SAND2016-3255PE

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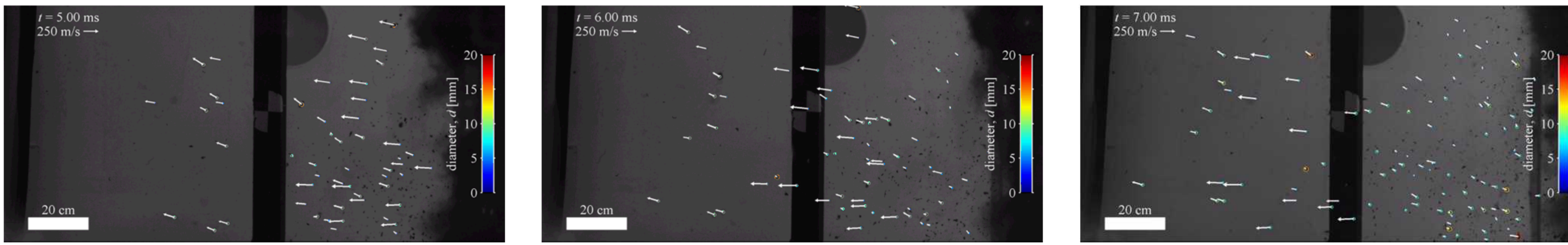

Experimental Methods for Dynamic Failure

ARL Dynamic Failure Form

Phillip L. Reu, Daniel R. Guildenbecher, Steven W. Attaway, Tim J. Miller, Enrico Quintana, Yi (Ellen) Chen, Mark U. Anderson, Jason Wilke

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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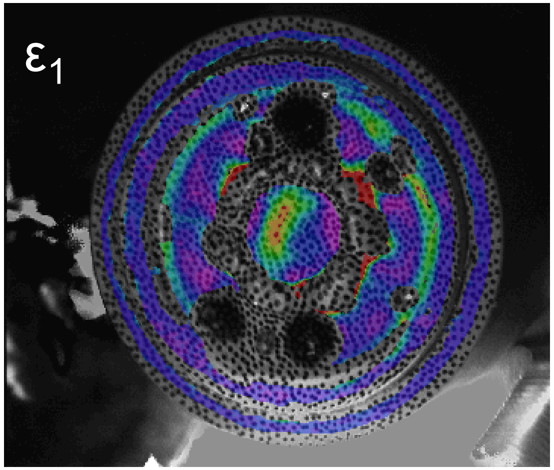
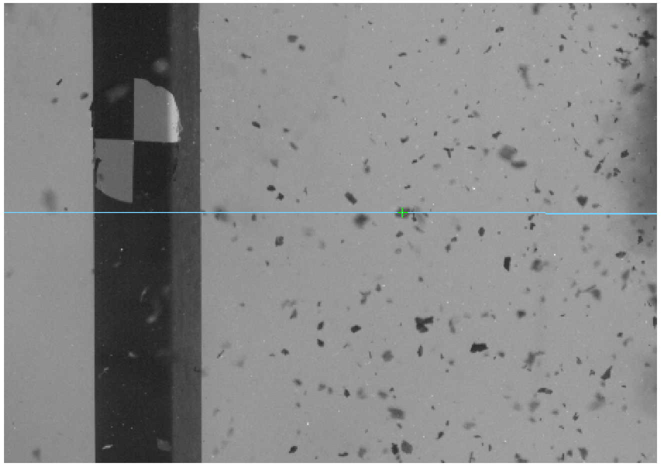
Full characterization of explosive devices is important for engineering and model validation.

Fragmenting material/device



Flash X-Ray Movies

Fragment tracking/Computer Vision



Soft-Catch Techniques

DIC for case failure
- 5 MHz shape, deformation, and strain
- Fast enough for nearly all situations

X-Ray for early fragment evolution
- 5 MHz X-ray movies
- Can see through smoke and flash
- Measure internal components

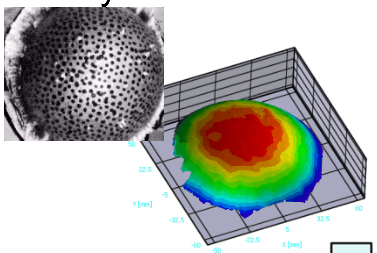
Multi-Camera Computer Vision
- >25 kHz frame rate
- Visualize particles after leaving smoke & flash
- Measure velocity, size and rotation

Fragment soft-capture and postmortem

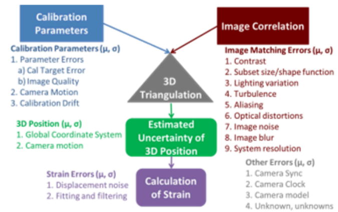
Fragment capture
- Investigate influence of capture on fragments

Digital Image Correlation – A revolution in full-field engineering measurements

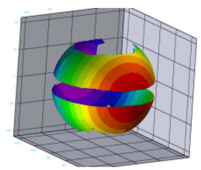
1MHz displacement, velocity and strain



Stereo-DIC Uncertainty Quantification
From colors to metrology.

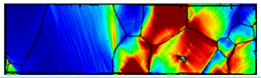


360º coverage



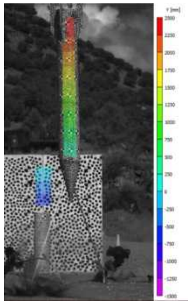
DIC for Material Properties
- Quantified Uncertainty
- More parameters per test
- Parameter interaction
- High-throughput
- Model validation

Grain Scale strain
J. Carroll

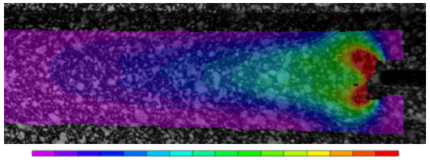


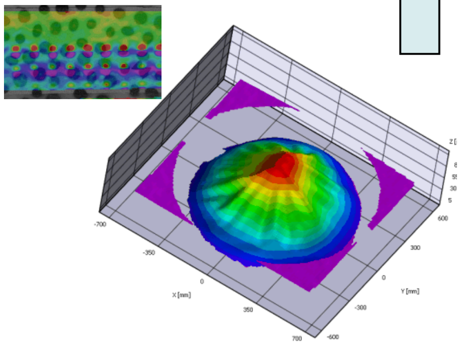
2005 | 2007 | 2009 | 2011 | 2013 | 2015

Introduction of DIC to Sandia

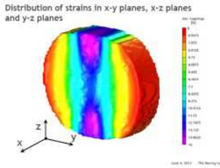


Crack-tip and Fracture Strain





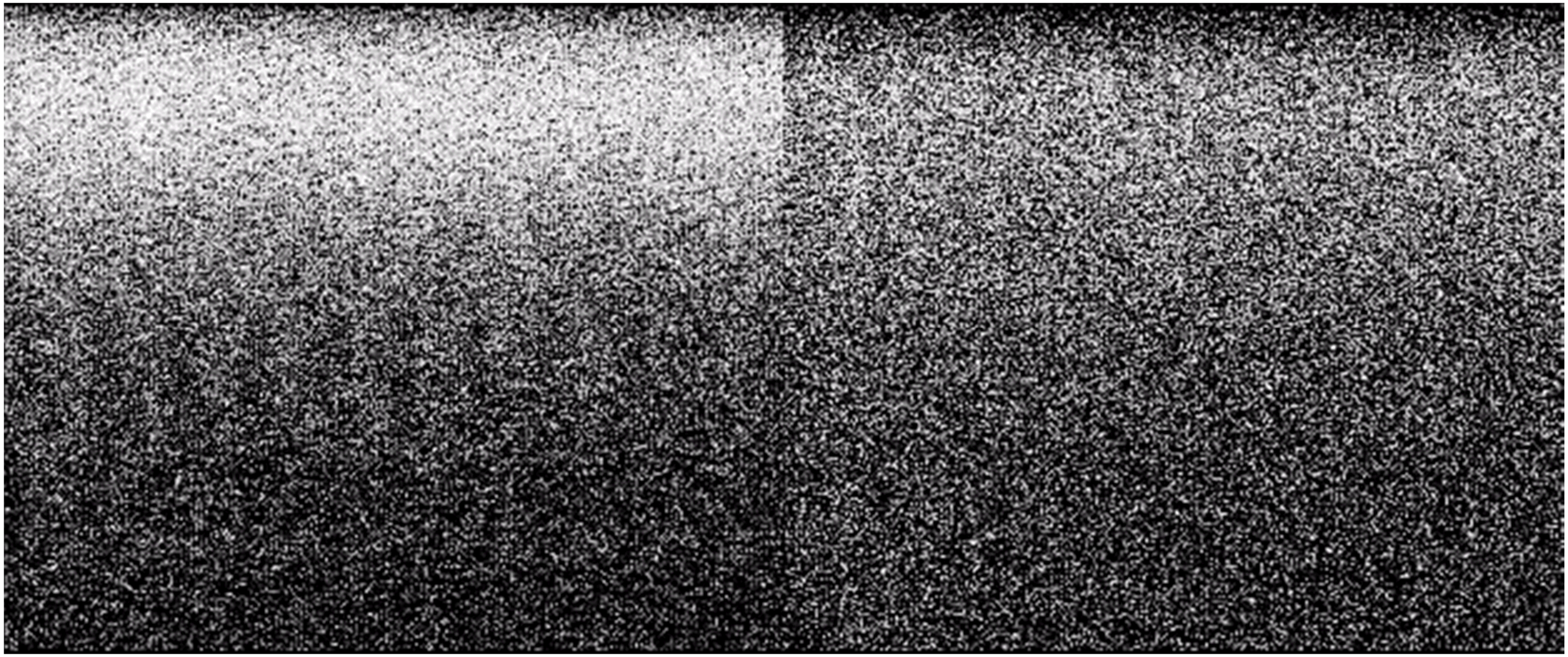
Explosive Panel Deformation

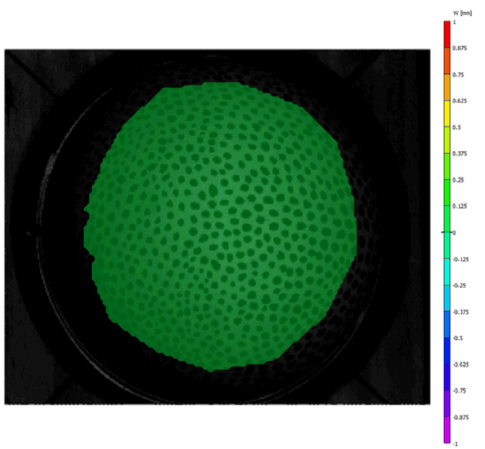


Volumetric DIC
M. Sutton (USC)

Experimodelment: Inverse techniques for Material Properties

1-MHz acquisition of stereo-images for DIC





Cased Explosive Work with Marcia Cooper (SNL)

Rich full-field data sets are now available.

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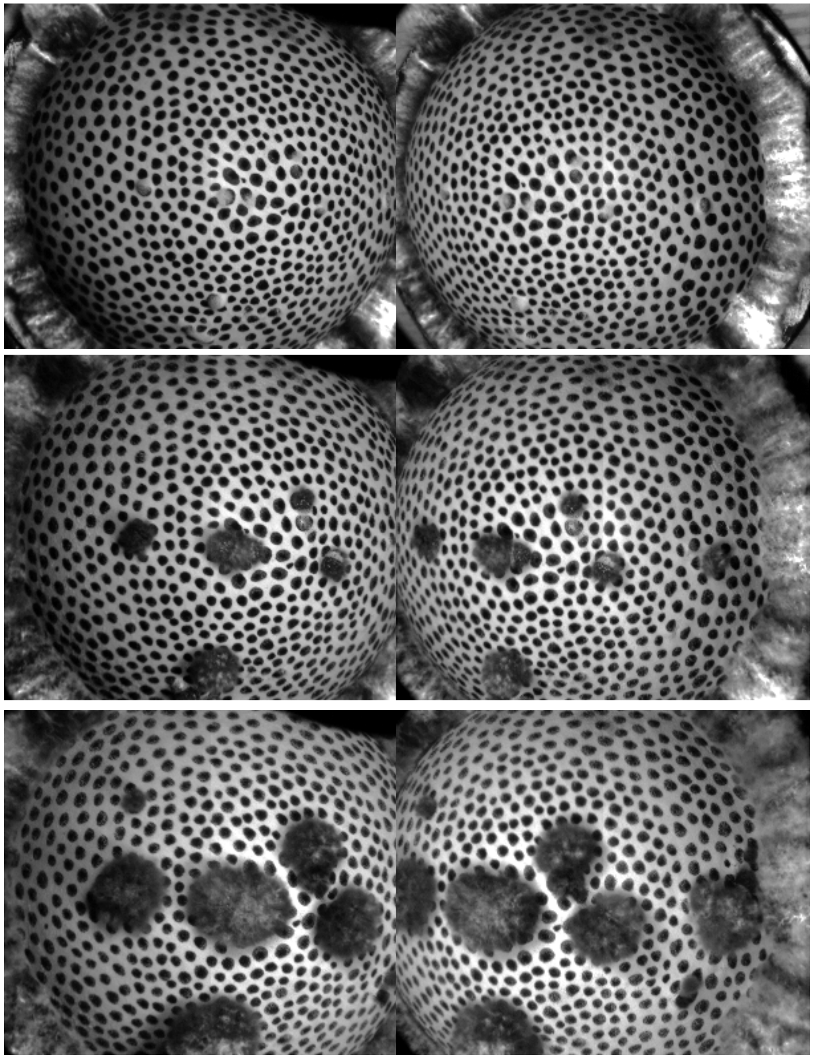
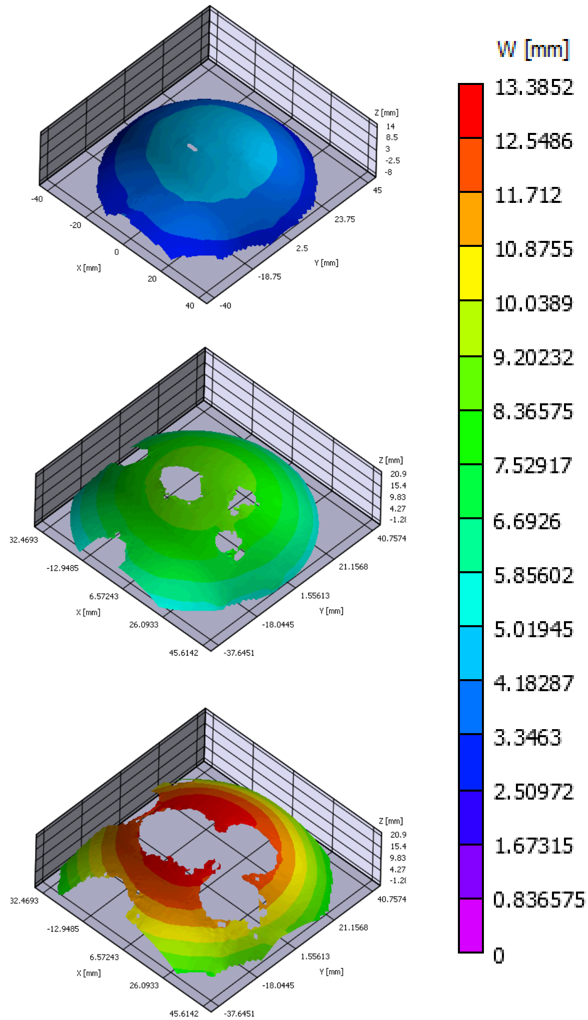
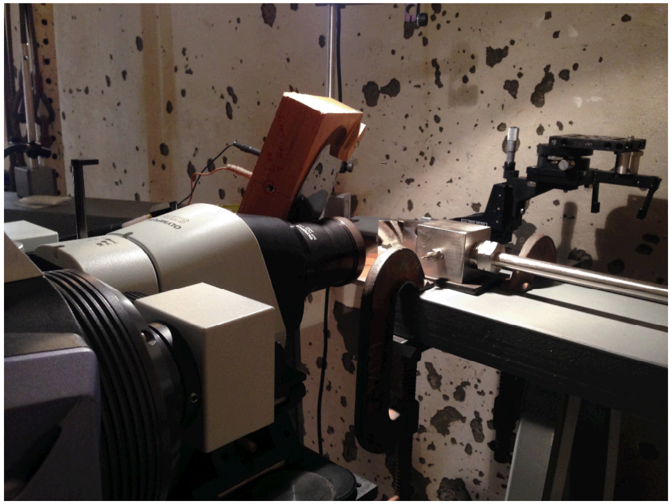


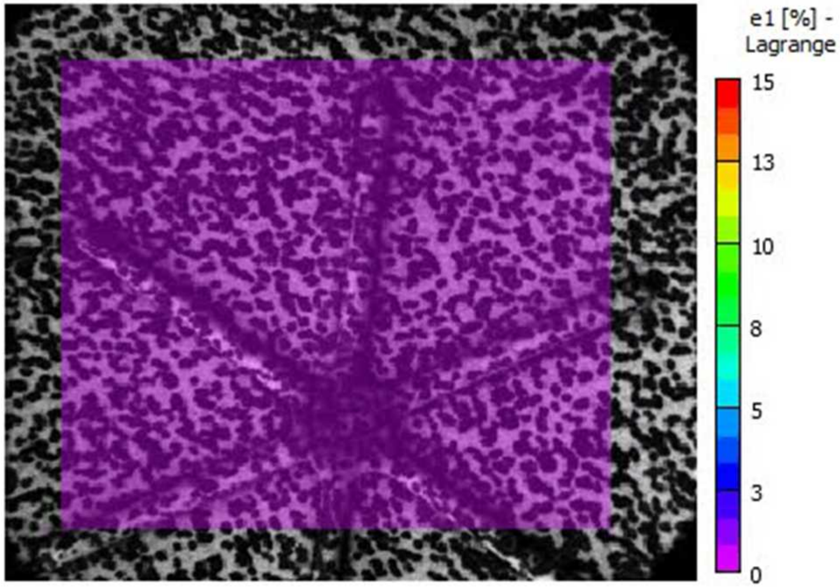


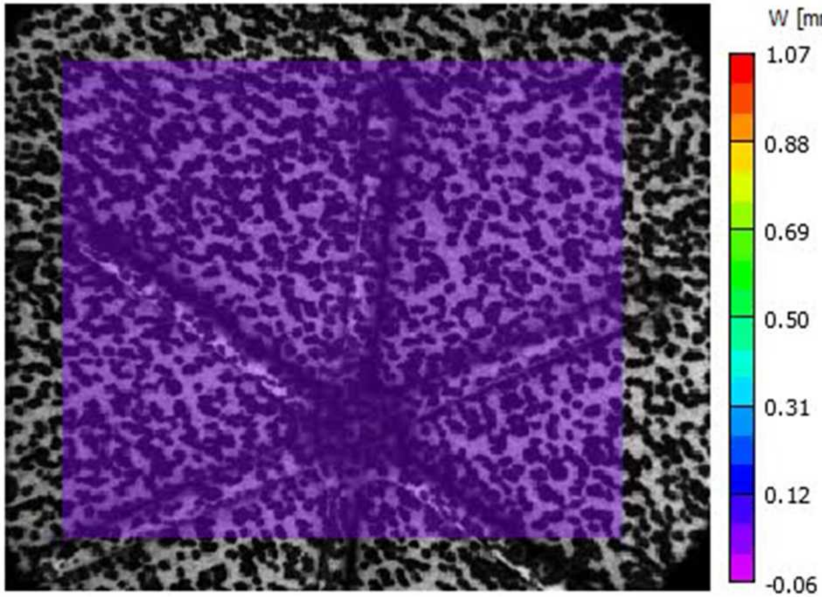
Data Includes

- 3D-Displacement
- 3D Velocity
- In-plane strain
- Measurement of jet volume
- Visualization of case failure

Shock tube dynamic testing would be a good method for high-rate loading in a more benign environment.



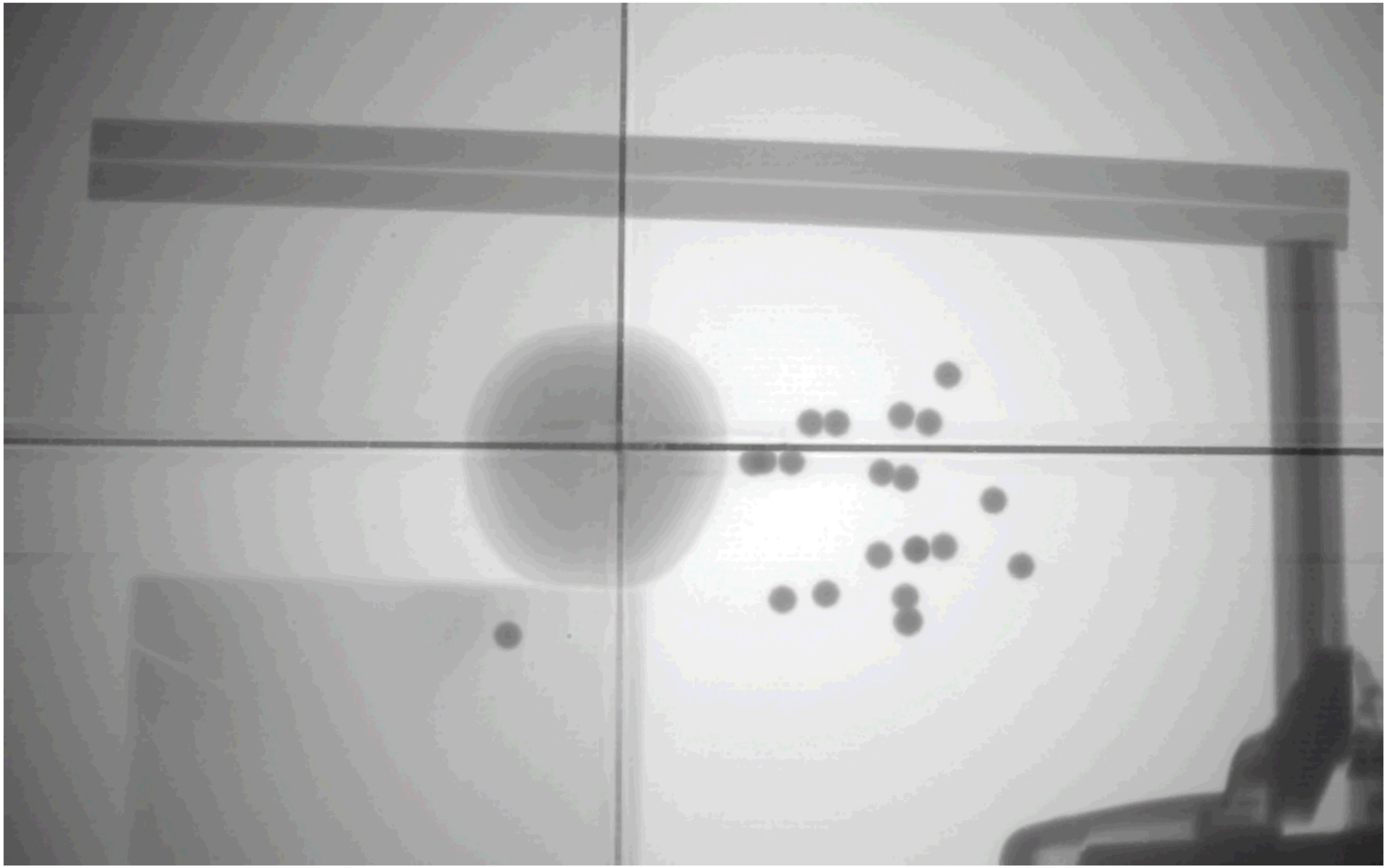




Shock Tube DIC

- A test bed for high rate material failure
- Simpler test environment
- Ability to load specimens repeatably
- No smoke or flash to contend with

X-Ray movies have been demonstrated at up to 25-kHz and 1MPixel resolution



Flash x-ray movies are now possible. Likely up to 5 MHz. And in Stereo!

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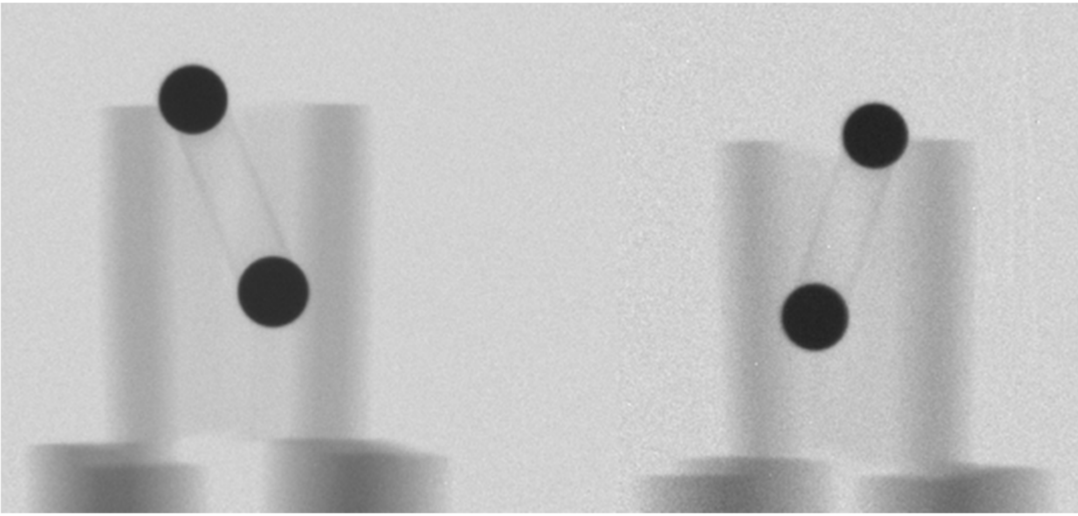
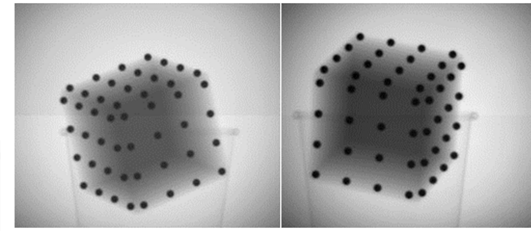
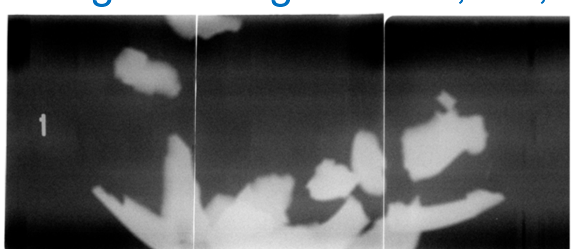


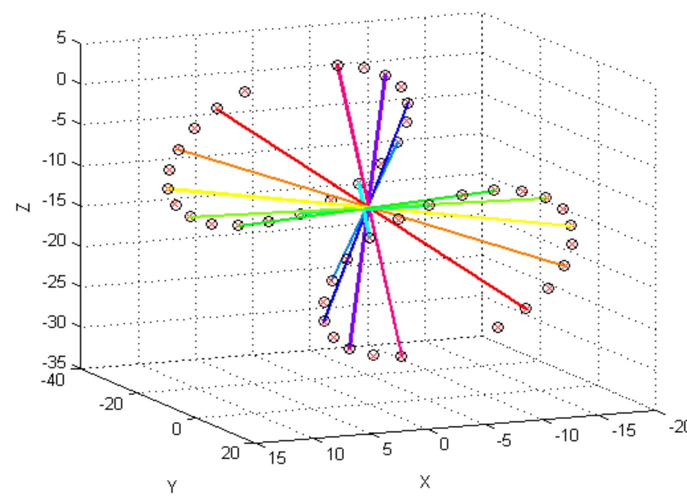


Stereo-X-ray Calibration

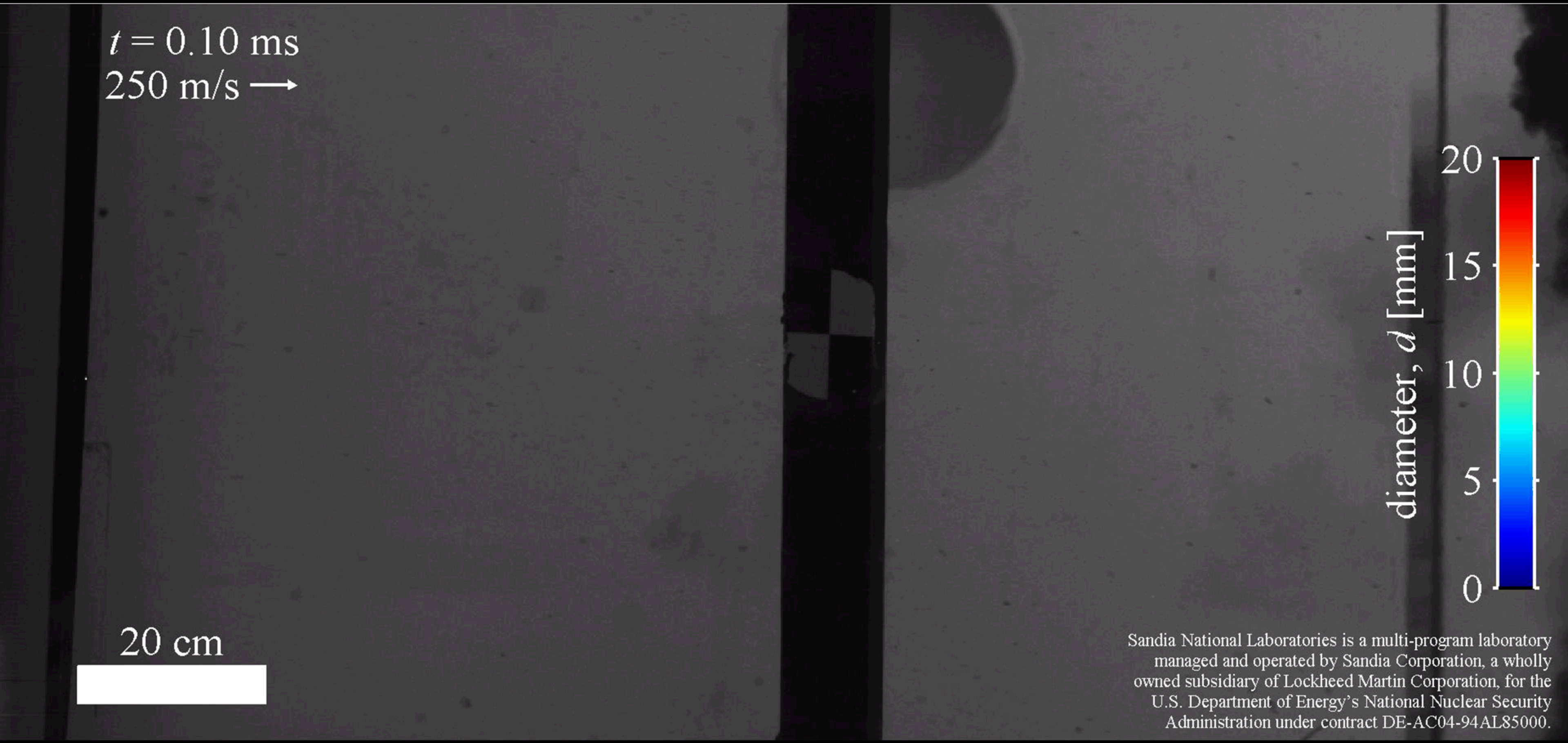
High-Speed X-ray
- 50-ns Pulse length to stop motion
- Currently 9 frames available at any rate
- Imaging up to 1 Mpixel and 5 MHz
- Images through smoke, fire, etc.



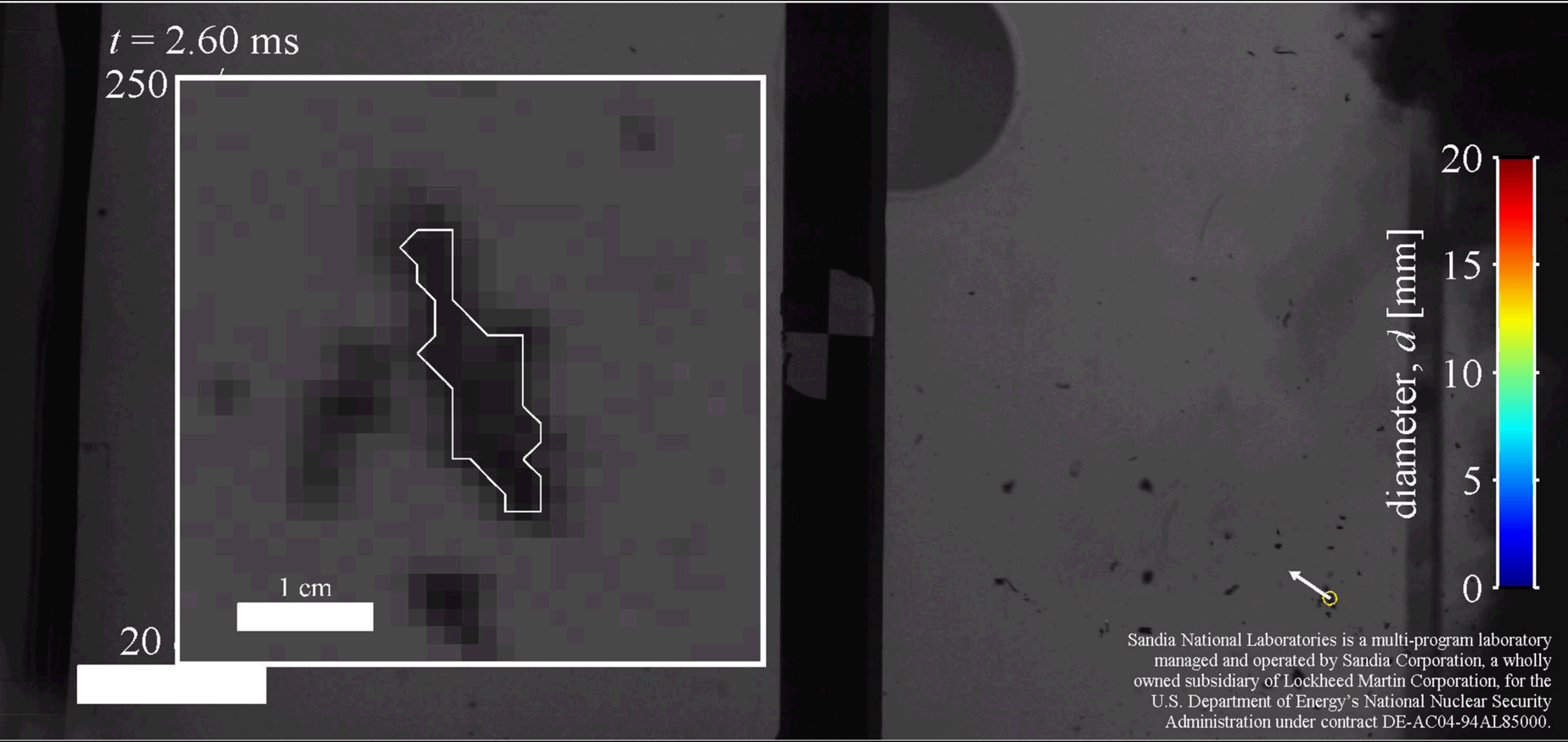
Goal: Early time case rupture and fragment evolution.



High-speed cameras and advanced image processing methods provide new insight into fragment dynamics

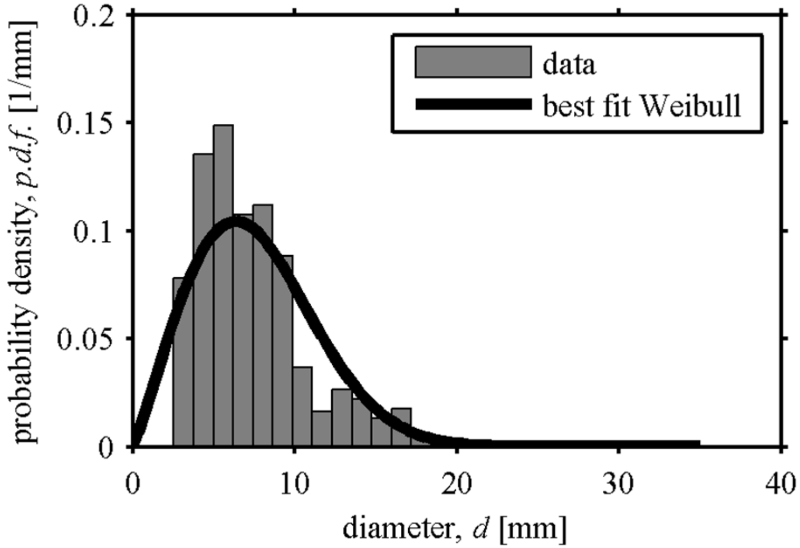


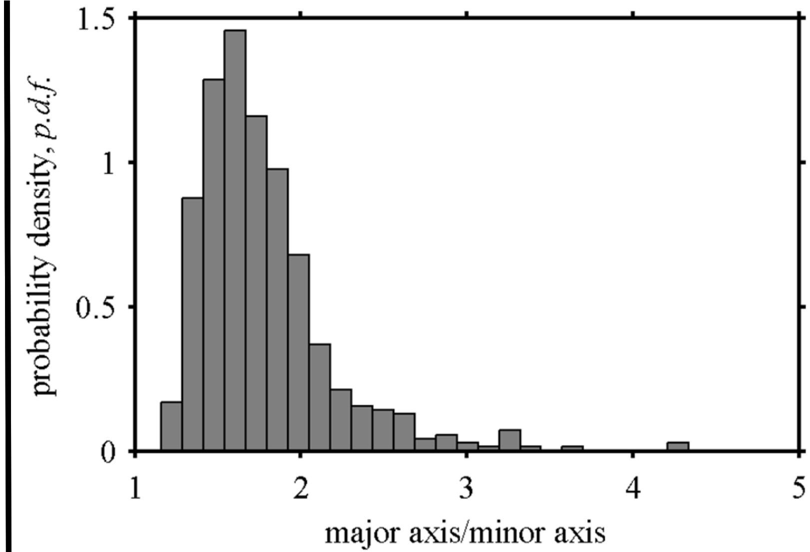
Individual trajectories give detailed size, velocity, and orientation

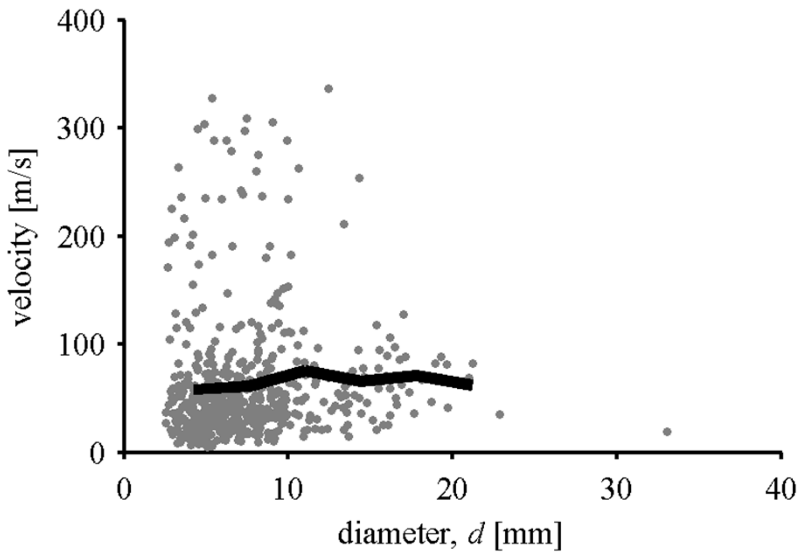


Note: video shows one example trajectory, all fragments are tracked in this manner

Data provides in depth size-velocity information





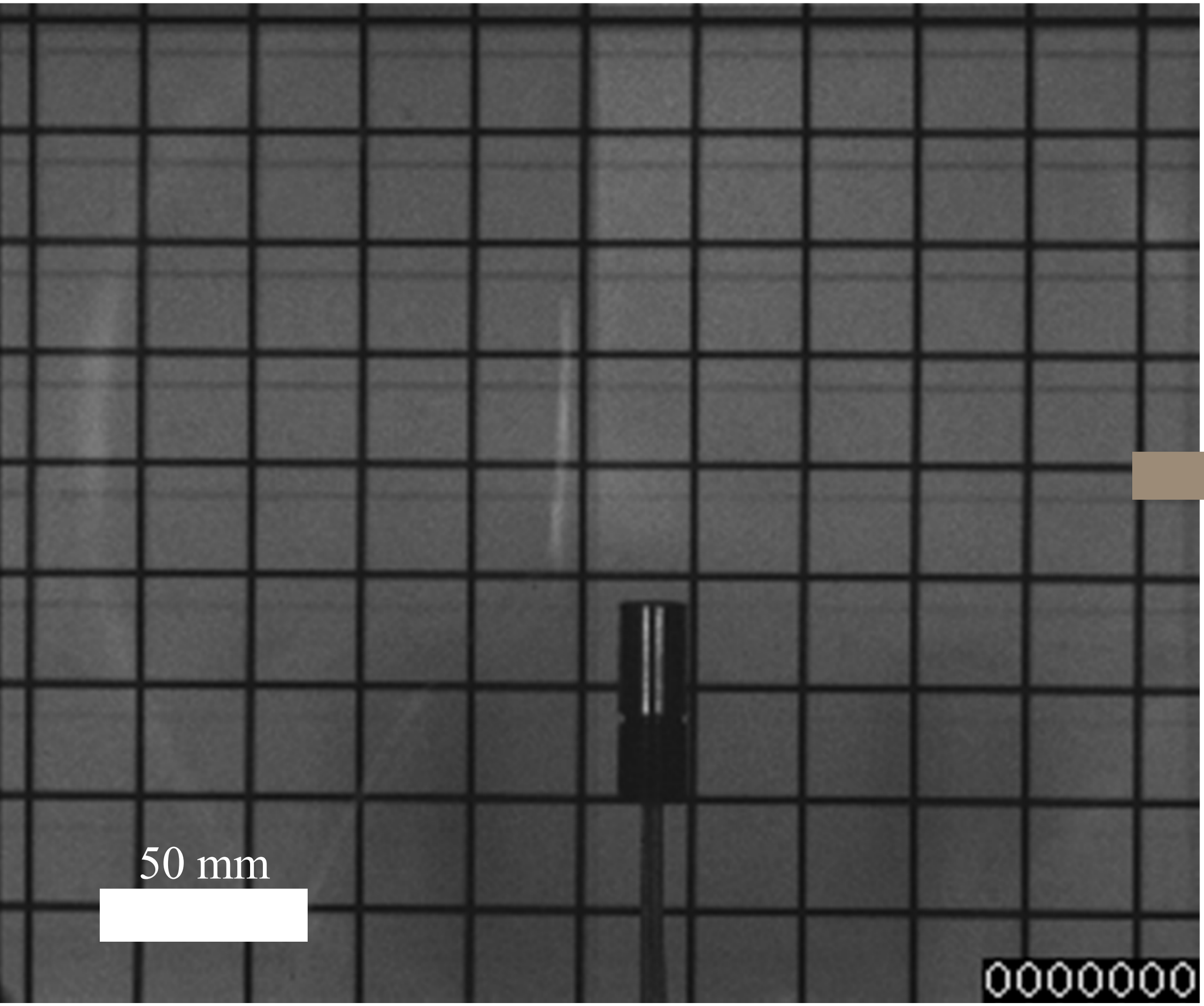


Next steps:

- Increased recording speed and field of view for larger munitions
- Stereo or trinocular system to remove out-of-plane biases
- Improved localization and tracking routines to measure remaining fragments
- Attempt to correlate fragments with early time x-ray videos

Full-scale experiments can provide important information. Still, our ability to capture the statistics of dynamic failure is limited by time and cost.

Opportunities for sub-scale experiments



RP-80 detonator, time in μs

A "mini" explosive
- **Detonation**
- **Case fracture**
- **Reactive burn**
- **Soot production**
- **Fragment propagation**

Sub-scale experiments could provide new opportunities for verification and validation of munitions models

Diagnostics are available to probe many of these dynamics

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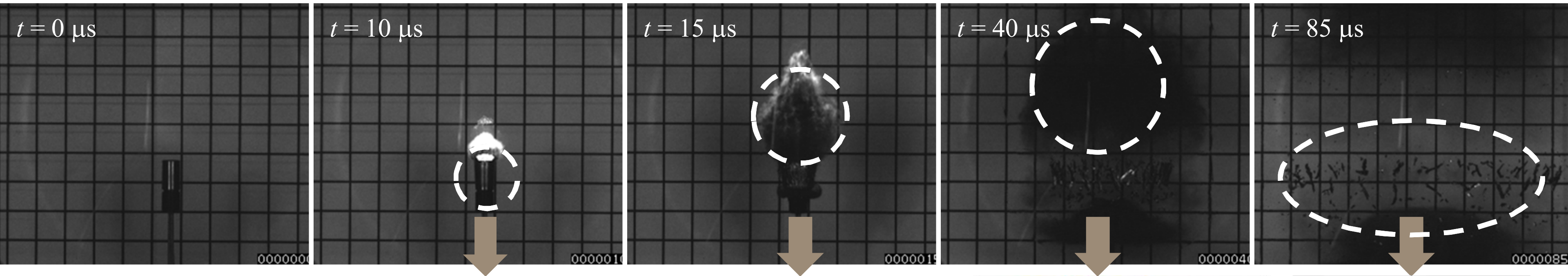
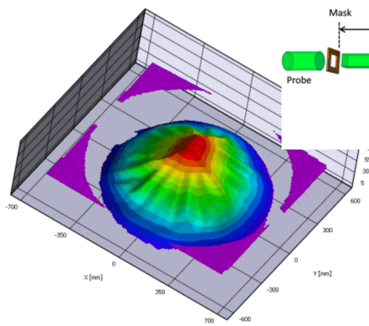
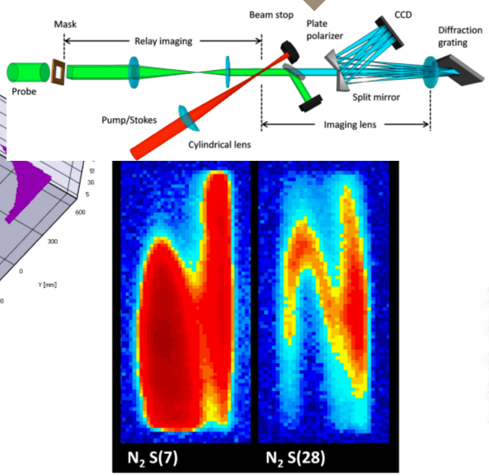
case deformation **fireball dynamics** **soot growth** **fragmentation**

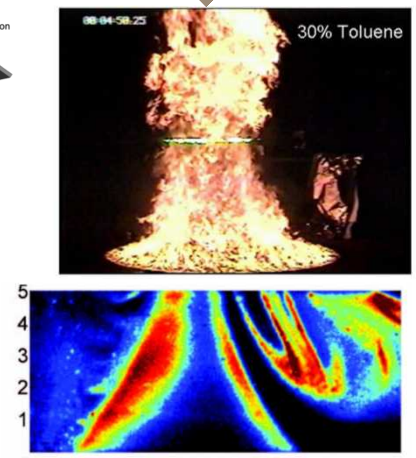




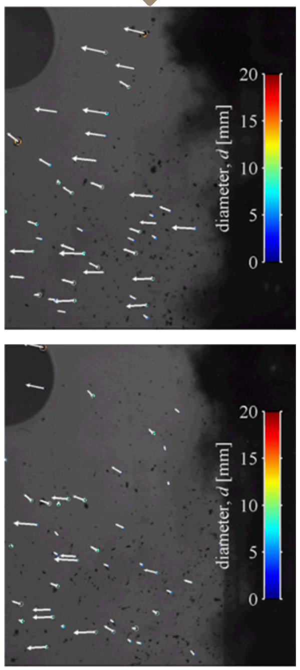
DIC



CARS



LII



Particle tracking / DIH

Note: many of these have been proven elsewhere. R&D is needed to investigate challenges in explosive environments including increased data rates.

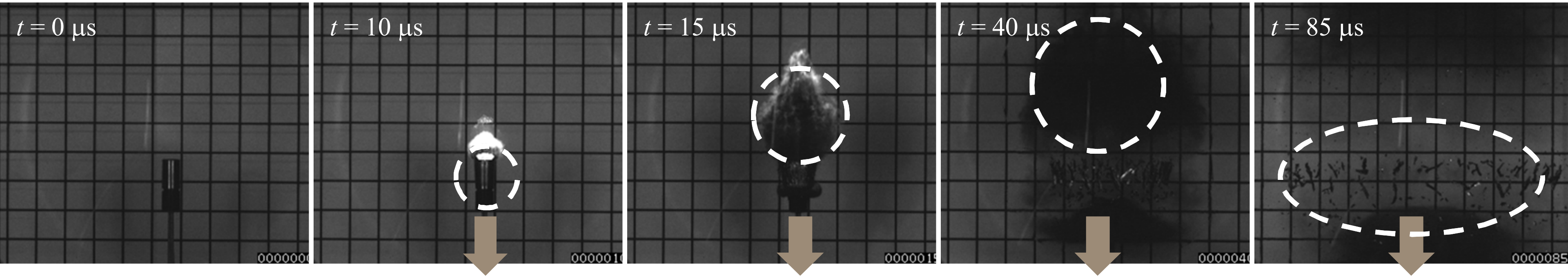
In a sub-scale environment we could probe all the way from case deformation to late time burn and particle propagation

Backup

Proposed work: Detailed diagnostics of an exemplary explosive

Goal: Detailed spatial and temporal characterization of explosive dynamics

- Comparison with simulation would allow for identification of the most critical modeling deficiencies and improve focus of future modeling efforts



case strain quantified using 5 MHz DIC

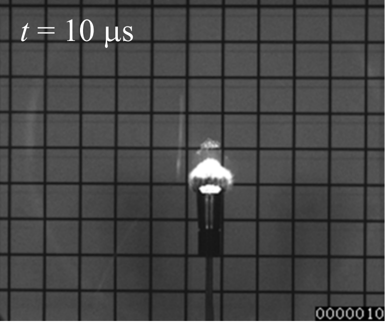
Fireball temperatures and major species concentration (O_2, N_2) using 500 kHz CARS and LIF

Soot structure and concentration using 50 kHz LII

3D fragment tracking and sizing using 20 kHz DIH

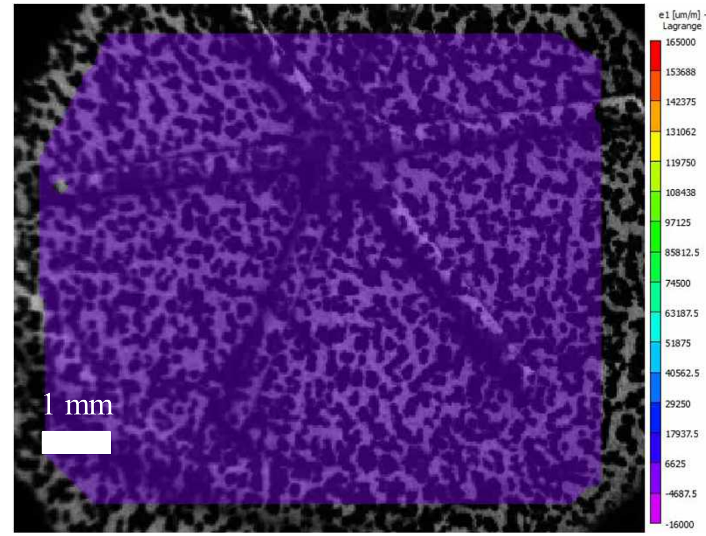
Detailed characterization of this nature is virtually impossible at munitions scale, particularly given the limitations of cost!

Caveat: This work would be complementary to large scale tests and benefit model validation. Due to differences in length and time scales, *full-scale tests remain vital.*

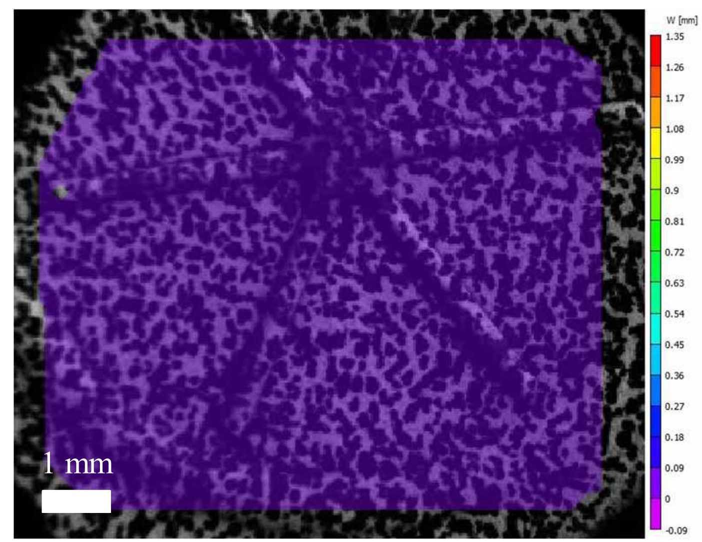


5 MHz DIC quantifies case strain rates

Experimental configuration for 1 MHz DIC of a closure disk



Measured in-plane displacements



Measured out-of-plane displacements

<u>Digital Image Correlation (DIH):</u> image based method for 3D quantification of surface displacements

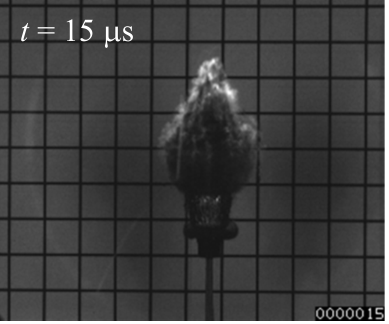
- Will be used to quantify early time case strain rates at 5 MHz

<u>Advantages:</u>

- Full field data from single-shot experiments
- Already proven at these sizes and scales

<u>Challenges:</u>

- New techniques needed for surface speckling of explosives
- Cameras will need to be protected from damage due to fragments and pressure wave



500 kHz CARS and PLIF give temperatures and species

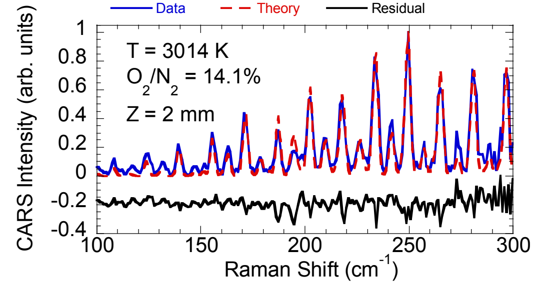
Coherent Anti-Stokes Raman Scattering (CARS) and Planar Laser Induced Fluorescence (PLIF): laser based methods for in-situ temperature and major species concentrations (N_2, O_2) at a point, along a line, or even in a 2D image plane

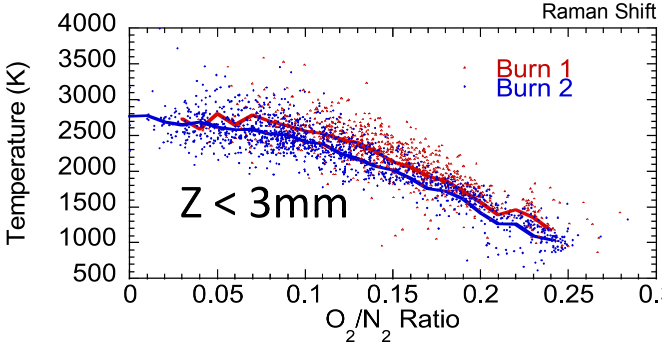
Advantages:

- Non-obtrusive, high precision (1% or better)
- Does not rely on path averaging like traditional emission spectroscopy of explosives, eliminating the associated uncertainty
- Time delayed, pump/probe eliminates noise caused by scattering off particles in the flow
- Potential to resolve temperature and concentration gradients with accuracy greatly exceeding current methods

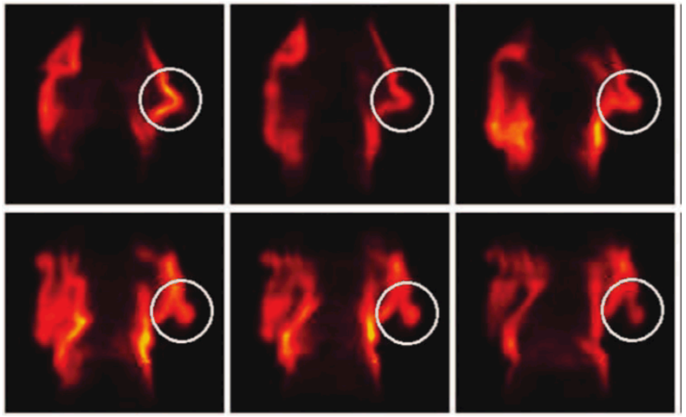
Challenges:

- Ultra high-speed (100s of kHz) CARS is a nascent technology which has not been proven in this environment

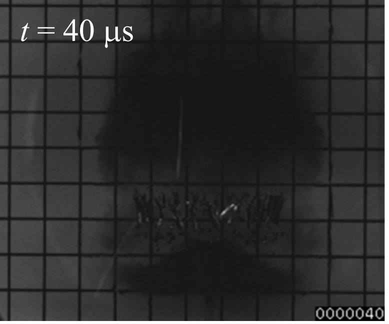




CARS temperature diagnostics in a metallized propellant flame



50-kHz OH PLIF imaging in turbulent flames (Meyer/Gord group, Iowa State/AFRL)



50 kHz LII quantifies soot concentration

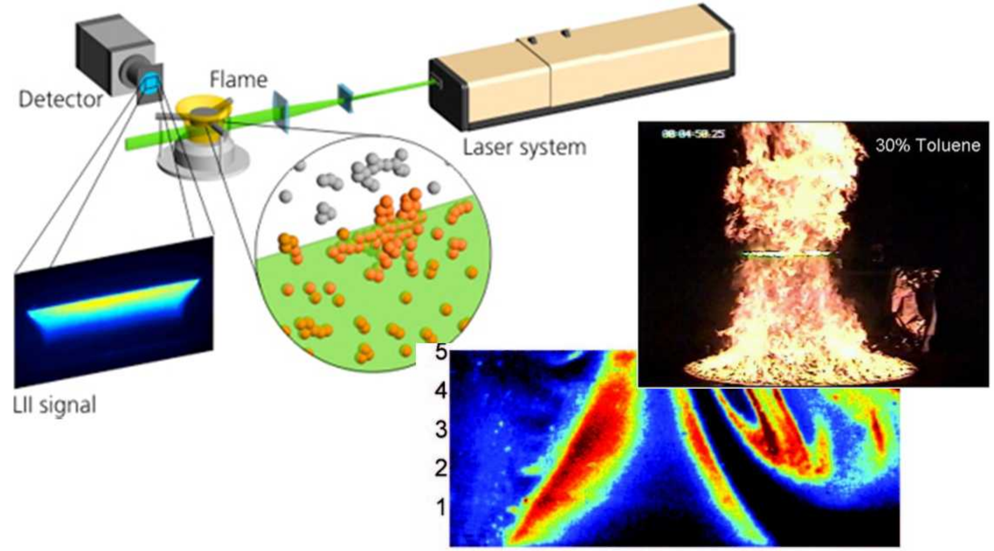
<u>Laser-induced incandescence (LII):</u> method for 2-D imaging of soot concentration and particle size (TIRE-LII). Can potentially be utilized for other aerosol species as well.

<u>Advantages:</u>

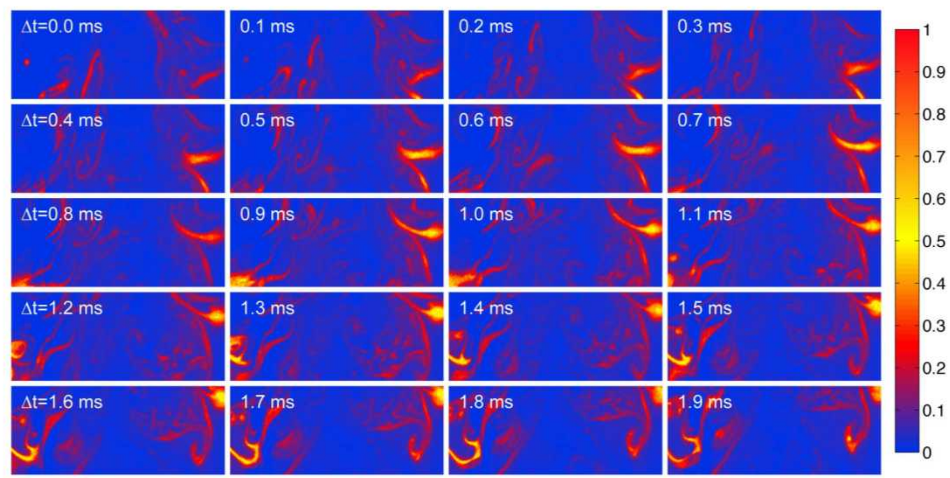
- High spatial (50 mm) and temporal (30 ns) resolution. Capable of resolving soot layers that are sub-millimeter scale
- Two-dimensional quantitative imaging
- Relatively straightforward to implement compared to many other diagnostic approaches

<u>Challenges:</u>

- Beam absorption in optically thick environments.
- Must limit laser energy to avoid perturbing measurements.
- Laser and detector technology for kHz detection has only recently been developed. High-speed version of this technique is in its infancy.



Pool Fire LII at Sandia



10-kHz LII, J. Michael et al. Appl. Opt. 2015

Enabling technology: Pulse-burst laser

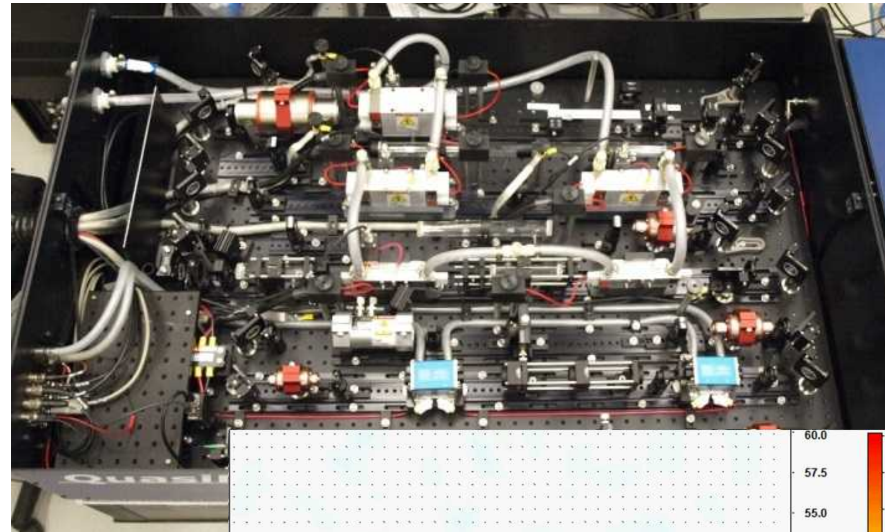
These measurements have only recently become possible with the emergence of pulse-burst laser technology

- SNL's pulse burst produces bursts of pulses with repetition rate up to 100s kHz and pulse energies of 100s of mJ.
- To date the pulse burst has been mostly applied for velocimetry

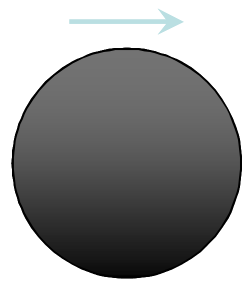
The proposed work extends this technology to spectroscopic thermochemical measurements

Challenges:

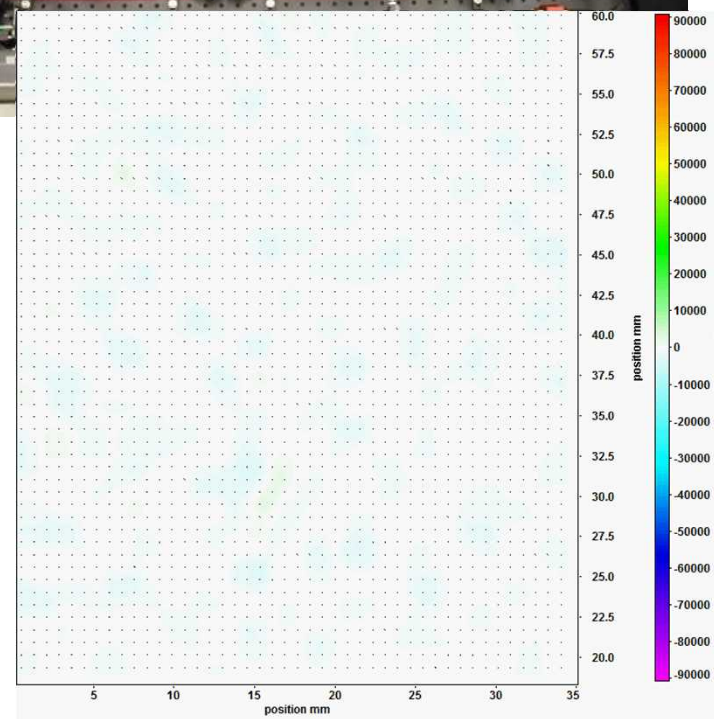
- Will require advanced OPO/OPA technology for wavelength tunability
- Technology must be extended to the ps and possibly even the fs regime
- Energy levels and repetition rates may need to be extended beyond the capabilities of our existing laser



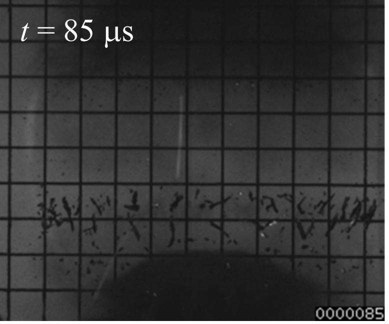
Full Span Cylinder



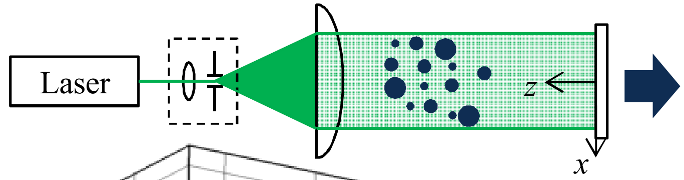
Re = 1.8×10^5

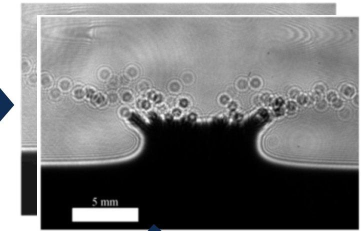


50 kHz PIV measurements by Wagner *et al*



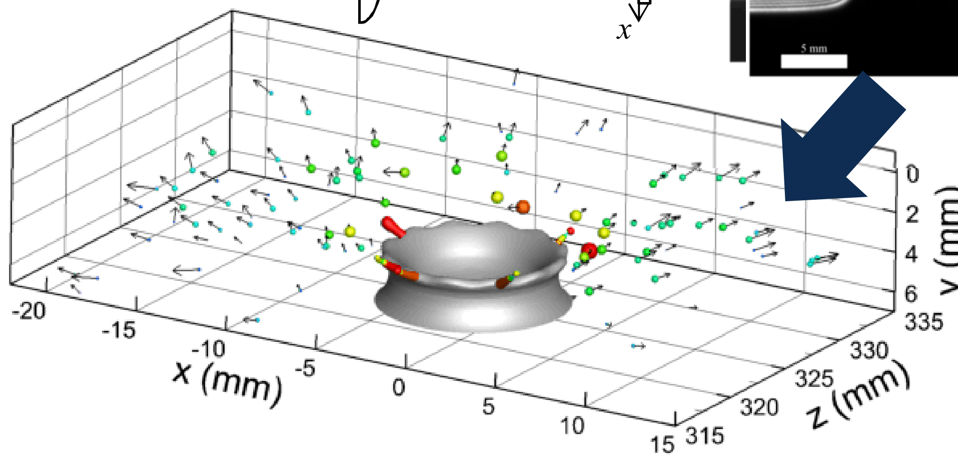
20 kHz DIH yields fragment trajectories and sizes

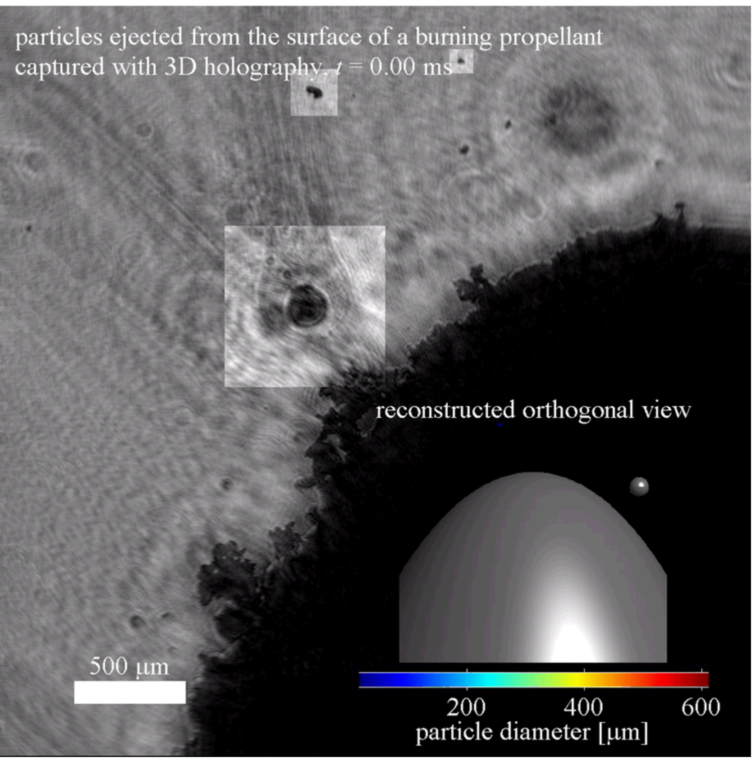




Digital In-line Holography (DIH): laser-based method for 3D quantification of particle positions, sizes, and velocity

- Will be used to quantify fragment size and velocity statistics at 20 kHz



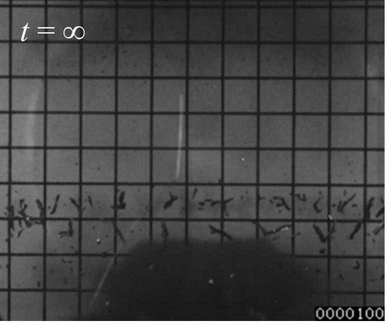


Advantages:

- Size-velocity correlations from single shot measurements
- Active illumination overcomes flash
- Quantifies non-spherical fragment properties

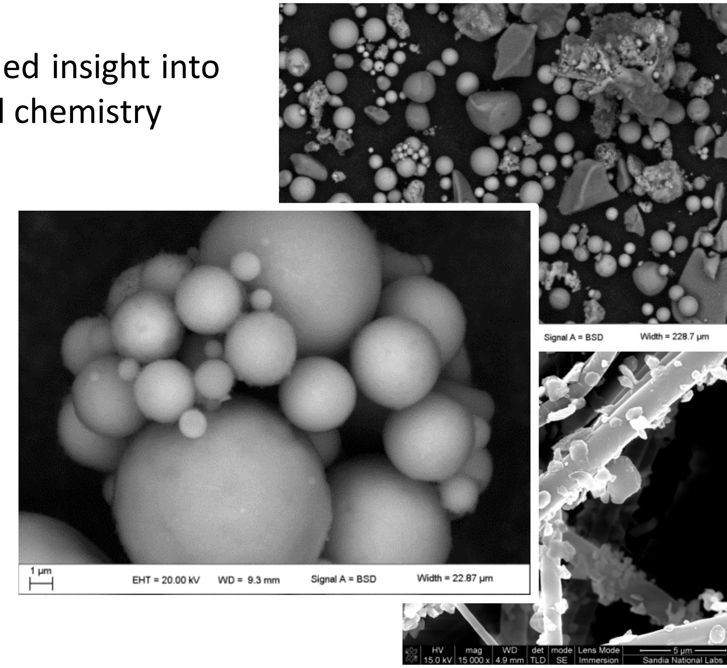
Challenges:

- Image degraded by soot and index of refraction gradients
- Particle size dynamic range and field of view must be carefully matched to the experiment



Particle sampling for detailed micro-chemistry/structure

- Particle collection and analysis provides detailed insight into soot and sub-micron particulate structure and chemistry



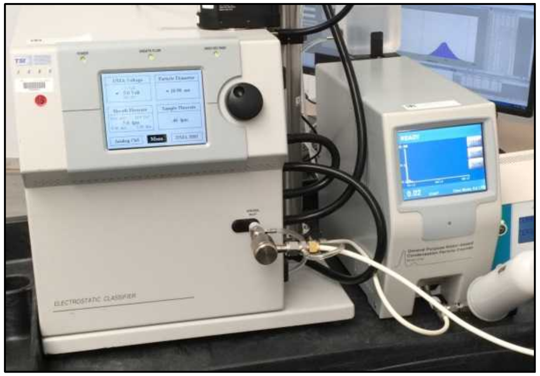
Advantages:

- Quantify size distribution of sub-micron particulate
- Provide soot optical properties needed for LII measurements
- Possible to measure particulate chemistry

Challenges:

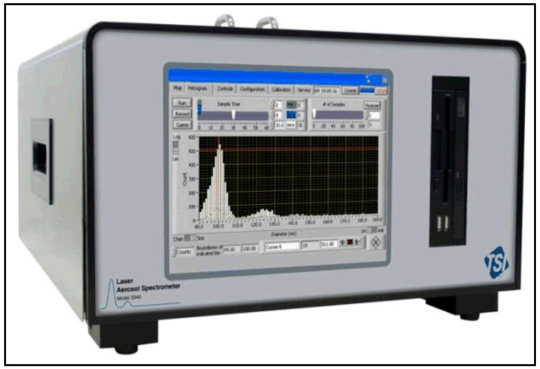
- Sampling techniques must be carefully designed to avoid biases

- Electrical mobility
  - 1-1000 nm



- Mechanical mobility
  - 0.4-20.0 µm

- Light scattering
  - 0.09-7.5 µm

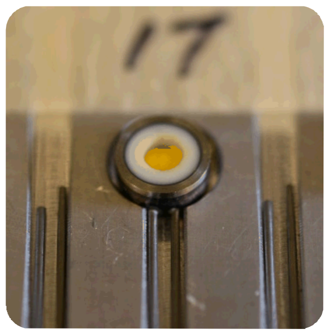


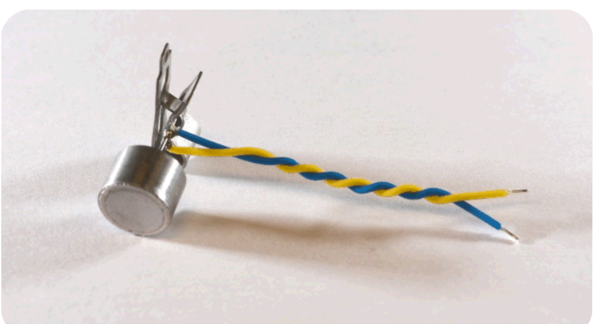
Expansion on commercial detonator based experiments

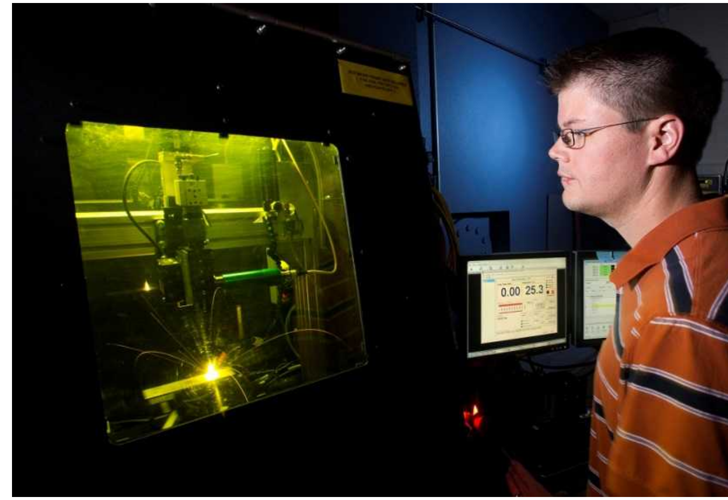
Sandia National Laboratories

Custom laboratory scale components produced by SNL

- While use of commercial detonators allows for relatively inexpensive test units, the material set and geometry is limited.
  - May not be fully representative of materials or geometries of interest







Advantages:

- Use of variety of materials (energetic as well as inert casing) to better approximate a configuration of interest
- Ability to tailor experimental explosive devices to be better suited for model validation
- Flexibility to iterate on designs quickly

Challenges:

- Scaling configurations of interest to laboratory sizes presents unique challenges
- Configurations of interest deviate may from typical SNL explosive components