# Neutron Imaging of Advanced Engine Technologies


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**ACE052**
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# Project Overview

## Timeline

- Started in FY2010
- Ongoing study

## Budget

- FY2010: $100k
- FY2011: $200k
- FY2012: similar funding levels

## Partners

- BES-funded Neutron Scientists and facilities
- University of Tennessee
- NGK

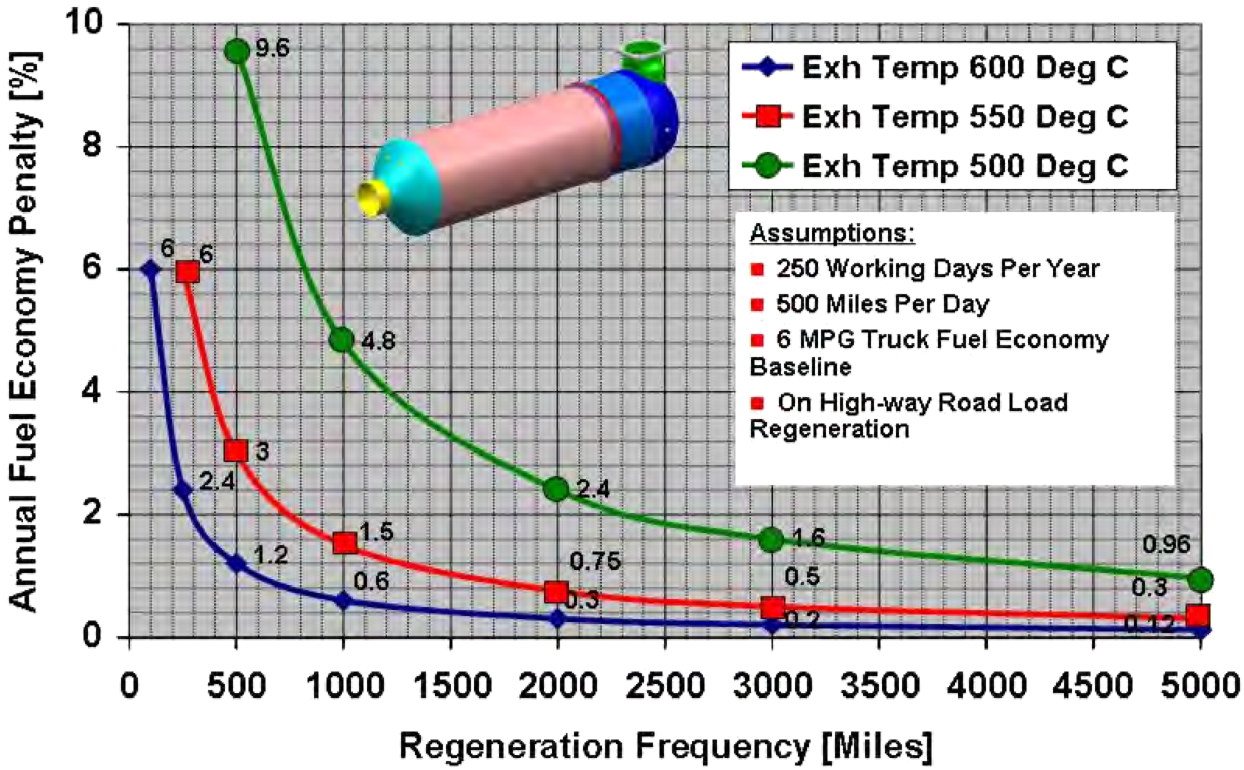
## Barriers

- 2.3.1B: *Lack of cost-effective emission control*
  - Need to improve regeneration efficiency in diesel particulate filters (DPFs)
- 2.3.1C: *Lack of modeling capability for combustion and emission control*
  - Need to improve models for effective DPF regeneration with minimal fuel penalty
- 2.3.1.D: *Durability*
  - Potential for thermal runaway
  - Ash deposition and location in DPFs which limit durability

# Objectives and Relevance

Develop <u>non-destructive, non-invasive</u> neutron imaging technique and implement it to improve understanding of advanced vehicle technologies

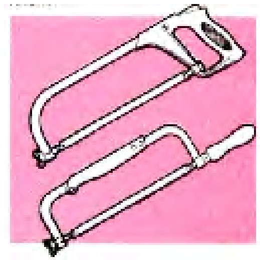
- Current focus on diesel particulate filters (DPFs)
  - Improve understanding of regeneration behavior
  - fuel penalty associated with regeneration
  - Improving understanding of ash build-up
- Additional areas of interest
  - Fuel injectors
  - EGR coolers




*Graphic provided by Detroit Diesel.*

# Non-destructive techniques needed for iterative approaches and to ensure layers are not disturbed

- Destructive Techniques
  - Limited spatial resolution
  - TEM, SEM and EPMA



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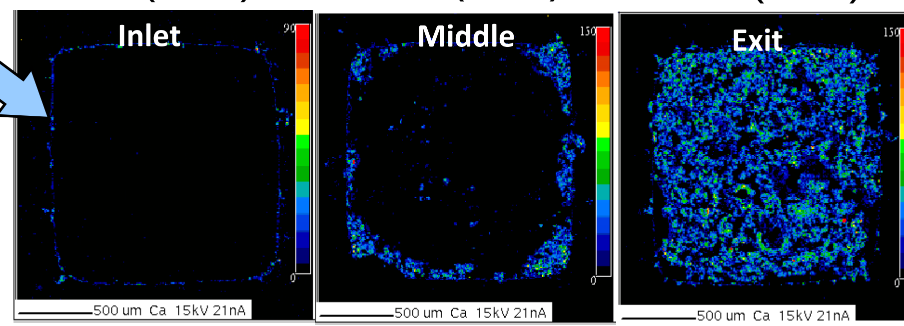
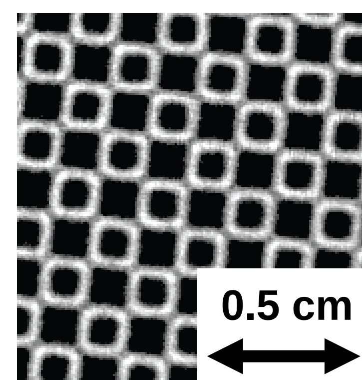
Inlet (17%) Middle (50%) Exit (83%)




*EPMA image from T.J. Toops, et al. SAE 2008-01-2496.*

- Non-destructive techniques
  - X-rays
    - Good axial resolution, but poor radial resolution
  - Neutrons


*X-ray from T.J. Toops, et al. SAE 2009-01-0289*




*Neutron Image from Bilheux, et al. SAE 2009-01-2735*

# Milestones

- Obtain images with significantly increased resolution that identifies interactions of soot and ash with DPF walls (9/30/2011).
  - On target

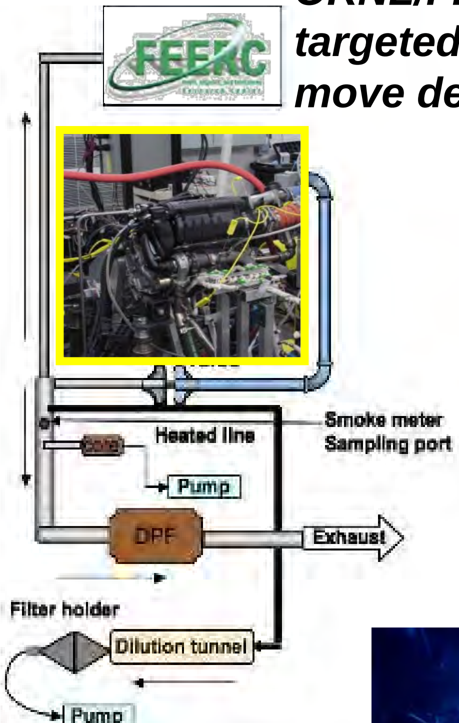
- Construct spray chamber and obtain initial spray images (9/30/2011).
  - On target

# Collaborations

- Basic Energy Sciences
  - High Flux Isotope Reactor (HFIR) and
  - Spallation Neutron Source (SNS)
  - Development and operation of beamline facilities, neutron scientists time
- NGK
  - Donating materials and contributing accelerated ash filled samples
- Michael Lance, Scott Sluder and Keely Willis (Propulsion Materials project)
  - Working on EGR cooler fouling project with several industrial partners
  - Caterpillar, Cummins, DAF Trucks, Detroit Diesel, Ford, GM, John Deere, Modine, Navistar, PACCAR and Volvo/Mack
  - US Army
- University of Tennessee
  - Developing algorithms for improving contrast and removing artifacts
- Technical University of Munich
  - Initial neutron imaging efforts

# Approach

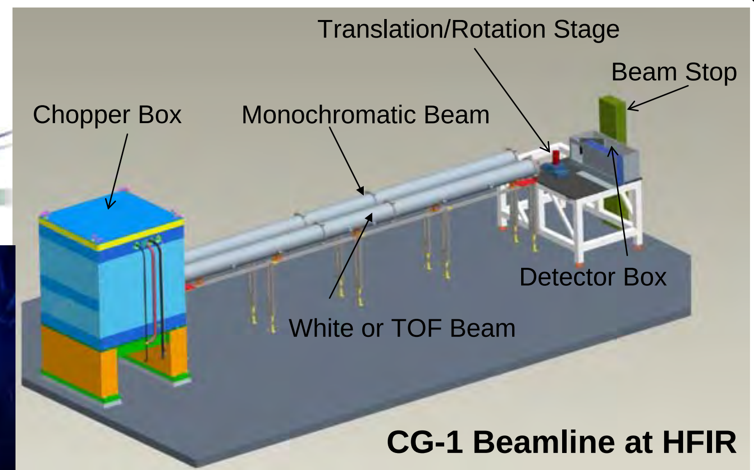
***Operate engine at ORNL/FEERC under targeted conditions; move device to HFIR***



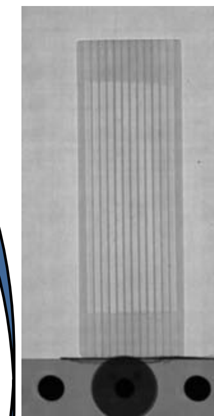

***Receive devices from industrial partners for analysis***

NGK

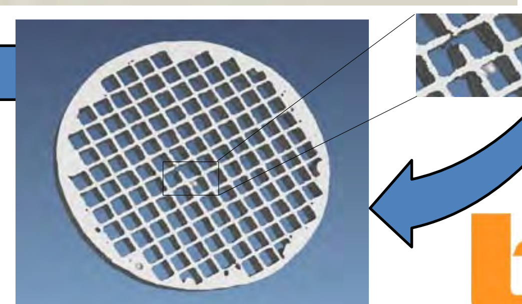
***Record raw images of devices using neutron beam***




**CG-1 Beamline at HFIR**



***Reconstruct device using neutron computed tomographic techniques***



***Improved understanding published and disseminated to modelers and engine controllers***

# Summary of Technical Accomplishments

- Developed and implemented fully automated neutron computed tomography equipment and reconstruction software. Performed 3D imaging of:
  - 3" x 6" clean DPF to demonstrate tomography capability
  - 1" x 3" DPFs that have been filled with ash
    - continuous regeneration and periodic regeneration (NGK)
    - artificially filled
  - 1" x 3" DPFs with soot deposited on the walls
  - Catalyzed and uncatalyzed 1" x 3" DPFs for impact of washcoat

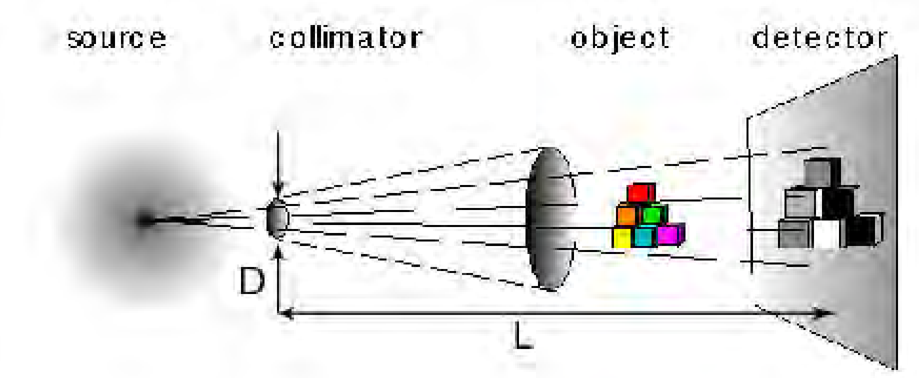
- Improved resolution of neutron detector and can now achieve:
  - 100 micron resolution for a 7 cm x 7 cm field of view, or
  - 50 micron resolution for a 5 cm x 4 cm field of view

- Calibration samples for model ash prepared and measured

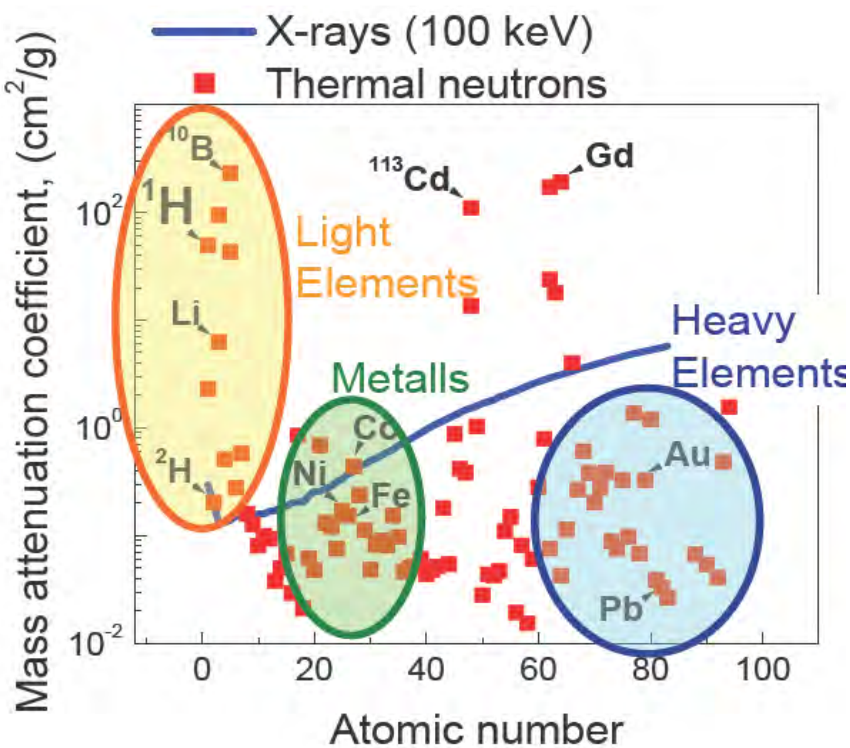
# Technical Details

# Neutrons are absorbed by a range of elements including light elements

- Neutrons are heavily absorbed by light elements such as Hydrogen and Boron
  - Can penetrate metals without absorbing
  - Highly sensitive to water and hydrocarbons/fuel
    - Can image carbon soot layer due to absorption of water and HC
  - Image is based on absence of neutrons
- X-ray imaging relies upon absorption of heavy elements




http://neutra.web.psi.ch/What/index.html

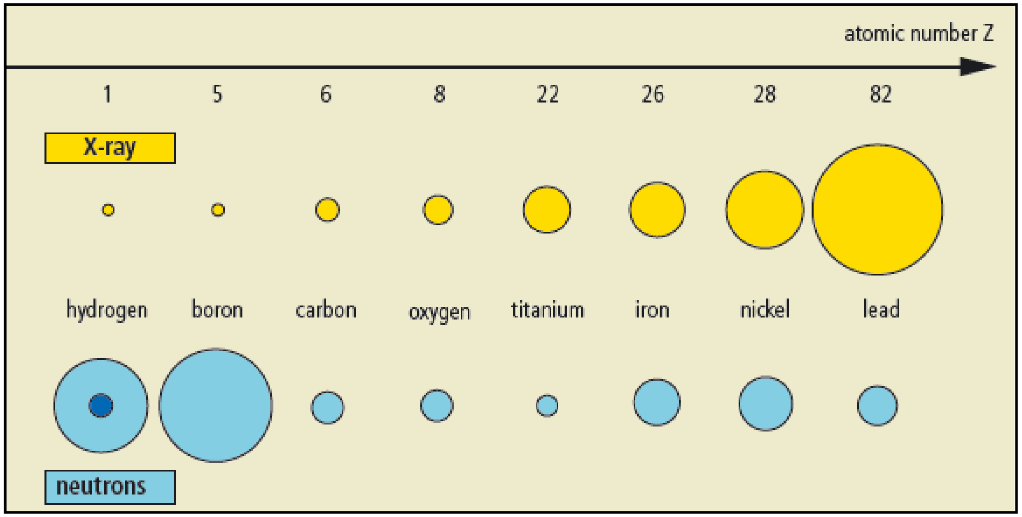


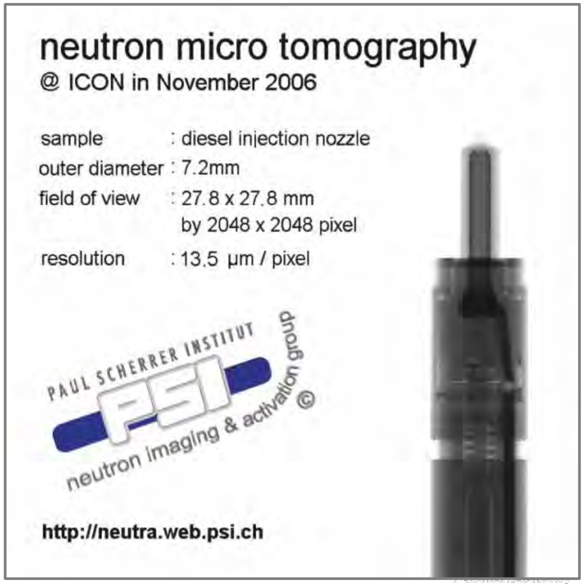

***Neutron imaging is a complementary analytical tool***

Reference: N. Kardjilov's presentation at IAN2006
http://neutrons.ornl.gov/workshops/ian2006/MO1/IAN2006oct_Kardjilov_02.pdf

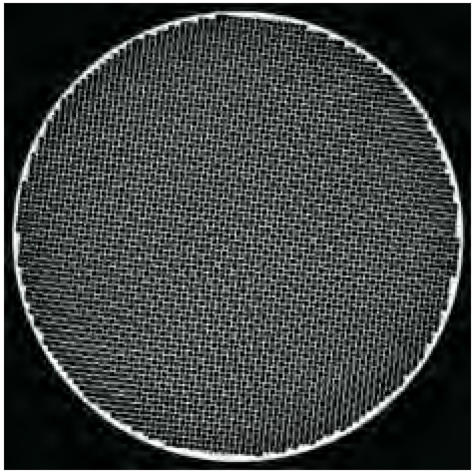
# Neutrons offer unique imaging opportunity

- With the ability to penetrate dense materials, neutrons offer the ability non-destructively analyze working systems
- Demonstrations show the potential applications
  - Yet to be demonstrated under realistic operating conditions (videos made at Paul Scherrer Inst.)
- Tomography can be applied to unravel detailed 3D structure based on neutron absorption
  - Relies on computed reconstruction of device
  - Rotating device and recording absorbed neutron allows rebuilding device and virtual cross-sectional analysis

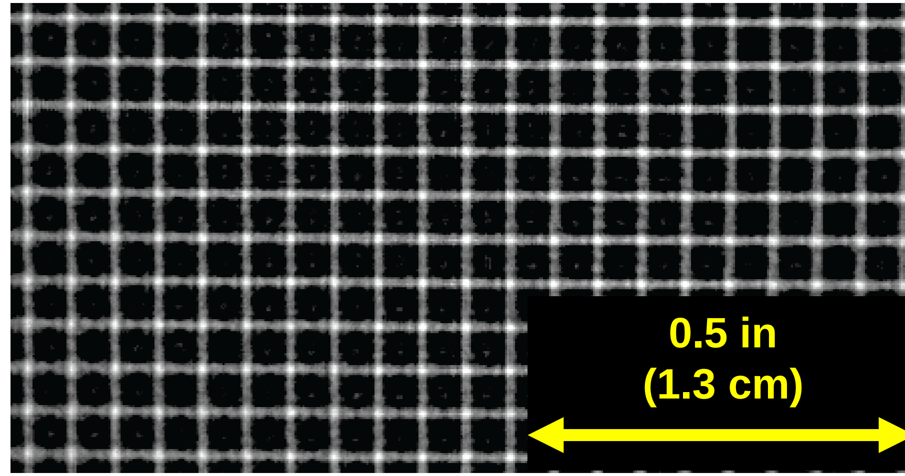



# Initial images recorded at TUM show potential to visualize soot layer in DPF



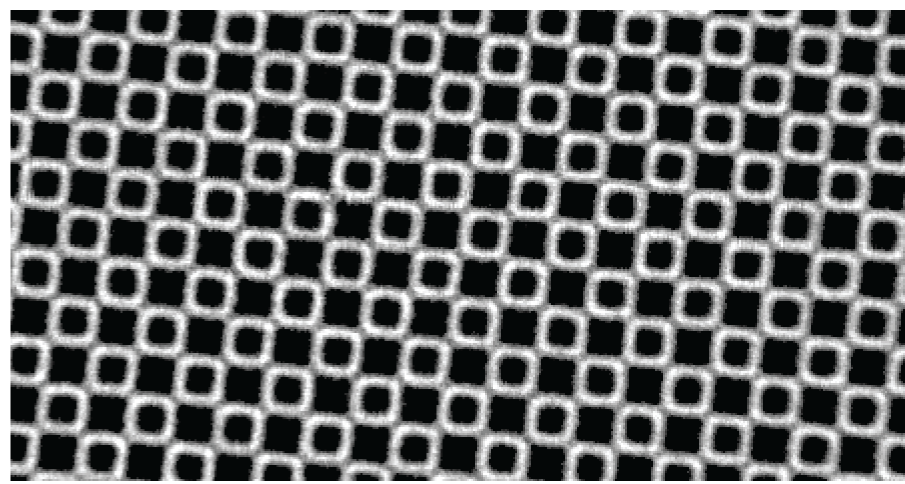
**Full 5.7” x 6” DPF Filled at ORNL imaged at TUM**

TECHNISCHE UNIVERSITÄT MÜNCHEN




**Clean DPF**

- Initial results from full DPFs
  - ANTARES Imaging Facility in Munich, Germany, with DPFs from ORNL
  - Technical University of Munich
- Soot layer is present in alternating channels
  - increased contrast required for quantitative analysis



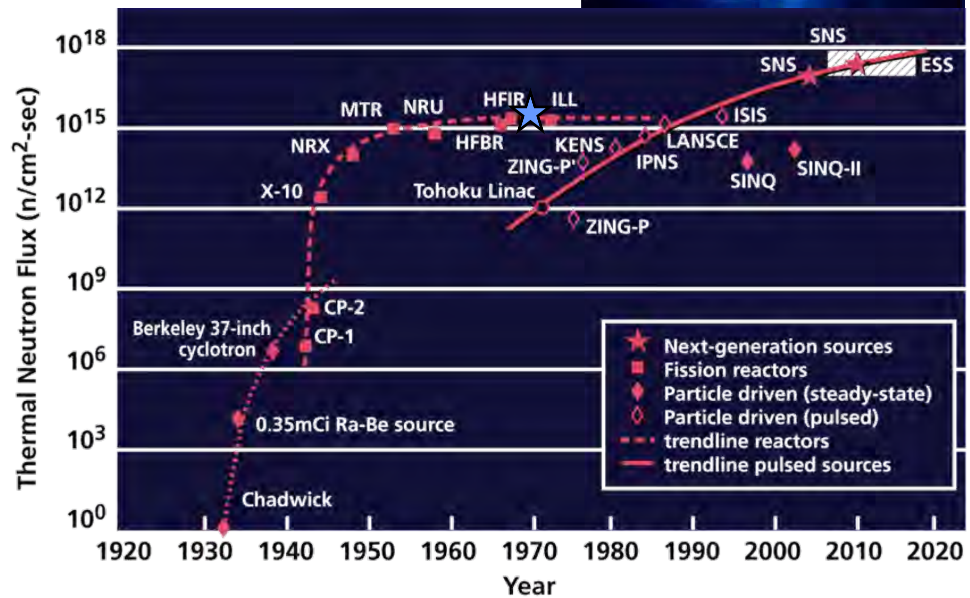
**Particulate filled DPF**

*Neutron images from Bilheux, et al. SAE 2009-01-2735*

# Neutron imaging capabilities at ORNL

- High Flux Isotope Reactor (HFIR)
  - Steady (i.e., non-pulsed) neutron source; “white” beam
  - Imaging capability has been developed in parallel during this program
  - Imaging beamline recently incorporated into user program
    - Neutron scientists efforts have been part of the development process

- Spallation Neutron Source (SNS)
  - Most intense pulsed neutron beams in the world; energy selective
  - Multi-laboratory effort funded by DOE Office of Science
  - Letter Of Intent (LOI) of imaging beamline approved

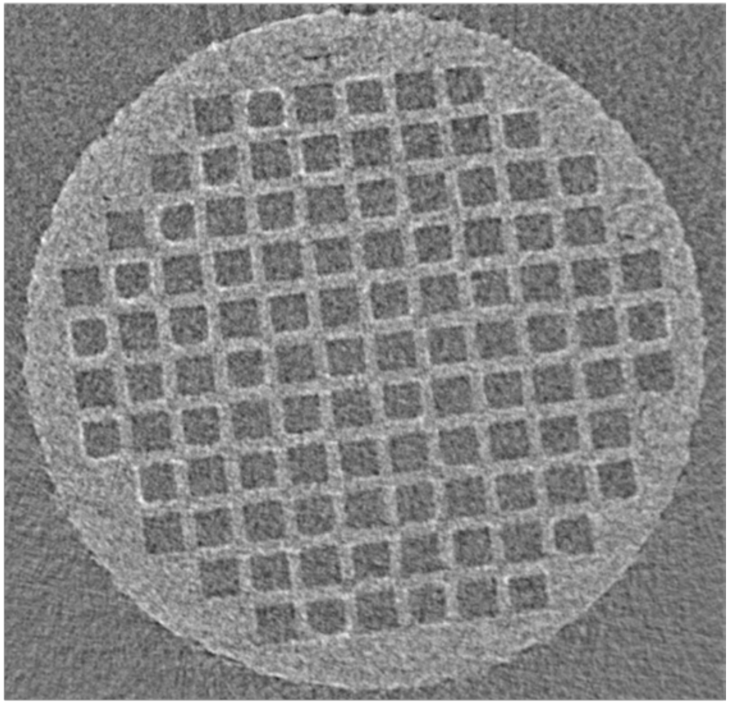


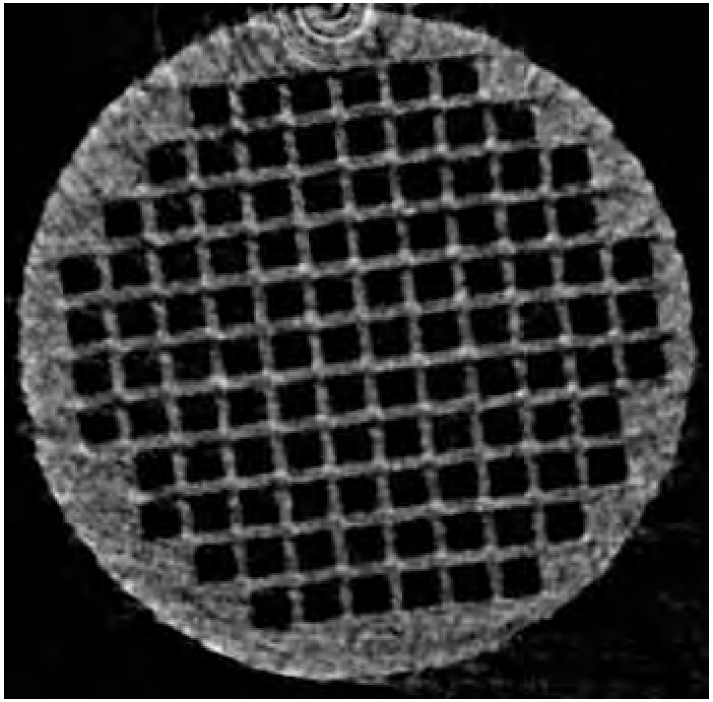

(Updated from *Neutron Scattering*, K. Skold and D. L. Price: eds., Academic Press, 1986)

*Protons hit a Mercury target and “spall” off neutrons with a repetition rate of 60 Hz*

# Establishing high quality neutron images depends on equipment and computational technologies

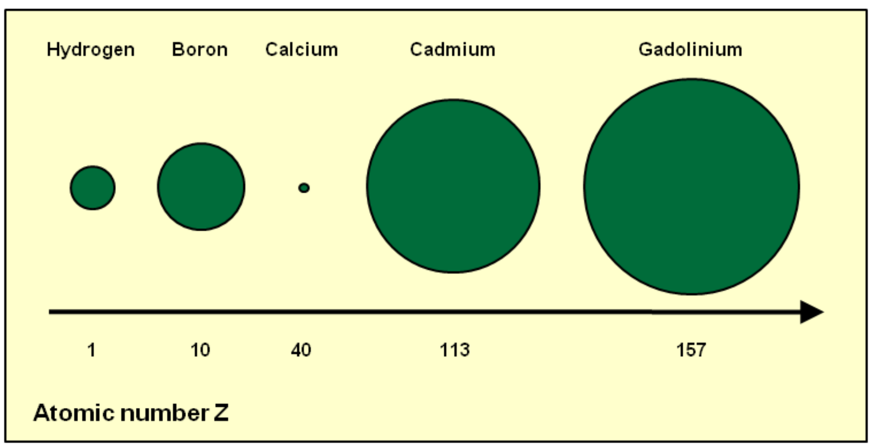
- Neutrons absorbed by device are combined build tomographic image
- To improve image quality data is processed to improve contrast
  - Techniques employed: Back-Filtered (Left) vs. Iterative (Right) Projection
  - Back Filtered Projection: Grainy aspect and noise prevent data analysis
  - Iterative projection promising with increased contrast, but lose some sharpness at edges
- Filtering algorithms still under development

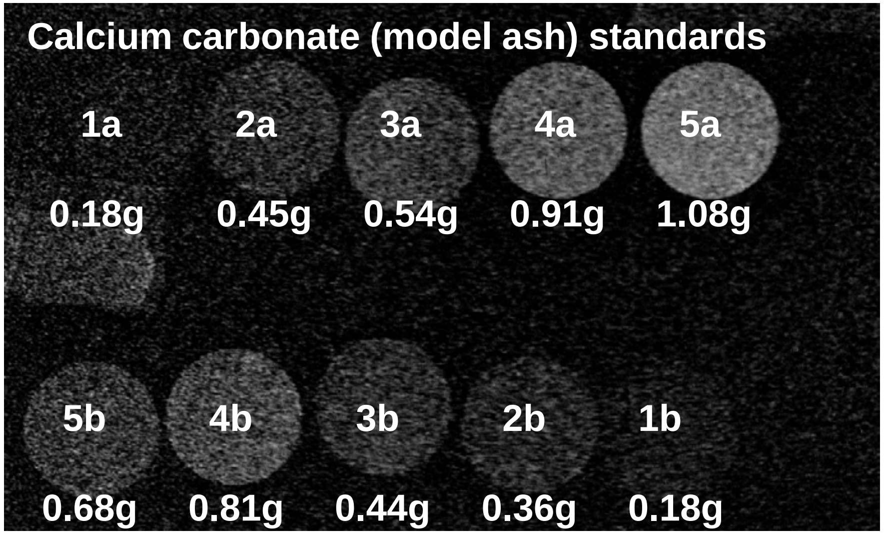


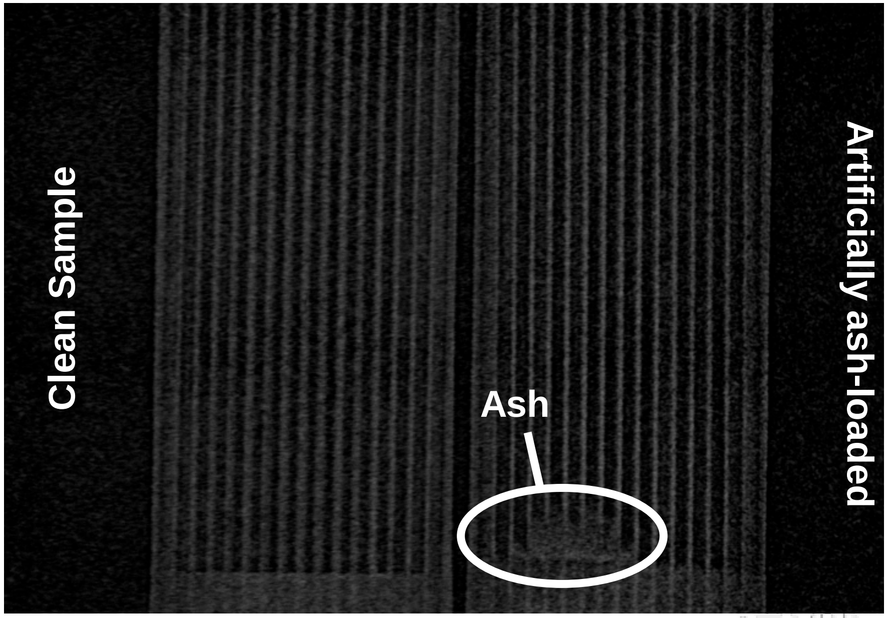


# Distinguishing Ca-based model ash is difficult

- Model ash (calcium carbonate) standards
  - pressed into disks
  - two densities studied
    - a: 507 $g/cm^3$
    - b: 370 $g/cm^3$
  - Model ash approach by NGK*
- Ash artificially loaded in portion of DPF
  - difficult to distinguish from sample
- Ca adequately simulates exhaust ash, BUT has poor Neutron absorbtivity
  - Visualization relies on water adsorption



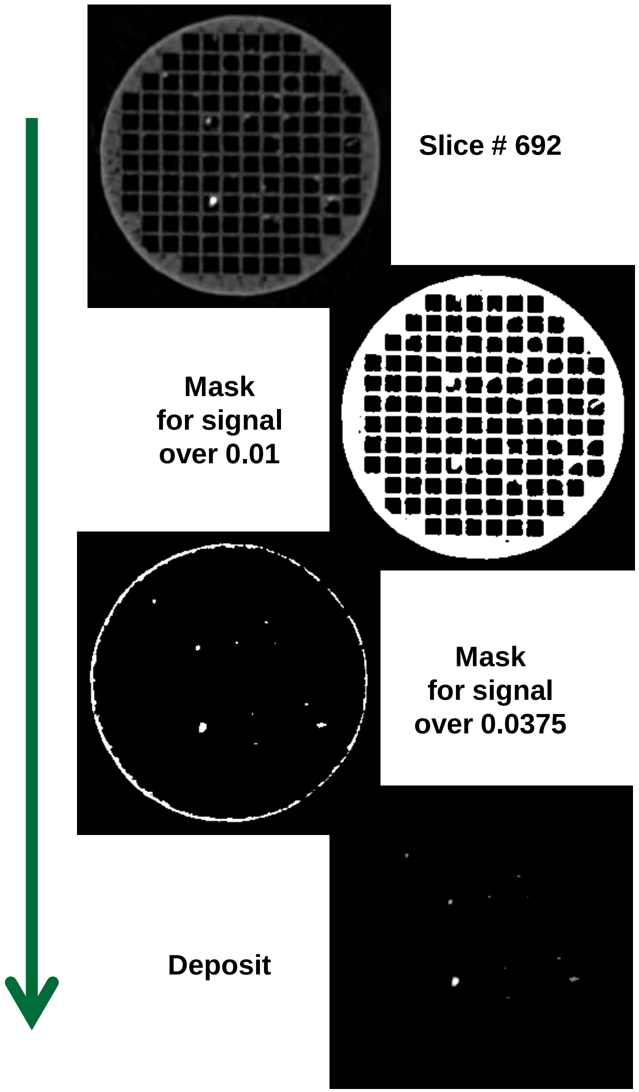



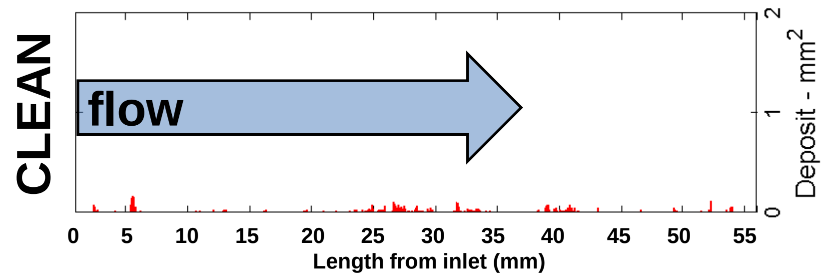

* - S. Fuji and T. Asako, SAE 2010-01-2171

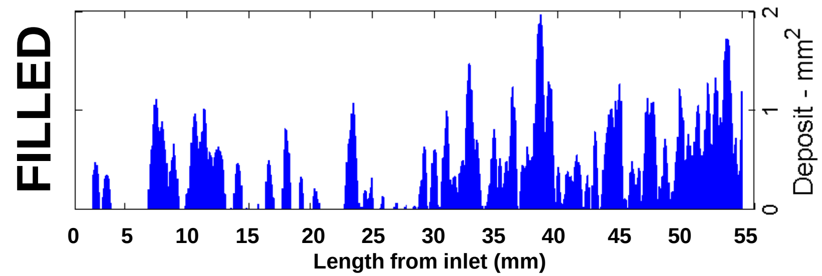
# Neutron computed tomography and data analysis employed to show particulate profile in DPFs

- Imaging process methodology




- 1”x3” DPF with unique particulate profile
- Particulate cross-section as a function of the length of the DPF
  - Elemental ID possible w/pulsed source*



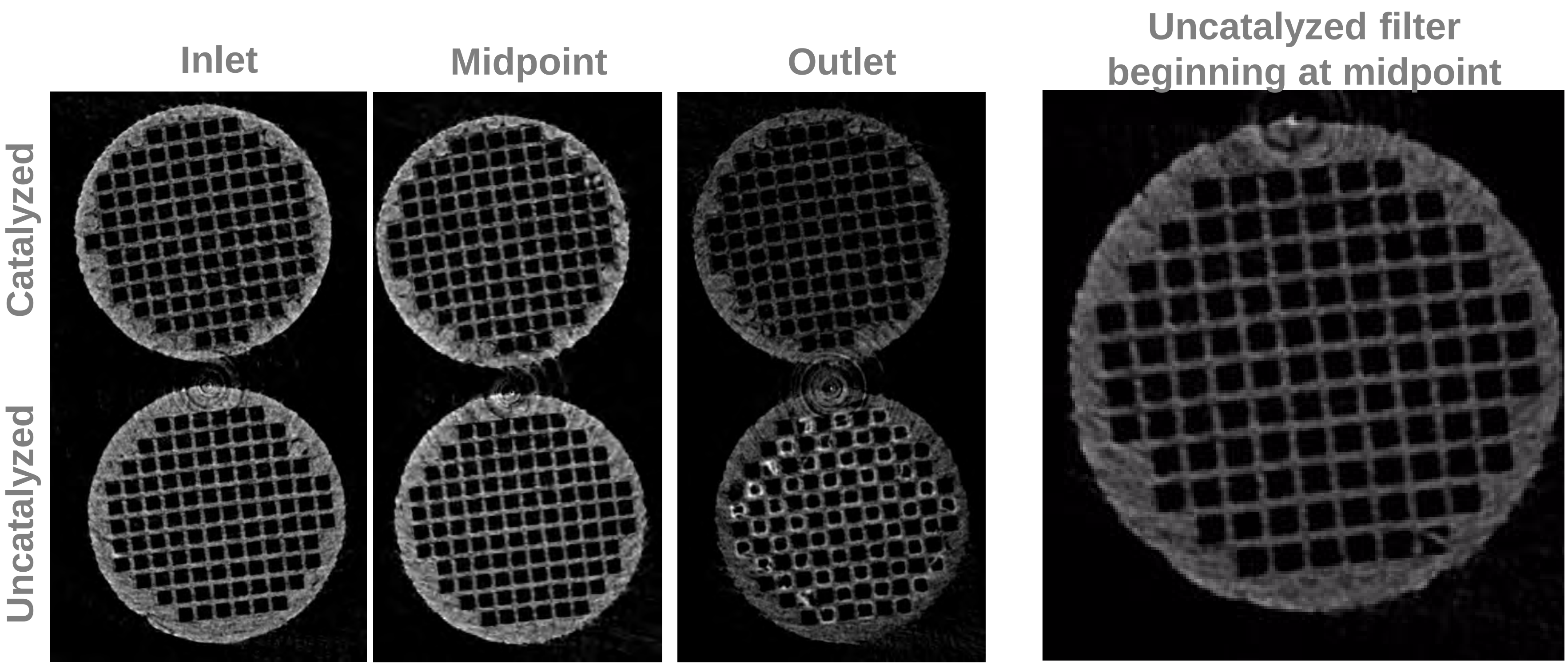




Side-view of filled DPF

* - W. Kockelmann et al., Nuclear Instruments and Methods in Physics Research A 578 (2007) 421

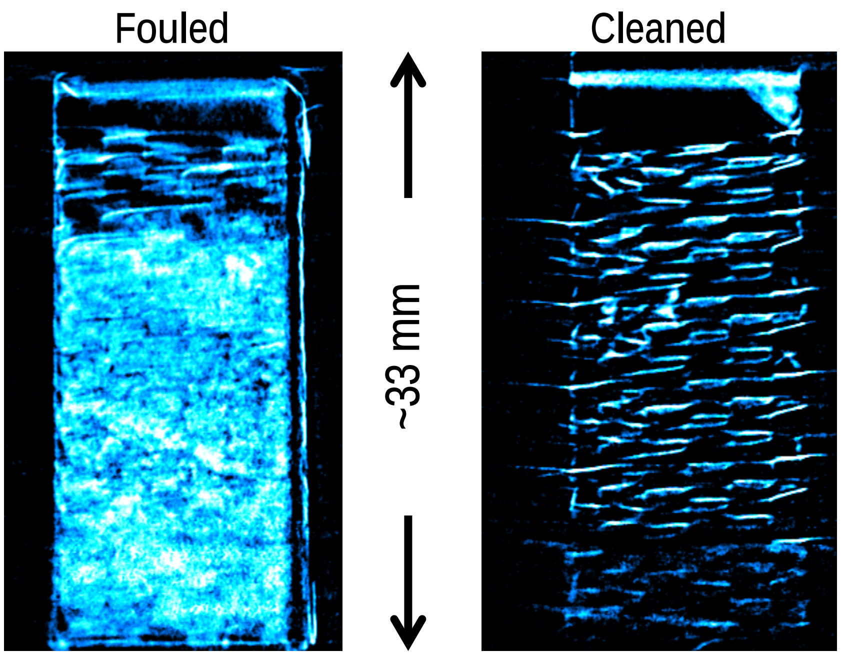
# Neutron computed tomography and data analysis of catalyzed and uncatalyzed DPFs

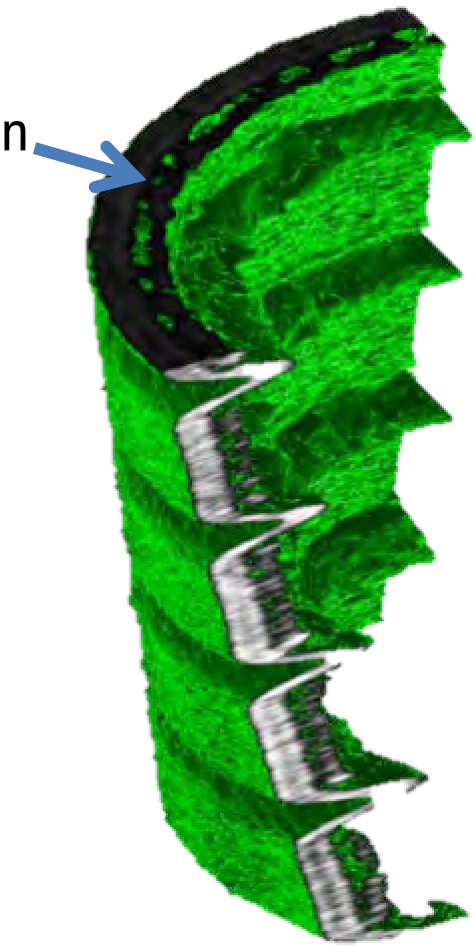
- Catalyzed and uncatalyzed DPFs analyzed
  - Identical DPF materials which were regenerated in bench reactor at 650°C
- Uncatalyzed DPF has particulate remaining near the outlet
  - Efforts ongoing to develop ring filtering algorithm



# Imaging Techniques also being applied EGR cooler fouling study

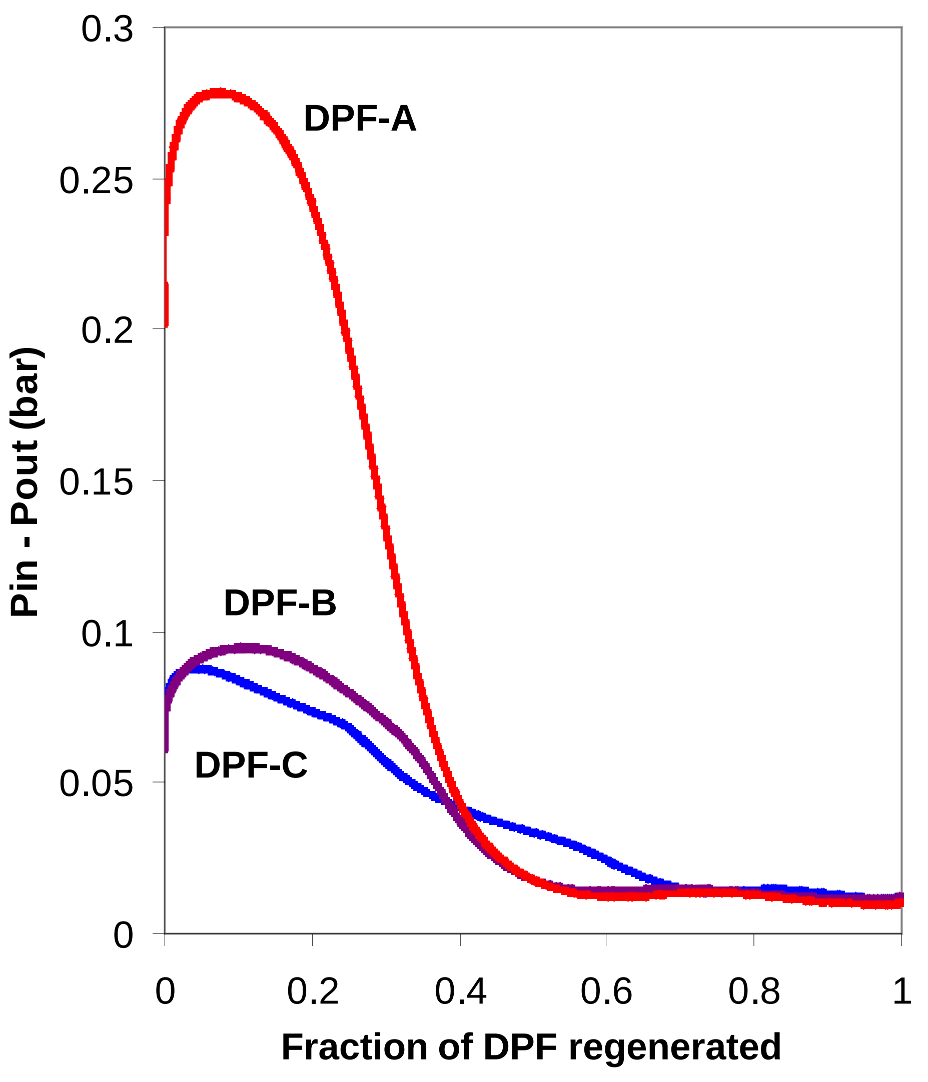
- EGR cooler fouling being studied in Propulsion Materials project
  - Michael Lance (PI) and Scott Sluder
- Able to identify local and global features
  - Local: like mudcracks and delamination
  - Global: fouled versus cleaned



# Future work

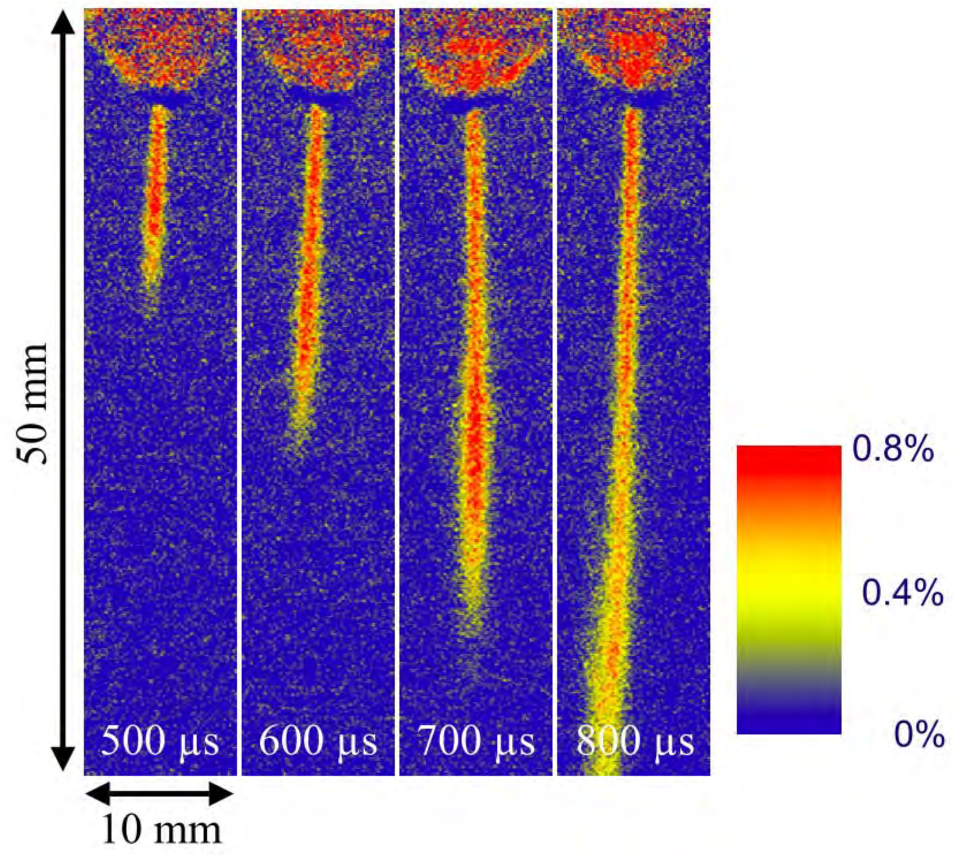
- DPF partial regeneration
  - Pressure drop goes to background levels after only 50% of the DPF is regenerated
  - Where is the soot being regenerated?
  - Are regenerations complete?
- Ash loading with more sensitive model ash
  - Boron or gadolinium doped
  - Packing density studies
- Fuel injection systems and engine flows



# Fuel spray imaging

- Fundamental insight into *near-nozzle* and *in-nozzle* fuel behavior necessary for improved simulation and design.
  - Boundary conditions
  - Liquid break-up mechanisms
  - Evaporation timescales
  - Cavitation

- Neutron imaging provides new information which is complimentary to current methods
  - Laser-based methods not well suited for dense sprays and unable to penetrate metal making *in situ* measurements difficult or impossible
  - X-ray based methods able to penetrate metal but require fuel doping and do not interact with vapor

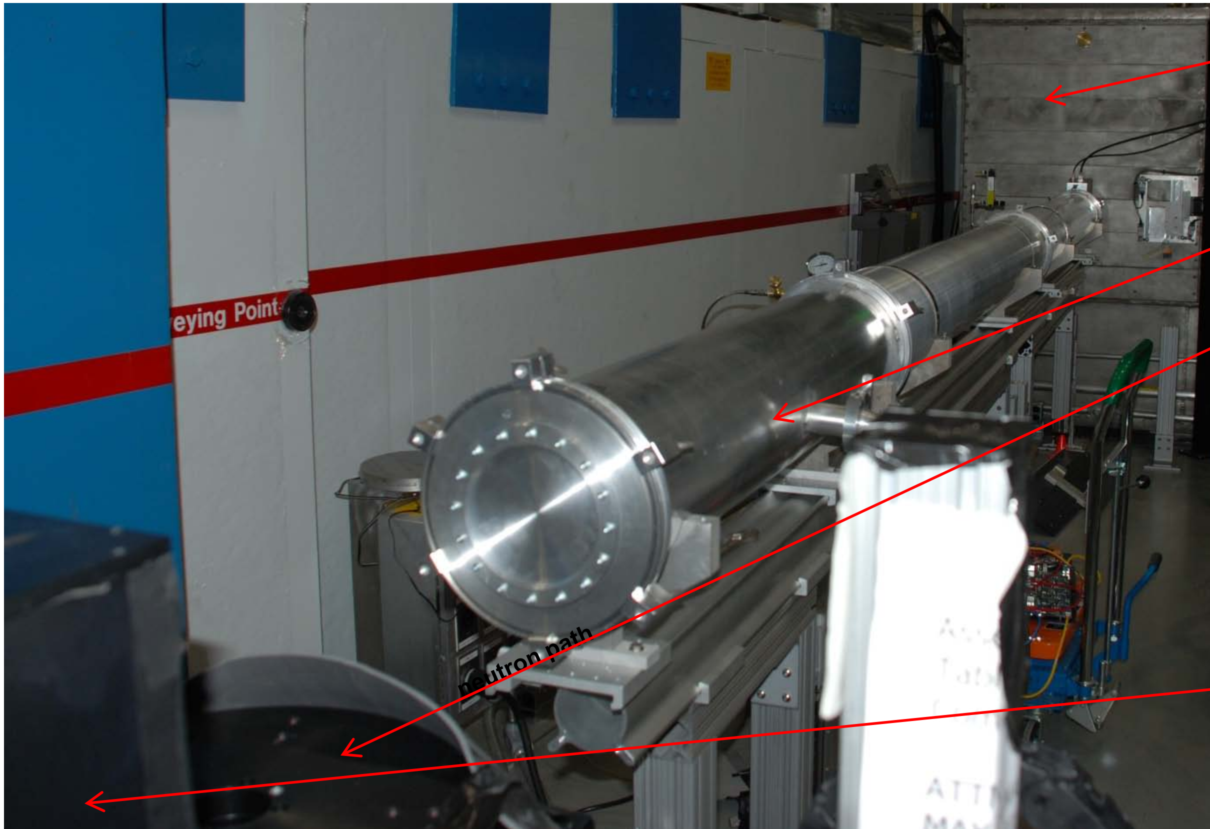



Bosch CR injector imaging performed at Institu Laue-Langevin (Grenoble) with steady neutron beam. Adapted from van Overberghe 2006

# Summary

- Relevance: Develop non-destructive, non-invasive neutron imaging technique and implement it to improve understanding of lean-burn vehicle systems
  – Improved understanding targeting fuel economy improvements and durability
- Approach: Neutron Imaging as a unique tool applied to Automotive Research areas to visualize, map and quantify H-rich deposit (soot/ash) in engine parts as well as looking at fuel dynamics inside spray (not achievable with x-rays)
  – DPFs, EGR coolers, Fuel Spray
- Collaborations: BES, Industrial (NGK), Govt. Labs (ORNL and PNNL) and Universities
- Technical Accomplishments:
  – The HFIR CG1 beamline is operating and offers both 2D and 3D capabilities
  – Demonstration of usefulness of neutron imaging techniques for automotive research
- Future Work:
  – Filtering algorithms and full data analysis on remaining samples
  – Several more samples to measure (DPFs, EGR coolers and batteries)
  – New challenge: Looking at running fuel spray

# Technical back-up slides




Chopper Box

He-filled Al flight tubes

Sample stage (translation and rotation for neutron Computed Tomography)

Detector housing (CCD, lens, mirror and scintillator)

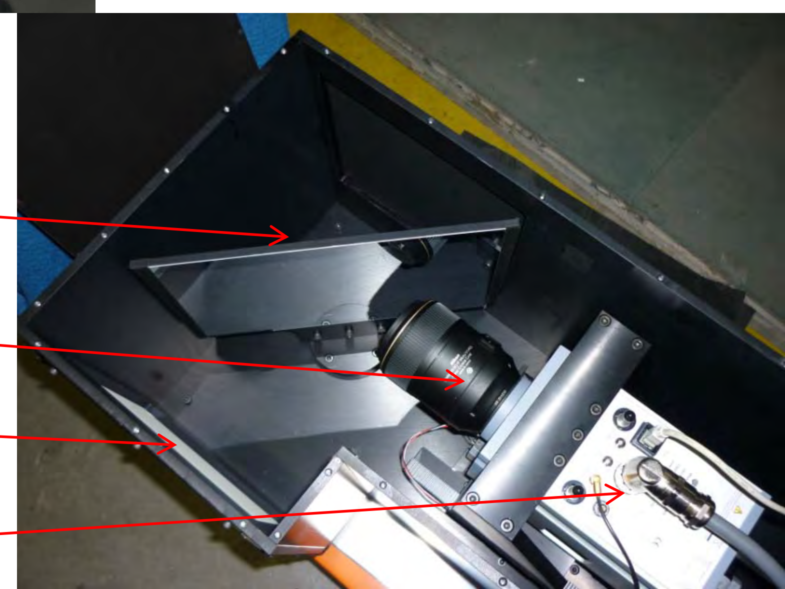
**HFIR CG1D beamline**
**Achievable Resolution:**
**-50 microns**
**- $\Delta\lambda/\lambda$ ~ 10% (in TOF mode)**

Mirror

Lens

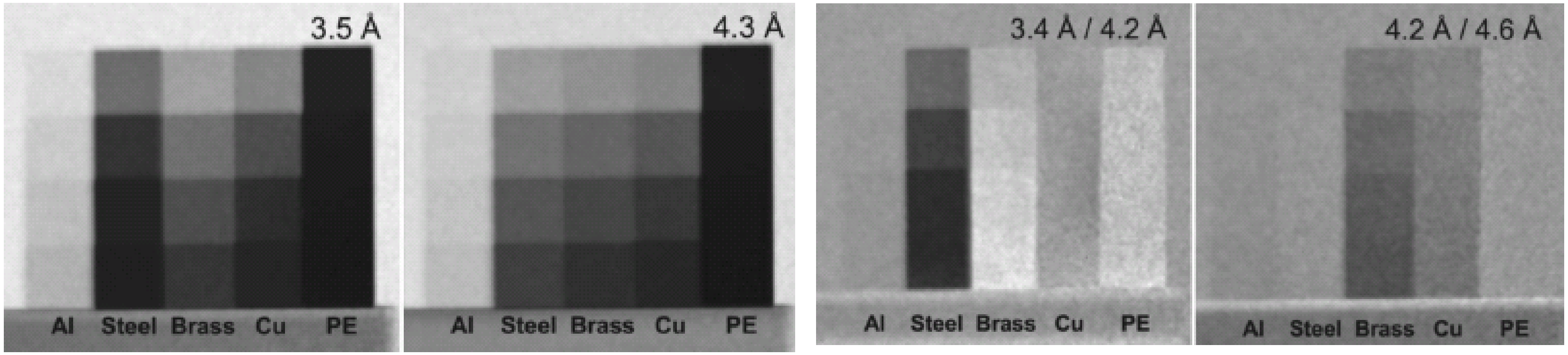
LiF/ZnS scintillator (25 to 200 microns thick)

CCD



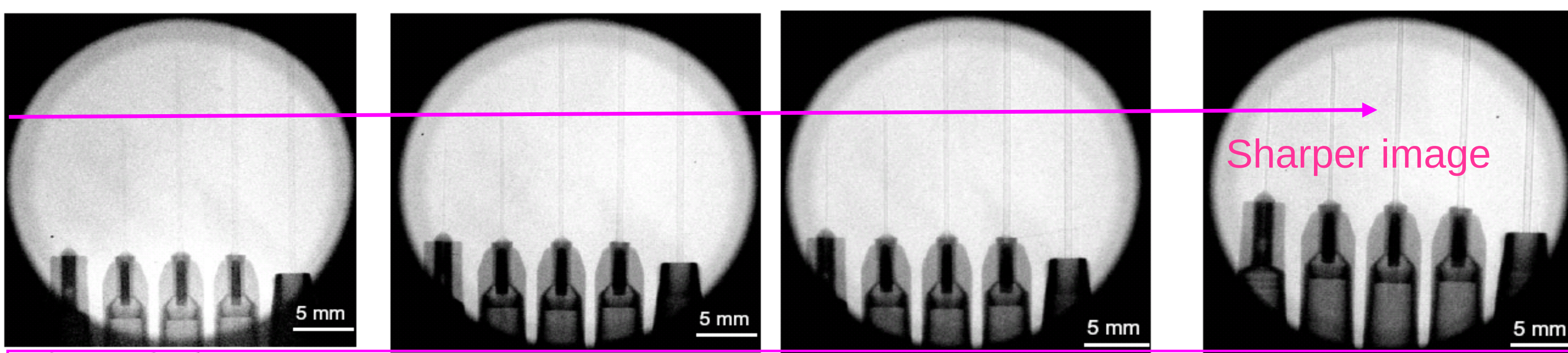
# Techniques still under development to enable image enhancement and elemental contrast

- Bragg edges




W. Treimer et al., Appl. Phys. Lett. 89 (2006). 5 min exposure, 150 microns detector resolution, 2 x $10^{4}$ $cm^{-2}$ $s^{-1}$ Courtesy of N. Kardjilov.

- Phase Contrast




Distance sample to detector: 0 cm
Distance pinhole to sample: 650 cm
Pinhole diameter: 0.5 mm
Exposure time: 180 min

Distance sample to detector: 25 cm
Distance pinhole to sample: 650 cm
Pinhole diameter: 0.5 mm
Exposure time: 180 min

Distance sample to detector: 50 cm
Distance pinhole to sample: 650 cm
Pinhole diameter: 0.5 mm
Exposure time: 180 min

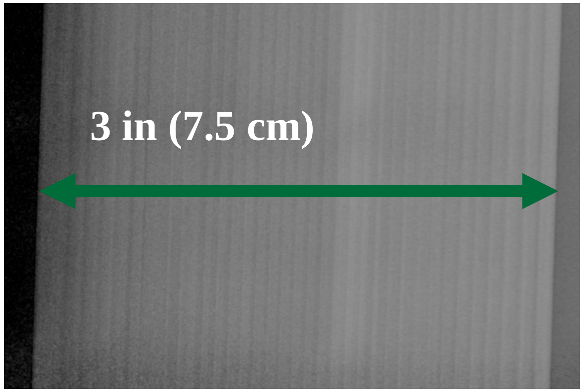
Distance sample to detector: 100 cm
Distance pinhole to sample: 650 cm
Pinhole diameter: 0.5 mm
Exposure time: 180 min

N. Kardjilov et al., NIMA 527 (2004) 519-530.

# Ash loading in 3”x6” DPF

- Because the ORNL CG1D imaging prototype beamline is NOT designed/optimized for neutron imaging measurements:
  - image processing is very demanding
  - currently working on data filtering and artifact correction algorithms
- The deposition of Na ash is clearly visible

Clean DPF




DPF with Ash