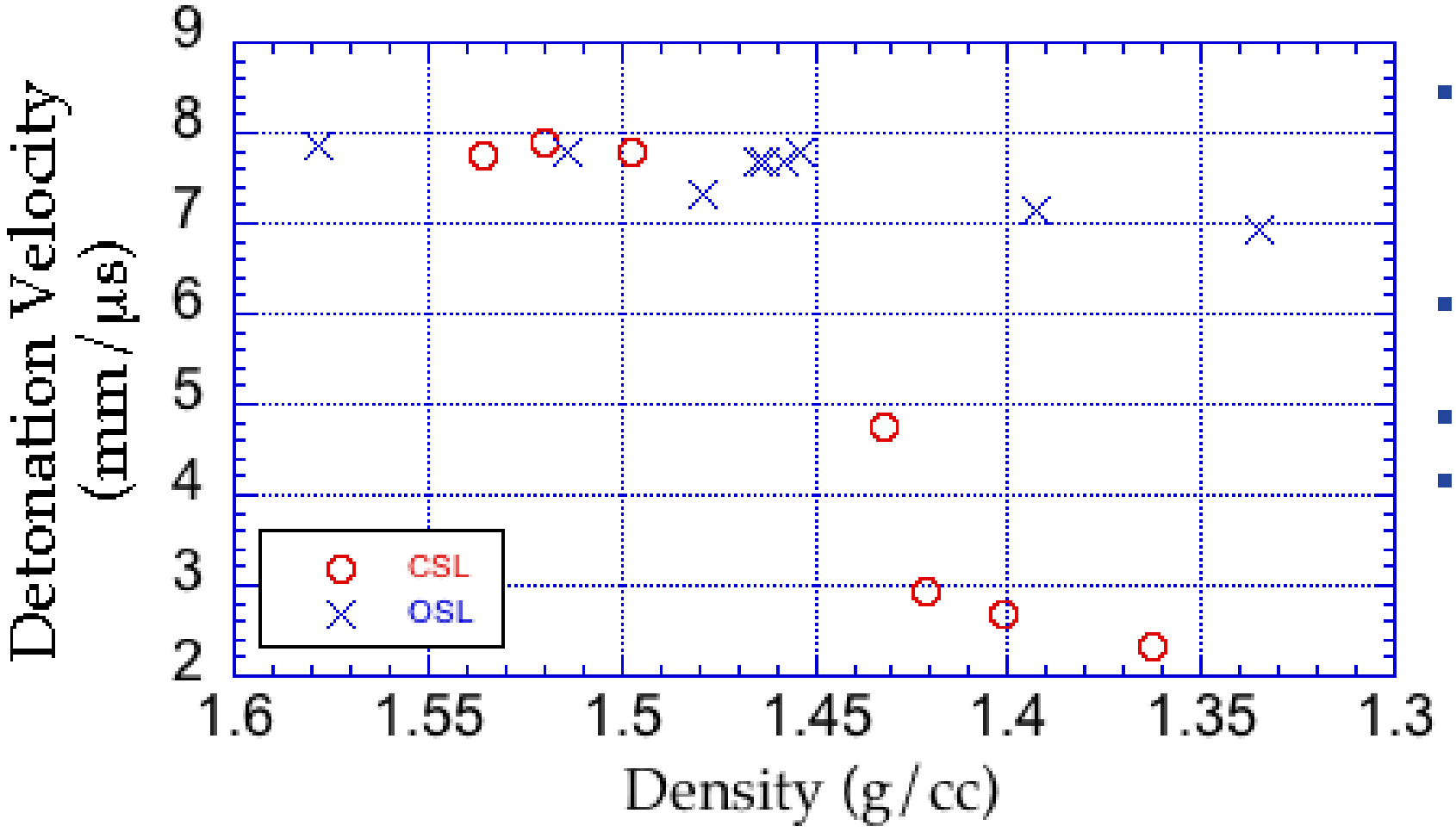
First Explosive Metamaterial

- Directional control of detonation propagation by controlled structure.



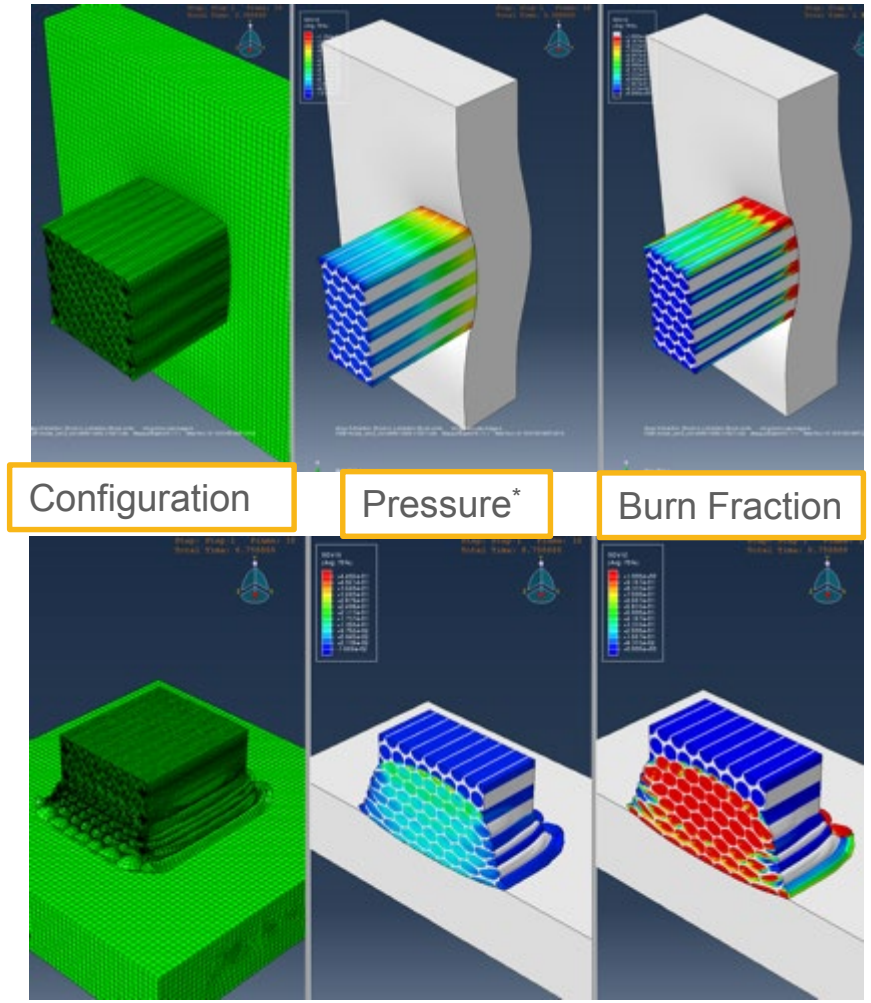


Divergent Behavior Modified Through Structure.



- As the void area. increases, detonation can continue through OSL parts, but not through CSL parts(!).
- AM does not significantly detract from detonation velocity.
- TMD of the Material is ~1.665g/cc.
- Plot is in Density, Controlled through r/a spacing.

Theoretical confirmation of directional detonation using AM.



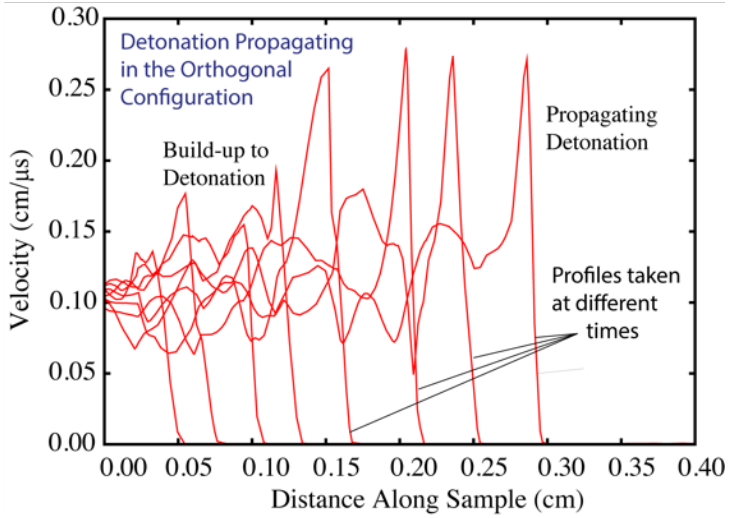
* Pressure scale offset = x 0.8

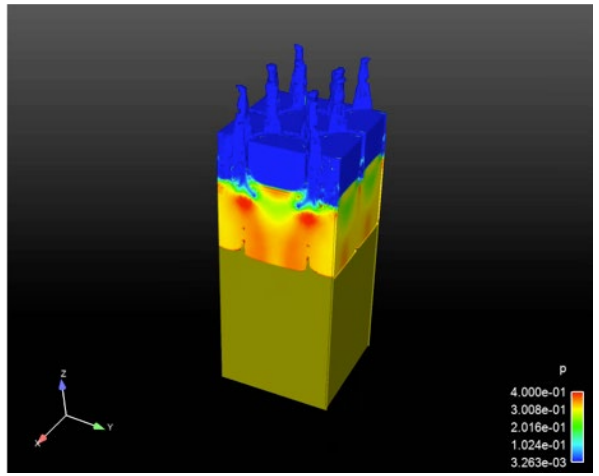
Co-linear stack

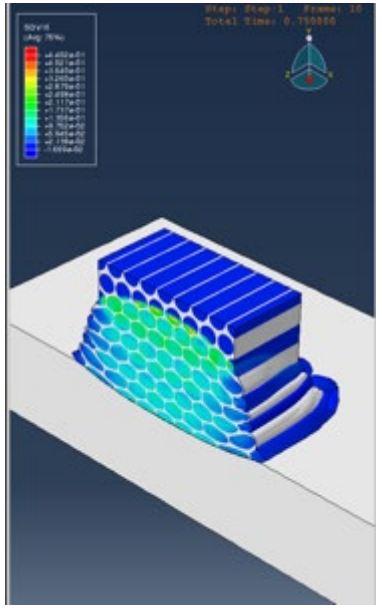
(extinguishing)

Orthogonal stack

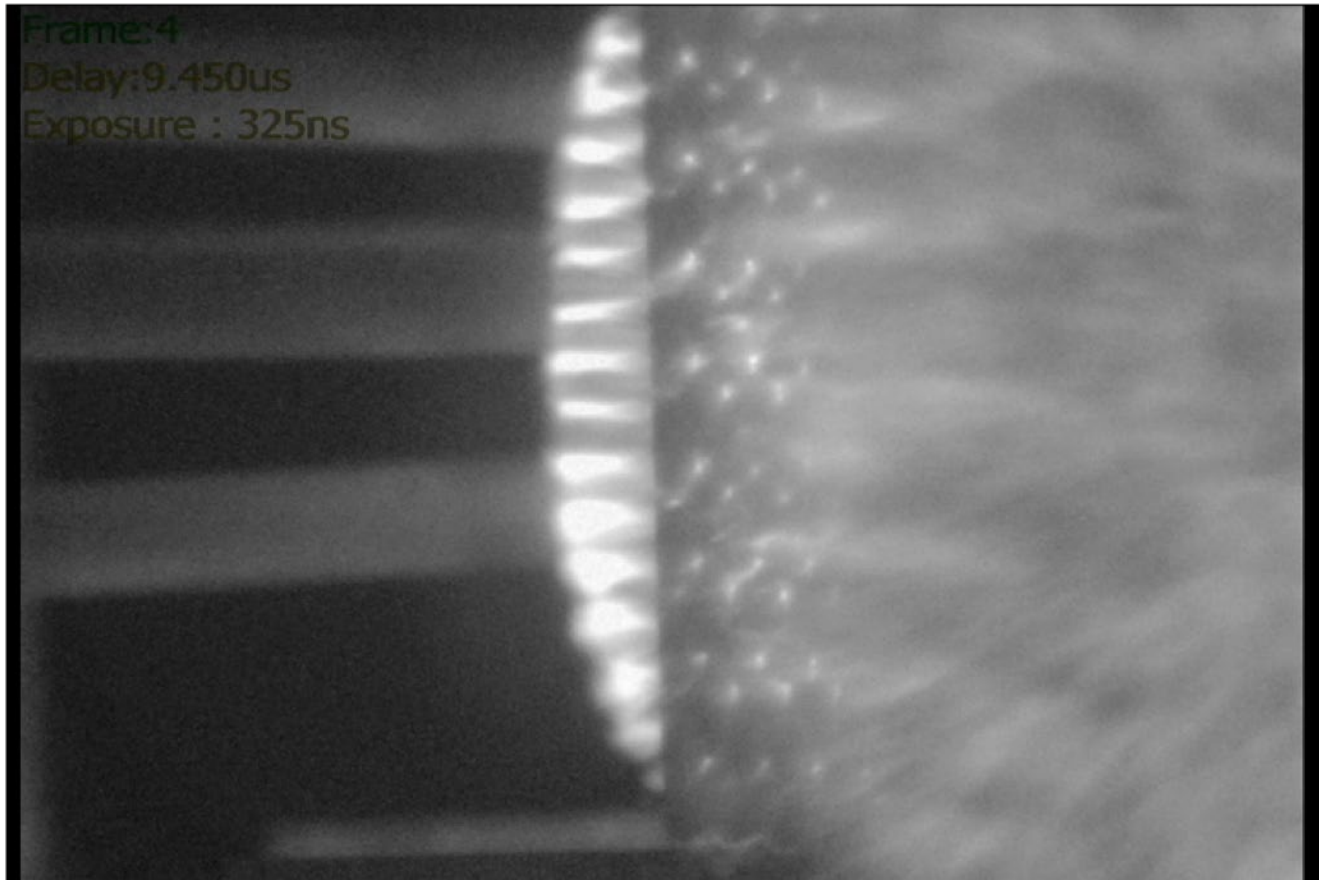
(propagating detonation)

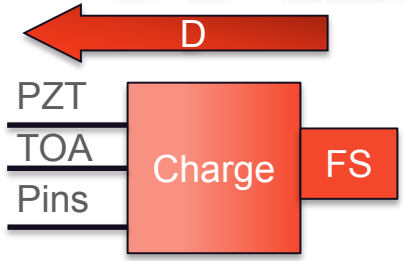


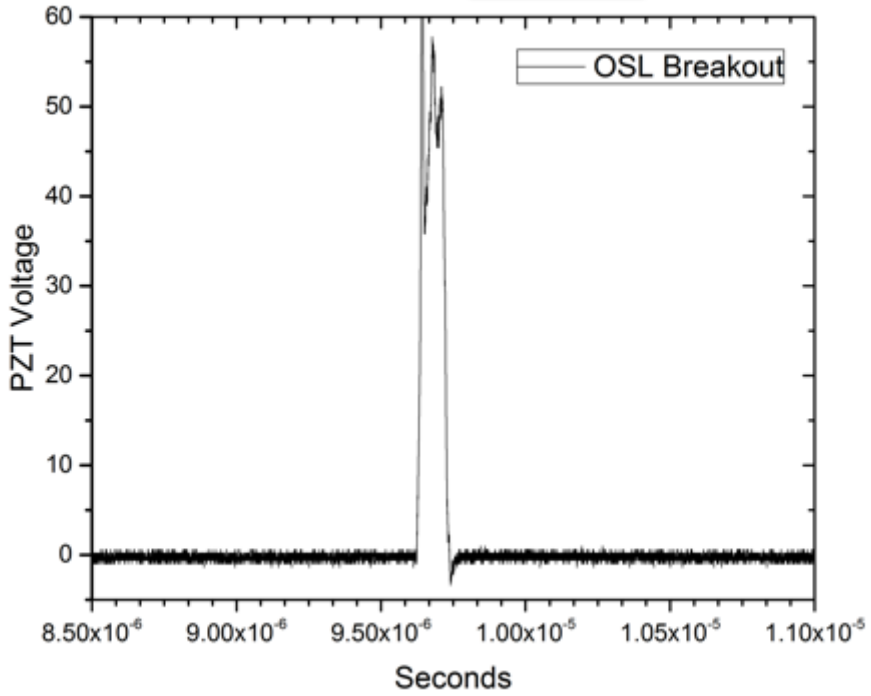




OSL Breakout

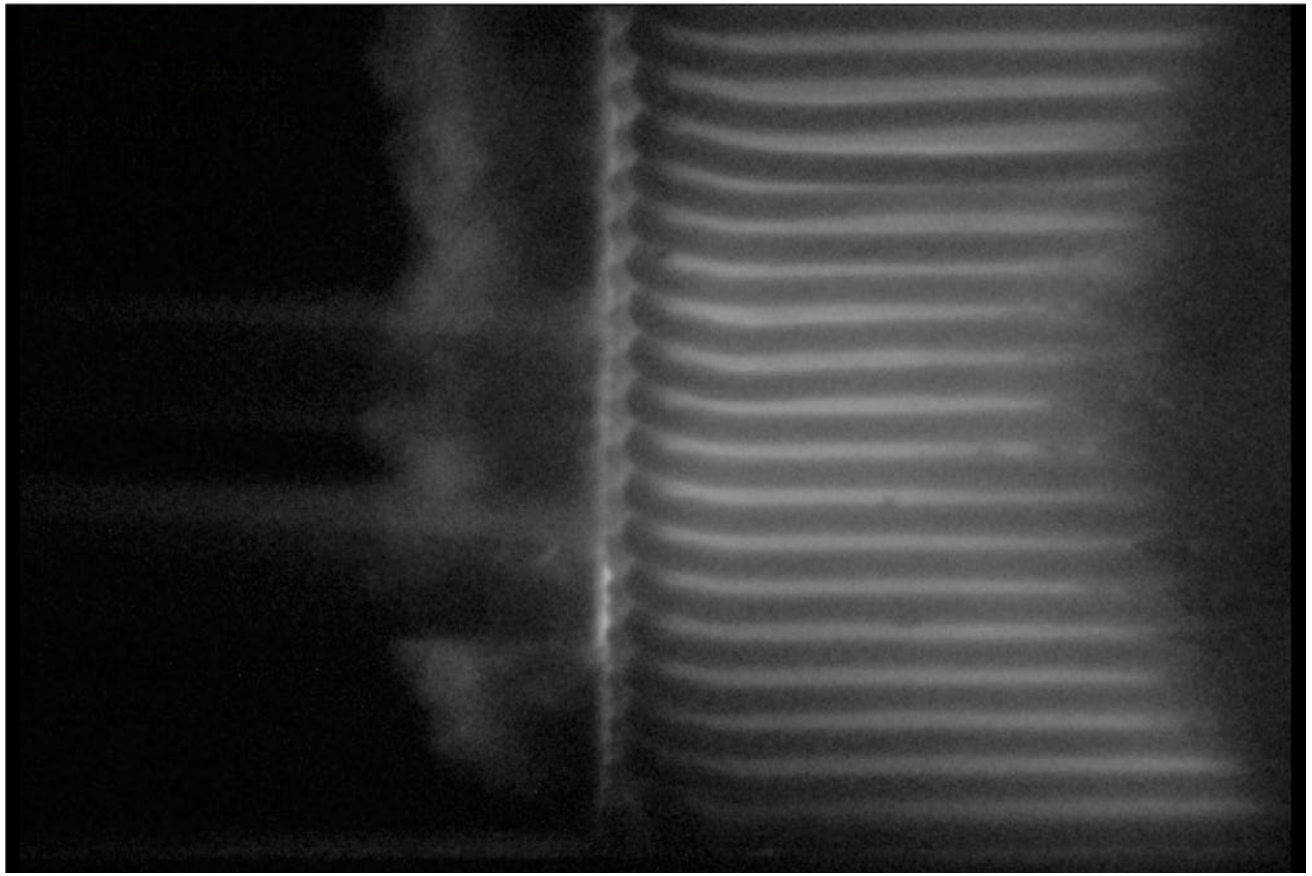


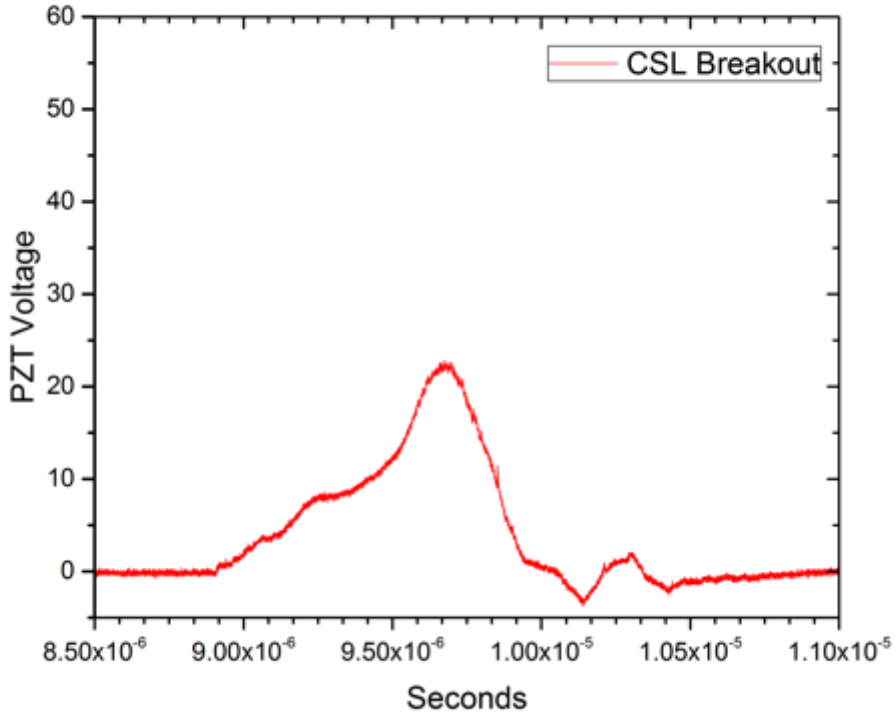




- Single shock front at breakout.
- D_v=7.8 km/sec

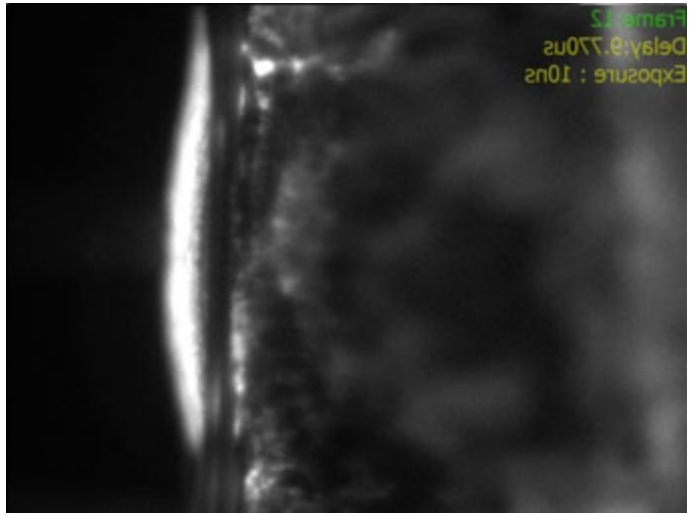
CSL Breakout



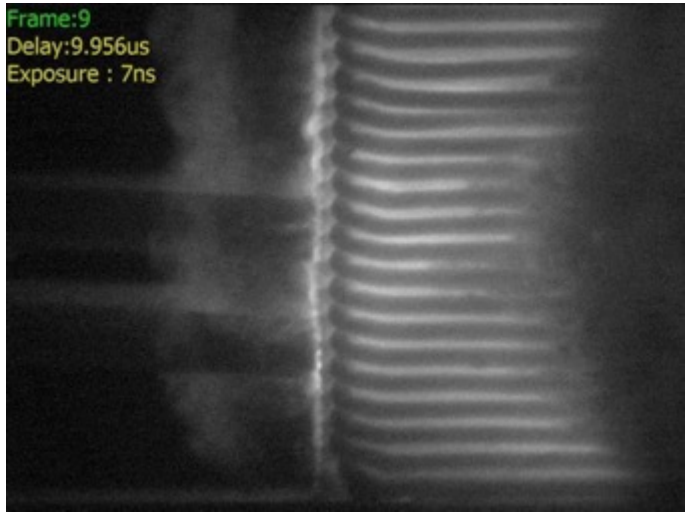


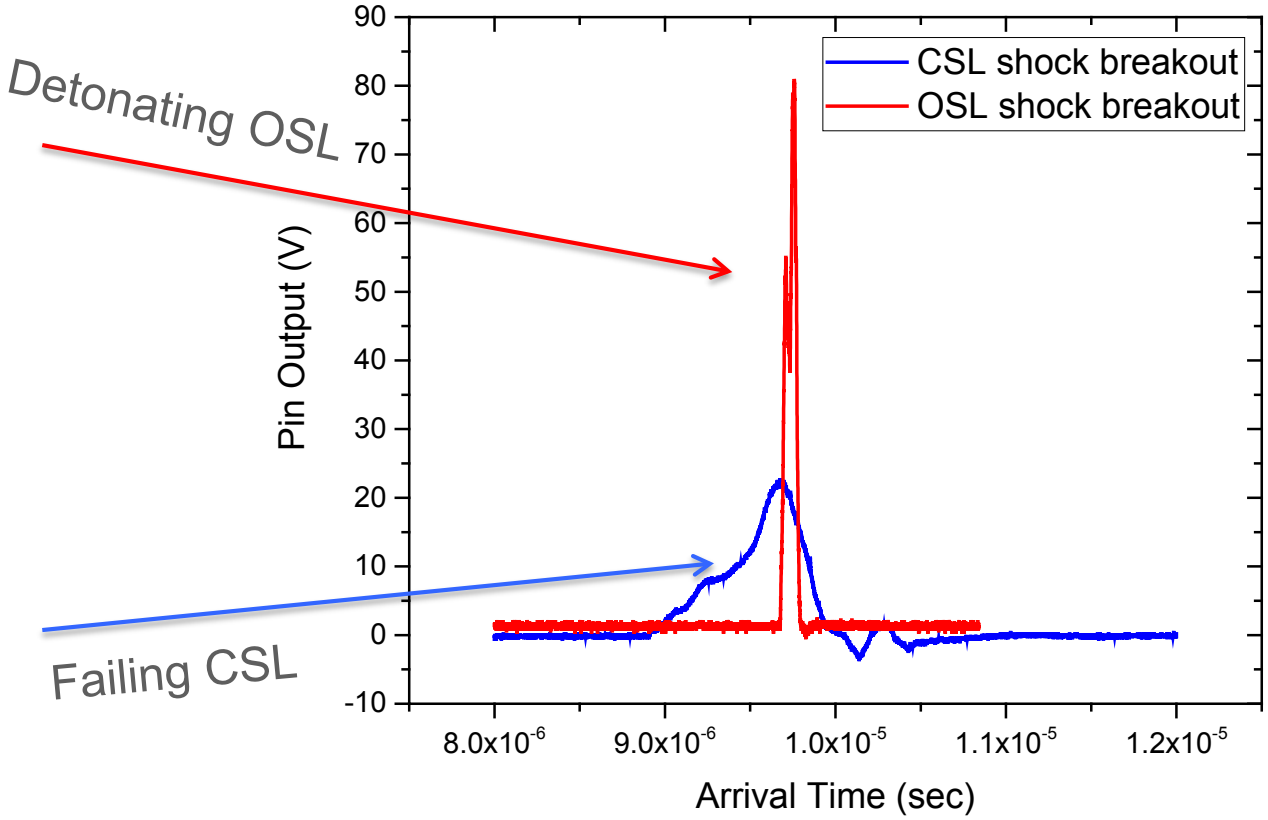
- Identical spacing to previous, OSL sample (at OSL / CSL divergence).
- Imaging captures early arrival of precursor shock.
- Burn front well behind the precursor- pins destroyed before arrival.

PZT pin output



D

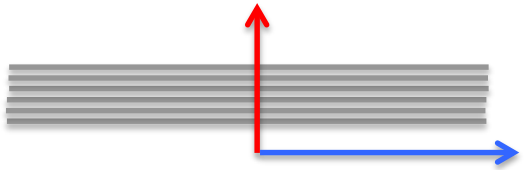


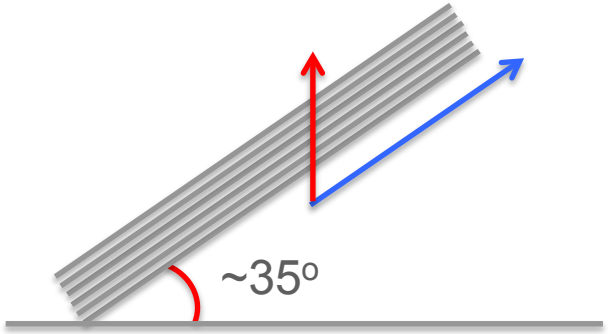


- **CSL TOA pins destroyed before burn front arrival.**
  - CSL part (blue trace) is longer!
- **D_v=7.8 km/sec.**
- **V_p=13.5 km/sec**

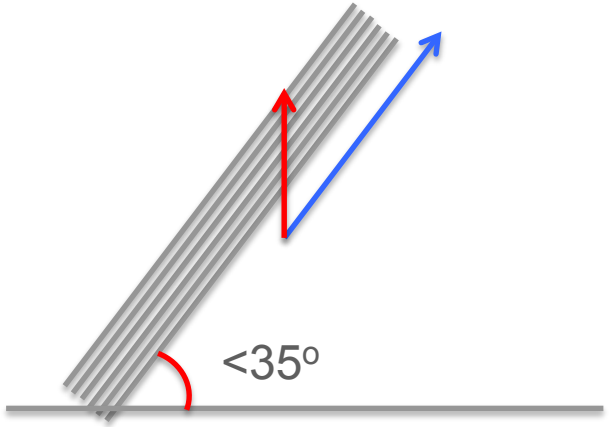
Simple Geometric Treatment of Channel Velocity

- V_D=7.8 km/sec.
- V_C= 13.5 km /sec.
- Θ_e=35°*.
- *V_c will be formulation and structure dependent.





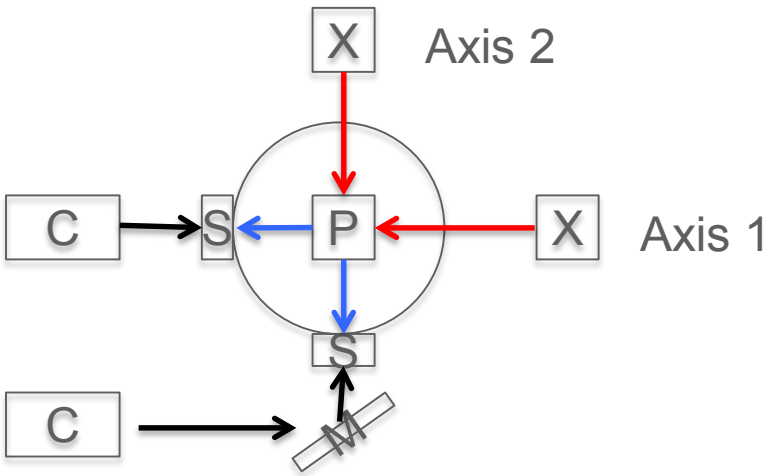
Preceding shock directional velocity = detonation velocity



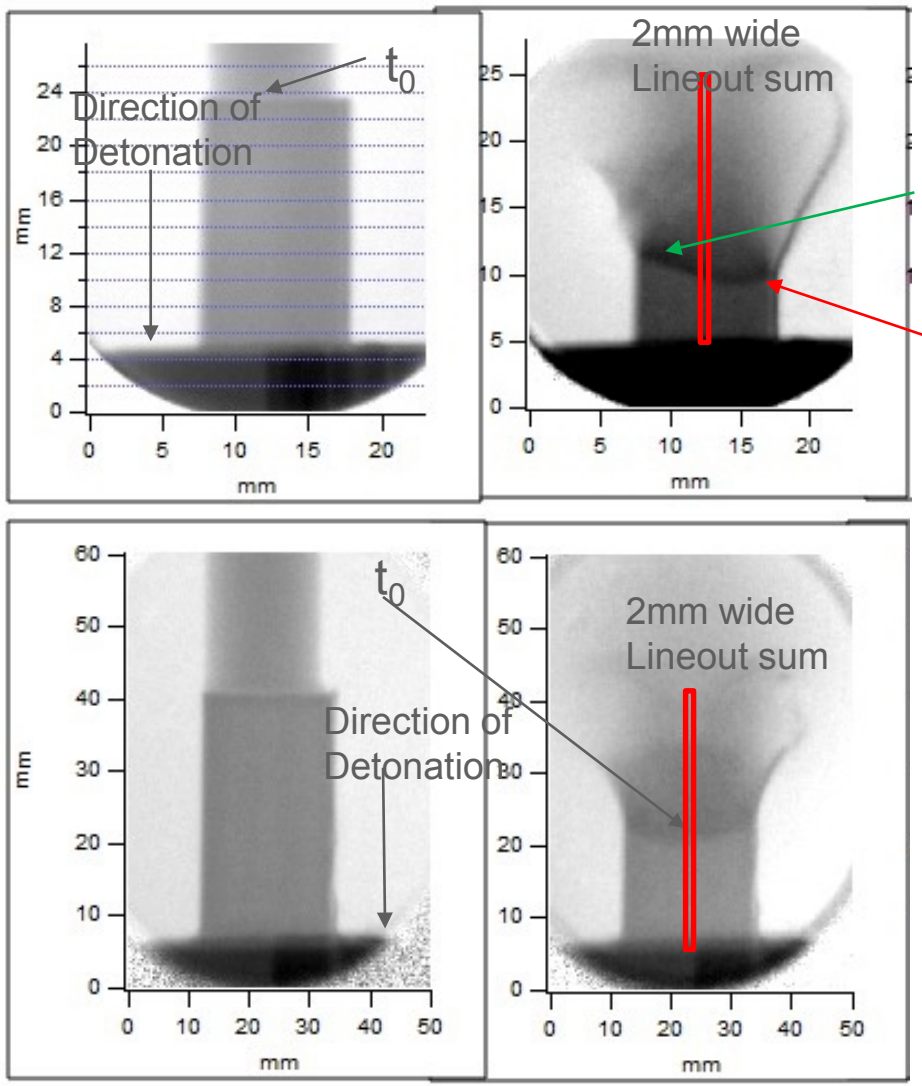
Preceding shock directional velocity escapes detonation. = failure

Radiography lineouts, Detonation vs. Failure

Radiography Setup.
Note, All data is from axis 1



- X= xray source
- S= scintillator
- C=Camera
- P= part
- M= mirror



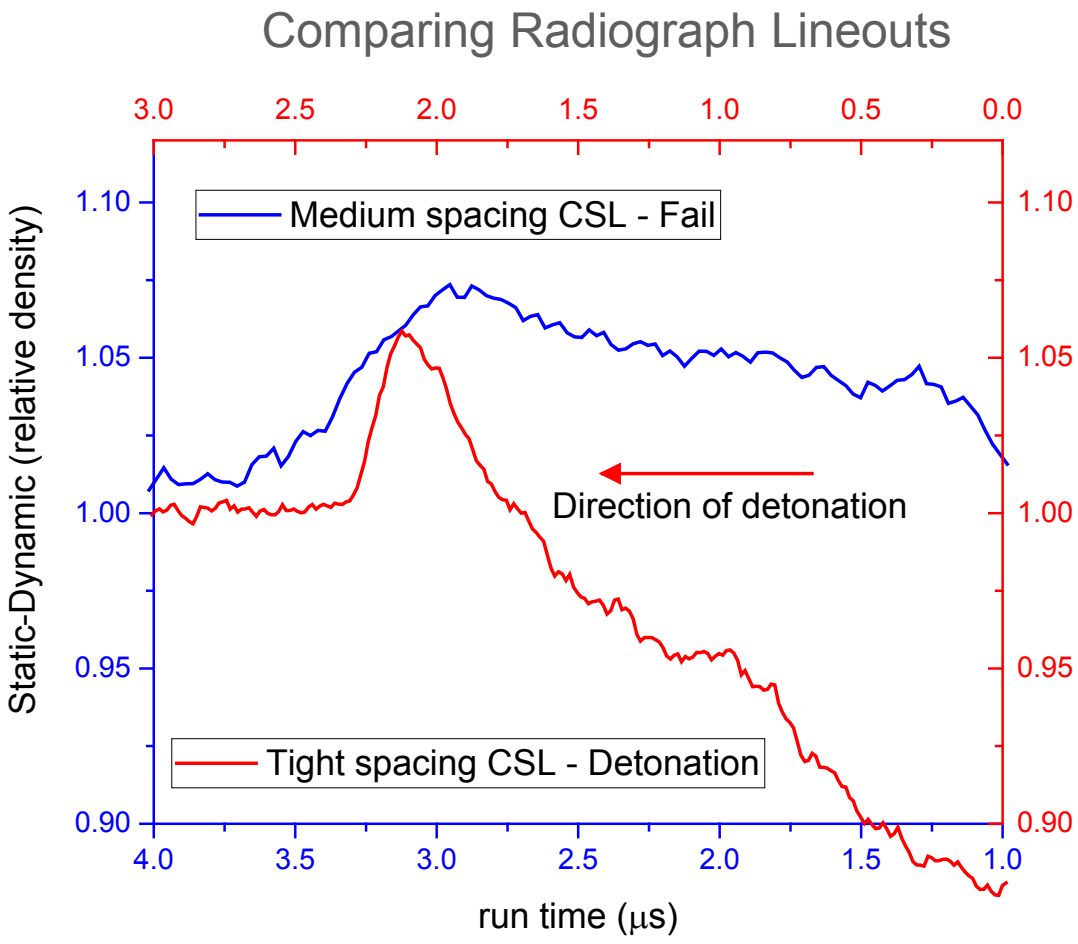
Tight Spacing (detonation)

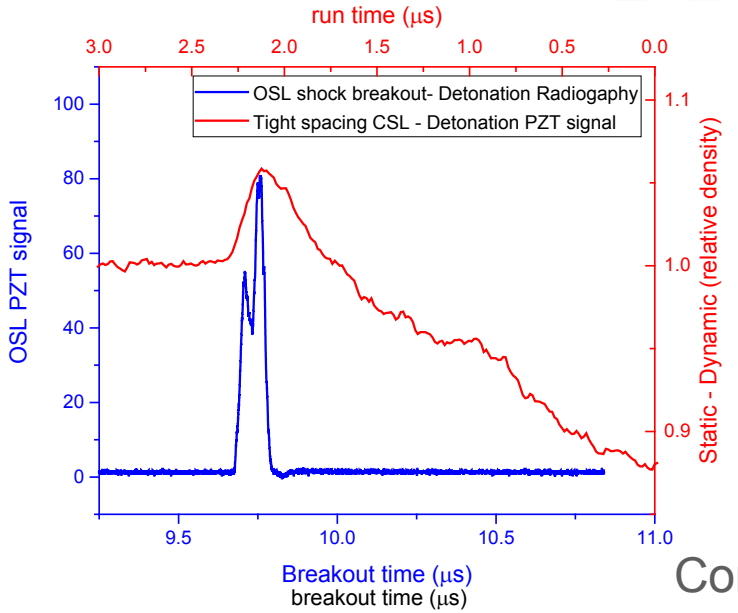
Higher density –slower transition

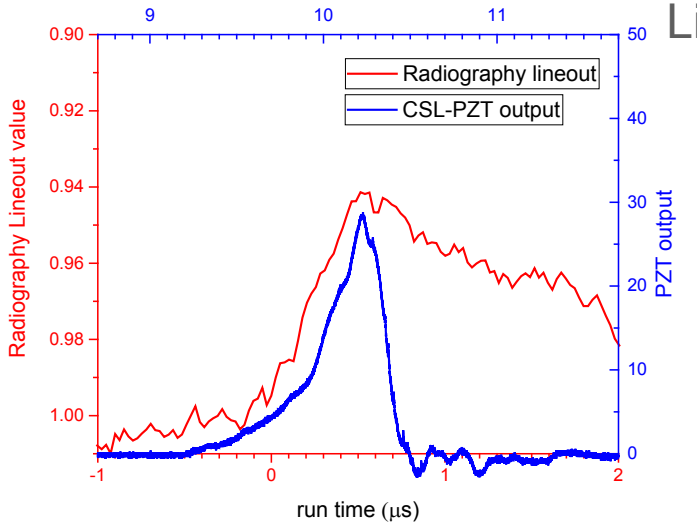
Lower density –faster transition

Open Spacing (fail)

PZT pin output vs radiography lineout - detonation



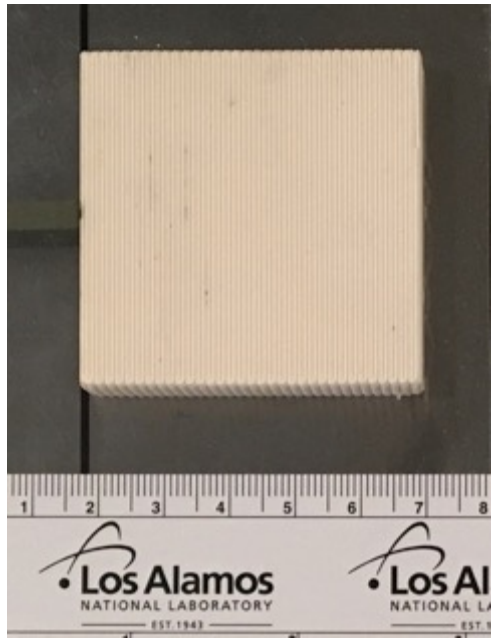


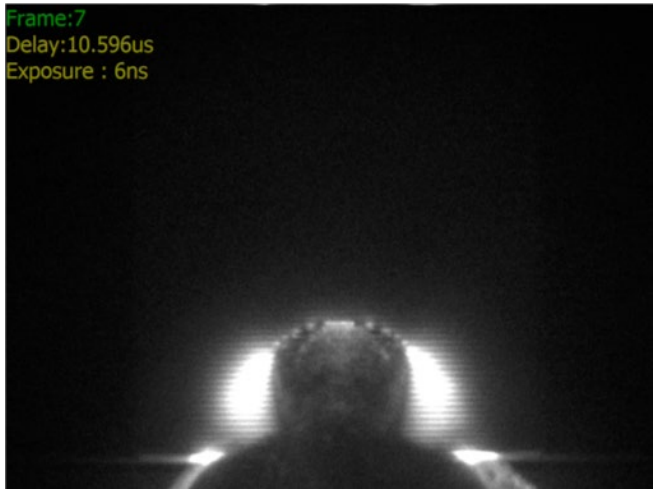


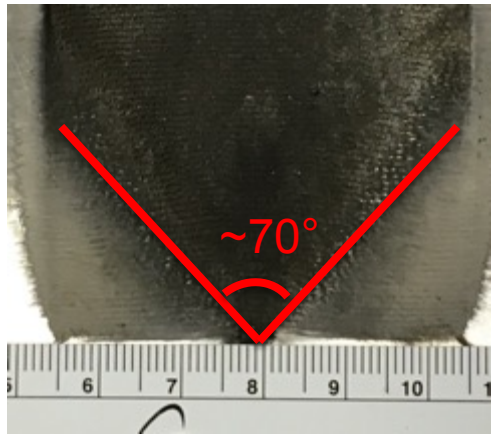
Comparing Radiograph Lineouts to PZT output

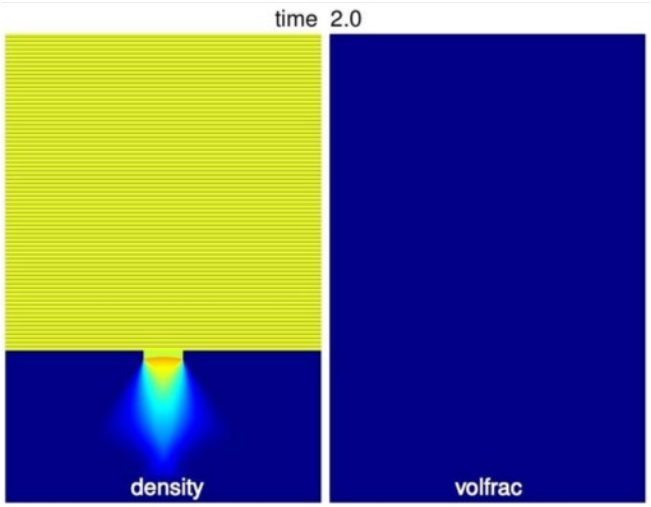
Detonation spread in OSL

- **5x5 cm square sample of printed AMX7001.**
  - Spacing corresponds to OSL detonation but CSL failure.
  - Donor charge =4cm Primasheet 1000.
  - Donor oriented in OSL direction.
  - High speed imaging and SURF modeling shows Detonation spread.
    - CSL direction retarded.
  - Spread “fan angle”= 70°, (half angle= 35°!).



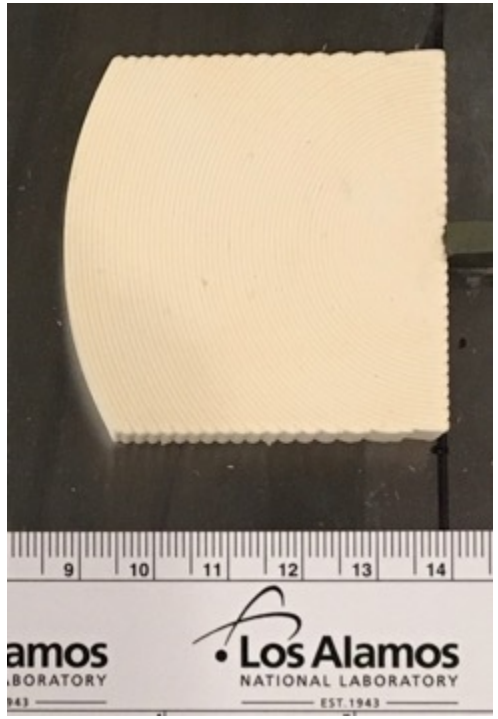


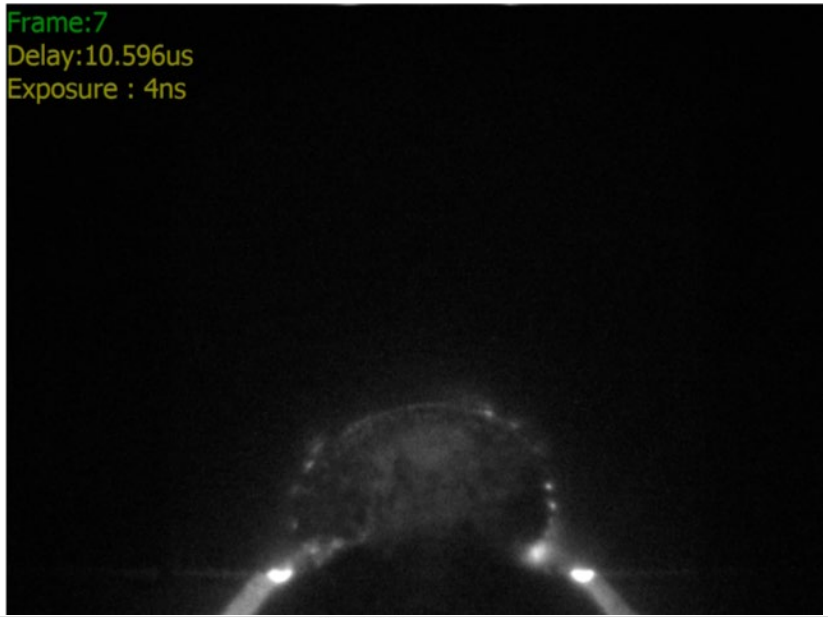


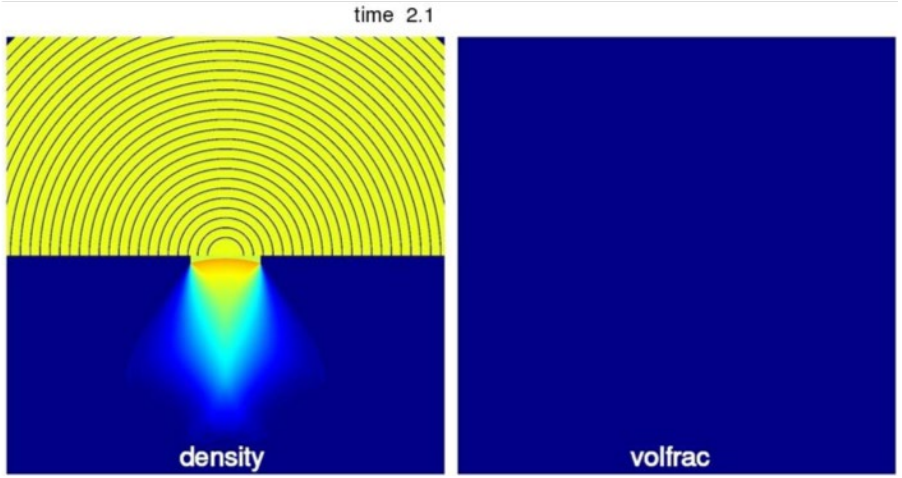


Radial Detonation Spread

- **Radial Symmetry makes all directions orthogonal to the donor charge input.**
  - Nested radial geometry with expanding radii.
  - Full area detonation.
  - Spreading captured by model.
- **Many more geometric variations to investigate.**







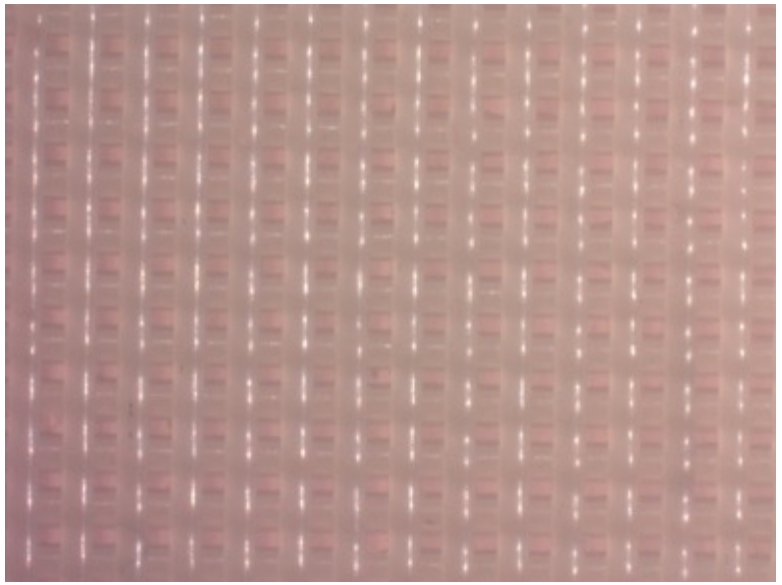
Introduction of FDM

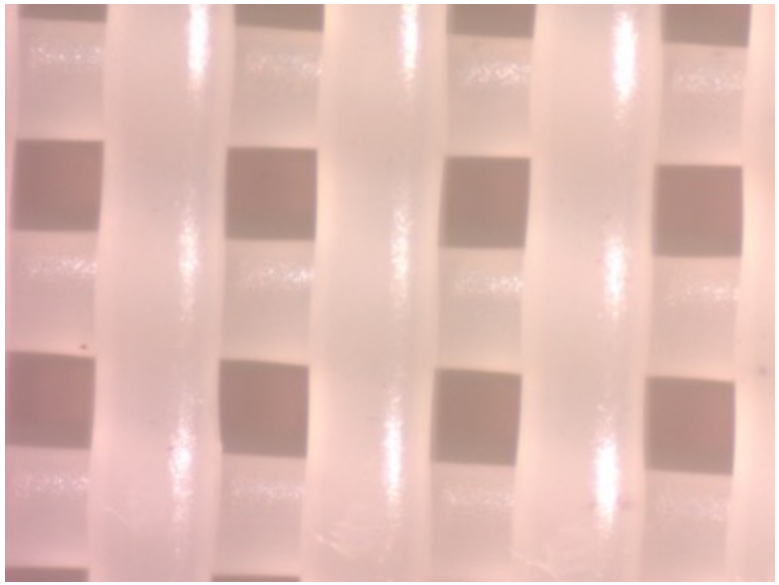
- **Due to high crystal loading (≥70% HMX in AMX 7001),achievable feature size reduction is limited.**
- **FDM (thermal extrusion) printing extrudes directly from the melt.**
  - No size limitations due to crystals jamming orifice.
  - Limitations due to flow mechanics are <50μm.
- **Project began with availability of BEX-1.**
  - Solidus transition time too long.
  - Bubble formation.
  - Crystallization yielded brittle strands.
  - Refinement led to AMX 7002.

AMX 7002

- AMX 7002
  - ETN-based eutectic.
    - Formed from acetone solution.
  - Print Temp= 55°<x<60°C
  - Decent strand detachment from nozzle.
    - Allows for more complex shapes requiring non-print travel moves.
  - Formed into slug and extruded through custom thermal extruder.

    Thinnest layer height attempted = 50μm.



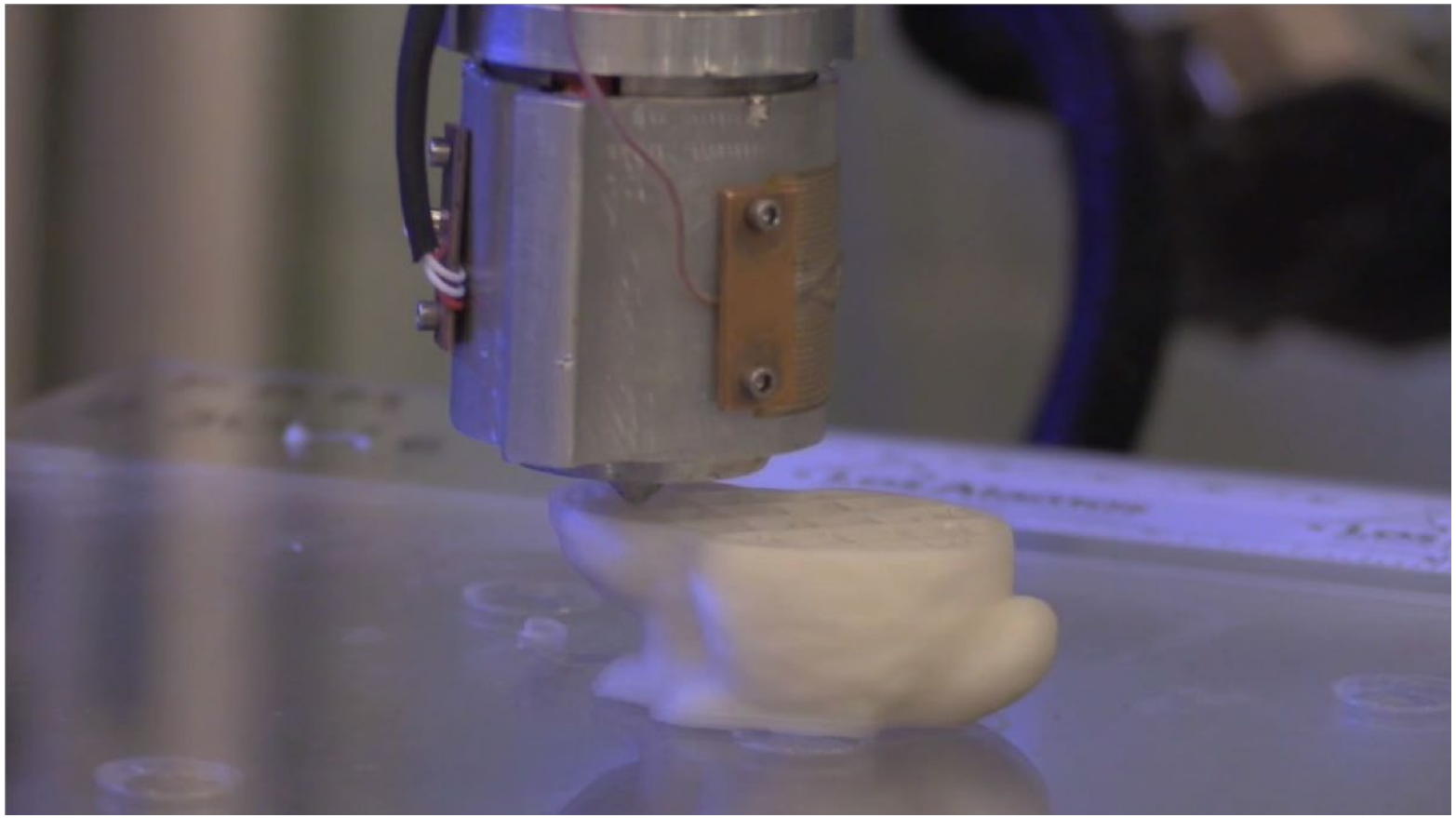


- **Initial prints showed high quality extrusion and interlayer bonding.**
  - Strut diameter = 375 μm.
  - Pad structure analogous to DCS samples.

Demonstration of FDM quality

Timelapse continued

- Luckily, we had a backup camera.

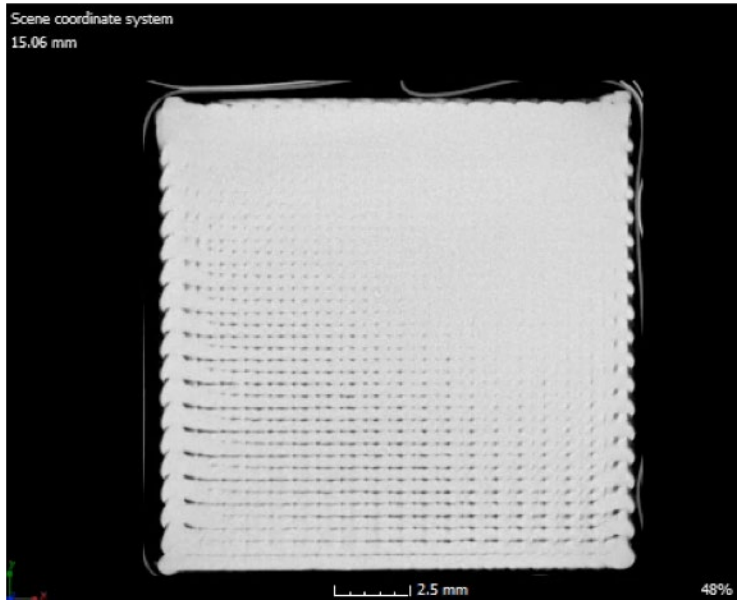


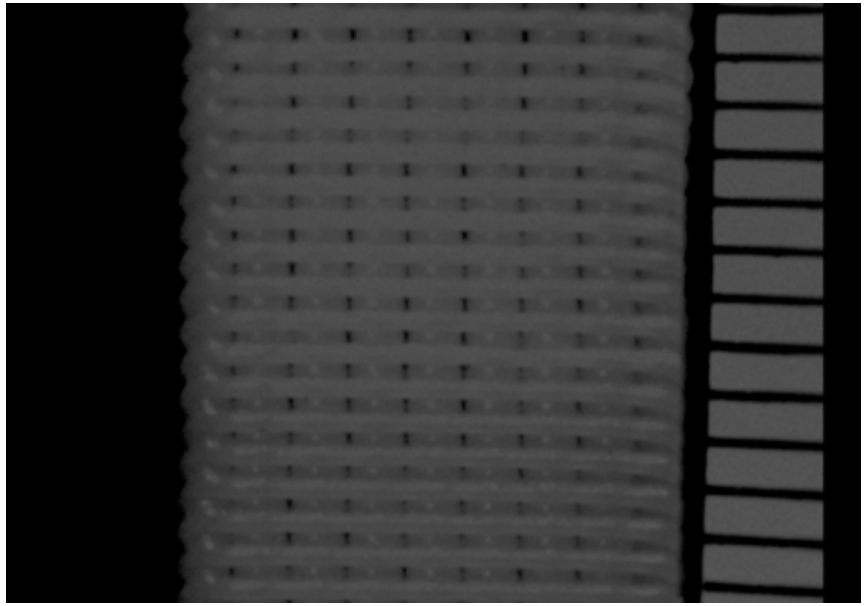
FDM final product.

- **AMX-7002 LAAMB (Los Alamos Additively Manufactured Bunny)**
  - “Stanford Bunny”
  - Used to demonstrate computer rendering quality.
  - Adopted by AM community to show texture quality of 3D prints

AMX 7002 structured detonation experiments.

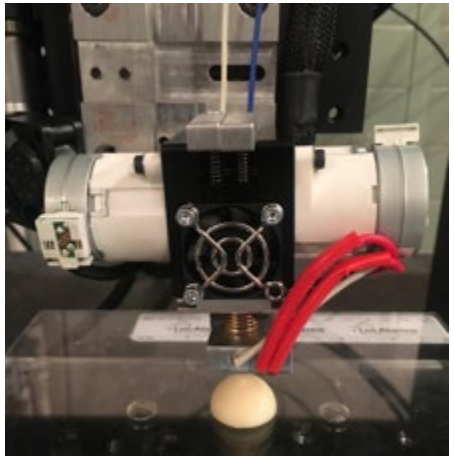
- **Using 7002, Pad structures can be produced at aspect ratios allowing imaging of structure – shock interactions.**
  - 5 cm tall cubic lattice printed.
  - SIMX capable of capturing multiple images of shock traversing gaps.





Print Quality and Grading Possibilities through FDM

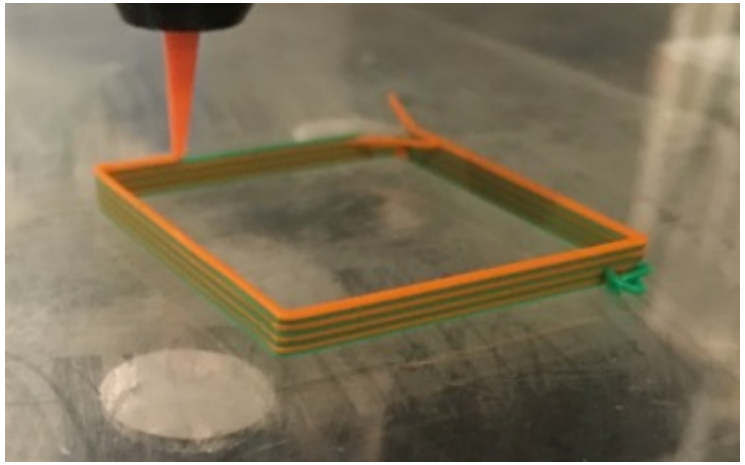
(above) Multi-point initiator. Showing “Spider web defects.
(below) 2 component FDM mixing extruder.



- **FDM filament advantages:**
  - Safety!
    - Spool HE strand with separation.
  - Build Quality.
    - Drool, Spider web reduction.
  - Material Mixing.
    - AMX 7002 formulation prepared pristine and seeded with microballons.
      - » Microballoons = changes in sensitivity.
    - Mixing similar formulations in fully melted state at µL volumes.
  - Graded sensitivity / detonation velocity printing.

Looking ahead :

- **Instrumental development in AM seemingly exponential.**
- **Translation to Energetics a little slower.**
  - Material Development.
- **Exciting time in the development of new technologies.**
  - Time when the interesting experiments are still easy.
  - As AM techniques improve, experiments will get more complicated.
  - 2D transitioning to 3D with tech development.



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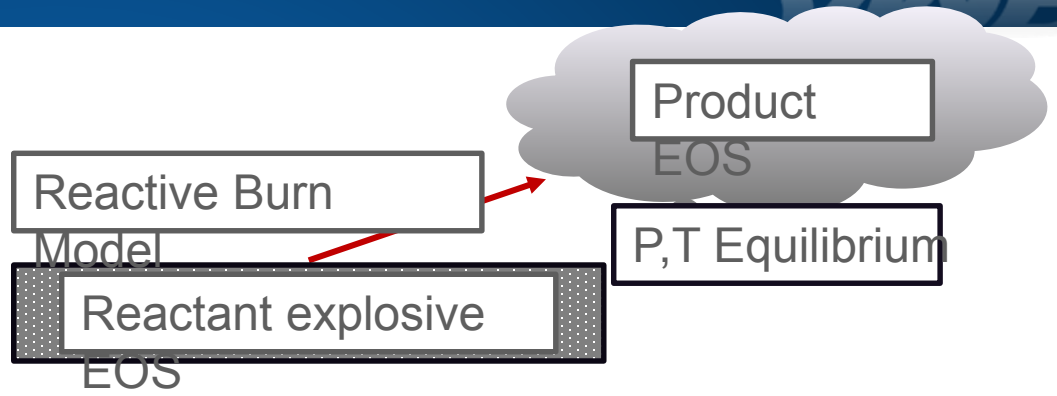
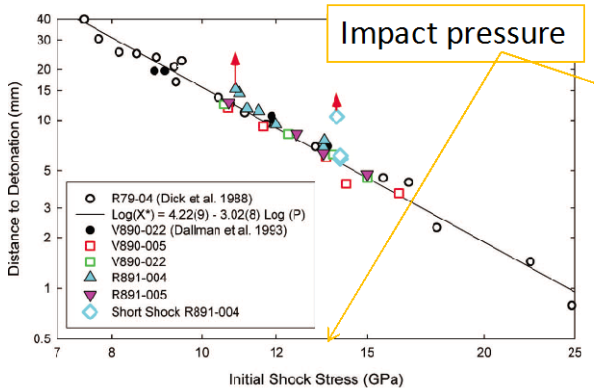
  - Energetic AM community: SNL, LLNL, AFRL, ARDEC.

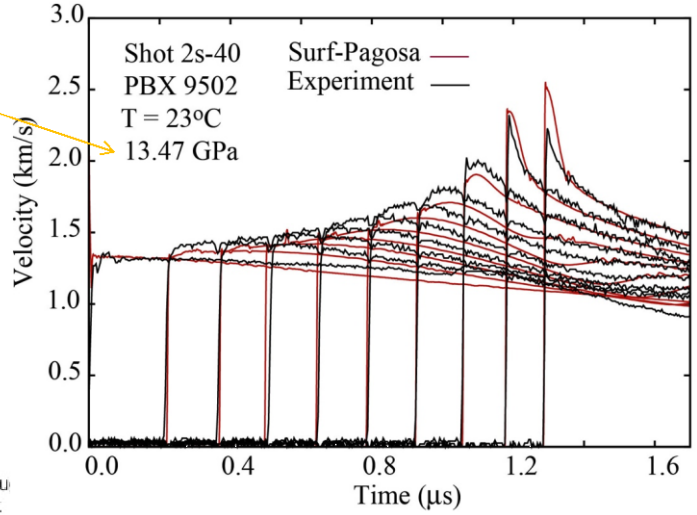
QUESTIONS?

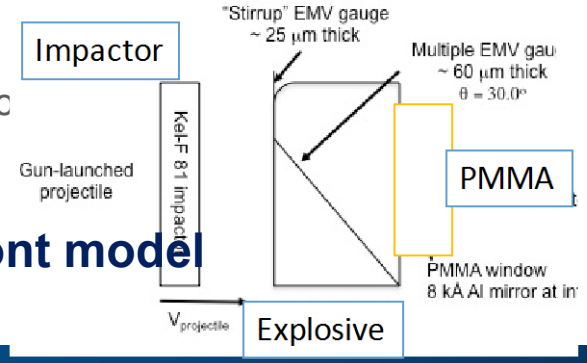
To model these experiments, we use the LANL-developed SURF reactive burn model.

- SURF is an HE reactive burn model developed by Menikoff and Shaw*.
- SURF is suitable for high velocity impact, where Shock-to-Detonation (SDT) is likely.
- SURF captures the details of the build up to detonation, not just the pop plot.
- SURF is able to capture *short shocks* and *dead zones.* Burn models like Forest Fire can not. (This is critical for AM simulations!)









*R. Menikoff & M. S. Shaw (2012): The SURF model and the curvature effect fc
PBX 9502, Combustion Theory and Modelling,
DOI:10.1080/13647830.2012.713994

SURF is the scaled uniform reactive front model

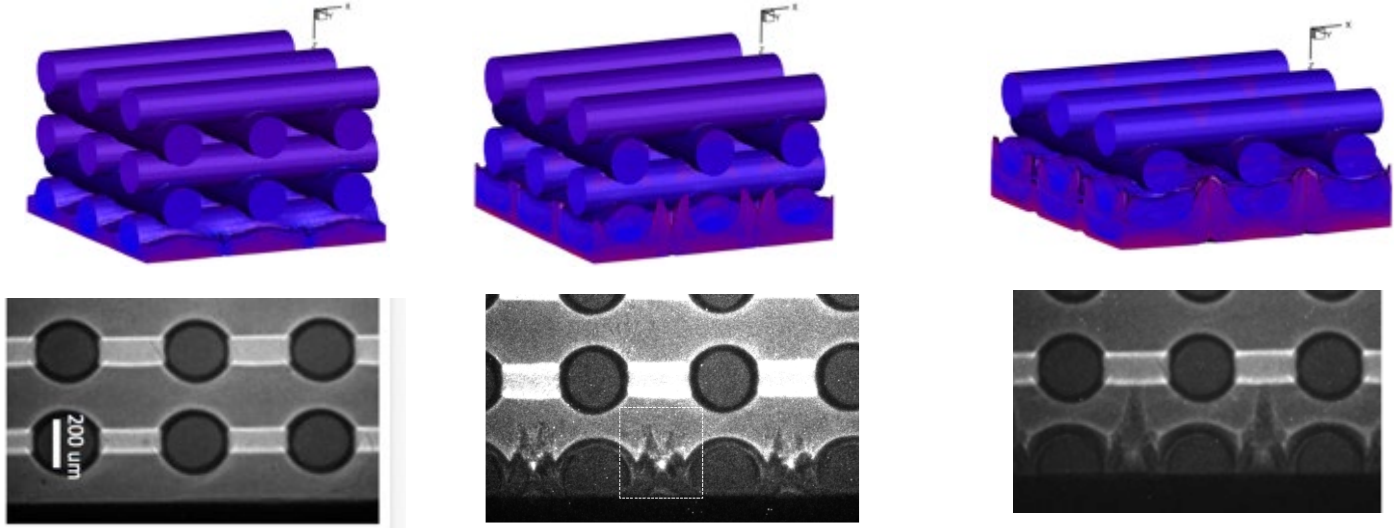
Shock Interactions were modeled in ABAQUS.

Deformation sequence at u=0.7 km/sec (density)

ABAQUS

SC structure

PCI

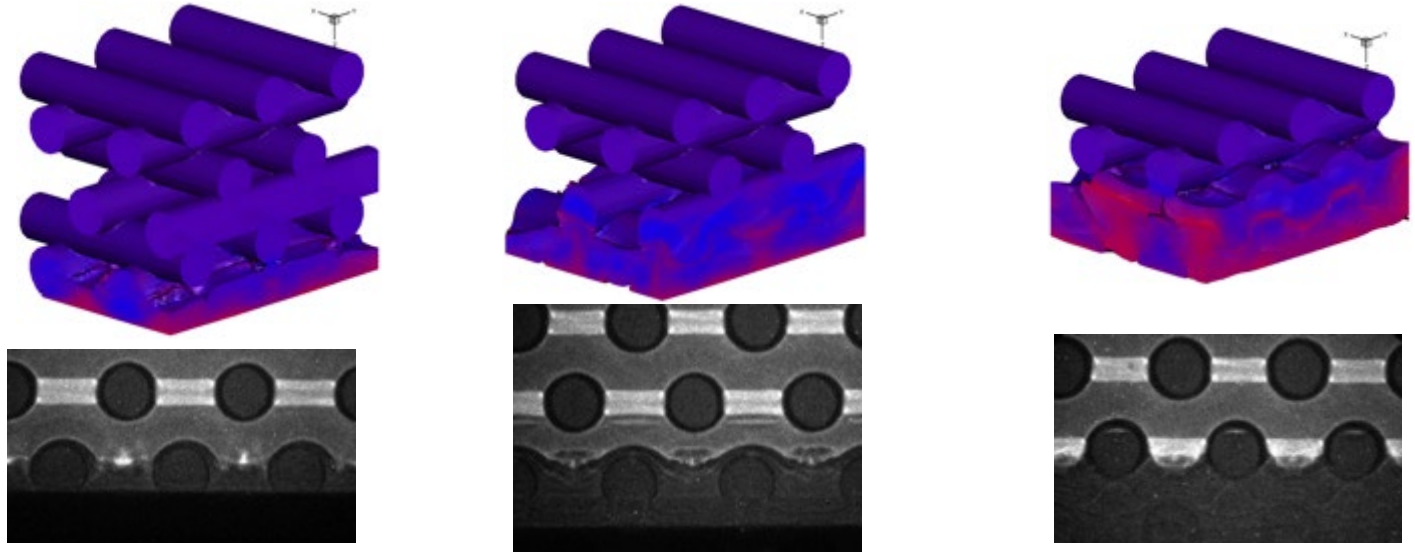


- The adjacent struts extrude between the next layer
- Creates a doublet in the jet which then consolidates into a single jet as more layers are compressed by the shock front

ABAQUS

FCT structure

PCI



- Jetting is thwarted by the layer symmetries
- A shaped wave is formed by blunting of material extrusion