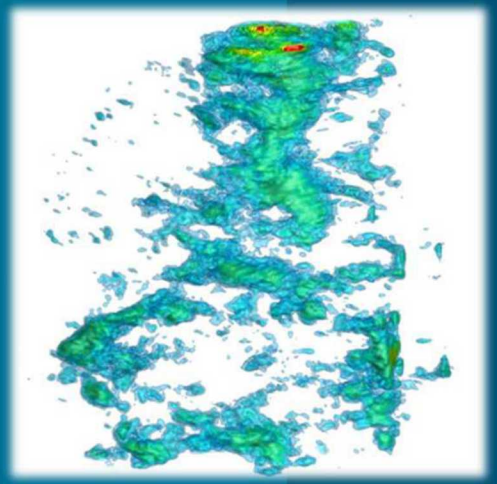
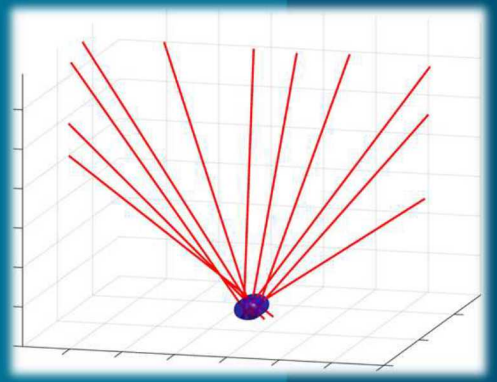
SAND2019-0979PE

Development of X-ray Imaging for Multiphase Flows





PRESENTED BY

Benjamin R. Halls

University of Virginia

January 31, 2019, Charlottesville, VA

SAND2019-
Previously cleared: SAND2018-14348C,
88ABW-2018-3510, 88ABW-2018-1181

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Outline of Presentation

Motivate x-ray measurements

Overview of x-ray physics

Overview of the impinging jet spray

Hypotheses:

- Can polychromatic x-ray sources be used for quantitative mass distribution measurements?
- Can we capture four-dimensional information using tomography?
- Can x-ray fluorescence be used to measure liquid mixing in sprays?
- Can we map the out-of-plane information without tomography?
- Can we measure the liquid temperature using x-ray diffraction?

Overview of explosive devices

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Dense Sprays and Need for X-rays

Dense Droplet Fields
- Multiply scattered photons
- Large Liquid Structures
- Refracted or reflect photons

Advanced Optical Techniques
- Reviewed by Linne in PECS
- Ballistic Imaging
  - Temporal gating
- Structured Light Imaging
  - Spatial encoding
- Optical Connectivity
  - Total internal reflection

Interference Free
- Local geometry does not perturb measurement

Radiography / Attenuation
- Photoelectric absorption
- Scattering

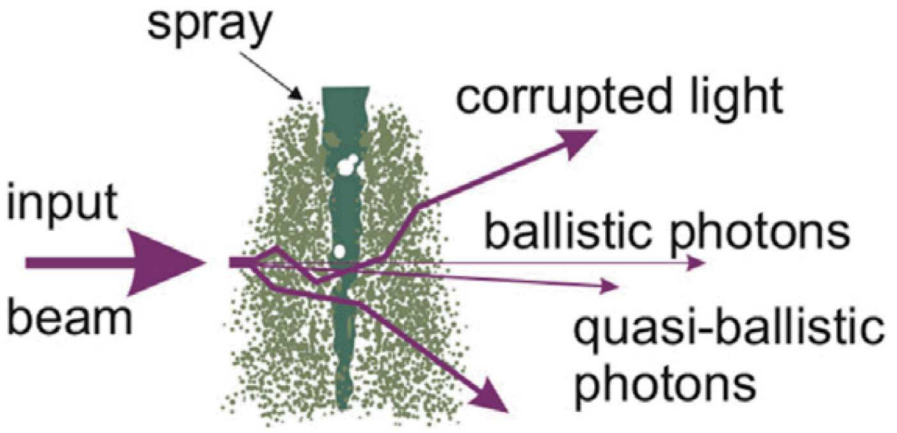
X-ray Fluorescence
- Photoelectric absorption
- Emission of characteristic x-ray

X-ray Scattering
- Compton scattering
- Rayleigh scattering

Impinging Jet Spray

Visible X-ray

Halls et al., Opt. Express (2017)



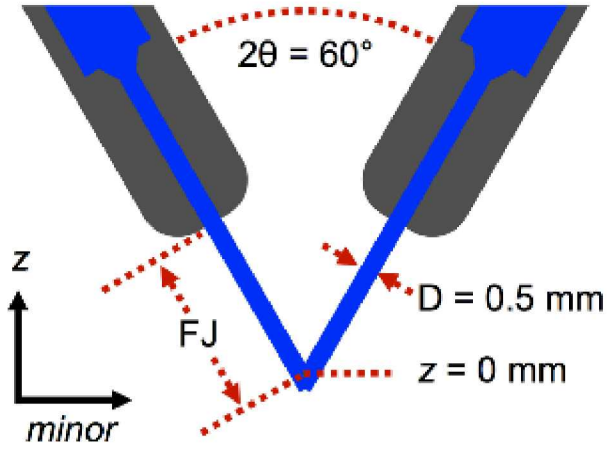
Linne, PECS, 2013

Impinging Jet Spray

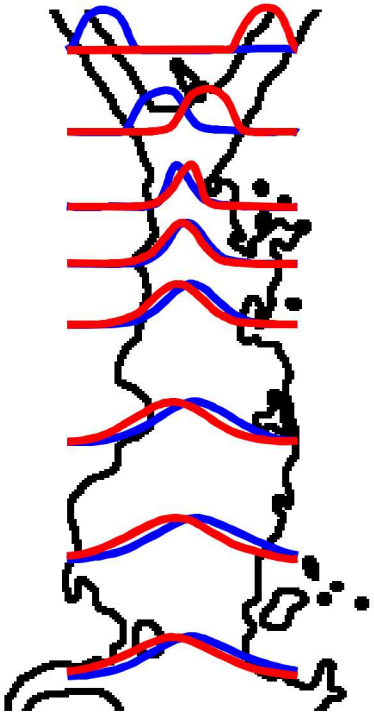
Impinging Jet Injector

- Rapidly mix and atomize fluids
- Jets collide and form a sheet, ligands, and droplets

Injector Diagram

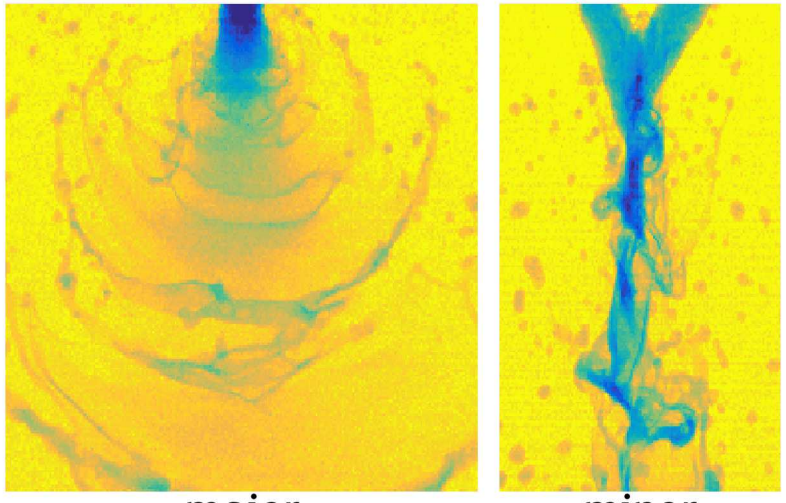


Time-Averaged X-ray Fluorescence



Halls et al., Opt. Express (2015)

High-Speed X-ray Imaging



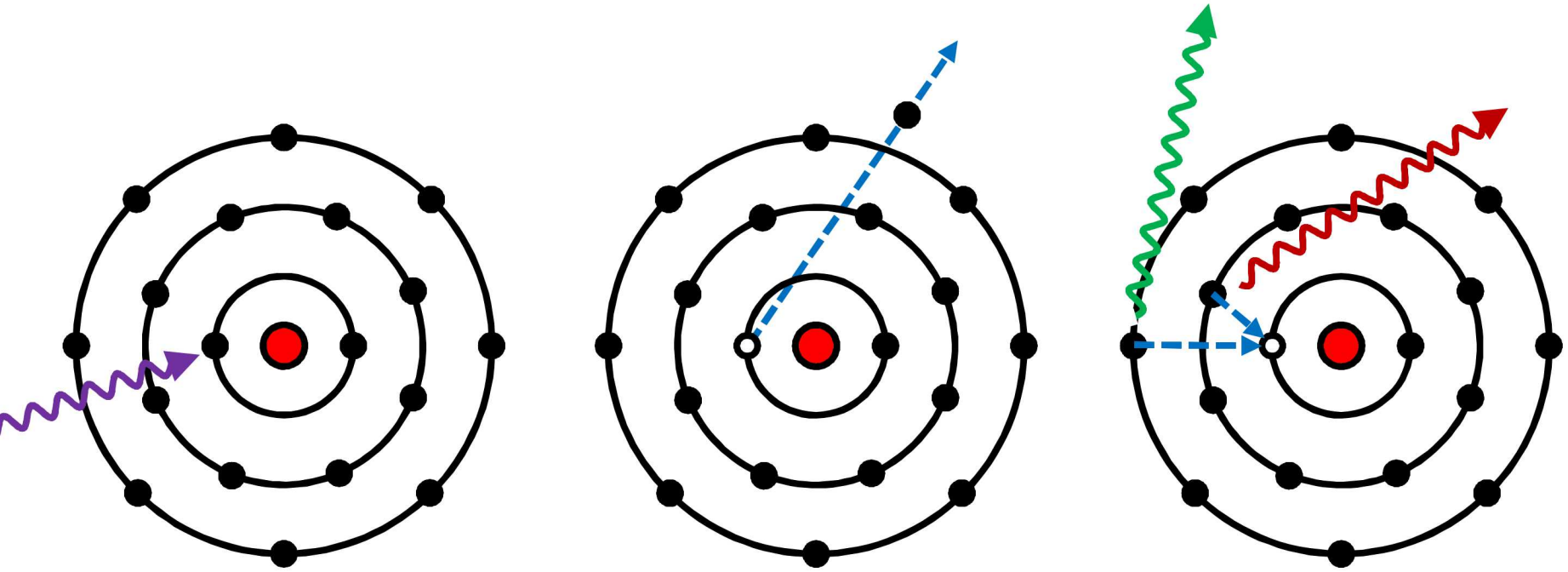
major *minor*

Halls et al., Opt. Express (2017)

Attenuation and Fluorescence

Photoelectric Absorption

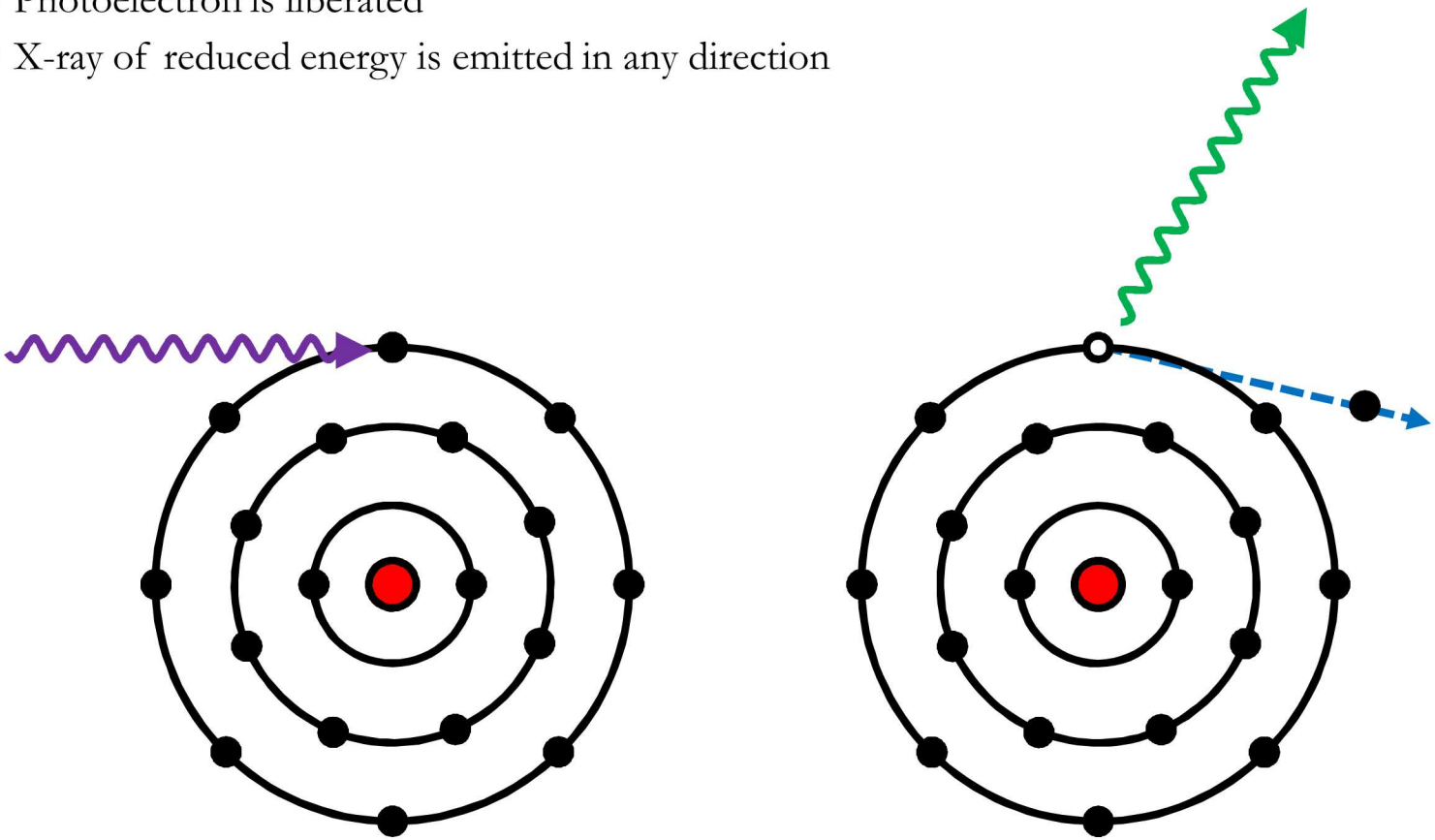
- All photon energy absorbed by electron
- Photoelectron is liberated
- Outer electron fills vacancy, may produce characteristic photon



Inelastic Scatter

Compton (inelastic) Scatter

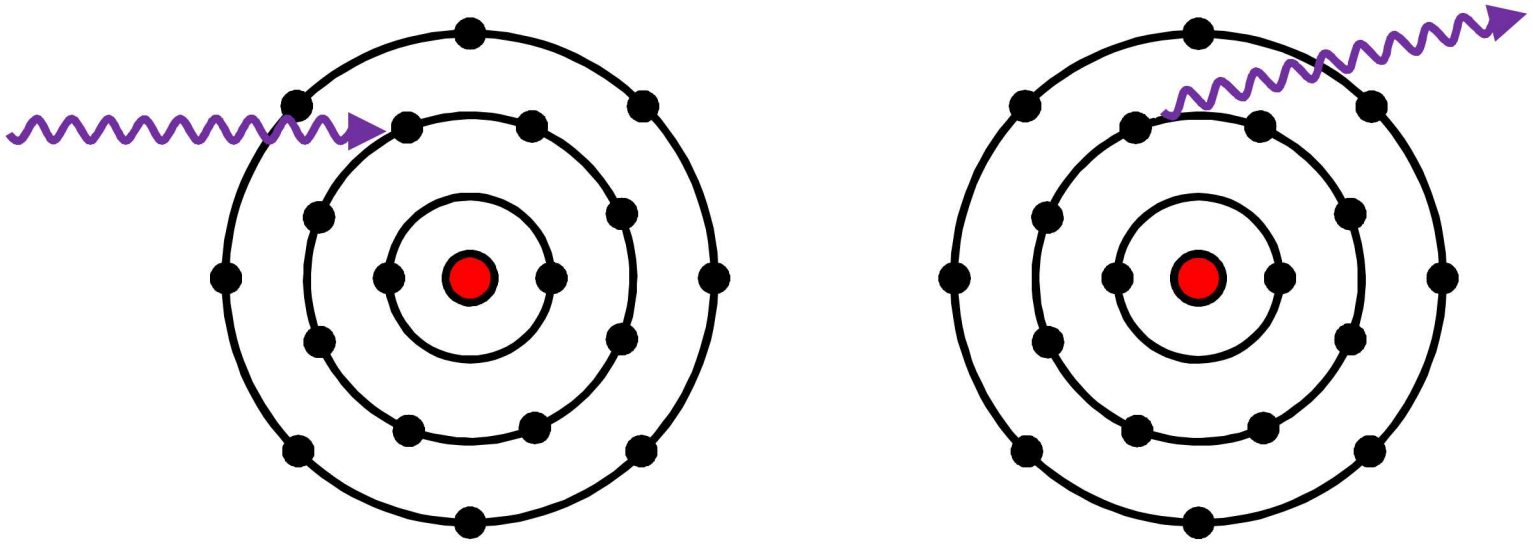
- Some photon energy is absorbed by electron
- Photoelectron is liberated
- X-ray of reduced energy is emitted in any direction



Elastic Scatter

Rayleigh (elastic) Scatter

- Photon wiggles electron, leaves at new angle, predominantly forward
- Coherent event



Challenges with X-ray Diagnostics

Path-Averaged Measurement (typically)

Tomography can be applied!

What happens when tomography is not feasible

High pressure applications?

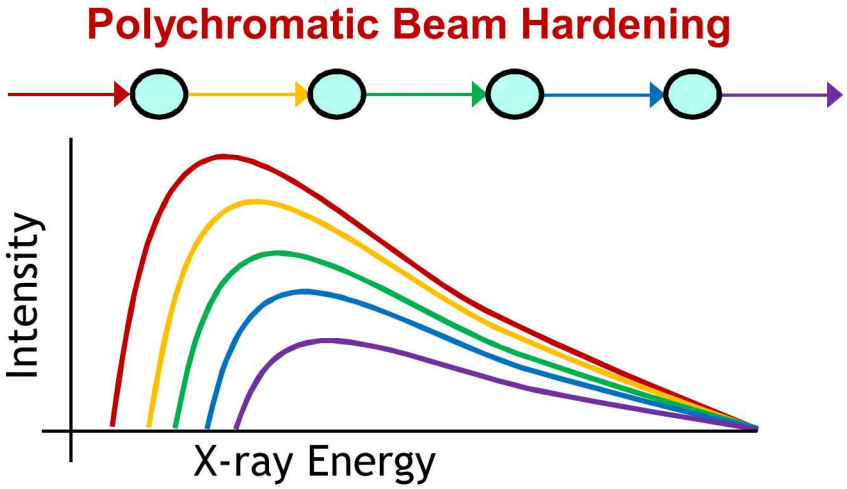
Wind tunnel applications?

Mass Distribution (typically)

Radiography and fluorescence are functions of local density

Phase contrast – highlight interfaces

SAXS – droplet sizes



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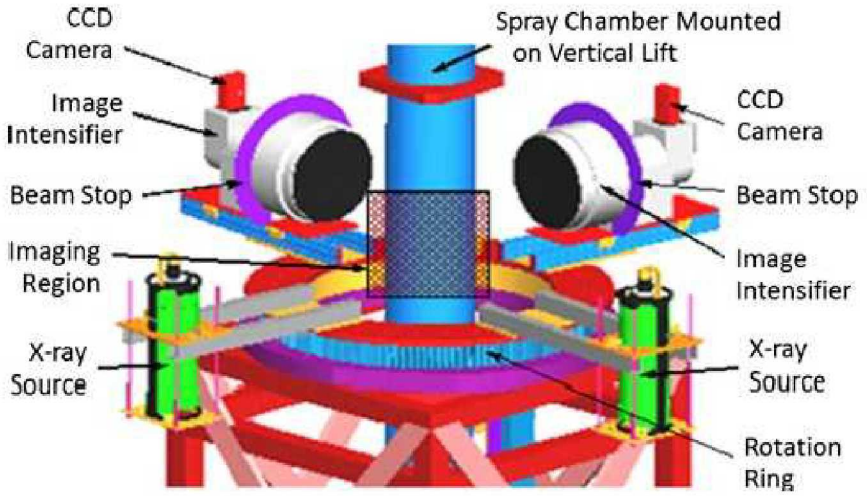
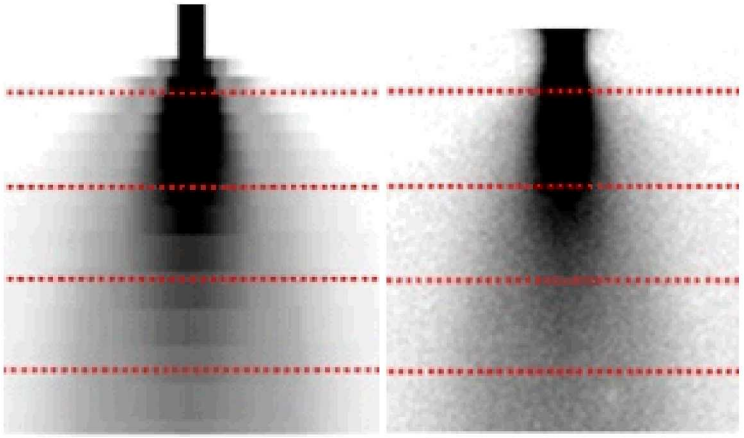
Time-Averaged Radiography and Computed Tomography

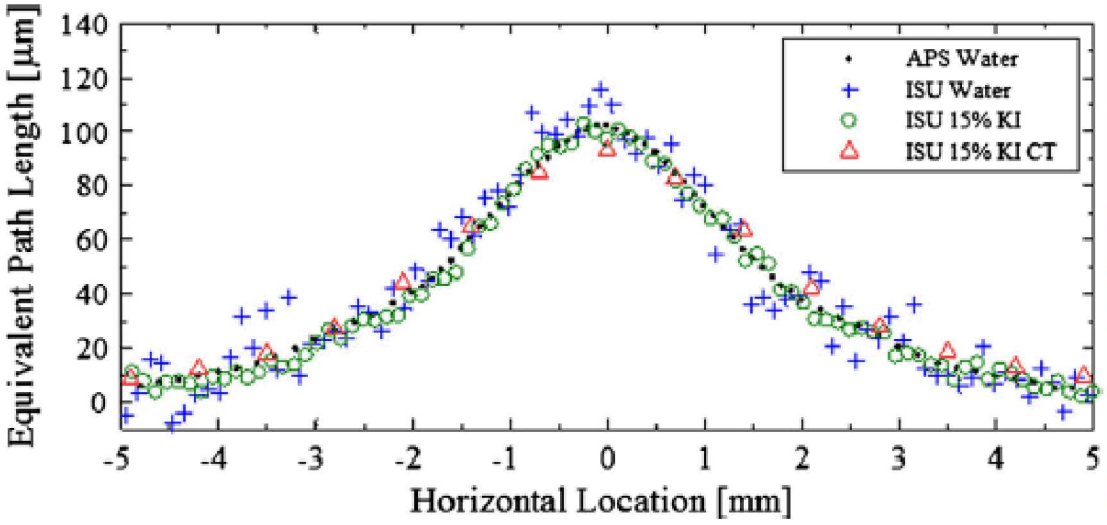
Time-averaged comparison of static anode tube source with synchrotron measurements

Measurement Schematic



Synchrotron **Tube Source**

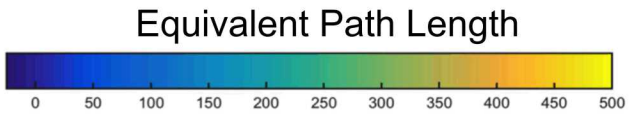


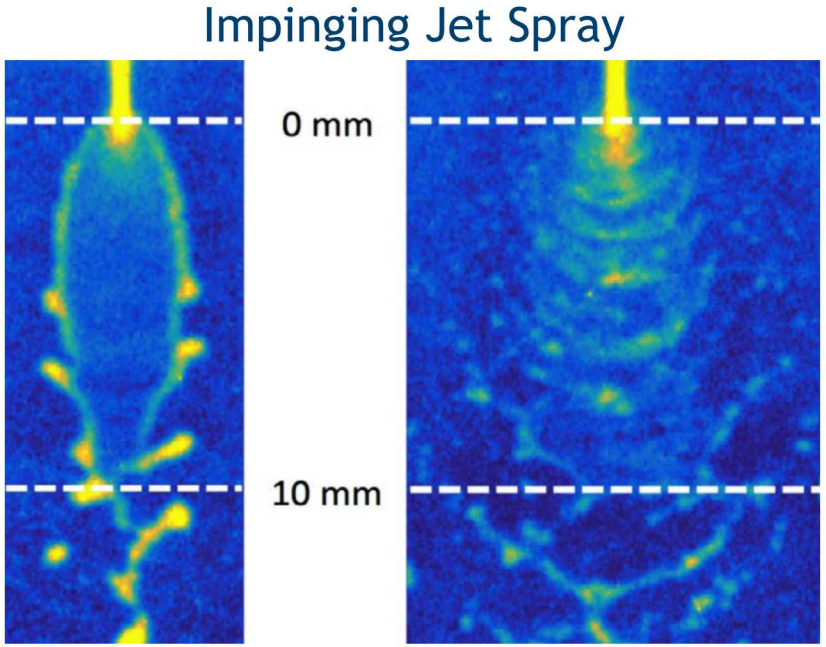


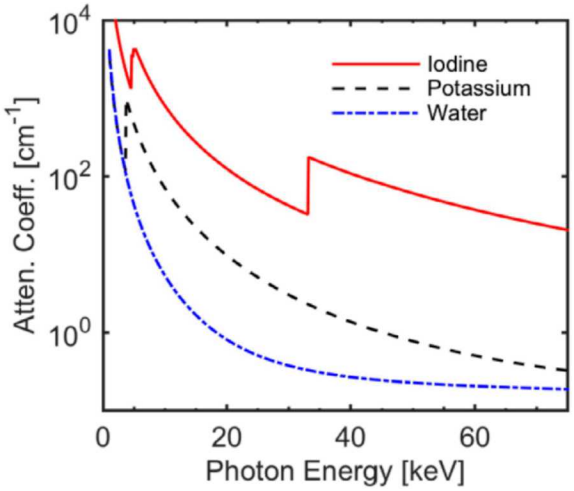
Halls et al., IJMF (2014)

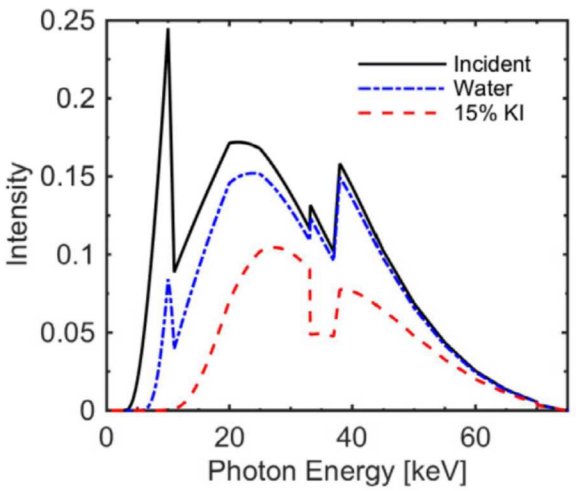
Flash X-ray Imaging

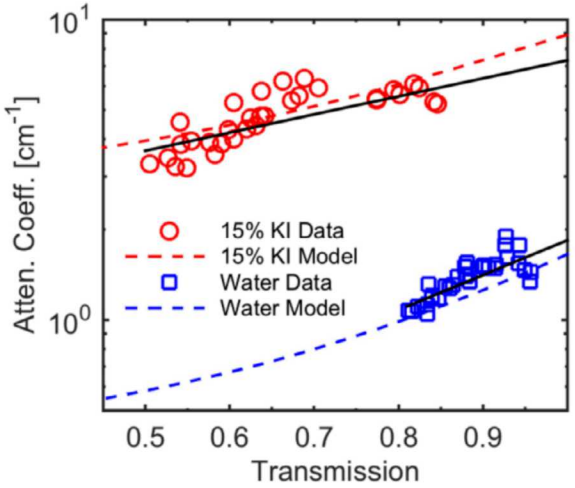
Quantitative measurement of mass distribution is possible with polychromatic x-ray source when the spectrally resolved attenuation coefficient has been determined.









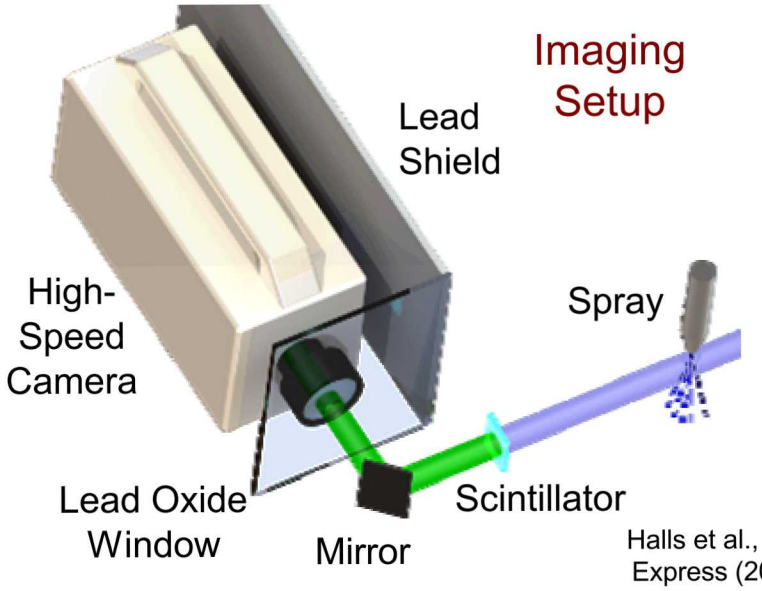


Halls et al., IJMF (2017)

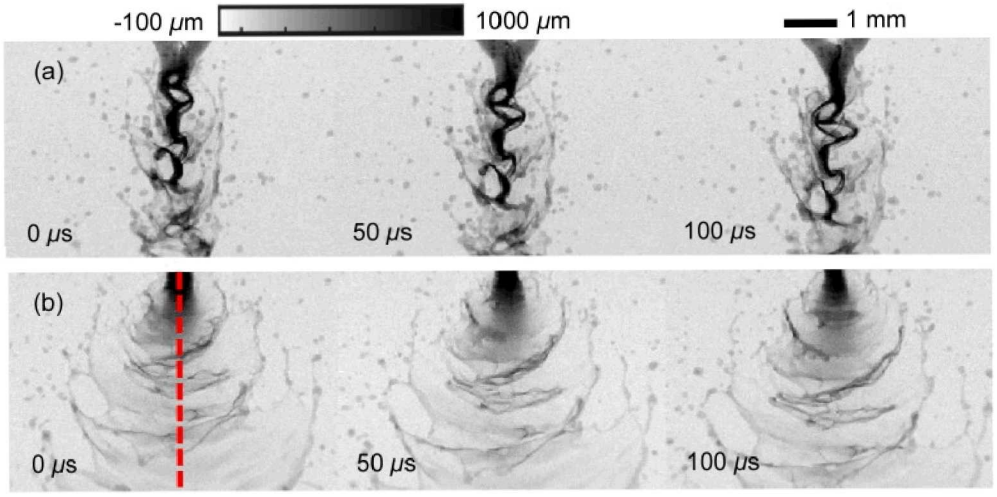
Synchrotron Radiography

Experimental Setup

- White beam
- 500-µm-thick YAG:Ce scintillator
- Photron SA-Z CMOS camera
- Nikon lens pair 105 mm & 50 mm, f/2.8
- Frame rate = 78 kHz
- <1 ns x-ray pulse, captured
- Spatial resolution ~40 µm



Halls et al., Opt. Express (2017)



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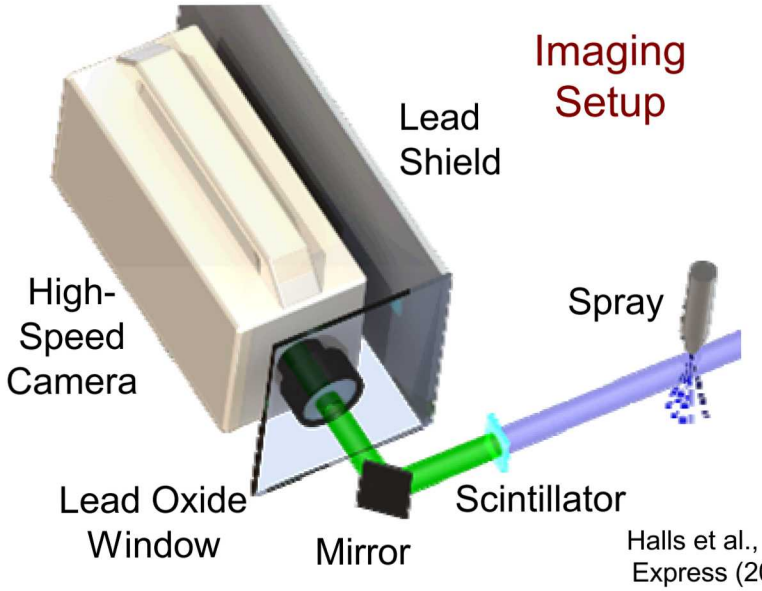
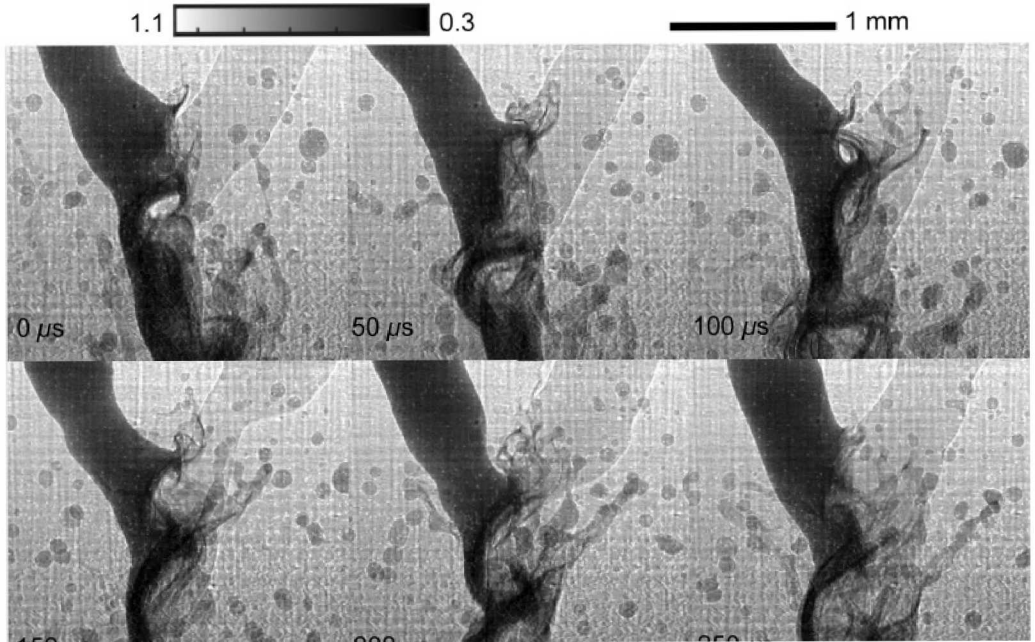


Halls et al., Opt. Express (2017)



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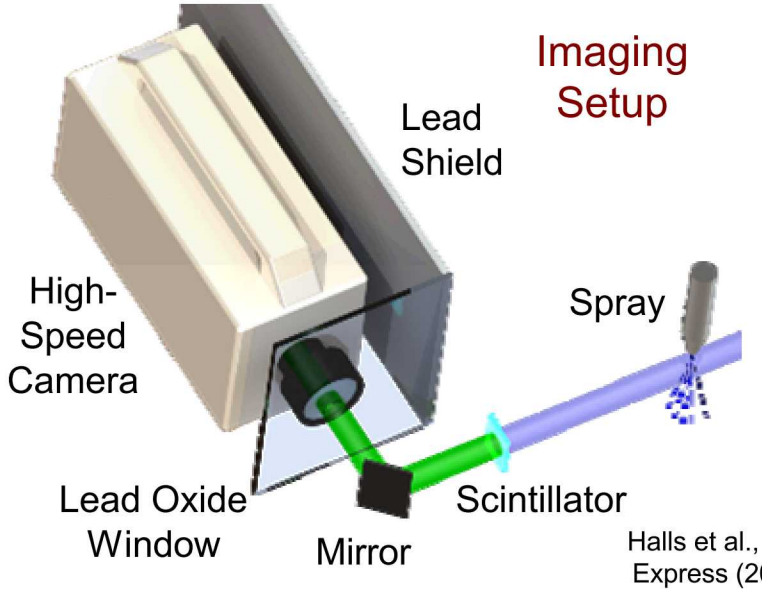
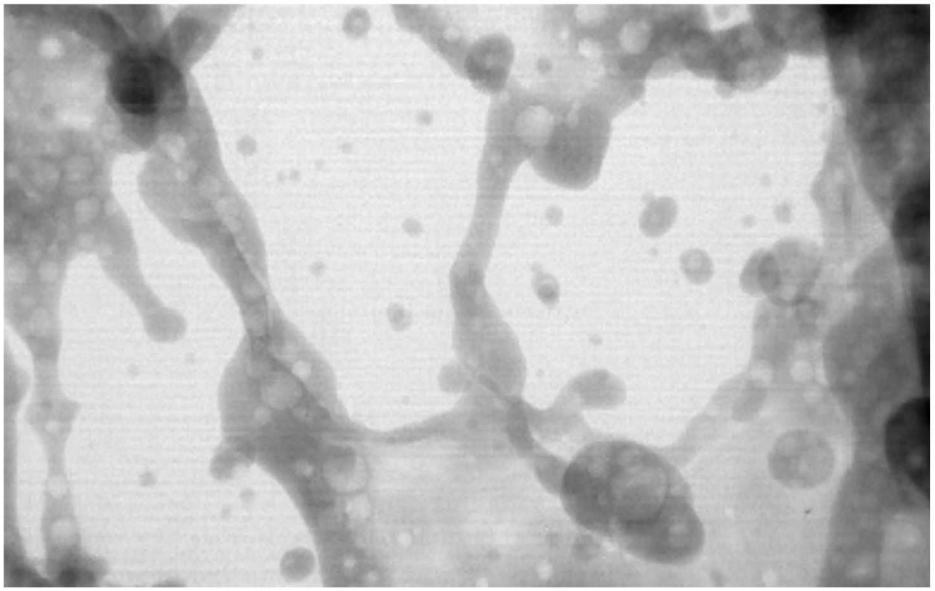


Halls et al., Opt. Express (2017)



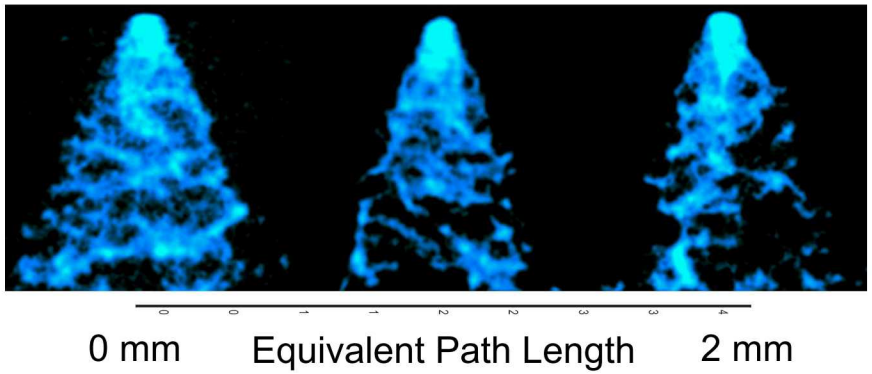
Radke et al., AIAA (2017)

Optimal Placement and Different Configurations

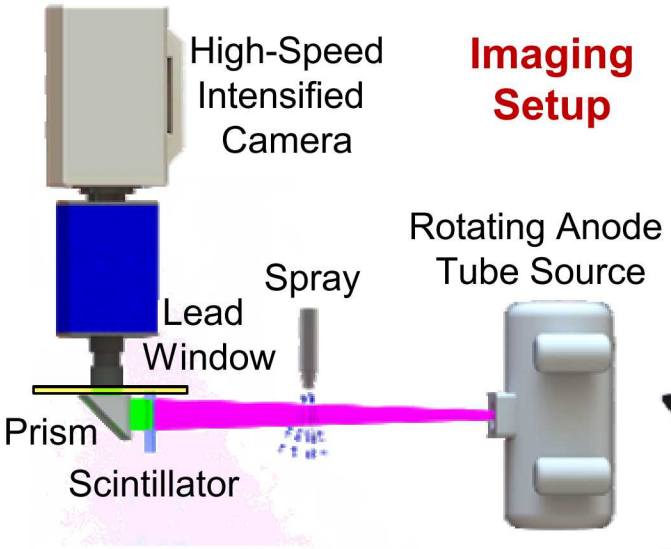
Experimental Setup

- Variable voltage x-ray source
- Photron SA-Z camera + IRO
- Nikon lens 50 mm / CsI scintillator
- Frame rate = 10–50 kHz
- 20 μs exposure
- Model imaging system
- Variable attenuation coefficient

3 Perspectives of Solid Cone Spray

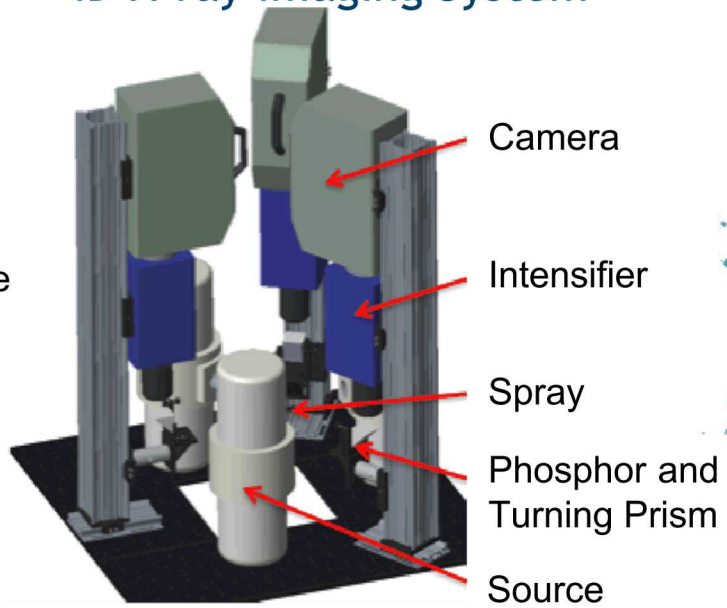


Imaging Setup

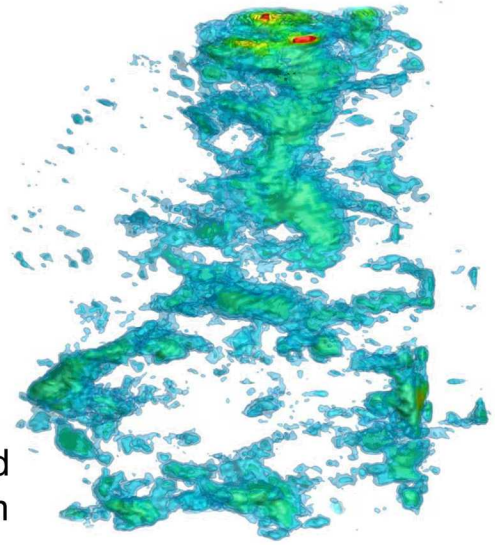


Halls et al., IJMF (2018)

4D X-ray Imaging System



Solid Cone Spray Reconstruction



Halls et al., LACSEA (2018)

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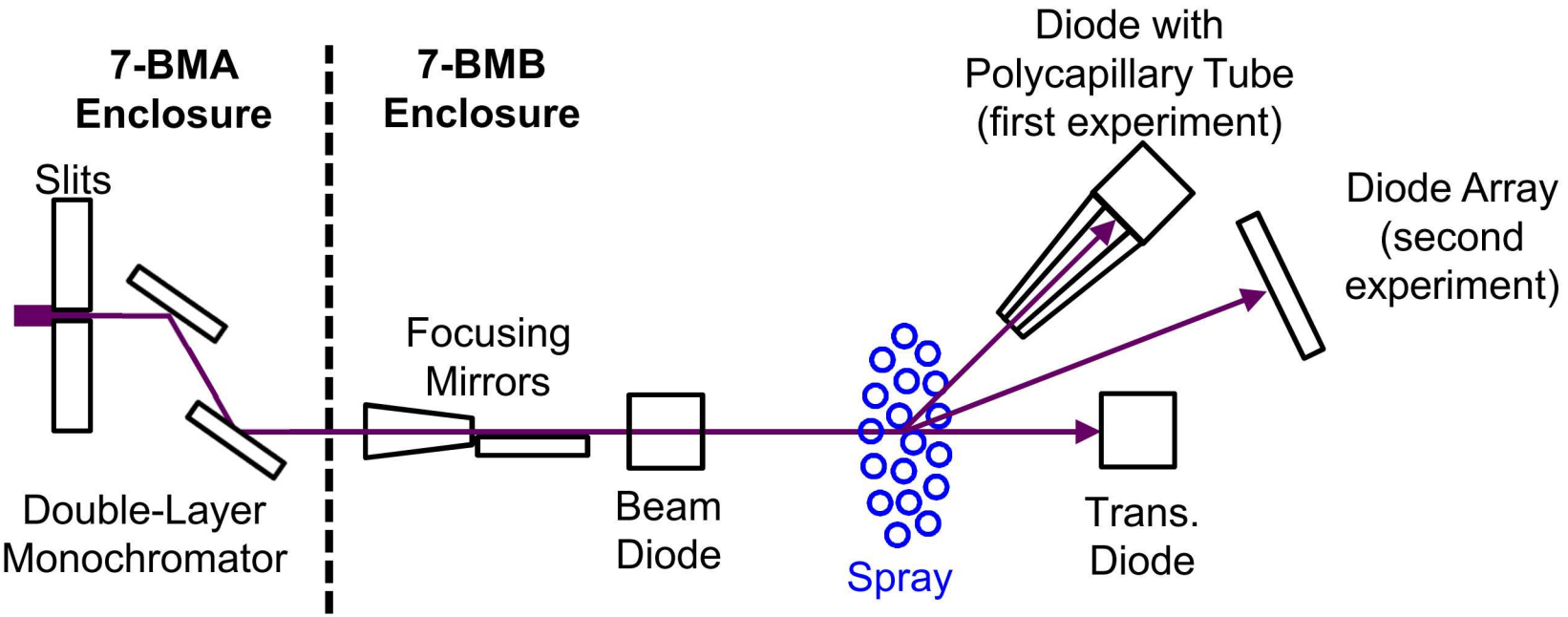
Synchrotron Measurements

Advanced Photon Source at Argonne National Laboratory

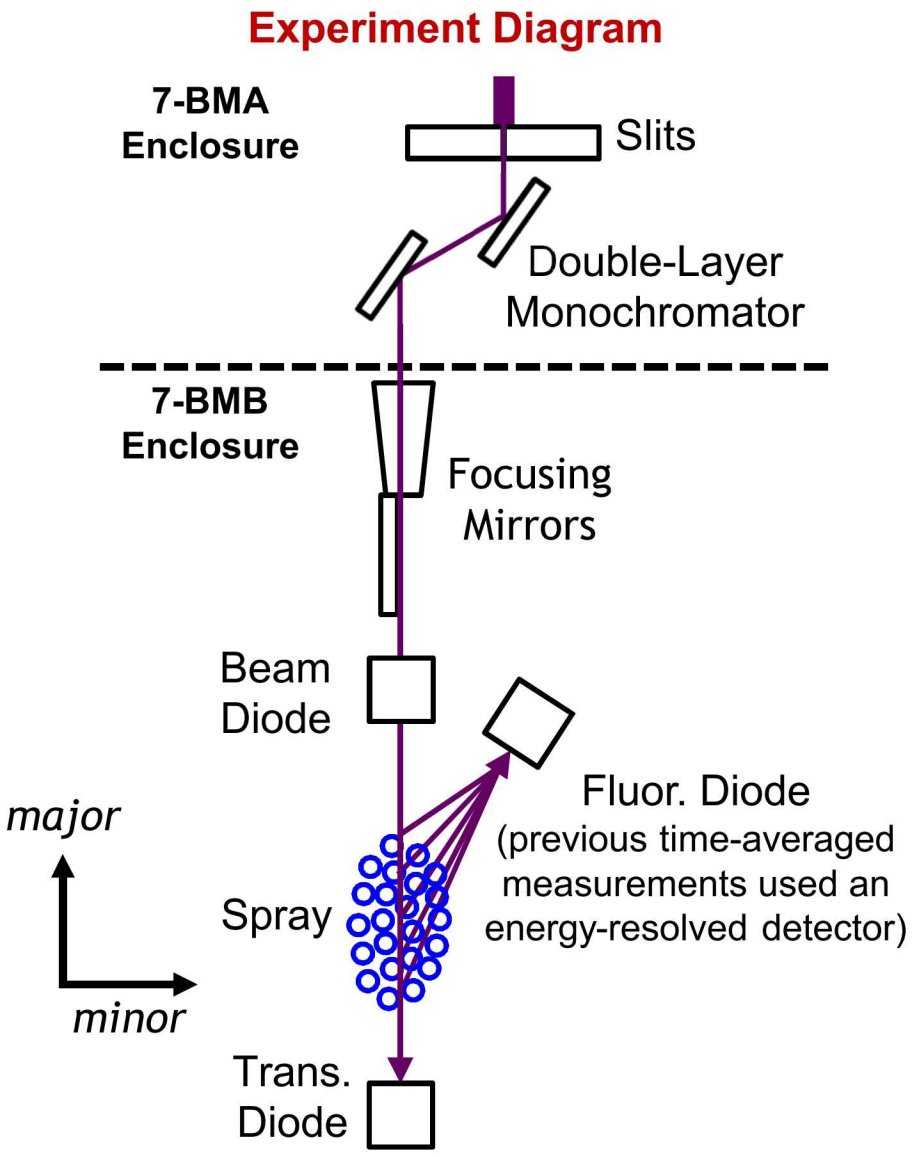
- 8–15 keV nominal energy ($\Delta E/E = 1.0$)
- $5 \times 6\ \mu m^2$ (vertical × horizontal) spot, using Kirkpatrick-Baez focusing mirrors
- Confocal Imaging: sample portion of x-ray beam with polycapillary tube
- X-ray thermometry: image scatter on photodiode array



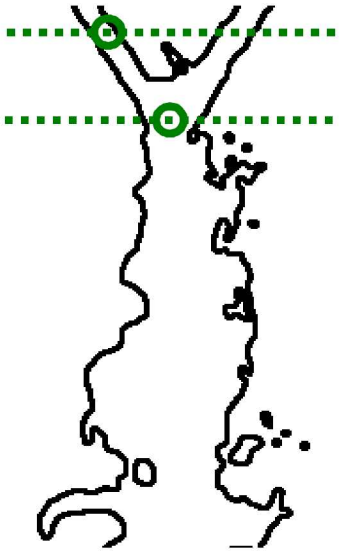
Synchrotron Measurements

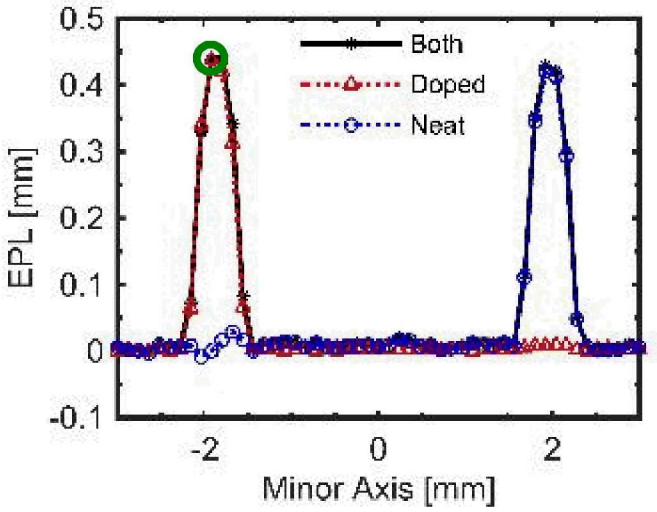
Experimental Setup

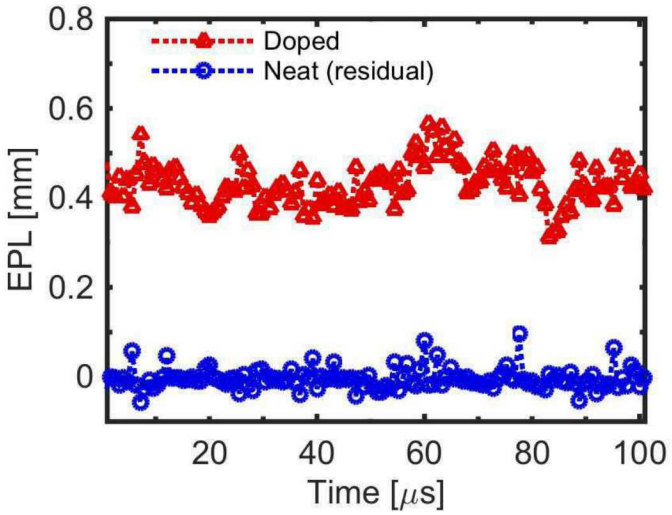
- 15 keV beam
- Spatial filtering
- Forward elastic scatter
- Isotropic fluorescence
- Impinging jet, Re = 5,000
- Doped jet = 2.5% NaBr by mass
- Fluorescence
- NaBr Kα line at 14 keV
- Neat jet = pure water
- Attenuation
- Neat = Both – Doped

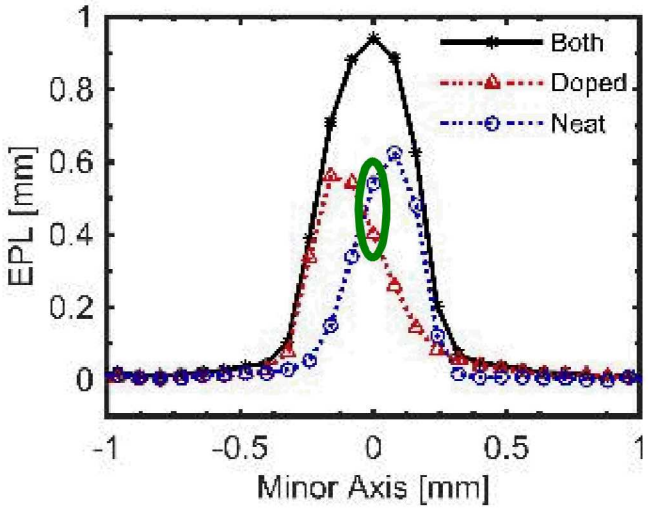


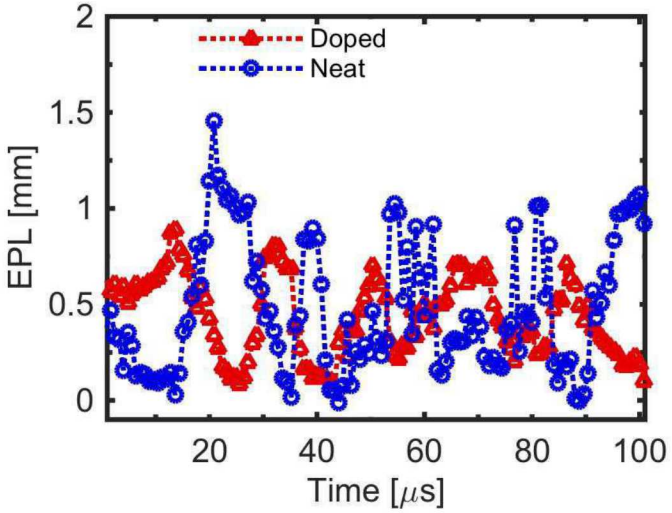
High-Speed X-ray Fluorescence











Halls et al., ILASS (2017)

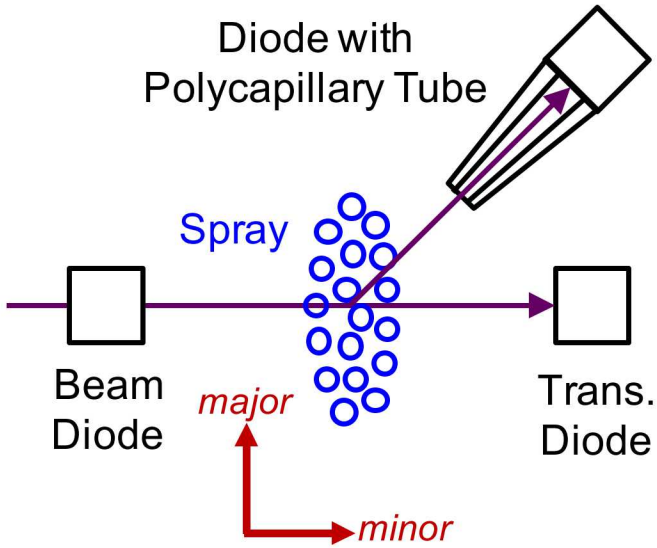
Confocal X-ray Scatter

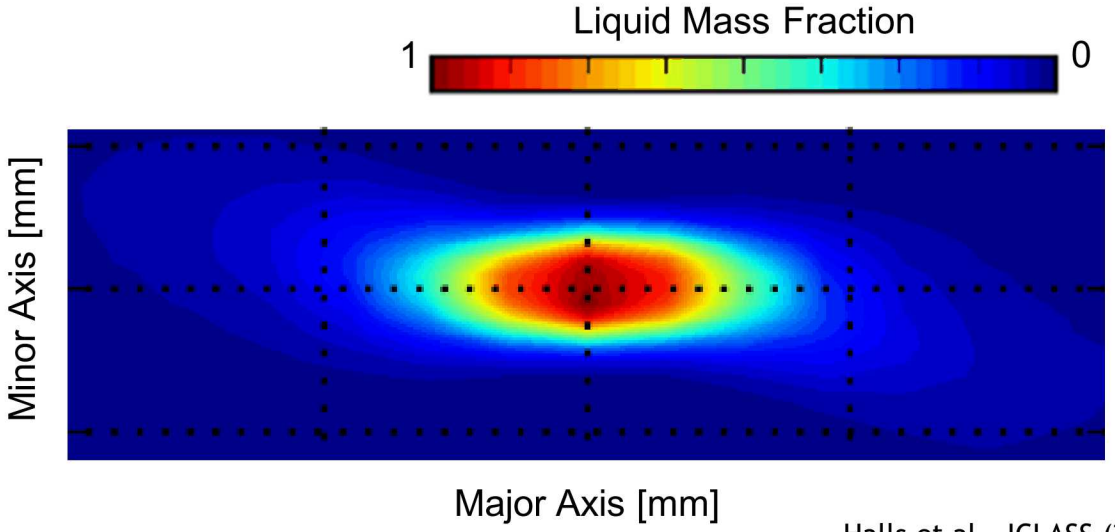
Diagnostic Setup

- PIN diode coupled to polycapillary at ~30°
- Measurement volume of $5 \times 6 \times 300\ \mu m^3$, based on polycapillary spatial resolution

Like-Doublet Impinging Jet Atomizer

- Distilled water
- Enclosed angle = 60°
- Jet diameter = 0.51 mm
- Reynolds = 5,000





Halls et al., ICLASS (2018)

X-ray Thermometry

Diffraction Pattern

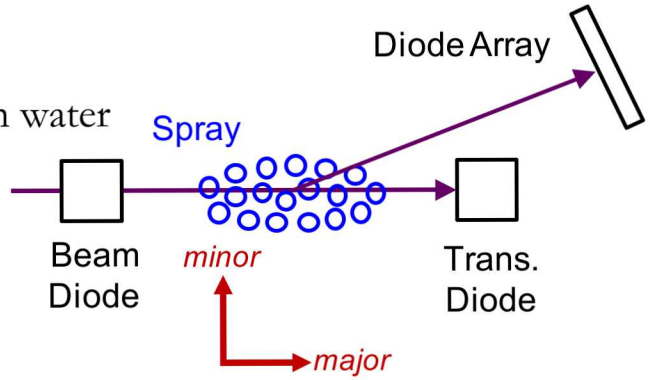
- Coherent scattering from nearest neighbor oxygen atoms in water
- Imaged 50 mm from spray

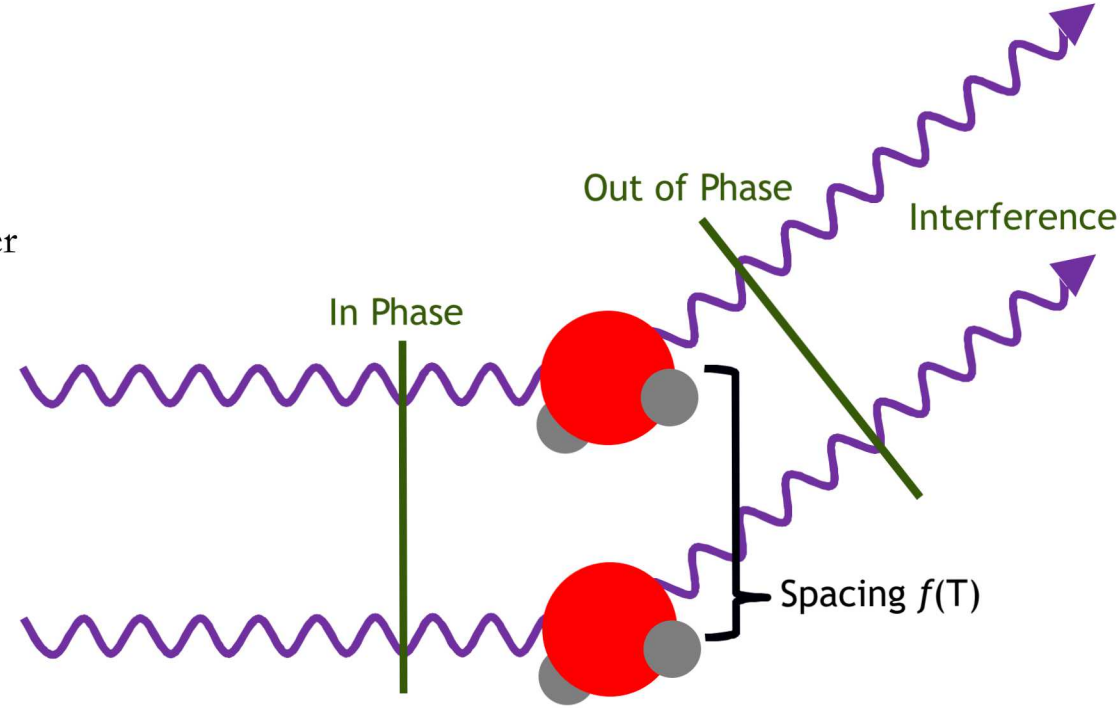
Dectris 100K Pilatus

- Photon counting photodiode array
- 20-bit detector
- 83.8×33.5 mm^2 active area
- 172×172 μm^2 pixel size

Shielding

- Metal foil blocked unwanted scatter





Halls et al., ICLASS (2018)

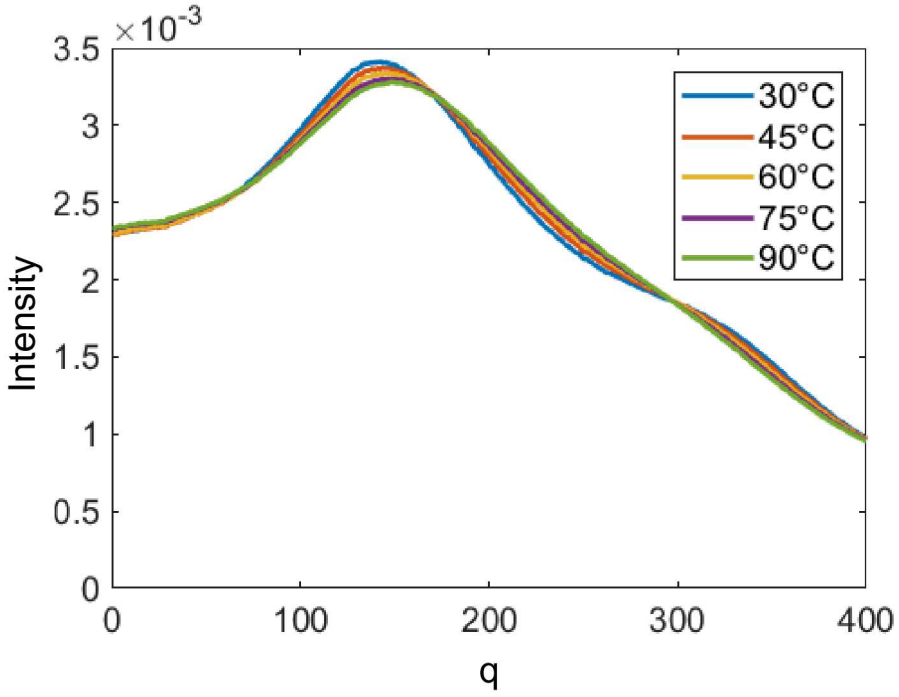
X-ray Thermometry

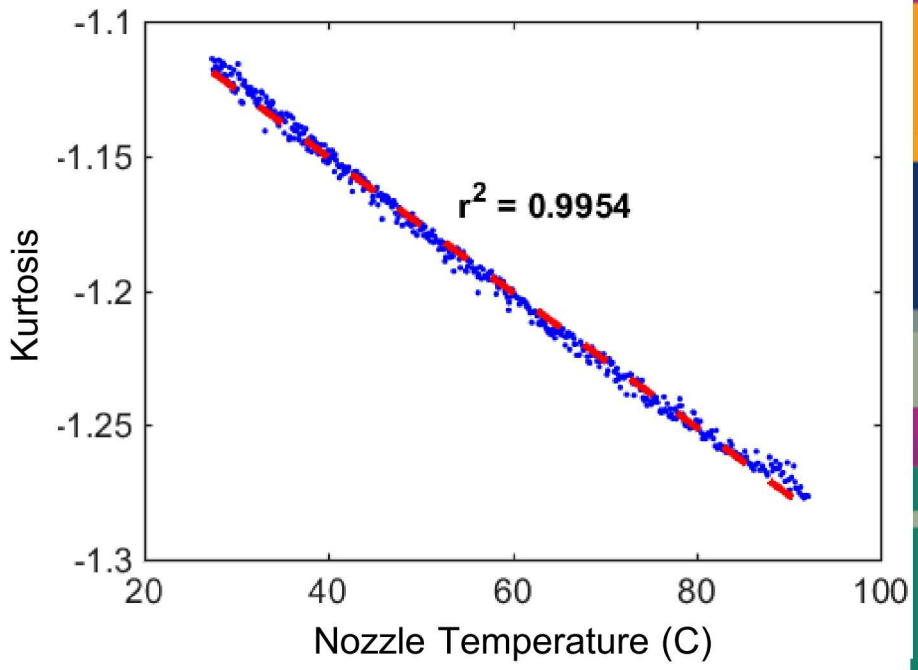
Diffraction Patterns

- Function of spacing
- Repeatable
- Good SNR, binned 2D array

Fitting Kurtosis

- Useful range of sensitivity
- Nearly linear
- ~3° C uncertainty

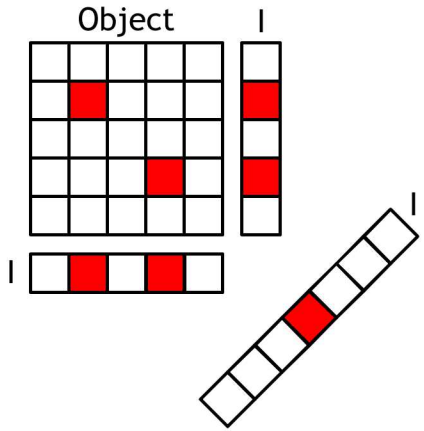




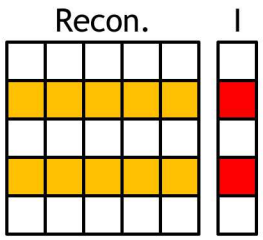
Halls et al., ICLASS (2018)

Traditional Tomography

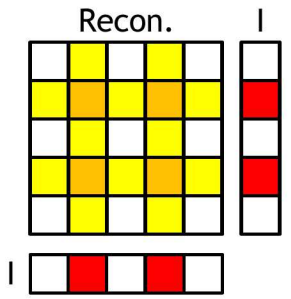
Object & Images



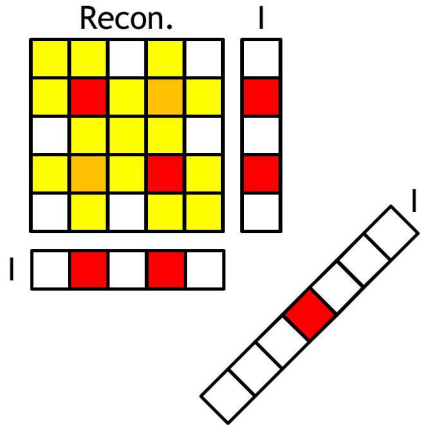
Back Projection 1



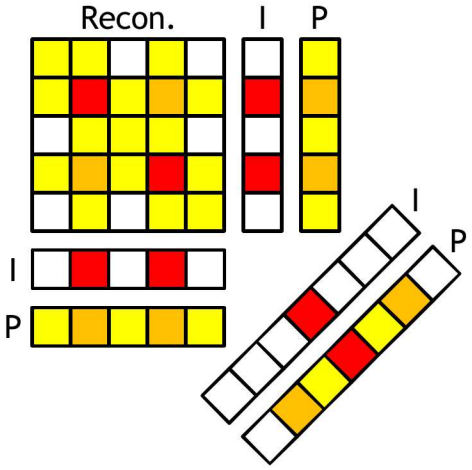
Back Projection 2



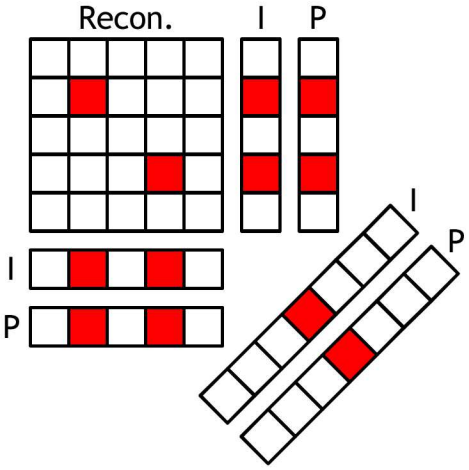
Back Projection 3



Guessed Images



Iterative ART



Outline of Presentation

Motivate x-ray measurements

Overview of x-ray physics

Overview of the impinging jet spray

Hypotheses:

- Can polychromatic x-ray sources be used for quantitative mass distribution measurements?
- Can we capture four-dimensional information using tomography?
- Can x-ray fluorescence be used to measure liquid mixing in sprays?
- Can we map the out-of-plane information without tomography?
- Can we measure the liquid temperature using x-ray diffraction?

Overview of explosive devices

Hypothesis:

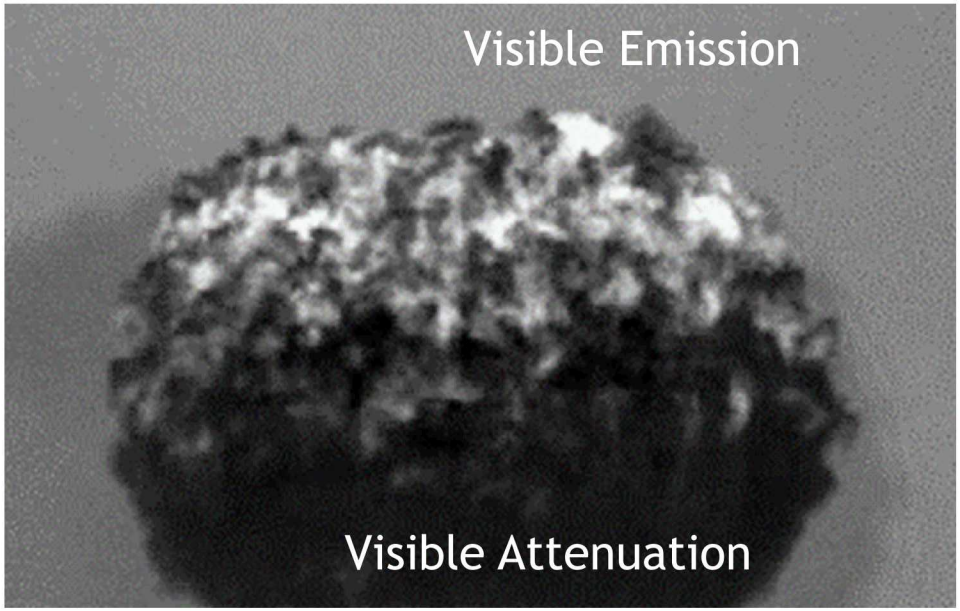
- **Can we leverage image parallax to measure 3D trajectories from only 4 images?**

Motivation

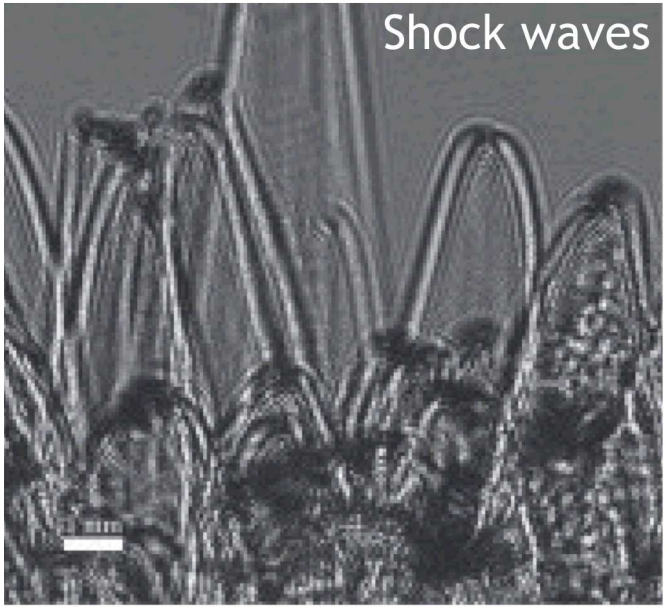
GOAL: Understand highly dynamic multiphase flows, inherently stochastic and three dimensional

OBJECTIVE: Measure particle mass, velocity, acceleration, shape, and time history

CHALLENGES: Visible emission, particulates can scatter visible light, shock waves, image parallax, limited number of views



Diffuse Backlight Imaging



Digital Inline Holography

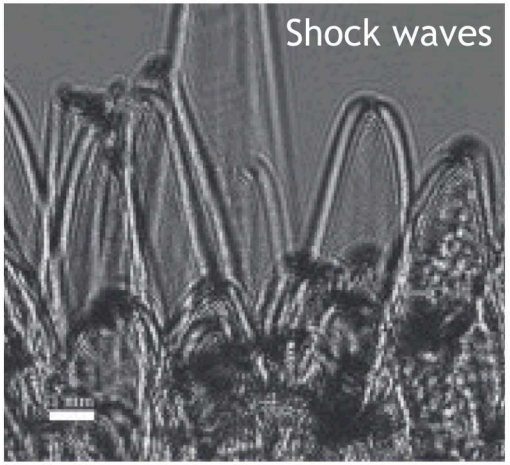
Guildenbecher et al., 2017

Flash X-ray Imaging for Explosive Diagnostics

GOAL: Understand highly dynamic multiphase flows, inherently stochastic and three dimensional

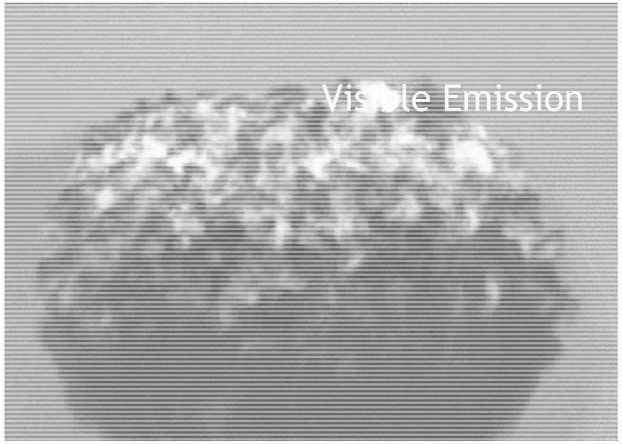
OBJECTIVE: Measure particle mass, velocity, acceleration, shape, and time history

CHALLENGES: Visible emission, particulates can scatter visible light, shock waves, image parallax, limited number of views

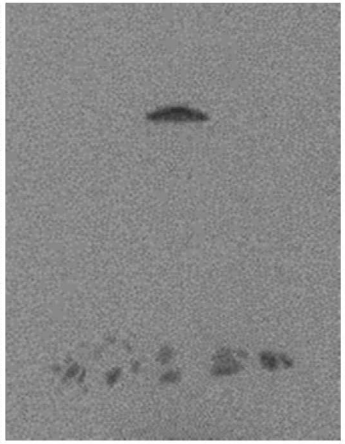


Digital Inline Holography

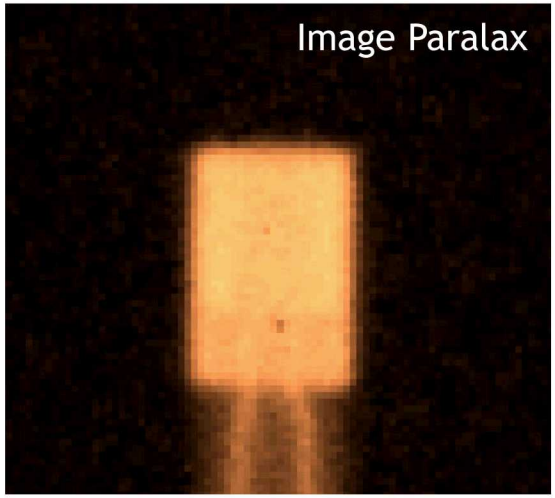
Guildenbecher et al., 2017



Diffuse Back Lit Imaging



X-ray Imaging



Phase-Locked Imaging

Time-Space Interlaced Tomography

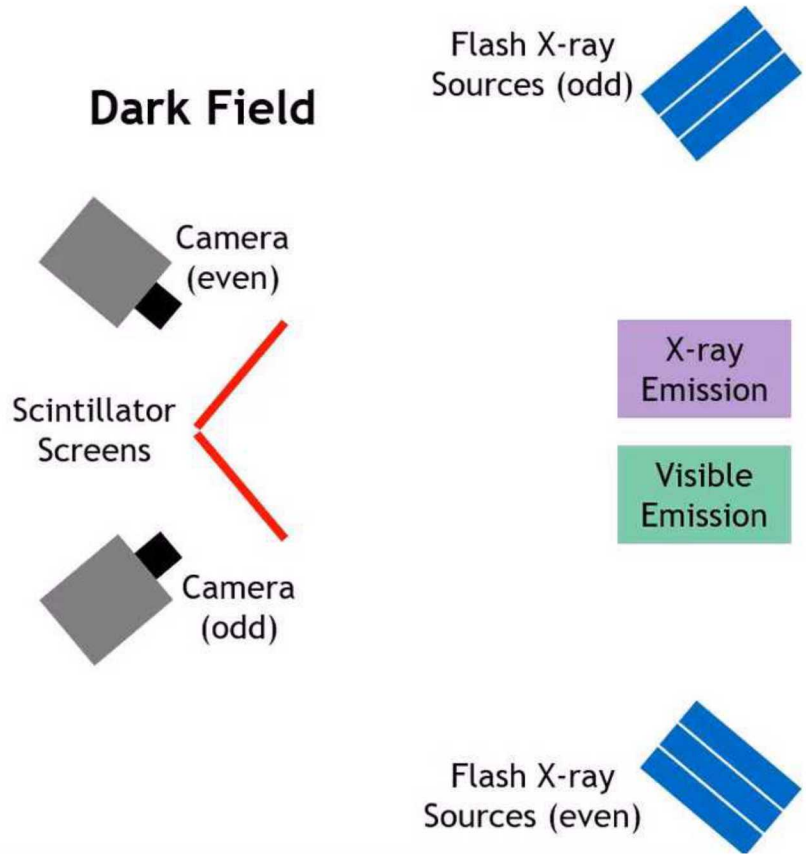
Image parallax becomes a benefit, holds 3D information

Flexible imaging systems: size, location, dynamic range…

Develop and apply TSIT to measure particles in a fragmenting device

OUTLINE:

- Experimental Geometry
- Synthetic Data
- Camera Calibration
- Static and Dynamic Shots
- Image Processing
- Trajectory Reconstruction
- Particle Reconstruction
- Uncertainty Analysis

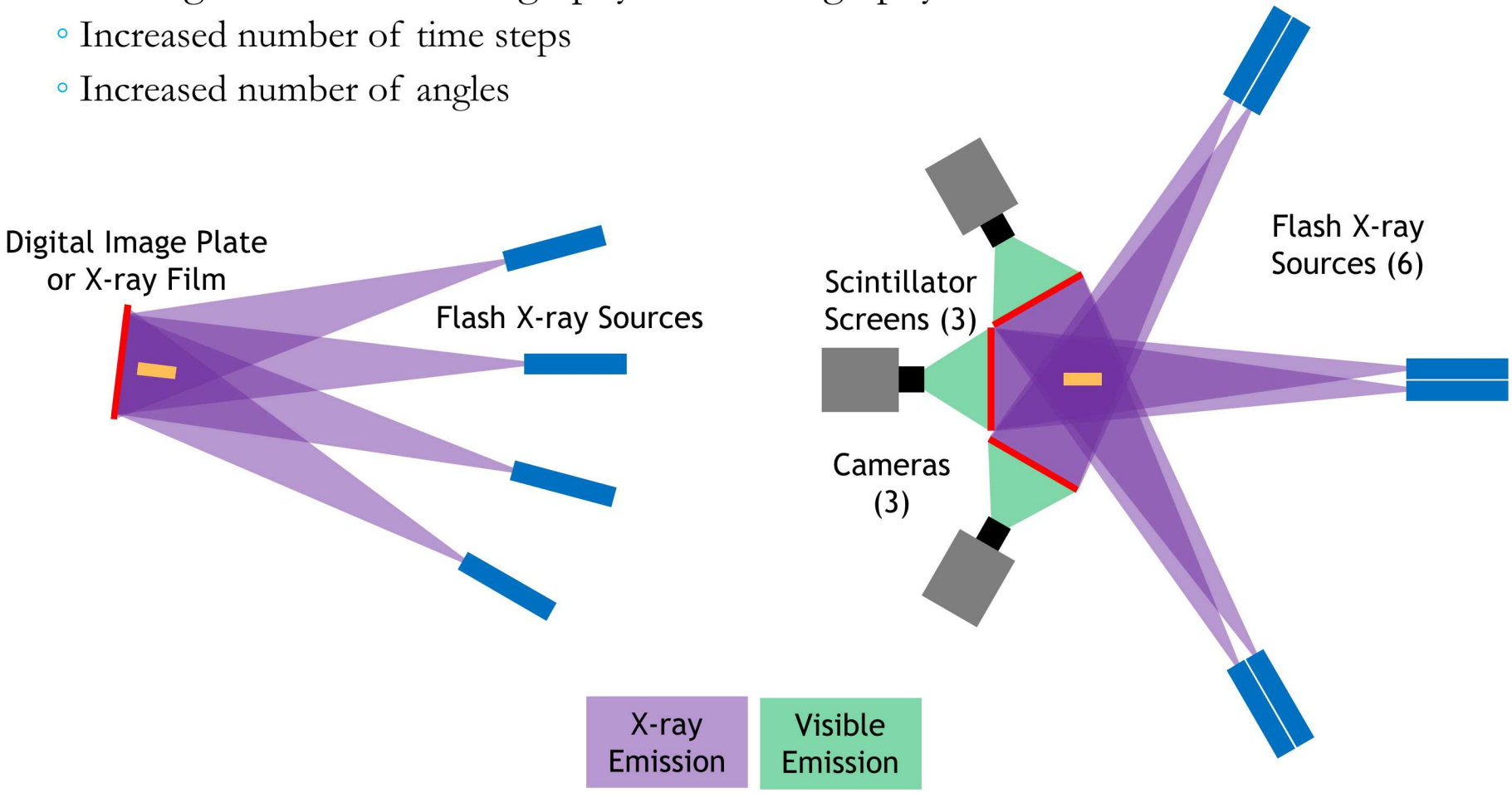


Optimal Placement and Different Configurations

Different configurations

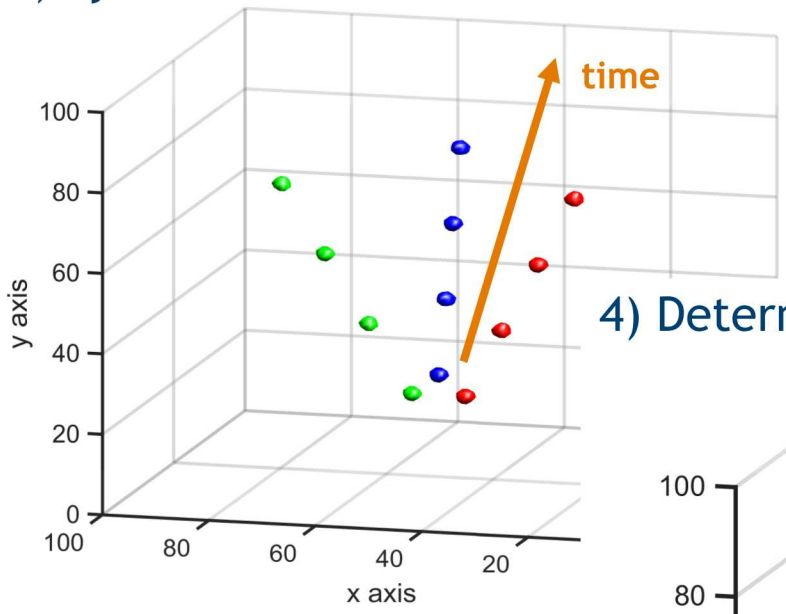
Advantages over flash radiography and stereography

- Increased number of time steps
- Increased number of angles

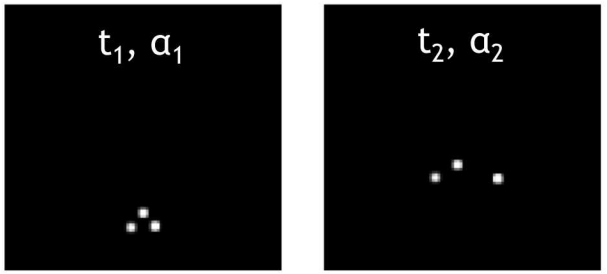


Reconstruction Process with Synthetic Data

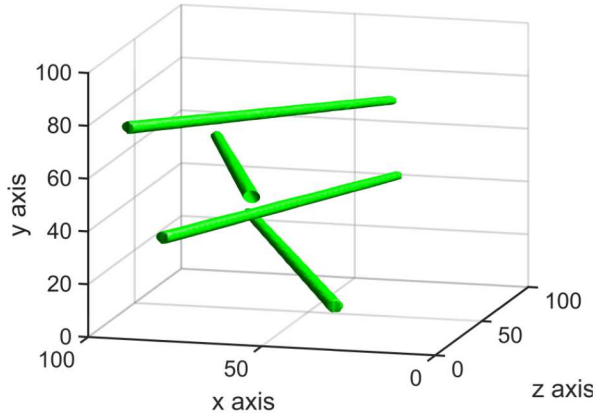
1) Synthetic Data



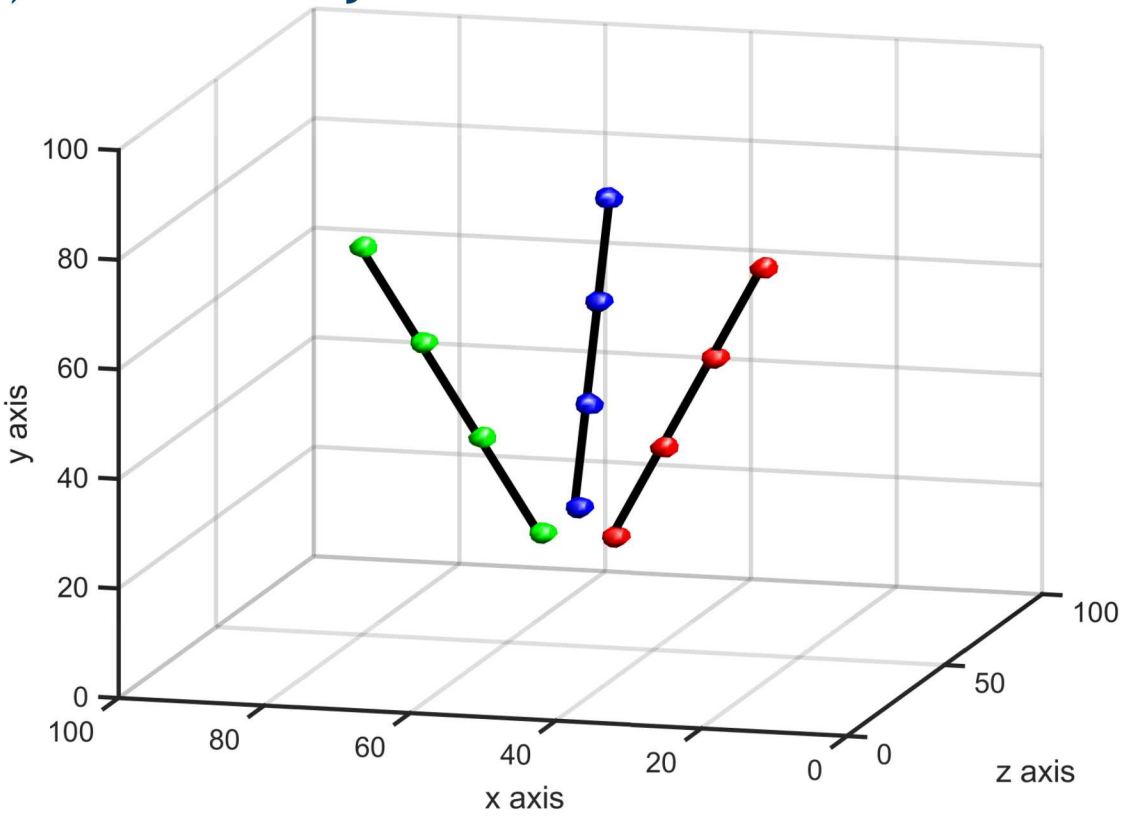
2) Perspective Images



3) Back Projections



4) Determine Trajectories



Experiment Specifics

X-ray Sources
- L3, **150 kVp**, W anode, Be window
- **62 kHz pulse rate**, ~70 ns pulse width
- 3 mm spot size, source to screen 70 cm
- Geometric mag. 1.25:1

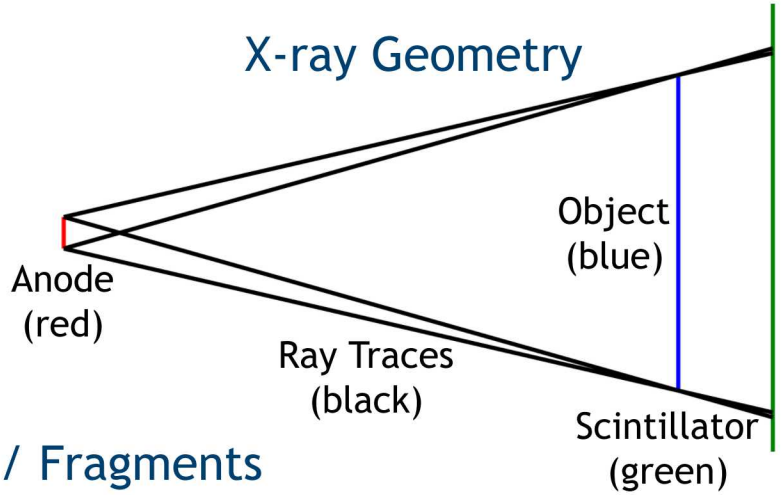
Spatial Resolution
- Pixel size = 145 μm
- 10–90% Rise dist. = 1.2 mm
- Voxel size = 580 μm
- **Volume resolution ~ 1.6 mm**

Explosive Device
- **Fragment size = 4–20 mm**

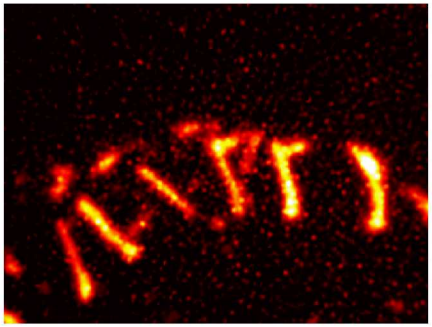
Scintillator Screens
- 45 ns decay time, 415–425 nm emission

High-Speed Cameras
- Phantom 2512, 50 mm f/1.4 Nikon
- **31 kHz frame rate**

X-ray Geometry



Particles / Fragments



Detector Region

Phantom 2512
31 kHz
768 x 1024

Phantom 2512
62 kHz
480 x 768

X-ray Image Processing

Dot Target Calibration
- LaVision software

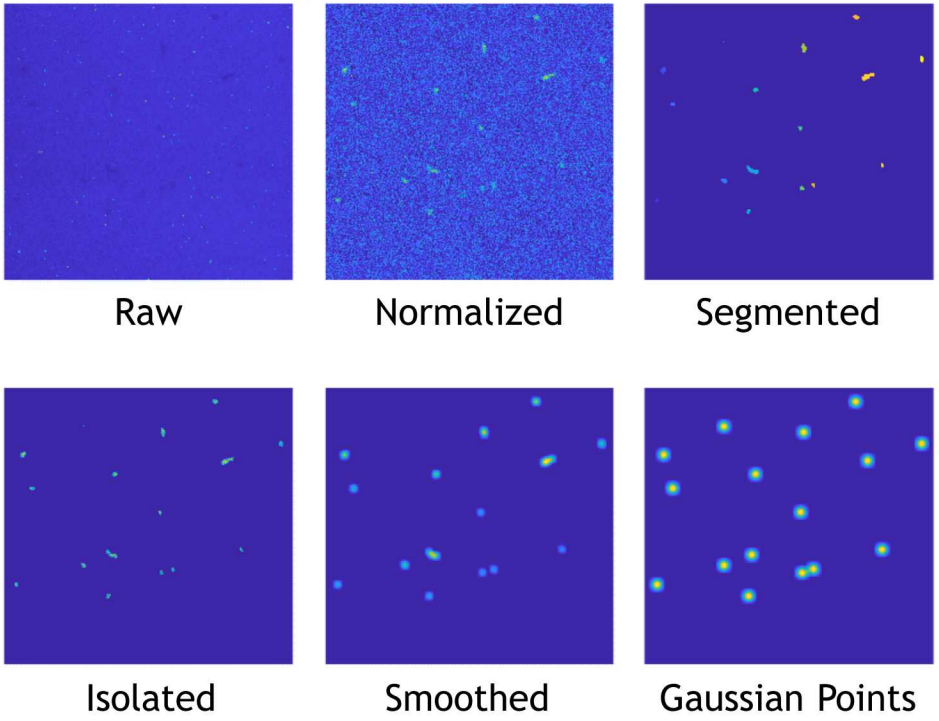
Remove Salt Noise

Normalization
- 2D Gaussian fit

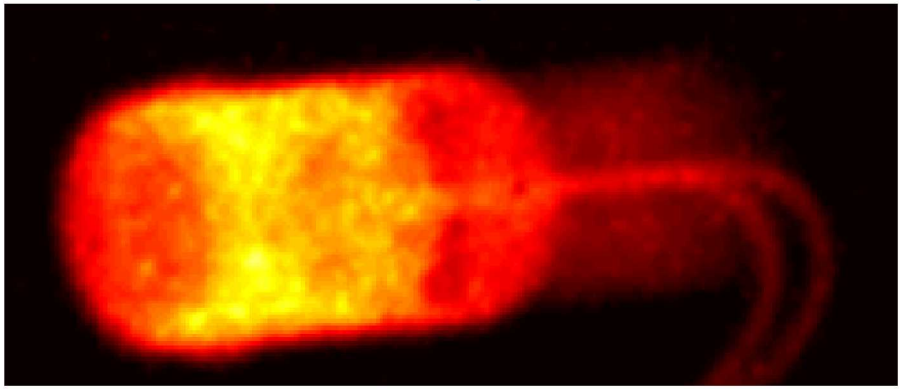
Equivalent Path Length
- Spectrally resolved attenuation coefficient
- Beer-Lambert law

Particle Segmentation
- Binarize image
- Select particles
- Determine center of mass to get 2D location

Image Processing Steps



Static Image of ED



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Normalization
- 2D Gaussian fit

Equivalent Path Length
- Spectrally resolved attenuation coefficient
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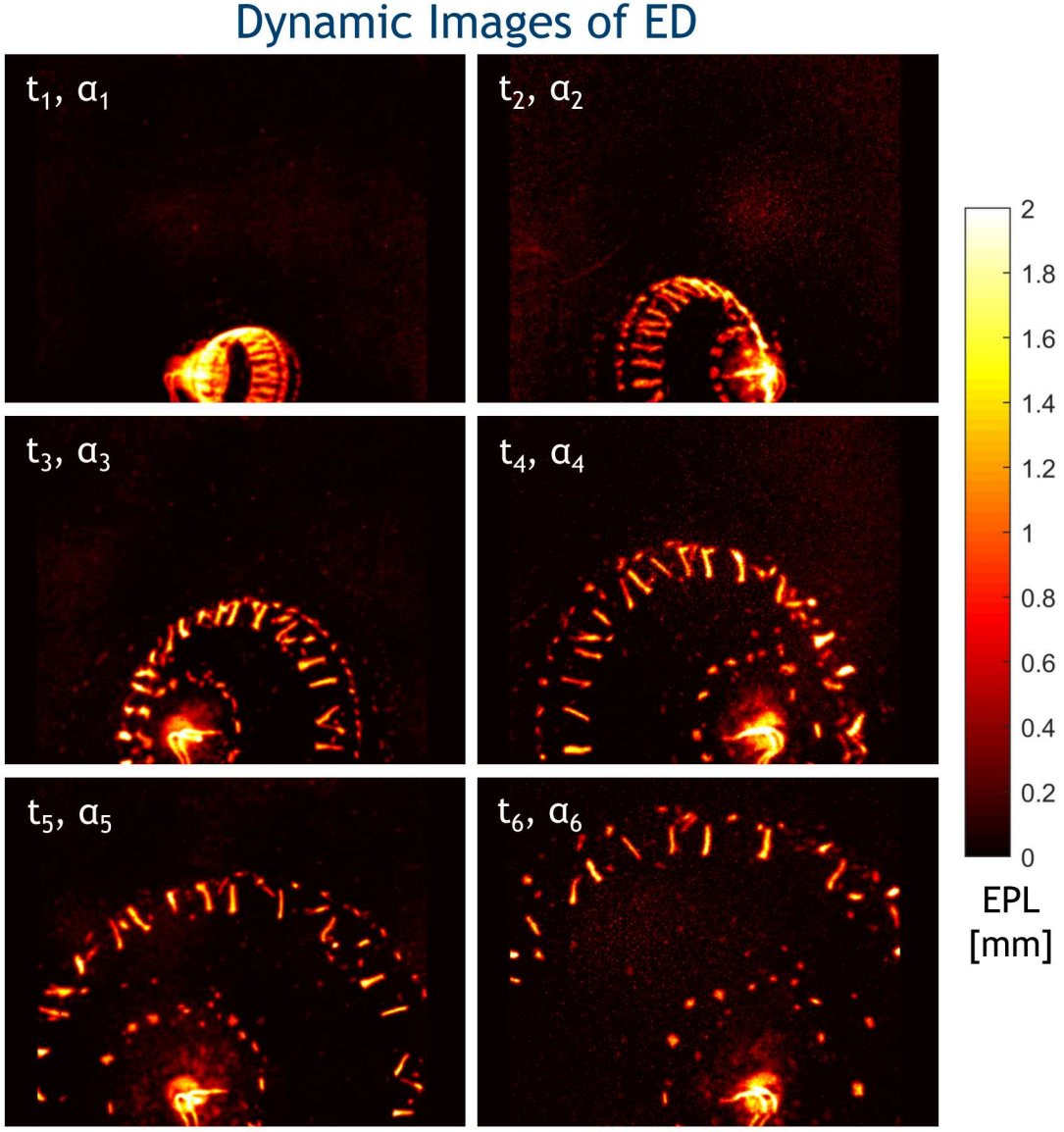
Particle Segmentation
- Binarize image
- Click particles
- Center of mass = location



X-ray Image Processing

Dot Target Calibration
- LaVision software

Remove Salt Noise

Normalization
- 2D Gaussian fit

Equivalent Path Length
- Spectrally resolved attenuation coefficient
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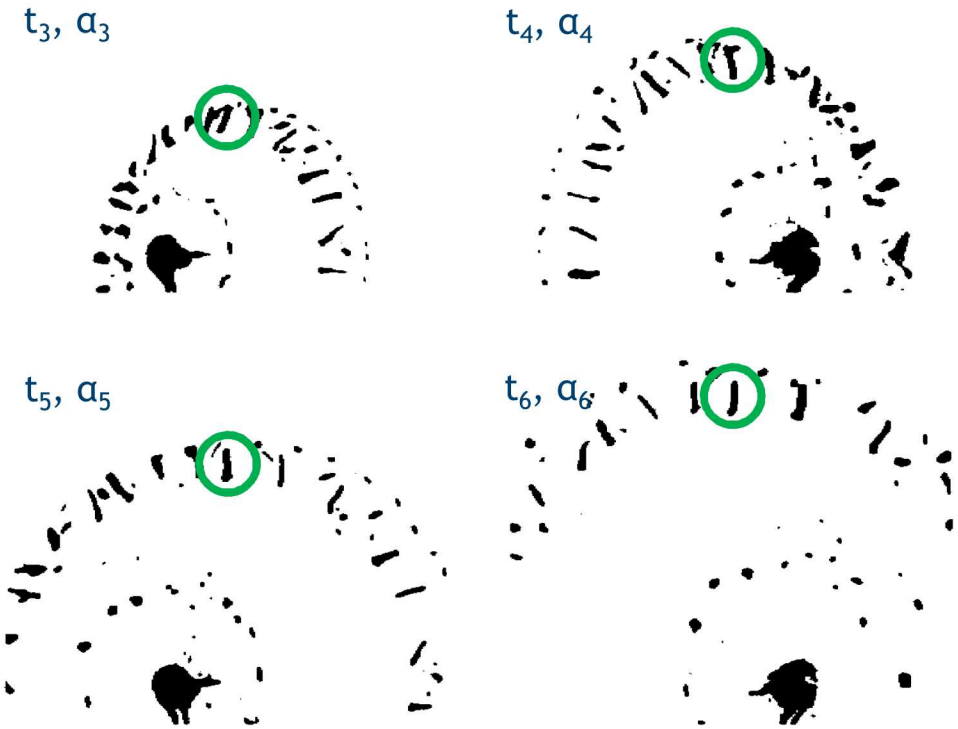
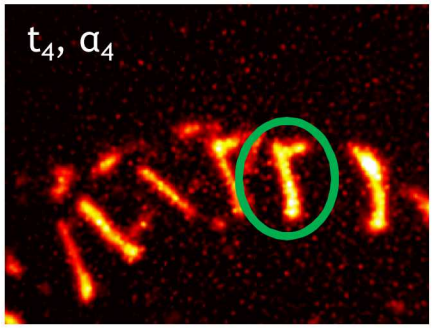
Particle Segmentation
- Binarize image
- Click particles
- Center of mass = location

Binary Dynamic Images of ED

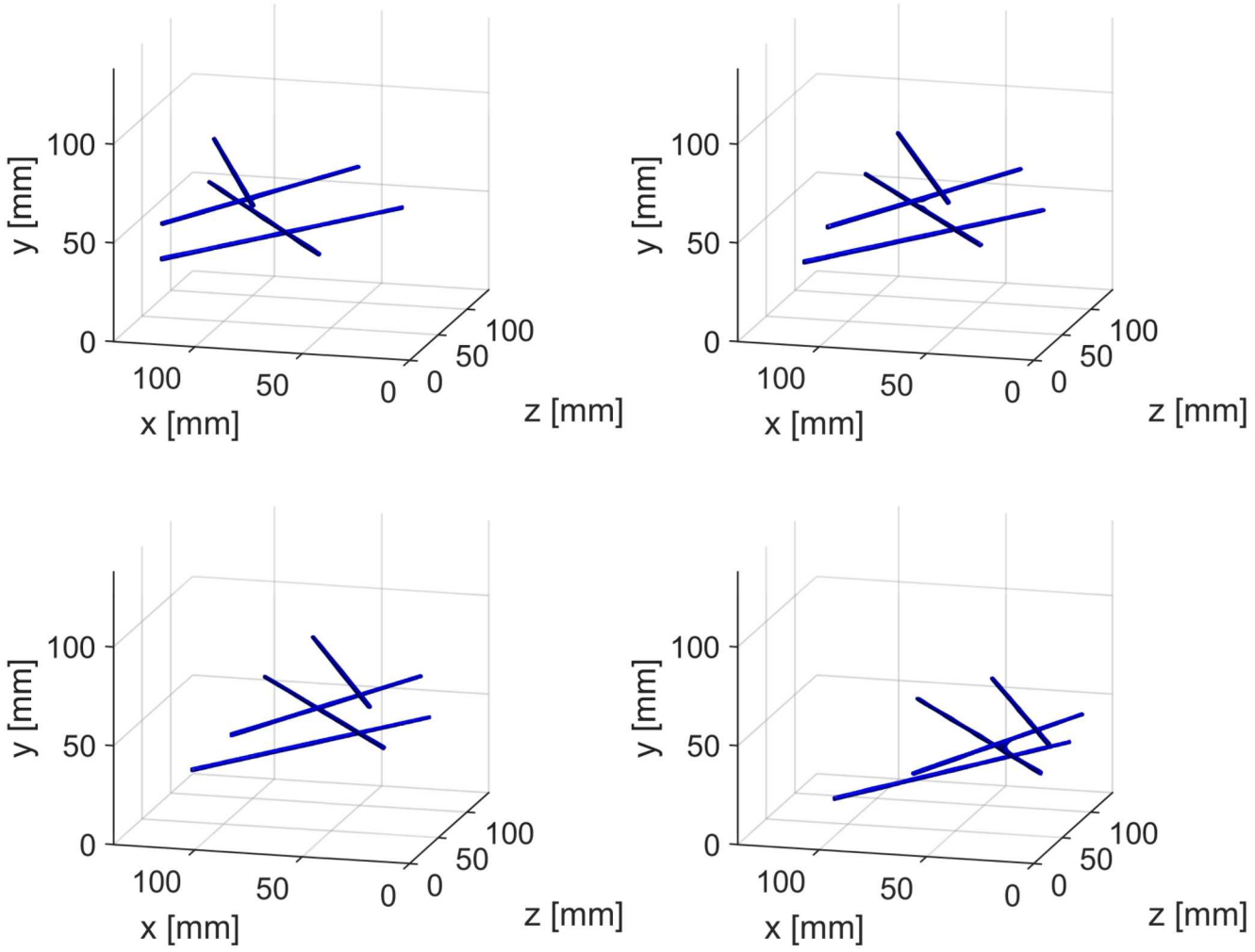




Back Projections of Centers of Mass

Indices of centers of mass are back projected through the volume

No lines intersect since the particle has moved in time

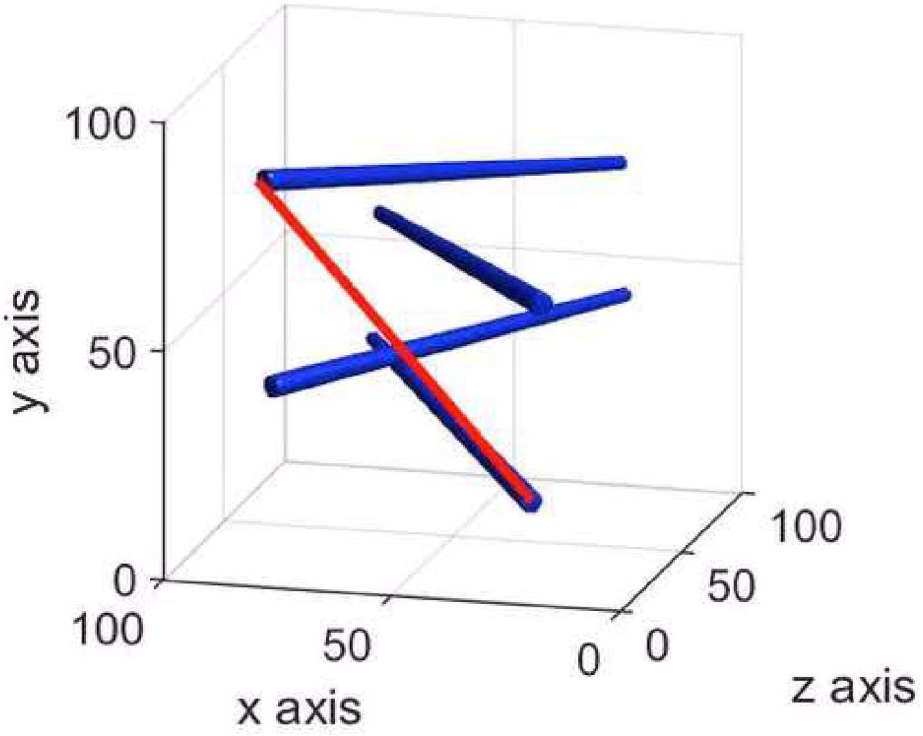


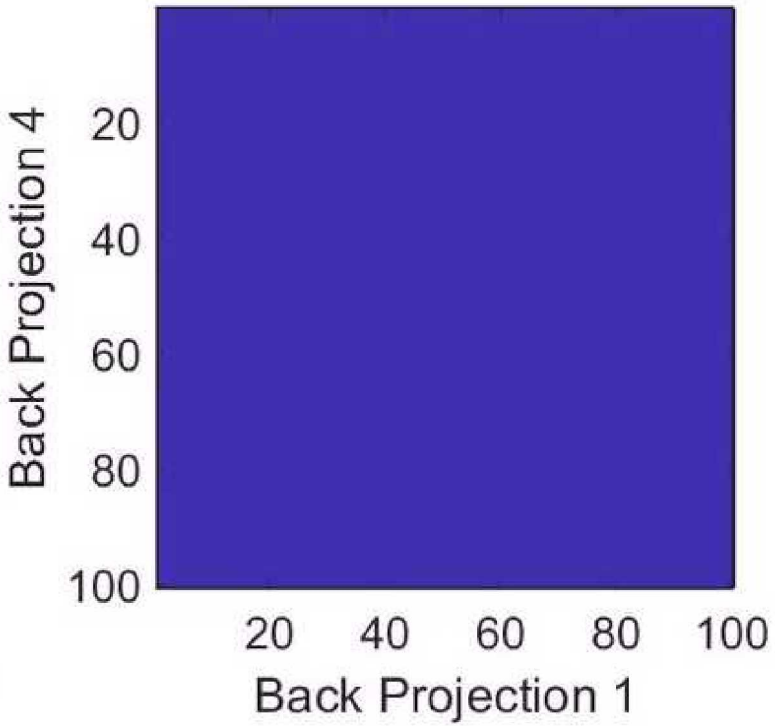
Search Process

1) Locate the possible particle location along the first and last projections

2) Map the space between to locate the other possible locations of the particle

3) The peak in the map marks the trajectory

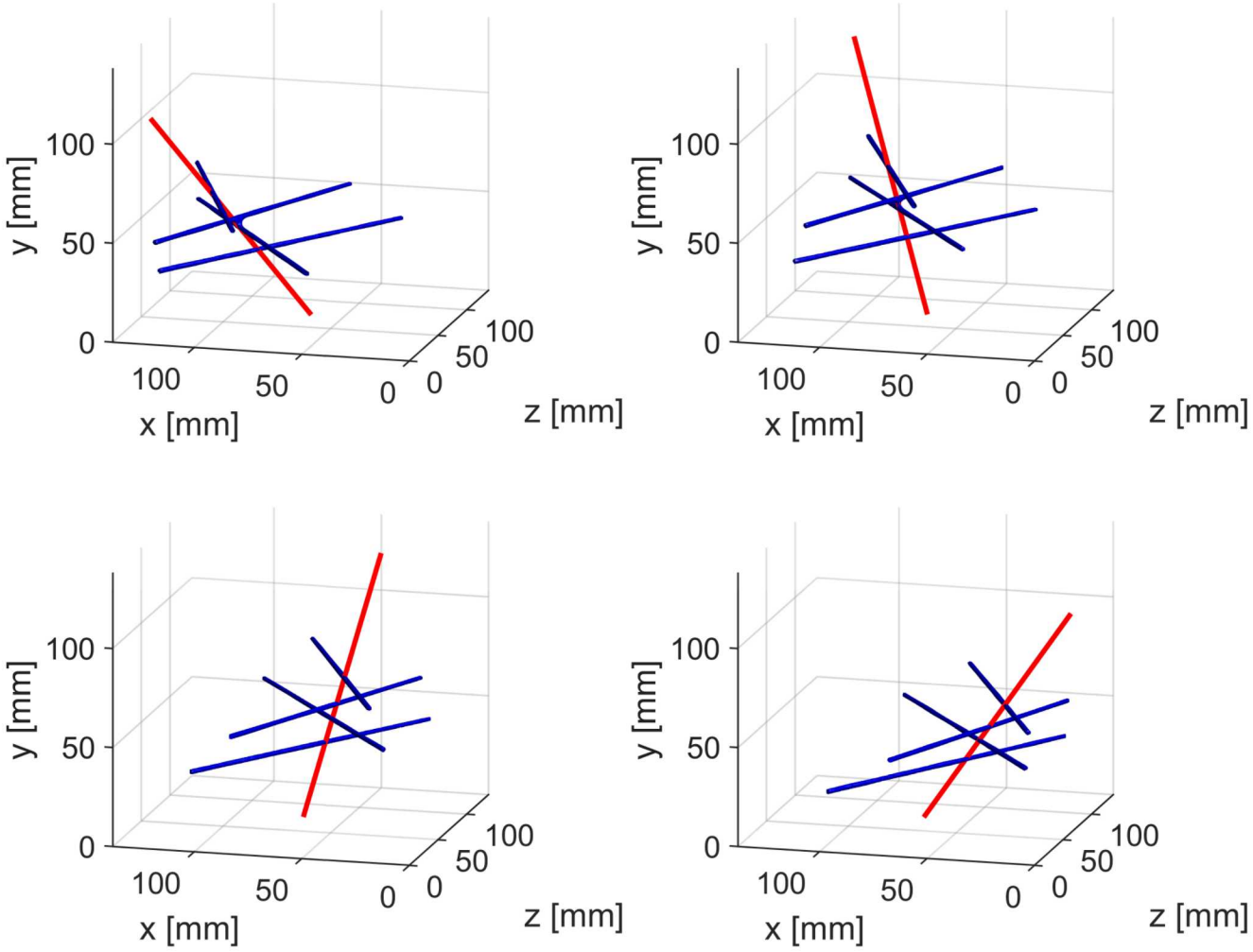




Search Process Complete

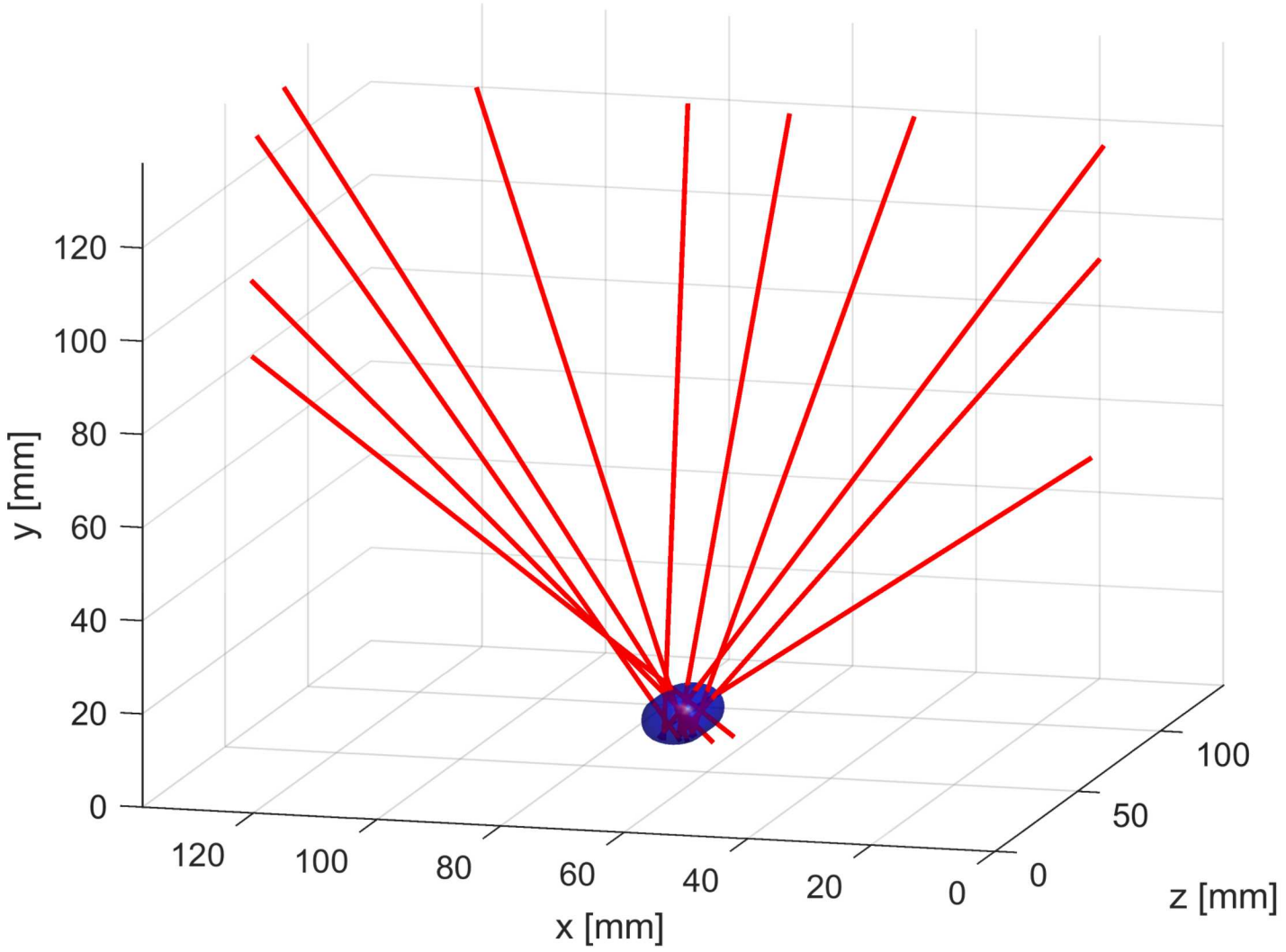
Lines fit to the back projections

Four back projections is the minimum number



Fragment Trajectories

All 11 trajectories mapped backwards in time to the location of the ED



Uncertainty Analysis

Good: You always get a reconstruction

- Reconstruction process will find most likely trajectory

Bad: You always get a reconstruction

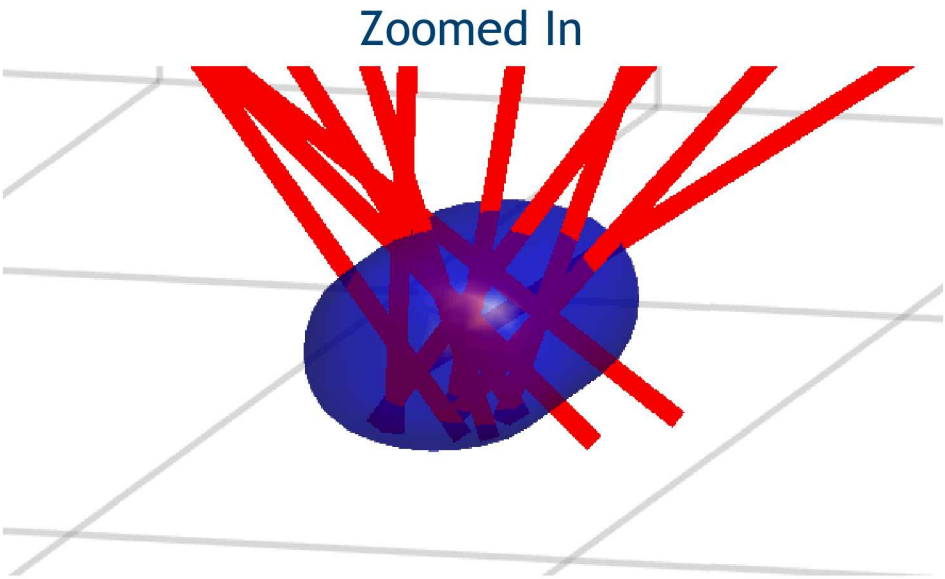
- Reconstruction process can find an incorrect trajectory

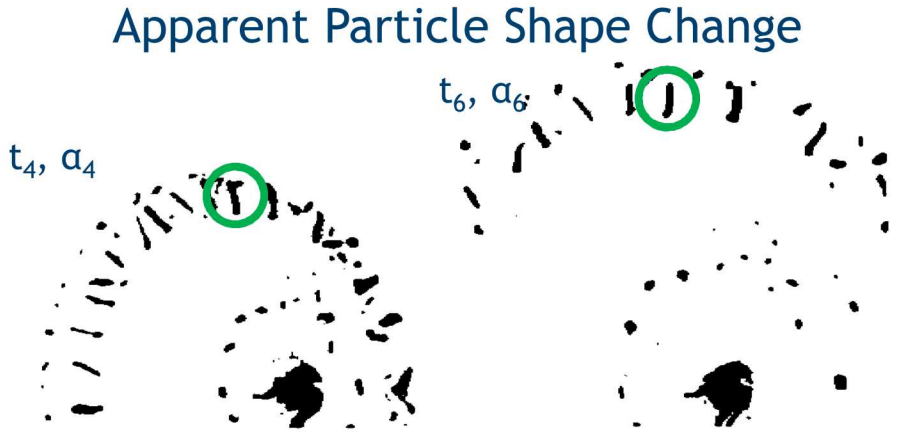
Causes of Uncertainty

- Camera–source calibration (dot target)
  - ~1 pixel
- Particle segmentation and center of mass determination

Volume Resolution ~1.6 mm

Spread of Trajectories ~10 mm





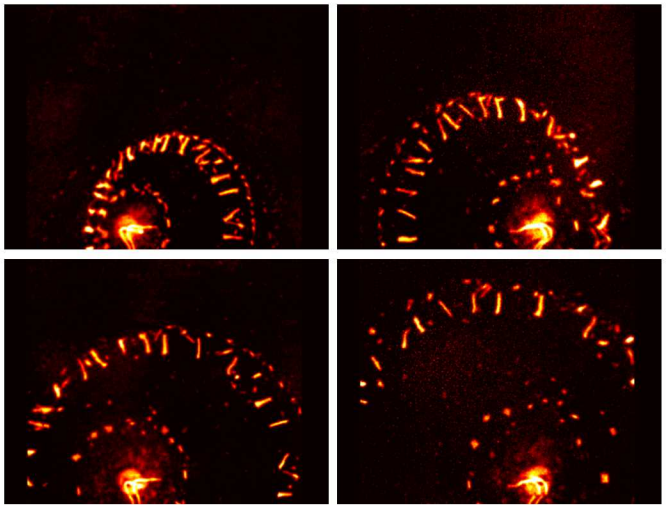
Summary

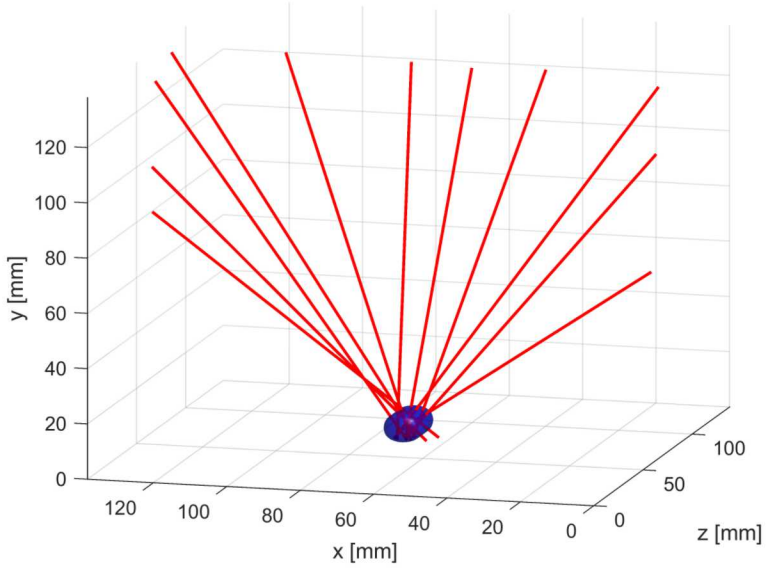
Space-Time Interlaced Tomography was develop and applied to measure high-speed particle trajectories

Synthetic data was used to verify the reconstruction process

Experimental flash x-ray data of a small explosive device was used to validate the reconstruction process and provide an estimate of the uncertainty

Future work will include further development to increase speed and accuracy of processing, application to various explosives, and isolate errors causing uncertainty through the use of synthetic data





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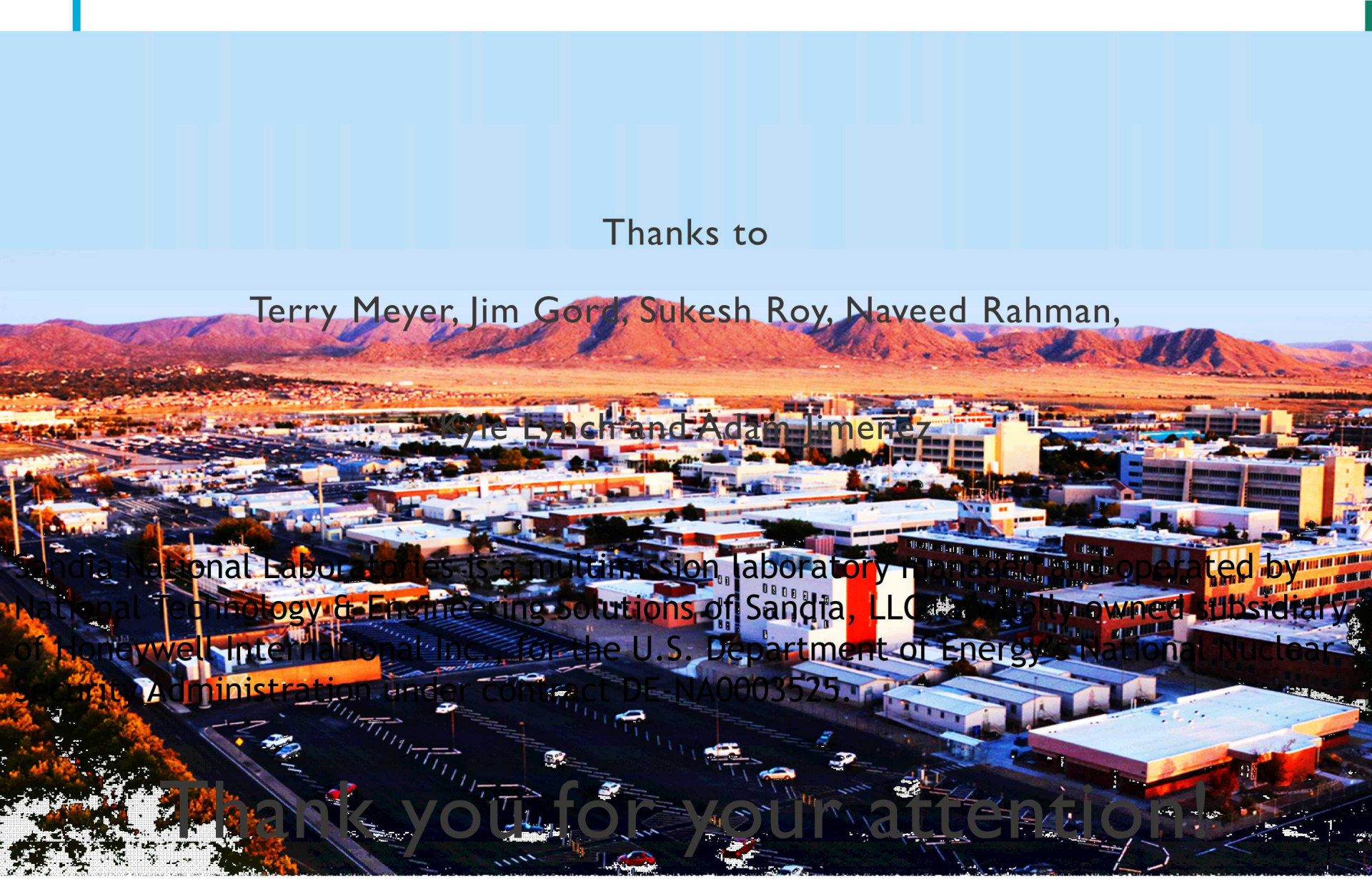
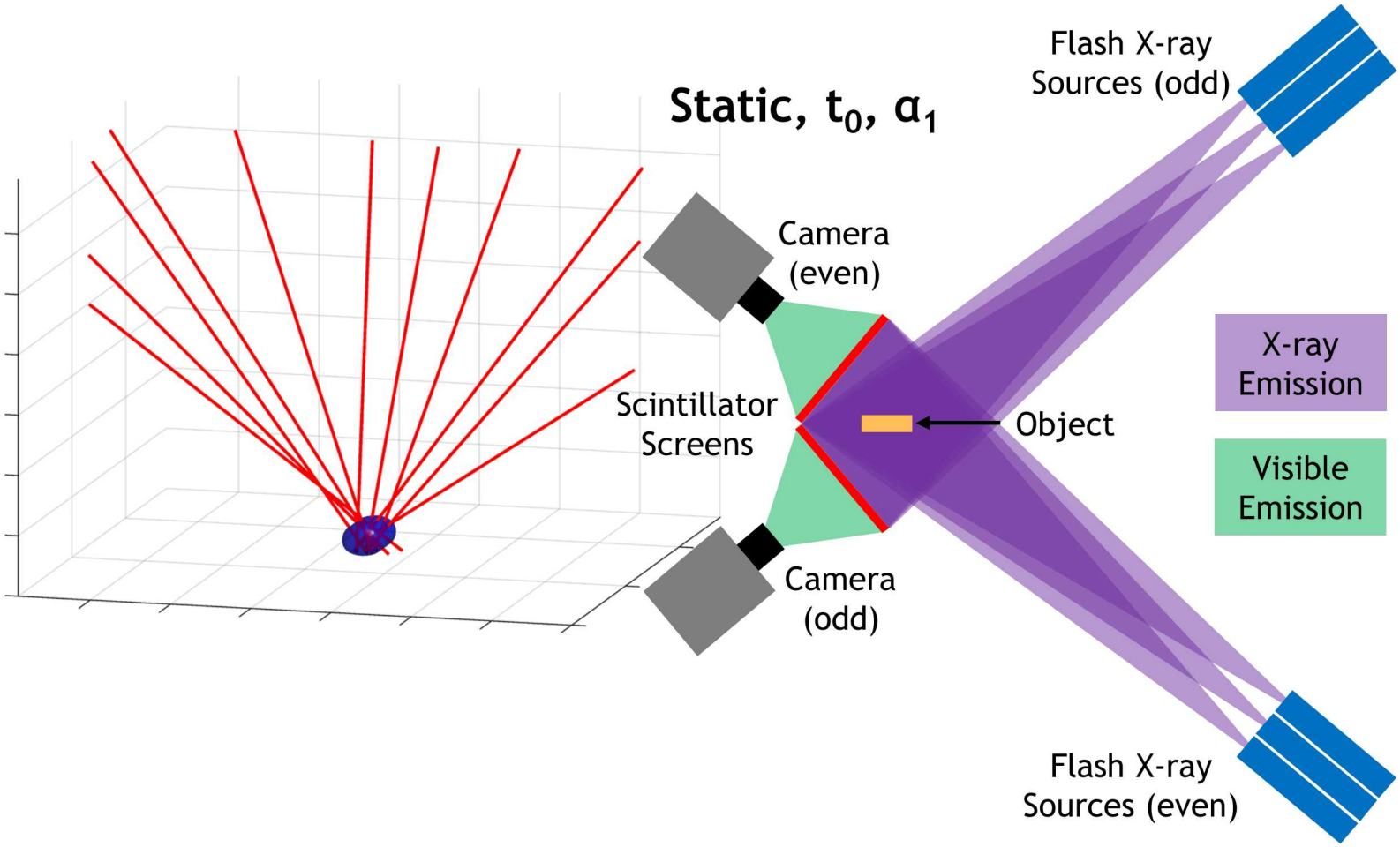


Thank you for your attention!

This presentation describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the presentation do not necessarily represent the views of the U.S. Department of Energy or the United States Government.


Static, t_0, α_1
Flash X-ray Sources (odd)
Camera (even)
Scintillator Screens
Object
X-ray Emission
Visible Emission
Camera (odd)
Flash X-ray Sources (even)