Neutron Imaging of Advanced Transportation Technologies

<u>Todd J. Toops</u> *(Principal Investigator)*

Charles E.A. Finney

Eric J. Nafziger

Oak Ridge National Laboratory

Energy and Transportation Science Division

Gurpreet Singh, Leo Breton and Ken Howden

Advanced Combustion Engine Program

U.S. Department of Energy

ACE052

June 18, 2014

Project Overview

Timeline

- Started in FY2010
- Ongoing study

Budget

- FY2014: $200k
- FY2013: $200k

Partners

- BES-funded neutron scientists/facilities
- Academia
  - University of Tennessee, MIT, University of Alabama
- Industry
  - GM, NGK

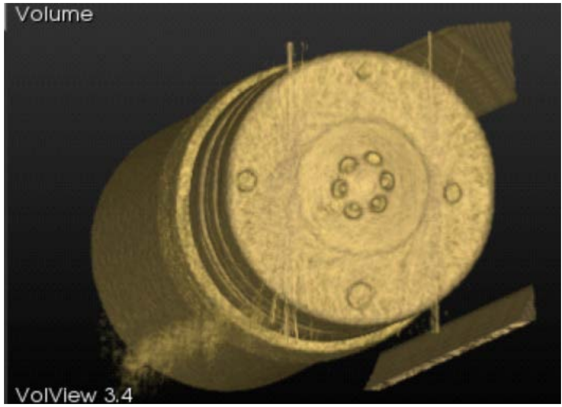
Barriers

- **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

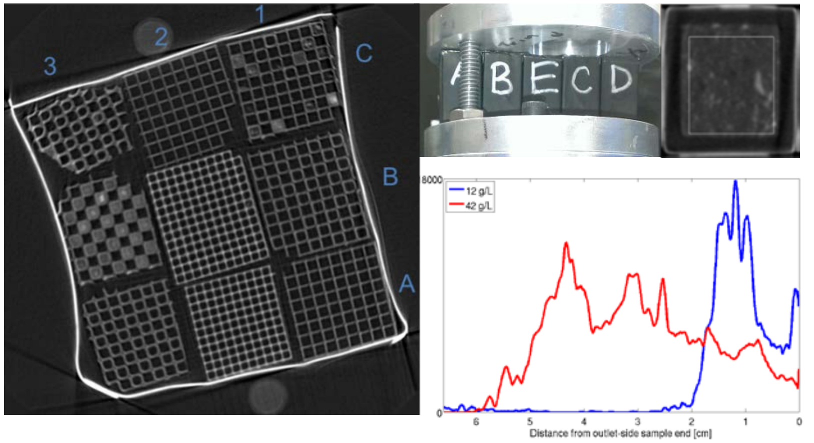
Objectives and Relevance

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

- Gasoline and diesel fuel injectors
  - Goal: Visualize internal flow dynamics
    - Cavitation location and timing
  - Aid model development injector design
    - Injector design has been shown to significantly influence efficiency and emissions

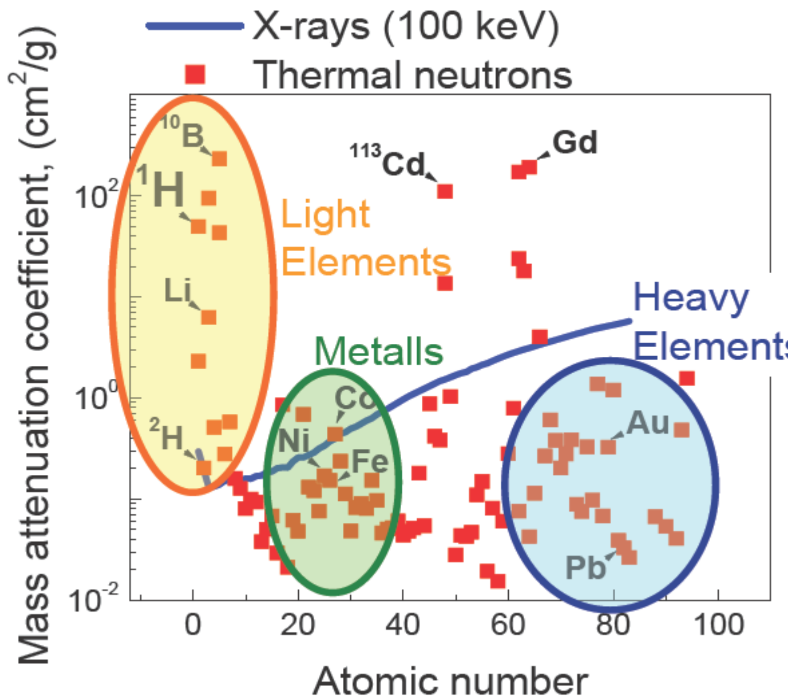


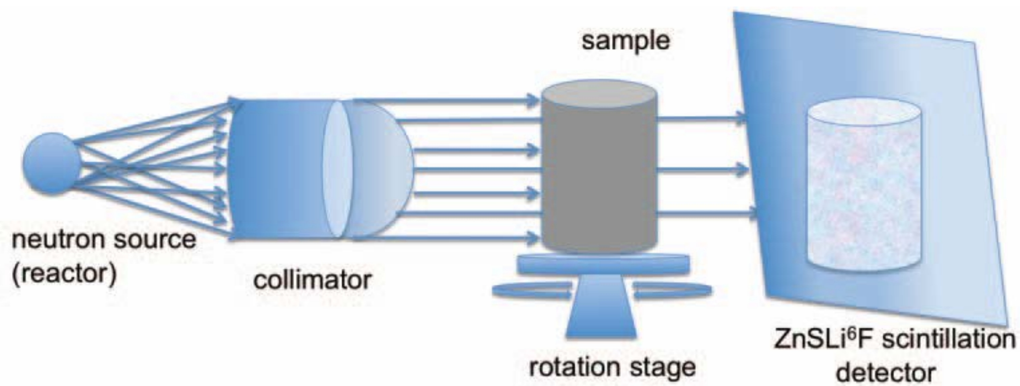
- Particulate filters (PF)
  - Both gasoline and diesel PFs
  - Improve understanding of internal distribution of soot and ash
    - Including density of ash
  - Comprehensive, quantitative device analysis enables validation of full-scale modeling



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 absorption increases for heavy/dense elements



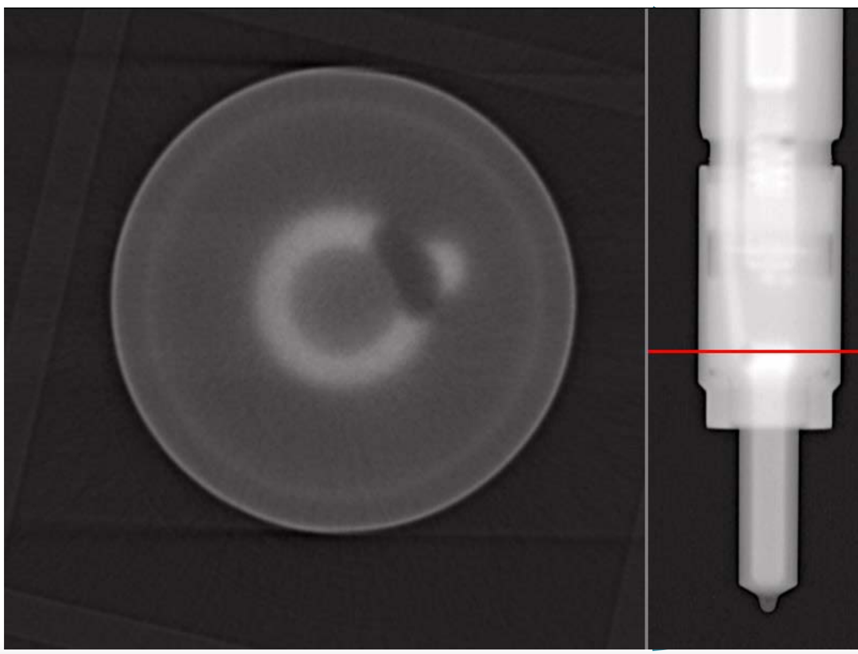


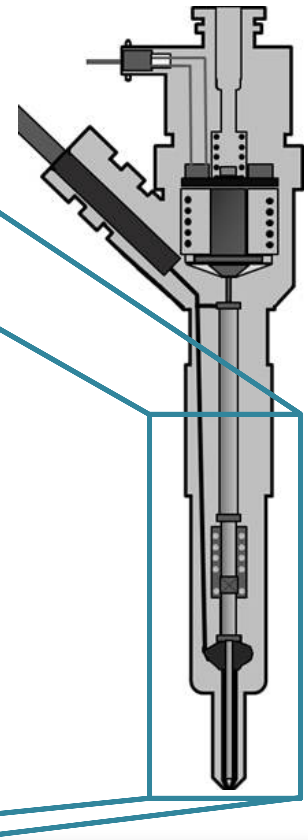
Neutron imaging is a complementary analytical tool

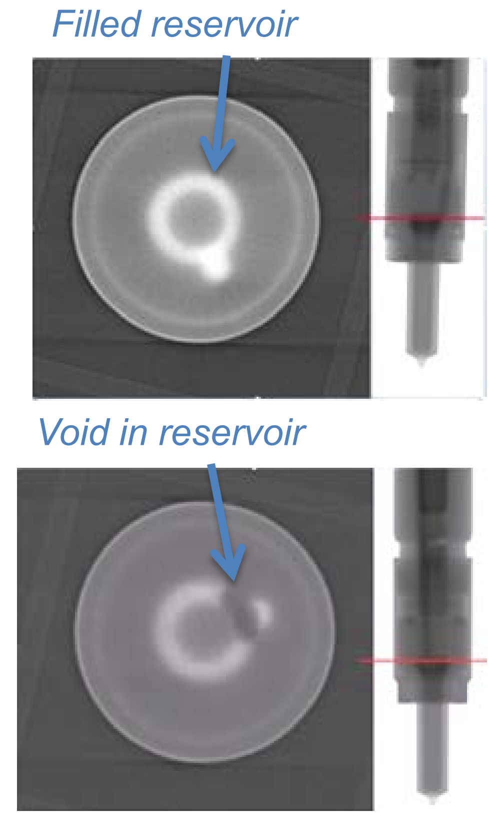
Attenuation Coefficient Reference: N. Kardjilov's presentation at IAN2006
http://neutrons.ornl.gov/workshops/ian2006/MO1/IAN2006oct_Kardjilov_02.pdf

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







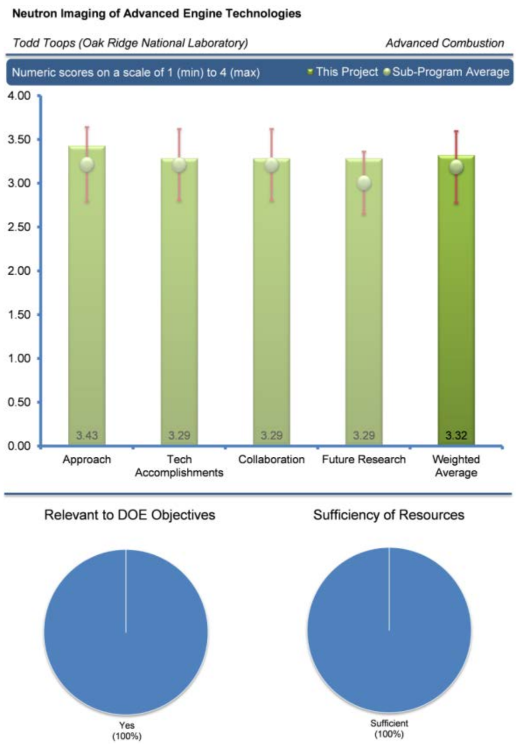
Milestones

- Determine temporal and spatial resolution of neutron imaging with respect to fluid density and flow in fuel injectors (9/30/2013).
  - **completed**
- Obtain Computed Tomography (CT) scans of particulate filters filled with gasoline direct injection engine particulate (12/31/2013).
  - **completed**
- Complete and submit manuscript on particulate filter regeneration studies (3/31/2014).
  - **submitted**
- Complete reconfiguration of spray chamber to enable evacuation and heating for outer injector condensation control (6/30/2014).
  - **completed**
- Image internal fluid during injection using a gasoline direct injection component (9/30/2014).
  - **on target**

Collaborations

- **Basic Energy Sciences** (Hassina Bilheux, Jean-Christophe Bilheux, Lakeisha Walker)
  - High Flux Isotope Reactor (HFIR)
  - Spallation Neutron Source (SNS)
  - Development and operation of beamline facilities
  - Neutron scientists time, data reconstruction, analysis and writing publications
- **University of Tennessee** (Jens Gregor)
  - Developing algorithms for improving contrast, 3-D tomography and removing artifacts
- **MIT** (Victor Wong, Justin Kamp, Alex Sappok)
  - Ash filled DPFs and detailed analytical discussions
- **University of California** (Anton Tremsin)
  - Development and installation of MCP detector at ORNL
- **University of Alabama** (Brian T. Fisher, Marcus Ashford)
  - Internal and external fluid analysis of fuel injectors, single -hole injector
- **GM** (Ron Grover)
  - Coordination of injectors, fluid dynamic modeling
- **NGK** (Shawn Fujii)
  - Donating materials and contributing accelerated ash filled samples

Response to reviewers' (7) comments



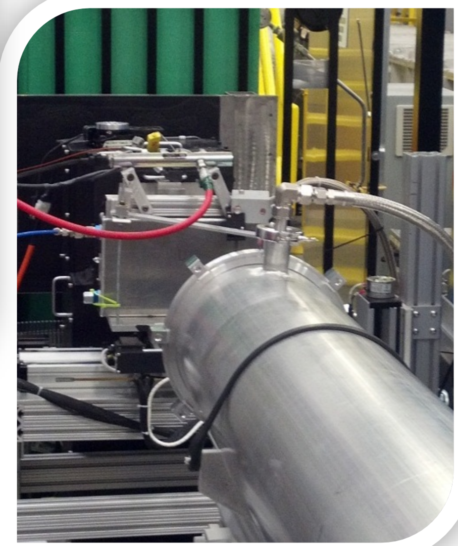
Project viewed to be providing interesting findings, but improved technique needed for injector study

- Approach and Relevance:
  - *Positive*: **excellent approach to study combustion and emissions**…provides info not available by other means…**directly relevant to improving engine performance**
  - *Recommendations*:
    1. Feels like a technique in search of a use for fuel injection (but worthy of $200k)
    2. Limitations: low neutron flux and resolution.
  - *Response*:
    1. Combination of high contrast with hydrogen and low contrast with metals indicates potential to advance the understanding in a needed area of research;
    2. Exact limitations we are striving to improve; relying on ORNL internal funding + BES
- Technical Accomplishments:
  - *Positive*: good progress…GDI and DPF results were interesting, of great interest… **providing new knowledge**…usefulness of neutron imaging demonstrated
  - *Recommendations*:
    1. Is resolution [good] enough to detect characteristics that matter?…work remains before the technique could yield results that would provide new understanding
    2. Looking at density gradients important, would provide useful data for better injectors
  - *Response*:
    1. We have successfully lobbied ORNL to upgrade beamline for hardware improvements
    2. Fluid density measurements throughout the injector are the focus of dynamic imaging study
- Collaborations, Future Plans, and Resources:
  - *Positive*: **very good collaborations**…right parties involved …investigators have responded well to suggestions…**future work being directed to technique improvement** …funds sufficient, may expand in future…**very good work on a relatively small budget**
  - *Recommendations*:
    1. Partnership of collaboration with a Tier I fuel injector supplier should be pursued
    2. Studying of deposit formation on DI gasoline injector nozzles
  - *Response*:
    1. We will strive to do this by the end of FY2014; teleconferences and if possible injectors
    2. Started this conversation years ago, but supplier backed off; will try again

Approach

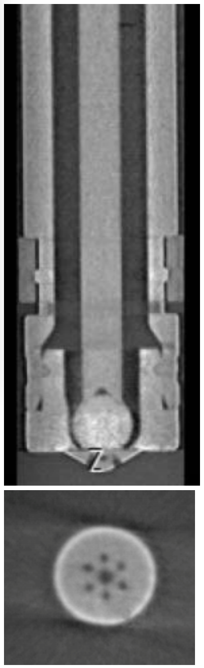
Receive or obtain relevant devices

Record raw images of devices with neutron beam, scintillator and detector



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

Reconstruct device using or enhance contrast using imaging software



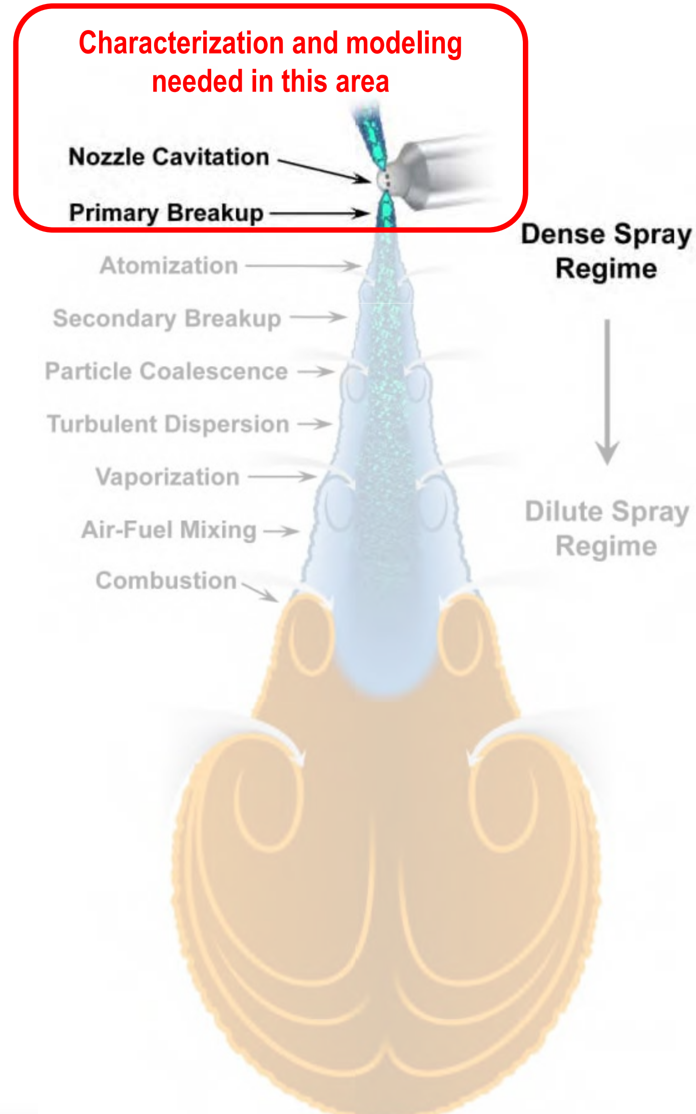
Technique being employed to study both internal geometries and fluid flow during operation

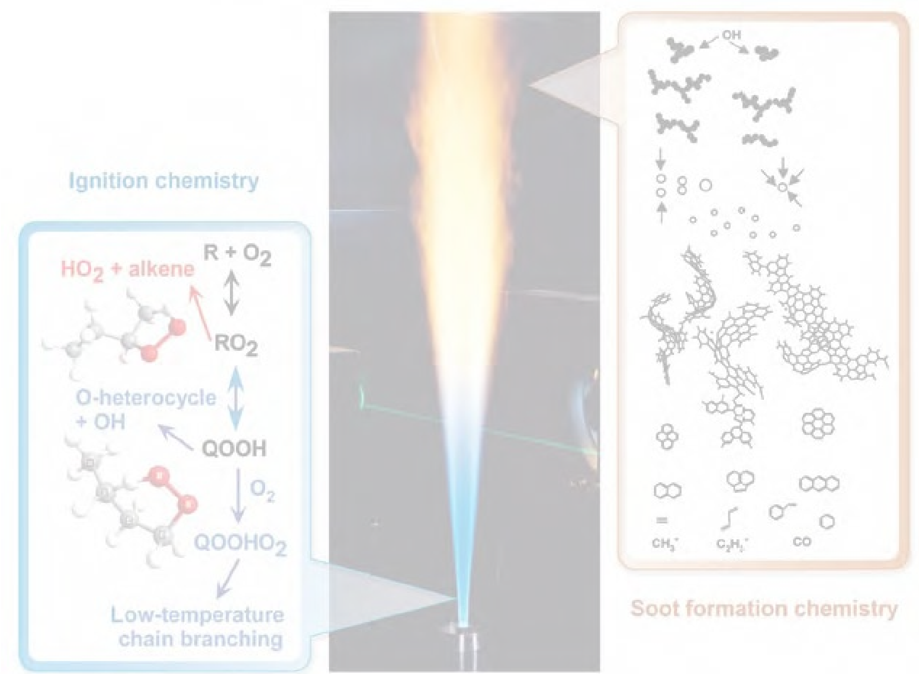
Summary of Technical Accomplishments

- Awarded ORNL-funded project to fully-develop the dynamic imaging capability for fuel injector study
  - Development and installation of new MCP detector
  - Higher resolution stroboscopic capability (demonstrated)
- Recorded higher resolution CT scan of commercial GDI-based injector
  - Including new fly-through movie
- Acquired or modified one- and two- hole GDI-based injectors
  - One designed for off axis one-hole operation
  - Others were modified 6-hole injectors that were sealed for one- or two-hole operation
- Initiated GPF-focused study
  - Obtained particulate profile for 4 GPFs using non-destructive technique
- In collaboration with MIT, used technique to quantify ash loading density profiles in a series of ash-filled samples

Spray pattern and impact on product formation has been heavily studied, but critical information is still needed

- Events occurring in the injector impact the spray dynamics and product distribution
  - Products form at different points in fuel spray
- Knowledge of how internal dynamics/events affect the spray pattern are not well understood
- Improved diagnostics critical to make this connection

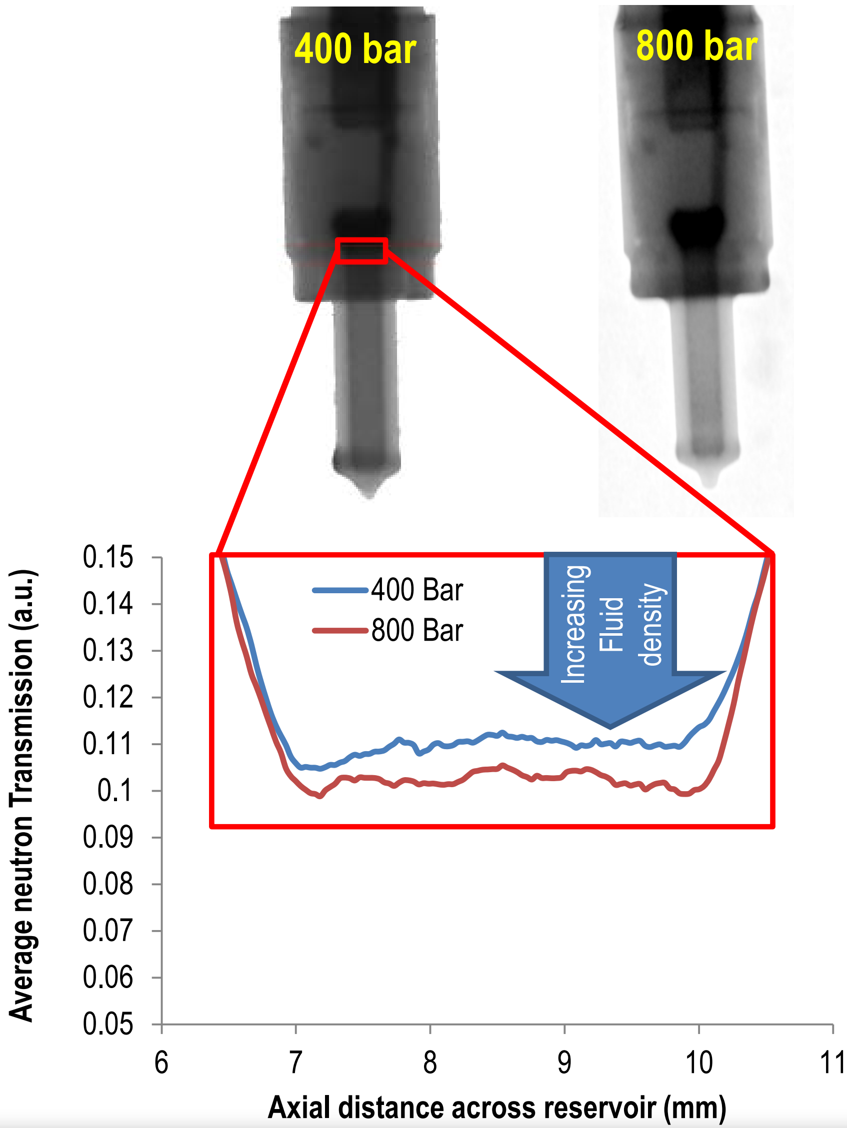




DOE report, "A Workshop to Identify Research Needs and Impacts in Predictive Simulation for Internal Combustion Engines (PreSICE)", March 3, 2011.

Last year the challenges of fuel injection were presented, which illustrated needs for improvement

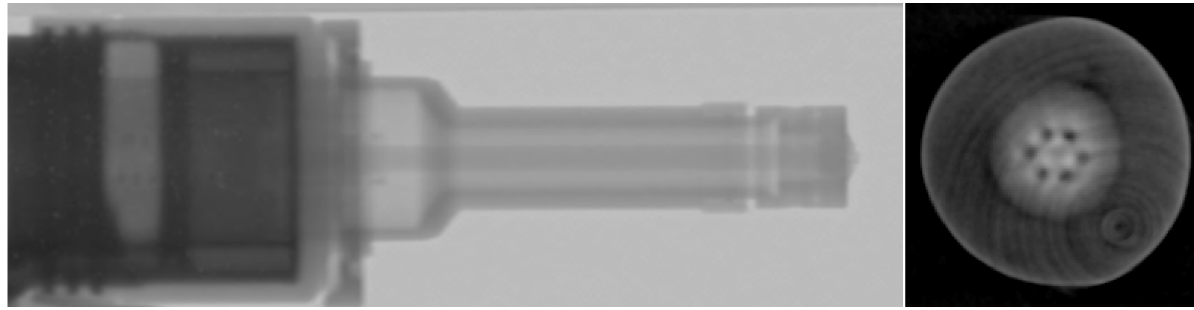
- Images captured are composite of entire injection event
- Analysis focused on identifying areas with density gradients
  - Results show denser fluid profile for 800 bar
  - Complicated by condensation on outside of injector
- Challenges and needs for improvement
  - Fluid condenses on outside of injector, interferes with visualization at pin holes
  - Meshing neutron exposure needs with typical injector operation
  - Initial resolution ~ diesel nozzle hole



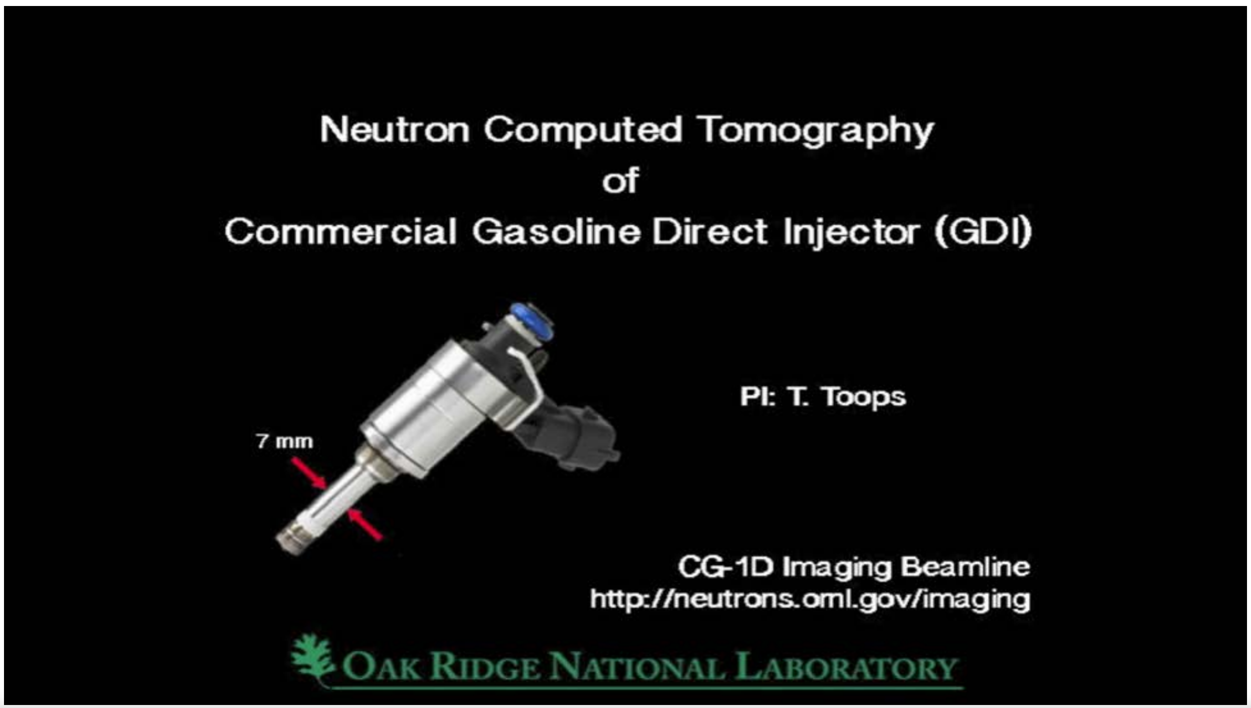
New MCP detector with improved resolution and improved synchronization capabilities

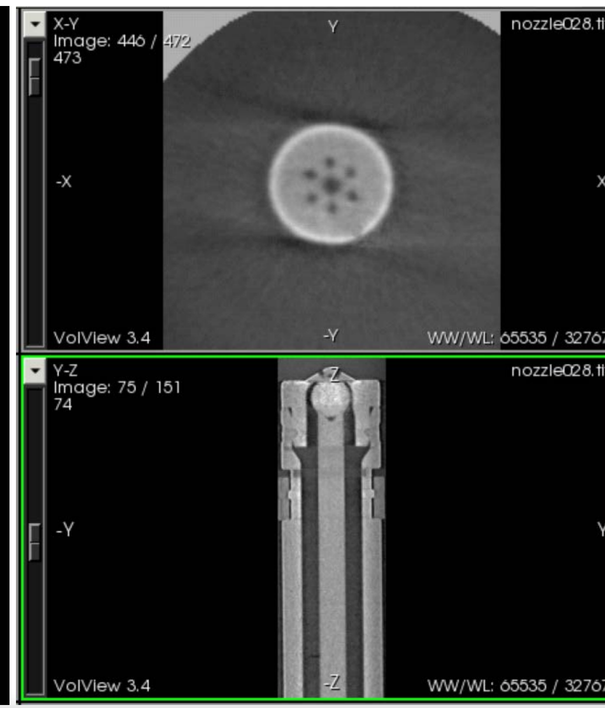
- ORNL invested internal funds for new detector
- Better resolution achieved with new detector
- Improved synchronization opportunities for dynamic imaging

Images using original CCD-based detector



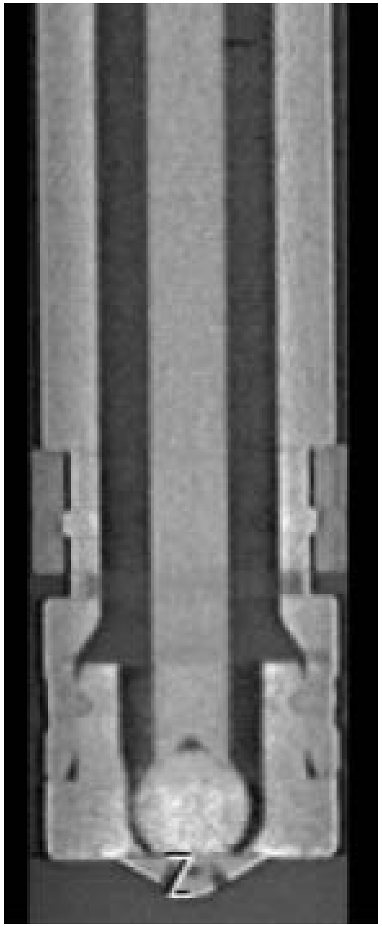
Initial images using new MCP-based detector

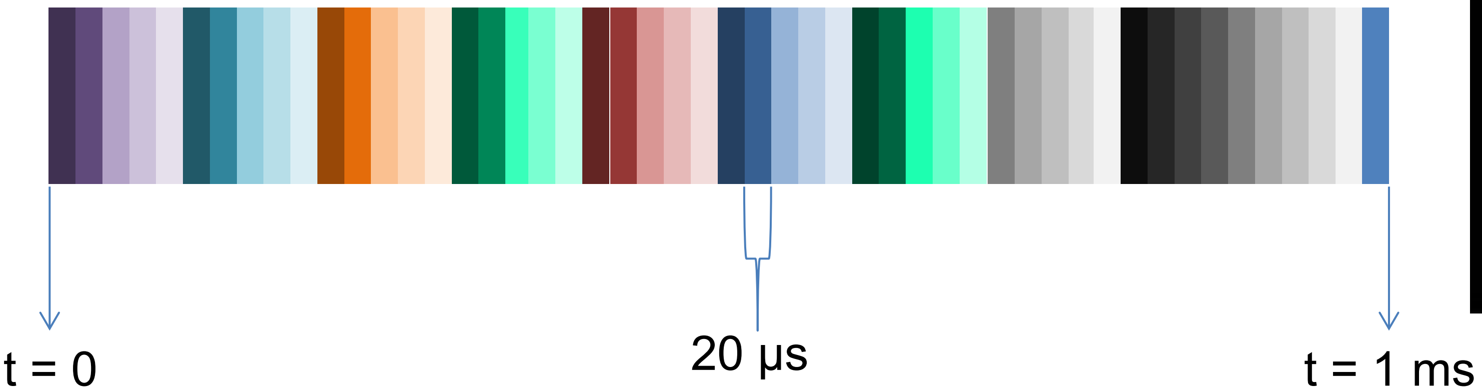




Goal is to develop technique to image internal fluid property changes with 1 ms injection, 20 µs resolution

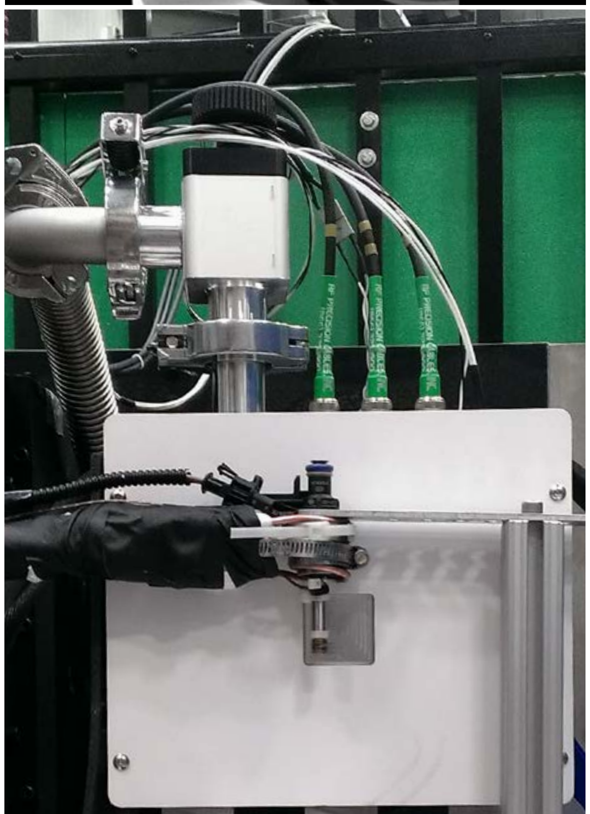
- To maximize cavitation during injection high rail pressures, heated nozzles and evacuated chamber to be used
  - Highest rail pressures (GDI: ~200 bar)
  - Heat nozzle to 100°C and evacuate the spray chamber
  - Increases likelihood of cavitation and limits condensation
- Injection timing for composite image:
  - 1 ms injection with 20 µs resolution (50 frames)
  - Targeting 30 s of neutron exposure for each 20 µs frame
- After proof of principle, move to more realistic systems with confidence



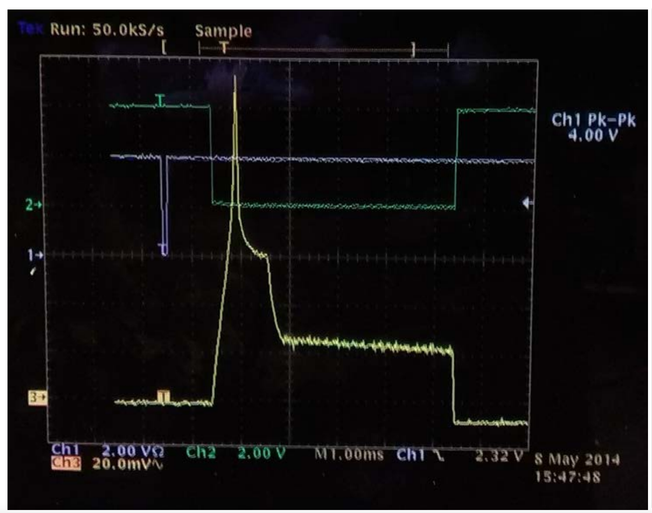


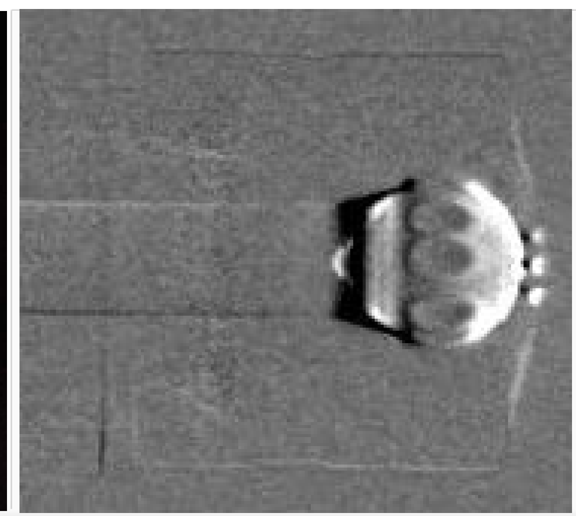
* - Another ORNL-funded project awarded to develop and validate this dynamic imaging capability with the relevant dynamic resolution.

Controlling software and mechanics of new detector allow stroboscopic synchronization



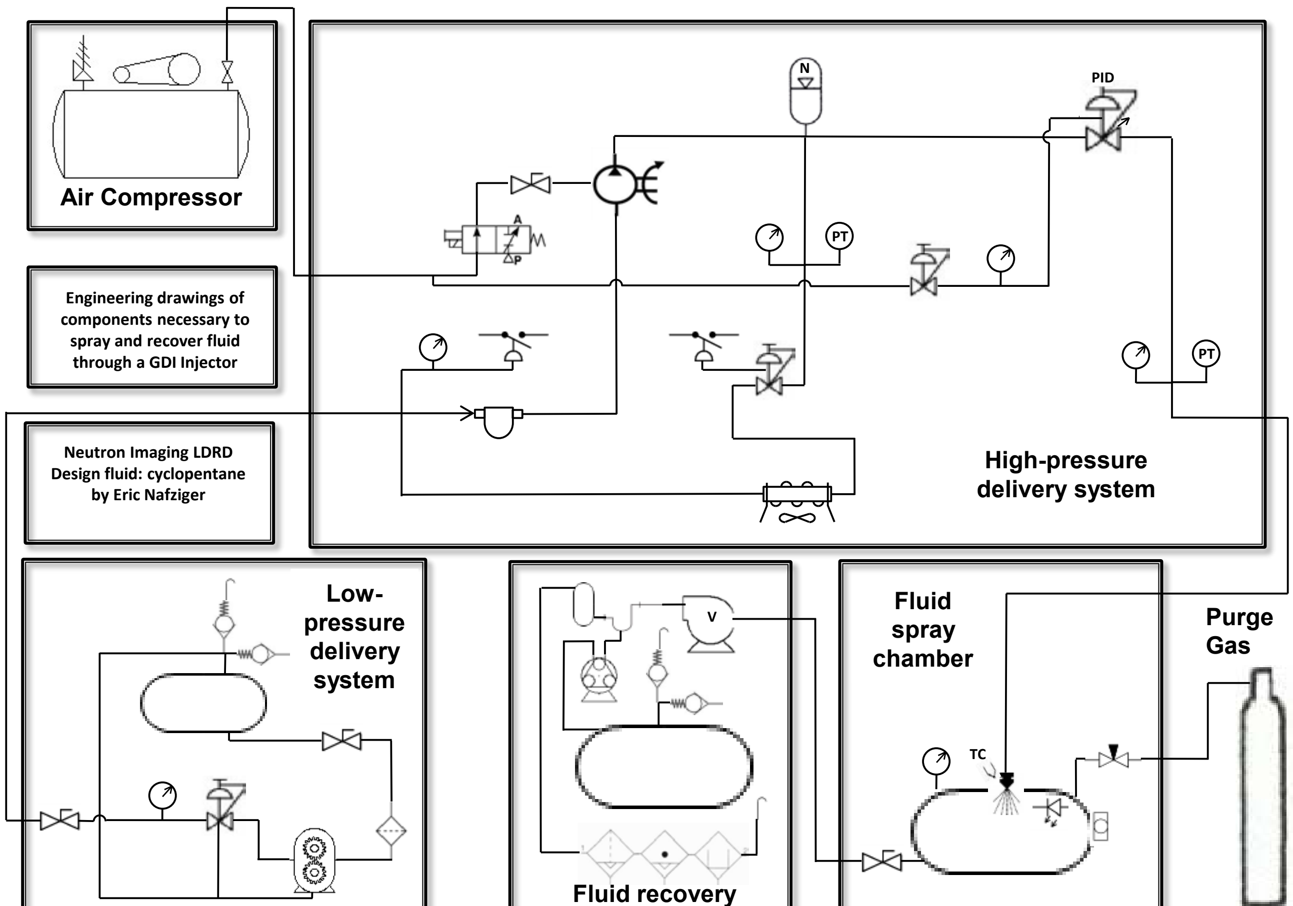
- Proof of principle movie obtained with computer fan
  - 19 microsecond frames
    - As low as 3 microsecond demonstrated
  - 28,000 images combined for each frame
- Moving to injector operation now
  - Demonstrated injector movement consistent with current trace being sent to injector
  - Strong current to open injector followed by lower current during stable region





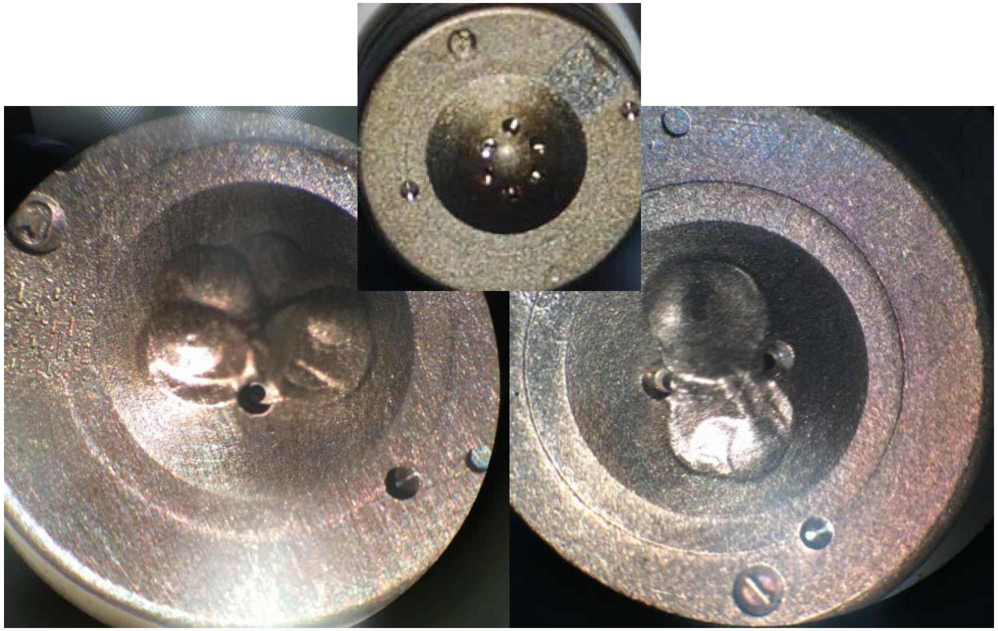
Developed fluid injection system to have precise control over injection pressure for GDI system

- Fluid delivery system with precise pressure control
  - Low and high pressure sides
- Evacuated spray chamber with continuous sweep gas

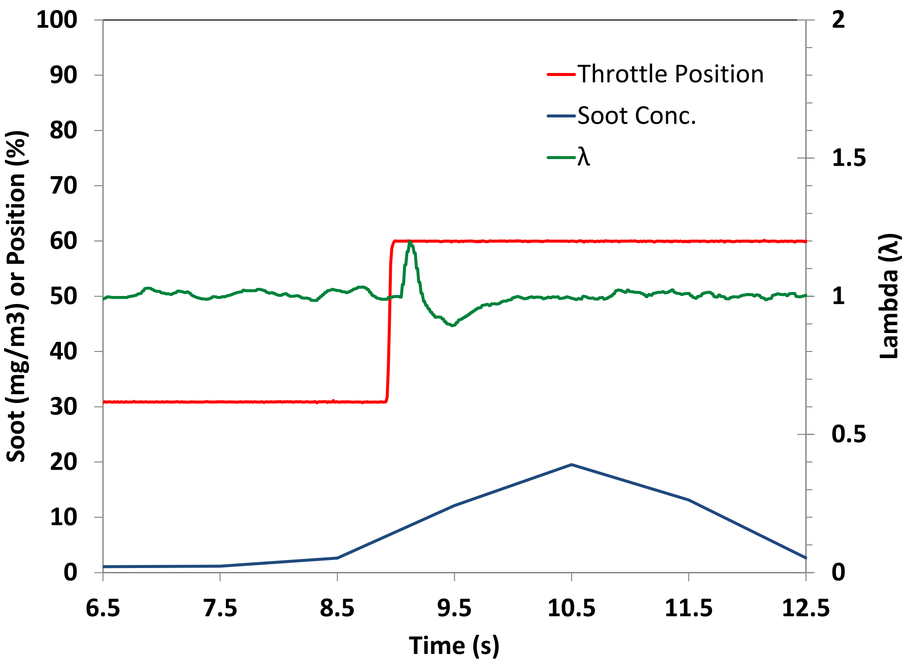


Obtained series of injectors from industrial partner and modified stock injectors

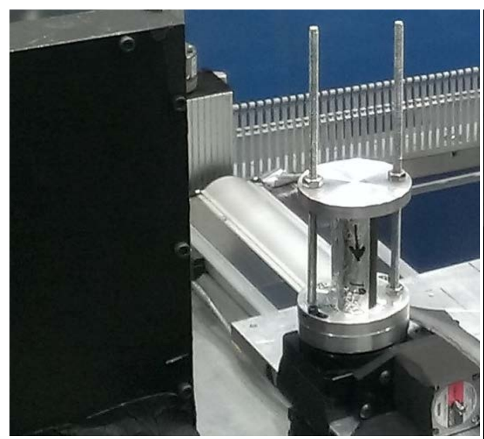
- Standard industrially representative 6-hole nozzle
- Specialized single hole injector ideally-suited for imaging experiments that will minimize interference of other holes
- Modified stock injectors for use in dynamic imaging campaign
- Starting with stock 6-hole nozzle
  - Modified for single hole and
  - two-hole nozzles
  - ideally-suited for imaging experiments

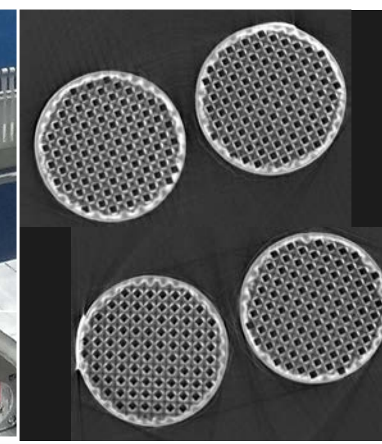


Analysis of GPF particulate initiated



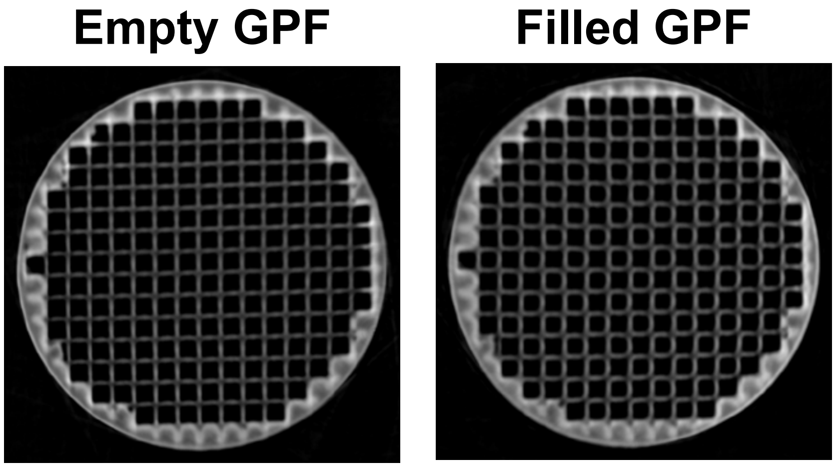
- GDI stoichiometric engine operated to mimic “tip-in” point of acceleration
  - novel approach designed to capture mode of maximum PM generation*
  - Brief period of rich operation (λ = 0.91) , medium-high load
  - Sample holder with four 1” GPFs
    - allows repeated measurements
    - Filled to nominal 4 g/L
- Characterize with Original CCD detector at HFIR

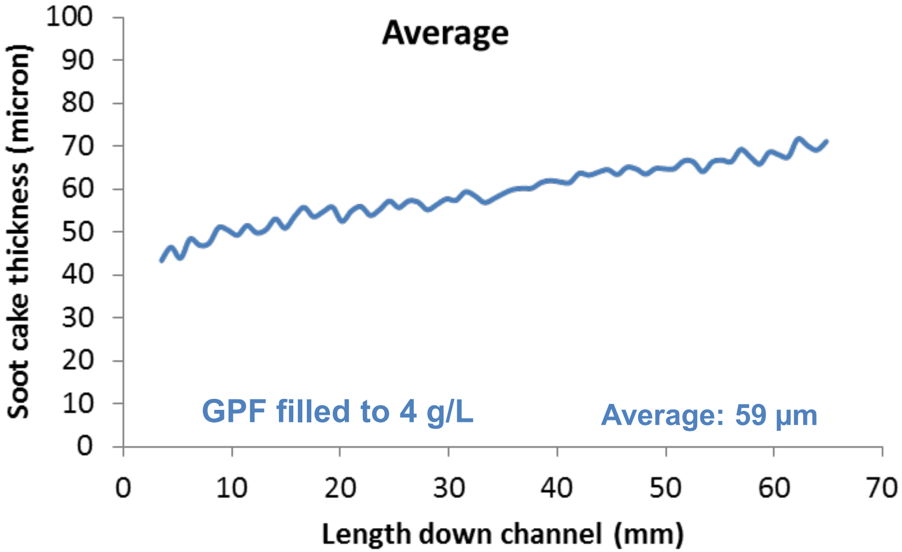




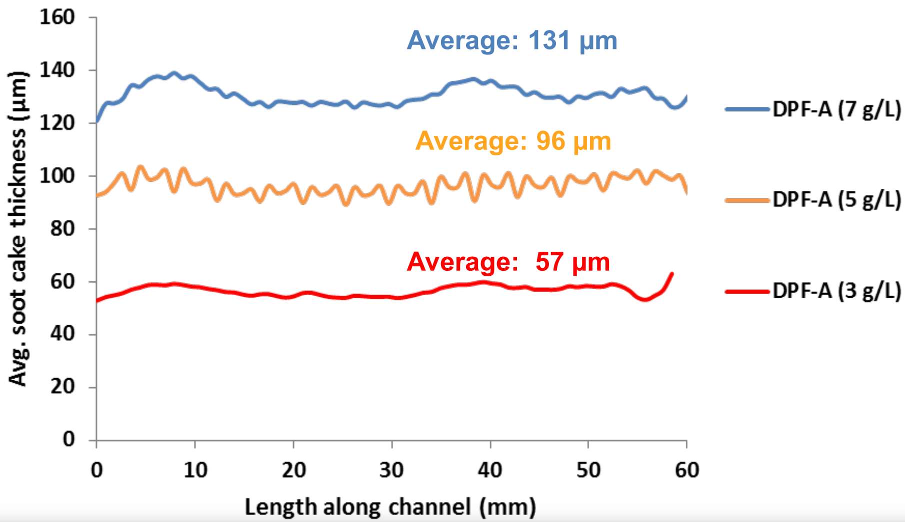
* - generated PM in ORNL collaboration: FT007, to be presented Thursday June 19

GPF analysis illustrates ~20% denser soot cake layers than DPF



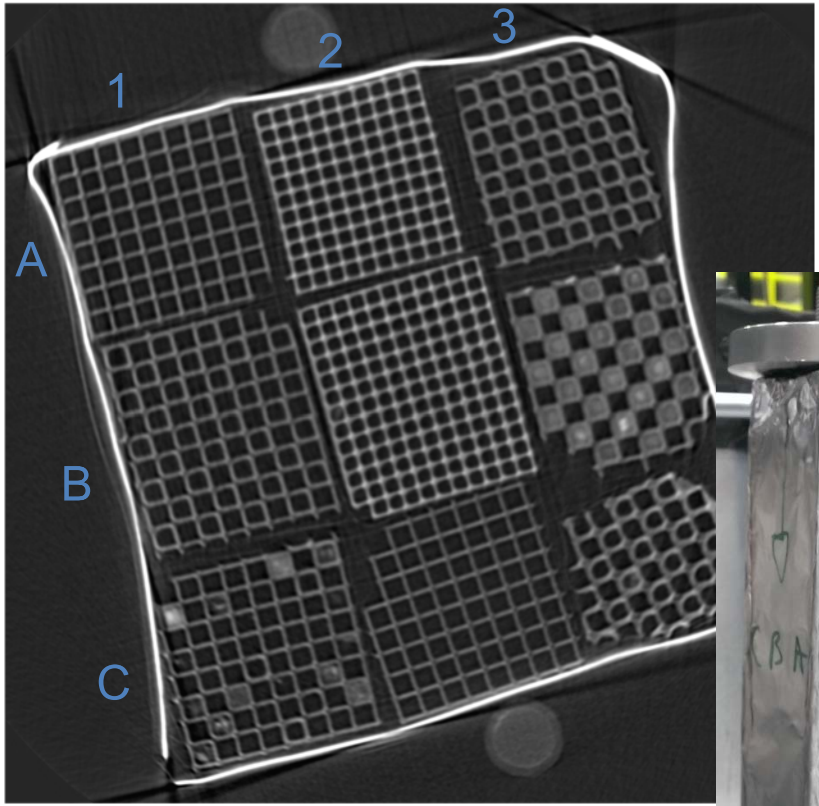


- Soot cake layer analysis performed by comparing empty GPF to filled GPF
  - Subtraction of areas
- All inlet channels analyzed for soot layer
  - Average: 59 µm
- Comparing the average for DPFs, nominally 20% denser with GPF soot
  - 76 micron expected



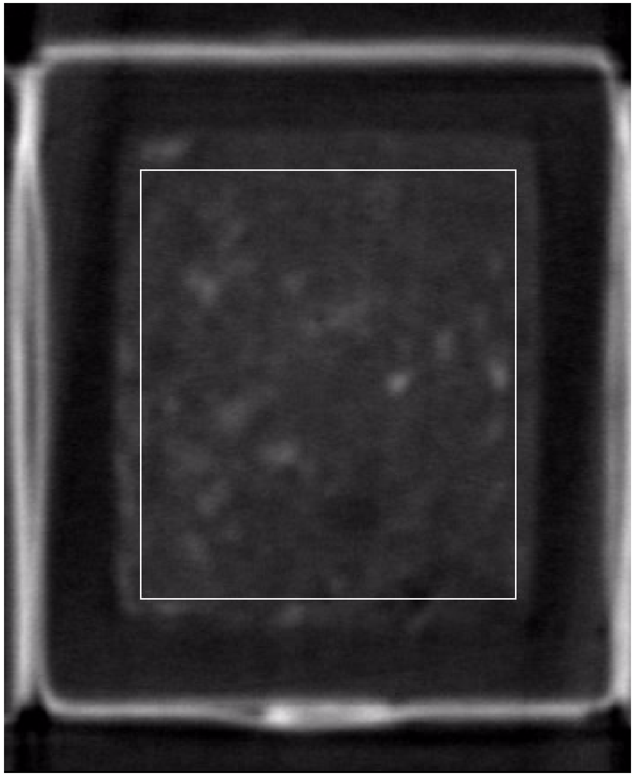
Collaboration with MIT to analyze ash distribution and quantify density profile

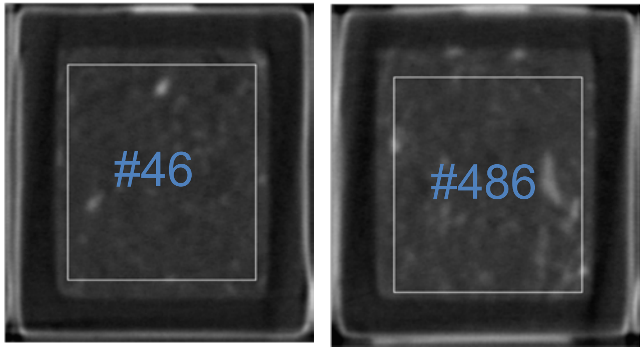
- Quantify ash densities in a series of DPF sections from MIT studies
  - A1: CJ4 25.2 g/L Cont./passive
  - B1: CJ4 25 g/L periodic/passive
  - C1: CJ4 24.6g/L periodic/passive
  - A2: DOC-A
  - B2: DOC-B
  - C2: Blank-DPF
  - A3: CJ4 12.5 g/L periodic/active
  - B3: CJ4 42 g/L periodic/active
  - C3: CJ4 33 g/L cont./active
- Well characterized samples and part of a large effort



Ash standard using CJ4-based ash

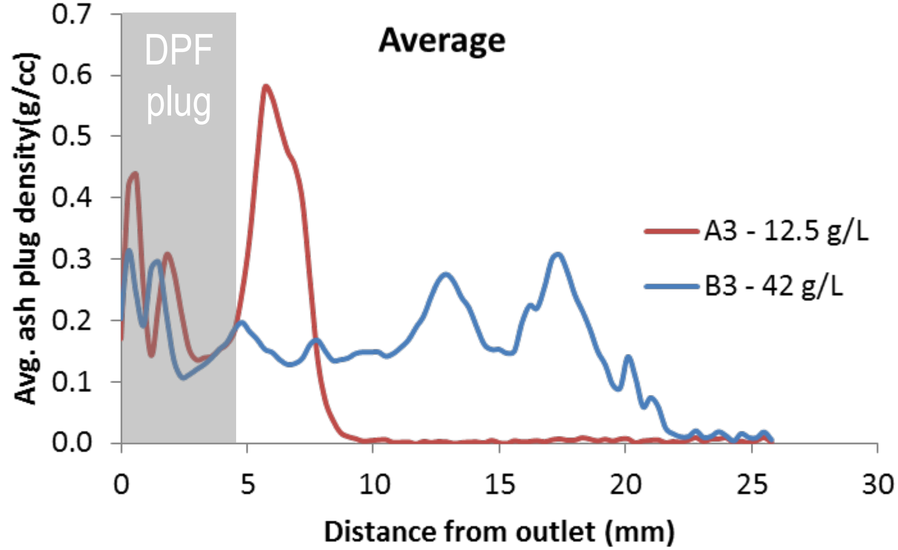
- Ash standard prepared with 0.52 g/cc
  - CJ4 ash provided by Justin
  - Placed in square aluminum construction
  - Filled and allowed to settle (3 times)
- Square piece placed in beam for CT scan; mimics ash in DPF
  - Single point calibration possible
- Calculated 12.9 g/cc/“count” for standard
  - Average intensity for a given slice is 0.040 “counts”

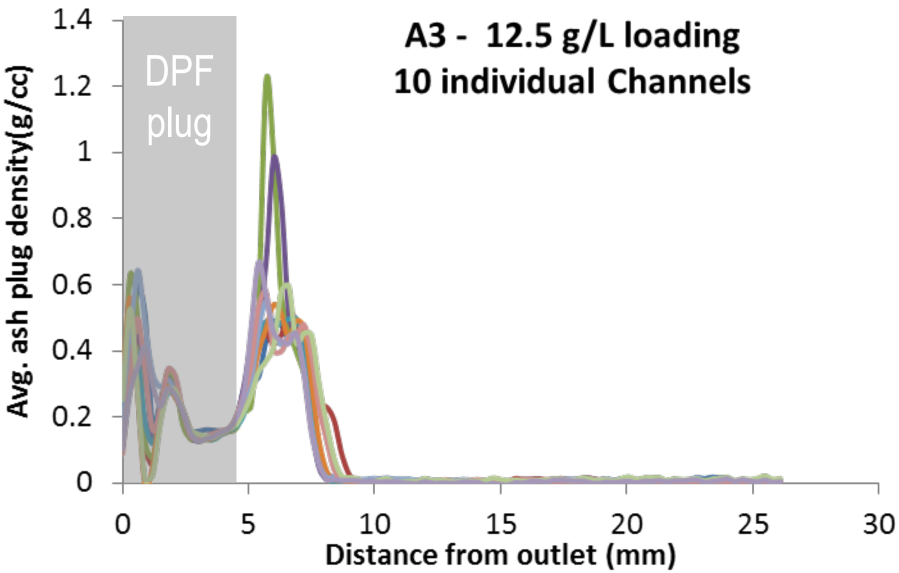


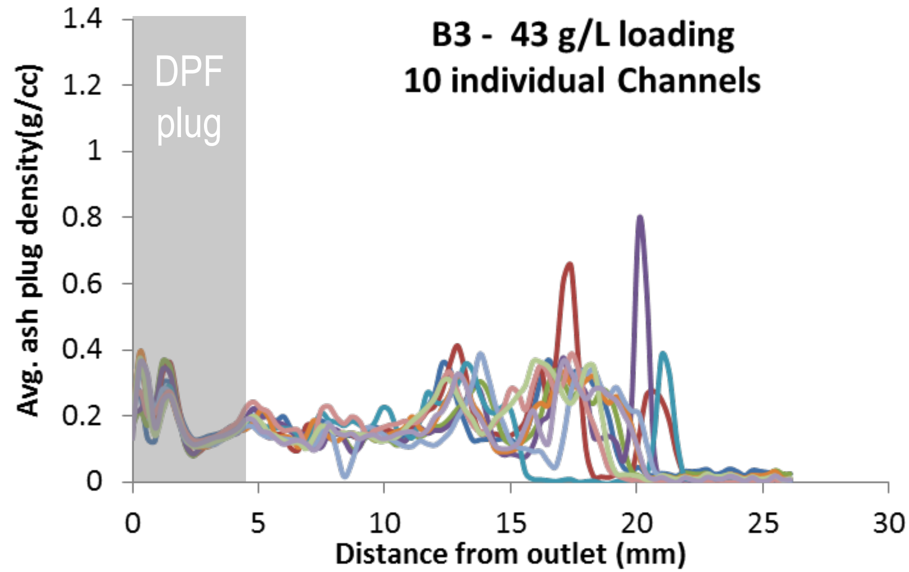


DPFs quantitatively analyzed

- DPFs being analyzed
  - A3: CJ4 12.5 g/L periodic/active
  - B3: CJ4 42 g/L periodic/active
- Densest areas appear to be at the front of the ash plug
  - Regardless of ash loading
- Ongoing study for several samples and validation







Remaining Challenges & Barriers, and Proposed Future Work

Remaining Challenges:	Future Work:
• Improvement of spatial and temporal resolution for fuel injector research	• MCP detector has been developed and obtained; initial install in January followed by modifications • Full installation completed; optimizing techniques now
• Synchronization of MCP detector with injector operation	• Once MCP detector is fully integrated into the imaging beamline coordination with fuel injector is critical for stroboscopic approach • Demonstrated with dry injector; moving to fluid injection
• Increase neutron flux for a decrease in the number of composite injections	• Once demonstrated to be successful at HFIR, efforts will be moving to the Spallation Neutron Source (SNS) • Increased flux at SNS and increased demand for beamtime; efforts toward dedicated beamline ongoing too
• Study progression of GPF regeneration compared to DPF	• Sequential regeneration study to be performed for an analogous comparison to prior DPF study
• Coordination of soot regeneration in ash-filled samples	• Heavy experimental effort required to systematically load PFs with ash and soot; • Partnering with MIT will continue on this front as allowed through their consortium; actively pursuing other partners

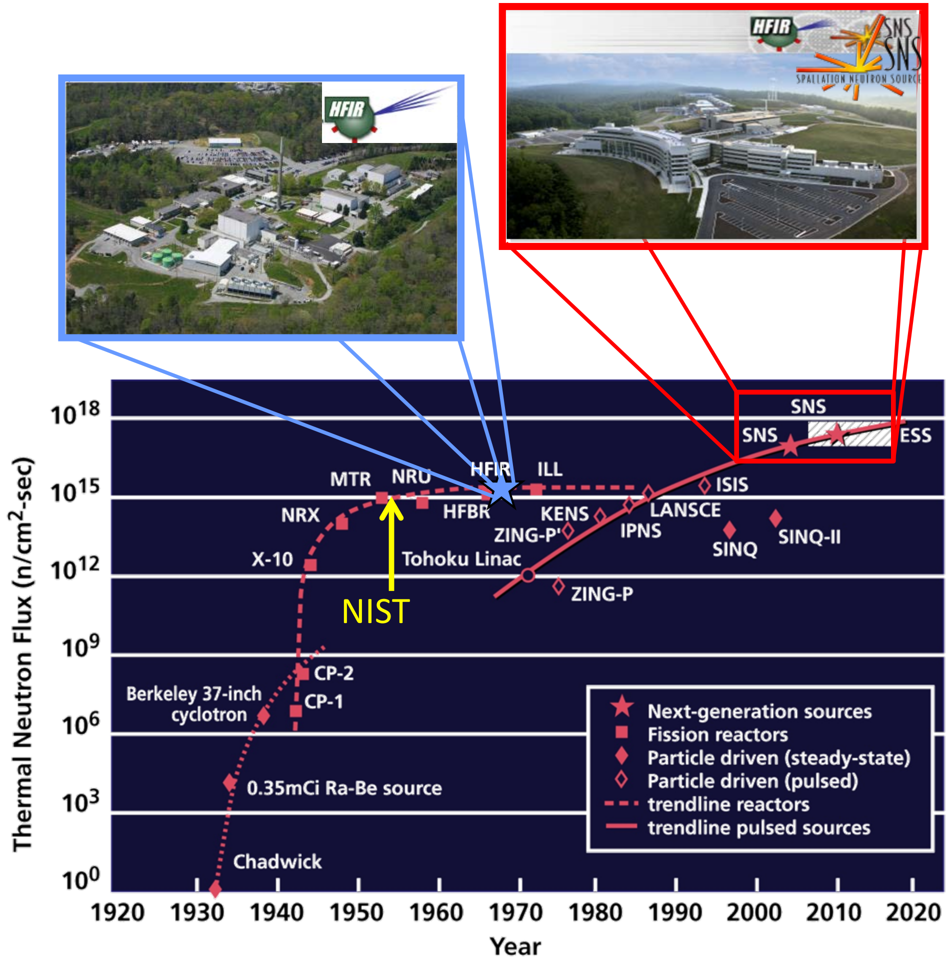
Summary

- **Relevance:**
  - 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
- **Approach:**
  - 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 injector
  - Fuel injectors being studied under both static and dynamic conditions; PFs under systematic static conditions
- **Collaborations:**
  - BES-funded scientists and programs, Industrial (NGK, Lubrizol and GM), and Academic (MIT, U. Tennessee, U. California and U. Alabama)
- **Technical Accomplishments:**
  - Awarded ORNL-funded project to fully-develop the dynamic imaging capability for fuel injector study
  - Obtained higher resolution CT scan of commercial GDI-based injector; Acquired one- and two- hole GDI-based injectors
  - Initiated GPF-focused study; demonstrated differences in soot loading profile compared to DPF (20% denser)
  - In collaboration with MIT, obtained quantified ash loading profiles in a series of ash-filled samples
- **Future Work:**
  - Full installation and integration of MCP detector with fuel injector system for stroboscopic approach
  - Sequential regeneration of GPFs for an analogous comparison to prior DPF study
  - Heavy experimental effort required to systematically load PFs with ash and soot;
  - Partnering with MIT to systematically load PFs with ash and soot; actively pursuing other partners

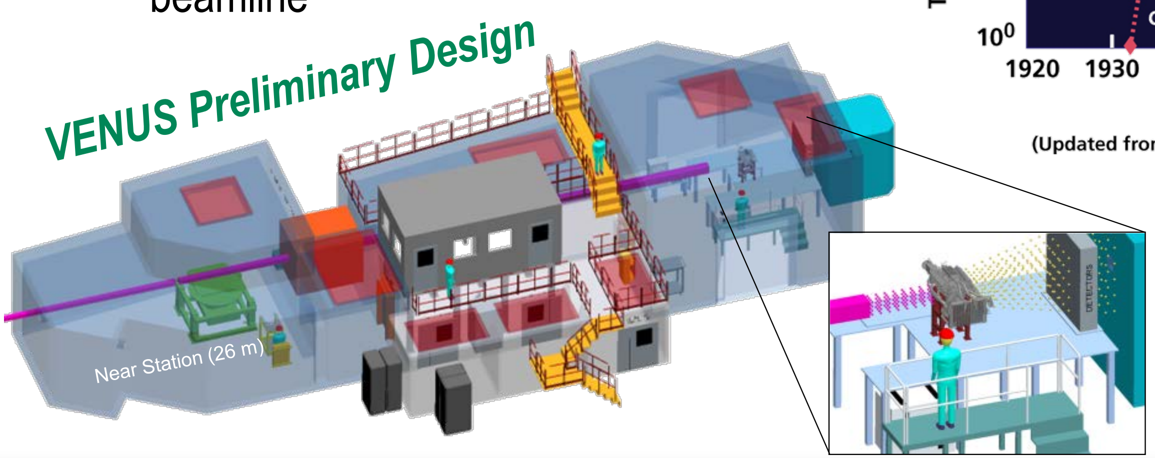
Technical back-up slides

Neutrons at ORNL

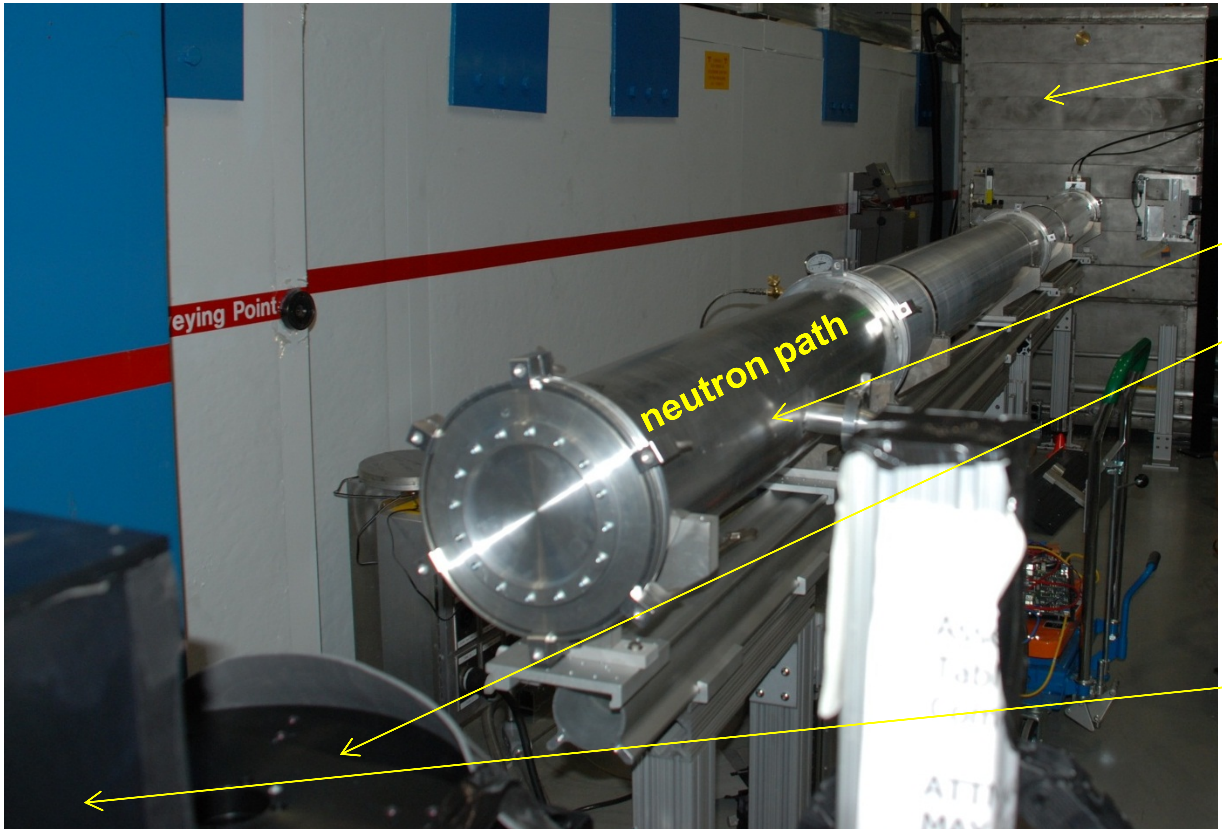
- High Flux Isotope Reactor (HFIR)
  - Steady (i.e., non-pulsed) neutron source; “white” beam
  - Imaging beam line accessible through user program
- Spallation Neutron Source (SNS)
  - Most intense pulsed neutron beam in the world
  - Energy selective
  - Fundraising ongoing for VENUS imaging beamline



(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



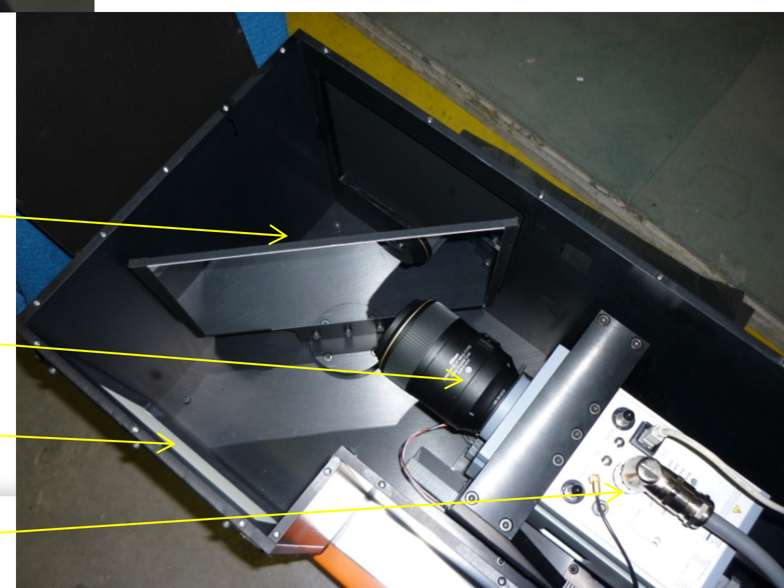
Chopper Box

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
- $\Delta\lambda/\lambda \sim 10\%$ (in TOF mode)



Mirror

Lens

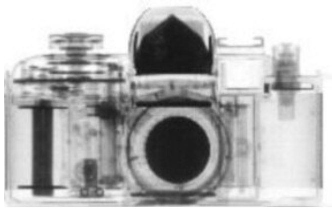
LiF/ZnS scintillator (25 to 200 microns thick)

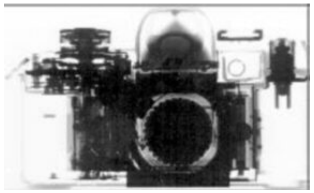
CCD

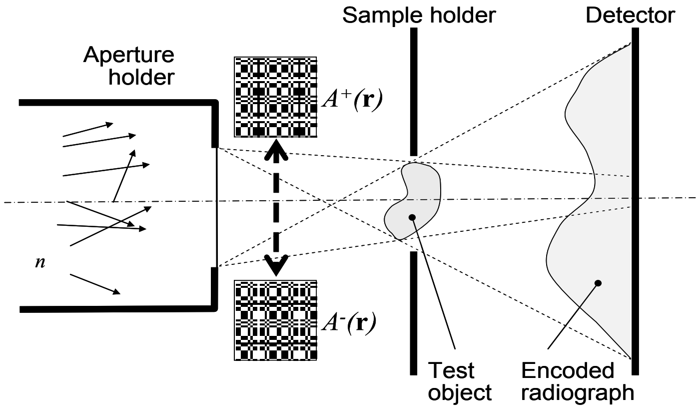
ORNL is working to extend neutron imaging resolution

- 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


Neutron

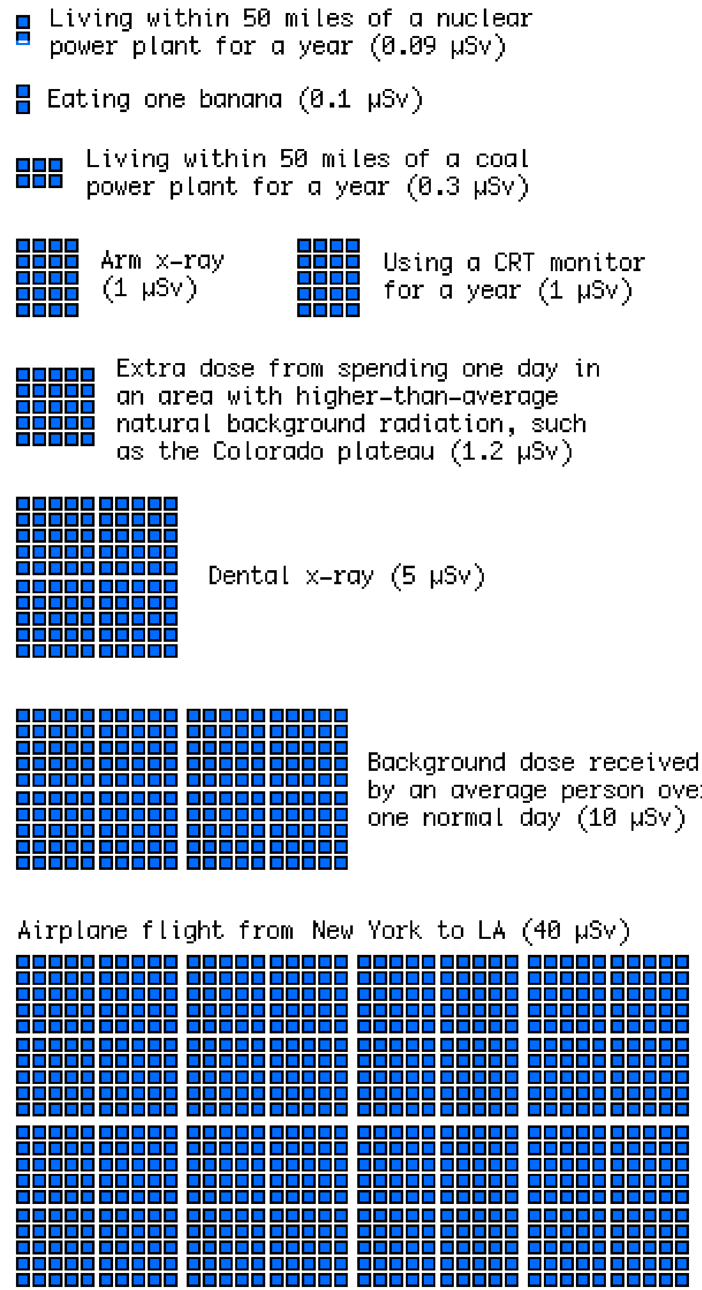

X-ray



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/)

Soot+ash samples : slice means