Neutron Imaging of Advanced Transportation Technologies

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Project Overview

Timeline

- Started in FY2010
- Ongoing study

Budget

- FY2013: $200k (requested)
- FY2012: $200k

Partners

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

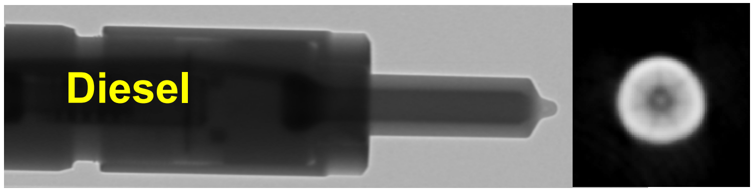
Barriers

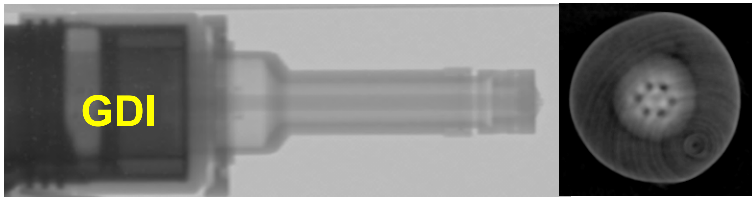
- 2.3.1B: *Lack of cost-effective emission control*
  - Improved regeneration efficiency in particulate filters (PFs)
- 2.3.1C: *Lack of modeling capability for combustion and emission control*
  - Improved models of fluid flow inside fuel injectors
  - Need to improve models for effective PF regeneration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

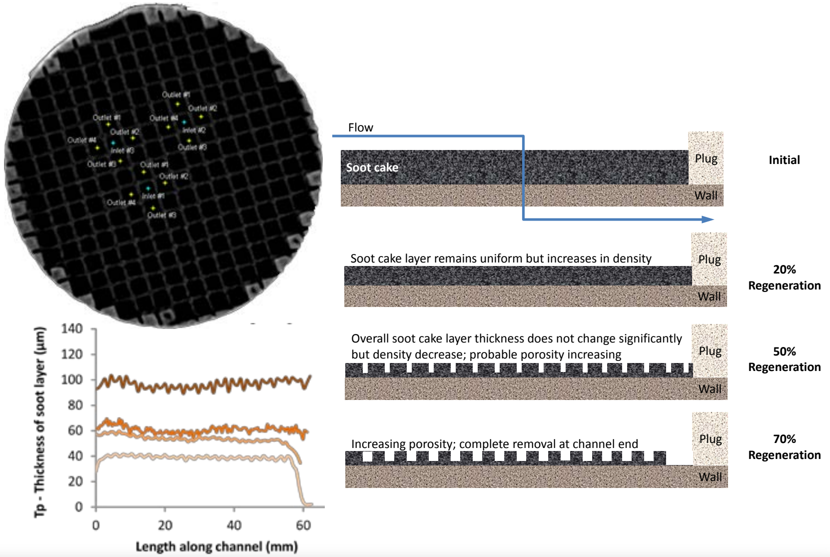
Objectives and Relevance

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

- Gasoline and diesel fuel injectors
  - Visualize internal flow dynamics
  - Cavitation and durability issues
  - Goal: aid model development injector design
    - Injector design has been shown to significantly influence efficiency and emissions*
- 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



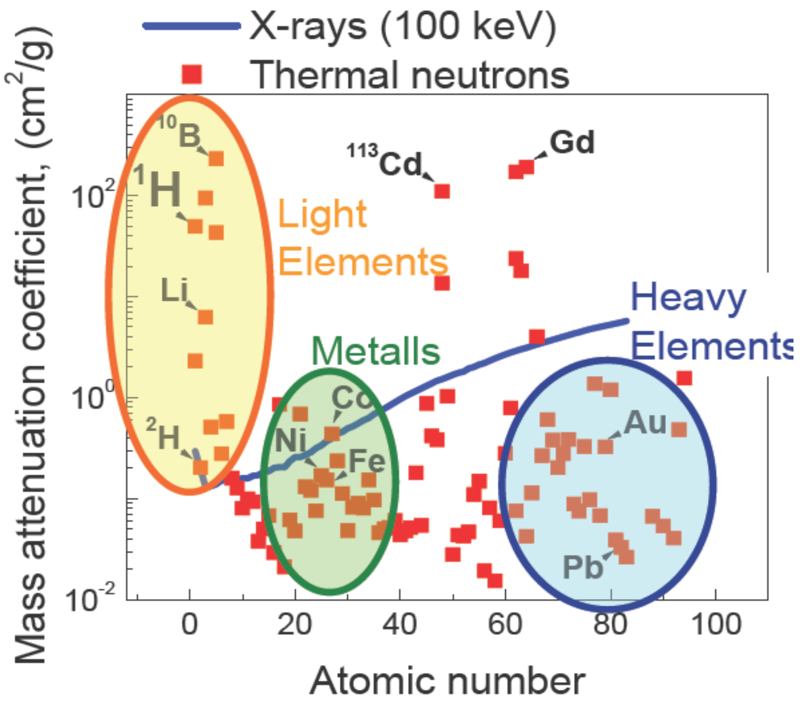


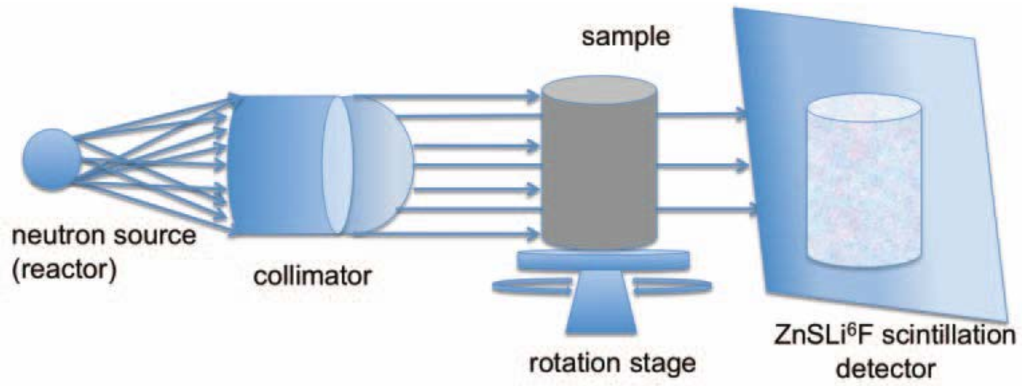


* - e.g., Keith Confer (Delphi), “Gasoline Ultra Fuel Efficient Vehicle”, 2012 DOE AMR, Crystal City, VA, ACE064, May 18, 2012.

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



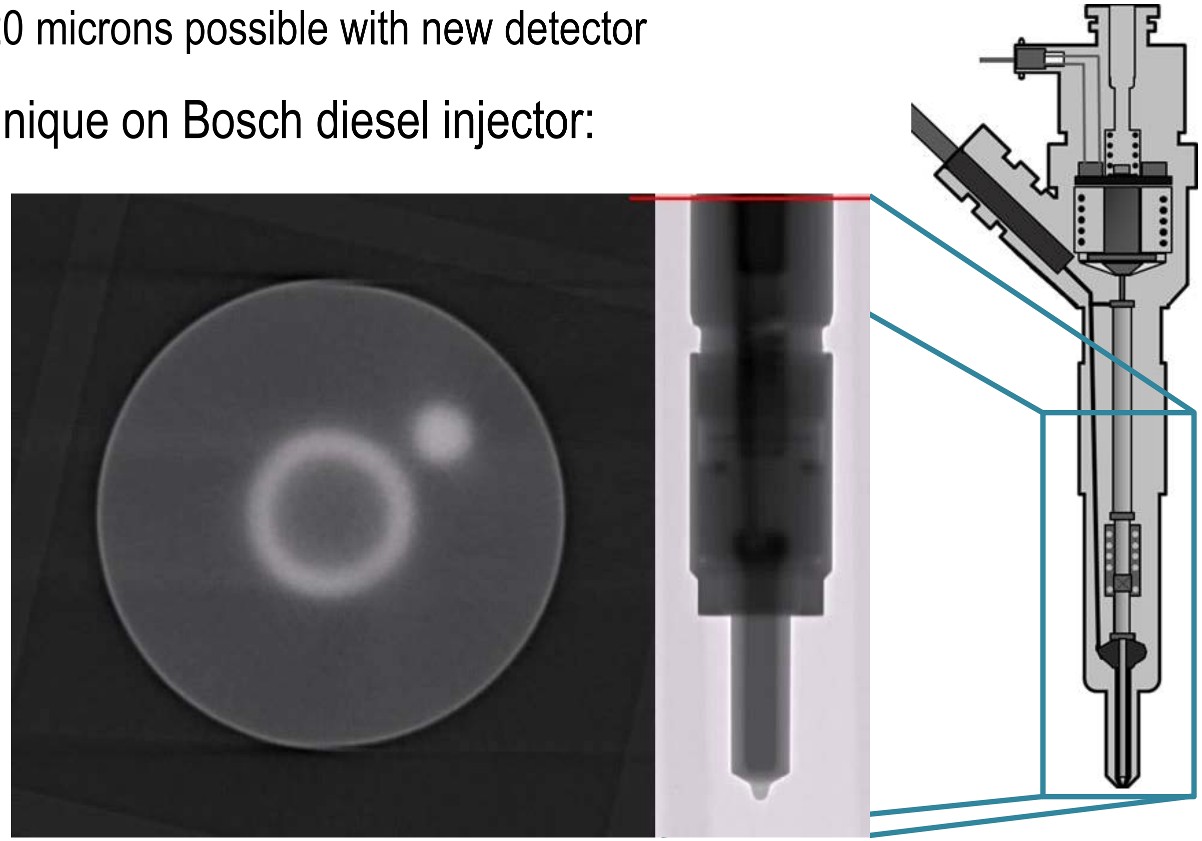


Neutron imaging is a complementary analytical tool

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

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
  - Currently ~50 microns achievable at ORNL's High Flux Isotope reactor (HFIR)
  - As low as 10-20 microns possible with new detector
- Illustration of technique on Bosch diesel injector:



Milestones

- Measure sequential soot distribution changes in diesel particulate filters as a function during a series of partial regenerations (9/30/2012).
  - **Achieved**
- Determine temporal and spatial resolution of neutron imaging with respect to fluid density and flow in fuel injectors (9/30/2013).
  - **On target**

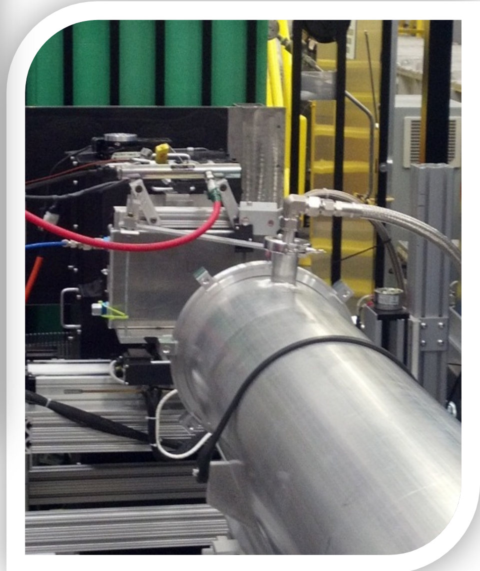
Collaborations

- Basic Energy Sciences
  - Hassina Bilheux, Sophie Voisin, Lakeisha Walker
  - 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, 3-D tomography and removing artifacts
- University of Alabama (Brian T. Fisher)
  - Internal and external fluid analysis of fuel injectors
- Technical University of Munich (Burkhard Schillinger and Michael Schulz)
  - Initial neutron imaging efforts

Approach

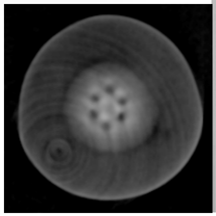
Receive or obtain relevant devices

Record raw images of devices using neutron beam



Non-destructive technique allows multiple studies to be performed on single commercial or prototype device

Reconstruct device using neutron computed tomographic techniques



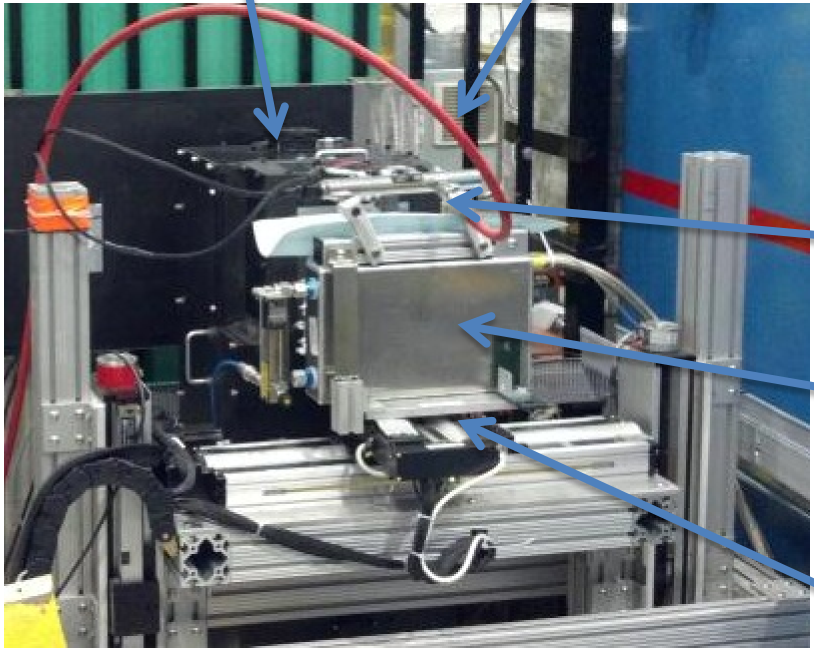
Technique being employed to study both internal geometries and fluid flow during operation

Summary of Technical Accomplishments

- Implemented spray chamber with portable fluid delivery system for high pressure fluid delivery for diesel injectors at HFIR
  - Investigated impact of rail pressure on fluid density profiles in injector
- Completed 3-D tomography fresh injector for GDI
- Completed particulate filter regeneration study
  - Particulate filters filled to 3, 5, and 7 g/L
  - sequentially regenerated to 20%, ~50%, 75%, and 100%
  - Soot cake density initially increases followed by sharp decrease starting at ~50%
  - Proposed conceptual model to describe soot cake thickness and density during regeneration
- CT-scan of ash deposits from a continuously regenerated PF and a periodically-generated one
  - Observe both dense and “fluffy” ash deposits
  - Future efforts to quantify density using standards

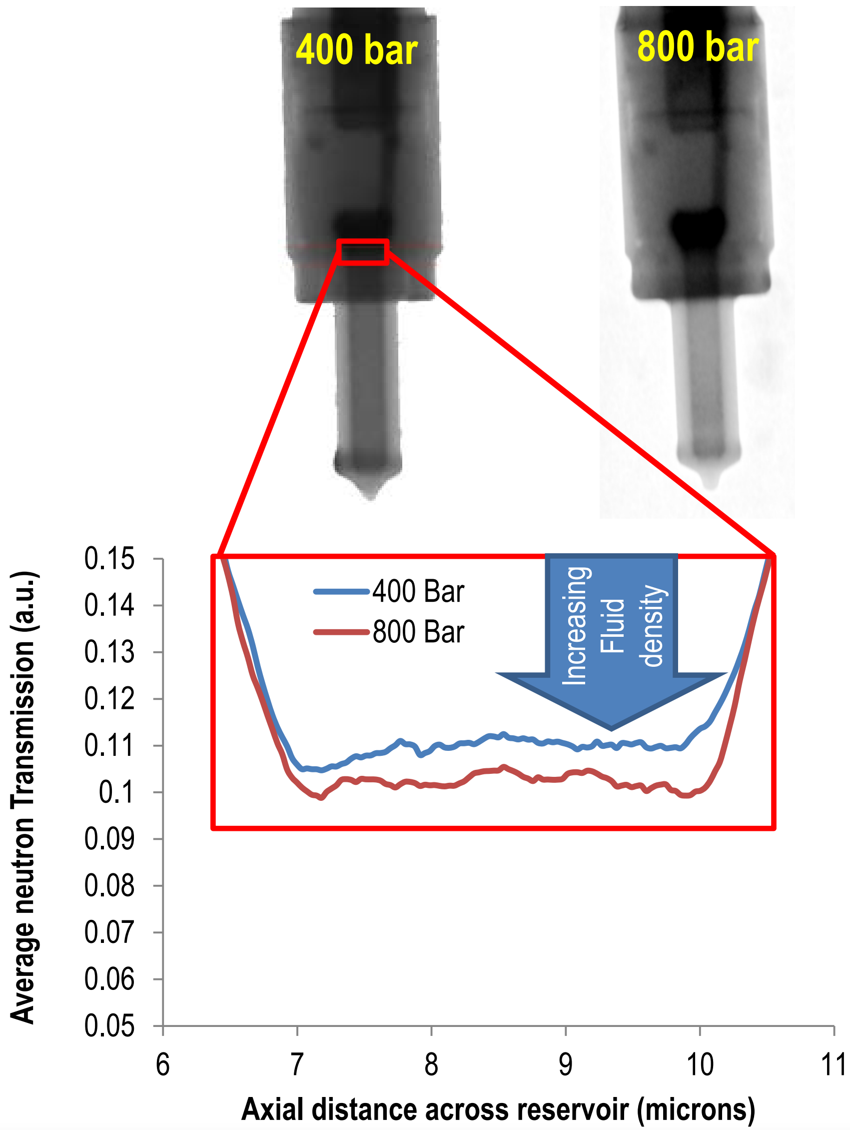
Spray chamber designed for imaging during injector operation

- Fundamental insight into intra-nozzle fluid dynamics for improved simulation and design
  - Potential visualization of cavitation, liquid break-up mechanisms, evaporation timescales
- Complements current methods
  - Laser-based/optical methods unable to penetrate metal
    - Neutron "windows" are metal
  - X-ray based methods able to penetrate metal but not as sensitive to fuel/vapor
  - Neutrons excel with dense liquids
- Spray chamber designed
  - Up to 2000 bar fuel delivery to nozzle
  - Easily adaptable to wide range of injectors, fuel rails, and pumps
  - One-, two- and seven- hole nozzles
  - Full electronic control to drive pump, injector, and DRV valves



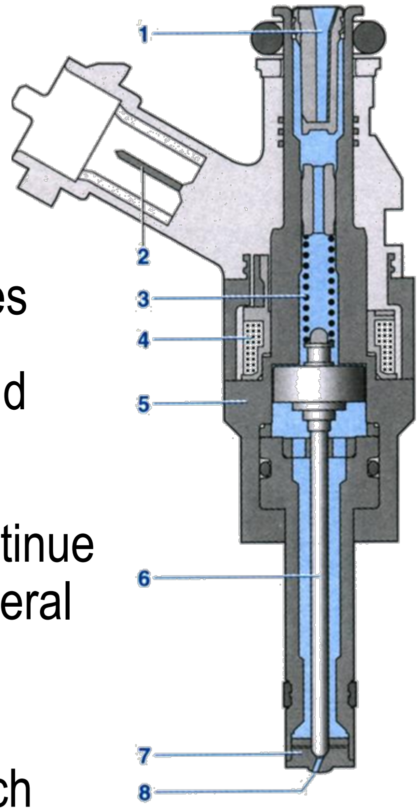
Initial injection images obtained while varying rail pressure

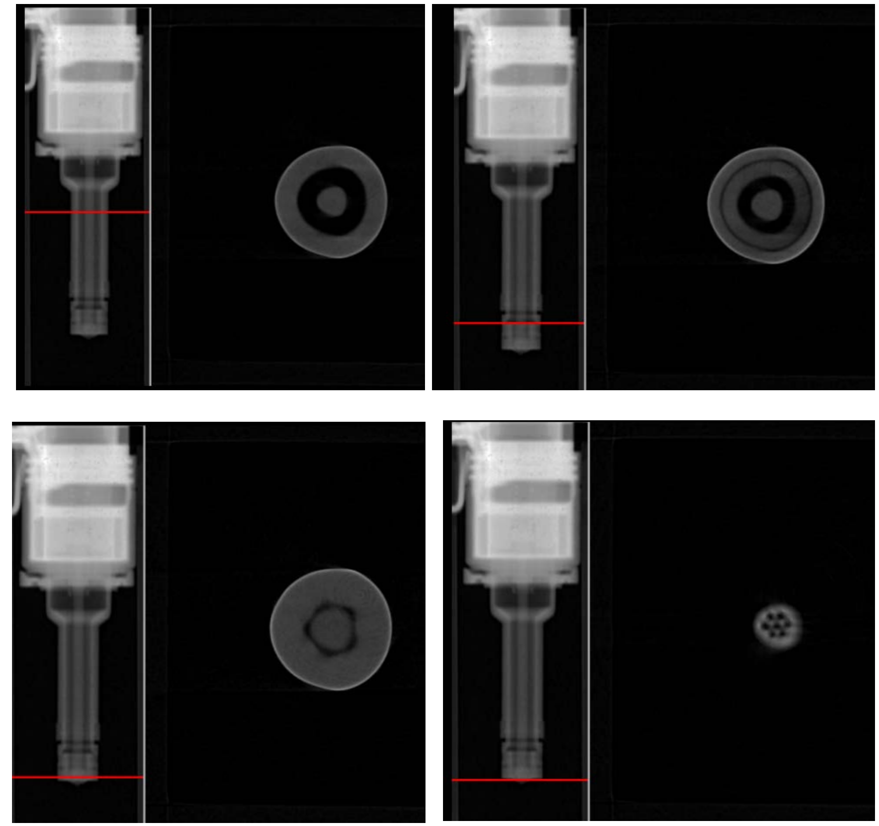
- Effects of rail pressure on internal fluid density
- Images captured are composite of entire injection event
  - 5 ms injection event
  - Operated at >200 Hz such that injector was open nearly continuously
- Analysis focused on identifying areas with density gradients
  - Preliminary results show denser fluid profile for 800 bar
  - Analysis is ongoing for areas of low density associated with cavitation
- Challenges
  - Fluid condenses on outside of injector, interferes with visualization at pin holes
  - Meshing neutron exposure needs with typical injector operation
  - Current resolution ~ diesel nozzle hole



Gasoline direct injection investigation started

- Strong interest in gasoline in-cylinder injectors (GDI)
- Resolution of HFIR detector meshes well with GDI injector holes and orifices
  - 400-500 microns holes
- Developing system for fluid injection
- Dynamic injection will continue to be a challenge, but several paths forward being investigated
  - Stroboscopic approach with injector/detector timing well-linked
  - Increased neutron flux
  - Increased resolution



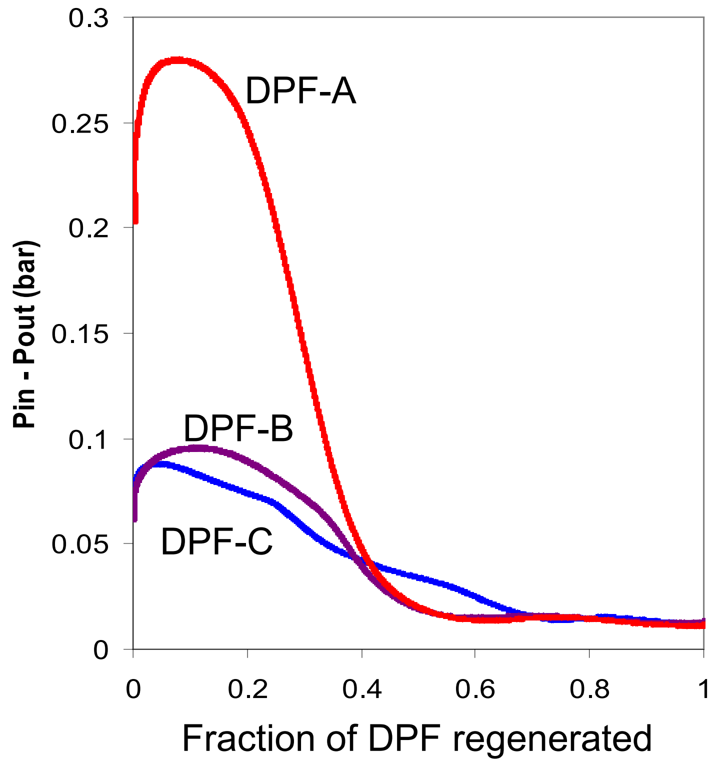


1. Fuel inlet
2. Electrical connection
3. Return spring
4. Solenoid
5. Injector body
6. Pintle valve needle
7. Pintle head and seat
8. Spray hole/orifice

Example GDI schematic obtained from:
http://www.autospeed.com/cms/gallery/article.html?a=107830&i=11

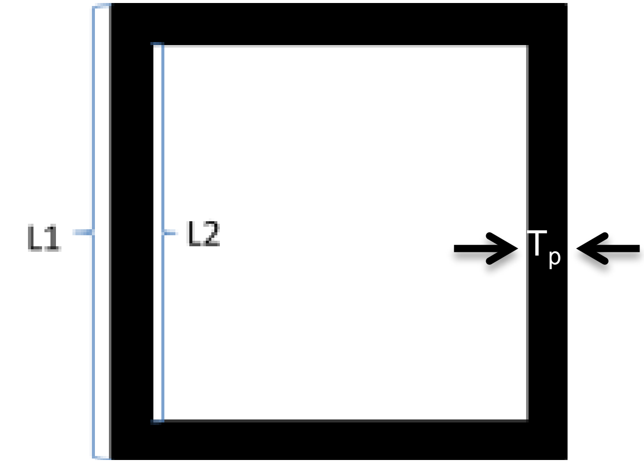
Systematic approach to investigate how particulate profiles change during regeneration

- 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 all regenerations



Soot loading profiles quantified with image analysis

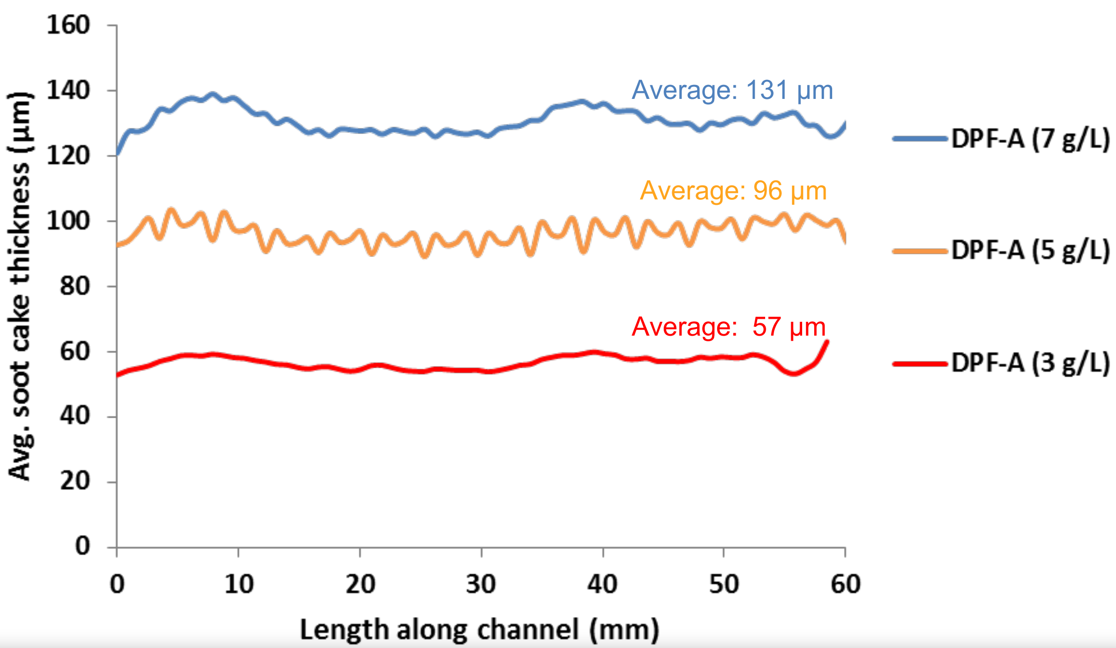
- Particulate was difficult to distinguish from wall
  - However, inlet channels have smaller pore openings than outlet channels
- Employ inlet versus outlet calculation routine
  - Does not take into account cake densities
- Sequential loading clearly identified in filters
  - Relatively even distribution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

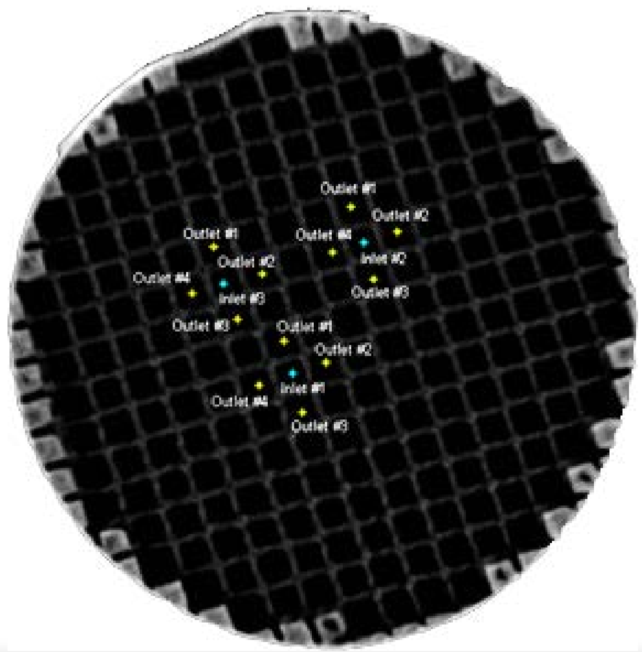


A_{outlet} = *L1 x L1 (open channel area)*

A_{inlet} = *L2 x L2 (filled channel area)*

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





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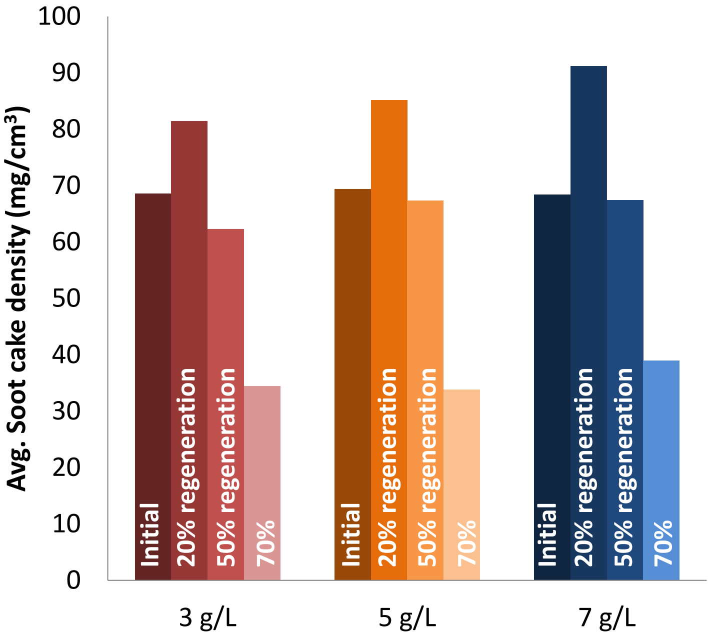
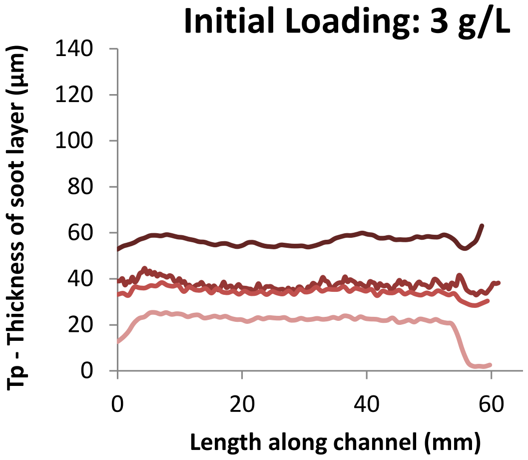
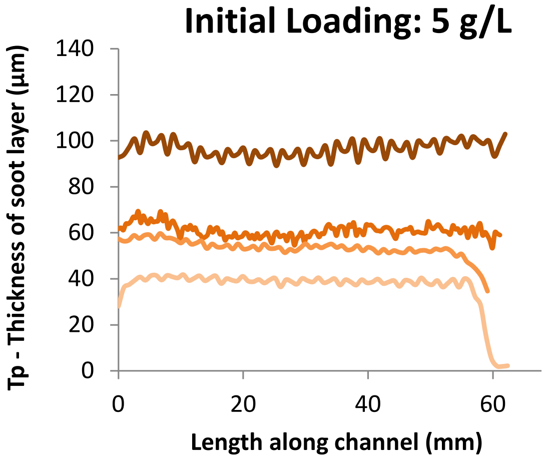
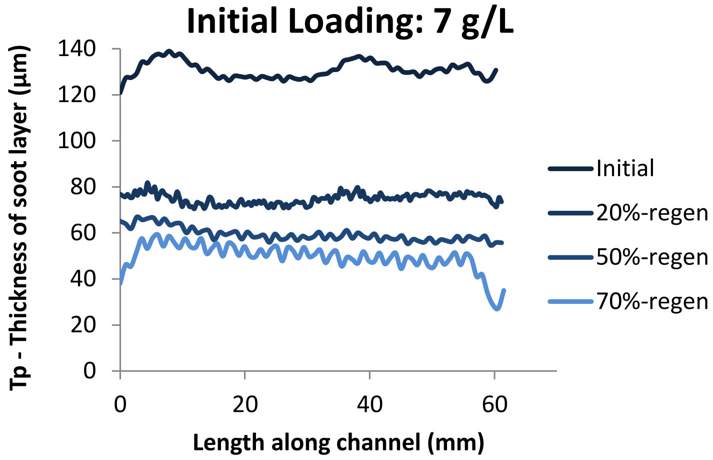
Packing density initially increases during regeneration followed by sharp decreases

- Initial loading of the PFs shows identical soot cake density
- During first 20% regeneration, soot cake compresses significantly
  - density increases by 15-25%
  - uniform distribution maintained
- After 20% regeneration, the soot cake density decreases significantly
  - Based on results of other studies this suggest that pores are opening in the layer; efforts ongoing to quantify this
- At 70% regeneration there are indications that the end of the channel has complete soot removal



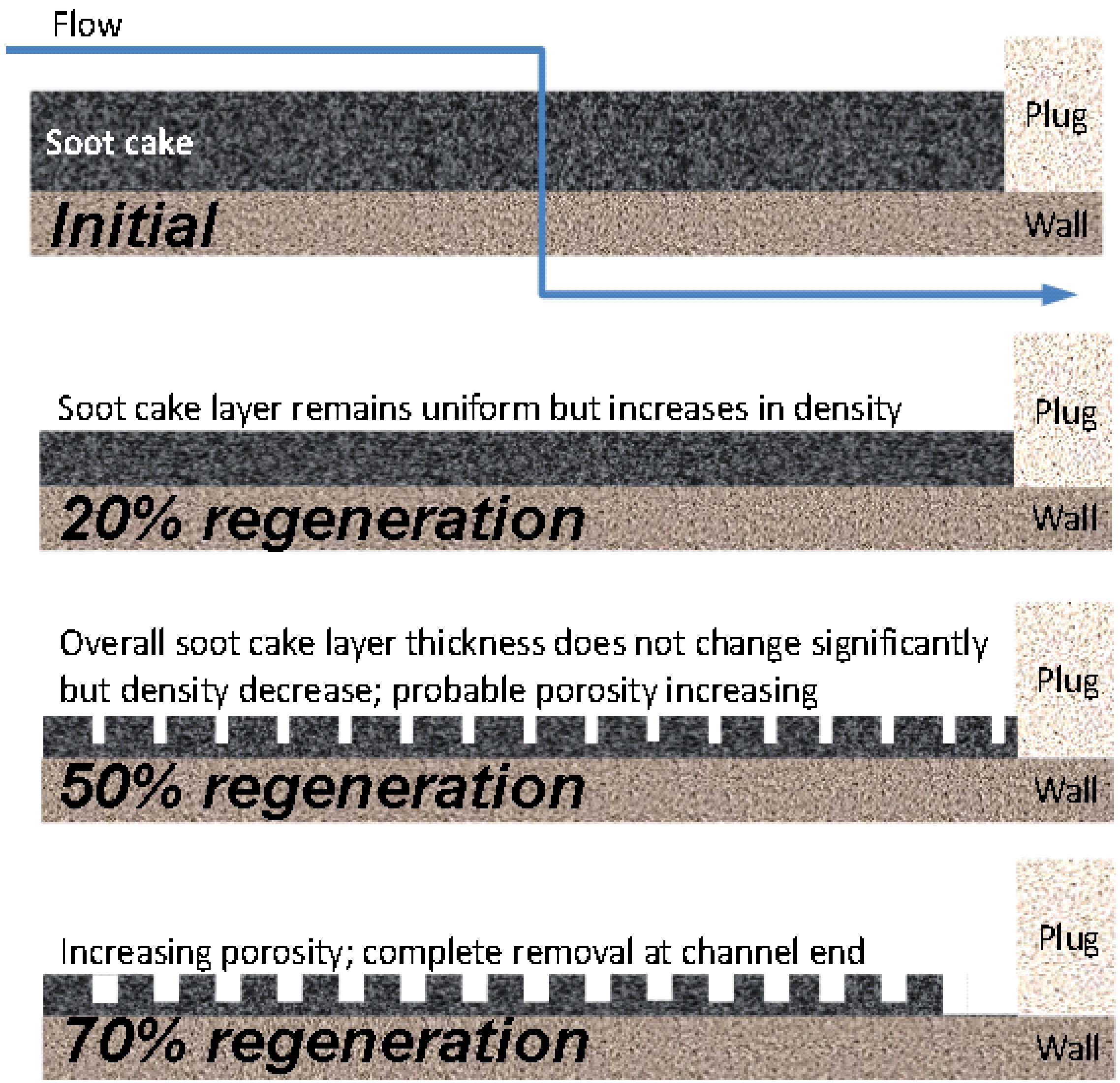






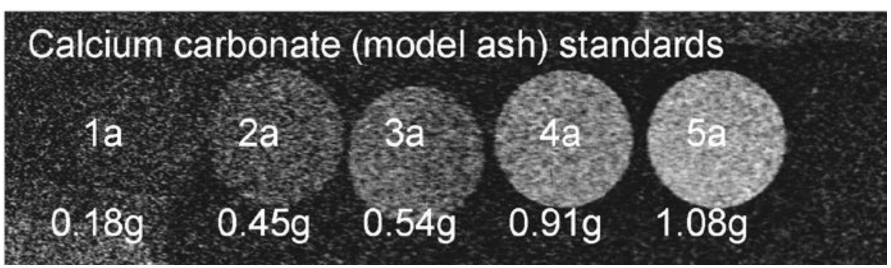
Conceptual model proposed based on neutron imaging observations

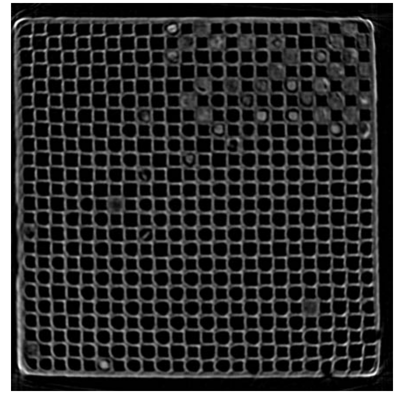
- Soot cake clearly observed in filters
  - thickness can be quantified using non-destructive techniques
- Soot cake layer shows initial ~uniform thickness
- Soot cake density increases significantly during initial 20% regeneration
- After 20% regeneration, density decreases as porosity develops
  - Verification ongoing

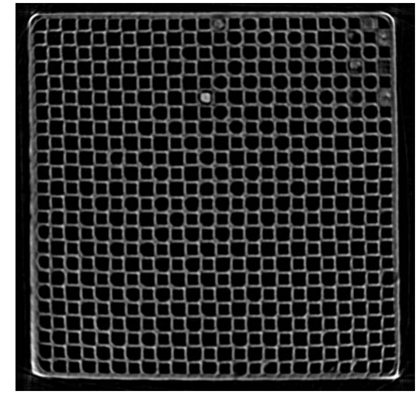


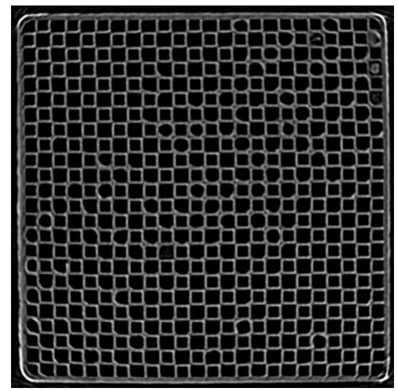
Ash deposits readily visible in SiC DPF section

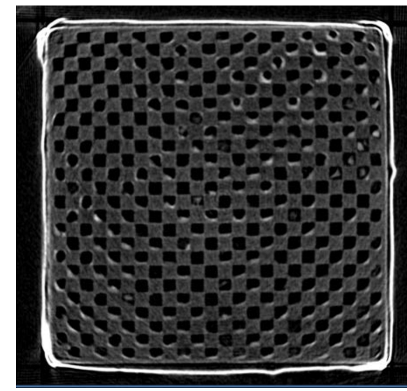
- Full size SiC DPF filled by NGK
  - using accelerated ash loading technique*
  - DPF shown was periodically regenerated
- Removed one section of DPF for analysis
  - Movie starts at the outlet
- Some ash deposits form layer on wall
  - Maldistribution evident
- Plugs readily observed
  - Dense plugs have pulled away from the wall
  - “fluffy” ones fill the channel
- Calibration approach possible to determine density of ash layers and plugs
  - Standards of same model ash prepared (below)
  - Neutron interactions scale w/ mass

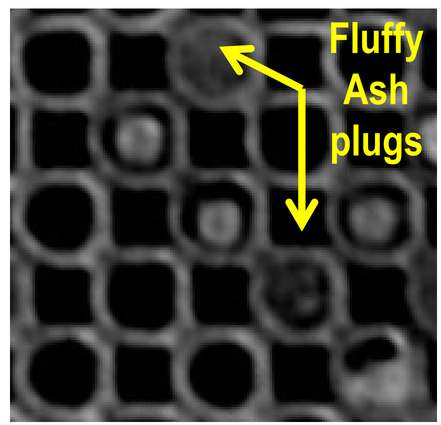


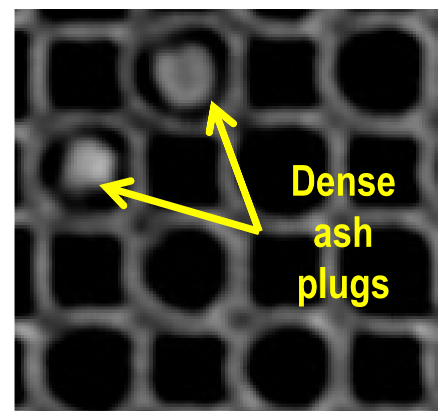












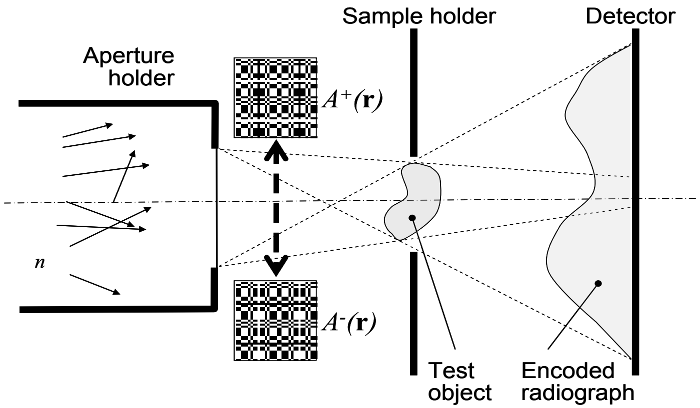
Future work

- **Develop system for fluid/fuel injection with GDI**
  - Lower rail pressure than current system, but same chamber can be used
- **Continue with more detailed fluid dynamic study within fuel injectors**
  - Requires stroboscopic approach with detector shutter and fuel injector coordination
  - Aiming for 20 μ-second resolution with 1 ms injection
    - Comprised of ~million images of the same 20 μ-second partition of the injection
  - Focus on cavitation studies and internal fluid dynamics
    - identifying conditions that lead to cavitation
    - with improved resolution, correlate internal injector dynamics to near nozzle spray patterns
  - Adapt chamber to eliminate fluid build-up on injector
- **Incorporate ash-laden and gasoline particulate samples into PF study**
  - Working with partners to obtain parts as possible
  - Quantify density using standards

Methods/Instrumentation development ongoing through BES and ORNL (internal) funds

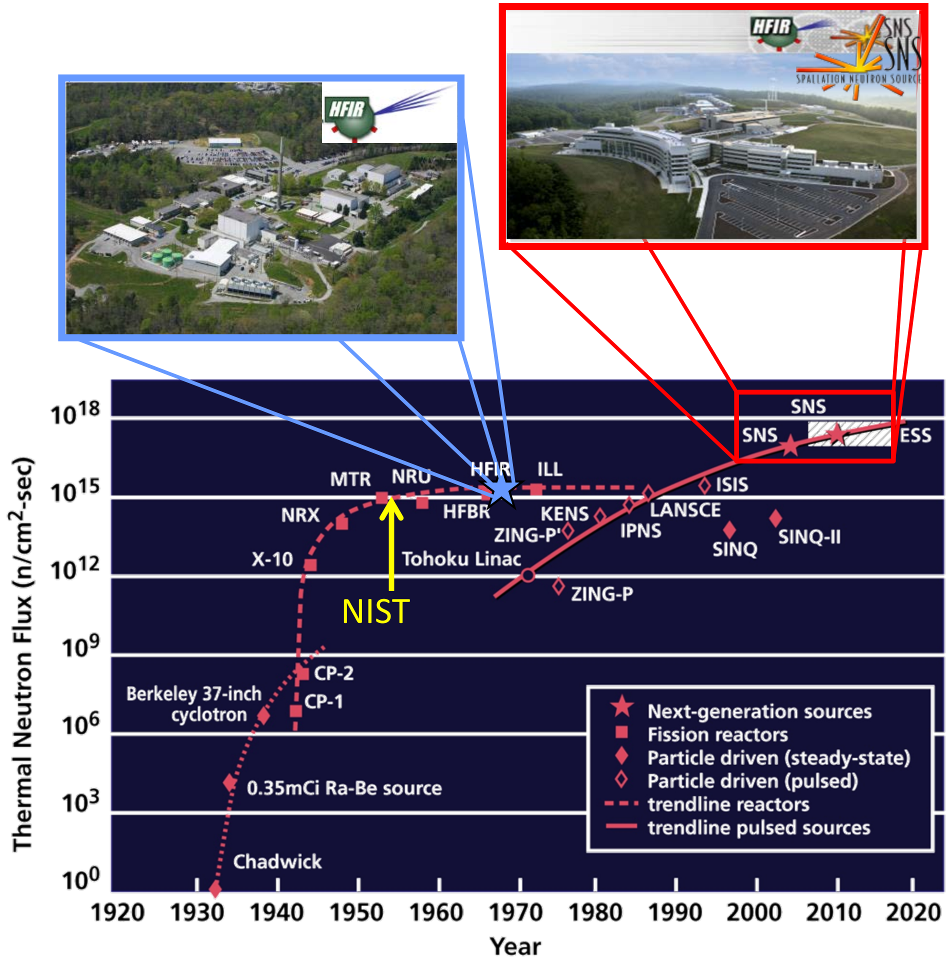
- Internal funds for Micro-channel plate detector
  - Improves resolution to ~20 µm
  - Record images at 1 µs
- BES-funded scientist has project to further improve resolution
  - Coded source creates many high resolution sources in a coded pattern
  - Resolution Goals
    - 5-10 µm for first coded source imaging system
    - 1 µm for final revision
  - Single pinhole for magnified imaging will drastically cut neutron flux
    - source size begins to control resolution
- Stroboscopic approach and needs for current and future neutron flux
  - Proposal submitted (internal funding) to accelerate development of stroboscopic technique and implement a proof-of concept at SNS

BES Early Career Awardee at ORNL (Philip Bingham) improving resolution with magnification

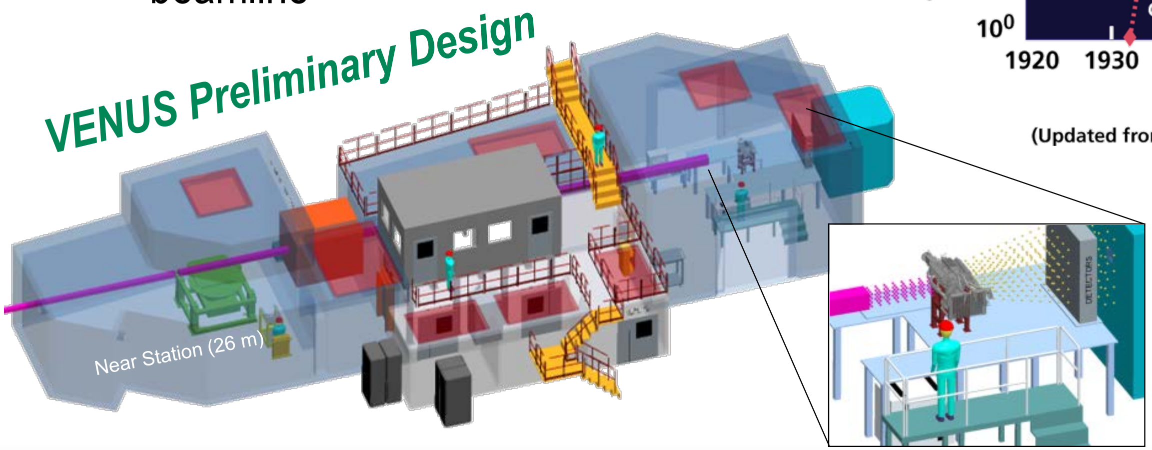


Neutrons at ORNL

- High Flux Isotope Reactor (HFIR)
  - Steady (i.e., non-pulsed) neutron source; “white” beam
  - Imaging beam line accessible through user program
- Spallation Neutron Source (SNS)
  - Most intense pulsed neutron beam in the world
  - Energy selective
  - Fundraising ongoing for VENUS imaging beamline



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



Estimated Beam Characteristics		
	Near Station	Far Station
Max Field of View (cm x cm)	40x40	90x90

Summary

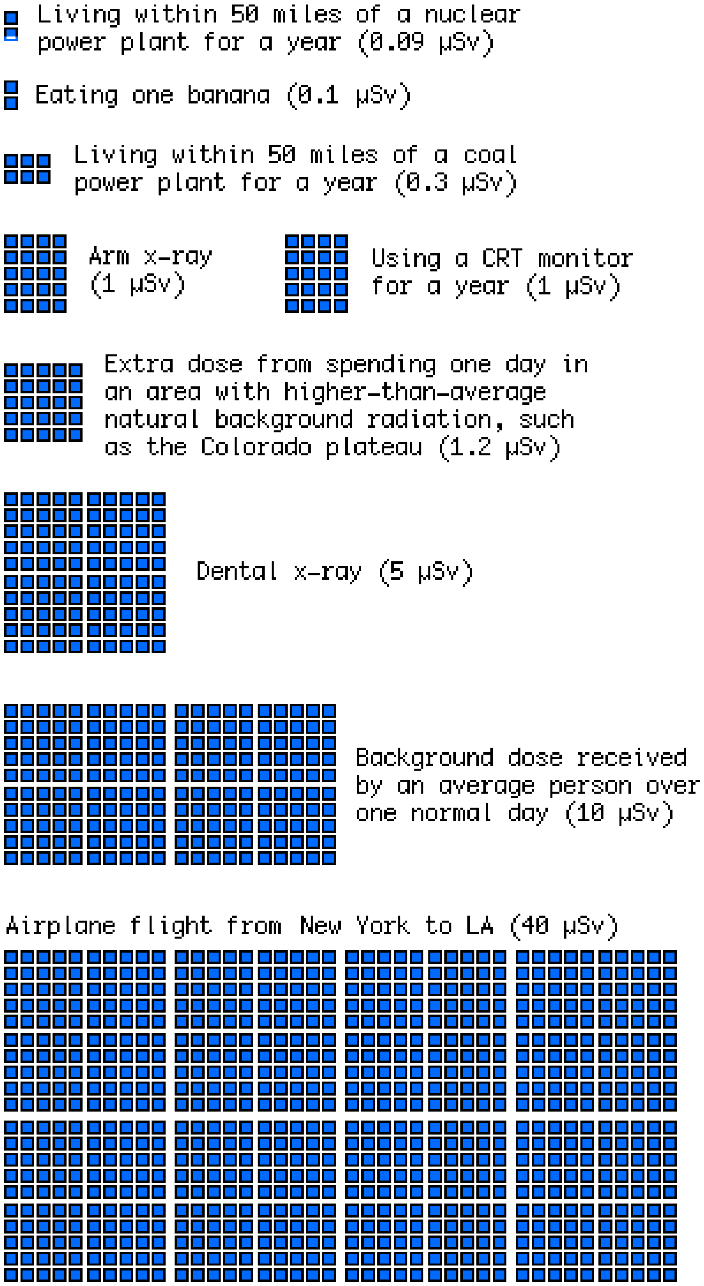
- <u>Relevance</u>:
  - Non-destructive, non-invasive analysis to improve understanding of lean-burn vehicle systems targeting fuel economy improvements and durability; focused on fuel injectors and particulate filters
- <u>Approach</u>:
  - Neutron Imaging as a unique tool applied to automotive research areas to visualize, map and quantify deposits in engine parts as well as looking at fuel dynamics inside spray (not achievable with x-rays)
  - DPFs, EGR coolers, Fuel injectors
- <u>Collaborations</u>:
  - BES, Industrial (NGK, GM and Navistar), and Academic (U. Alabama and U. Tennessee)
- <u>Technical Accomplishments</u>:
  - Imaged injections using high rail pressure delivery system with diesel injectors at HFIR
  - CT-scan of injector for GDI
  - Completed particulate filter regeneration study
  - CT-scan of ash deposits from a continuously regenerated PF and a periodically-generated one (not shown)
- <u>Future Work</u>:
  - Stroboscopic intra-nozzle fluid dynamics in diesel fuel injector
  - Increased resolution

Technical back-up slides

Radiation/Activation

- Average radiation exposure
  - Working at HFIR for 12h, handling specimens: 10-20 μSv
  - Airplane trip Knoxville to DC: ~10 μSv
  - 1 day on earth: ~10 μSv
  - Chest CT-Scan: 7000 μSv

- After exposing materials to neutron beam, they can become "activated"
  - materials give off radiation as they return to their stable state
  - Time of decay varies for materials and time-in-beam
- SiC particulate filters (PFs)
  - After 20 hour CT scan
    - Can be handled within 10 minutes
    - Can be removed from facility within 1 day
- Injectors
  - After 20 hour CT scan
    - Can be handled within 30 minutes
    - Can be removed from facility after ~1 year



"source": Randall Munroe's Radiation Dose Chart (http://xkcd.com/radiation/)

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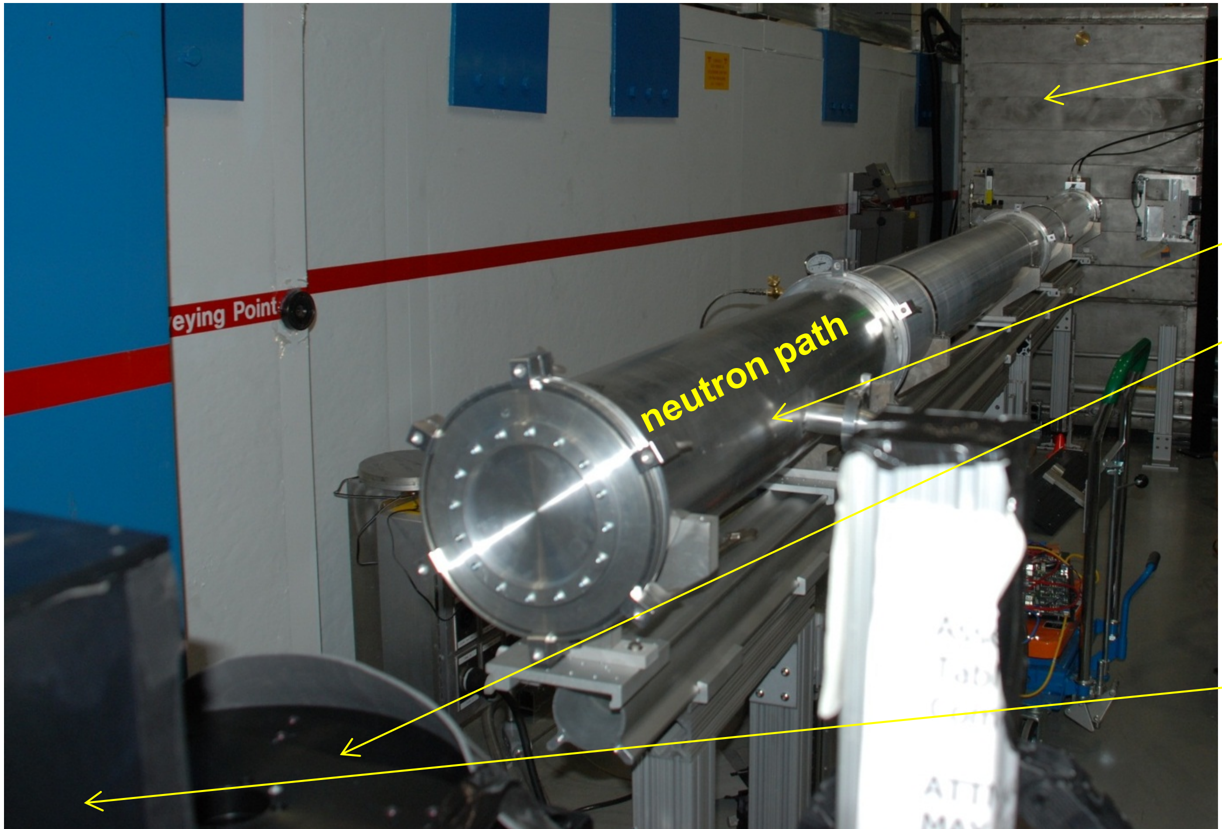


Chopper Box

He-filled Al flight tubes

Sample stage (translation and rotation for neutron Computed Tomography)

Detector housing (CCD, lens, mirror and scintillator)

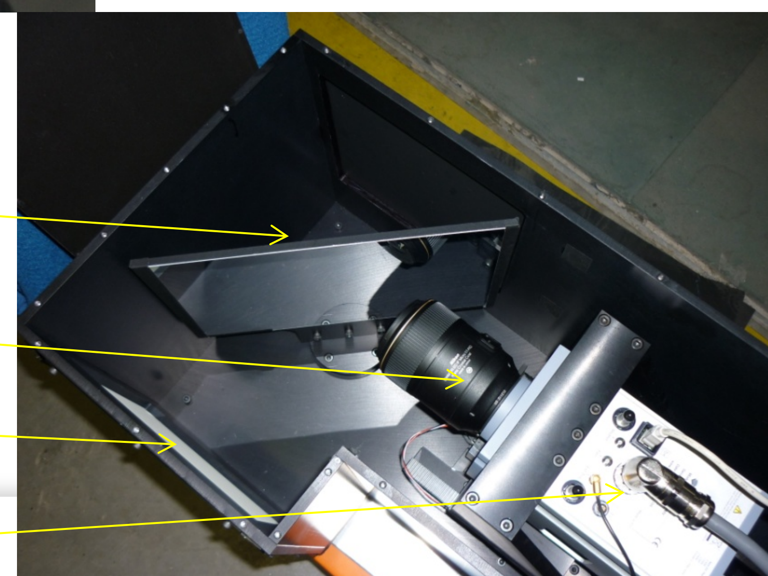
HFIR CG1D beamline
Achievable Resolution:
-50 microns
- $\Delta\lambda/\lambda$ ~ 10% (in TOF mode)

Mirror

Lens

LiF/ZnS scintillator
(25 to 200 microns thick)

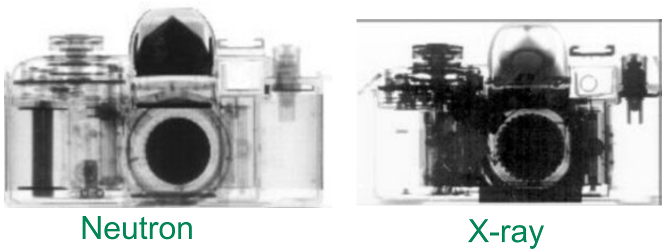
CCD

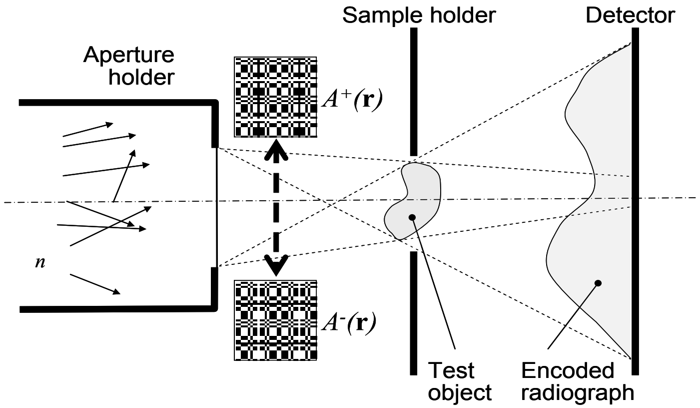


ORNL is working to extend neutron imaging resolution

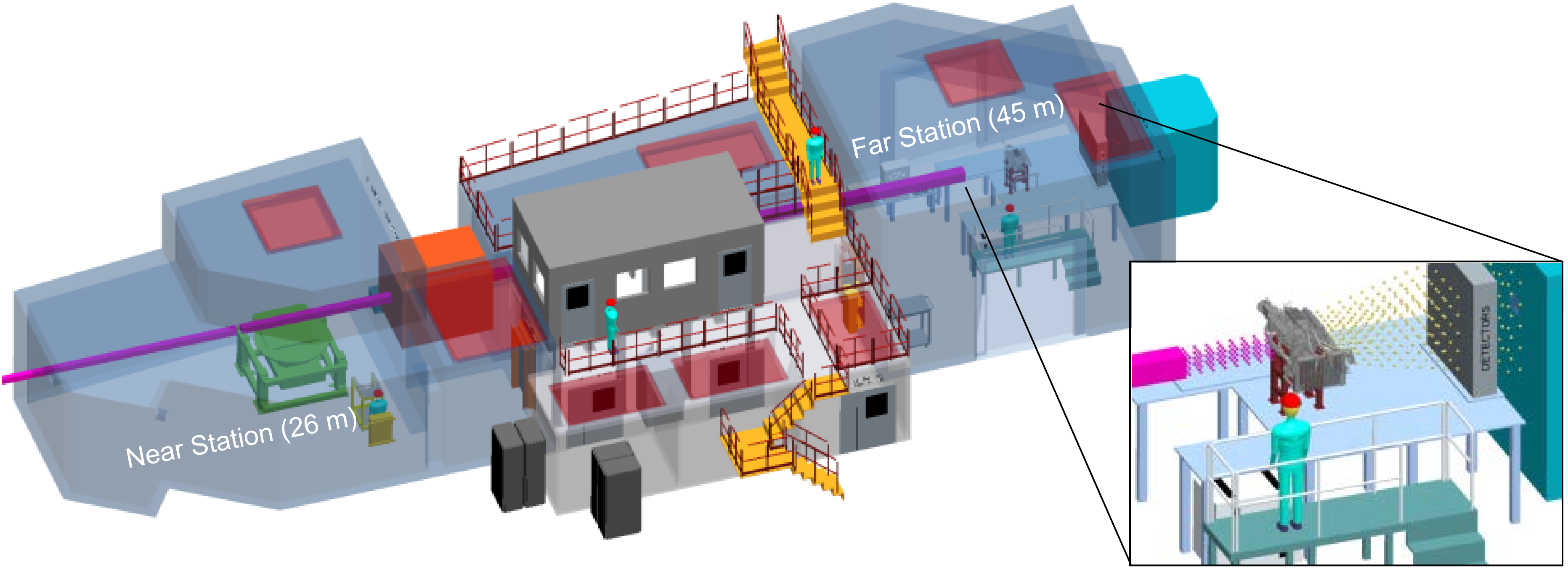
- Current resolution
  - Direct imaging (no magnification) limits resolution of neutron imaging to detector system resolution
  - Camera/scintillator system resolution 30-50μm
  - Micro Channel Plate (MCP) resolution 10-20μm

- BES funded early career award effort focused on improving resolution with magnification
  - Magnification will ease limitations due to detector resolution limit, but source size begins to control resolution
  - Single pinhole for magnified imaging will drastically cut neutron flux
  - Coded source creates many high resolution sources in a coded pattern
  - Resolution Goals
    - 5-10 μm for first coded source imaging system (late 2012)
    - 1 μm for final revision





VENUS Preliminary Design (BL10)



There will be no other neutron imaging facility like VENUS

- Brightest neutron source
- Largest L/D (high resolution)
- Largest FOV (~1m×1m)
- Energy-dependent neutrons
- Orthogonal x-ray system

Estimated Beam Characteristics		
	Near Station	Far Station
Sample Position (m)	26	45
Pinhole Size (cm)	2-6	4-10
Geometrical L/D	1300-430	1125-450
Maximum Field of View (cm x cm)	40x40	90x90
White Beam Range(Å)	0-40	0-40
White Beam Integrated Flux (n/cm2/s)	10^{10}	10^{8}
Energy Resolution ($\Delta\lambda/\lambda$)	0.2%	0.1%
Orthogonal X-Ray (keV)	320	450-1000