

Synchrotron X-ray Imaging for High-Speed Characterization of Multiphase Flows

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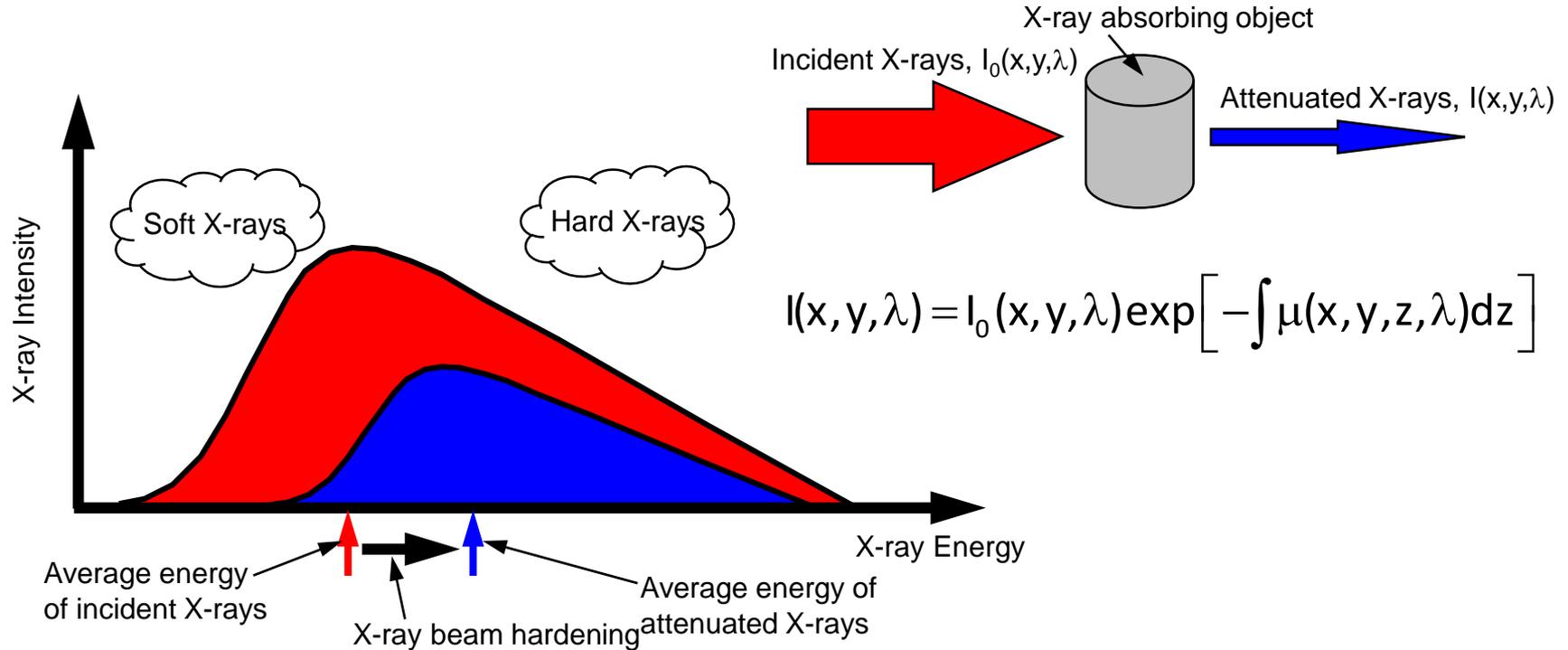
Outline

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 - b. White beam imaging
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 - d. Phase contrast imaging
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Introduction: Multiphase flows are a challenge

- Highly complex fluid flows
 - Opaque, Newtonian and non-Newtonian, phase-induced turbulence
 - A better understanding of the transport and hydrodynamic characteristics are needed for process improvements, optimization, and CFD validation.
- Measurements are complicated
 - Optical access is limited; Highly dynamic; Invasive probes can alter the flow
 - Noninvasive measurements can provide qualitative and quantitative data of opaque and multiphase flow characteristics
 - **Our focus is on X-ray flow visualization**

X-ray Fundamentals



Synchrotron X-rays

Advanced Photon Source (APS), Argonne National Laboratory

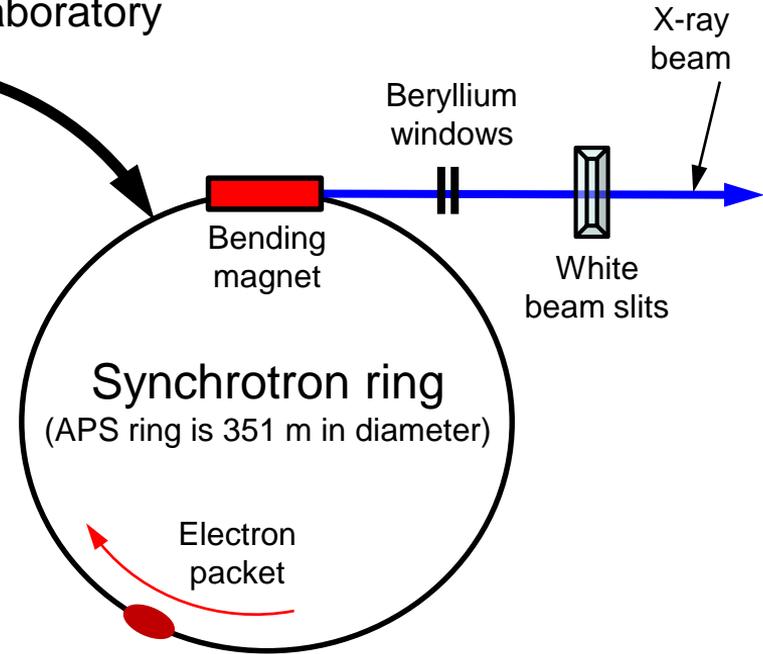
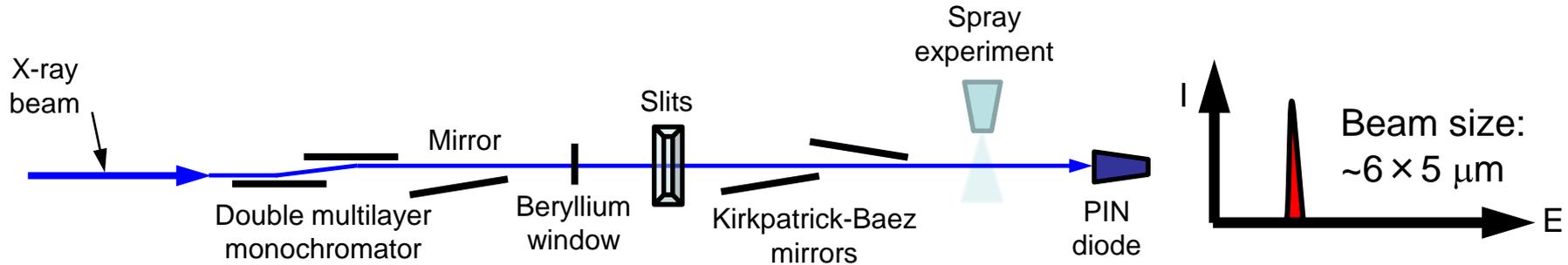


Photo acknowledgement: Advanced Photon Source, Argonne National Lab, https://www1.aps.anl.gov/sites/default/files/aerial_2010.jpg

Focused beam radiography



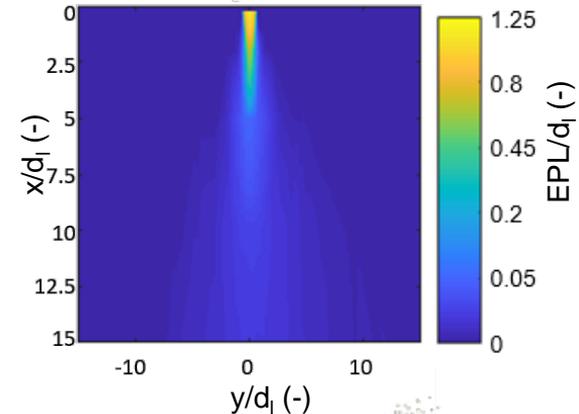
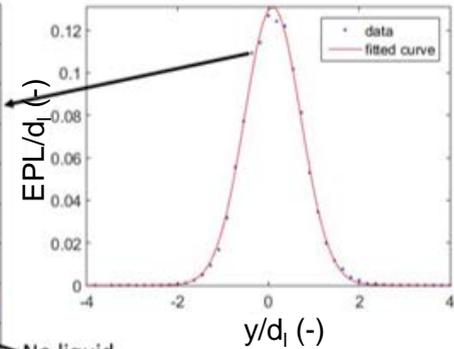
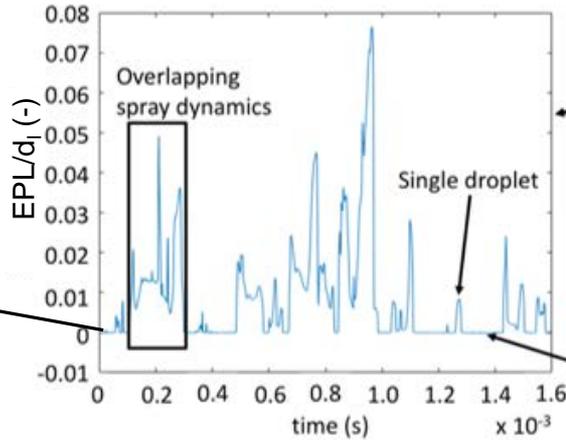
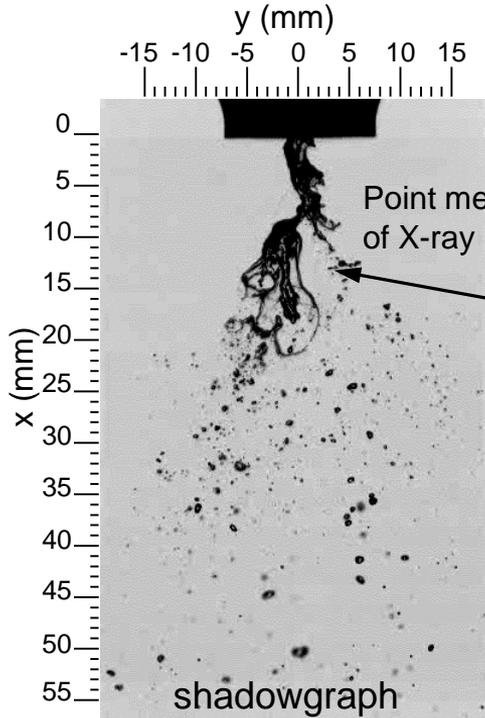
- High-speed data acquisition (270 kHz in our current studies)
- Can measure equivalent path length directly at the measurement location using Beer-Lambert's law:

$$I = I_0 \exp(-\mu \cdot \ell)$$

I_0 : intensity of the incident beam
 I : intensity of the beam after passing through the spray
 ℓ : equivalent path length (EPL)
 μ : attenuation coefficient

- A: High temporal and spatial resolution
- A: Monochromatic beam
- A: Direct EPL measure
- D: Point measurement
- D: Time consuming

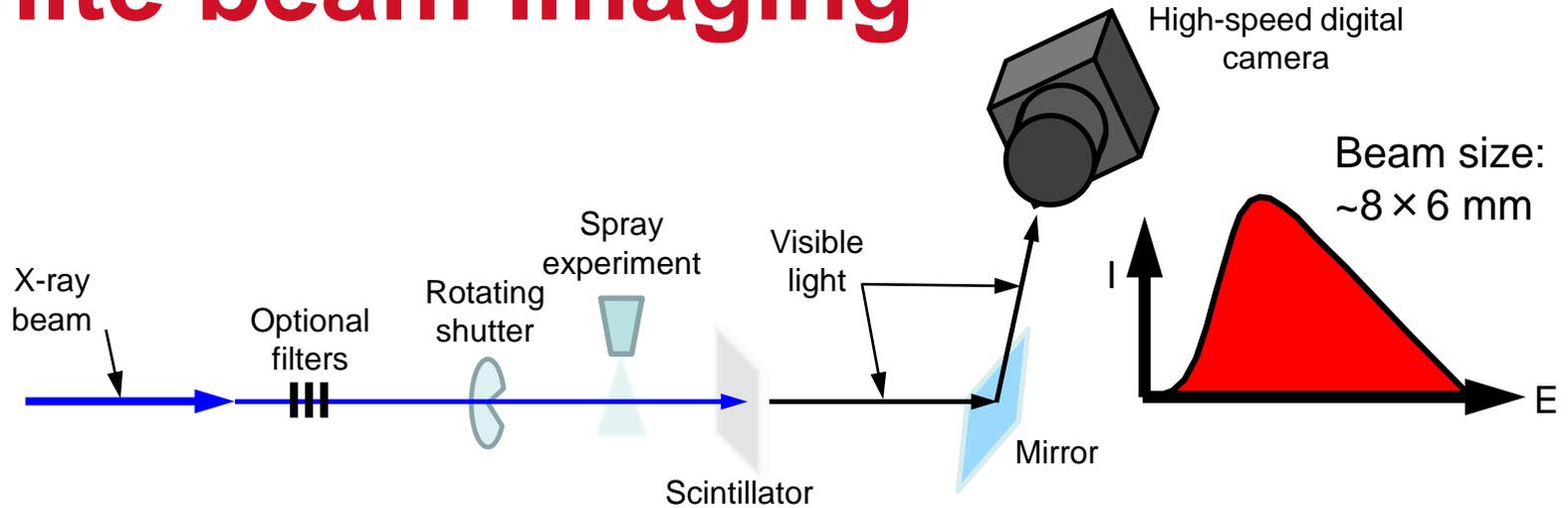
Focused beam example



$Re_l = 1,100$
 $Re_g = 21,300$
 $M = 6$
 $SR = 0$

Image acquisition frame rate: 6000 fps
Image playback frame rate: 10 fps

White beam imaging

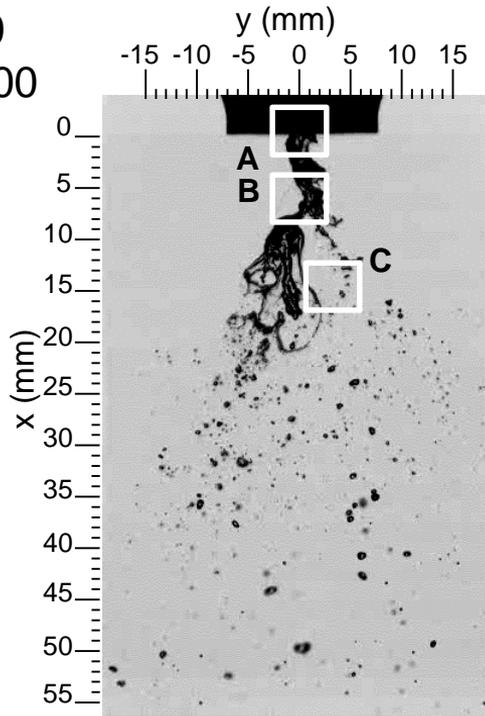


- Can use high-speed cameras
- 2-D projection image
- Can see internal structures

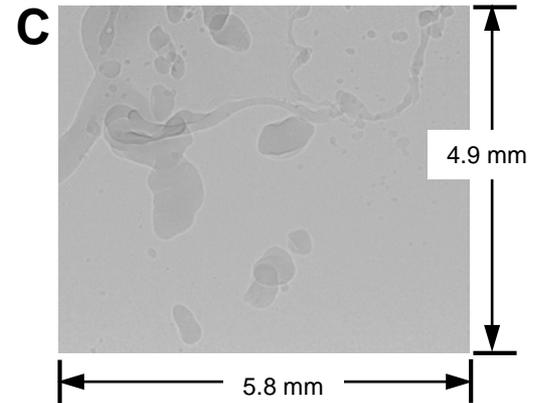
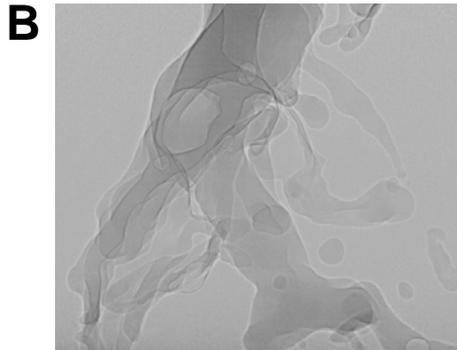
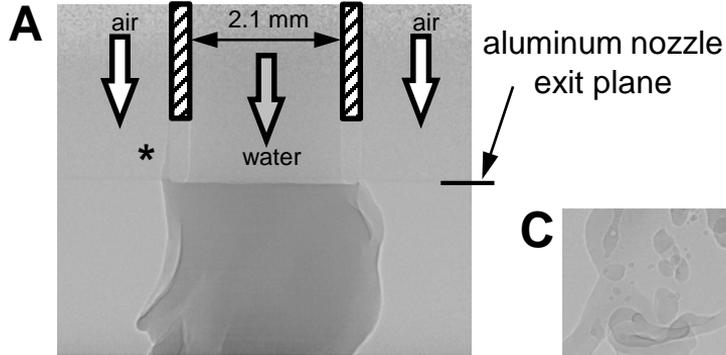
- **A: High energy flux**
- **A: High-speed flow visualization**
- **A: Can view internal structures**
- **A: Highly collimated**
- **D: Broad energy spectrum**
- **D: Limited field of view**

White beam imaging example

$Re_l = 1,100$
 $Re_g = 21,300$
 $M = 6$
 $SR = 1$



shadowgraph

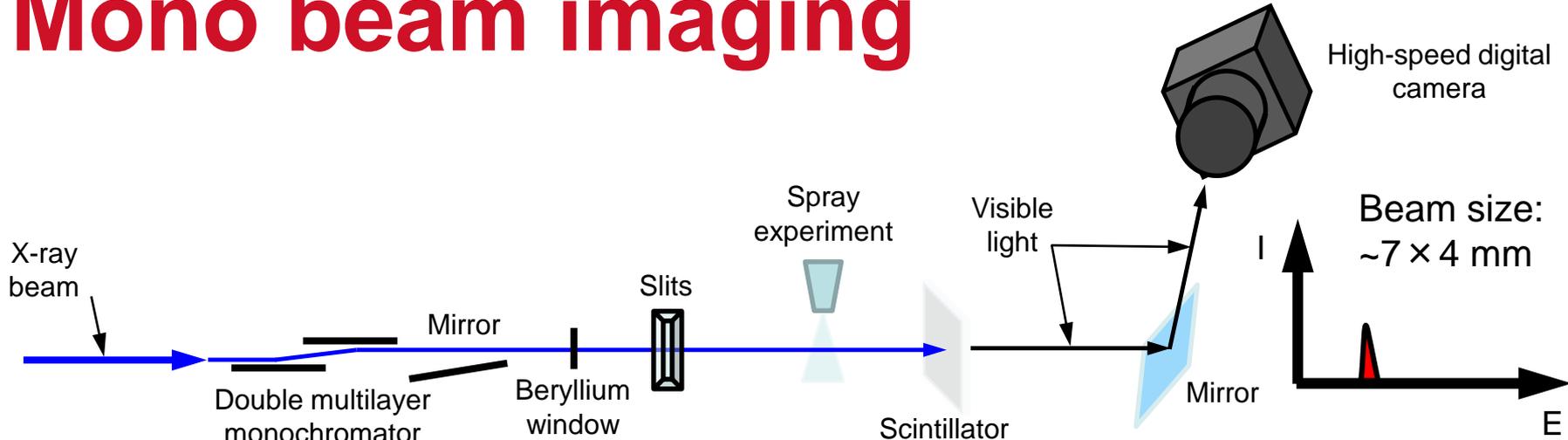


All images:

Image acquisition frame rate: 6000 fps

Image playback frame rate: 10 fps

Mono beam imaging



- Monochromatic X-ray beam
- 2-D projection image using larger beam area
- Lower beam flux than white beam
- Slower image acquisition
- Can show instantaneous equivalent path length over wide region

- **A: Monochromatic beam**
- **A: Direct 2-D EPL measure**
- **A/D: Field of view**
- **D: Slower than white beam (lower energy flux)**
- **D: Nonuniform background**

Mono beam example

Instantaneous EPL:

$Re_l = 1,100$
 $Re_g = 21,300$
 $M = 6$
 $SR = 0$

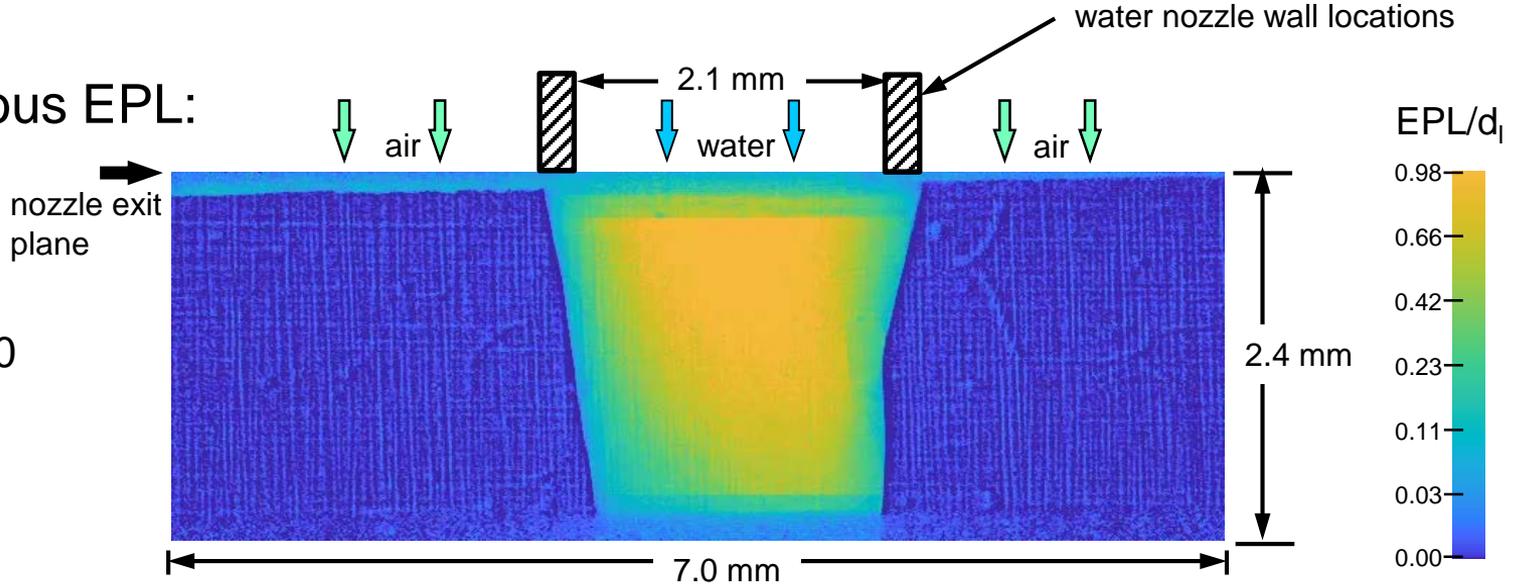
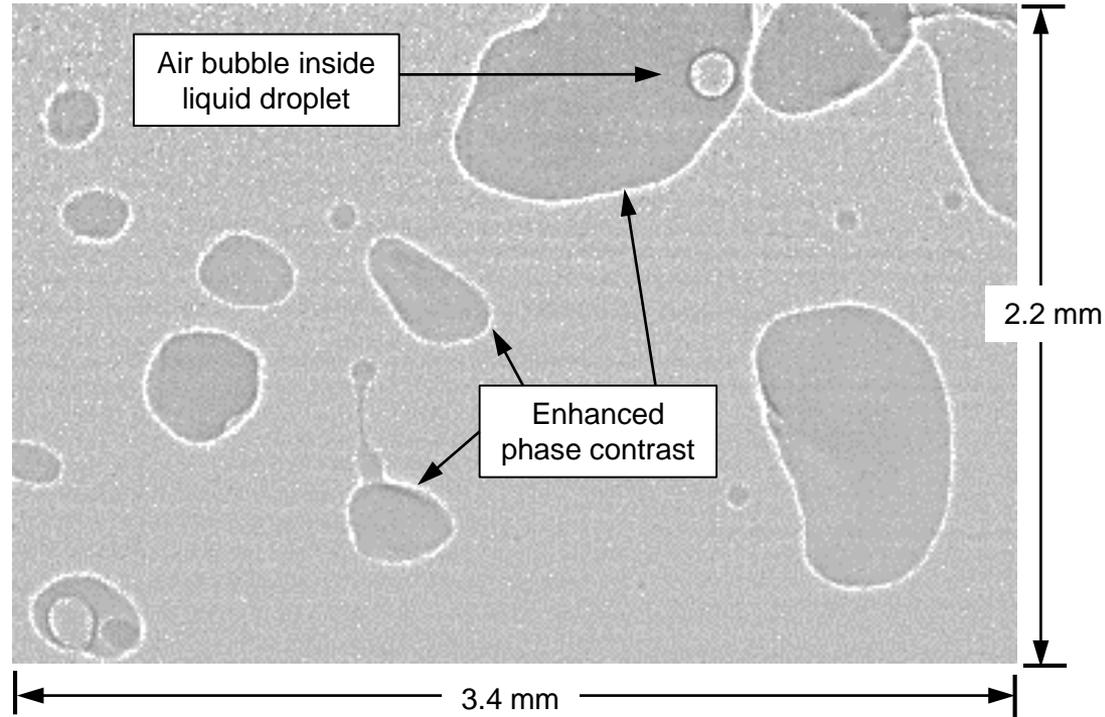


Image acquisition frame rate: 7200 fps
Image playback frame rate: 12 fps

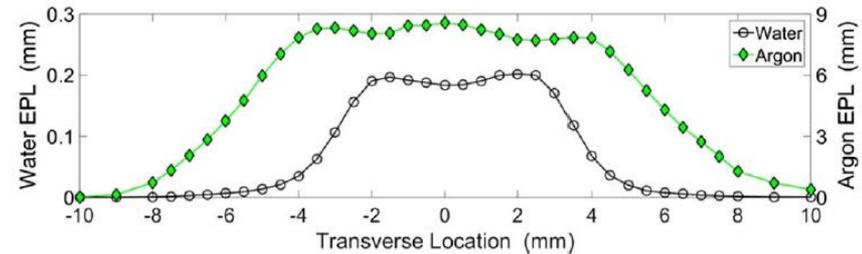
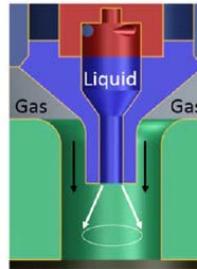
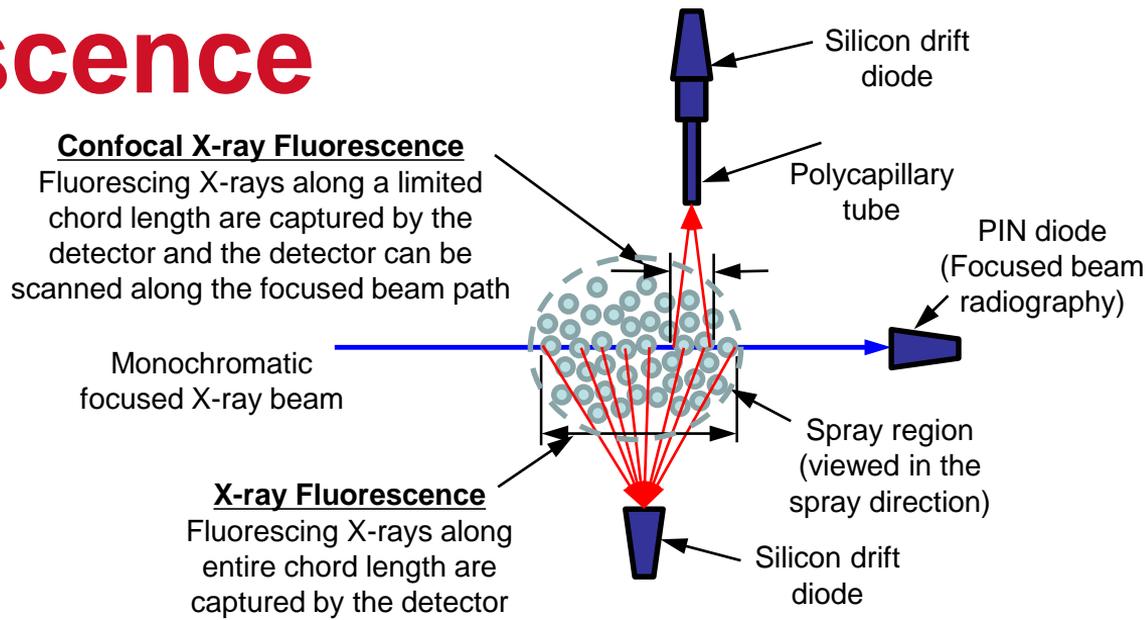
Phase contrast imaging (PCI)

- Requires a high-energy coherent X-ray beam
- Phase shift is produced at the gas-liquid interface, creating a Fresnel diffraction pattern, which enhances the absorption contrast at the interface
- Can result from white beam imaging



X-ray fluorescence

- High flux from synchrotron X-rays are used to excite an X-ray fluorescing media such that the media will uniformly emit X-rays with a characteristic spectrum.
- The strength of the emitted signal is proportional to the amount of the media in the beam path.
- Seed one constituent with fluorescing media to discriminate between two constituents

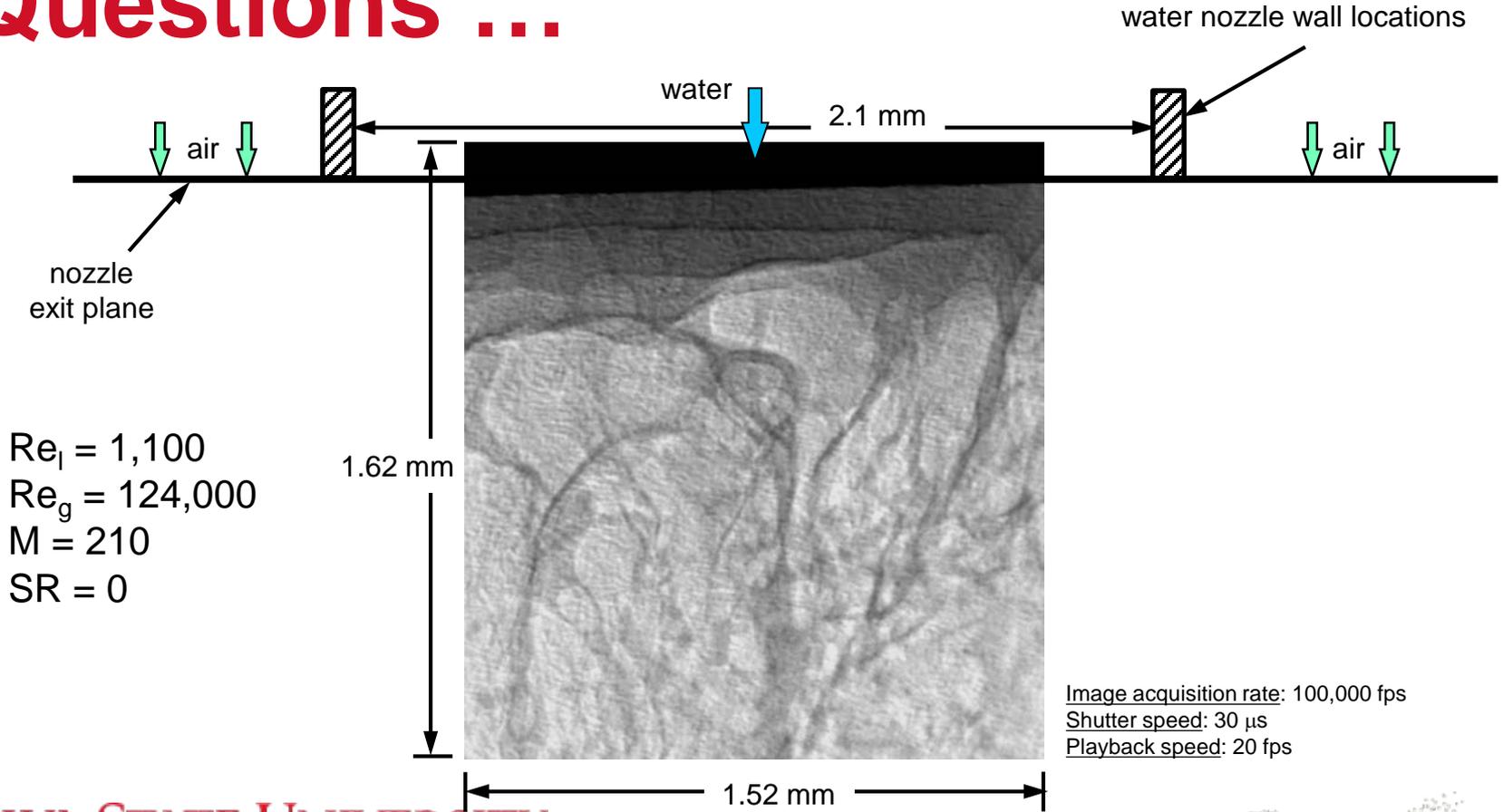


From: Radke et al., Optics Letters, 40(9), 2029-2032, 2015.

Conclusions

- X-rays from a synchrotron source provide several methods to characterize multiphase flows
- Provide high spatial and temporal resolutions
- Allow for flow visualization of high-speed opaque fluid flows
- Can quantify equivalent path lengths.

Questions ...



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