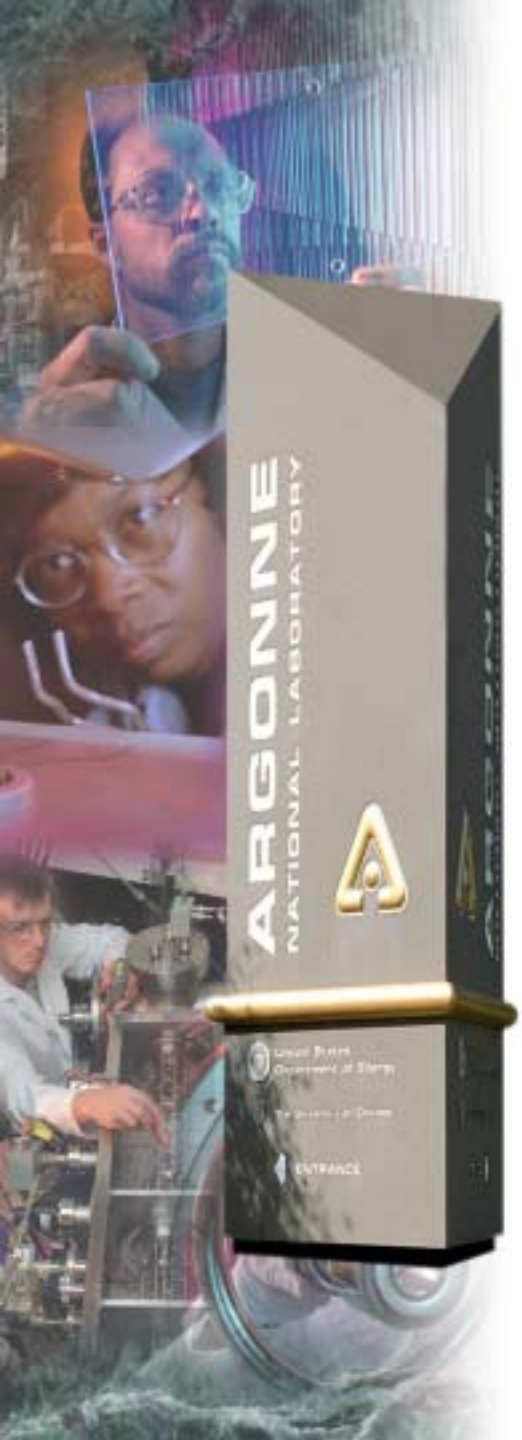

Ultrafast X-radiography and Tomography of High-Pressure High-Speed Fuel Sprays

Workshop on Emerging Scientific Opportunities Using X-ray Imaging
Fontana, Wisconsin

August 29-September 1, 2004

Jin Wang
Experimental Facilities Division
Argonne National Laboratory

Office of Science
U.S. Department of Energy

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Johannes Schaller, Jochen Walther	Robert Bosch, GmbH
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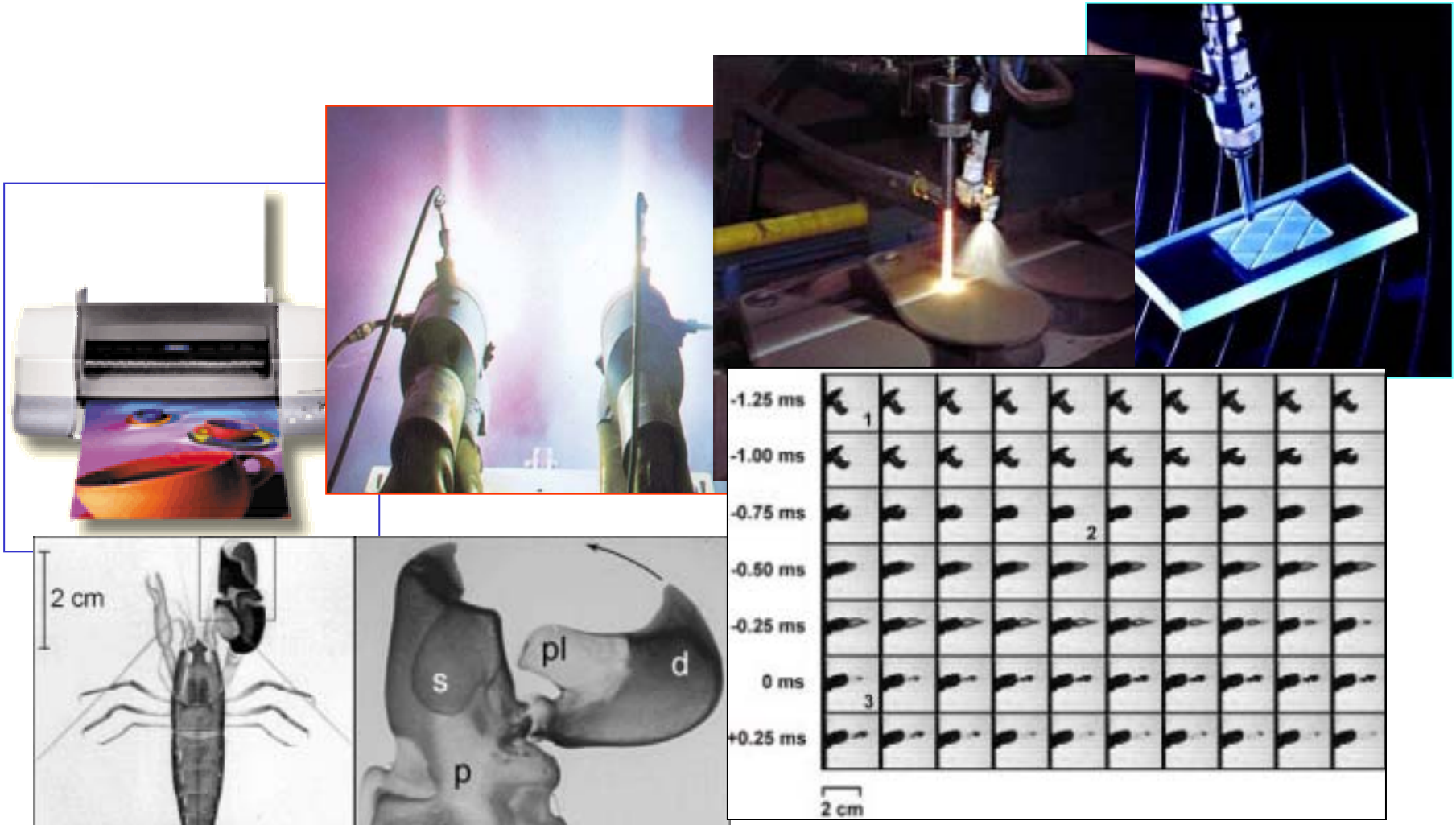
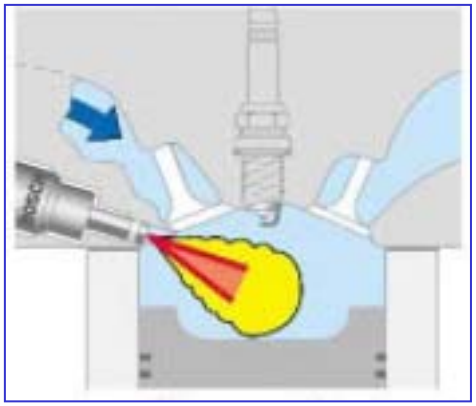
Spray Applications



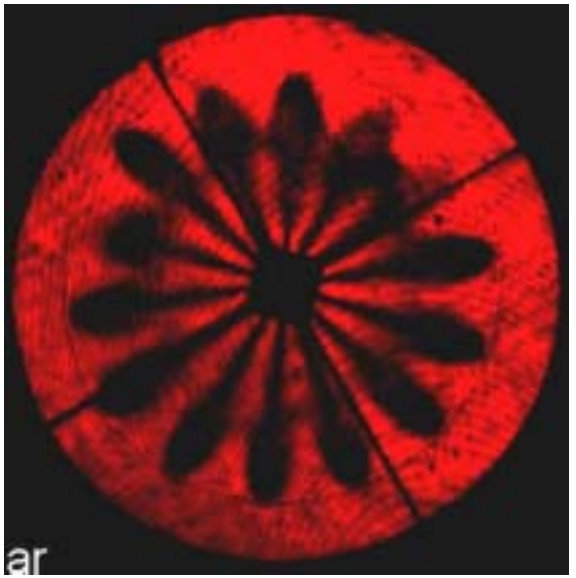
How Snapping Shrimp Snap:Through Cavitating Bubbles
Versluis *et al.*, ***Science* 289** 2114 (2000)

Fuel Sprays

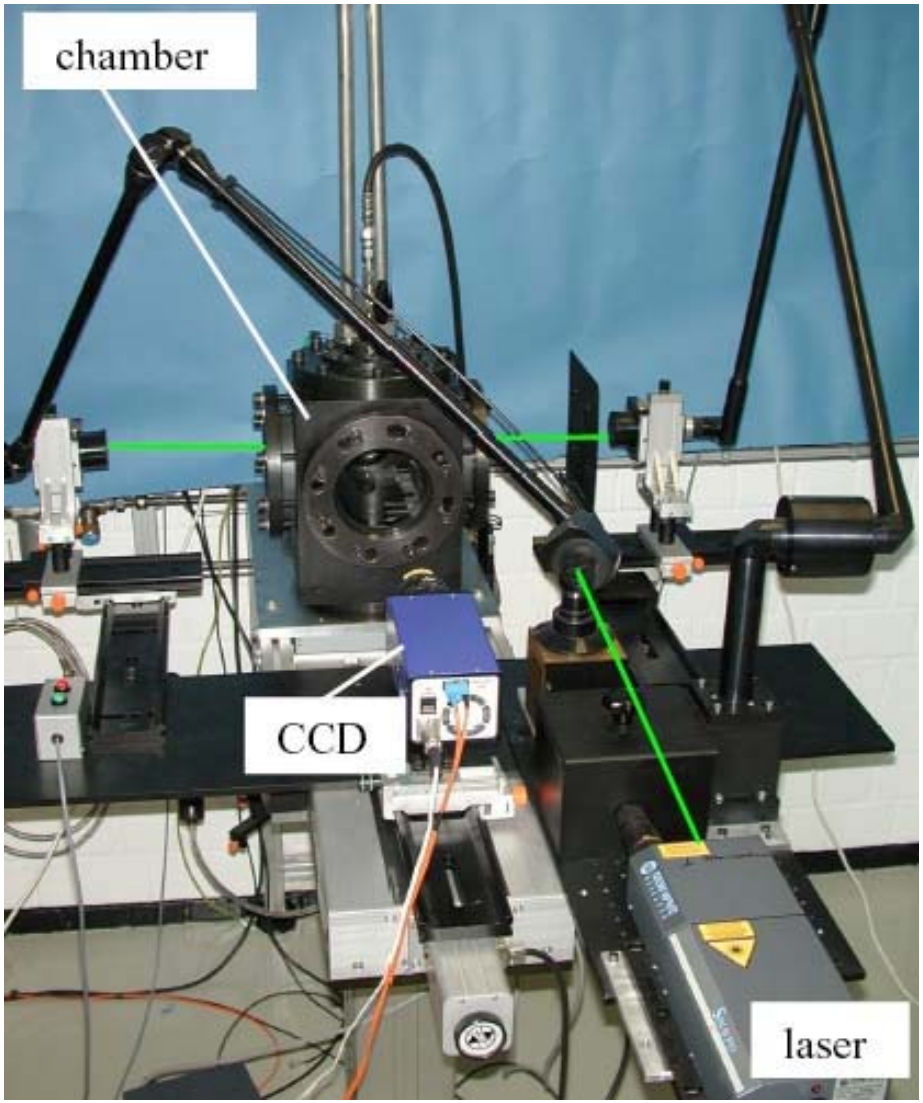


- Liquid fuel sprays are part of energy sources for propulsion and transportation systems including internal combustion engines (ICE).
- Combined with development of new injection mechanism, study of fuel spray and combustion is aimed to achieve more economical use of fuels and better control of pollutants.

- Optimized fuel spray penetration, atomization and mix with air charge in cylinder is a key for a clean and efficient combustion.
- Realistic fuel spray characterization is the first step and crucial for a realistic combustion simulation.



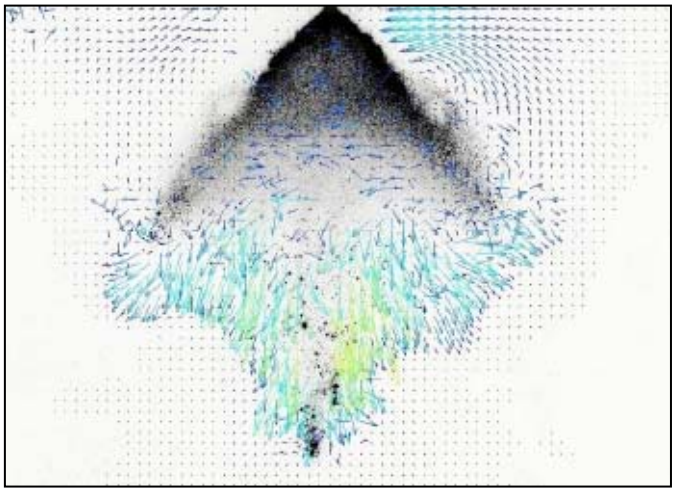
Conventional Diagnostics



- shadow, Mie, Schlieren imaging
- scattering
- laser-induced fluorescence
- interferometry

Pros and Cons

- non-intrusive
- temporally and spatially resolved
- commercially available
- opaque in region near a nozzle
- not quantitative close to nozzle

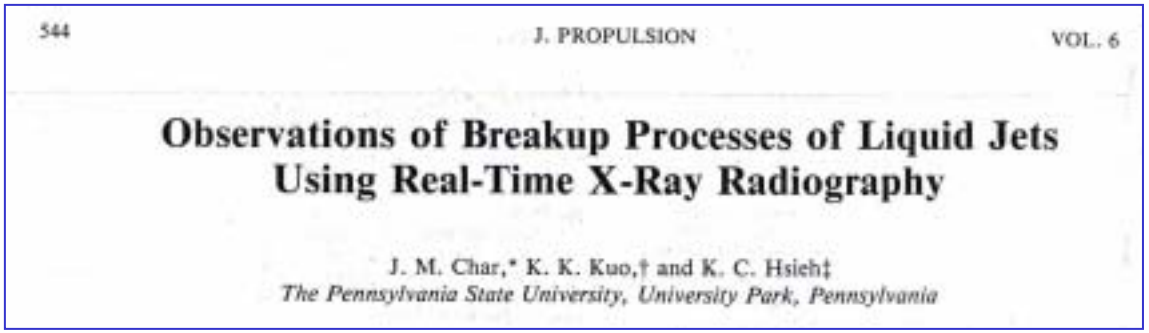


Outlines

- Approaches
  - Time-resolved monochromatic x-ray radiography and tomography
- Diesel Sprays
  - Direct imaging of shock waves using fast 2-D detector
  - Quantitative analysis of Mach-cone
  - A *new era* of fluid dynamic simulation effort
- Gasoline Sprays
  - X-radiography from various directions
  - **Ultrafast X-Tomography**
- Summary and Outlook
  - Edge-enhanced, phase-contrast imaging
    - Through the nozzle
    - Imaging the liquid droplets
    - Particle imaging velocimetry
  - Micro- and nano-focusing for time-resolved, full-field imaging

X-radiography

- Polychromatic radiography have been demonstrated since 80's:



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Observations of Breakup Processes of Liquid Jets Using Real-Time X-Ray Radiography

J. M. Char,* K. K. Kuo,† and K. C. Hsieh‡
The Pennsylvania State University, University Park, Pennsylvania

Limited to nozzles in large scale (a few mm)

$$I/I_0 = \int \rho(\lambda) e^{-\mu_m(\lambda)\cdot M} d\lambda \Big/ \int \rho(\lambda) d\lambda$$

→ **Difficult to obtain Quantitative results**

- Use of monochromatic x-ray beam radiography makes determination of the fuel mass quantity in the beam ( ) is EASY!

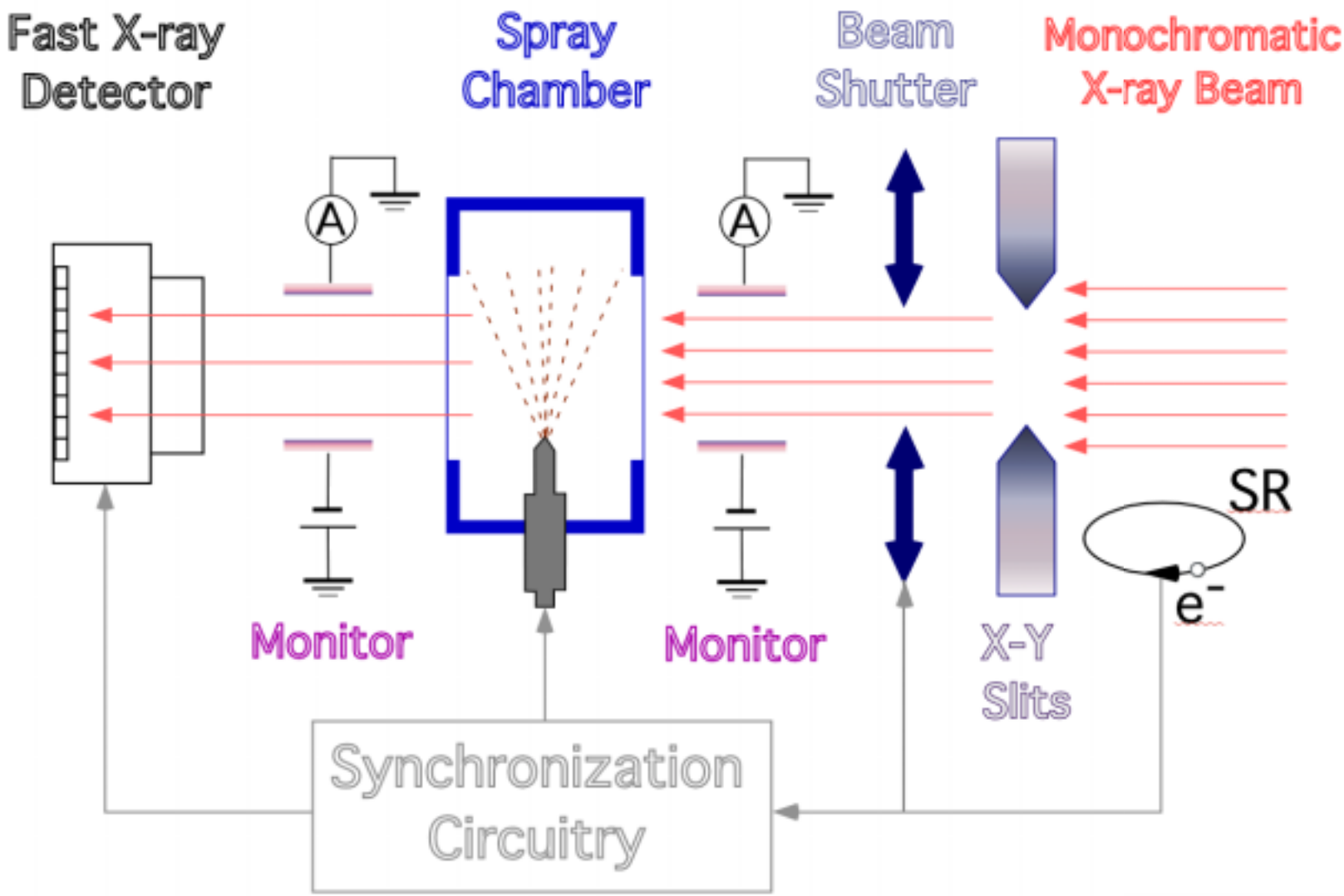
$$I/I_0 = e^{-\mu_m \cdot M}$$

X-ray Transmission

Mass absorption coefficient

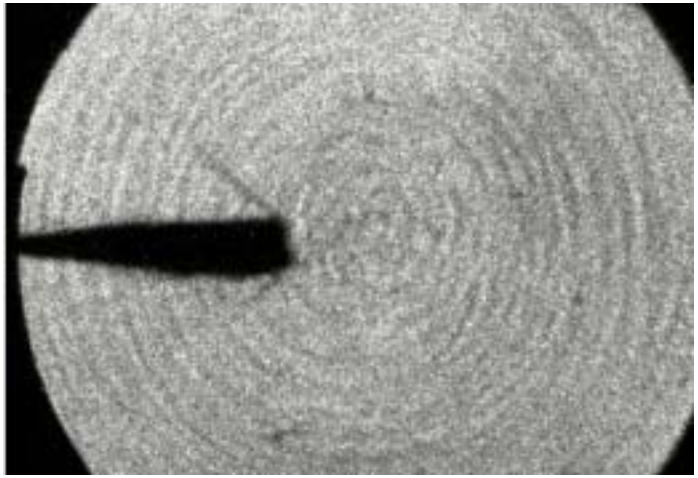
Fuel mass in the beam

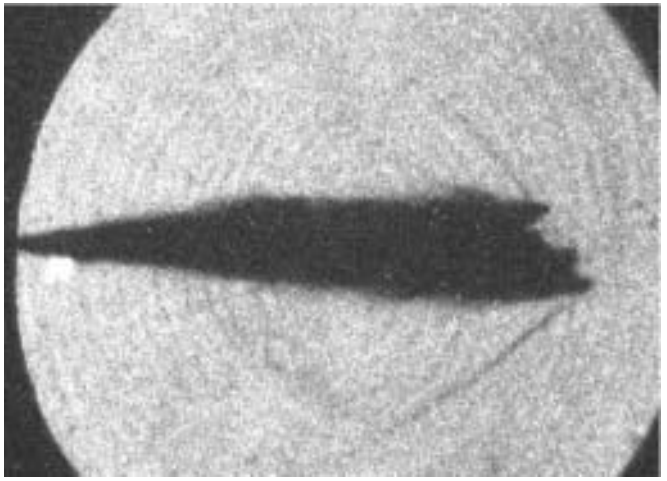
Experiment Setup



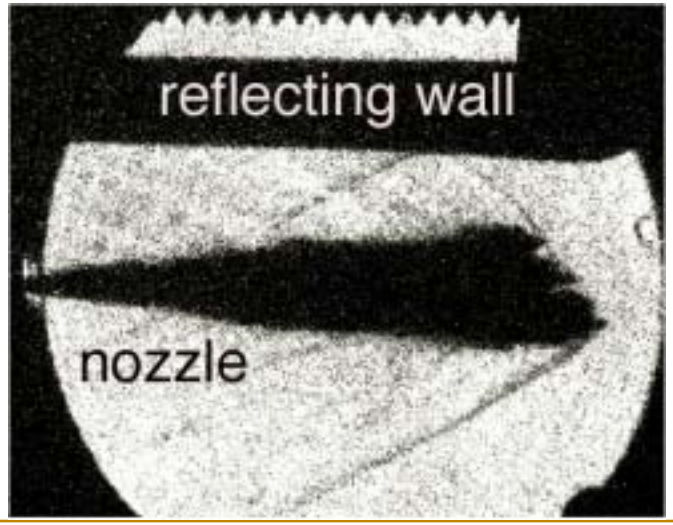
Shockwave Visualization

The first shock discovery was the shockwaves generated by fuel sprays





Reflection off a wall



Parameters:
Injection pressure 80 MPa
Injection duration 0.5 ms
Ambient gas: SF_6 @ 0.1 MPa

images collected by
J. Schaller and J. Walter, Robert Bosch, GmbH

Shockwave Visualization by X-rays

Advanced Photon Source
Argonne National Laboratory

The first shock discovery was the shockwaves generated by fuel sprays

QuickTime™ and a
Video Format cvid decompressor
are needed to see this picture.

17 mm

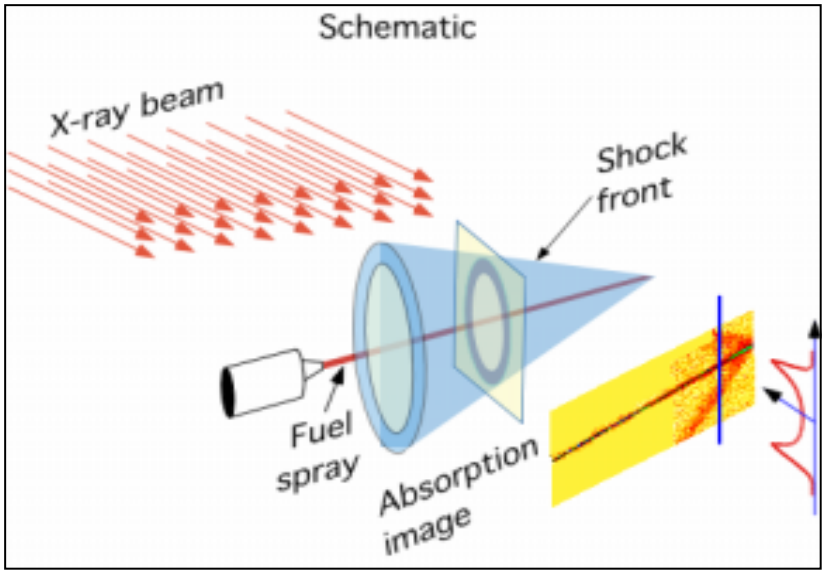
60 mm

Injection pressure: 135 MPa
Injection time: 0.5 ms
Ambient gas: 0.1 MPa SF_6

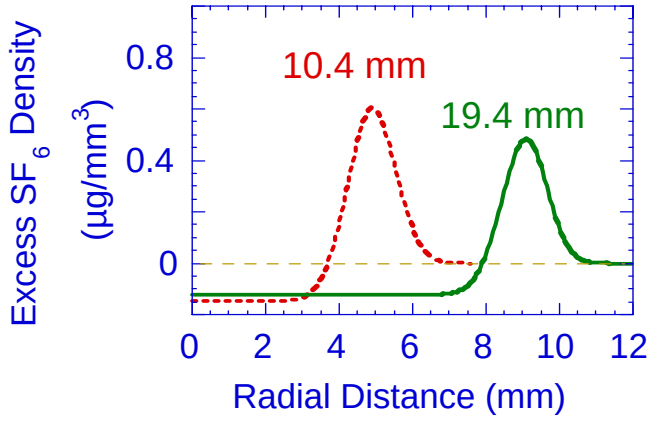
Data collected at D-1 station, CHESS:
Pixel Array Detector
Wide bandpass monochromator

MacPhee *et al.*, *Science*, **295**, 1261 (2002) with animation available on Science Website

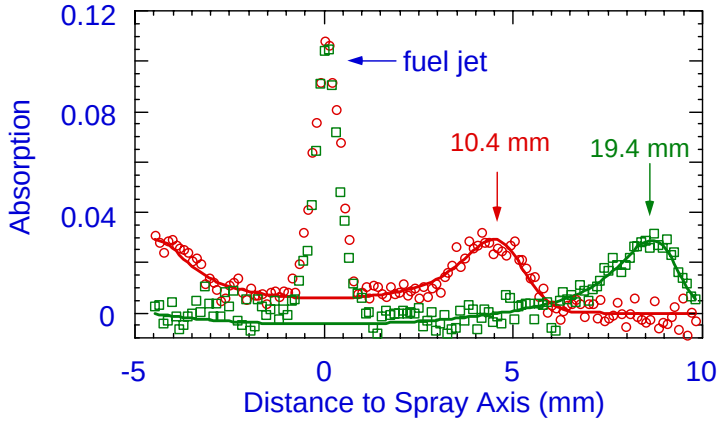
Quantitative Analysis



Density Deconvolution



Fit to line-of-sight-projected gas density

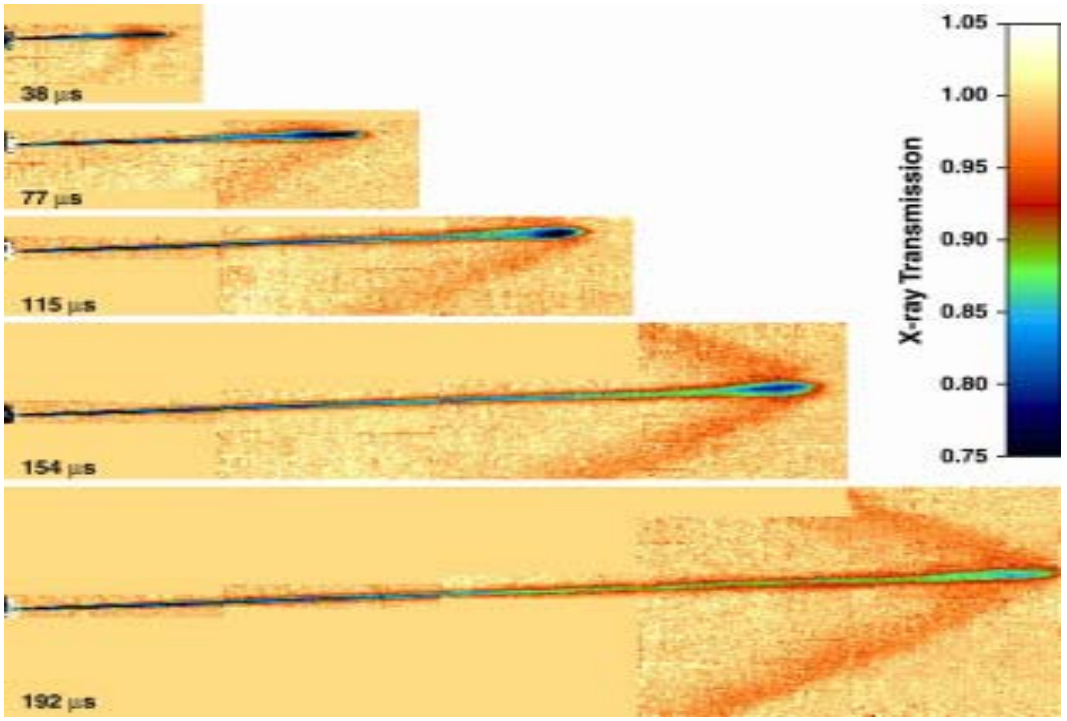


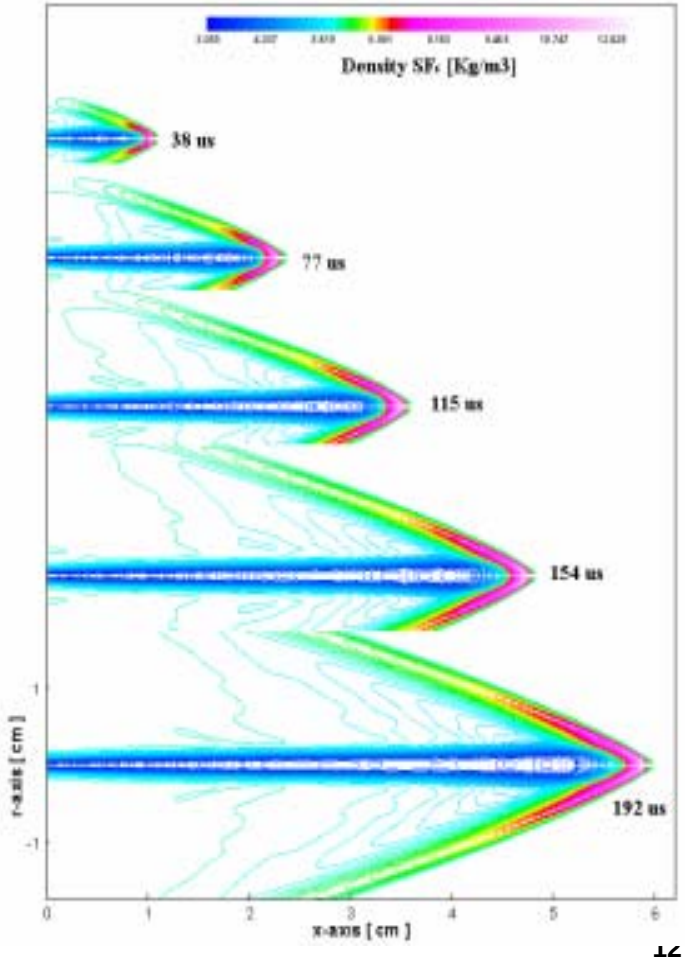
1. Mach cone gas distribution determined quantitatively!
2. Decompression behind the shock cone
3. Soft shock

CFD Simulation

- **Simulating shock waves with multiphase multidimension models**

  Simulation by3ew **Professor Ming-chia Lai and Dr. Kyun-su Im** at Wayne State University)

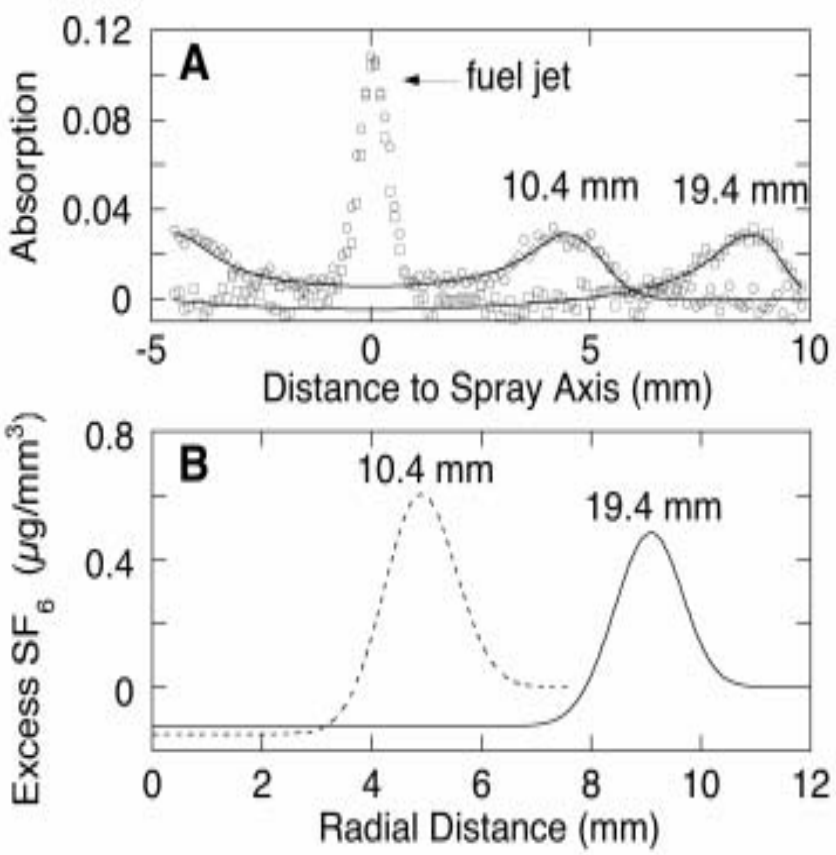




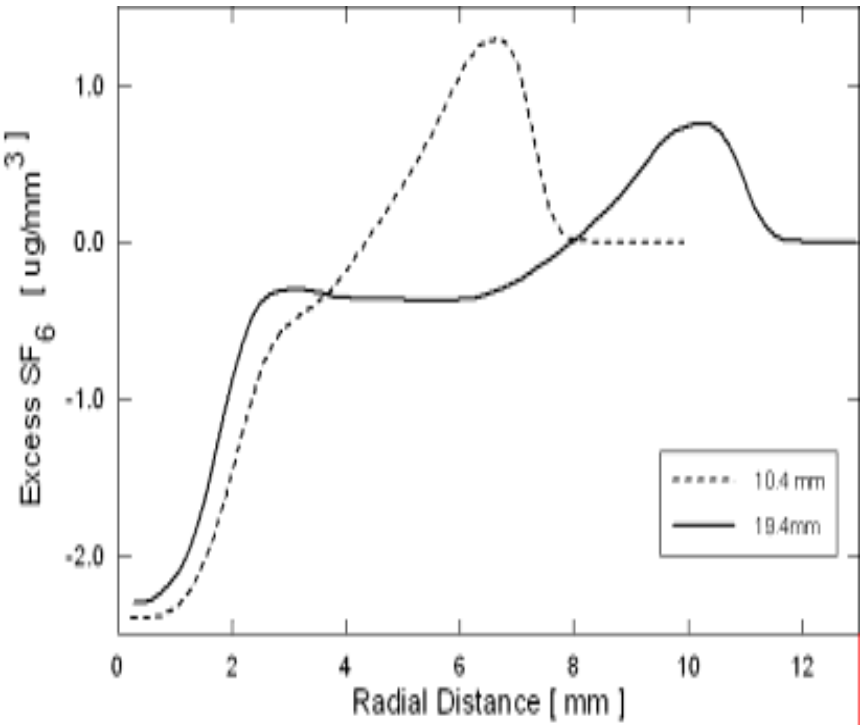
- Two phases: liquid particle and ambient gas
- Discrete particle tracking
- Nonevaporate sprays

CFD Simulation

Experiment



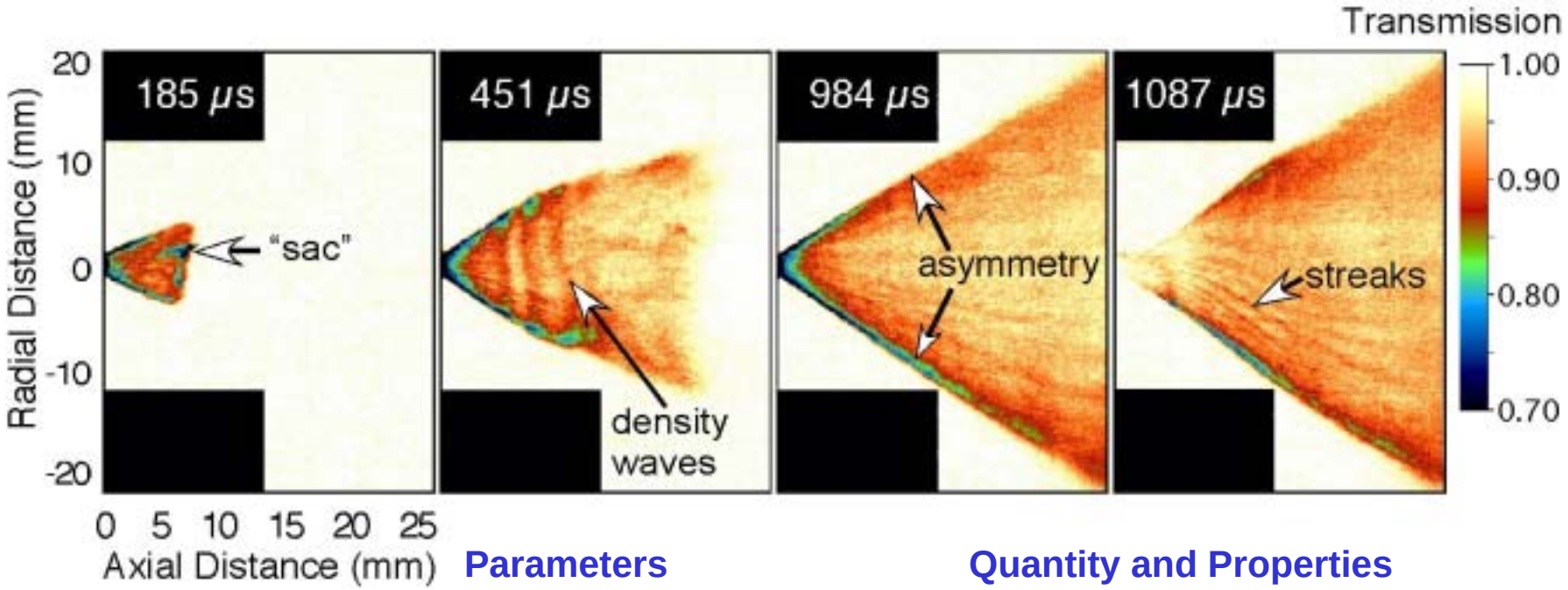
Simulation



Soft shock is real - not artifact

More details are revealed.

Gasoline Hollow-cone Sprays



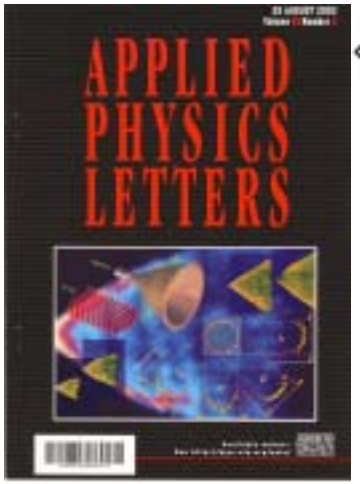
Parameters	Quantity and Properties
Injection system	GDI, outward opening nozzle
Orifice diameter	1.9 mm
Fill gas	N_2 , 0.1 MPa, 25 – 30°C
Fuel	Viscor® with Ce-additive
Specific gravity	0.8405 g/ml
Spray duration	1 ms (nominal)
Spray cone angle (full)	65° (0.1 MPa chamber pressure)
Region of interest	25 mm from the nozzle

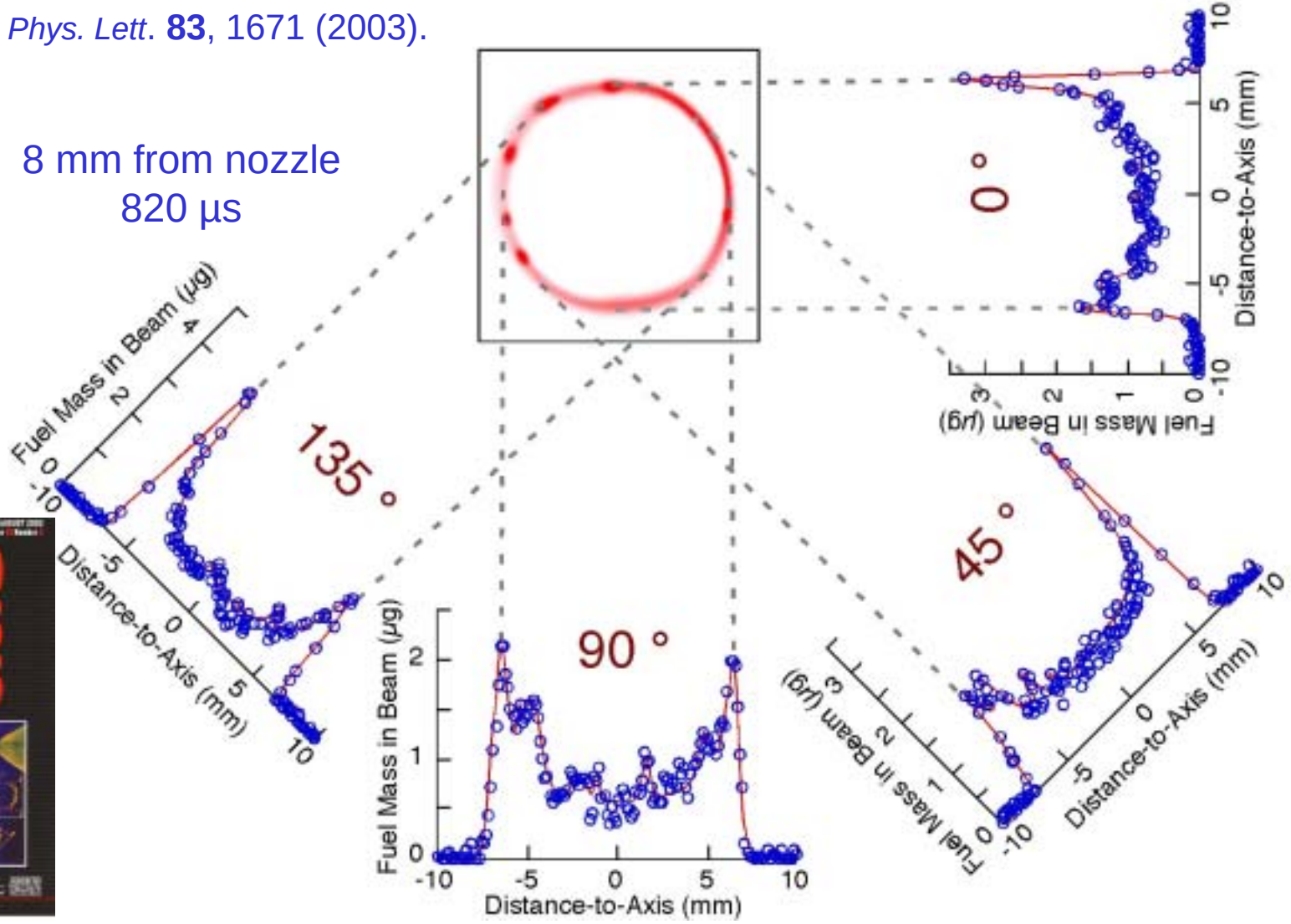
Multi-orientational Radiography

Advanced Photon Source
Argonne National Laboratory

Cai *et al*., *Appl. Phys. Lett*. **83**, 1671 (2003).

8 mm from nozzle
820 µs

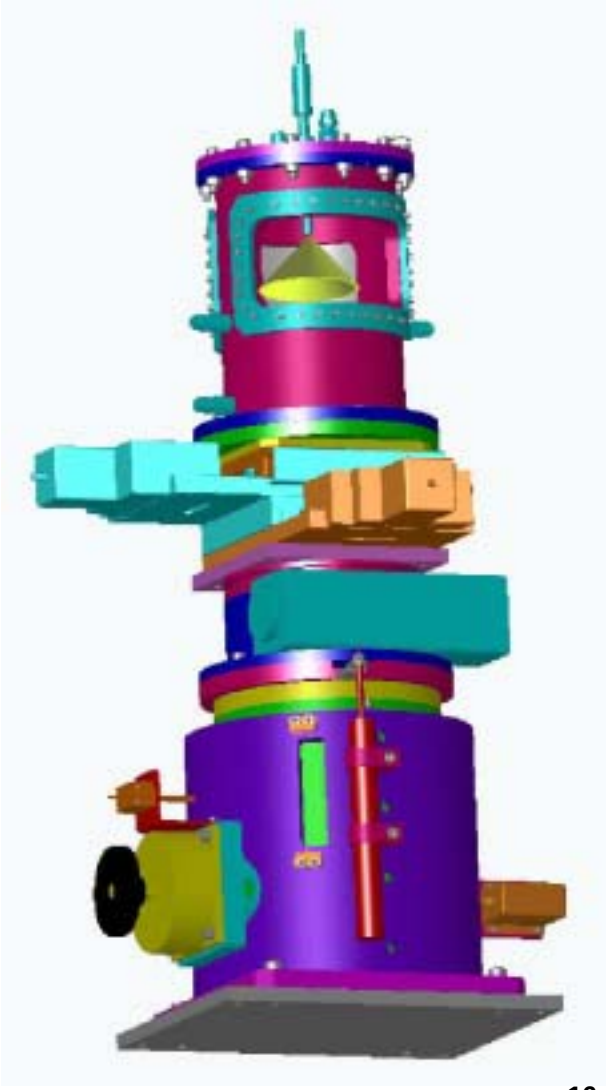




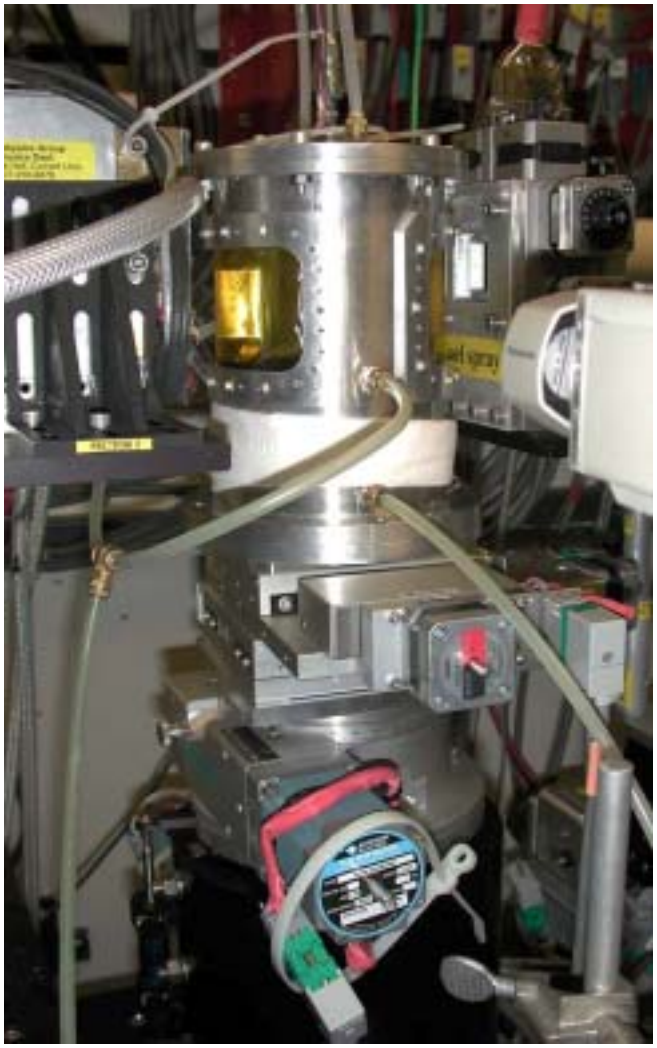
Ultrafast X-tomography

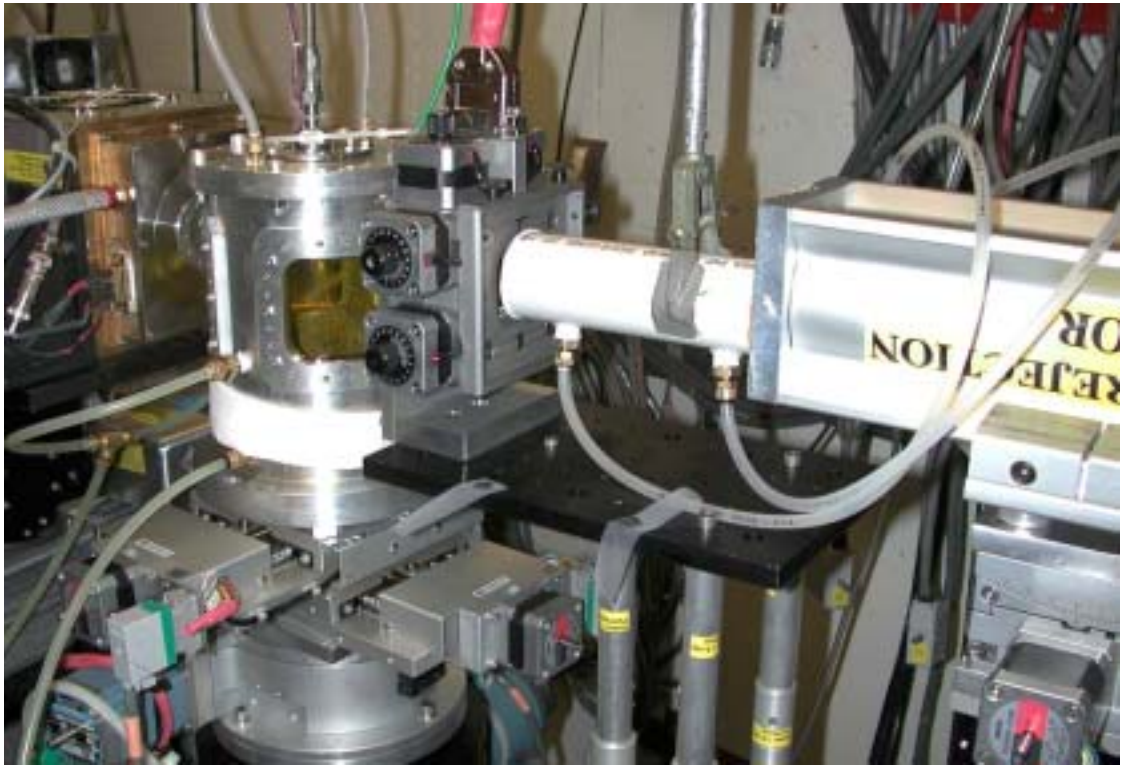
X-tomography is feasible, but many scientific and technical challenges need to be addressed:

- Environmental chamber for contain the spray
- Large x-ray transparent window
- High precision translation and rotation
- Precision timing
- Algorithm the handle time-resolved data
- Parallel computing



First Attempt at CHESS





Results

QuickTime™ and a
Cinepak decompressor
are needed to see this picture.

- 5.1 μs time-resolution, 76 time steps, 1 ms duration
- 1° angular steps, 180° total viewing angles
- 20 GB of data

Reconstruction from Data

3.8 mm from the nozzle, 490 µs from the start of the injection

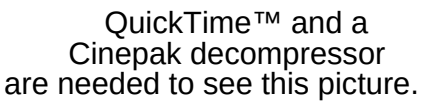
Sinogram

QuickTime™ and a
Cinepak decompressor
are needed to see this picture.

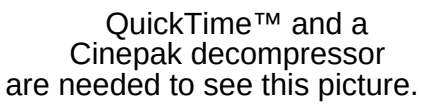
QuickTime™ and a
Cinepak decompressor
are needed to see this picture.

Reconstruction Goodness

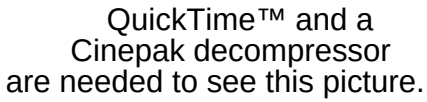
Reconstructed Spray



Reconstructed Hollow-Cone Spray



Surface View



Summary

- Many new discoveries on high-pressure fuel sprays have been made during the past three years.
- The experiments revealed quantitatively and unambiguously many characteristics of fuel sprays that were never previously known and/or that could not be measured by any other means.
- This technique has broken a new ground for fuel spray research and can be well-suited for studying transient events in dense plasmas and other optically opaque structures.

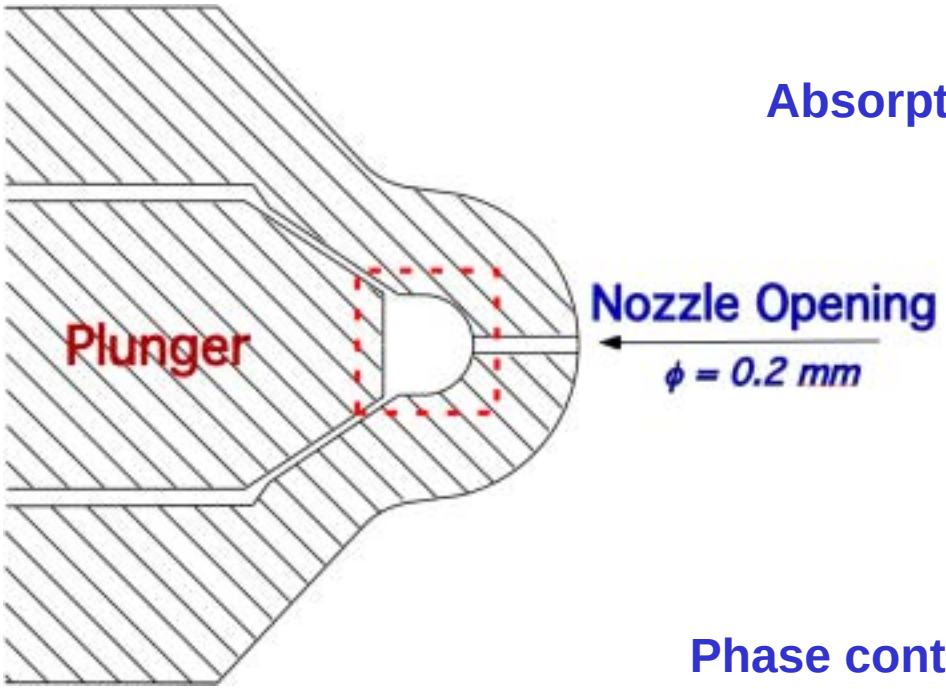
- The time-resolved tomography has been first demonstrated!

- Possibility of look through a real nozzle!

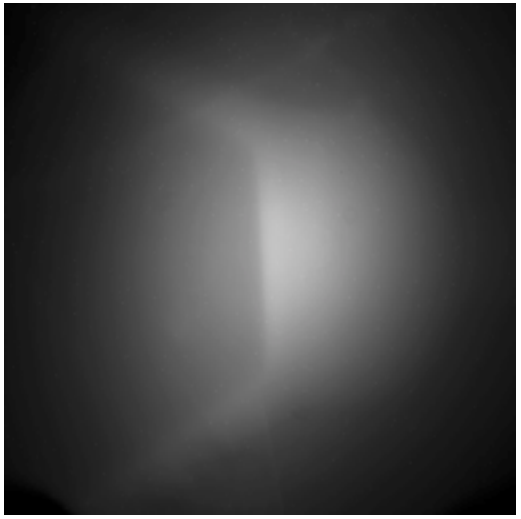
Edge-Enhanced Phase-Contrast

Advanced Photon Source
Argonne National Laboratory

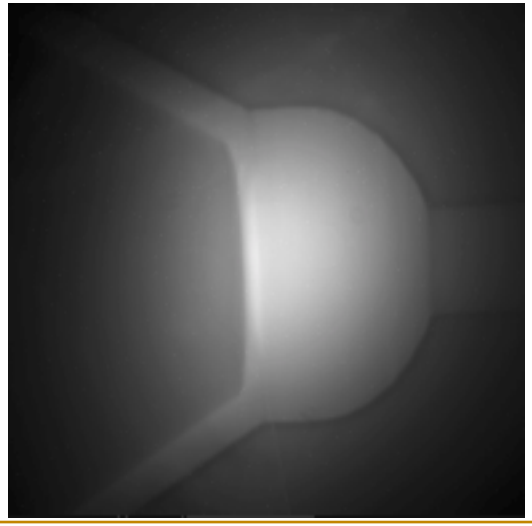
Collaborated with Kamel Fezzaa and Wah-Keat Lee of XFD/ANL



Absorption

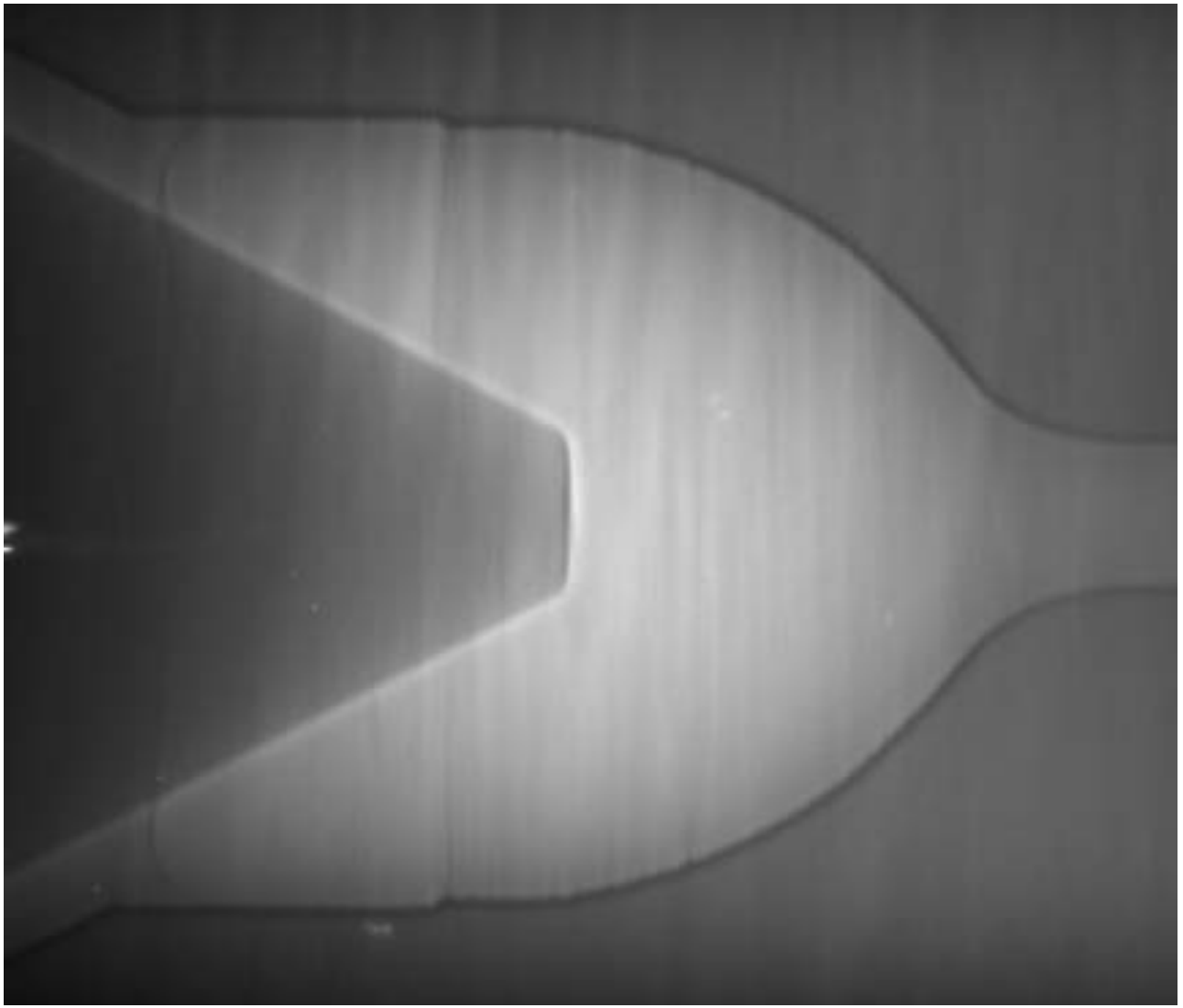


Phase contrast



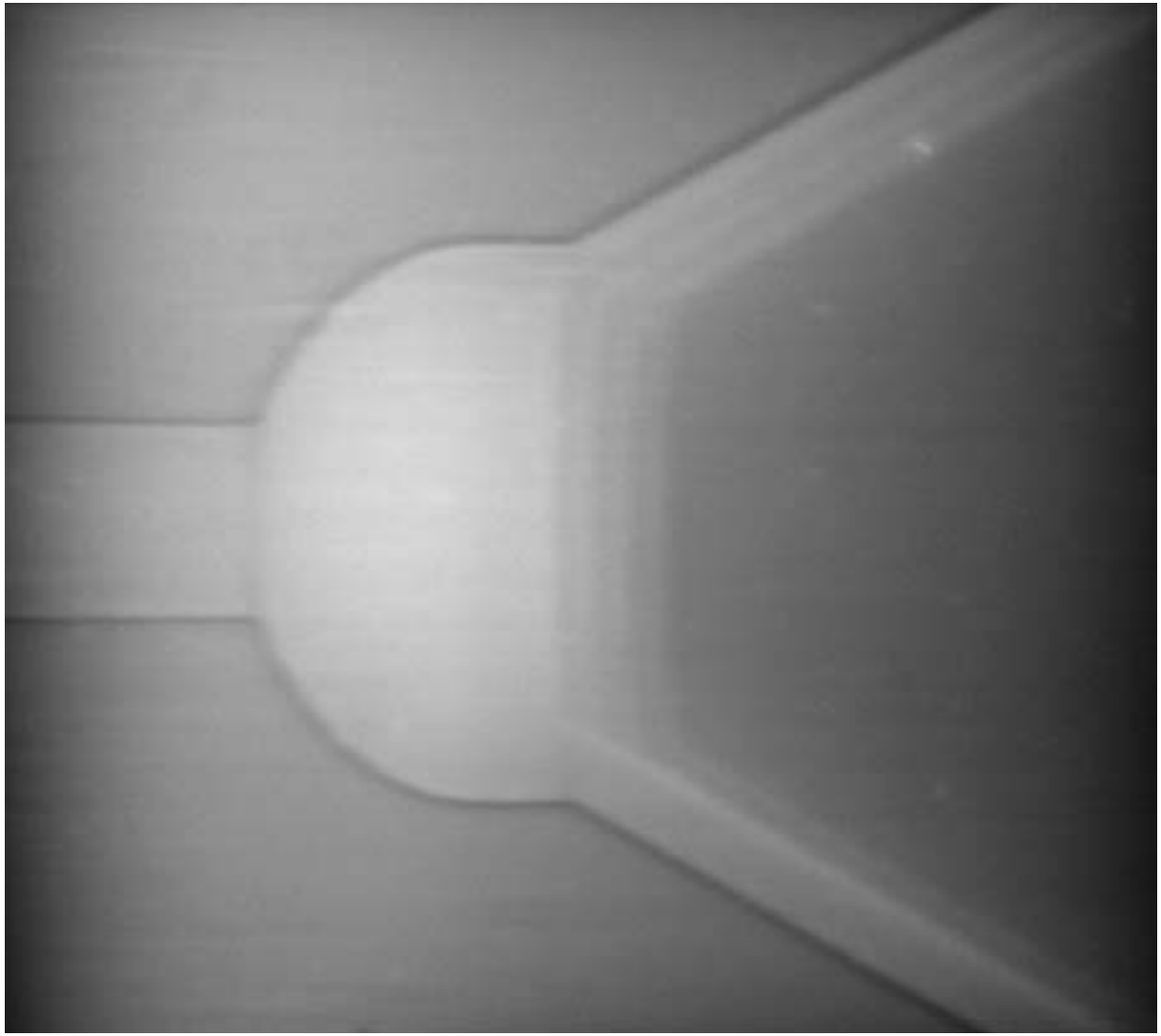
70 keV monochromatic beam (1ID, APS)

Filtered White Beam



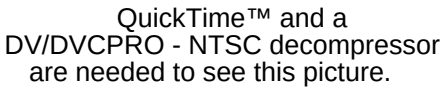
Data collected at 7-ID, APS

Ultrafast Imaging



Data collected at 7-ID, APS

The Action of Needle!

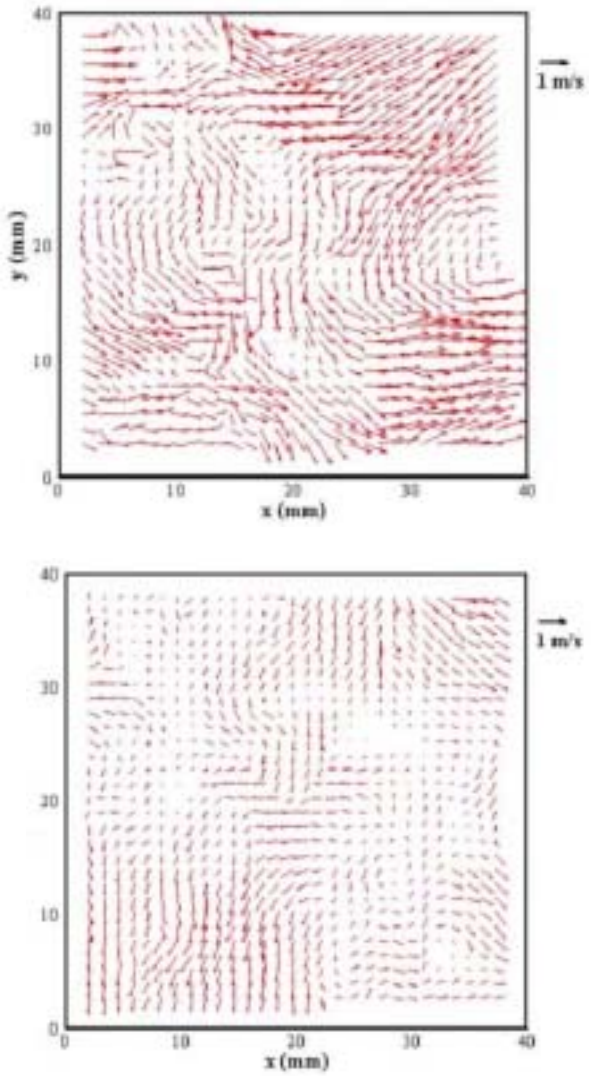


Bubbles!

QuickTime™ and a
DV/DVCPRO - NTSC decompressor
are needed to see this picture.

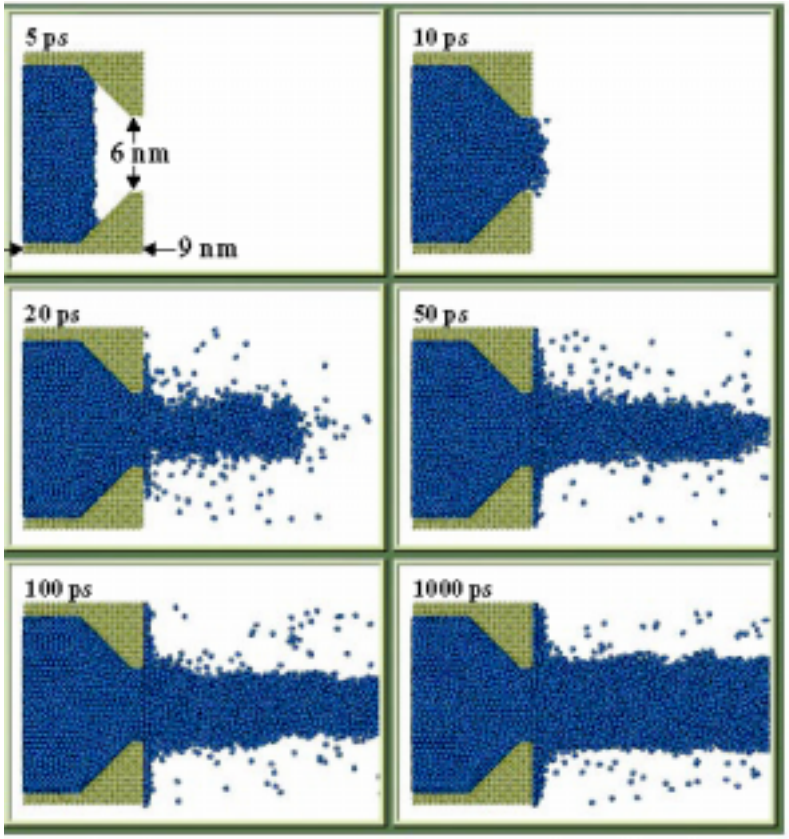
Future Directions

- **Ultrafast time-resolved phase-contrast image of liquid droplets outside of nozzles**
  - Microfocusing filtered white beam
- **X-ray version of particle imaging velocimetry**
  - Matured technique using laser imaging methods
  - Phase-contrast imaging provide enhanced particle edge detectability
  - Penetration ability of x-ray beam well-suited for multiphase flow with gas/liquid/solid mixture.

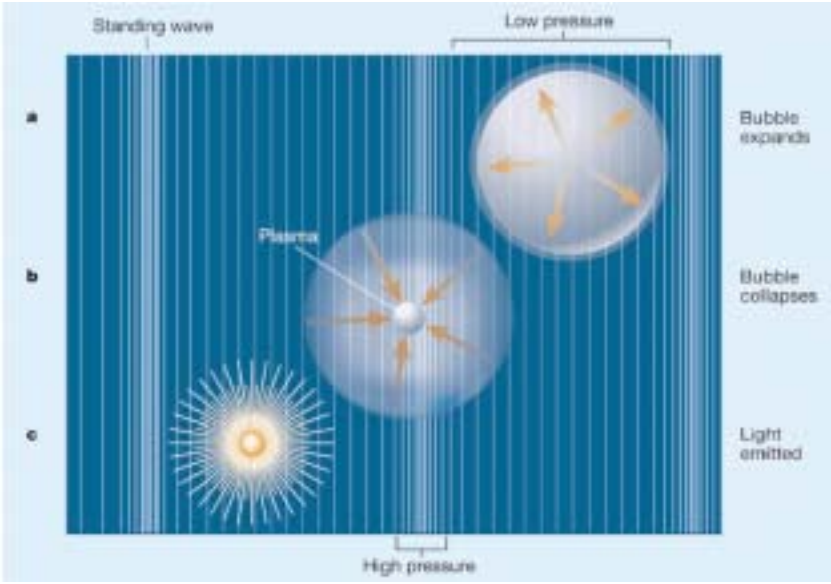


Future Directions

For smaller object, better than μm spatial resolution is needed, which demands Micro- and nano-focusing for phase contrast time-resolved, full-field imaging

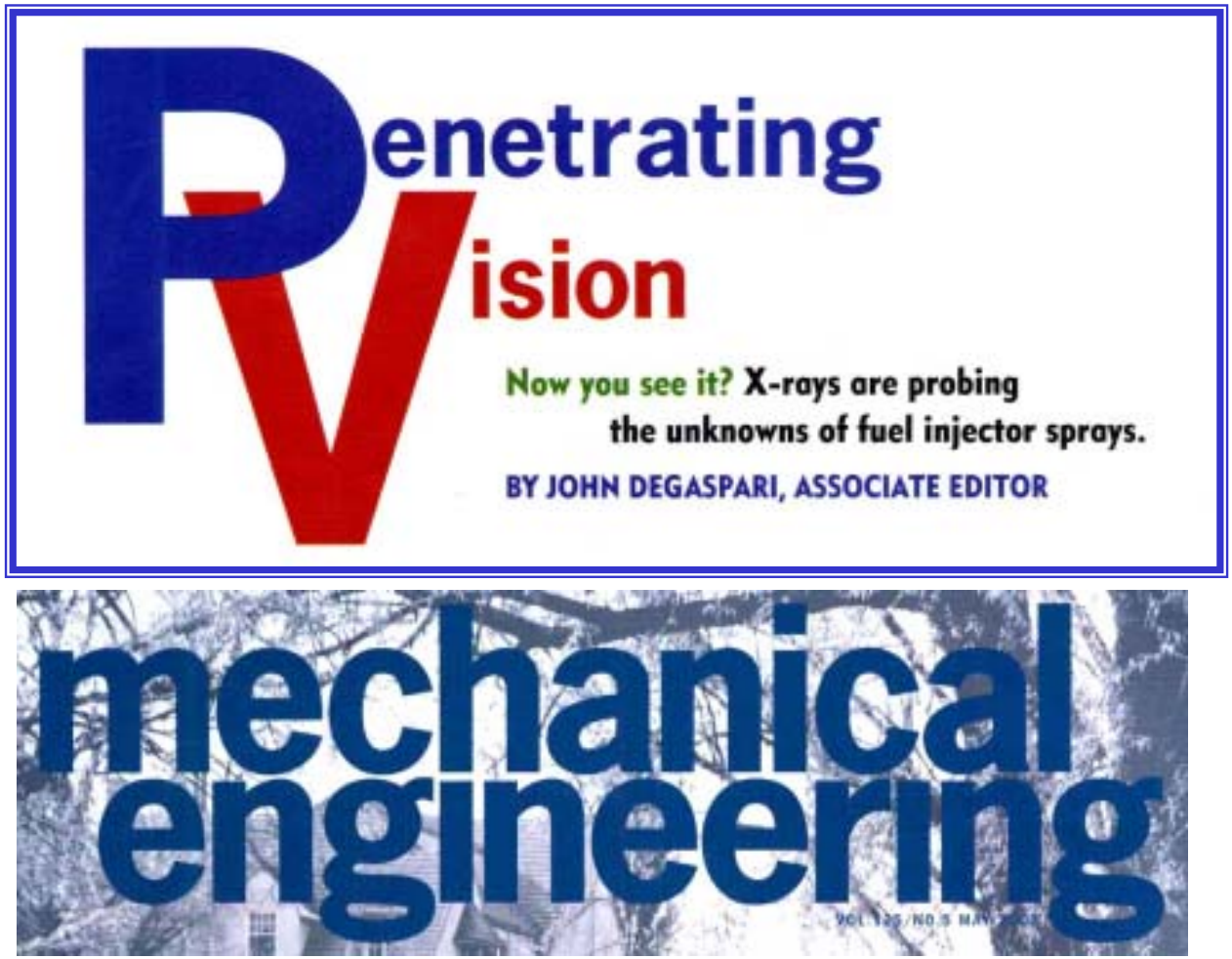


Formation, Stability, and Breakup of Nanojets
Moseler & Landman, *Science* **289** 1165 (2000)



Inside a micro-reactor
Lohse, *Nature* **418** 381 (2002)

Future Directions



May 2003