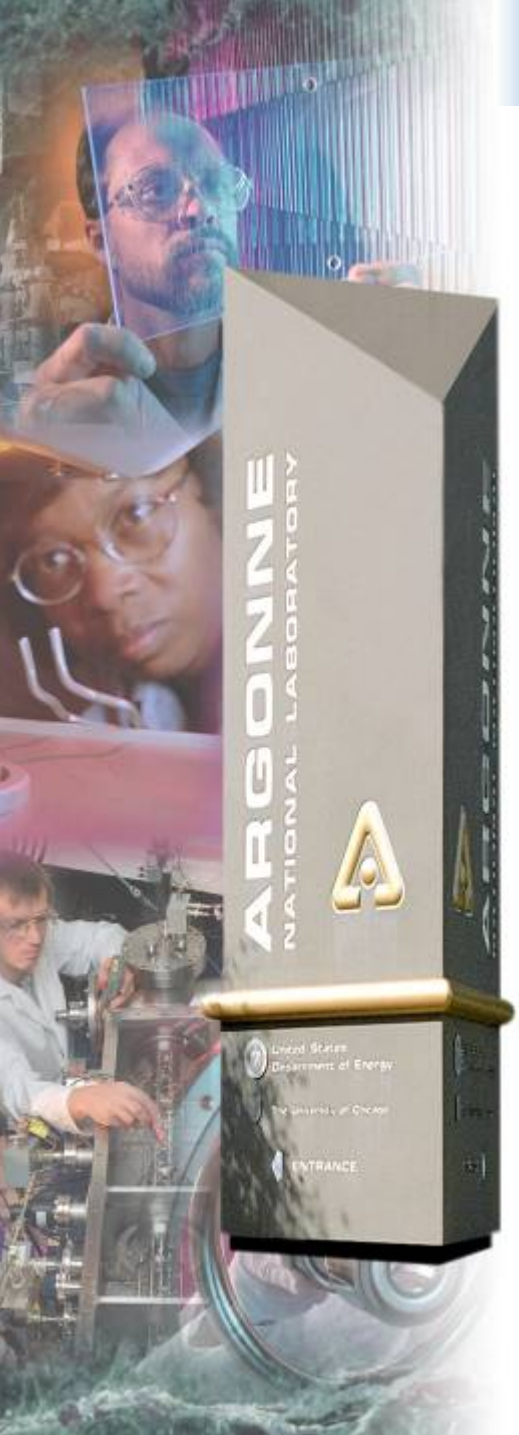


Ultrafast X-ray Phase-Enhanced Microimaging for Visualizing Fuel Injection Process and Diesel Sprays

11th Diesel Engine Emissions Reduction Conference

August 25, 2005

Jin Wang

Advanced Photon Source

Argonne National Laboratory is managed by
The University of Chicago for the U.S. Department of Energy

Collaborators

- **Kamel Fezzaa, Wah-Keat Lee, APS/ANL**
  - –Phase-contrast imaging
- **Seong-kyun Cheong, Kyoungsu Im, Xin Liu** (APS/ANL)
- **Chris Powell** (ES/ANL)
  - –Experiments
- **Ming-chia Lai** (ME/Wayne State University)
  - –Transient CFD simulation of in-nozzle flow

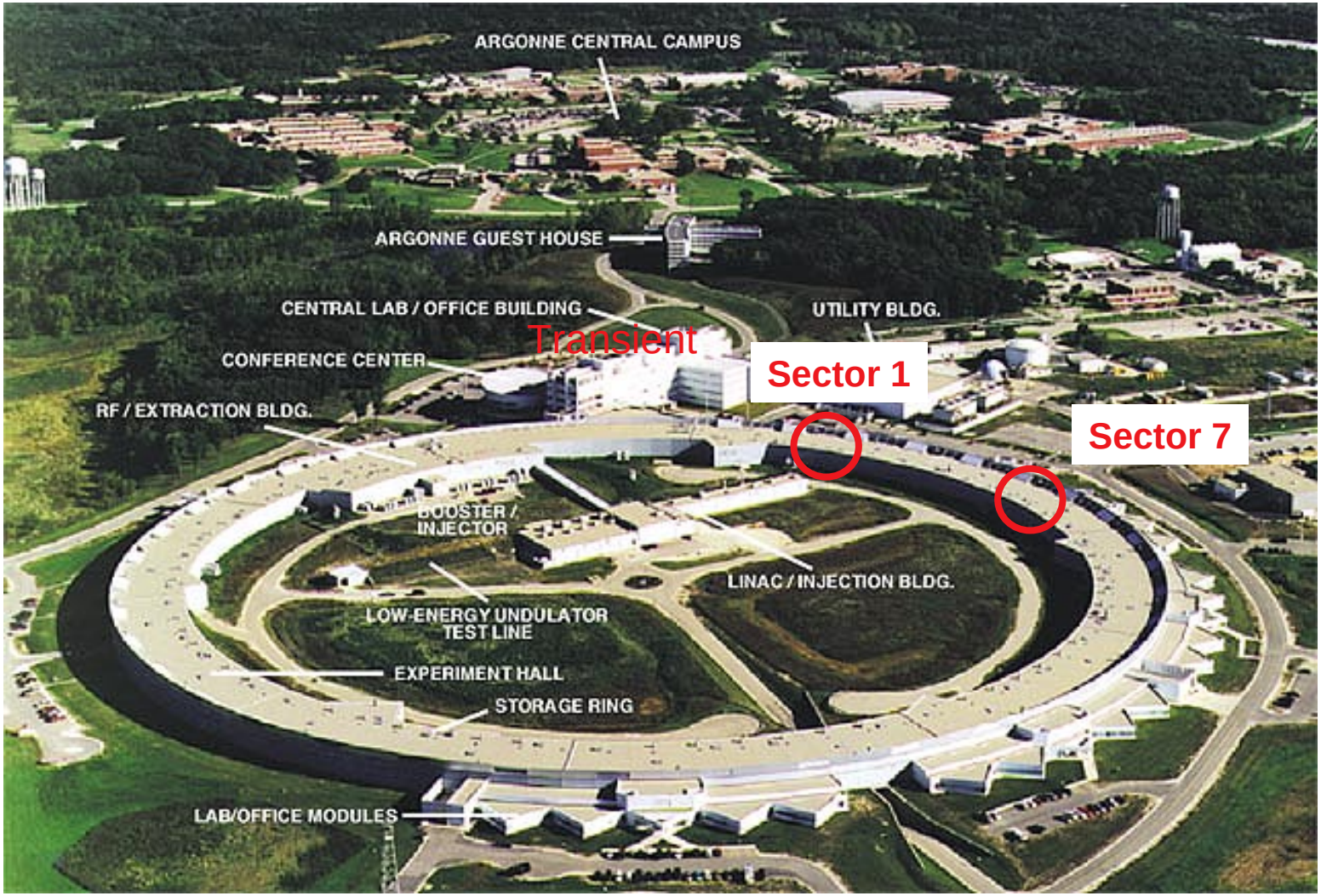
Experiments performed at XOR 1-ID, 1BM and **7-ID** beamlines of the **APS**

The use of the APS and this work are supported by the U.S. DOE, under contract W-31 109-Eng-38: APS operation funds.

Cheong and Powell are supported by OFCVT (managed by G. Singh/K. Stork)

Advanced Photon Source

- DOE User Facility: most intense x-ray source, 3000 users/year

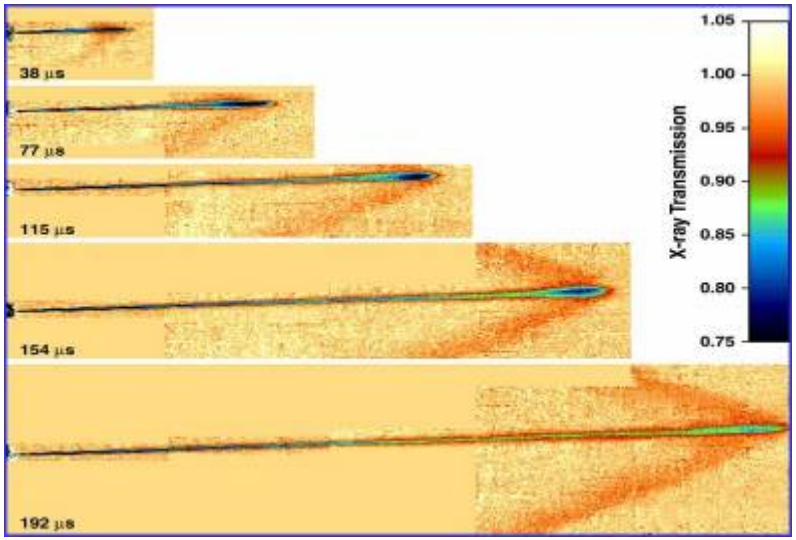


Outlines

- Opportunities, Challenges and Objectives
  - Greater impetus of understanding fuel injection systems
- Approaches - Ultrafast X-Ray Phase-Contrast Imaging
  - Phase-contrast vs. absorption (radiography)
  - Time-resolved In situ visualization with μs-temporal resolution
- Results: Pintle motions in Real Time During Injection Events
  - Longitudinal and transverse needle motion
  - Correlation between in-nozzle dynamics and external sprays
  - ***Transient*** CFD in nozzle simulation
- Summary and Future plans

Overview of the Spray Project at the APS and CHESS

- Ultrafast (µs) X-radiography of Diesel Sprays (OFCVT supported)
  - Spray mass distribution
  - Shockwave generation
  - Spray characteristics influenced by the nozzles

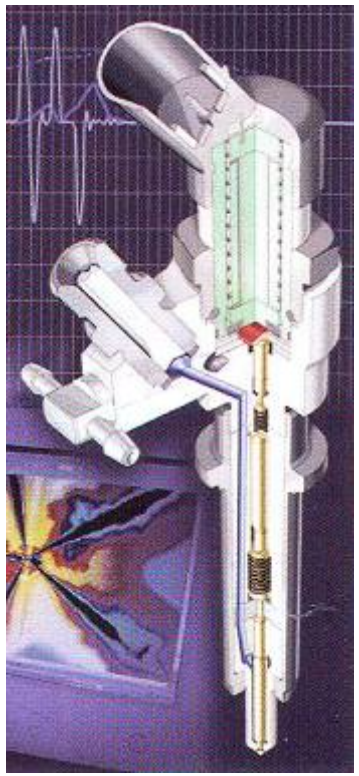


- Ultrafast (µs) X-tomography (ANL LDRD support)
  - Quantitative evolution of sprays (4D)
  - Unprecedented details of sprays
  - Structure and dynamics
  - Part of injection system design

Opportunities and Challenges

The Opportunities

- New developments in diesel direct-injection systems aim to achieve better fuel efficiency and better control of emissions.
- More effective fuel atomization requires higher injection pressure (>150 MPa), smaller orifice (< 100 µm), shorter and multiple injection events.



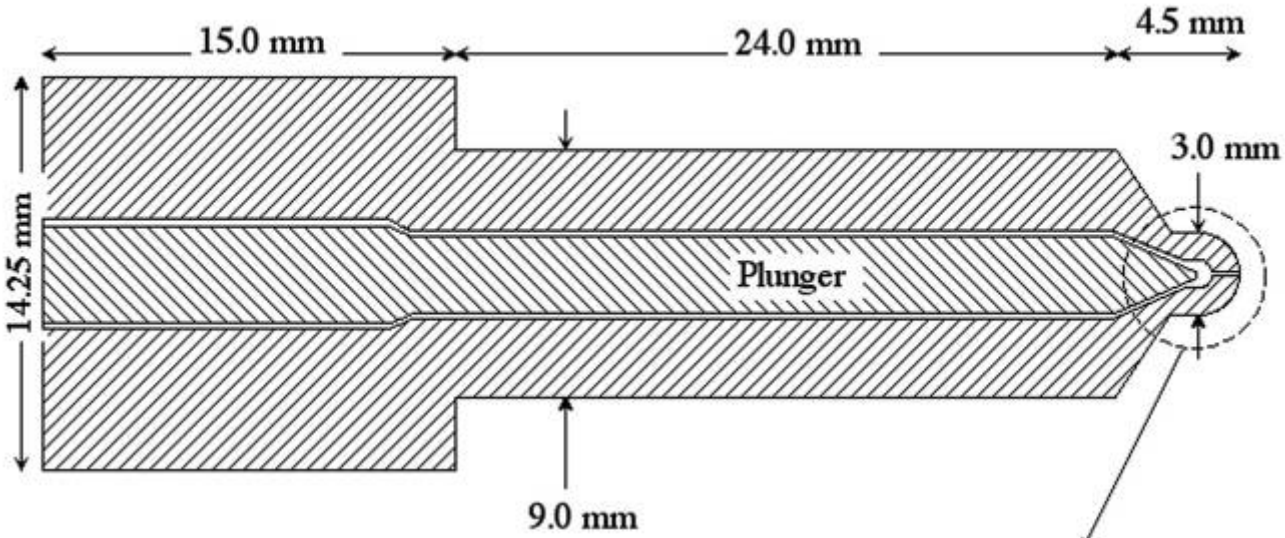
- the fluid dynamics both in- and outside of the injection nozzles.
- more impetus for in-nozzle characterization

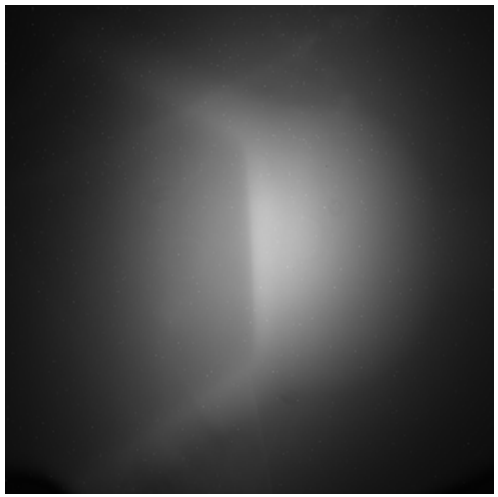
The Challenges:

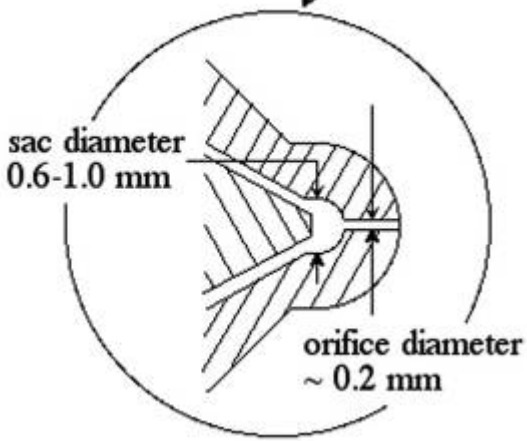
Can we make the impossible possible and shed some light into the dark nozzles?

High-Energy X-Radiography

- Using highly penetrative high-energy x-ray beam to see through the nozzle







70 keV, 0.17 Å

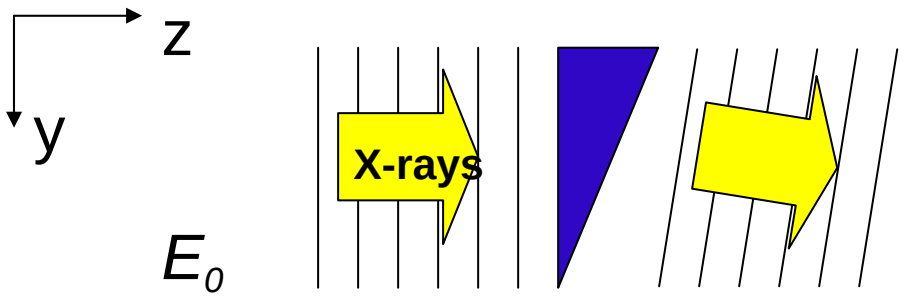
Contrast mechanism: absorption

Lee, Fezza, Wang, Appl. Phys. Lett.

87 084105 (2005)

New Approach: Phase Contrast

- In a simple transmission geometry



For X-rays:

$$n = 1 - \delta + i\beta$$

$$E_T = E_0 \underbrace{e^{-\frac{2\pi}{\lambda}\int \beta(y,z)\,dz}}_{\text{Attenuation}} \underbrace{e^{i(\varphi_o - \frac{2\pi}{\lambda}\int \delta(y,z)\,dz)}}_{\text{Phase}}$$

Contrast mechanisms

Energy dependence

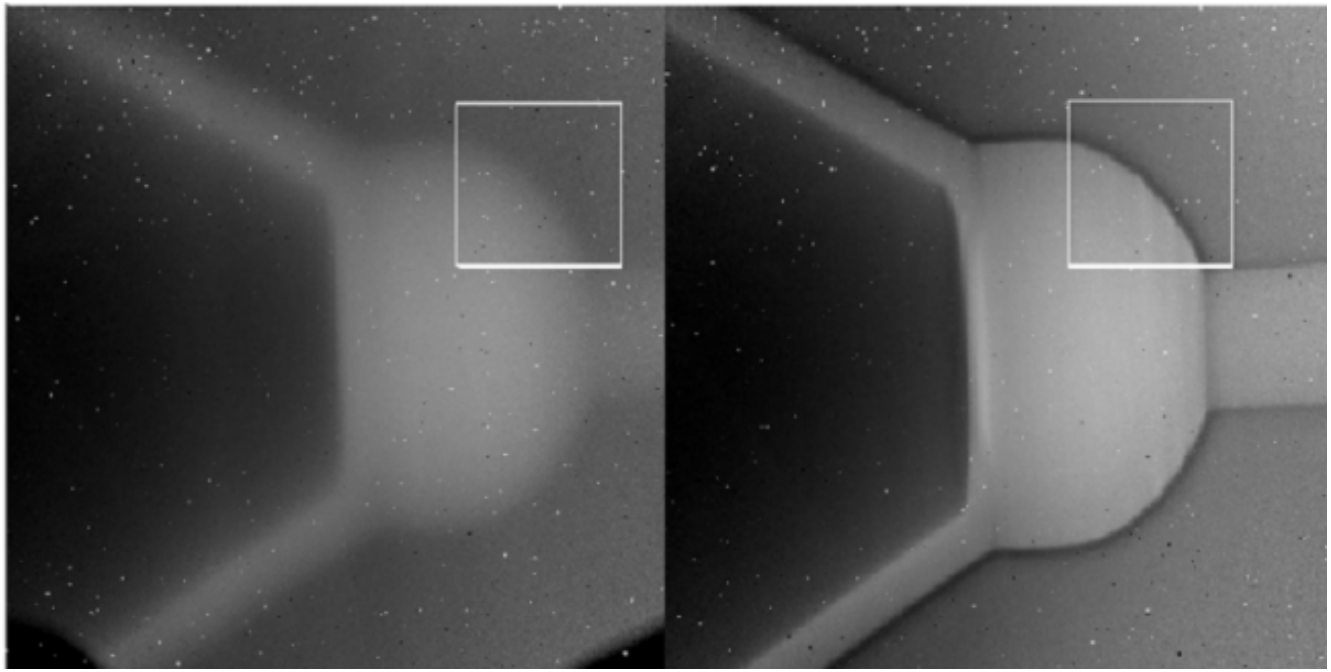
Attenuation → $\tau \propto Z^4 \lambda^3 \rho$

Phase → $\phi \propto \sigma \lambda$

Westneat, Betz, Blob, **Fezzaa**, Cooper, **Lee:** Tracheal respiration in insects visualized with synchrotron x-ray imaging, Science ***299***: 558-560 (2003).

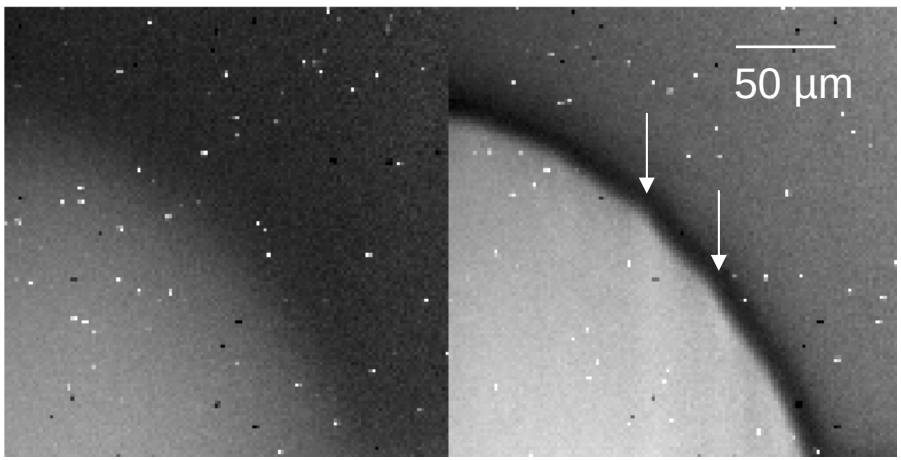
σ *density of electrons*

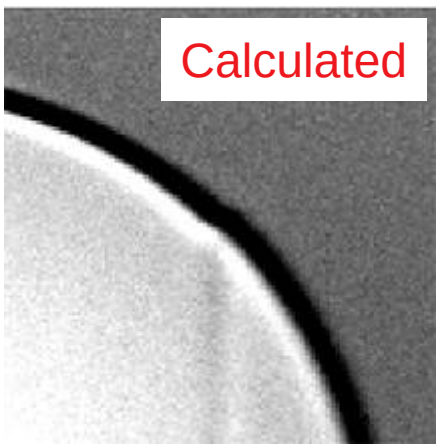
Absorption vs. Phase-Contrast



Absorption

Phase-contrast



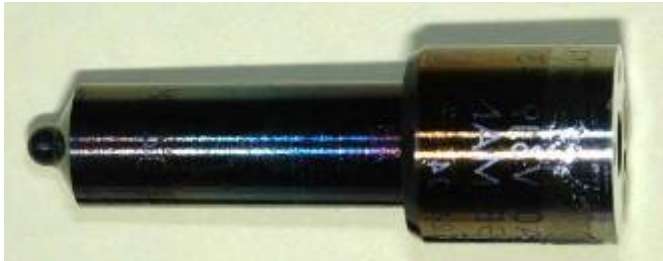


From Static to Ultrafast (μs)

Technical Challenges

- Much more intense x-rays: wide bandpass x-ray beams promise 10^3-10^4 more intensity
- kW-heat load: high-heat-load x-ray optics such as filters, beam-chopper, mirrors
- Ultrafast Detector: timing capability to synchronize with x-ray pulses, injection events

Single guide



Kamel and Wah-Keat have worked on this more than 5 years!

Needle Motion in a Production Nozzle

- Plunger with dual guides

Imaging parameters:

10 µs exposure time

Fixed delay time 10µs

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Injection parameters:

P_{inj} = 1000 bar

1 ms injection time

Data collected at 7-ID, APS

Correlating the Sprays Outside of Nozzle

- Spray can be imaged with x-radiography (Chris Powell's poster).

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

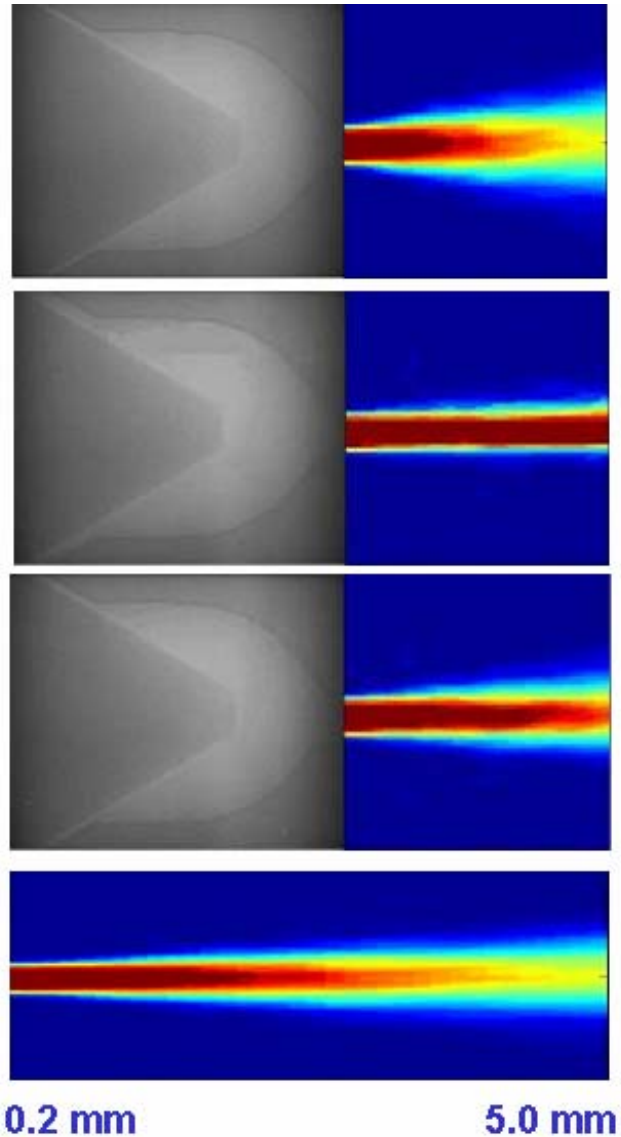
X-ray Transmission

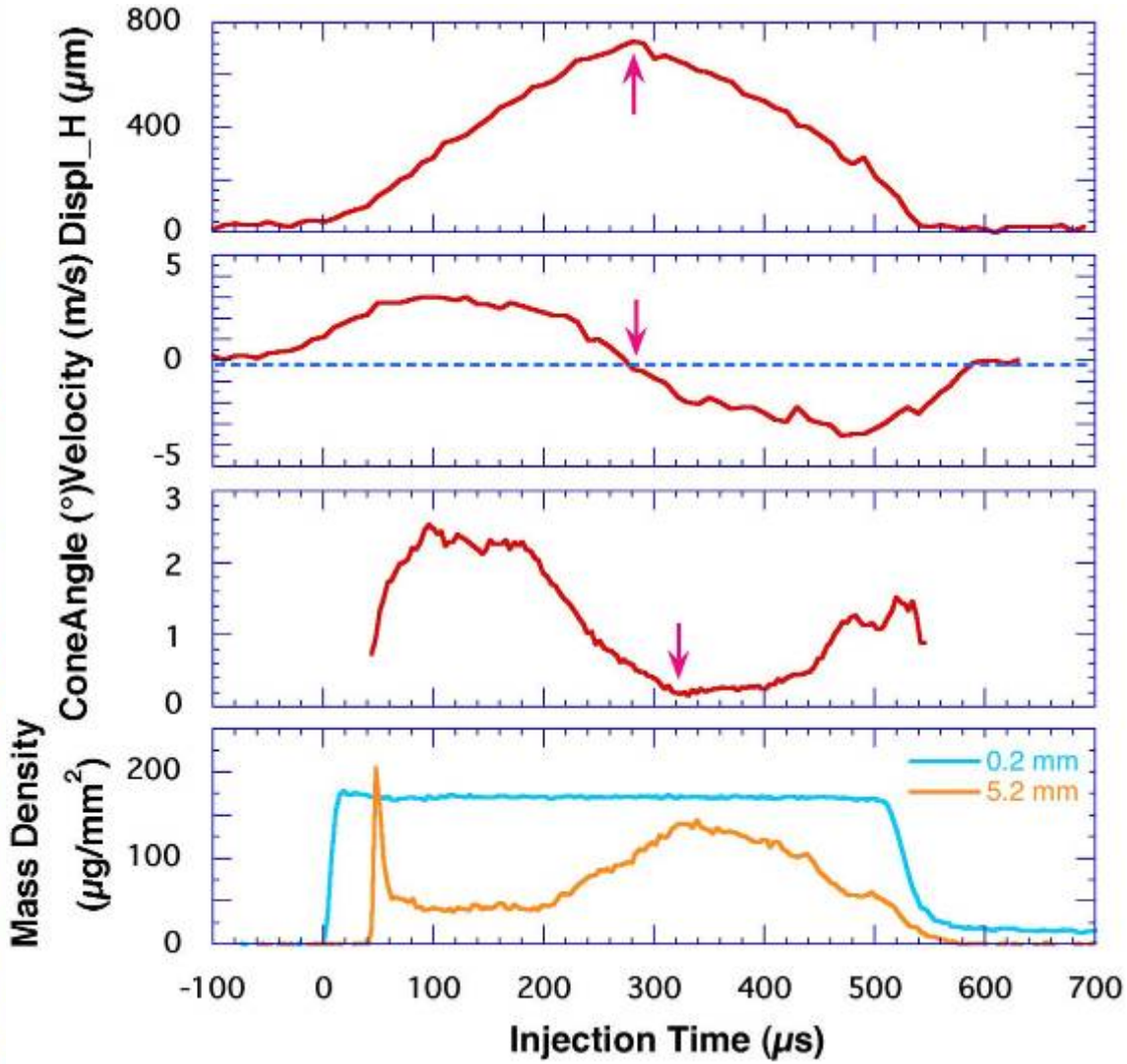
Mass absorption coefficient

mass in the beam

Quantitative Correlations

- Perfect correlation between needle motion and the spray cone angles



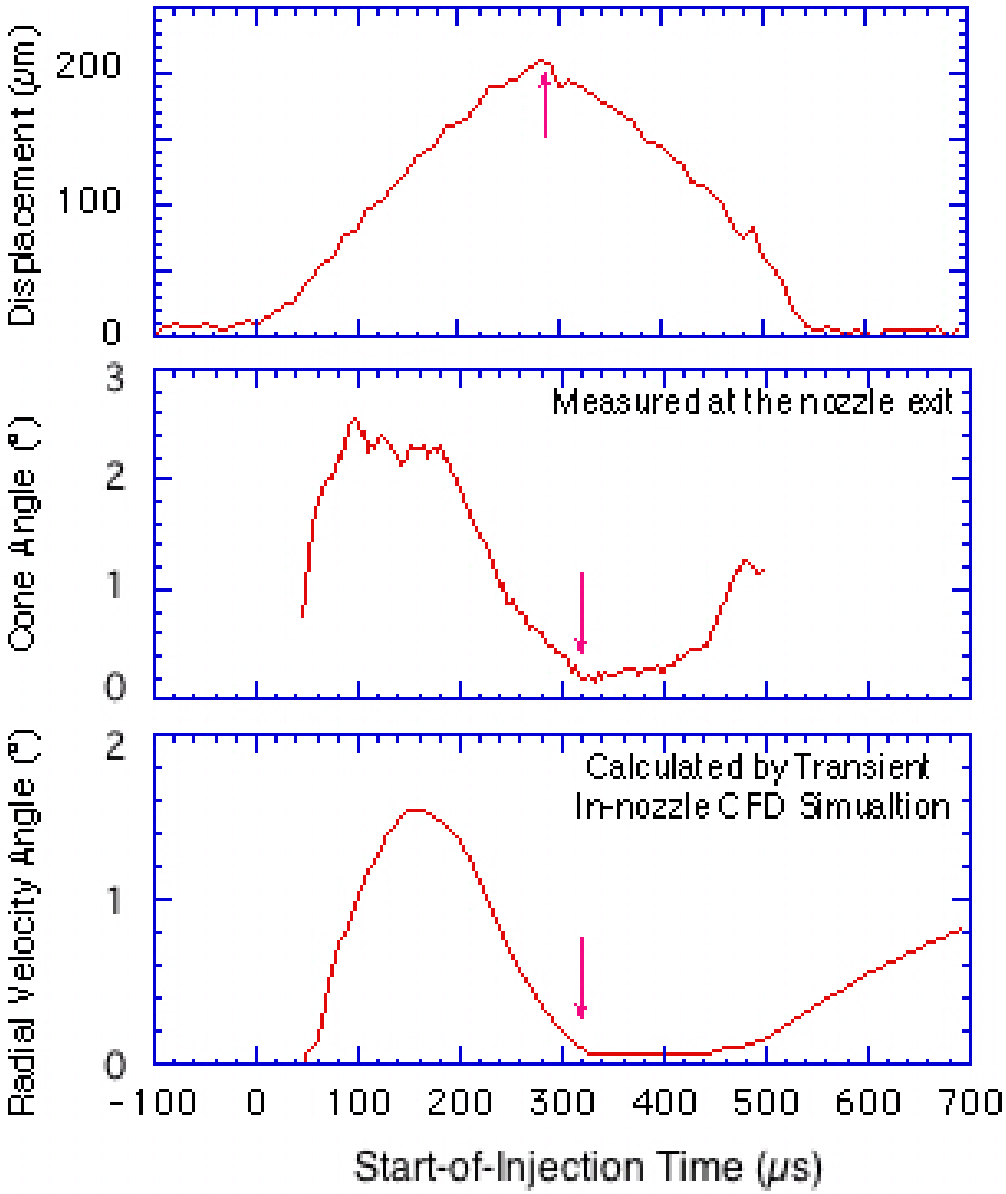


Transient in Nozzle CFD Simulation

- X-ray data was used to generating a moving grid system.
- 2D axisymmetric geometry with Flueent 6.1.2
- turbulence effects: the Realizable k-εturbulence model
- Cavitation: primary phase is diesel, the secondary phase is diesel vapor

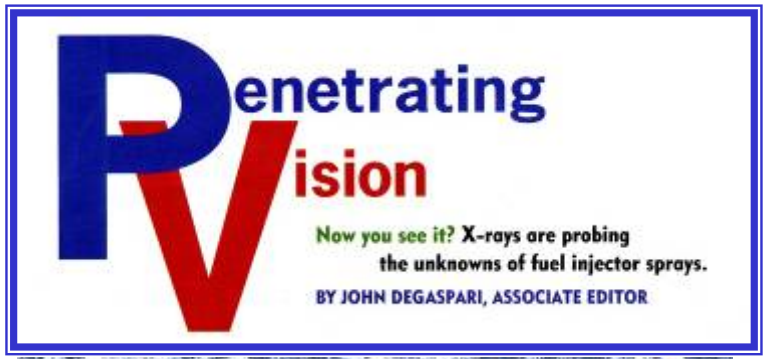
Radial Velocity Component of the Fluid

- Radial velocity component in nozzle is responsible for the cone angle outside of the nozzle.
- Again, perfect correlation between the measured spray cone angle and the evolution of the maximum radial angle of the fluid velocity at the nozzle tip (inside)



Summary

- Ultrafast (µs) x-ray phase-contrast imaging through the nozzle has been demonstrated
- Pintles have both longitudinal and transverse motions, which can now now be characterized quantitatively.
- The injection process is extremely transient, which causes dynamic in-nozzle flows
- the strong correlation between the pintle motion and the sprays
- This x-ray measurement can be an integral part in the injection system design process



May 2003

Not only can we have penetrating vision of fuel sprays, but also that of an injector

Vision: All injection nozzles are benchmarked with x-ray data!

Future Plans

- The x-ray imaging technique and optics needs significant improvement
  - spray systems (flexibility of tomographic measurement)
  - x-ray optics (many compromises right now)
  - detectors (current efficiency only 3% or so), 97% of photons are wasted.
  - single-shot (ps-ns) x-ray imaging of sprays

- Secure funding for further development of this technique and the applications
- In-depth study of the correlation the pintle motion and the sprays
- CFD simulation of *transient* in-nozzle flow
- John Woodford: Ni-plated nozzle
- Single-shot phase-contrast imaging of sprays
  - Current capability is 300 ns

Single-Shot Imaging of Fuel Sprays

- Single-Shot!
- Spray structures can be examined readily - droplet size
- Possible to track the spray flow - droplet speed
- Readily extendable to engine environment - high-P_a and T_a

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150 ps exposure time possible: 1 µm blur at 10,000 m/s

µs-Tomography

- Direct injection Sprays
- 5 µs time resolution, 150 µm spatial resolution
- 180 projections, 1° interval
- LDRD support ending this FY

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