SAND2018-12690C

X-ray scattering measurements for optically complex sprays

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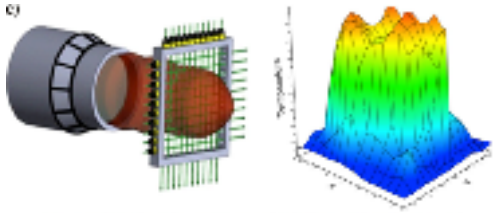
Full Engines to Canonical Sprays

- **Improved Propulsion-System & Fuel Performance**
- **Reduced Pollutant Emissions**
- **Enhanced Maintainability, Reliability, Affordability**

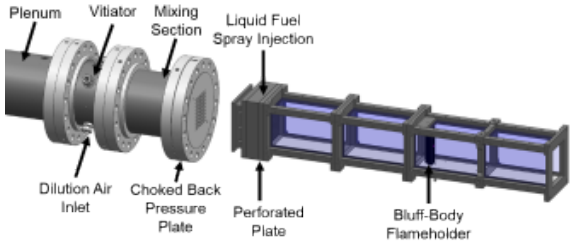
Full Engine

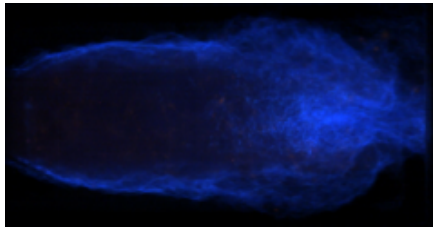
- Full Physics
- Limited Diagnostics



Engine Component

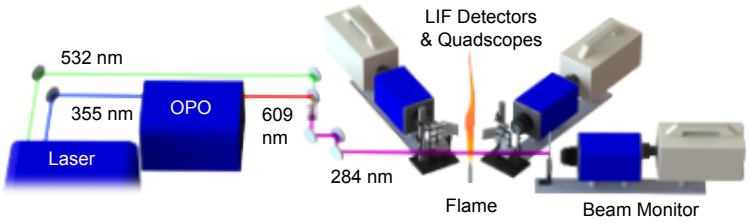
- Partial Physics
- Partial Diagnostics

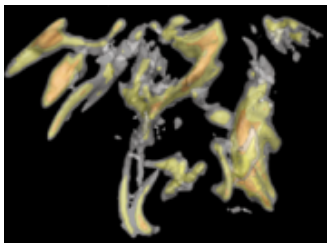




Laboratory Scale

- Limited Physics
- Full Diagnostics





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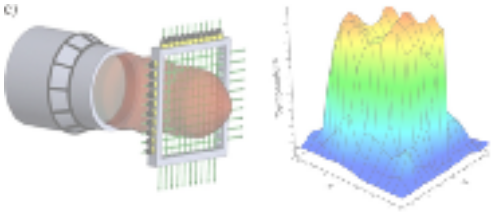
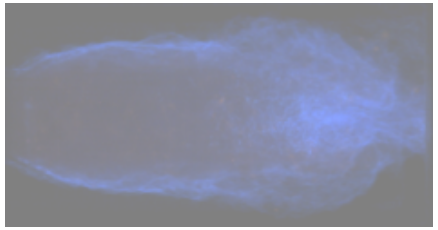


Measurement Challenges
- High-Pressure
- **Dense Sprays (x-ray)**
- 3D Dynamics
- Large Data Sets
- Limited Optical Access

Engine Component
- Partial Physics
- Partial Diagnostics



Laboratory Scale
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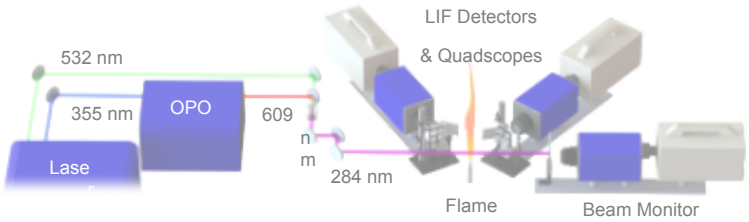
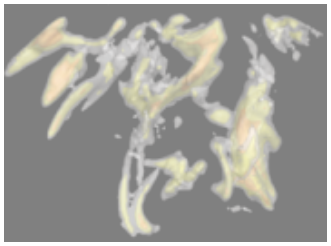
- Full Diagnostics





Dense Sprays

Dense Spray Definition

(working definitions)

- Spray formation region
- Optically dense spray
  - Traditional optical techniques such as line-of-sight and planar measurements can be perturbed

Dense Droplet Fields

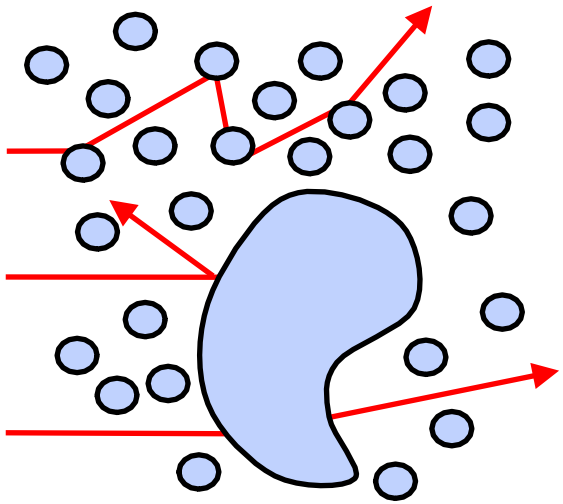
- Multiply scattered photons do not follow straight paths
- Photons need to be distinguished

Large Liquid Structures

- Refracted photons do not follow straight paths
- Structures need to be penetrated

Impinging Jet Spray

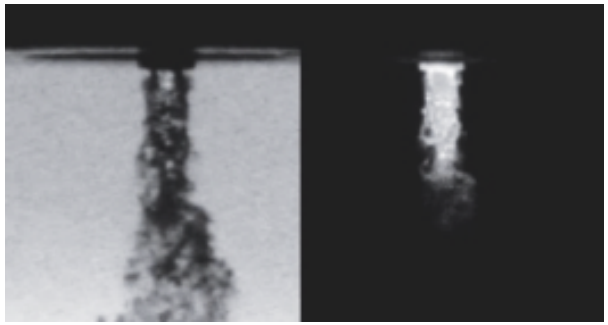
Visible



Dense Spray Diagnostics

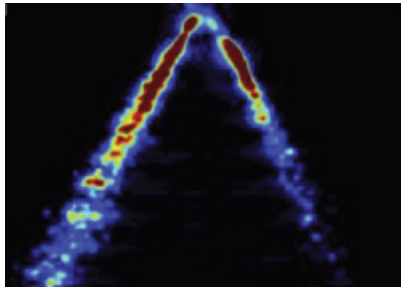
How can we overcome optical perturbations within sprays?

Optical Connectivity

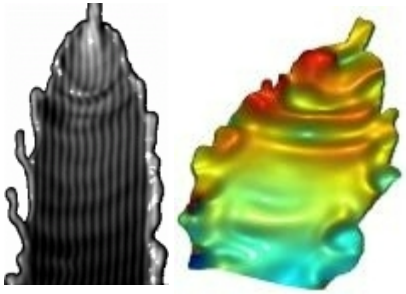


Charalampous et al., 2010

Structured Light

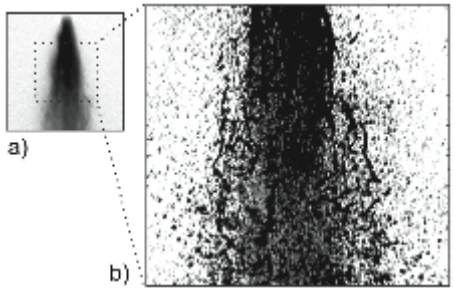


Kristensson et al., 2012

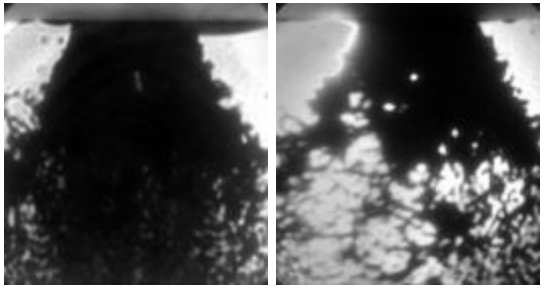


Halls et al., 2012

Ballistic Imaging



Linne et al., 2010



Schmidt et al., 2009

X-ray Diagnostics

Beer-Lambert Law

- Photoelectric absorption
- Rayleigh (elastic) scatter
- Compton (inelastic) scatter

Equivalent Path Length (EPL)

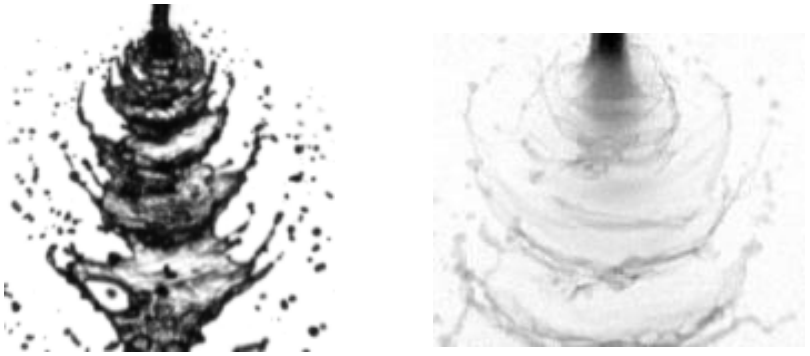
- Attenuation of liquid is equated to the equivalent path length of liquid

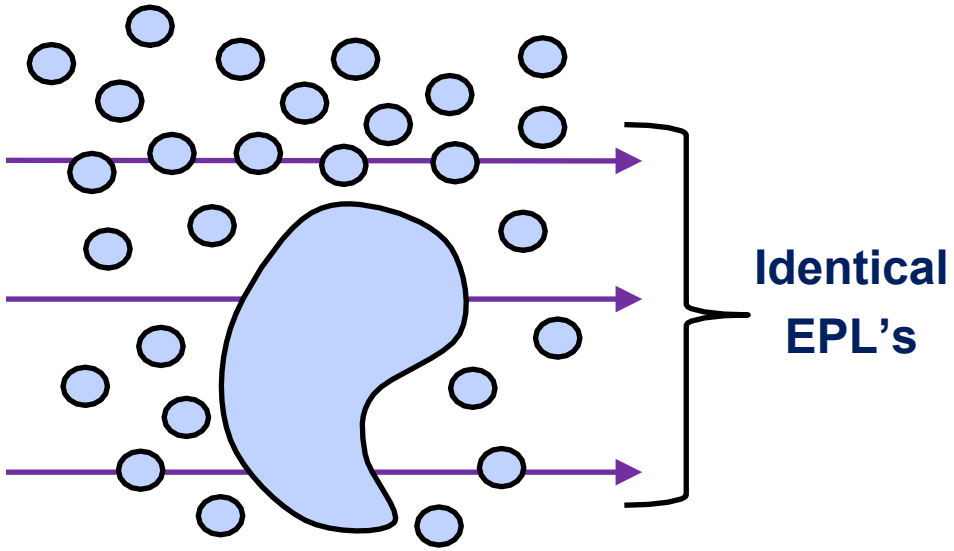
Interference Free

- Local geometry does not perturb measurement

Impinging Jet Spray

Visible **X-ray**

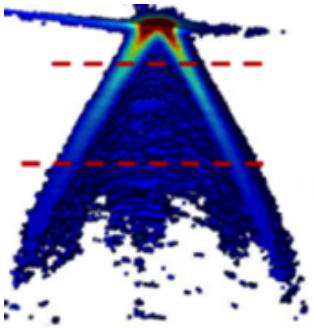




Tube Source Imaging

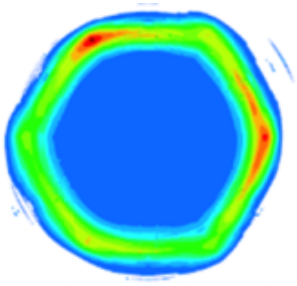
Tube Source Computed Tomography

Static Anode



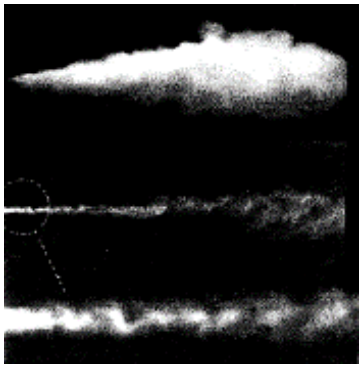
Schmidt et al., 2010

1 kHz Slice



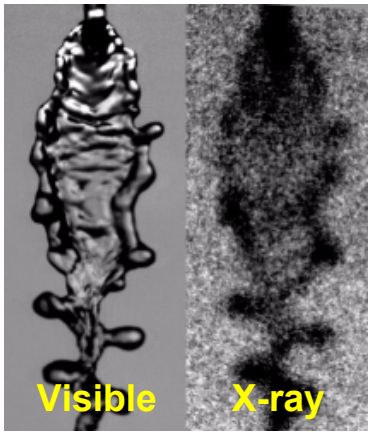
Lim et al., 2013

Flash Source



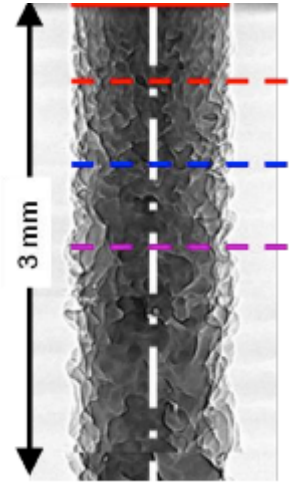
Birk et al., 1995

Static Anode



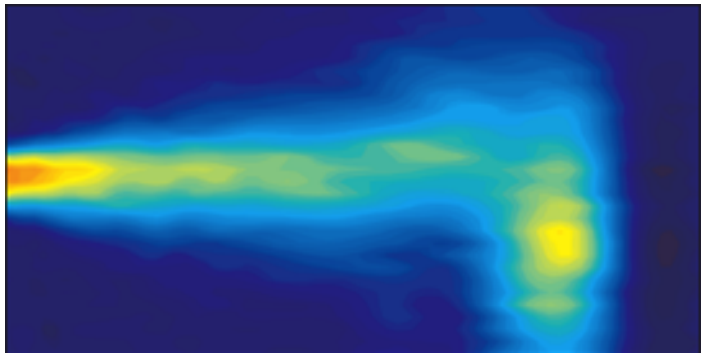
Halls et al., 2014

Phase Contrast



Lin et al., 2014

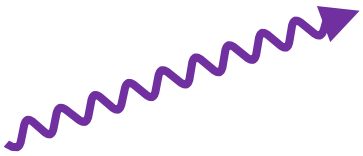
Synchrotron Radiography

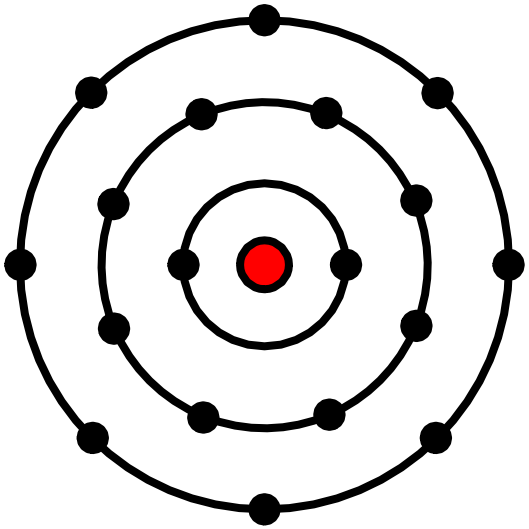


Leick et al., 2007

X-ray Interactions with Matter

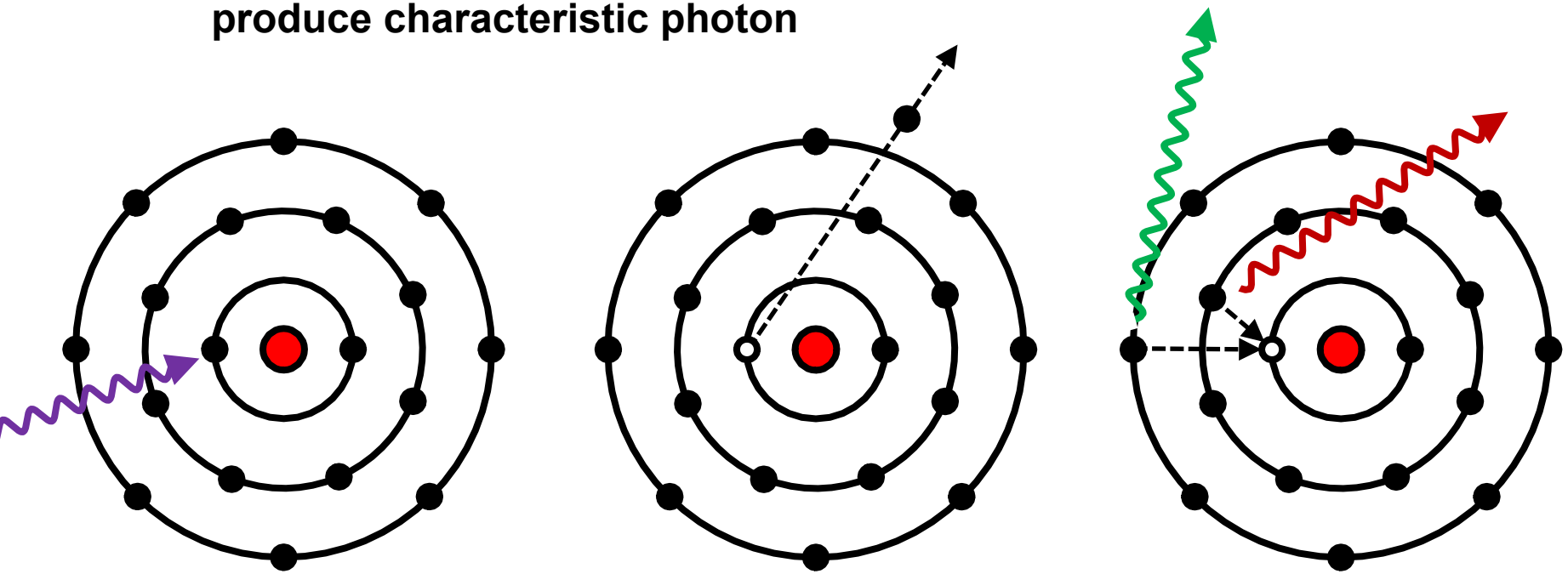
- Radiography / Attenuation
  - Photoelectric absorption
  - Compton scatter
- X-ray Fluorescence
  - Photoelectric absorption
  - Emission of characteristic x-ray
- X-ray Scatter
  - Compton scatter
  - Rayleigh scatter
- X-ray Diffraction
  - Compton scatter interference





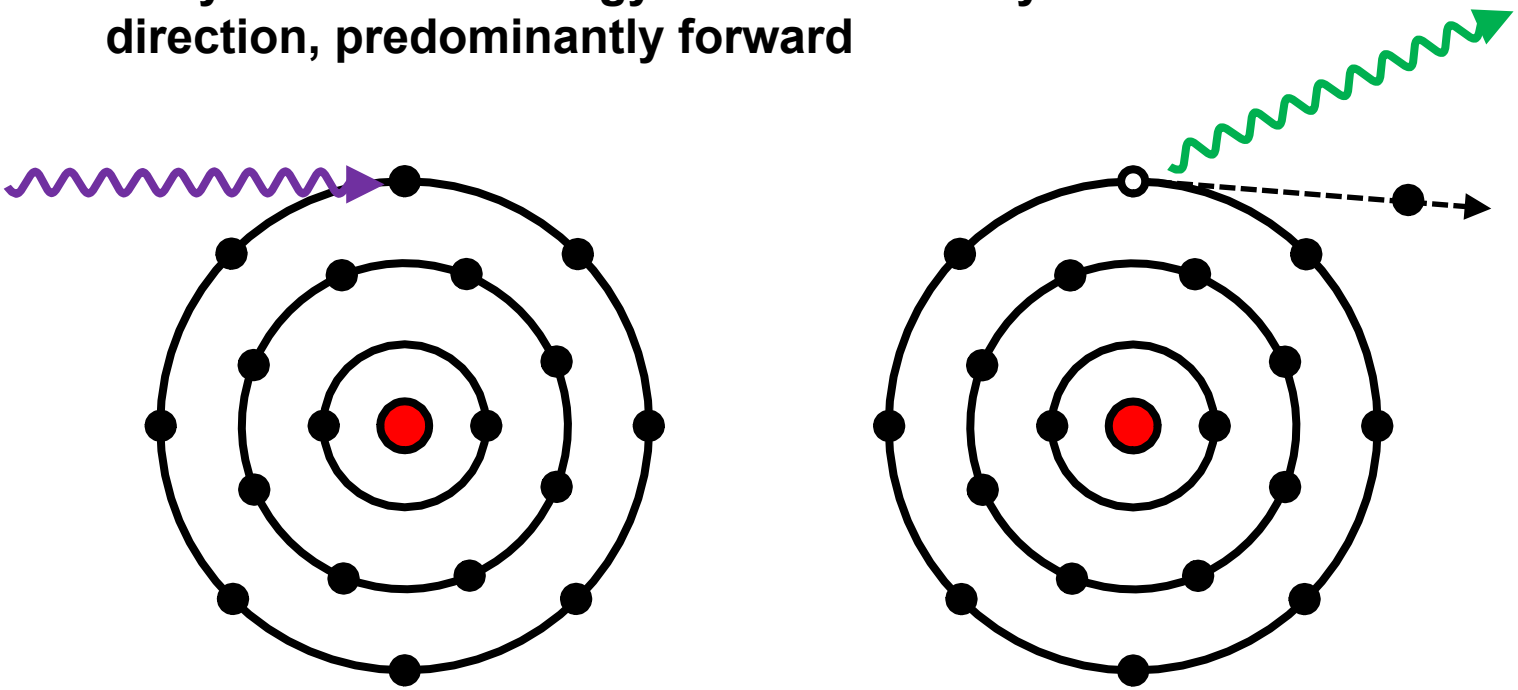
Absorption / Fluorescence

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



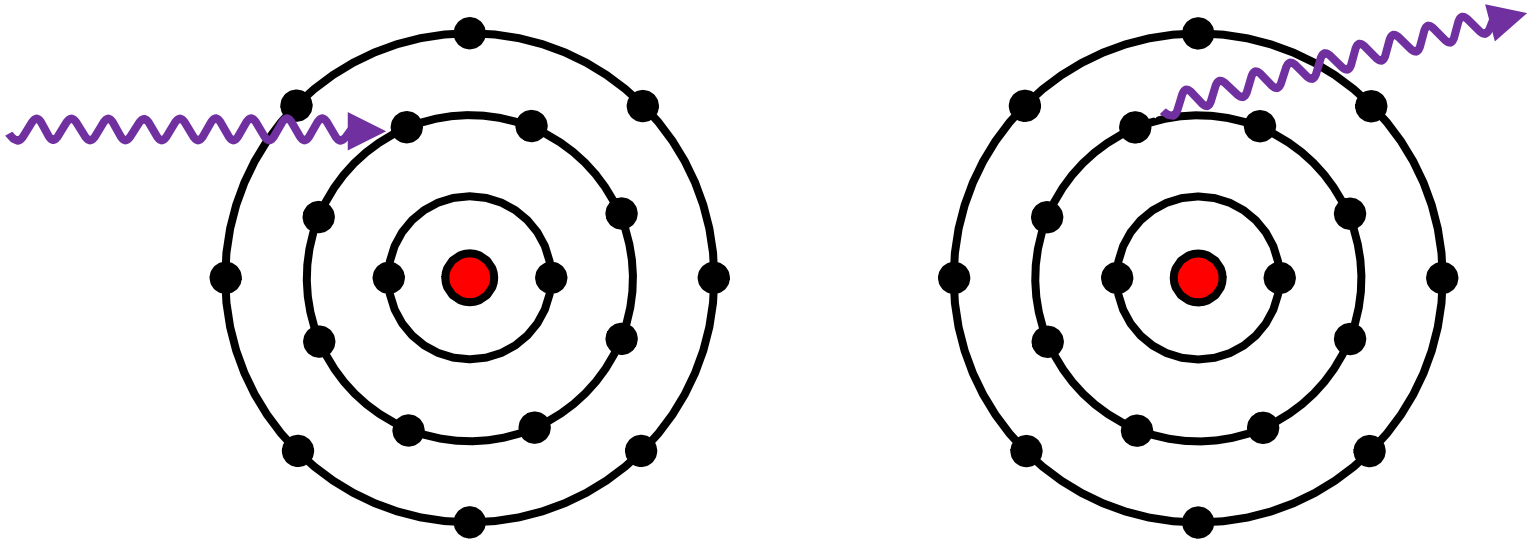
Compton Scatter

- Compton (inelastic) Scatter
  - Some photon energy is absorbed by electron
  - Photoelectron is liberated
  - X-ray of reduced energy is emitted in any direction, predominantly forward



Rayleigh Scatter

- **Rayleigh (elastic) Scatter**
  - **Photon wiggles electron, leaves at new angle, predominantly forward**



Challenges of X-ray Diagnostics

- Usually a path-averaged measurement
  - Tomography can be applied!
  - What happens when tomography is not feasible?

- Generally for mass distribution
  - Radiography and fluorescence are functions of local density
  - Phase contrast – highlight interfaces
  - SAXS – droplet sizes

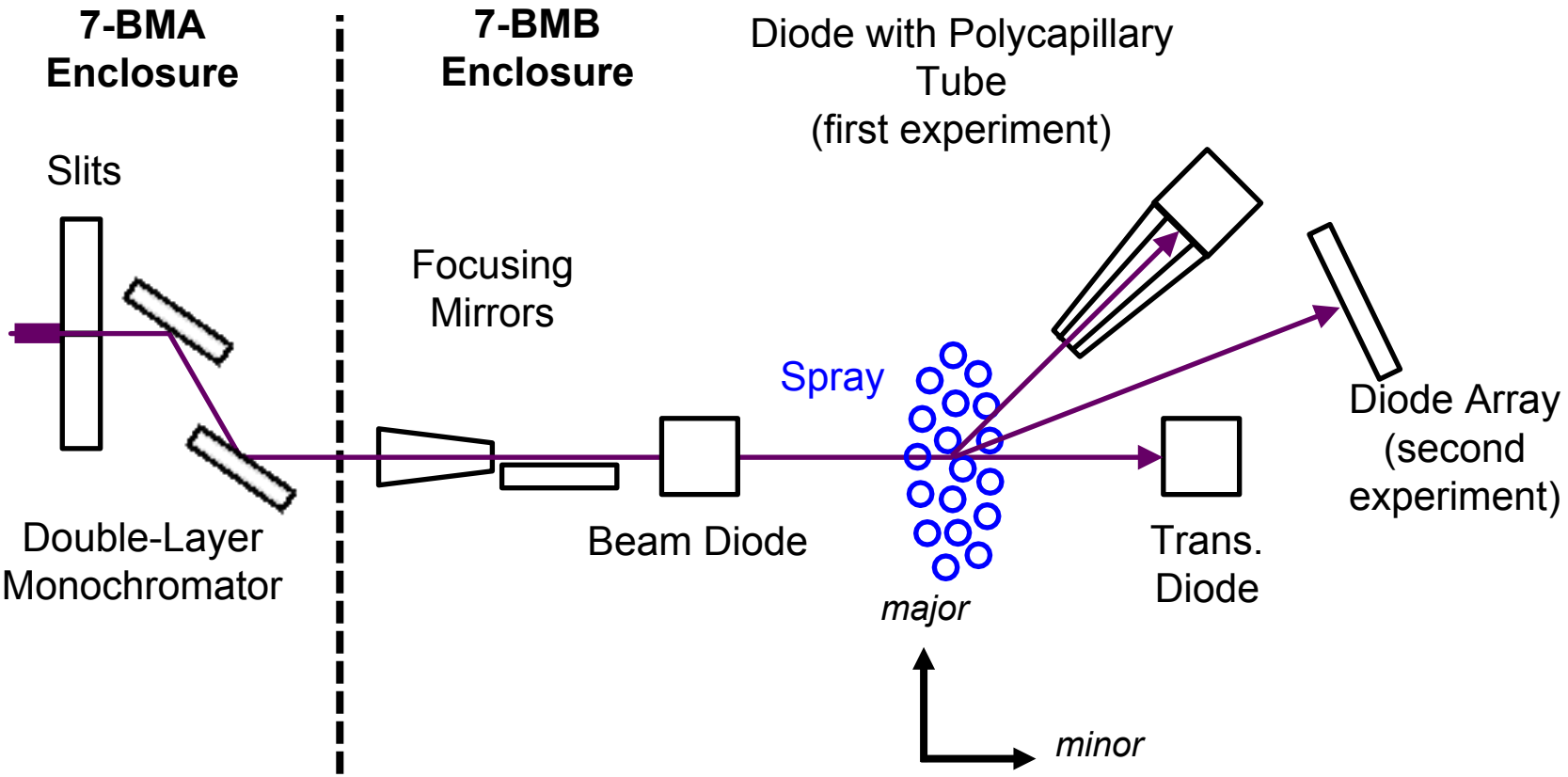
Confocal X-ray Imaging

- X-ray Scattering
  - Any and all materials scatter, good and bad
  - Any energy, good
- X-ray Fluorescence
  - Material specific, very good
  - Limited energy options, potentially bad

Experimental Setups

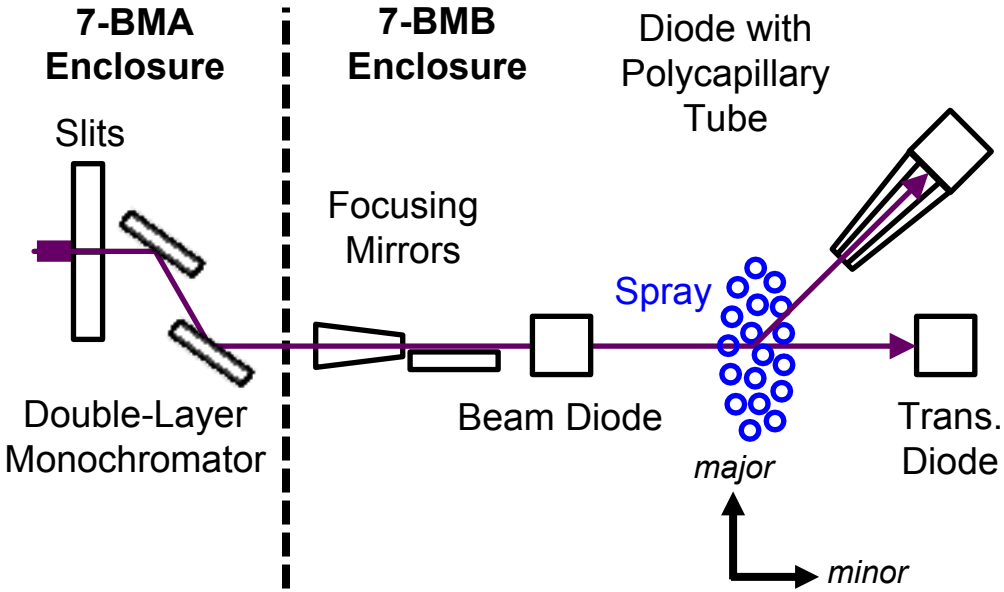
Advanced Photon Source at Argonne National Laboratory

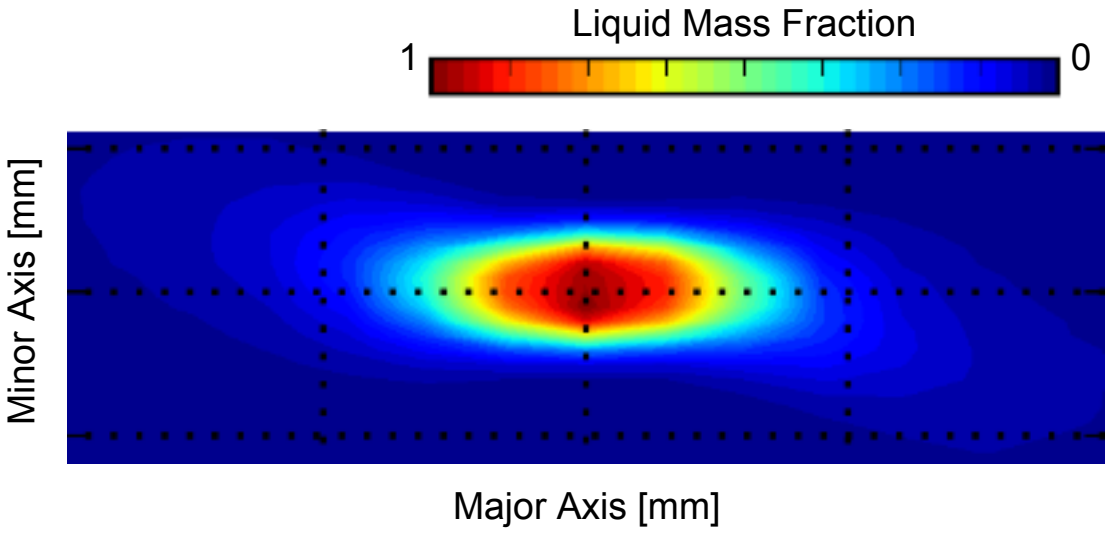
15 keV nominal energy (ΔE/E = 1.0), Kirkpatrick-Baez focusing mirrors focused to a 5 μm × 6 μm (vertical × horizontal) spot. Incident beam photodiode diamond, 55 μm thick. Transmitted beam photodiode Si, 300 μm thick. Focal length of 100 mm, yielding a focal spot size of 300 μm producing a measurement volume of 5 × 6 × 300 μm.



Confocal X-ray Scattering

- Diagnostic Setup
  - PIN diode at polycapillary
  - Polycapillary at ~30°
  - Scattering vector magnitude of q = 6.8 $Å^{-1}$
- Like-doublet impinging jet atomizer
  - Enclosed angle = 60°
  - Orifice diameter = 0.51 mm
  - Reynolds = 5,000





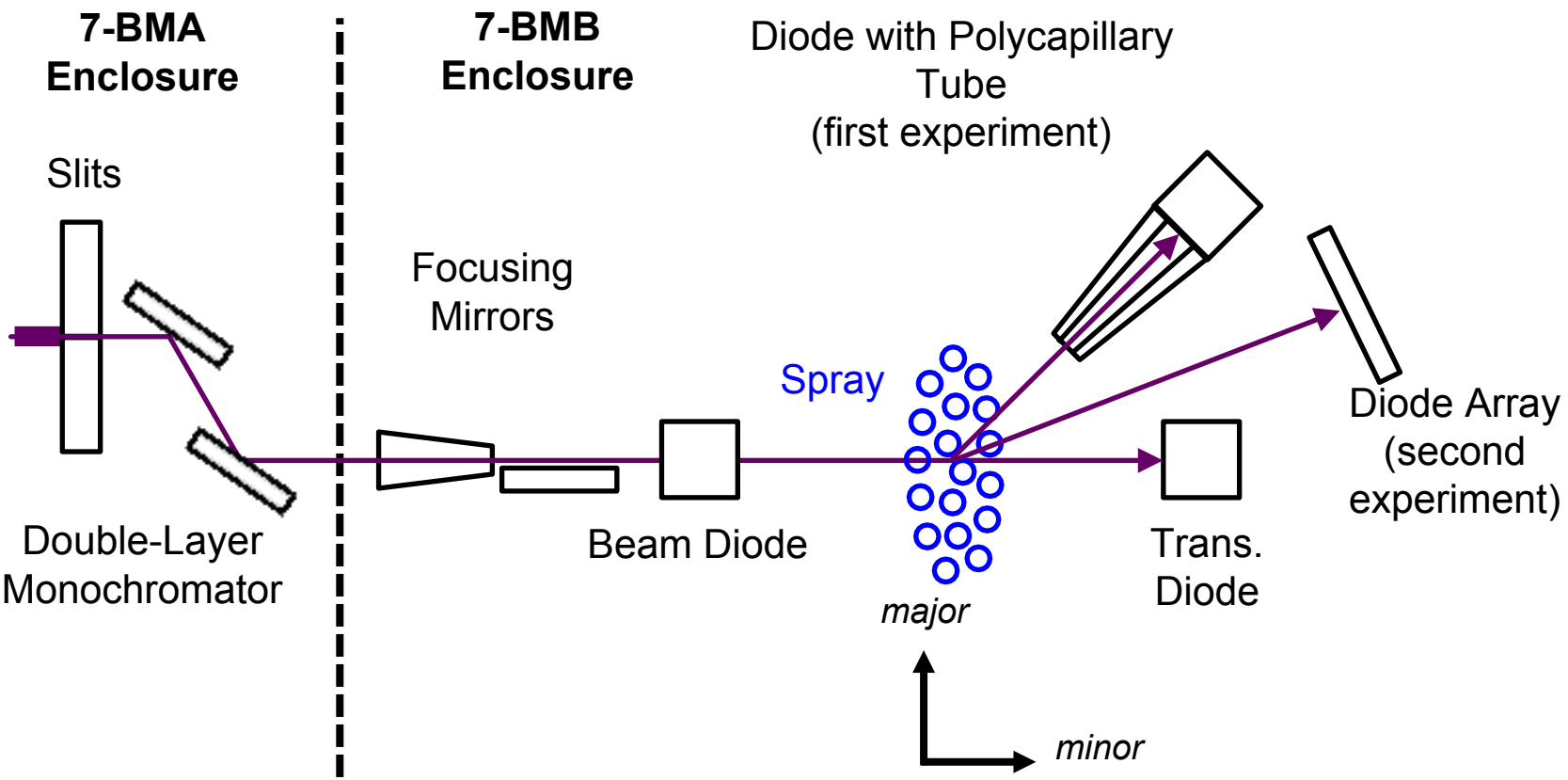
Thermometry

- Visible Regime
  - No x-ray source required
  - Optical perturbations

- X-ray Regime
  - X-ray source needed
  - Few optical perturbations
  - Path-averaged

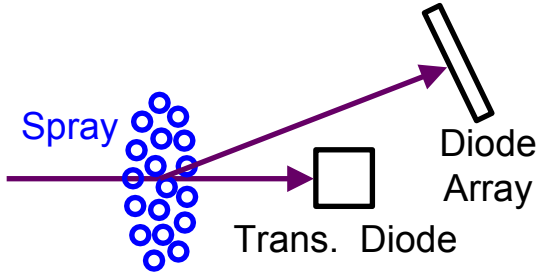
Experimental Setups

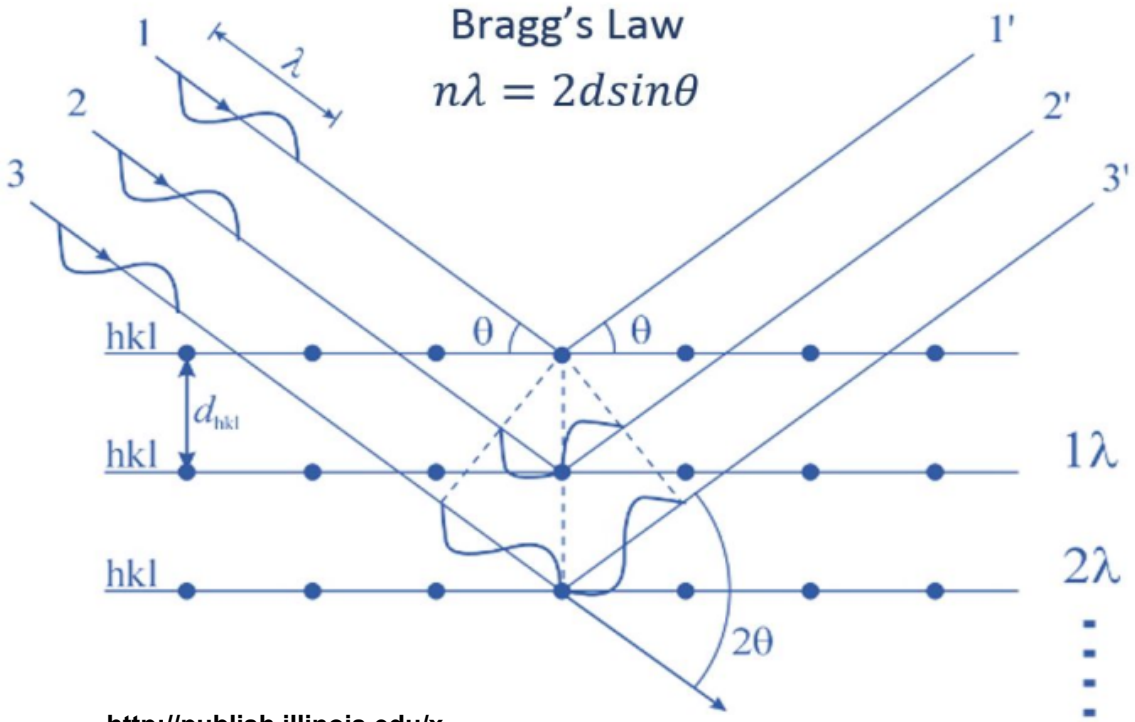
Advanced Photon Source at Argonne National Laboratory



Experimental Setups

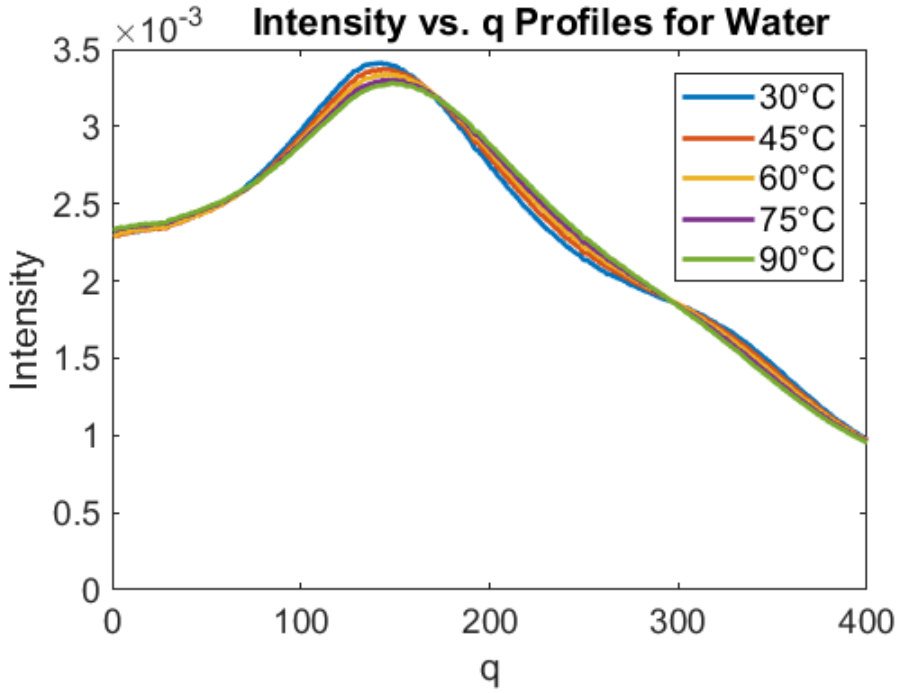
- X-ray diffraction pattern imaged by Dectris 100K Pilatus photodiode array, 50 mm from the spray.
- Single photon counting 20-bit detector, active area of 83.8 × 33.5 mm^2 (487 × 195), pixel size of 172 × 172 μm^2.
- Copper shield was placed between the PIN diode and photodiode array to reduce scattered x-rays.
- Collected the diffraction pattern from nearest neighbour oxygen atoms in the water molecules.

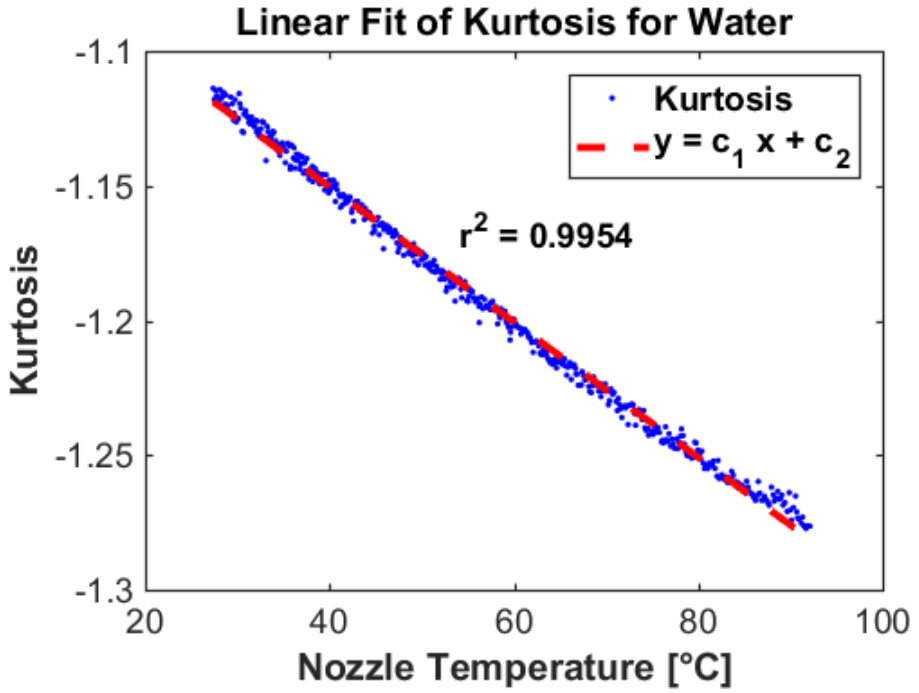




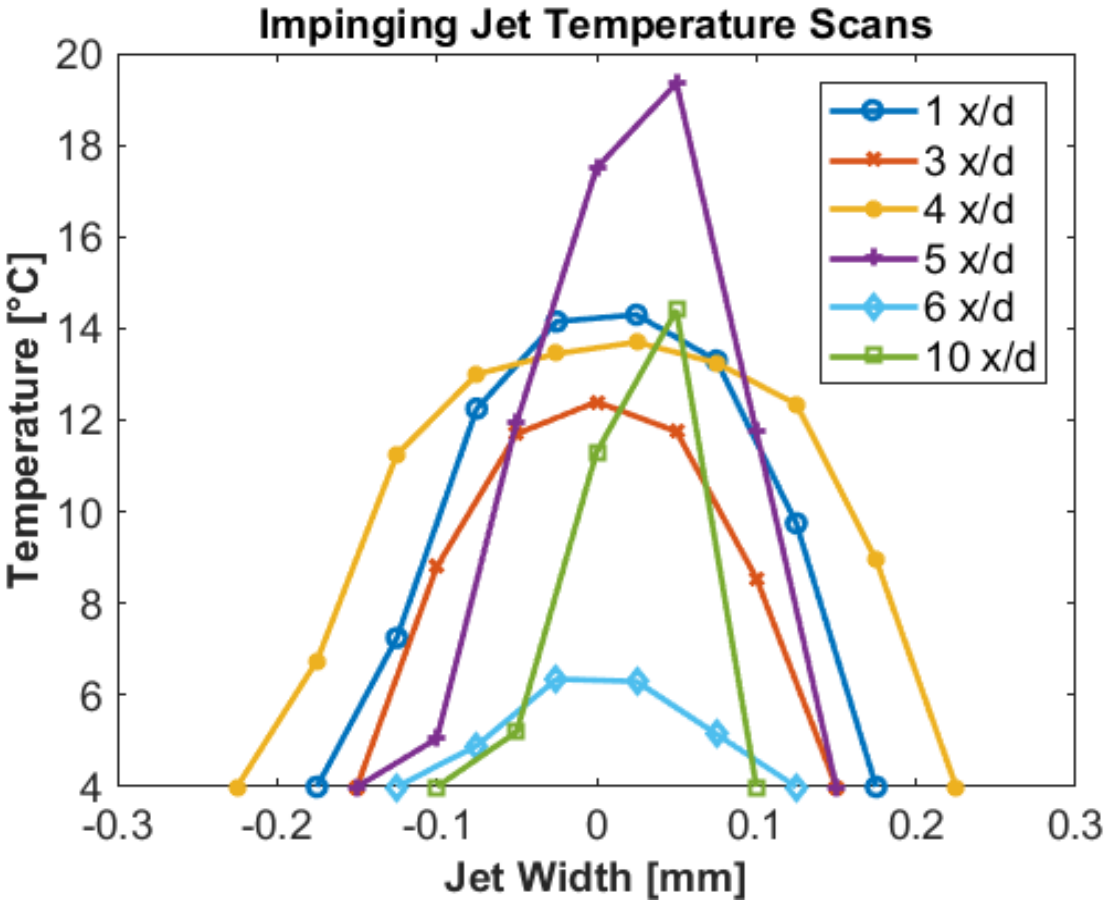
http://publish.illinois.edu/x-raycrystallography/files/2014/12/Braggs-Law.jpg

X-ray Thermometry Results

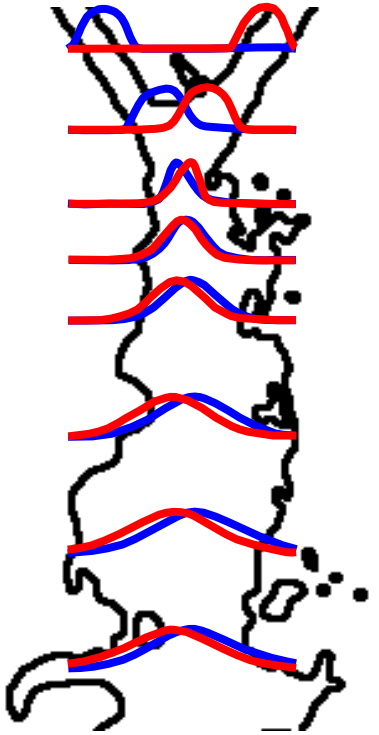




Temperature Mixing in Impinging Jets

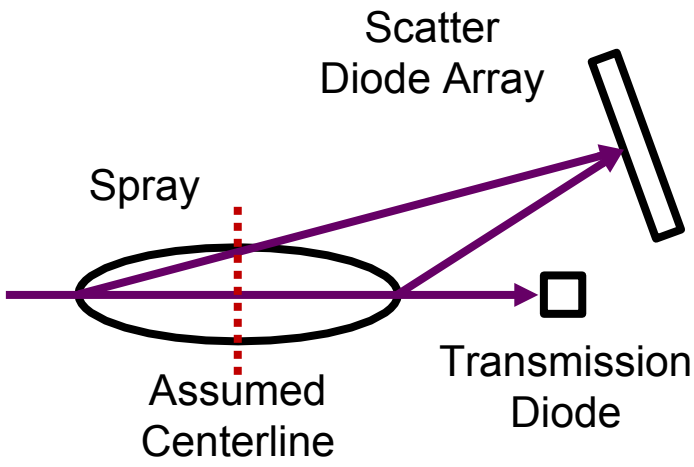


Previously measured mixing using x-ray fluorescence

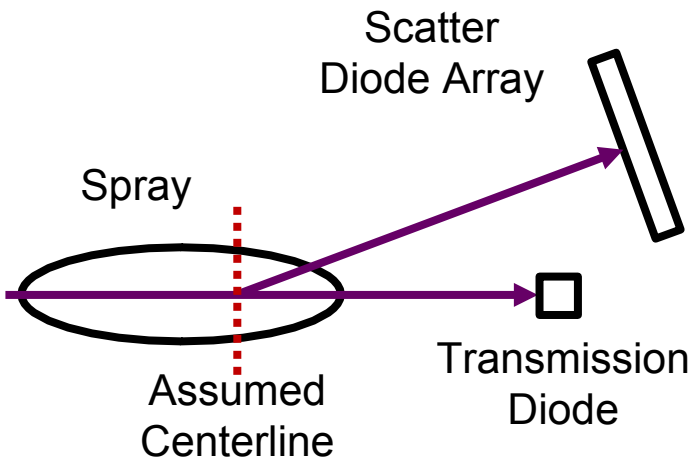


X-ray Thermometry Uncertainty

Wide spray induces blurred signal peaks



Offset spray induces offset signal peaks



Conclusions

- **Confocal x-ray scattering**
  - Elastic scatter dependent upon local density
  - Captures pointwise liquid mass distribution
  - No tracer required, but no liquid differentiation
- **X-ray Thermometry**
  - Nearest neighbor diffraction
  - Diffraction patterns function of atomic spacing
  - Atomic spacing function of temperature

Acknowledgments

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  - Air Force Research Laboratory
  - Air Force Office of Scientific Research
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  - Air Force Office of Scientific Research
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  - The National Science Foundation