Neutron Imaging of Advanced Transportation Technologies

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Project Overview

Timeline

- **Started in FY2010**
- **Ongoing study**

Budget

- **FY2010: $200k**
- **FY2012: $200k**

Partners

- **BES-funded Neutron Scientists and facilities**
- **University of Tennessee**
- **University of Alabama**
- **NGK**
- **Navistar**

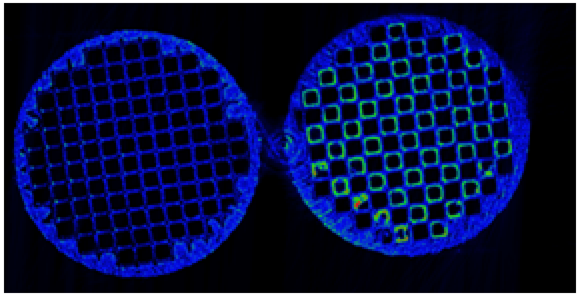
Barriers

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

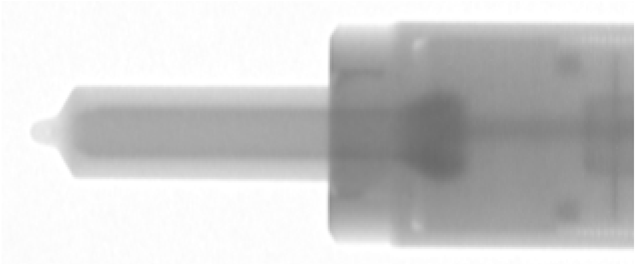
Objectives and Relevance

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

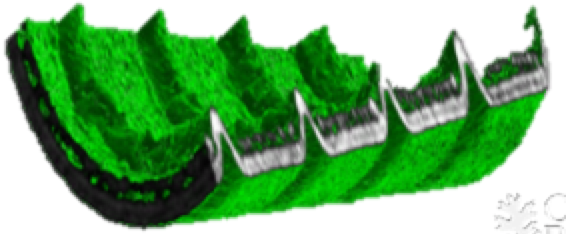
- **Current focus on diesel particulate filters (DPFs)**
  - Improve understanding of regeneration behavior
  - fuel penalty associated with regeneration
  - Improving understanding of ash build-up
  - Comprehensive, quantitative device analysis enables validation of full-scale modeling



- **Expanding role in diesel fuel injectors**
  - Internal and external dynamics, and their relationships
  - Cavitation and durability issues

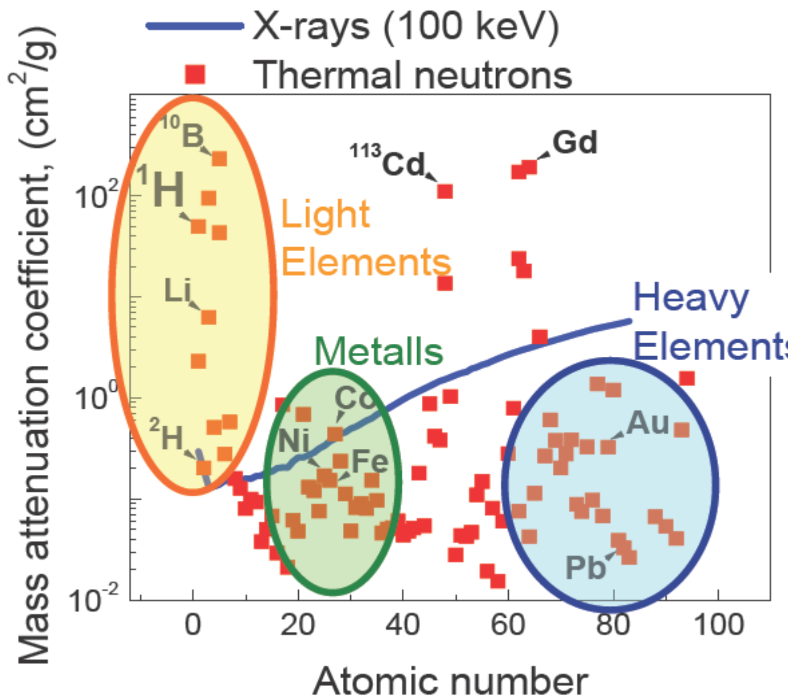


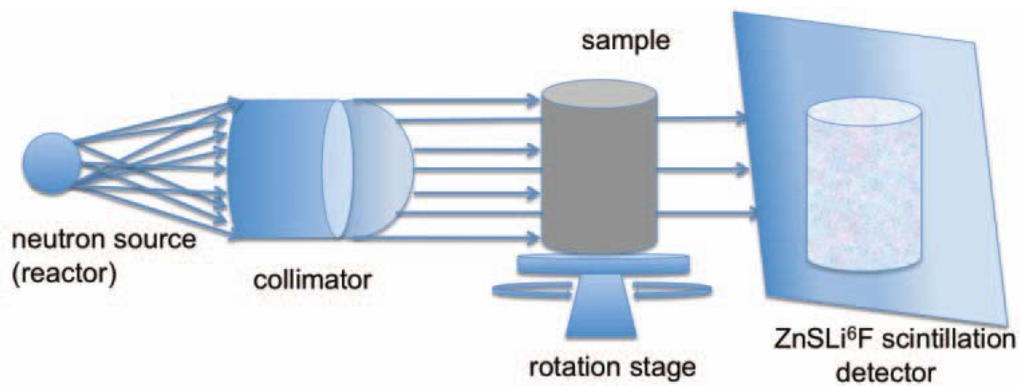
- **Complementary project on EGR cooler fouling being investigated in Advanced Propulsion Materials project**
  - Michael Lance (PI)



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**



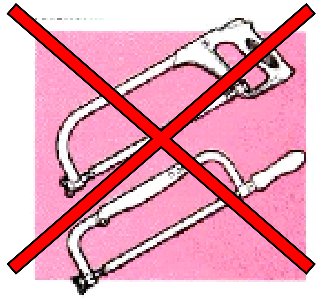


Neutron imaging is a complementary analytical tool

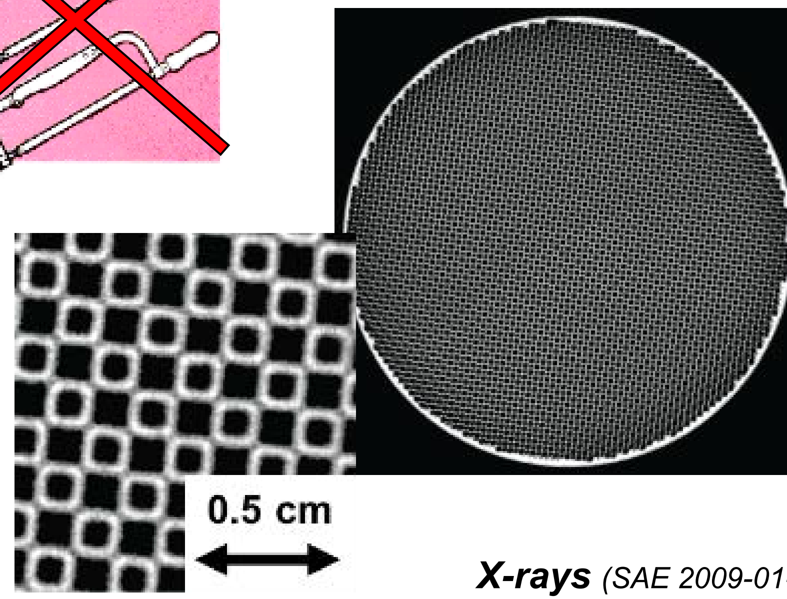
Attenuation Coefficient Reference: N. Kardjilov's presentation at IAN2006
http://neutrons.ornl.gov/workshops/ian2006/MO1/IAN2006oct_Kardjilov_02.pdf

Non-destructive techniques needed for iterative approaches and to minimize disruption

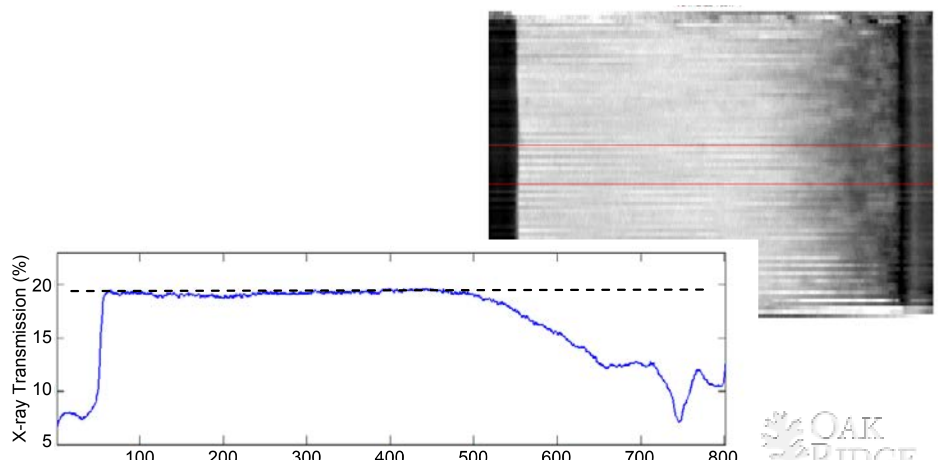
- **Non-destructive techniques**
  - Neutrons
    - Capable of high detail, 10-50 microns
    - strong absorbance with lighter elements
  - X-rays
    - Wide range of applications
      - low cost portable tomography
        - » Lacking in detail
      - Synchrotrons
        - » Higher cost, more detail
    - strong absorbance with heavy elements
- **Destructive Techniques**
  - Limited spatial resolution
    - Can only observe where specimen is fractured
  - TEM, SEM and EPMA
  - Iterative studies are difficult/impossible



Neutron CT scan *(SAE 2009-01-2735)*



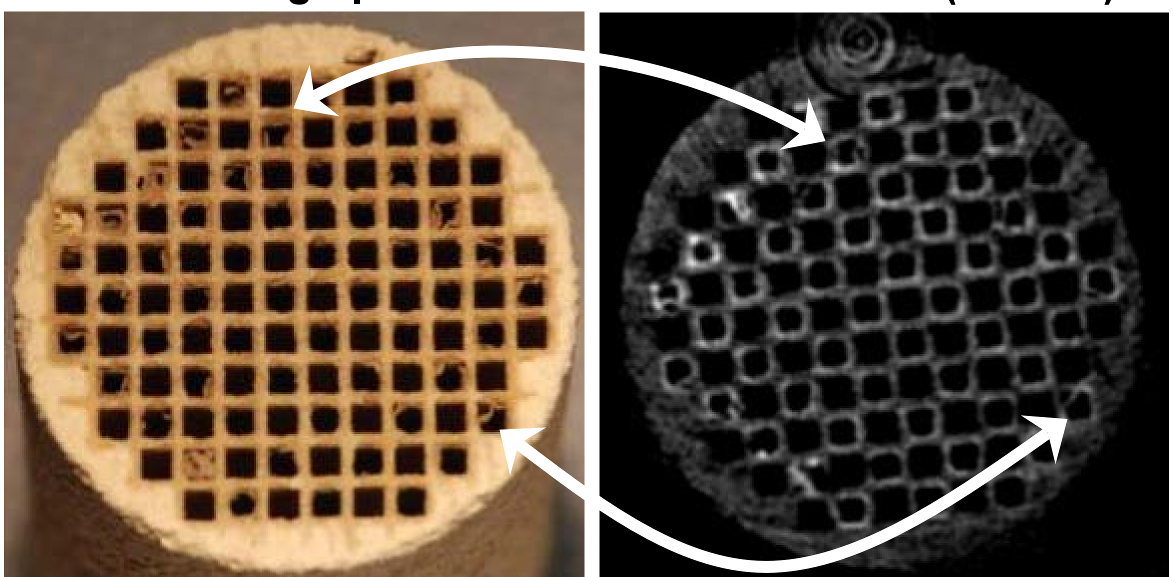
X-rays *(SAE 2009-01-0289)*

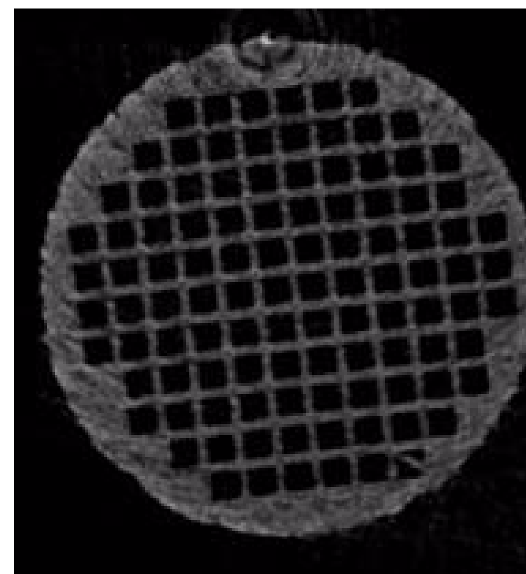


Complete sample analysis can be achieved with non-destructive techniques

- **Samples can be analyzed at one cross-section or a complete reconstruction can provide a cross-section of the entire sample at a resolution of the detector**
  - ~50 microns currently achievable at ORNL's High Flux Isotope reactor (HFIR)
- **Illustration of technique on catalyzed DPFs**
  - Catalyzed DPF washcoat visible on outlet channels, matches physical cross-section

Cross-sectional view of after cutting open DPF | **Neutron image "virtual" cross section (not cut)** | **Catalyzed filter beginning at midpoint going to inlet**





Milestones

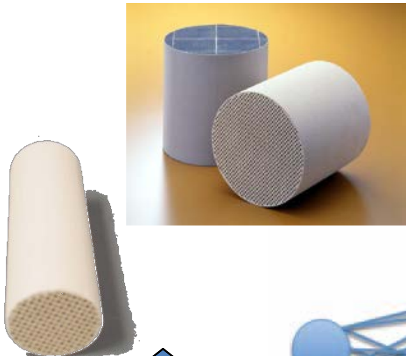
- **Obtain images with significantly increased resolution that identifies interactions of particulate with DPF walls (9/30/2011).**
  - Met

- **Measure sequential soot distribution changes in diesel particulate filters as a function during a series of partial regenerations (9/30/2012).**
  - On target

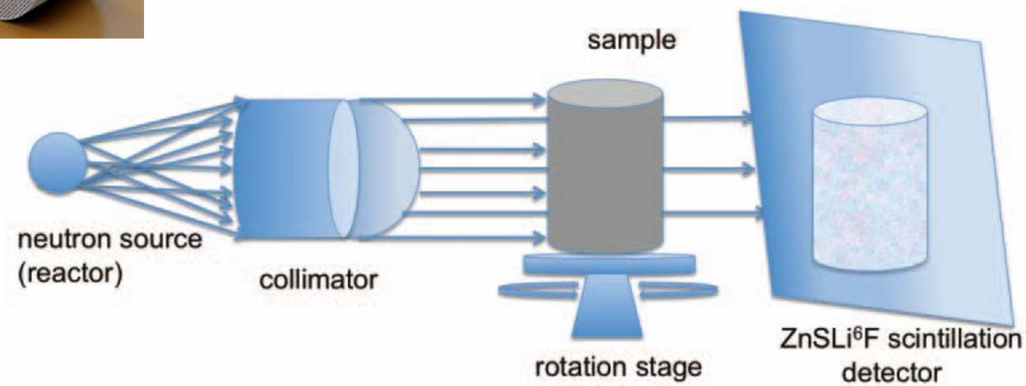
Collaborations

- **Basic Energy Sciences**
  - Hassina Bilheux, Sophie Voisin, Lakeisha Walk
  - High Flux Isotope Reactor (HFIR) and Spallation Neutron Source (SNS)
  - Development and operation of beamline facilities
  - Neutron scientists time, data reconstruction, analysis and writing publications
- **NGK (Shawn Fujii)**
  - Donating materials and contributing accelerated ash filled samples
- **Navistar (Brad Adelman)**
  - Contribution of soot loaded filters
- **University of Tennessee (Jens Gregor)**
  - Developing algorithms for improving contrast and removing artifacts
- **University of Alabama (Brian T. Fisher)**
  - Internal and external fluid flow modeling of fuel injectors
- **Technical University of Munich (Burkhard Schillinger and Michael Schulz)**
  - Initial neutron imaging efforts

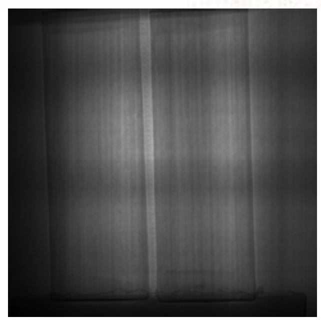
Approach emphasizes iterative studies

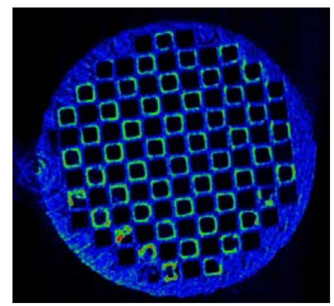


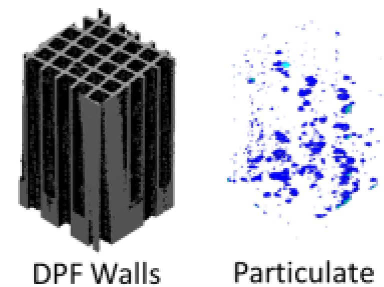
Receive devices from industrial partners or implement our own techniques



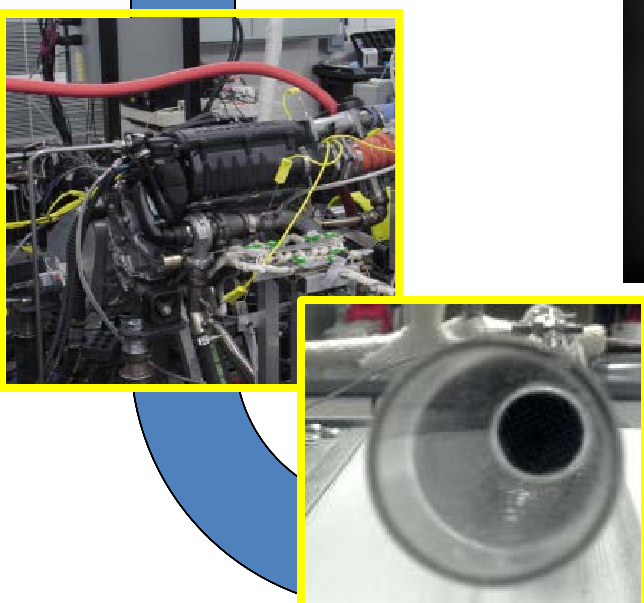
Record raw images of devices using neutron beam







Reconstruct device using neutron computed tomographic techniques



Iterate with engine/bench reactor for sequential study

Summary of Technical Accomplishments

- **Improved visualization tools to enable separation of neutron active particulate from filter walls**
  - Illustrated dense particulate pattern could be independently visualized from PF wall

- **Identified particulate depth as a function of length, radius, and particulate loading**
  - Particulate filters filled to 3, 5, and 7 g/L
  - Imaged with neutrons to identify particulate profile
  - Investigating during partial regenerations

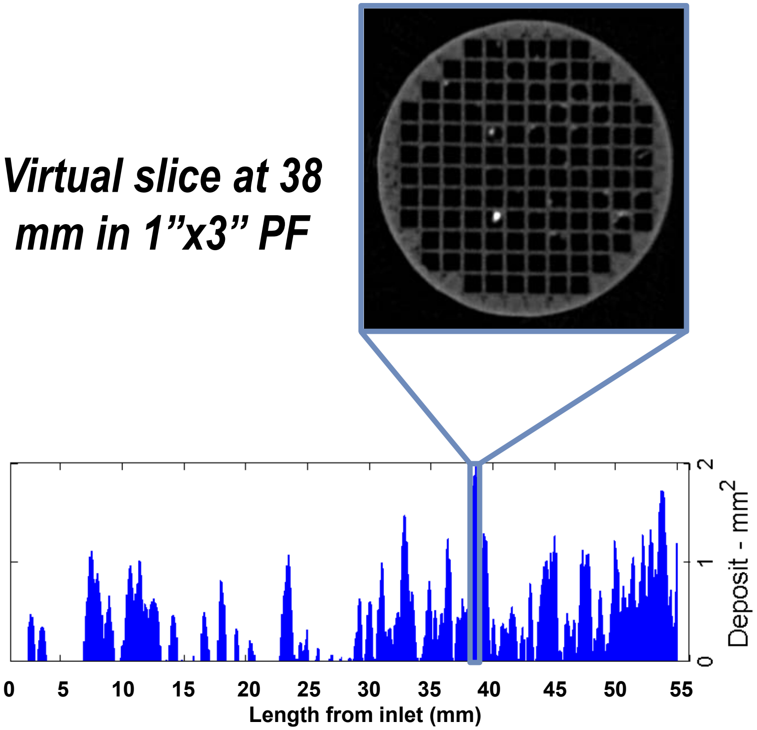
- **Built spray chamber with portable fluid delivery system for high pressure fluid delivery for diesel injectors**
  - No windows necessary; aluminum transparent to neutrons
  - Efforts focused on integrating spray timing with neutron detector shutter
  - Teaming with Prof. Brian Fisher (University of Alabama) for modeling of intra-injector flow and spray patterns

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

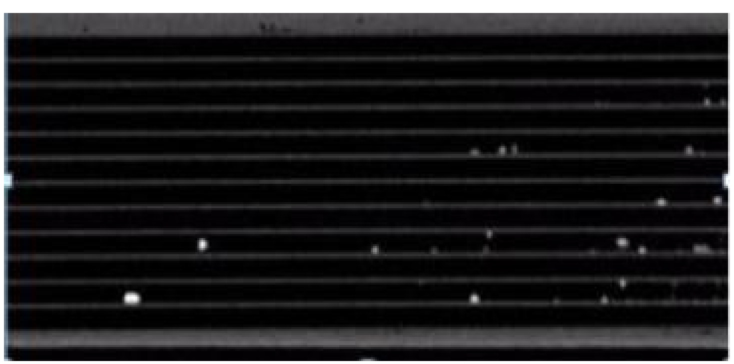
- **DPF with unique particulate profile**
- **Can be quantified to identify location of particulate as function of length or radius**
- **Can be visually analyzed with either:**
  - video reconstruction
  - 3-D image with geometrical separation

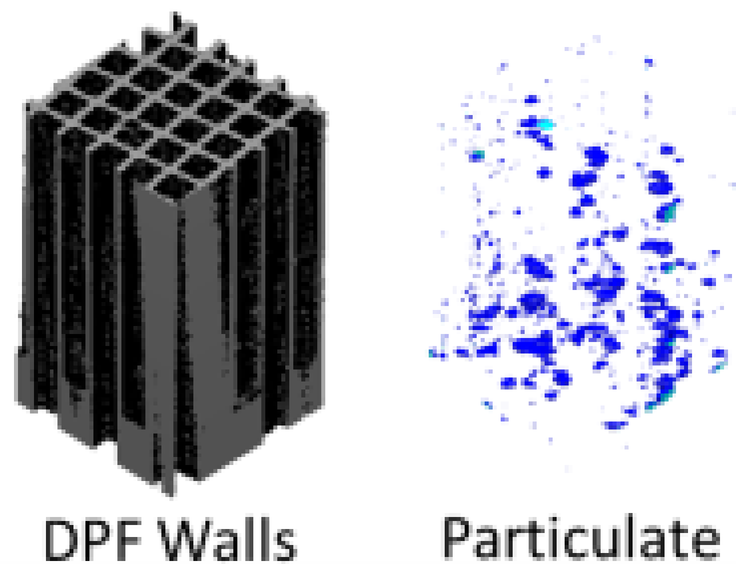
Virtual slice at 38 mm in 1"x3" PF

Particulate profile



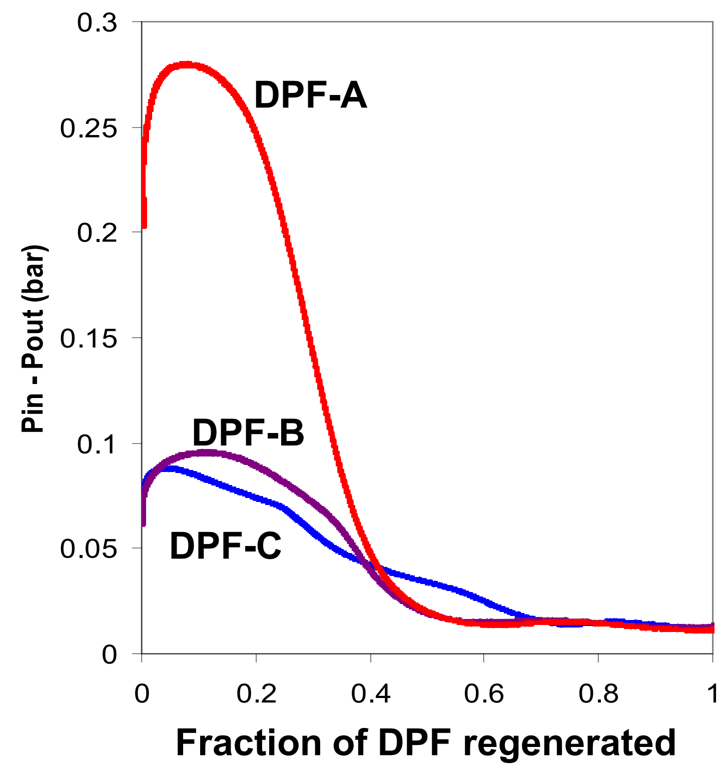
Side-view of filled PF





Systematic approach to investigate how particulate profiles change during regeneration

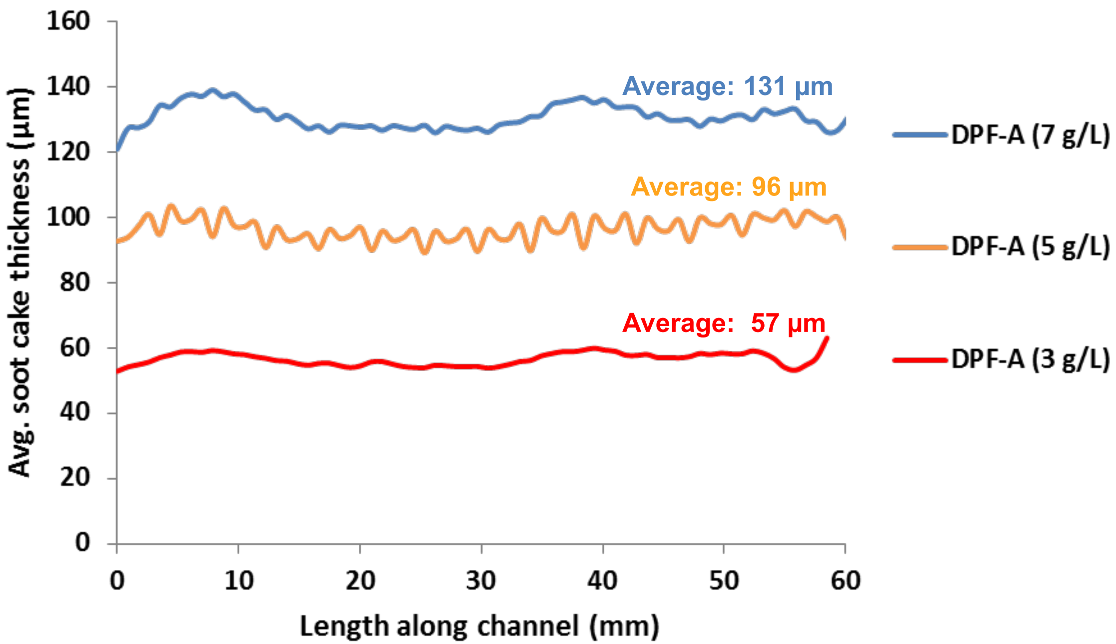
- **DPF partial regeneration**
  - Pressure drop goes to background levels after only 50% of the DPF is regenerated
  - Where is the soot being regenerated?
  - Are regenerations complete?

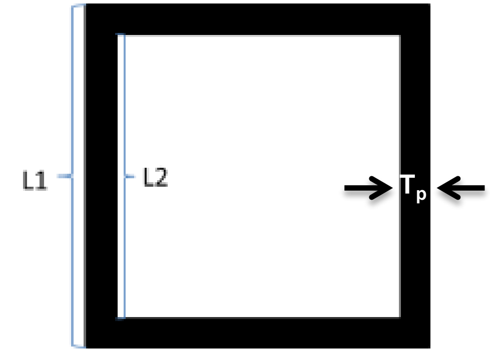


- **DPFs loaded in collaboration with Navistar**
  - Loaded to a total of 3, 5, or 7 g/L
    - used engine exhaust slipstream
  - Two types of SiC filters used
    - Symmetric and asymmetric inlet/outlet channels
- **Regenerate to 0%, 20%, 50%, 75% and 100%**
  - Completed 0% and 20%

Soot loading profiles quantified with image analysis; illustrate soot cake growth

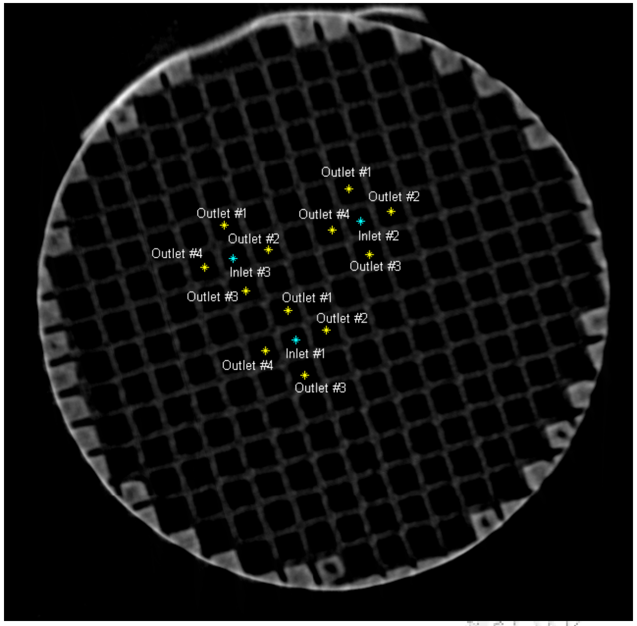
- **Particulate was difficult to distinguish from wall**
  - However, inlet channels definitely have smaller pore openings than outlet channels
- **Employ inlet versus outlet calculation routine**
  - Does not take into account cake densities
- **Sequential loading clearly identified in filters**
  - Relatively even distribution during loading





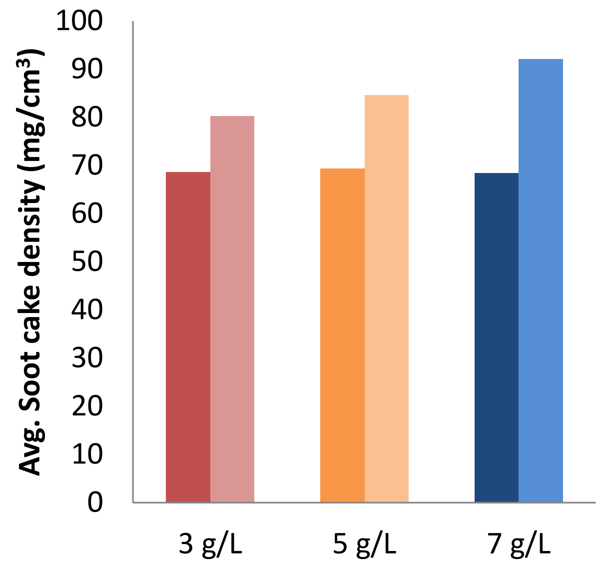
A_{outlet} = L1 x L1 (open channel area)
A_{inlet} = L2 x L2 (filled channel area)

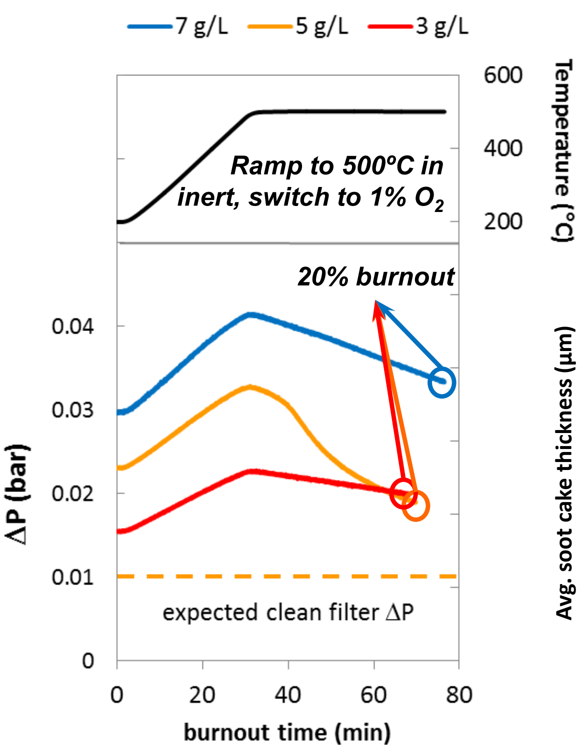
Particulate layer thickness: (T_P) = (L1-L2)/2

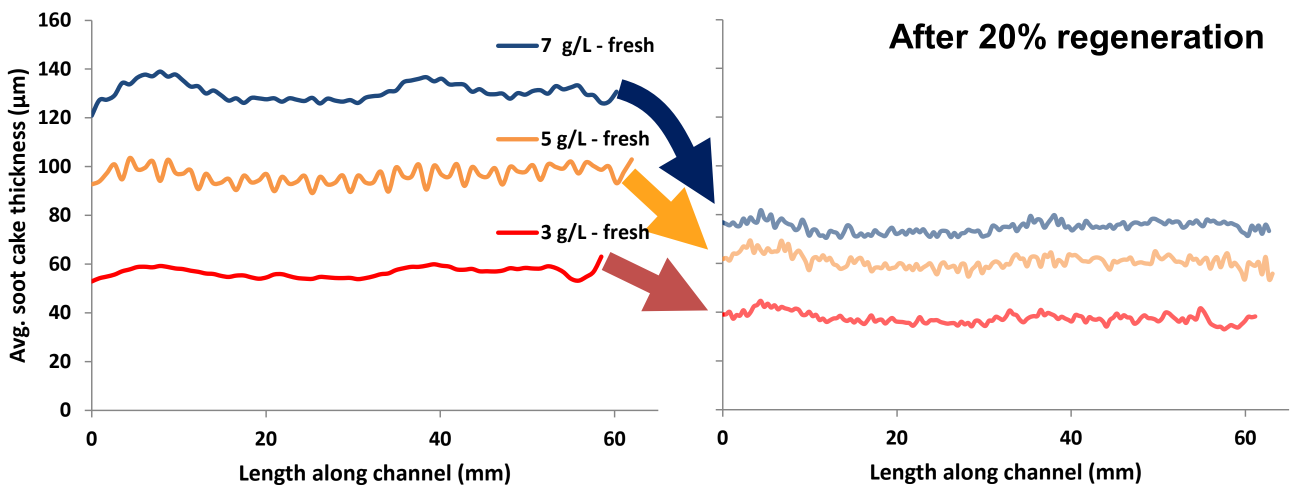


20% regeneration increases average packing density and maintains uniform distribution

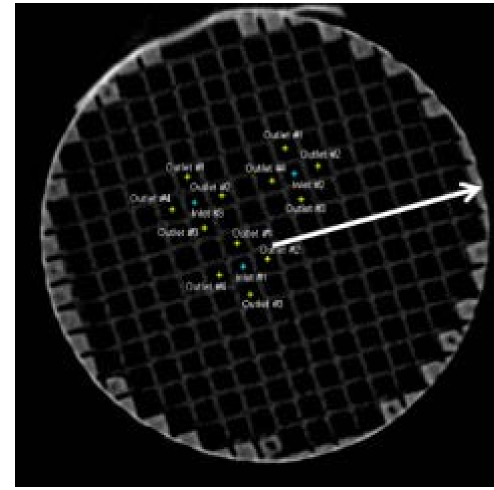
- **Regeneration in feedback controlled bench reactor**
  - Flow and temperature coordinated with FTIR and integration of CO and CO_2 products
- **After 20% regeneration soot cake density increases 15-25%**
  - Increases more for higher loading
- **Distribution profiles not significantly affected**



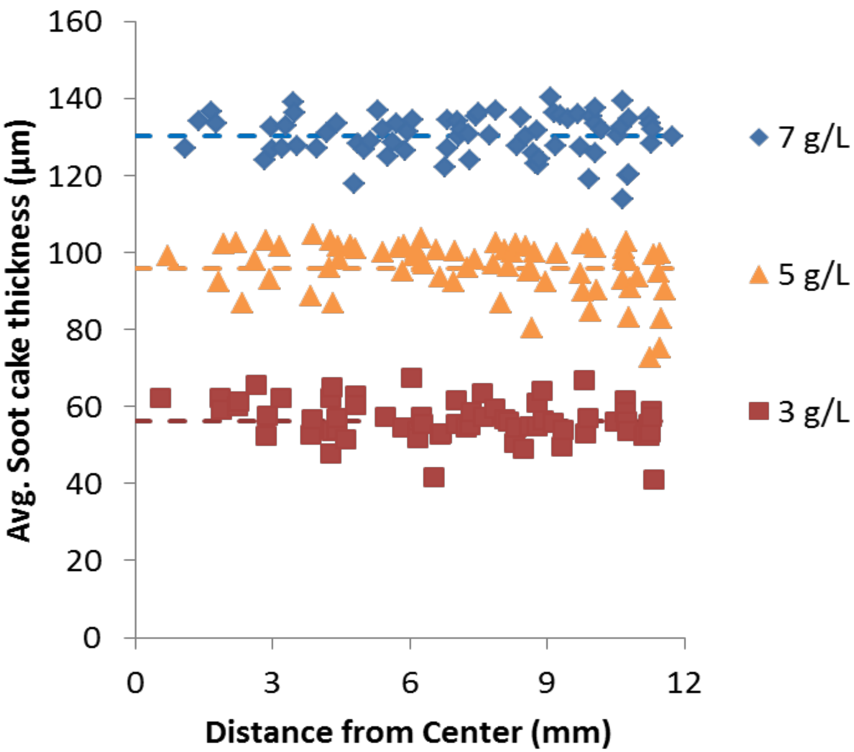


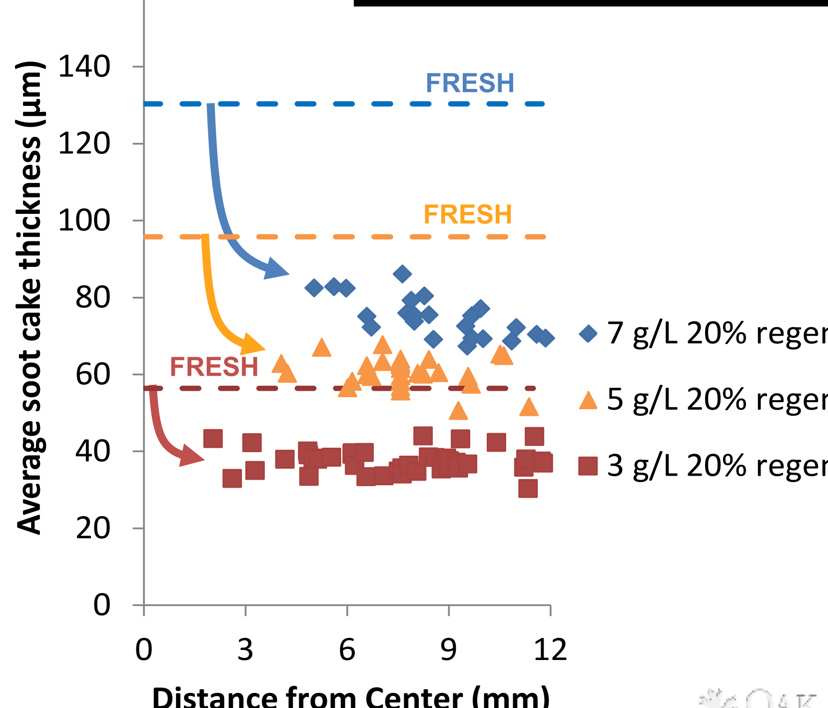


Particulate filter loading can be studied as function of radius as well as axial



- **Similar approach employed to study radial profiles**
- **Each data point below represents one inlet channel**
- **For fresh PFs studied, the radial variation was not significant**
  - Increased variability was observed near wall
- **After 20% regeneration, small slope observed in 7 g/L sample**
  - Other profiles maintain flat distribution



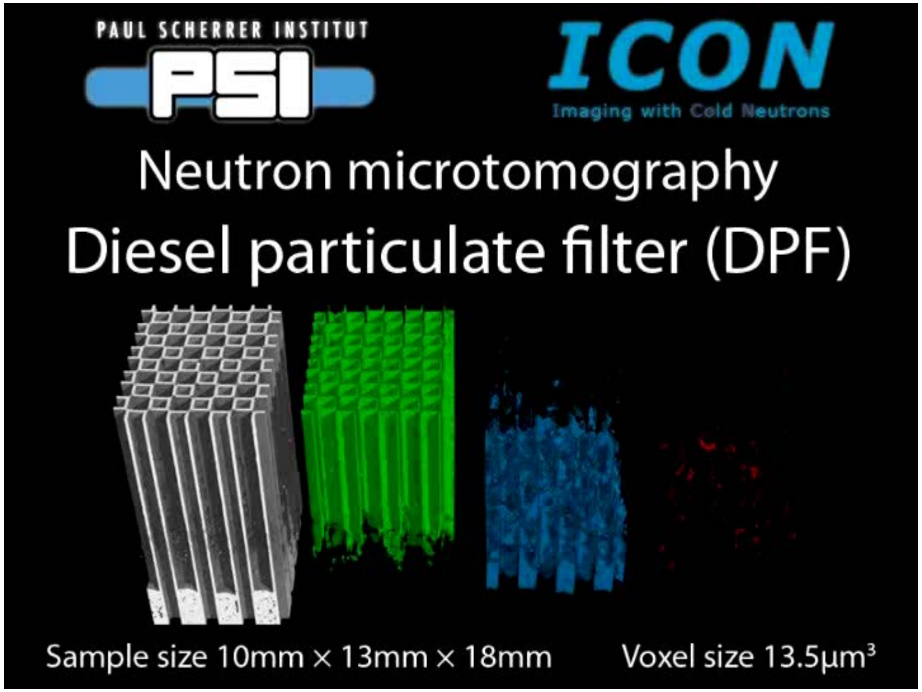


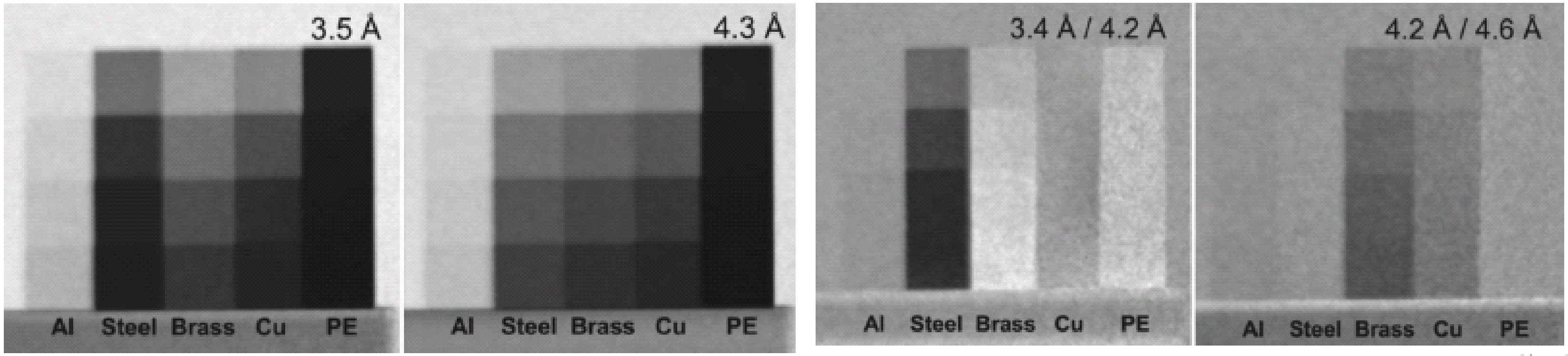
Ability to differentiate between different particulate is direction of future efforts

- **Recent demonstration shows the potential**
  – Video made at Paul Scherrer Institute

    http://neutra.web.psi.ch/images/movie/DPF_Microtomo2_loQ.avi

- **Currently our results from nuclear reactor generated neutrons are "white" energy**
  – Imaging beamline being developed at ORNL's Spallation Neutron Source (SNS) can be tuned for specific energies
  – Energy selectivity (Bragg Edge effect) can enable elemental identification

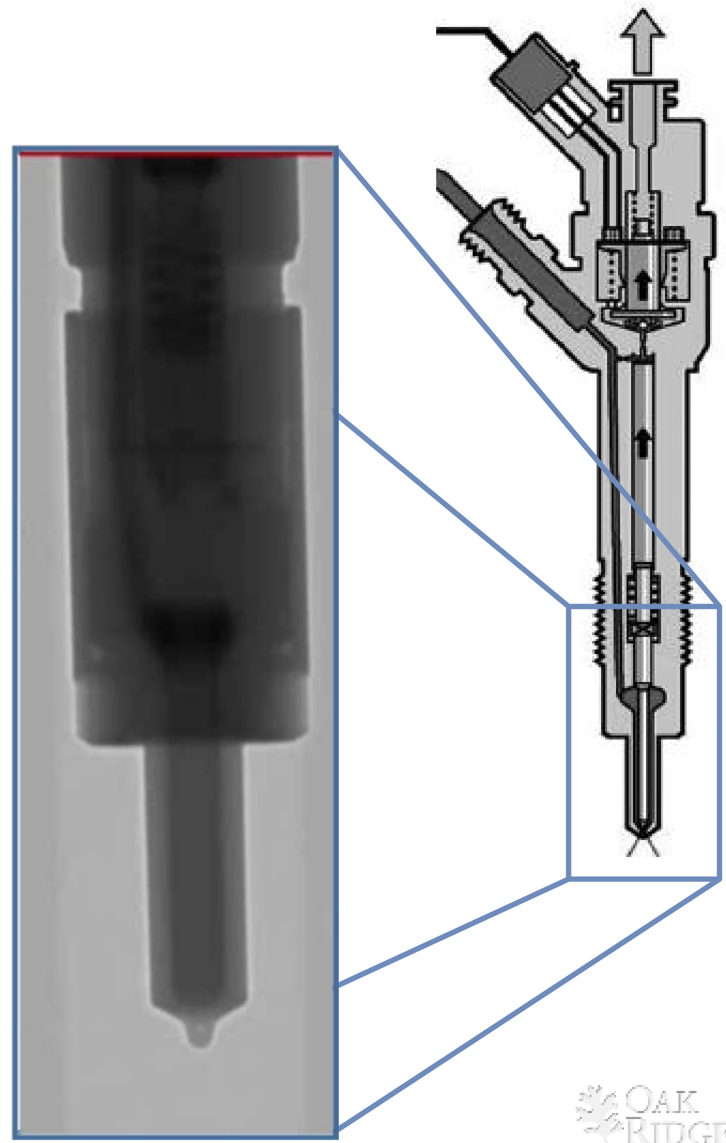




W. Treimer et al., Appl. Phys. Lett. 89 (2006). 5 min exposure, 150 microns detector resolution, 2 x 10^4 cm^{-2} s^{-1} Courtesy of N. Kardjilov.

Fuel injector studies initiated to understand near- and intra-nozzle fluid dynamics

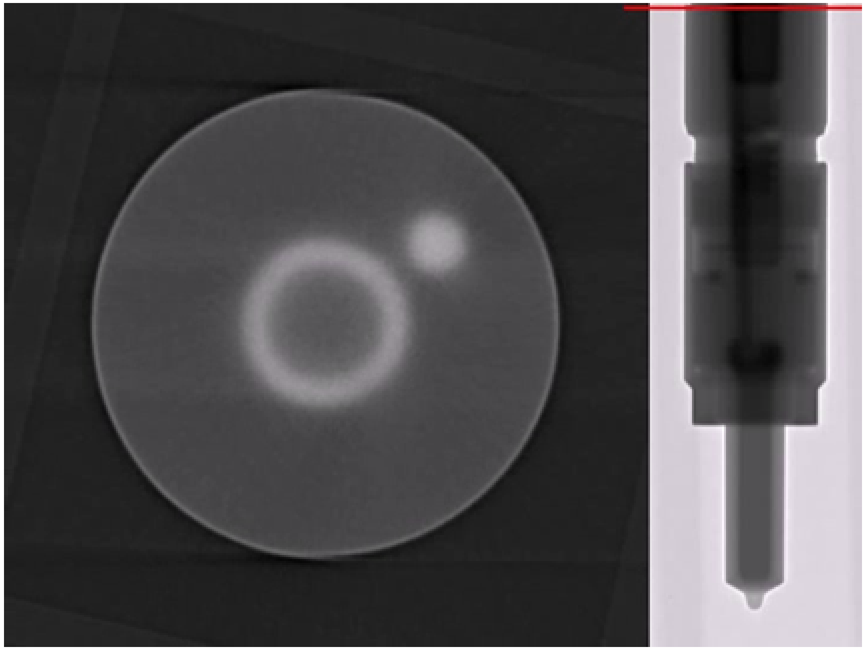
- **Fundamental insight into near-nozzle and in-nozzle fuel behavior necessary for improved simulation and design.**
  - Boundary conditions, Liquid break-up mechanisms, Evaporation timescales, Cavitation
- **Neutron imaging can provide new information that complements current methods**
  - Laser-based methods unable to penetrate metal making in-situ measurements difficult
    - Neutron "windows" are aluminum
  - X-ray based methods able to penetrate metal but not as sensitive to fuel and vapor



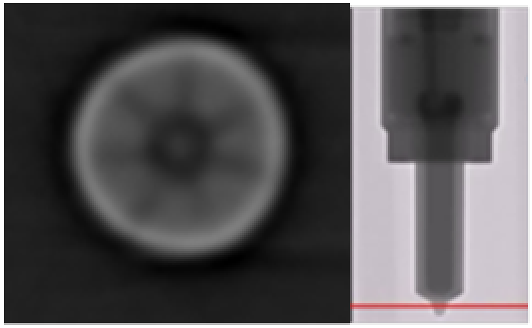
Initial fuel injector study on static device to investigate fluid-air contrast

- **Video illustrates detail achievable with approach**
  - Injection line (high pressure passage) is visible and filled with fluid

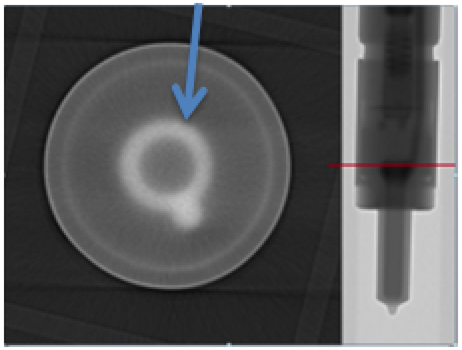
- **Although metal interacts weakly with neutrons, some contrast observed**
- **Able to see void inside injector**
  - Observing cavitation will be similar to the voids; higher resolution required



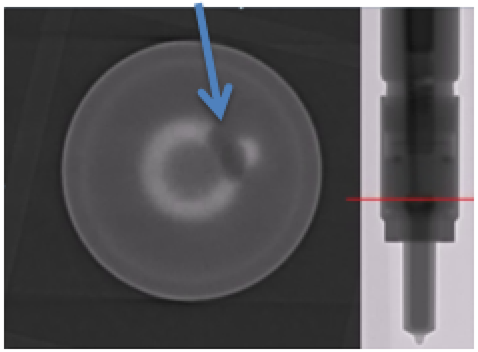
- ***Pinholes visible in empty nozzles***
  - Higher contrast expected with fluid



Filled reservoir

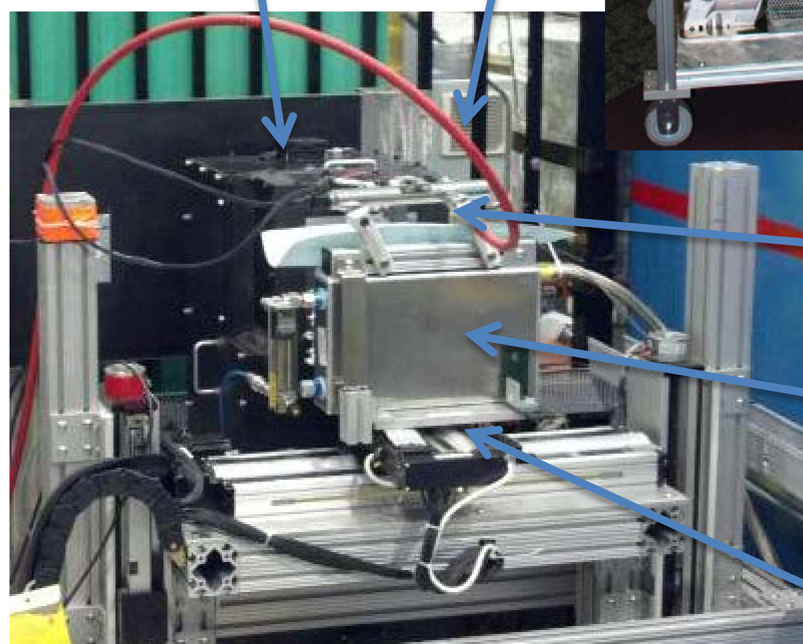


Void in reservoir



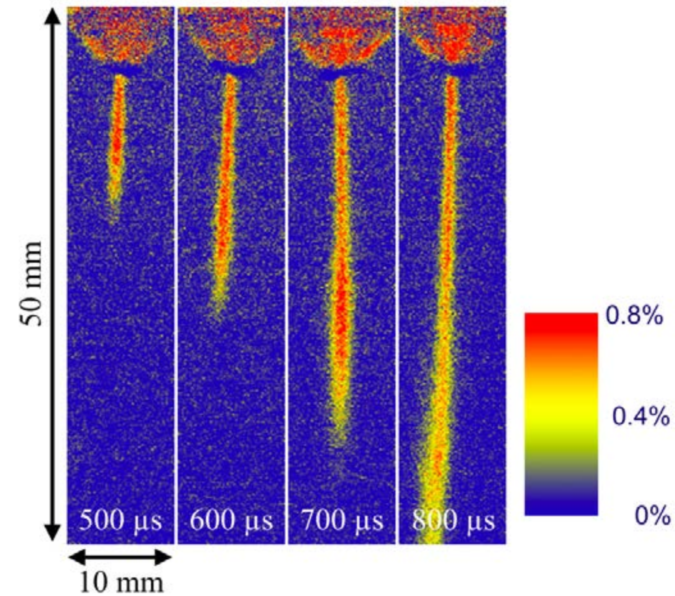
Spray chamber designed for imaging fluid flow inside and near nozzle

- **Up to 1800 bar fuel delivery to nozzle**
- **Easily adaptable to wide range of injectors, fuel rails, and pumps**
  - Denso
  - Bosch
  - Siemens
  - Delphi
- **One and two hole nozzles being employed to minimize spray blockage**
- **Full electronic control to drive pump, injector, and DRV valves**



Future work

- **Complete iterative regeneration study with DPFs**
- **Incorporate ash-laden and catalyzed samples into DPF study**
  - Implement neutron sensitive ash, and
  - investigate impact on soot loading and regeneration
  - NO_2 passive oxidation on catalyzed samples
- **Move to fluid dynamic study within fuel injectors**
  - Requires stroboscopic approach with detector shutter and fuel injector coordination
    - High neutron flux, like that at SNS, is also beneficial to this approach
  - Focus in cavitation studies
    - identifying conditions that lead to cavitation and injector degradation
  - With improved resolution, correlate internal injector dynamics to near nozzle spray patterns
- **Activities anticipate to move to SNS when VENUS is completed**

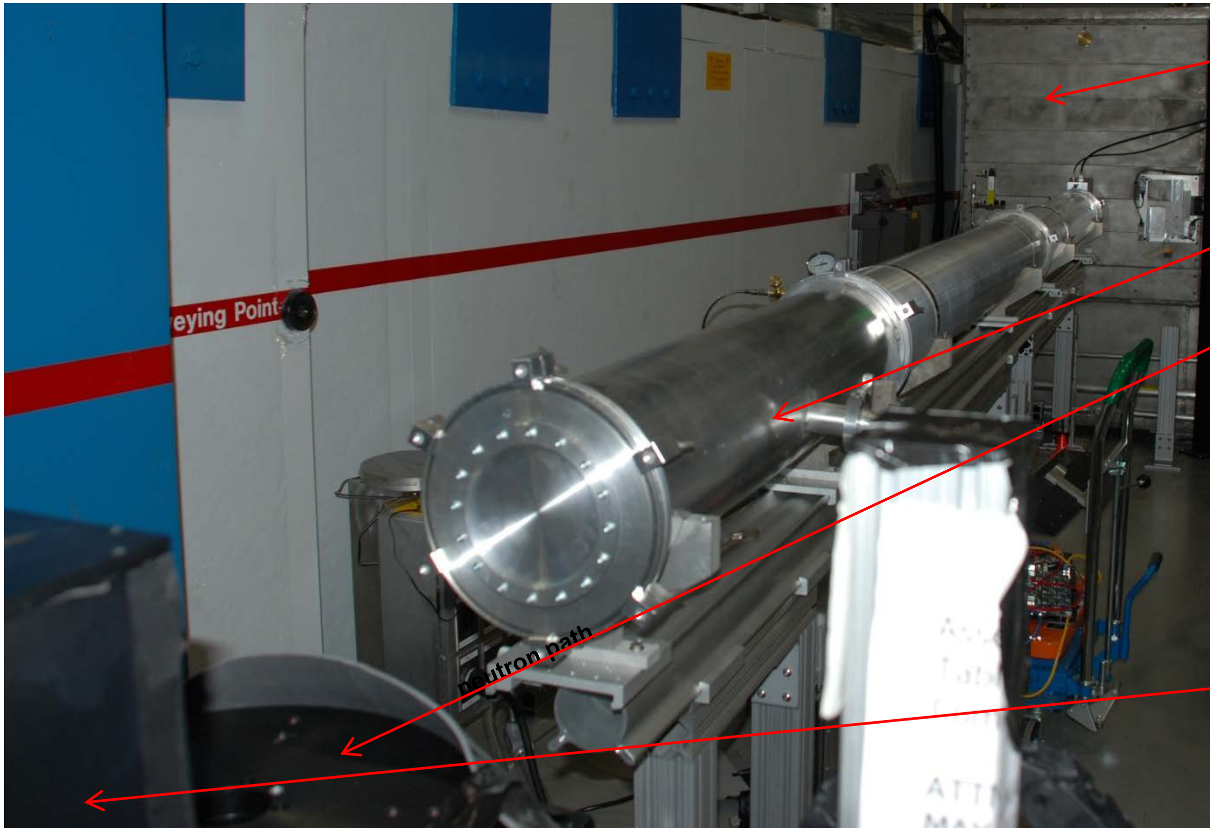


Bosch CR injector imaging performed at Institu Laue-Langevin (Grenoble) with steady neutron beam. Adapted from van Overberghe 2006 (thesis)

Summary

- **Relevance**:
  - Non-destructive, non-invasive analysis to improve understanding of lean-burn vehicle systems 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 injectors
- **Collaborations**:
  - BES, Industrial (NGK and Navistar), and Academic (U. Alabama and U. Tennessee)
- **Technical Accomplishments**:
  - Improved visualization tools to enable separation of particulate from filter walls
  - Identified particulate layer as a function of length, radius, and particulate loading
  - Built spray chamber with portable fluid delivery system for high pressure injections
- **Future Work**:
  - Complete iterative DPF study
  - Stroboscopic intra-nozzle fluid dynamics in diesel fuel injector

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)

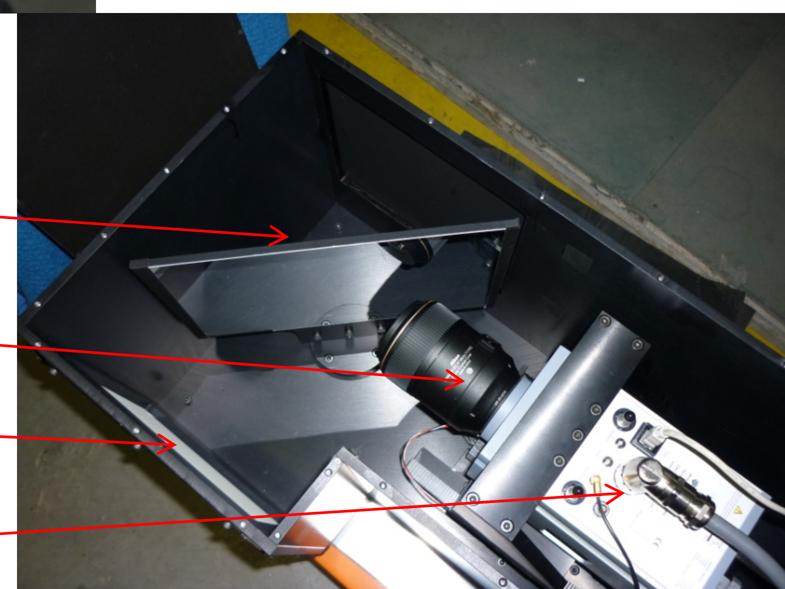
HFIR CG1D beamline
Achievable Resolution:
-50 microns
- $\Delta\lambda/\lambda$ ~ 10% (in TOF mode)

Mirror

Lens

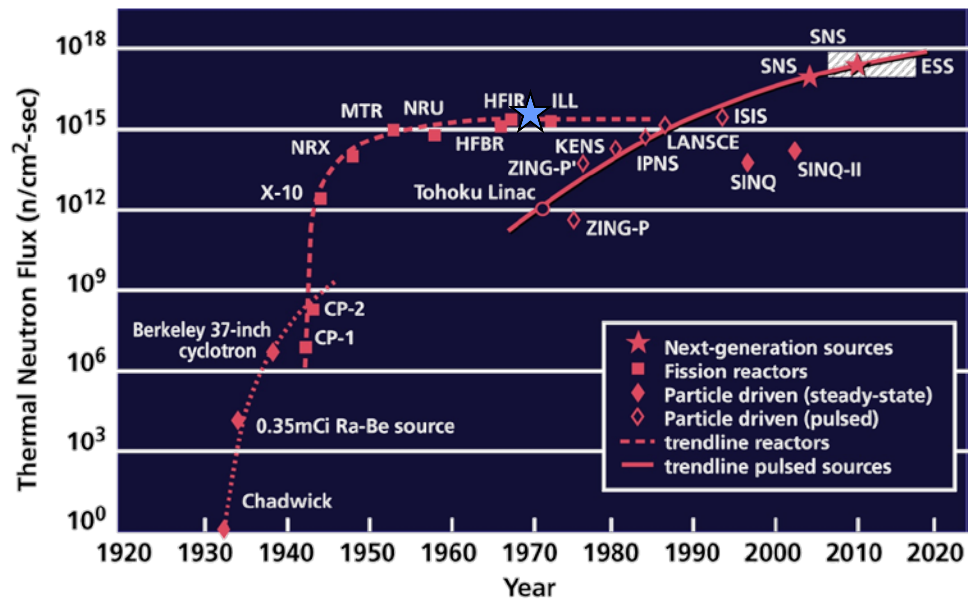
LiF/ZnS scintillator (25 to 200 microns thick)

CCD



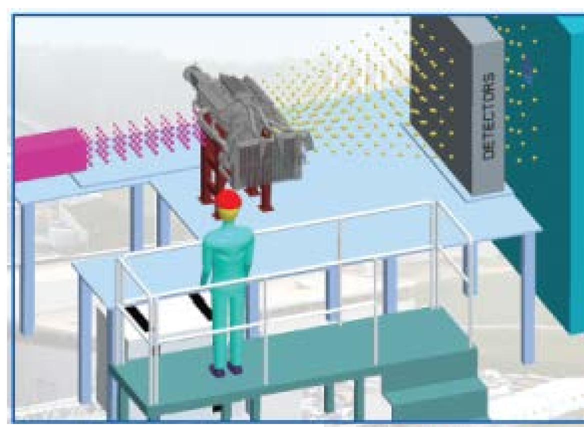
Neutron imaging capabilities at ORNL

- **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

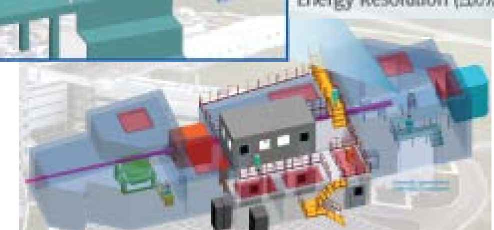


(Updated from *Neutron Scattering*, K. Skold and D. L. Price: eds., Academic Press, 1986)

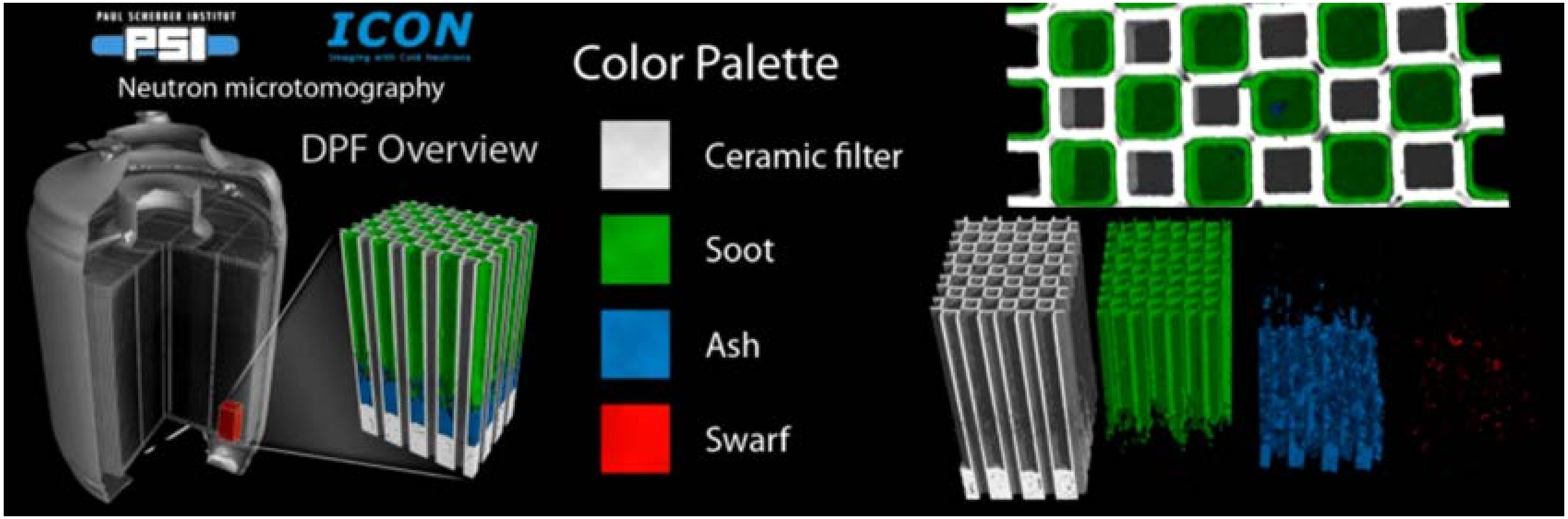
- **Spallation Neutron Source (SNS)**
  - Most intense pulsed neutron beams in the world; energy selective
  - Multi-laboratory effort funded by DOE Office of Science
  - Letter Of Intent (LOI) of imaging beamline approved



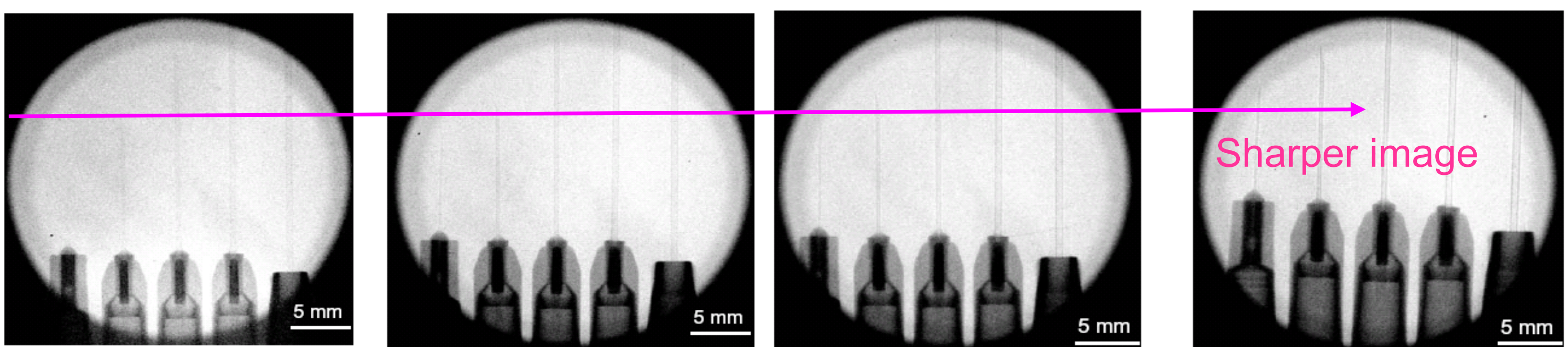
Estimated Beam Characteristics	
Maximum Field of View	90cm x 90cm
Length to Diameter Ratio (L/D)	>1000
Integrated Neutron Flux	10^8 n/cm2/sec
Neutron Beam Energy Range	0-40Å
Energy Resolution (Δλ/λ)	0.1%



Techniques still under development to enable image enhancement and elemental contrast



- **Phase Contrast**



Distance sample to detector: 0 cm	Distance sample to detector: 25 cm	Distance sample to detector: 50 cm	Distance sample to detector: 100 cm
Distance pinhole to sample: 650 cm	Distance pinhole to sample: 650 cm	Distance pinhole to sample: 650 cm	Distance pinhole to sample: 650 cm
Pinhole diameter: 0.5 mm	Pinhole diameter: 0.5 mm	Pinhole diameter: 0.5 mm	Pinhole diameter: 0.5 mm
Exposure time: 180 min	Exposure time: 180 min	Exposure time: 180 min	Exposure time: 180 min

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

PF Regeneration sequence

- **Regeneration in feedback controlled bench reactor**
  - Flow and temperature coordinated with FTIR and integration of CO and CO_2 products