Argonne NATIONAL LABORATORY

… for a brighter future

U.S. Department of Energy

UChicago ▶ Argonne LLC

Office of Science U.S. DEPARTMENT OF ENERGY

A U.S. Department of Energy laboratory managed by UChicago Argonne, LLC

# Practical Automotive Applications Derived from the APS Hard X-Rays

## USCAR Directors' Visit

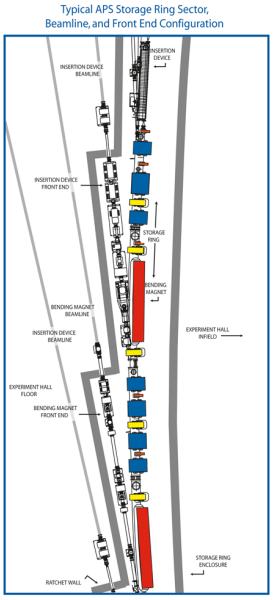
## October 30, 2008

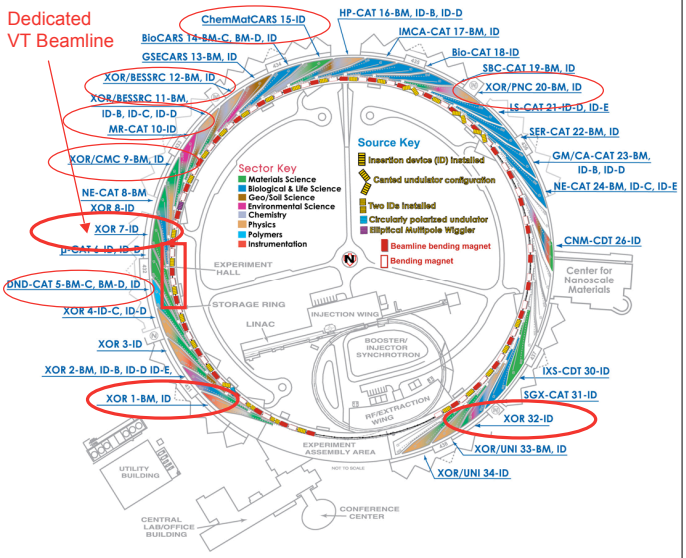

***Jin Wang***

*Argonne National Laboratory, Argonne, IL*
*wangj@aps.anl.gov*


## APS: Most Intense X-ray Source in Western Hemisphere

3500 Users/Year: physics, chemistry, materials science, biology, energy …



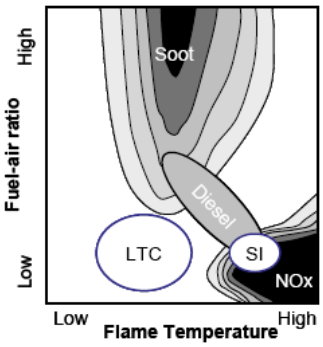
## *Outlines*

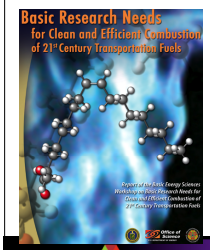
- Background: Sprays, Ultrafast x-ray imaging
- Applications
  - Fuel injection
    - *Diesel sprays*
    - *Gasoline Direct Injection sprays*
    - *Injection nozzles (George Fenske/ANL)*
  - Biodiesel
- Dedicated fuel spray beamline
- Research on Membrane for batteries
- Summary and outlook



## *Fuel/Air Mixing a Key to Combustion*

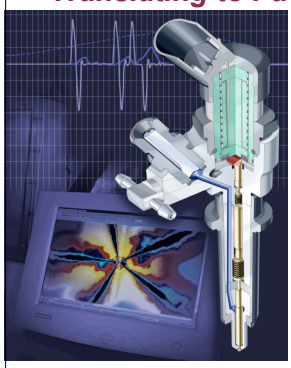
- Local mixture composition is a crucial parameter for
  - ignition
  - Combustion rate
  - Pollutant formation
- One crucial element is fuel injection
- Since 1892
  - Mr. Diesel invented diesel engine
  - Fuel sprays have never been visualized
  - Precombustion condition
  - Try-and-error process




"The evolution of fuel sprays plays a defining role … in determining both combustion efficiency and the formation of … pollutants. The physics and chemistry of this multiphase problem are difficult to probe experimentally, to understand theoretically, and model rigorously. …
This level of understanding may permit extraordinary new technologies, such as smart fuel injectors that adapt to changing fuel and load conditions, to permit fuel-flexible advanced engines to run cleanly and efficiently on a range of alternative fuels.."

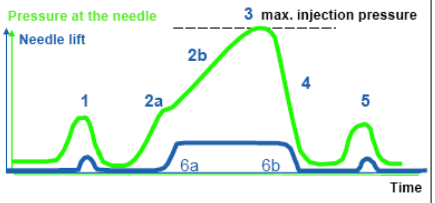
## *Translating to Fuel Injection Technology*



**New Requirements for Fuel Injection Equipment**

- Advanced common-rail-based FIE for combustion performance and control of **engine-out** emissions:
  - Higher injection pressure (> 200 MPa)
  - Optimized nozzles, smaller orifice (< 150 μm)
  - Shorter/multiple injection events, more dynamic
    - *Open/close pressure gradient*
    - *Speed of the needle, transient response, injection rate*
  - …

- More impetus for understanding fluid dynamics both in- and outside of the injection nozzles
- Validating in-nozzle flow and near-nozzle spray breakup simulation and combustion simulations.

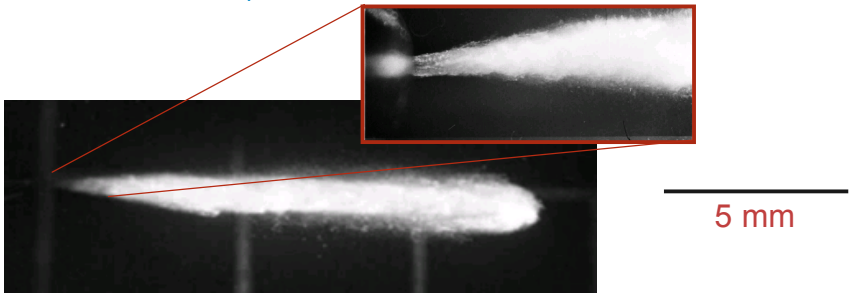



From Roger Busch/Bosch, DEER2004



## *Why Fuel Sprays Illusive?*

- High pressure injection generates large amount of small fuel droplet
  - Cloud surround the fuel jet
  - Optically dense and opaque - strong light extinction and scattering
  - No technique is effective to obtain quantitative
  - With sufficient temporal and time resolution




**The grand challenges:**

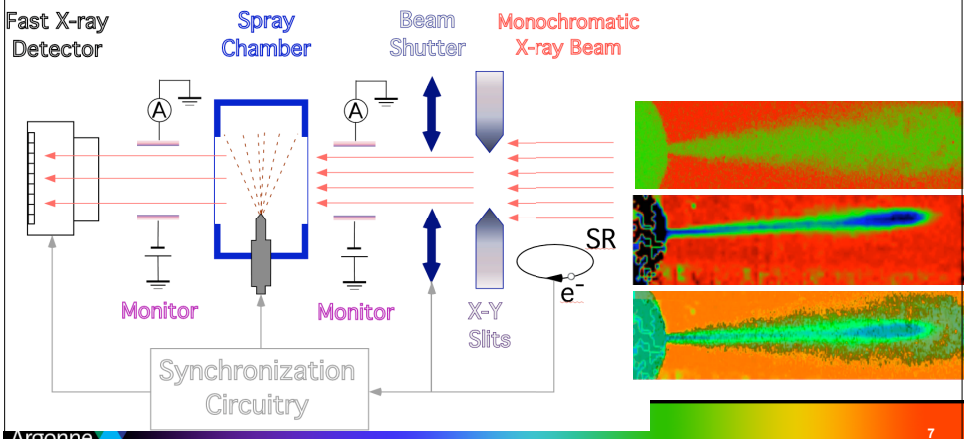
**Can we understand the fuel injection/spray breakup inside out ?**

## *Approach: X-radiography*

X-ray Transmission — Mass absorption coefficient — Fuel mass in the beam

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

- X-radiography
  - Penetration power of X-rays
  - Quantitative fuel mass distribution
  - μs temporal and 10s-μm spatial resolution



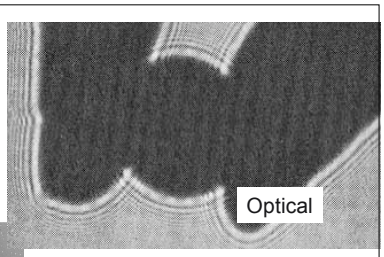


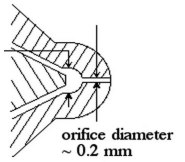

Argonne NATIONAL LABORATORY

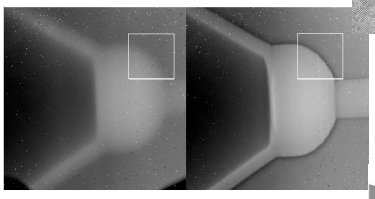
7

## *Phase Contrast Imaging*

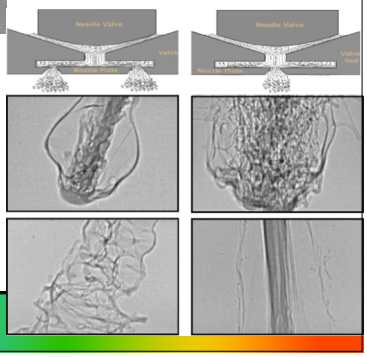
- Enhance interfaces: capable of imaging through real injection nozzles
  - μs time-resolution, μm spatial resolution



W.-K. Lee, K. Fezzaa, J. Wang, Appl. Phys. Lett. 87, 084105 2005



- Especially effective to visualize multiphase flows
  - 100 ps time-resolution, full frame, single-shot
  - Visualize instantaneous spray morphology
  - Direct observation of fuel breakup

Y. Wang, et al. "Ultrafast X-ray study of dense-liquid-jet flow dynamics using structure-tracking velocimetry" Nature Physics 4, 305 (2008).

Collaboration with Visteon Corporation (David Hung)

Argonne NATIONAL LABORATORY

## *Shockwaves Generated by Supersonic Spays*

- Both spray and shockwaves can be quantitatively visualized
- Spray mass distribution and ambient gas distribution


17 mm

60 mm

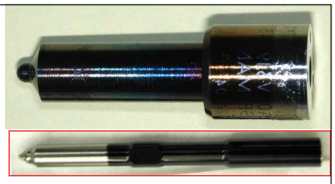
Injection pressure: 135 MPa
Injection time: 0.5 ms
Ambient gas: 0.1 MPa $SF_6$

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

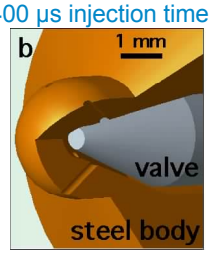
**MacPhee *et al.*, *Science*, 295, 1261 (2002) with animation available on Science Website**

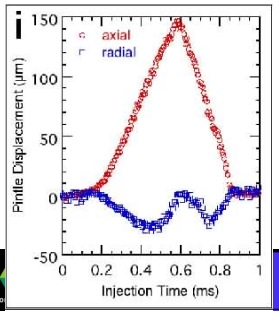


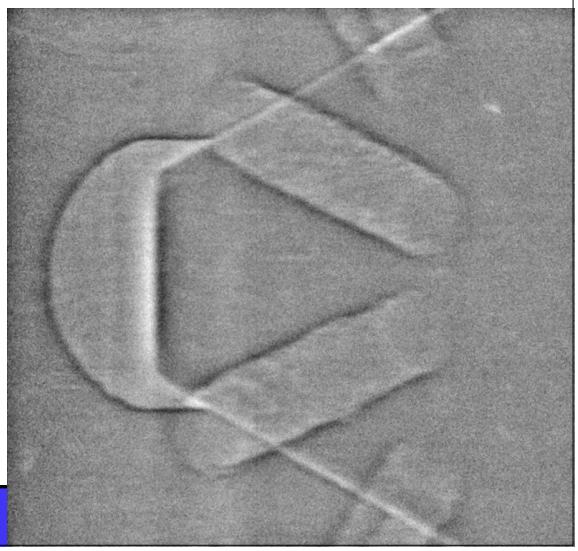
## *Pintle Motion During Injection*



- Production, dual-guided. 6-hole VCO nozzle
- 1000 bar $P_{inj}$, 1 bar $N_2$ ambient
- 400 µs injection time



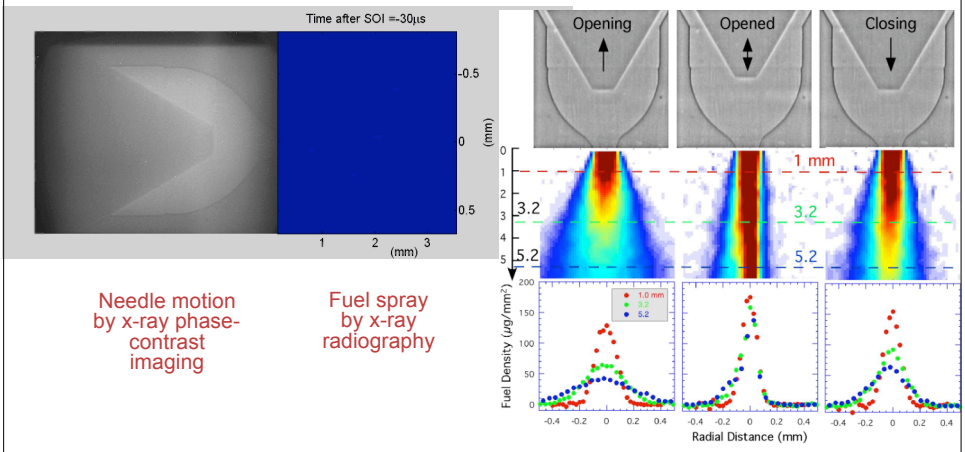



## *Correlation with the Needle Motion*

Cone angle can be perfectly correlated with the needle motion

1000 bar, 400 μs, into 1 bar He gas



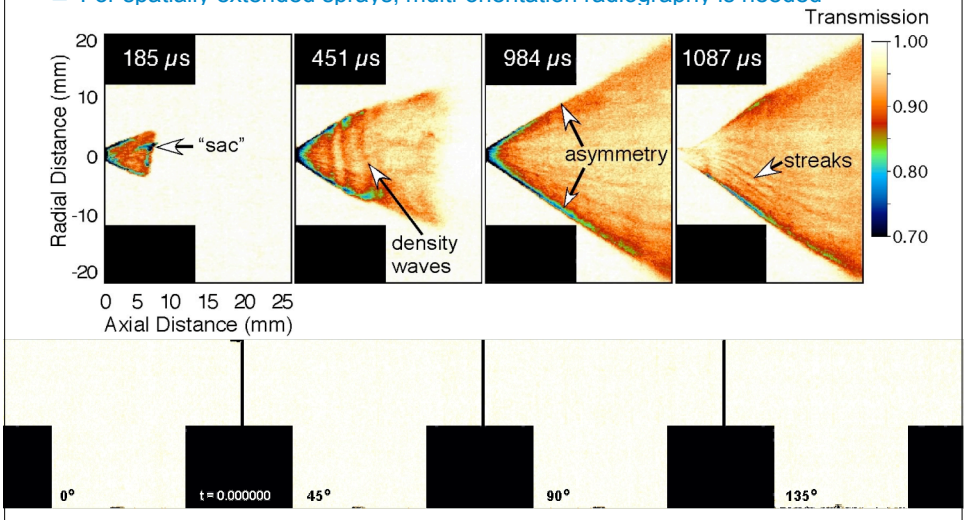

Needle motion by x-ray phase-contrast imaging

Fuel spray by x-ray radiography



## *Multi-Orientation X-ray Radiography of GDI Sprays*

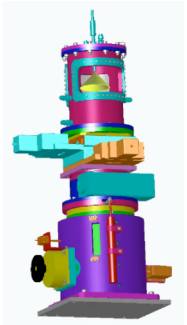
- For spatially extended sprays, multi-orientation radiography is needed

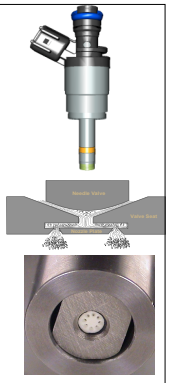


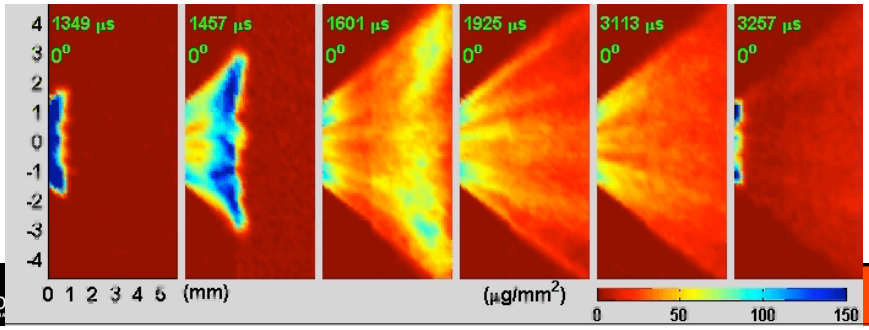

W. Cai *et al.*, *Appl. Phys. Lett.* **83**, 1671 (2003). Collaboration with Sol Gruner's group.

## *Ultrafast X-tomography - Multihole Cavitating Sprays*

- Feasible but challenging
  - 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







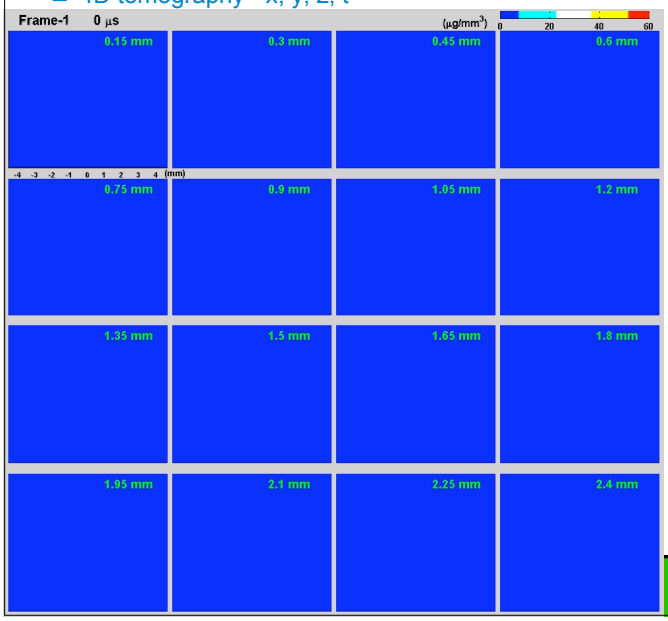

Argo

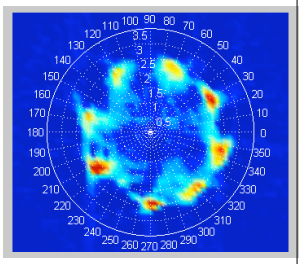
13

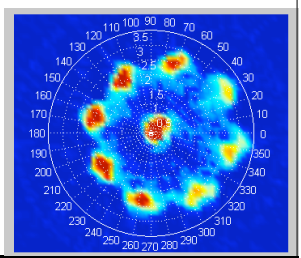
## *Reconstruction*

X. Liu, et al., SAE Paper 2006-01-1041 (also in SAE Transactions)

- 4D tomography - x, y, z, t





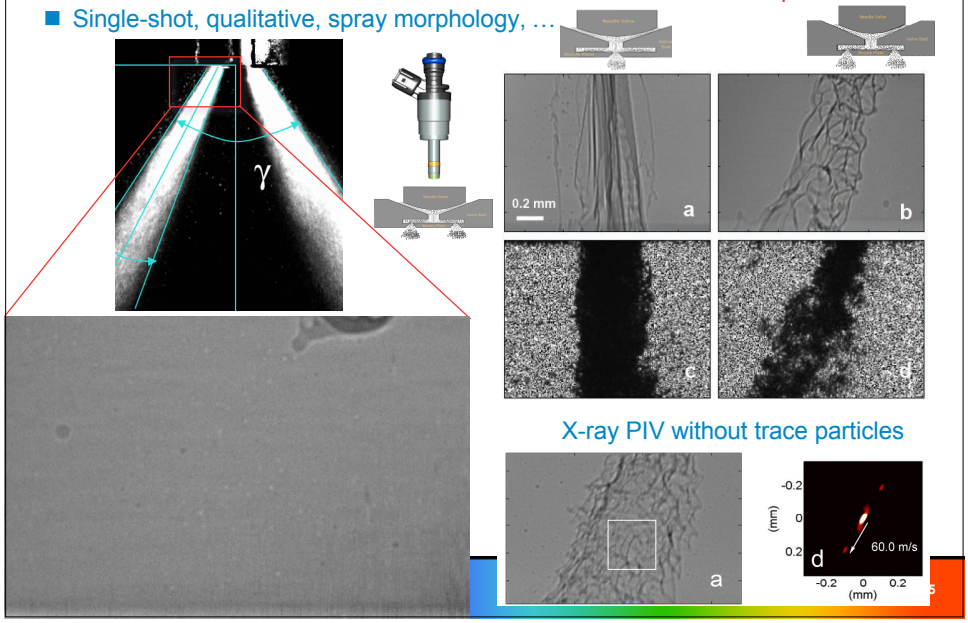
14

## *Cavitating Fuel Jets*

Y. Wang, *et al.* Nature Physics 4, 305 - 309 (2008).

- Liquid ligand, air/liquid matrices, optically opaque
- Single-shot, qualitative, spray morphology, …

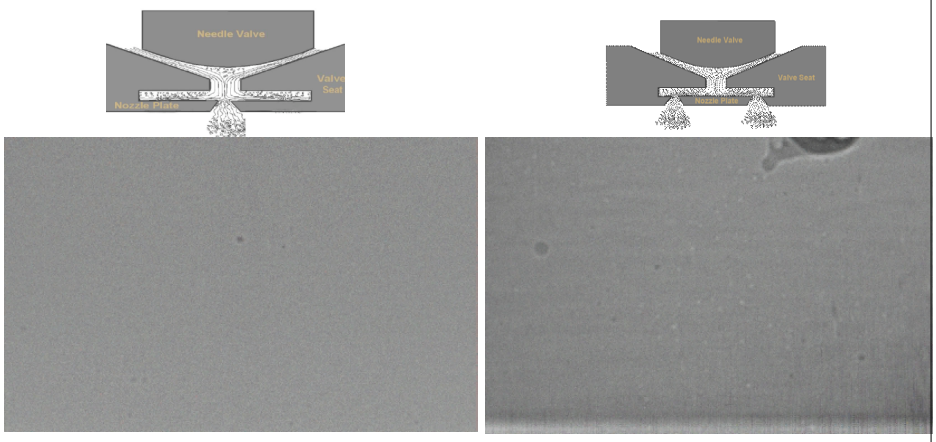
472 ns exposure




## *Two Types of Morphology*

Y. Wang, *et al.* Nature Physics 4, 305 - 309 (2008).

- Similar mass distribution but two completely different morphology

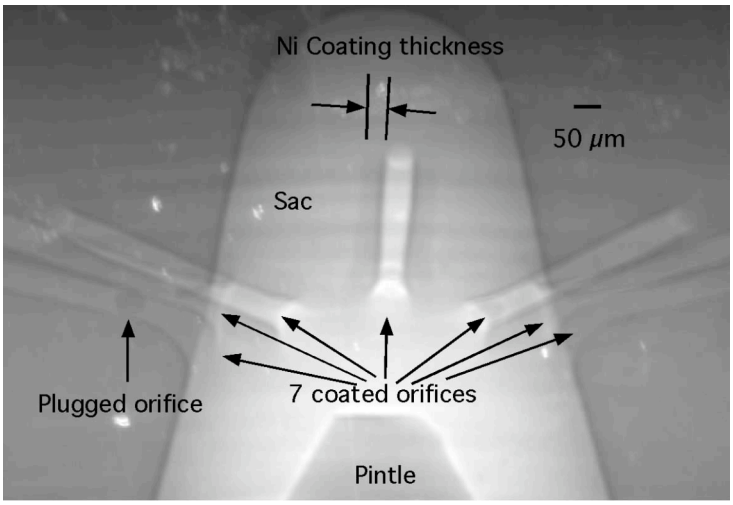



Argonne NATIONAL LABORATORY

16

## *Micro-orifice Nozzle by Ni Coating*

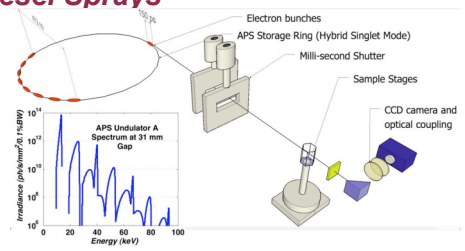
Collaboration with George Fenske's group - poster by Oyelayo Ajayi later

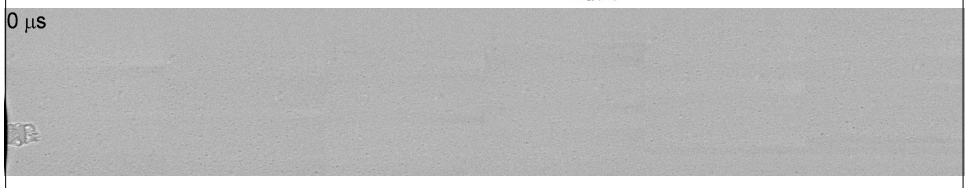





## *100-ps Single-shot Image of Diesel Sprays*

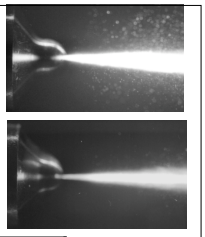
- 1000 bar injection pressure, 1 ms injection
- Ambient pressure 1 bar, RT
- Diesel with no additives
- Breakup behavior of sprays from different nozzles
- Field of view 2 mm (V) x 20 mm (H)




9 mm

## *Results - Breakup of Diesel and Biodiesel Jets*



- 100-ps single-shot x-ray phase-contrast Images

Diesel: #2 ultralow-sulfur diesel from Shell station, no additives
Biodiesel: cotton seed feed stock (within ASTM D6751-07b specs)
Injection pressure 500 bar, at 30°C

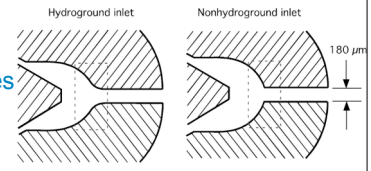
| | Surface Tension (mN/m) | Viscosity cSt | Specific gravity $Kg/m^3$ |
|---|---|---|---|
| Biodiesel | 33 | 5.0 | 888 |
| Diesel | 28 | 3.2 | 856 |

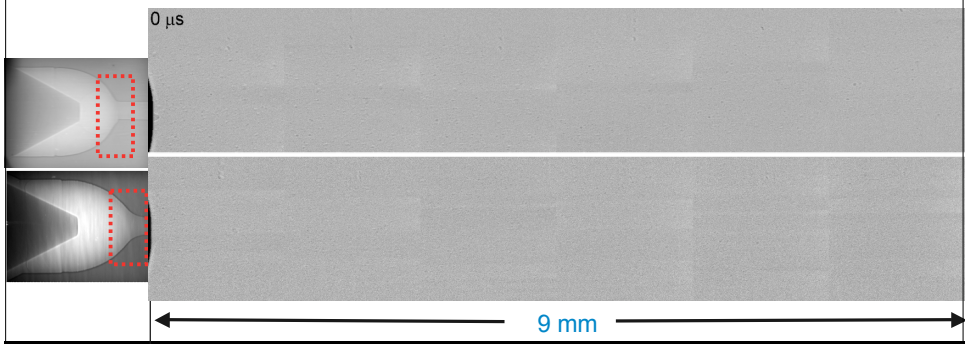
The spray morphology is drastically different for diesel and biodiesel by 100-ps single-shot imaging!



## *X-ray Imaging of the Two Sprays*

- Biodiesel with no additives
- Breakup behavior of sprays from different nozzles
  - nonydroground vs hydroground
- 1000 bar injection pressure, 1 ms injection
- Ambient pressure 1 bar, RT



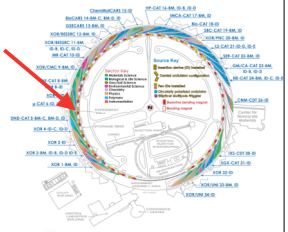
## *Need of a Dedicated Beamline*

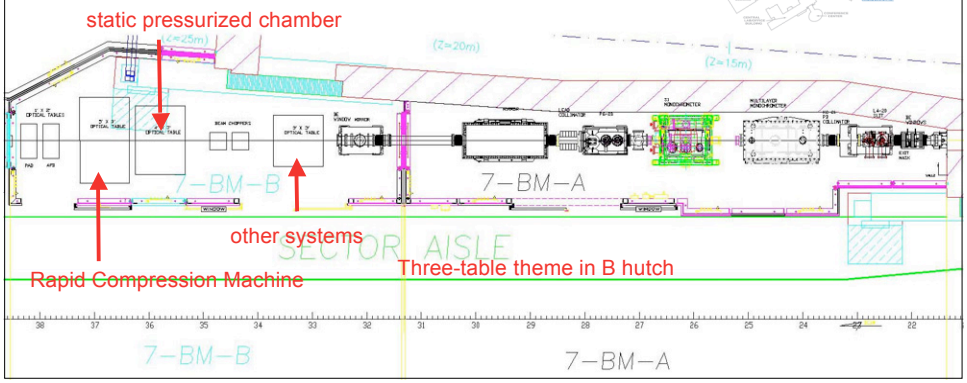
- Growing collaborators and partners from both industry and universities
  - Robert Bosch GmbH: diesel, and GDI)
  - General Motor R&D: diesel
  - Visteon Corporation: GDI, HCCI
  - Delphi Corporation: diesel, GDI
  - Caterpillar: heavy duty diesel
  - Daimler AG: diesel, GDI
  - Continental AG (Siemens VDO): Diesel, GDI
  - …
  - Brookhaven National Lab
  - Sandia National Lab
  - Air Force Research Lab
  - …
  - University of Wisconsin at Madison
  - Wayne State University
  - Cornell University
  - Michigan State University
  - Stony Brook University
  - Iowa University
  - University of Illinois at Chicago
  - University of California, Irvine
  - …
- Collaborations require sustainable beamtime at the APS.
- **How to get the sustainable beamtime at the APS?**



## *Dedicated Vehicle Technology Beamline at 7-BM*

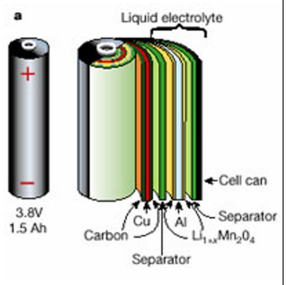
- Develop a dedicated and high-throughput fuel spray beamline
- Provide a centralized facility for transportation engine technologies
- A true partnership between VT/EERE and BES
- Rebuild Sector 7-BM beamline for this purpose
  - Partially built supported by BES ($3M)
  - Investment by Office of Vehicle technology of $850K.
  - Under construction, to be completed by January 2009



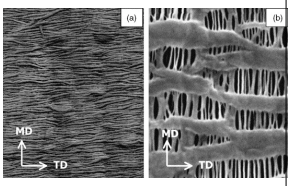


## *Synchrotron X-ray Research for Lithium Batteries*

- Challenges
  - Materials, characterization, performance, safety
- Approaches
  - In situ x-ray scattering
    - *Structure of electrodes, electrolyte and interfaces*
  - In situ x-ray spectroscopy
    - *X-ray absorption near-edge structure on oxidation states*
  - In situ x-ray imaging of components
    - *X-ray absorption near-edge structure on oxidation states*




- Breakthrough can be made by better understanding the membrane separators
  - Thin films of polymer/inorganic nanocomposites
  - Membrane morphology affects performance and safety
  - Degradation contributes power loss and thermal breakdown
  - X-ray can be an effective in situ tool to understand
    - *Structures*
    - *Structural changes*
  - Sector 8 at the APS is dedicated to study membrane thin films






## *Summary and Future Plans*

- The use of the APS intense x-rays can be very practical for vehicle technologies
- Many breakthroughs have been made for understanding fuel spray phenomena by
  - Understanding morphology of the sprays
  - Mapping mass distribution of the fuels
- This has marked the first time since the invention of diesel engine in 1890s.
- Diesel sprays are extremely sensitive to slight changes in injection nozzles.
- Extremely effective in revealing the impact of biodisel
- Injection system needs to be modified to accommodate various fuels
  - Injection conditions
  - Combustion timing
  - …
- Dedicated VT beamline will impact the community even more significantly

- Plans
  - More engine-like conditions for diesel injections
  - GDI, HCCI, HCCI-Si hybrid sprays
  - Biofuels with wider-range of physical properties
  - Membrane research to improve Li batteries