

Next-Generation Heavy-Duty Powertrains

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ACE133 Overview: Next-Generation Heavy-Duty Powertrains

Timeline

- **FY 19-21 AOP Lab Call project ^a:**
 - *AOI 1B: Heavy/Medium Duty Combustion Research [ORNL]*
- **October 2019 – September 2021**
 - **FY 20-21 Progress presented here**
 - *FY 19 reviewed, FY 20 not reviewed*

Budget

Task	FY19	FY20	FY21
Task1: Advanced diagnostics + Cummins CRADA	\$300K	\$250k	\$250K
Task 2: Neutron imaging for MD/HD	\$200K	\$100k	\$100K
Task 3: Next generation MD/HD LTC	\$250K	\$250k	\$250K
Task 4: Cold-start/restart for electrification of MD/HD engines	\$300K	\$100k	\$75K

a. Start and end dates refer to the life cycle of FY 19-21 Lab Call Project

b. From 2019 Vehicle Technologies Office AOP Lab Call, DE-LC-000L072

Barriers

21st Century Truck Partnership Barriers

- **Internal Combustion Engine Powertrain:** Reduction of combustion heat losses + Combustion system improvements
- **Electrification:** Data to support optimization of complex powertrains

MD-HD Combustion Lab Call Barriers^b

- Improved understanding of the combustion processes to increase engine efficiency and reduce engine-out emissions
- Identify /address barriers to commercialization of LTC into MD/HD vehicles
- Challenges of cold-start and restart for electrification of MD/HD powertrains

Partners

- Regular status reports to DOE
- Industry technical teams, DOE working groups, and one-on-one interactions
- Industry: Cummins (CRADA partner), Daimler Trucks, SwRI
- Engine Combustion Network (ECN)
- Universities: U. Wisconsin, U. of Central Florida
- DOE Labs: SNL, ANL
- VTO: Other ACE projects, Co-Optima, Previous FOA project
- Support to DOE VTO, Strong links to 21CTP, Advanced Engine Crosscut, AEC MOU, IEA Combustion Task
- DOE Office of Science User Facilities [SNS at ORNL]

Relevance: Overall Objective and Barriers

Overall Relevance and Objectives of Tasks:

- **R&D needed to advance the foundational knowledge base for the next generation of MD/HD engine systems to increase engine efficiency and reduce engine-out emissions.**
- **Portfolio of focused, integrative early-stage combustion research tasks to provide data for improving predictive models and future engine designs for conventional and electrified MD/HD truck powertrains.**



Barriers from 21st Century Truck Partnership (21CTP) Blueprint*

- **Internal Combustion (IC) Engine Powertrain:** Drive engine efficiency goals, research to enable combustion modes that lower heat transfer losses and engine out emissions
 - Reduction of combustion heat losses + Combustion system improvements
- **Electrification:** Development of detailed powertrain requirements based on robust data specific to medium- and heavy-duty vehicles
 - Data to support computational methods for optimizing highly integrated powertrains with their increased complexity, supported by experiments in hybrid/electric-capable heavy-duty powertrain laboratories

Foundational Medium-Duty/Heavy-Duty Combustion Research

Removing Barriers for MD/HD Low-Temperature Combustion

Advancing Medium-Duty/Heavy-Duty Electrification

Barriers from FY 19-21 VTO Lab Call (MD-HD Combustion):

- Improved **understanding of combustion processes** to increase engine efficiency and reduce engine-out emissions
- Identify and address fundamental **barriers to commercialization of LTC** into MD/HD vehicles
- Challenges of **cold-start and restart for electrification** of MD/HD powertrains

All Milestones for FY 20 and FY 21 Met or On-Track

Month/Year	Task	Milestone	Status
12/19	Task 1	Provide design for in-cylinder diagnostic validation with neutron diagnostics.	Met
06/20	Task 2	Complete preliminary neutron imaging campaign of an MD/HD fuel injector.	Met
12/20	Task 3	Complete characterization of deterministic features of cyclic instability at lower loads. Characterize control authority with LTC on a single-cylinder engine platform.	Met
12/20	Task 1	Develop and demonstrate in-cylinder optical probe for spectral characterization.	Met
03/21	Task 3	Complete integration of HL for use in transient experiments.	Met
03/21	Task 4	Complete analysis and time-alignment of transient emissions and combustion data for start-stop set.	Met
06/21	Task 3	Complete GCI engine map suitable for use in ECU for transient experiments.	On-track
09/21	Task 1	Apply diagnostic for measurements on the Cummins ISB engine.	On-track
09/21	Task 2	Verify operation of the optical probe in the neutronic engine during off-beam testing at the National Transportation Research Center.	On-track
09/21	Task 3	Complete transient experiments with GCI.	On-track

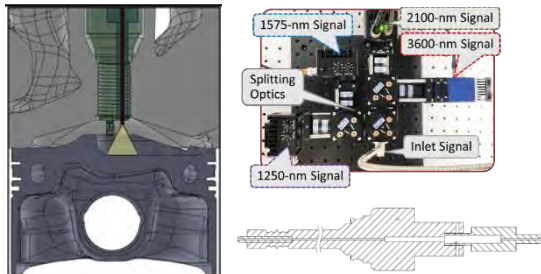
Time	Go/No-go Decision Description	Task
FY19/Q4 (12 months)	<p><u>Criteria:</u> Demonstrate proposed temperature diagnostic from down-selected diagnostics.</p> <p>Go Path Action: Continue development leading to new high-fidelity data sets.</p> <p>[Go Decision Made]</p> <p><u>No-go Path Action:</u> Select alternative path for diagnostic.</p>	Task 1 – Advanced Diagnostics

Overall Approach Across 4-Tasks Addresses 4 Key Data Needs/Barriers for MD-HD Vehicles

Integrated approach spanning fundamentals to vehicle system to address the needs for improvements with MD/HD engines

Need: Advance fundamental understanding to improve predictive models and future engine design

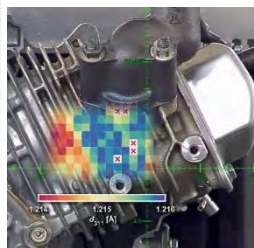
Task 1 Approach: Advanced diagnostics for MD/HD engine systems, including Cummins CRADA



Surface Temp Diagnostic

Need: Develop fundamental data sets using x-ray and neutron diagnostics

Task 2 Approach: Neutron imaging and diffraction of MD/HD engine system components using ORNL Neutron Science User Facilities



Diffraction: Neutronic Engine



Imaging: Diesel Injectors

Need: Overcome technical barriers for achieving high-load operation and addressing low stability

Task 3 Approach: Experimental LTC engine experiments for MD/HD vehicles using single/ multi-cylinder platforms



Single-cylinder MD Engine



Multi-Cylinder GCI

Need: Address lack of understanding of cold-start and restart emissions for electrified MD/HD truck applications

Task 4 Approach: Vehicle system simulations and hardware-in-the-loop experiments with prototype MD hybrid system



Multi-cylinder MD Engine + Hybrid Drive Transient HIL Powertrain Laboratory



Apply diagnostics in Neutronic Engine
Co-Validate both approaches

Deploy Gen 2 Probe in Single-Cylinder Engine

Matched MD Engine Platform

Advanced MD/HD Powertrain Laboratories

Deployable In-Situ Diagnostics

DOE Neutron Science Facilities

MD/HD Advanced Combustion Labs

Detailed Emissions/PM Characterization

Task 1: Advanced Diagnostics Including Cummins CRADA

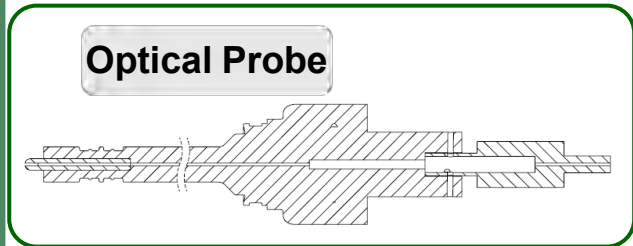
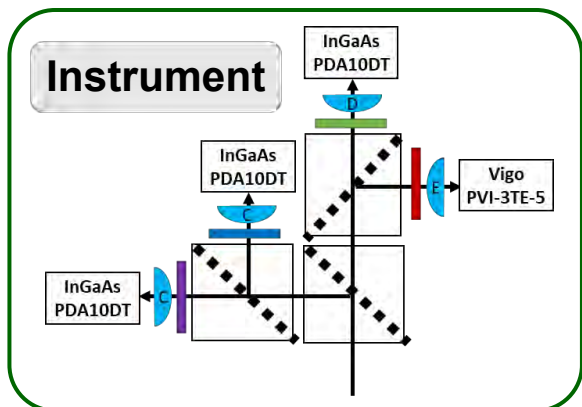
Tim Lutz & Bill Partridge, Cummins & ORNL PIs [Sneha Neupane, Gurneesh Jatana, Sriram Popuri]

End-of-Project Goal: Establish new diagnostics for improved data on in-cylinder **surface temperatures** that will be **suited for use in realistic engines, including in-field use** with industrial partners; apply data to tune, assess, and improve predictive models.

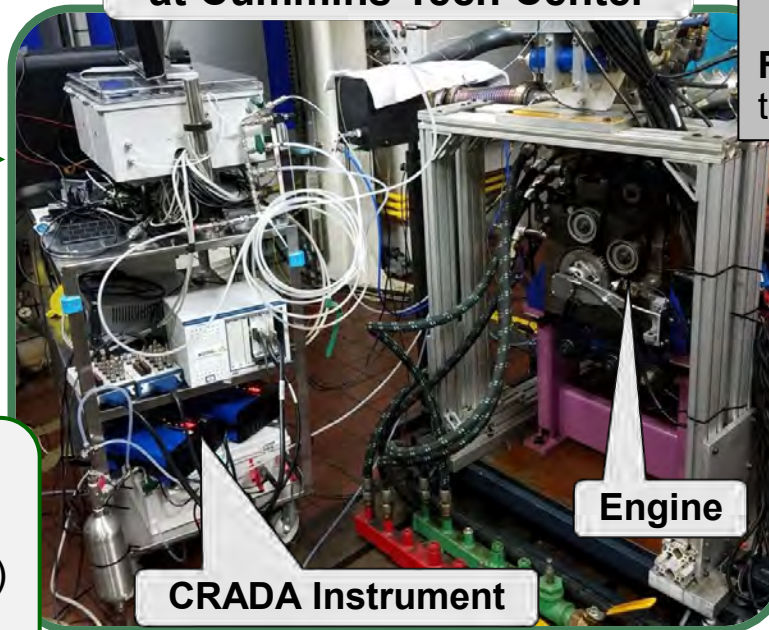
Improving Multi-Cylinder Engine Uniformity & Efficiency Through Novel Diagnostics
 Focus on *Minimally Modified OEM Metal Engines*

Project builds on previous experience and successful development of unique diagnostics suitable for use in production viable engines

Focus: In-cylinder temperature measurements



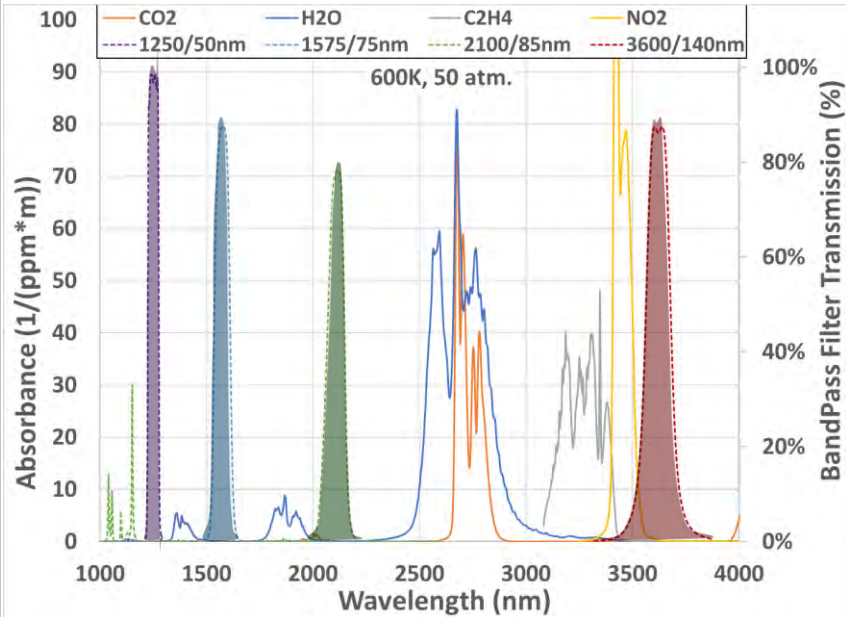
Development Applications at Cummins Tech Center



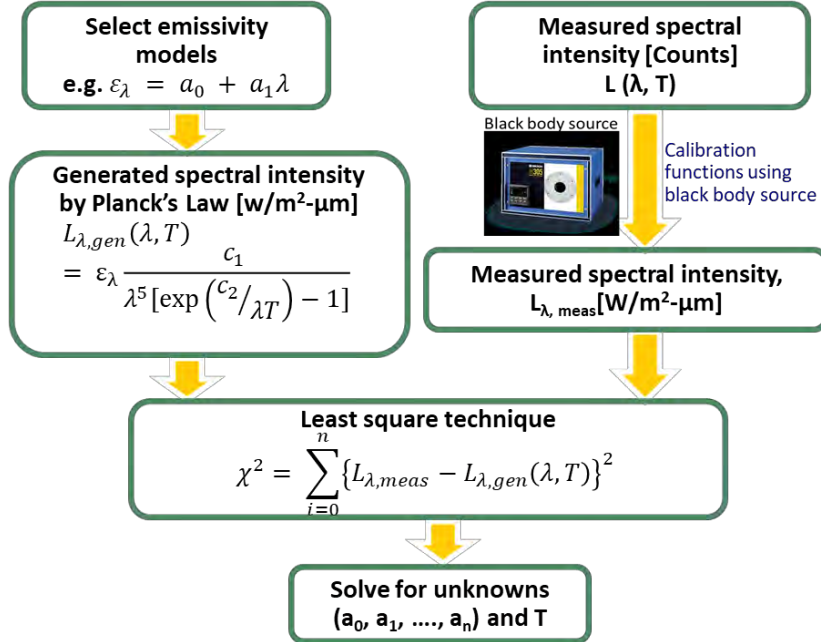
- Other CRADA Diagnostics:**
- Fast EGR (H₂O, CO₂, T, P)
 - Fast PM
 - Fuel-in-Oil
 - SpaciMS, other

Lab Development of In-Cylinder Transient Surface-Temperature Diagnostic

4-BandPass Pyrometry - Filter Selection

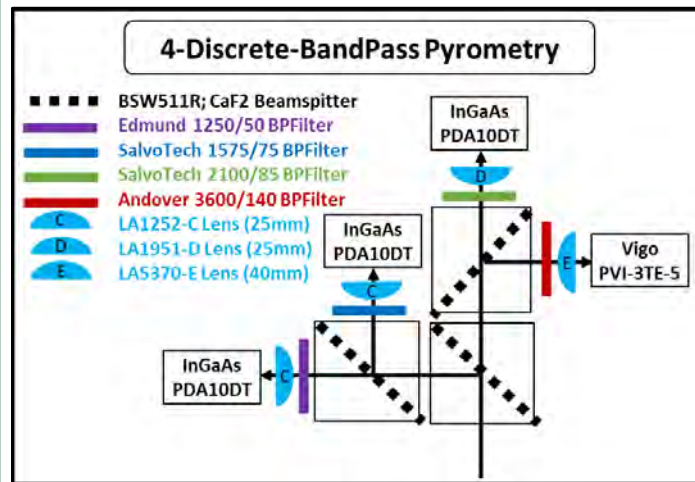
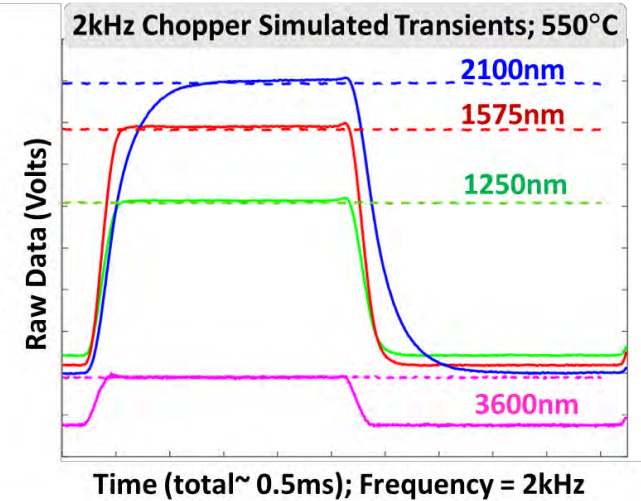


MRT: Multi-spectral Radiation Thermometry



Lab Demo & Validation

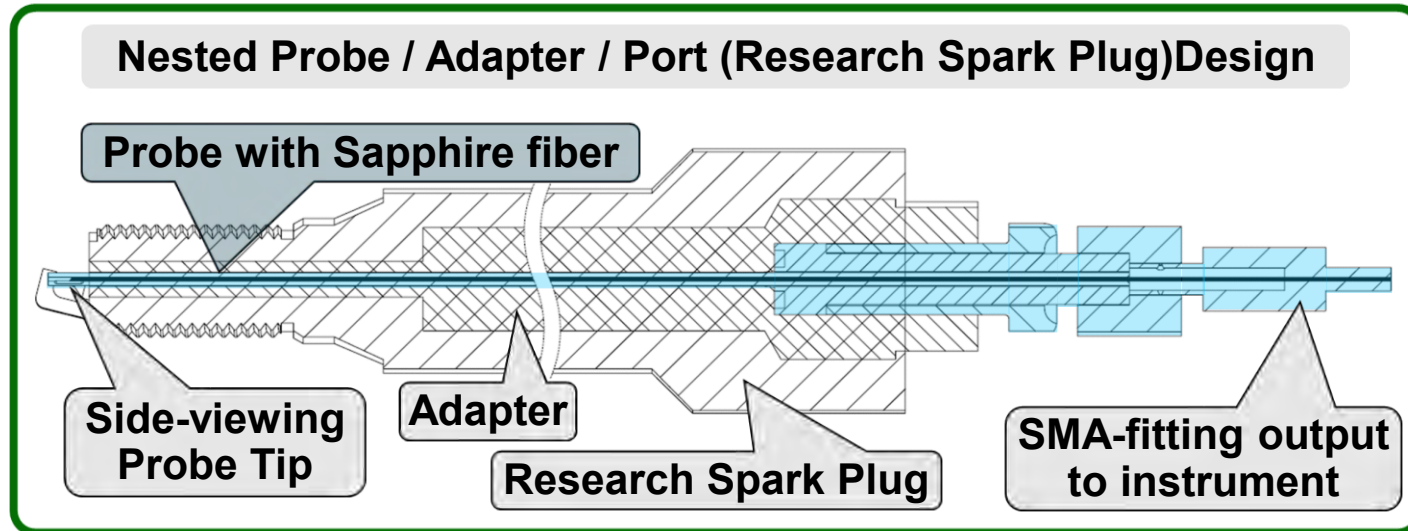
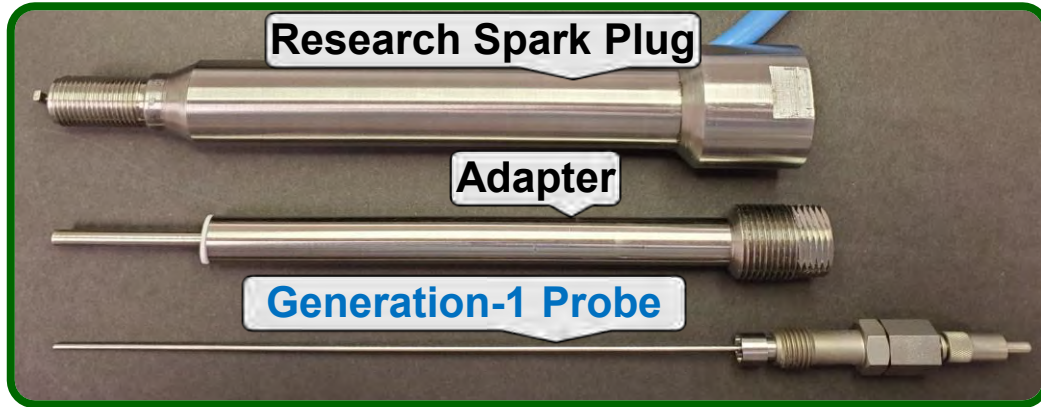
True (°C)	400	448	501	553	601	698	802
MRT (°C)	396	441	490	549	606	715	814
% Error	1.0	1.6	2.2	0.6	-0.8	-2.4	-1.4



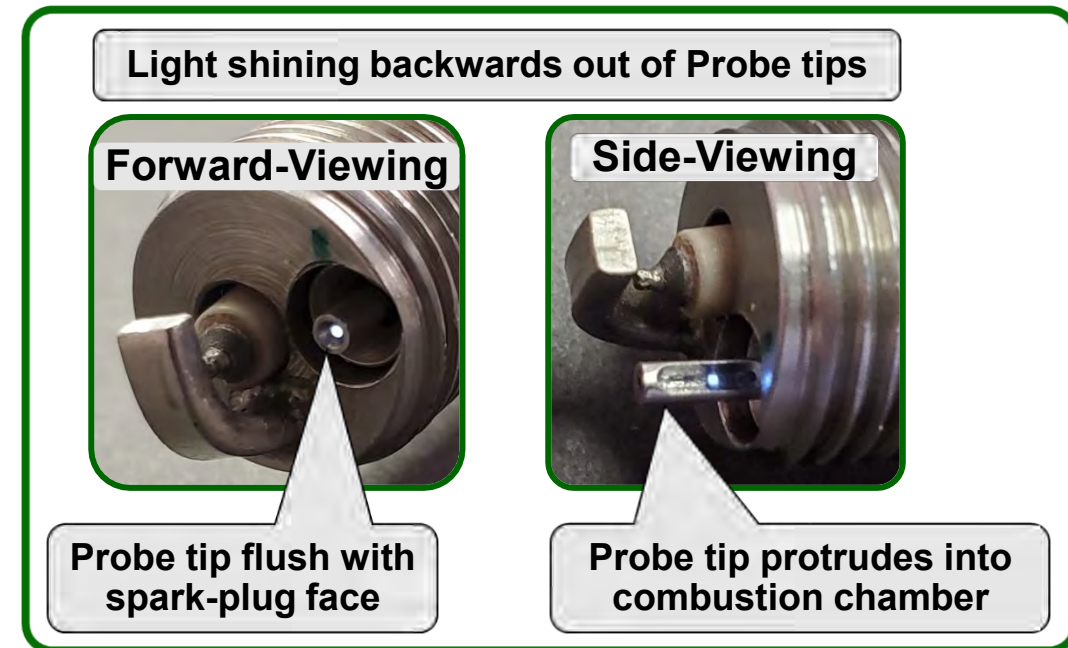
- Select BandPass filters accounting for major combustion species
 - **Rules of Thumb:** Min λ filter number, Max λ spread, uniform λ spacing
- MRT method to solve for Temperature and emissivity
 - 4 unknowns requires 4 bandpass filters
- **>95% Accuracy & >99% Precision for 2 kHz steady state T measurements**
- **Same Accuracy & Precision with 2 kHz chopper-simulated transients**
 - **37-115-μs rise resolved : 0.2-0.7 crank-angle-degrees at 1000 RPM**

Optical-Probe Design for In-Cylinder Measurements

Generation-1 Optical Probe Design

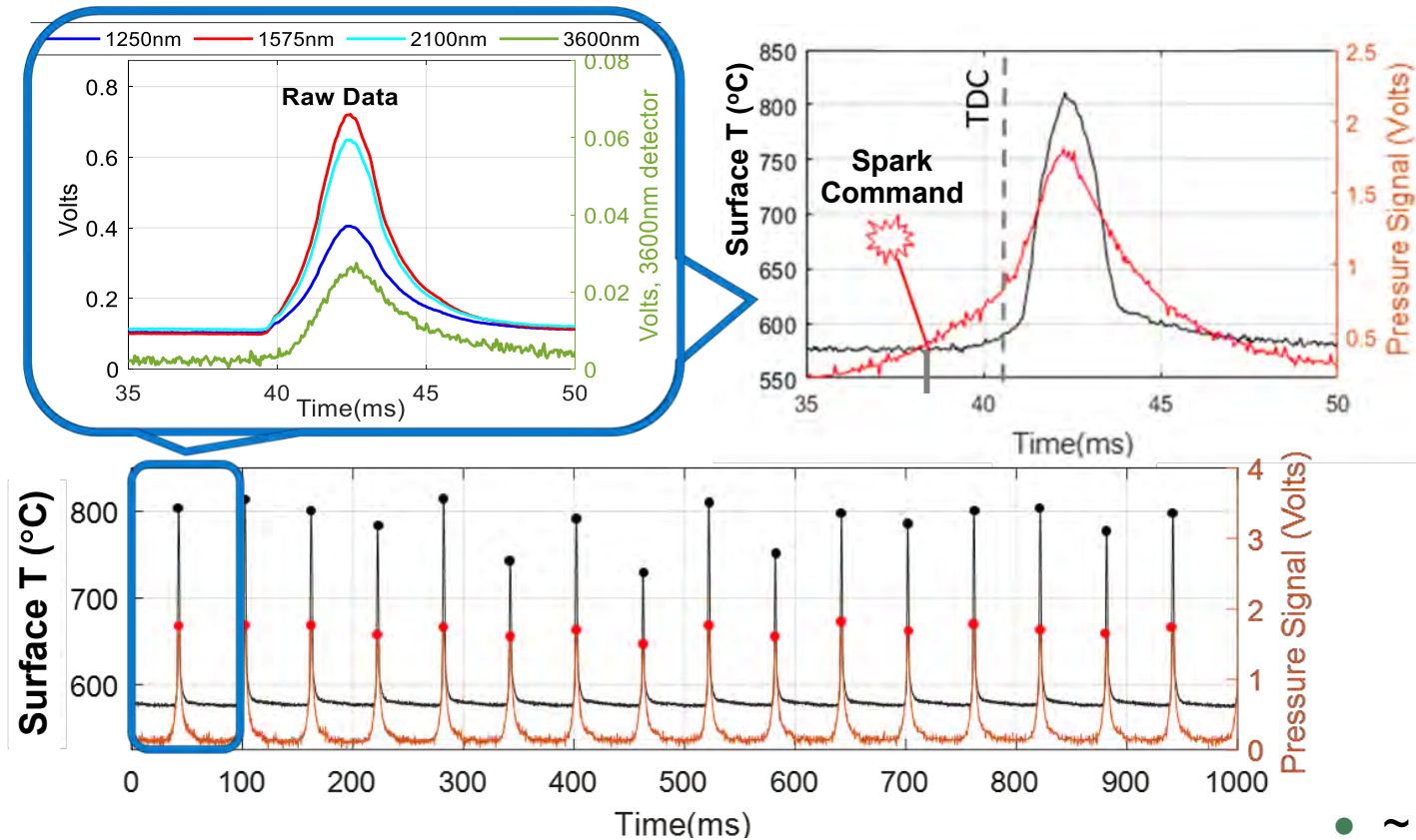


- Generation-1 Probe design
 - **Based on 316SS 1/16-in OD capillary**
 - Provides needed long-deep hole to secure fiber
 - Houses & secures 450- μ m OD sapphire optical fiber
 - Forward- and side-viewing probe tips
 - Link to instrument with optical fiber
- Nested Probe \ Adapter \ Port design
 - Access in-cylinder via port in Research Spark Plug
 - Adapter links Probe to Port

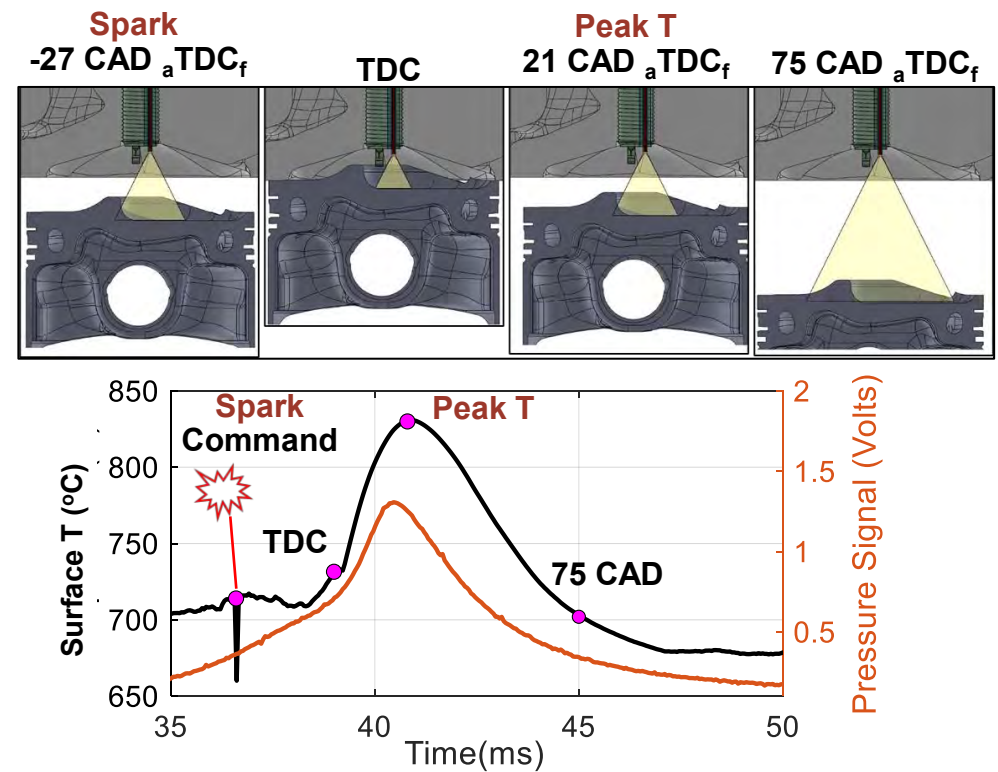


In-Cylinder Surface-Temperature Diagnostic Demonstrated on GM LNF Engine

Side-Viewing Probe



Forward-Viewing Probe



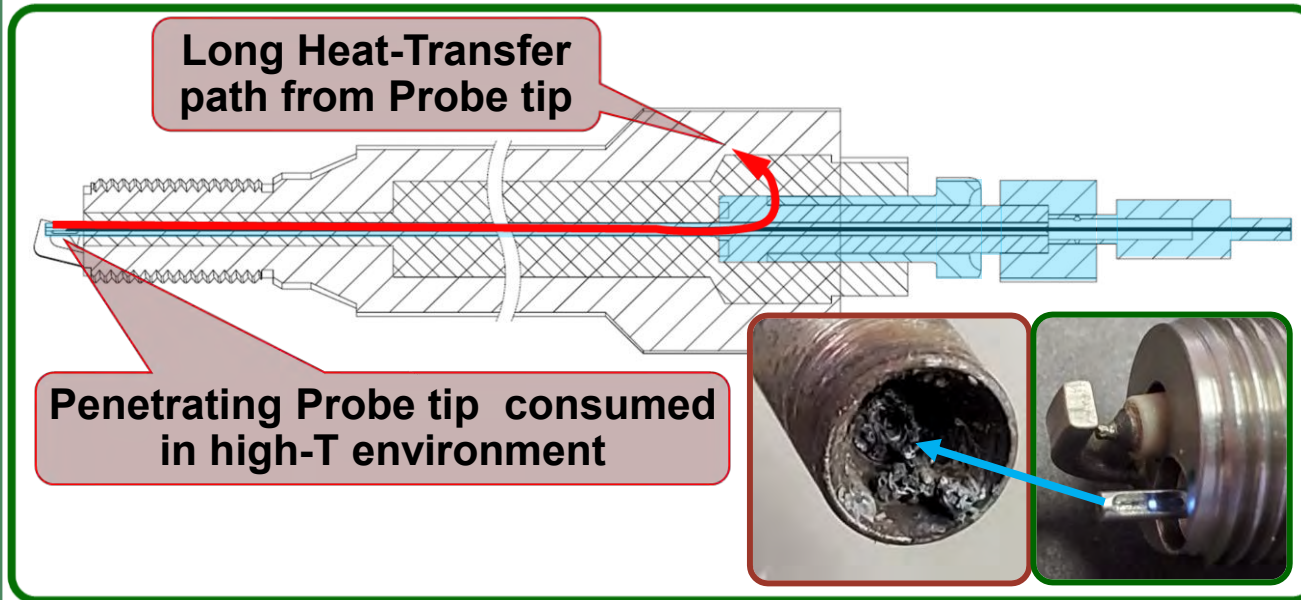
- 4 surface emission signals follow 5-ms (60-CAD) transient
 - Better 3600nm signal should help
- Calculated T synchronous with cylinder-P transient
 - T & P fluctuate together with combustion variations
- To do: compare to measurements & CHT modeling

- ~ Same view factor for Spark & Peak T, different T
- Calculated Piston T consistent expectation
 - Saturated 1575nm signal distorts T transient

**First In-Cylinder Measurements Demonstrated:
Validate, Improve & Apply to Cummins ISB Engine**

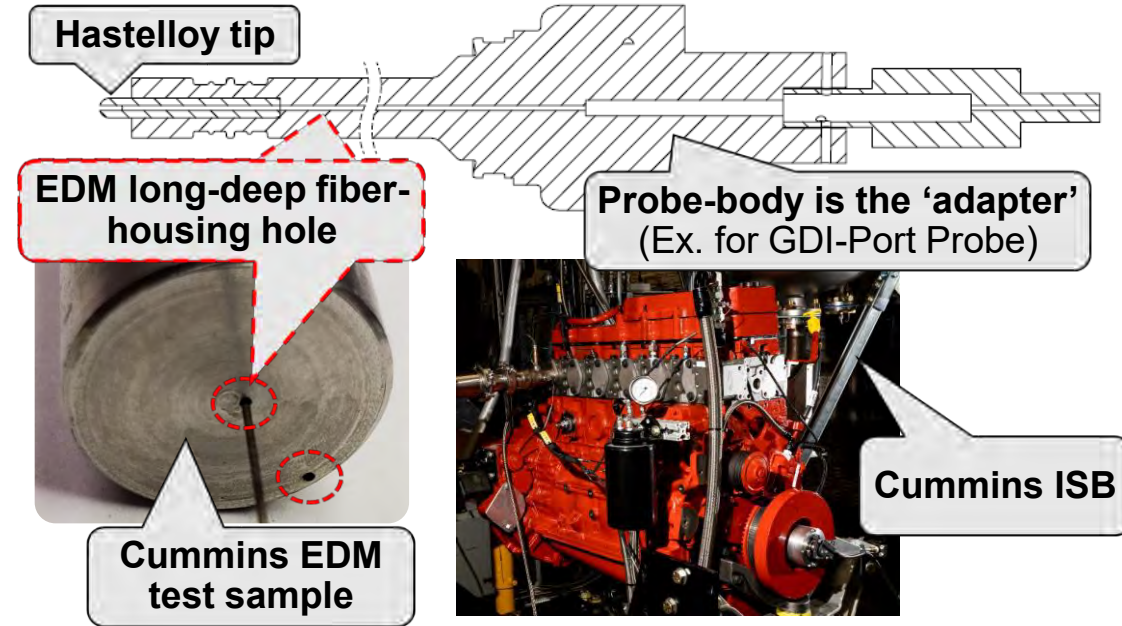
Valuable Findings for Improving Gen-2 Optical-Probe Design for In-Cylinder Measurements

Generation-1



- Forward-viewing Probe worked at low & high load
 - Flush mounted tip is in cooler region
- Side-viewing probe tip failed at high load
 - Probe tip penetrated into higher-T zone
 - **Large HT resistance between Probe tip & heat dump**
 - Penetrating capillary tip overheated and burned
- **Improve heat transfer & material selection**

Generation-2



- **Gen-2 Probe design is more robust**
 - Hastelloy or Inconel penetrating tip as needed
 - EDM fiber-housing hole in larger probe body
 - 0.022-in ID, 4.25-in long hole in 304SS demonstrated!
- Cummins leading ISB-Probe & head access design
- **Demo on ORNL ISB in Q4-FY21 (Milestone)**
- **Campaign at Cummins Technical Center Fall '21**
 - Compare to Cummins' CHT surface-T calculations

Task 2 - Neutron diagnostics targeting applications to MD/HD engine components

Martin Wissink, PI

End-of-Project Goal: Demonstrate applicability of neutron diagnostics to challenges in MD/HD engine components

Neutron Imaging at ORNL's High Flux Isotope Reactor (HFIR)*



HFIR is the highest flux reactor-based neutron source in the US
Neutron imaging at HFIR CG-1D Beamline

Neutron Computed Tomography (CT)



Highly penetrating and non-destructive technique for obtaining finely resolved geometric information (50-100 μm) over a large field of view (7 x 7 cm)

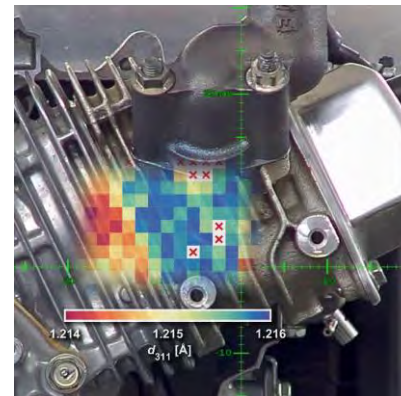


Neutron Diffraction at ORNL's Spallation Neutron Source (SNS)*



SNS is the world's most intense pulsed neutron source
Neutron diffraction at SNS VULCAN beamline

In-situ strain/stress/temperature measurement in running engine



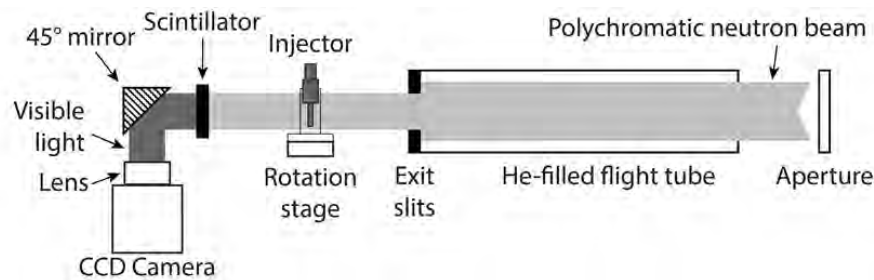
- Neutron diffraction can directly measure **lattice strain** inside bulk materials
- With known material properties, this can tell you both the **temperature** and **stress** throughout the entire volume of a part
- Can be done under **dynamic conditions**, and even in **moving parts**

Neutron imaging offers many potential applications to MD/HD engine components

- Neutrons have the unique ability to see hydrocarbons through metal with high contrast
- Cold neutron imaging at ORNL's High-Flux Isotope Reactor (HFIR) can investigate internal geometry and dynamics in regions not accessible to other diagnostics
- Explore feasibility of applying techniques demonstrated on GDI to diesel injectors

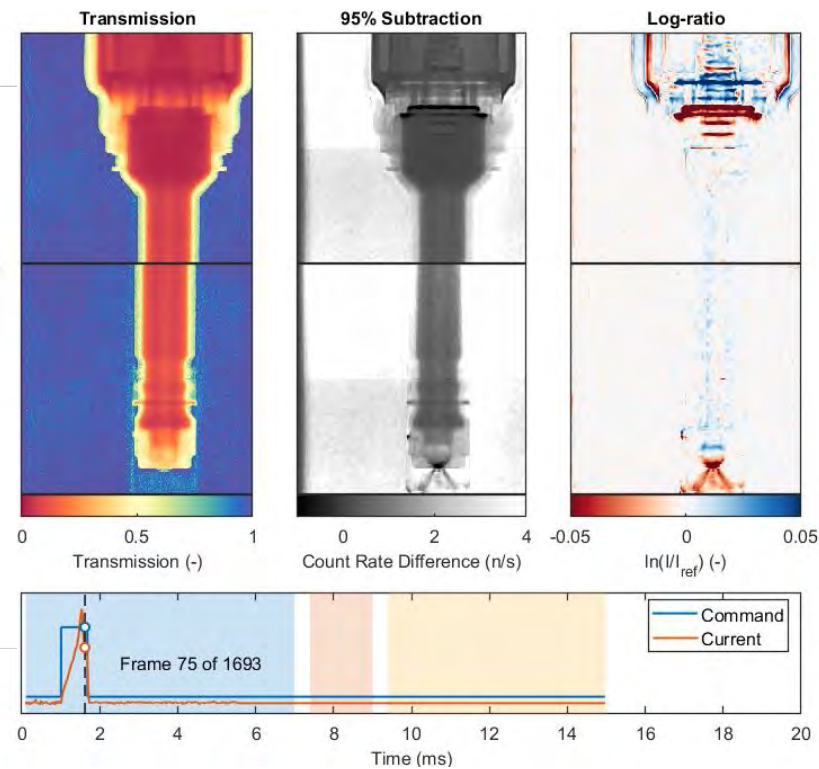
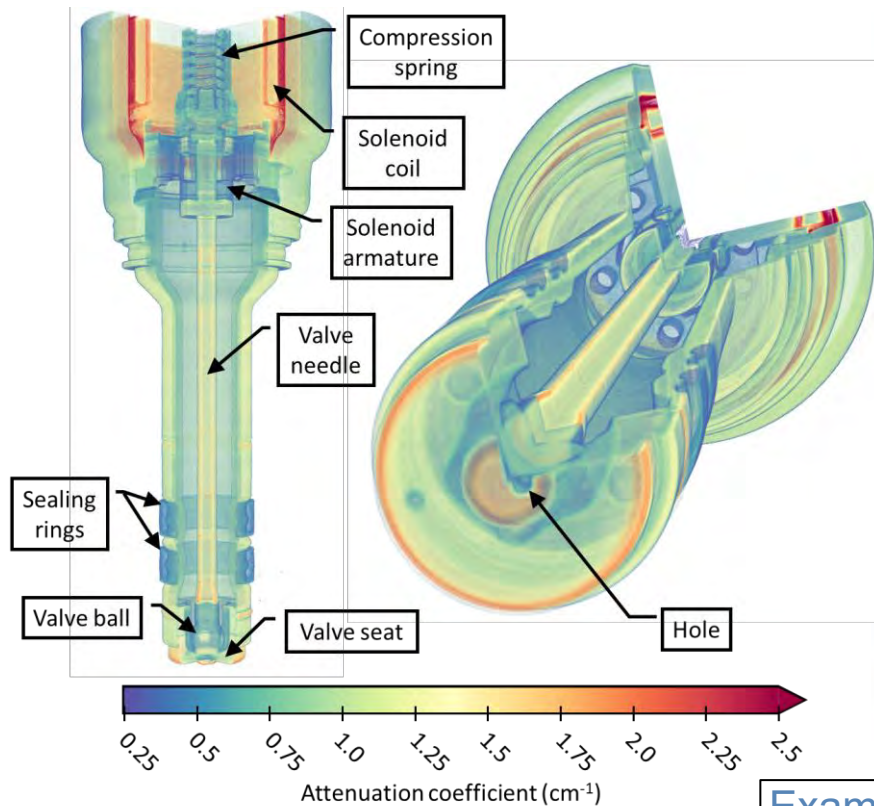
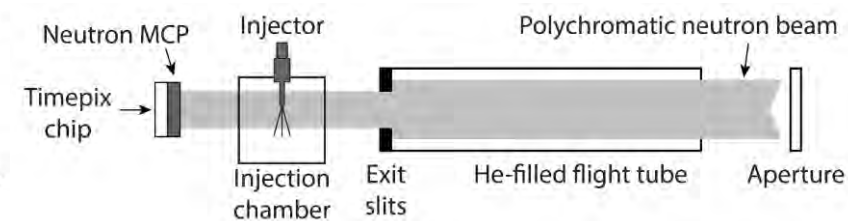
Neutron computed tomography

Detailed geometric information in thick metallic samples

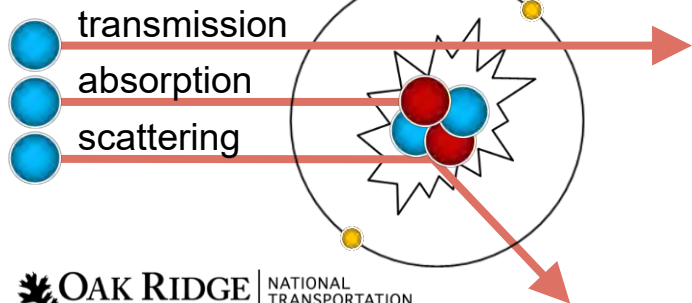


High speed neutron imaging

Mechanical and fluid dynamics inside metal devices



Neutrons



Injectors push the temporal and spatial resolution limits of diagnostics

– good test case for applicability of neutron imaging to MD/HD engine components

- Proof of concept: two-part CT scan* was performed on ECN diesel injector to determine what features can be resolved and to inform creation of an internal hydraulic model
- All components are visible, and volume/area of all flow passages and chambers are quantifiable
 - Inlet and outlet orifices from control chamber are too small to resolve with existing detector
 - New detector is currently being commissioned and expected 2-3x improvement in spatial resolution

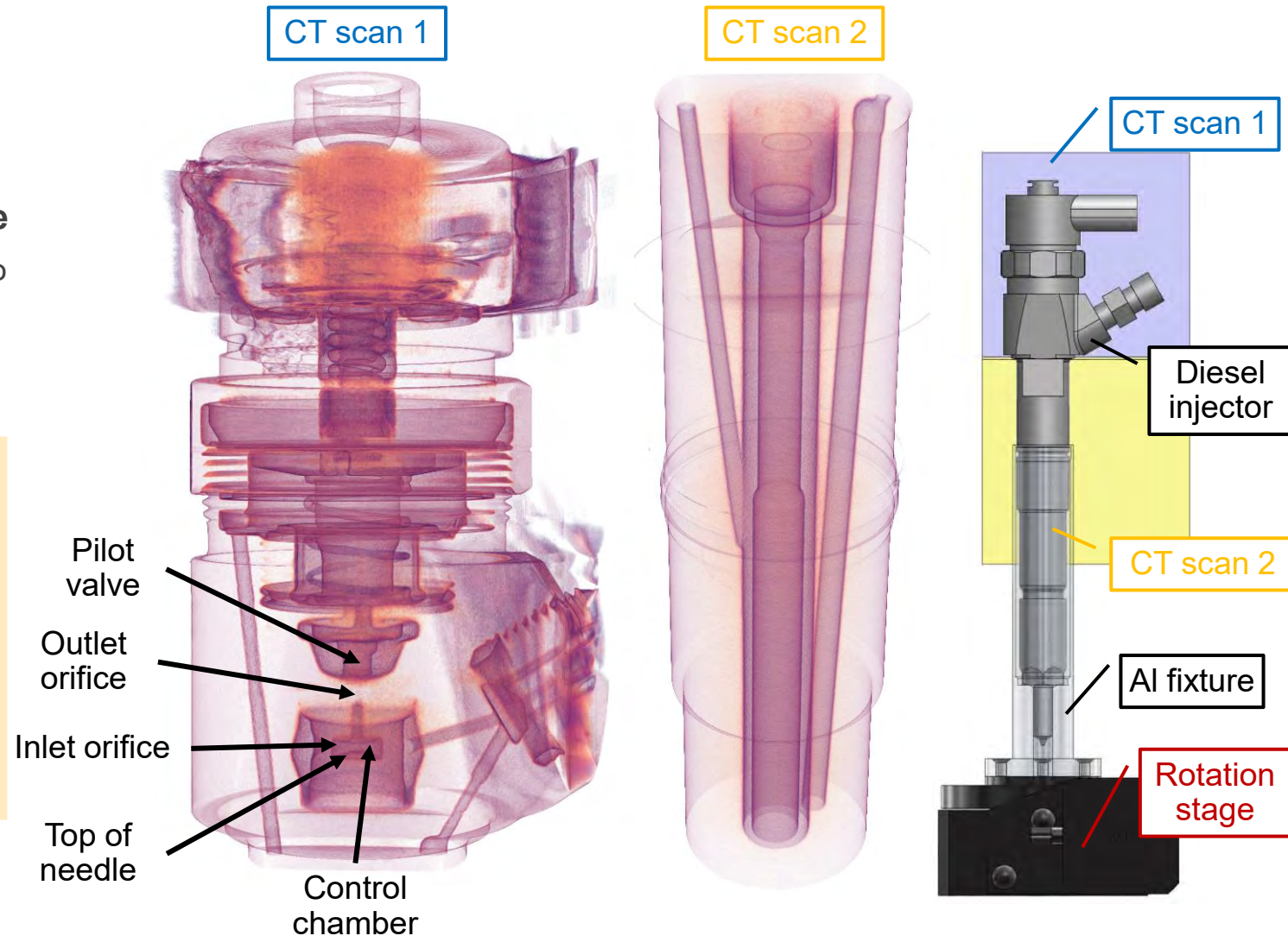
Non-destructive neutron imaging diagnostic opportunities include:

- Geometric characterization
- Internal deposits – from nozzles to armature
- High-speed actuation dynamics

All have impacts on spray, repeatability, durability

*Backup Slide on Neutron Computed Tomography Scan details

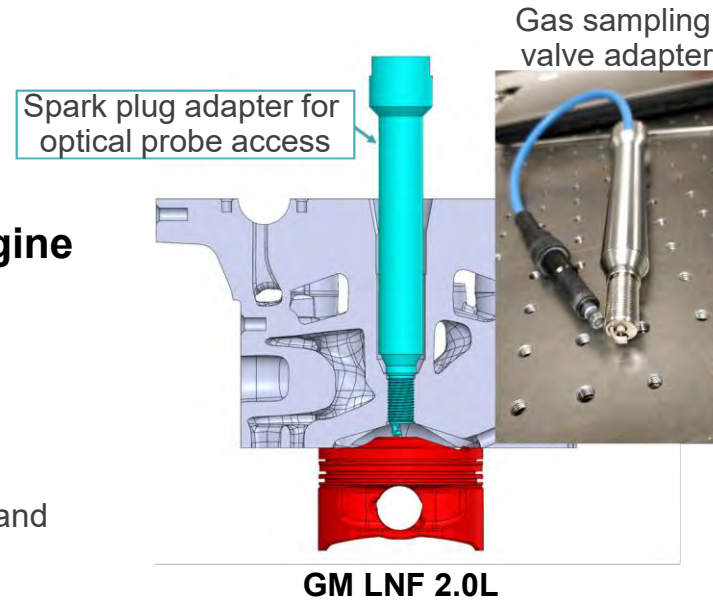
CT Reconstruction of ECN diesel injector 210679



Combine Task 1 Optical Temperature Diagnostic with “Neutronic Engine”

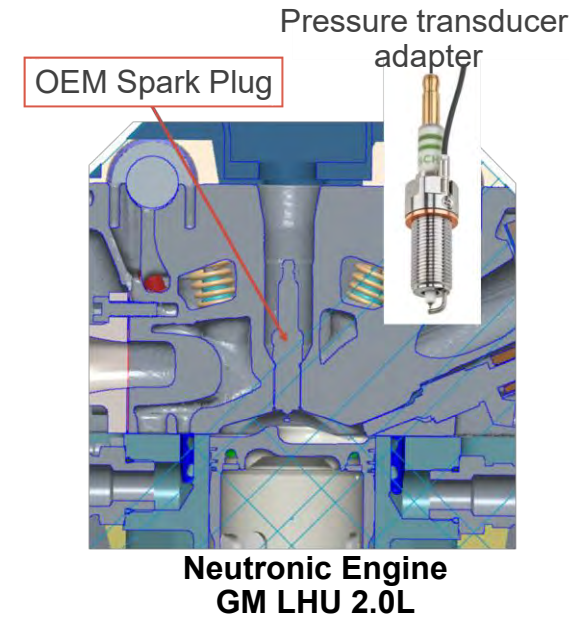
- **Neutronic engine being developed at ORNL within the PACE consortium (ACE145)**
 - Will enable time-resolved measurement of temperature at locations **inside** the metal components of the engine using neutron diffraction
 - Simultaneous application of the two diagnostics for critical boundary condition data **on surfaces** and **within components** in running engines
- **Current task is to modify probe for use in neutronic engine**
 - Analyze all materials to identify potential concerns with neutron activation, attenuation, or scattering
 - Mitigate potential for neutron damage to electronics
 - Verify operation of the optical probe in the neutronic engine
- **Calibration experiment being designed***
 - Provide a controlled environment to co-validate the optical diagnostic and the neutron diagnostic using a pulsed laser heat source with a high temporal resolution heat flux probe
 - Establish data alignment, binning, reduction, and validation approaches

Existing probe mount for LNF engine



GM LNF 2.0L

Potential mounting solution for neutronic engine

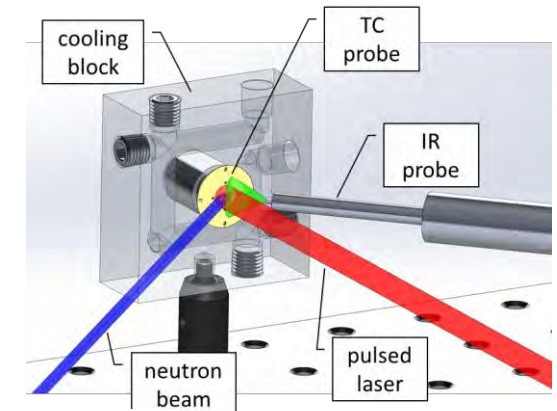


Neutronic Engine
GM LHU 2.0L

PACE heat flux probe



Multi-modal calibration experiment*



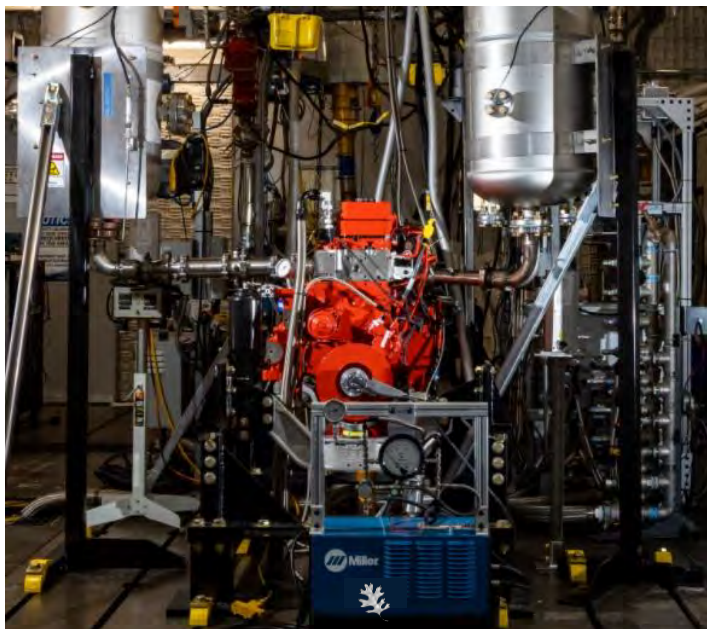
FY21	FY22	FY23	FY24
Current program	Future planning*		
Demonstrate optical probe in neutronic engine	Calibration experiments	Operando time-resolved measurements inside combustion chamber in both static and moving components	Develop MD/HD configuration for neutronic engine (modular platform)

Task 3: Next generation LTC engines for MD/HD Vehicles: Gasoline Compression Ignition (GCI)

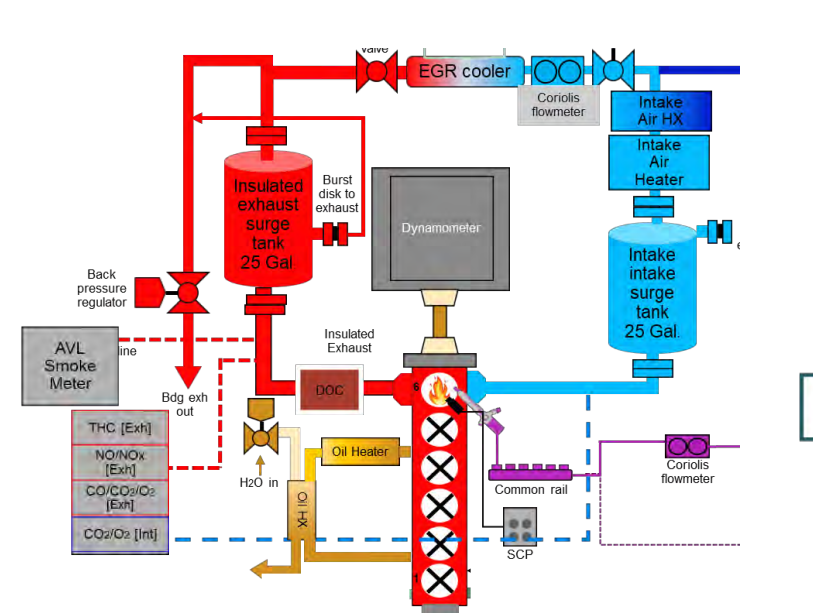
Scott Curran, PI [Brian Kaul, Chloe Lerin]

End-of-Project Goal: Experimentally demonstrate a pathway to improved engine efficiency with gasoline-range fuels and help determine whether LTC might represent a pathway to meet and exceed future emission targets.

FY20/21 – Low-load GCI experiments using a Single-Cylinder Engine Platform



Single-cylinder Cummins ISB platform at ORNL used in FY20 experiments



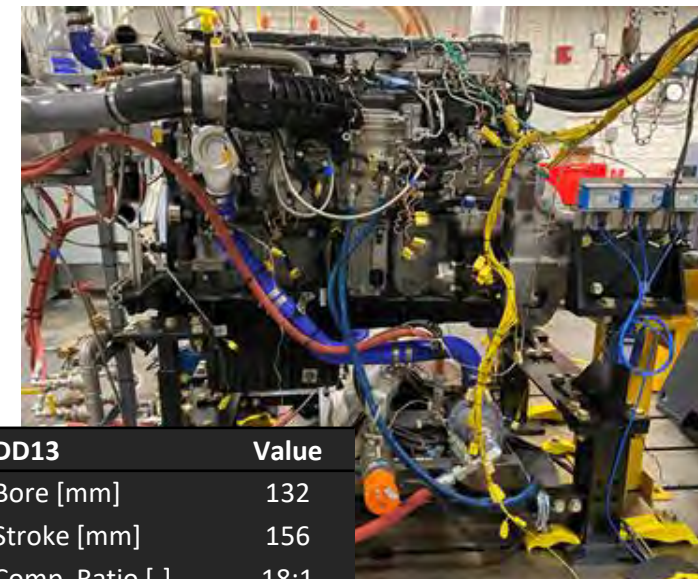
Cummins ISB	Value
Bore [mm]	107
Stroke [mm]	124
Comp. Ratio [-]	20:1
Disp. (1-cyl) [L]	1.12

Single Cyl MD Diesel Engine

E0 Gasoline	Value
RON	91
MON	83
AKI	87
T10/50/90 [°C]	45/98/161

Regular-Grade Gasoline

Late FY21 – Transient GCI using a Multi-Cylinder Engine Platform



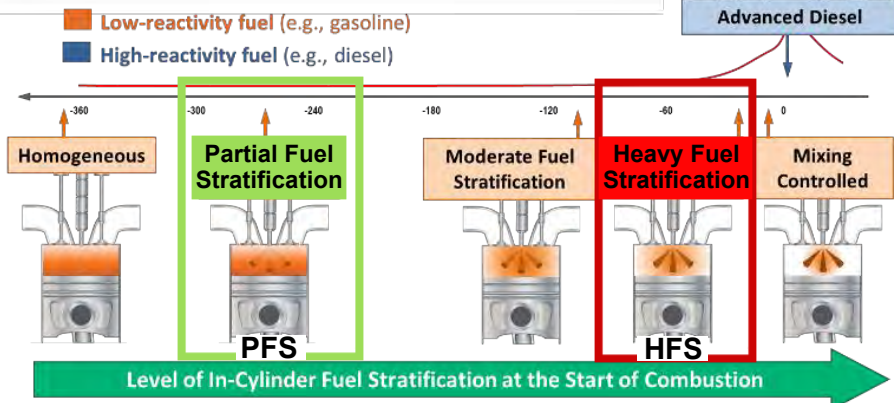
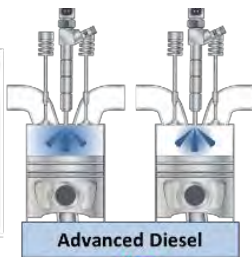
DD13	Value
Bore [mm]	132
Stroke [mm]	156
Comp. Ratio [-]	18:1
Disp. (1-cyl) [L]	2.13

Multi-cylinder Detroit DD13 platform at ORNL for use in FY21 experiments

Translation of PFS and HFS Strategies with Market-Grade Gasoline to MD Single-cylinder Engine

Goals of SCE GCI Research

- Evaluate ability of **conceptual model of GCI fuel-air stratification**/ previous strategy development to **translate to MD/HD platforms**
- Low-load LTC requirements for PFS and HFS**
- Low-load control authority** [next slide]
- Compare the findings from previous ORNL LD GCI to new MD single-cylinder research platform*



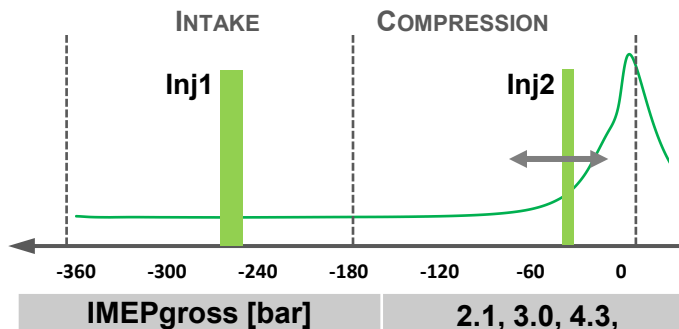
Single-Cylinder MD GCI Experiments

Stratification Levels	HFS, PFS
Fuel	87AKI E0 Gasoline
Engine speed [rpm]	1200
IMEPgross [bar]	2.1, 3.0, <u>4.3</u> , 8.7, 10.0
Fuel System	Stock diesel injection
CR [-]	20:1

Figure | Dempsey, Curran, Wagner, IJER - <http://ijer.sagepub.com/content/early/2016/01/14/1468087415621805.full.pdf+html>

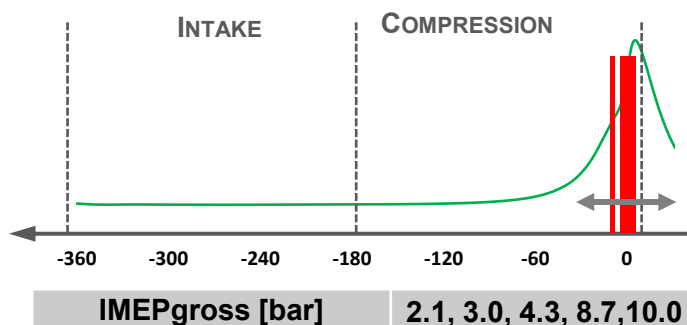
Successful strategy translation

PFS Injection Strategy



LTC levels of soot/NOx, but limits on load (MPRR limit)/ controllability

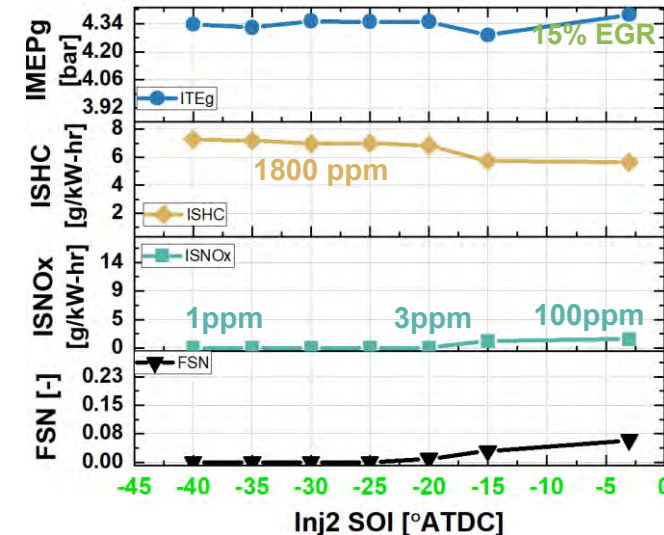
HFS Split Injection Strategy



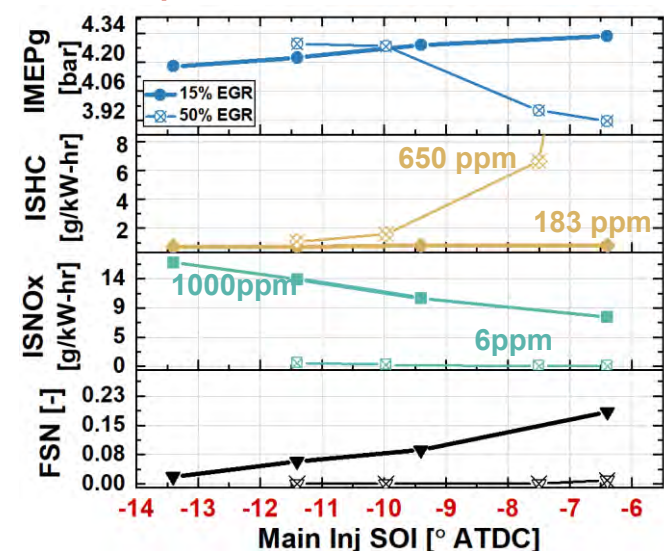
50% EGR levels required for LTC levels of soot/NOx
Strong control authority

LTC requirements at lower loads

1200rpm, 4.3 bar IMEP, 1.12 bar boost

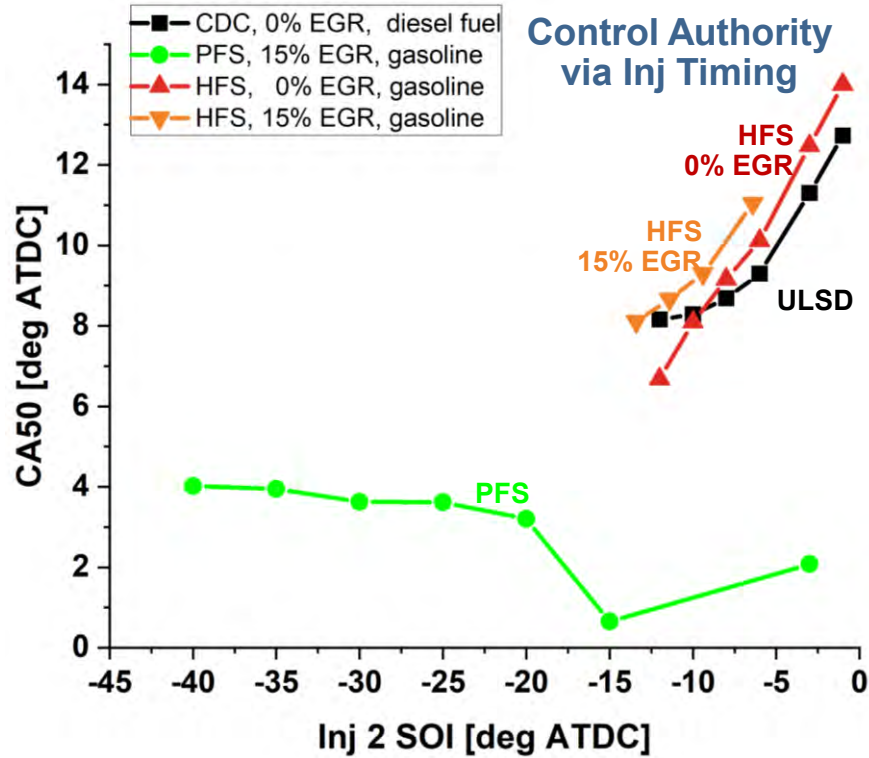


1200rpm, 4.3 bar IMEP, 1.12 bar boost

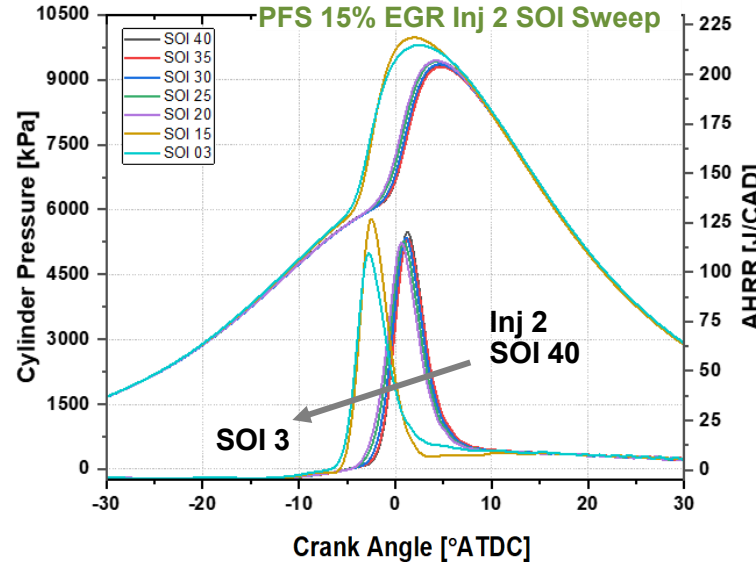


HFS: Diesel-like CA50 vs. SOI Response, PFS: Lack of Control Authority at Low Boost Levels

- Experimental investigate GCI fuel stratification bookends at low loads/ moderate/low boost
- Previous GCI research has shown operability challenges with market-grade gasoline at low loads

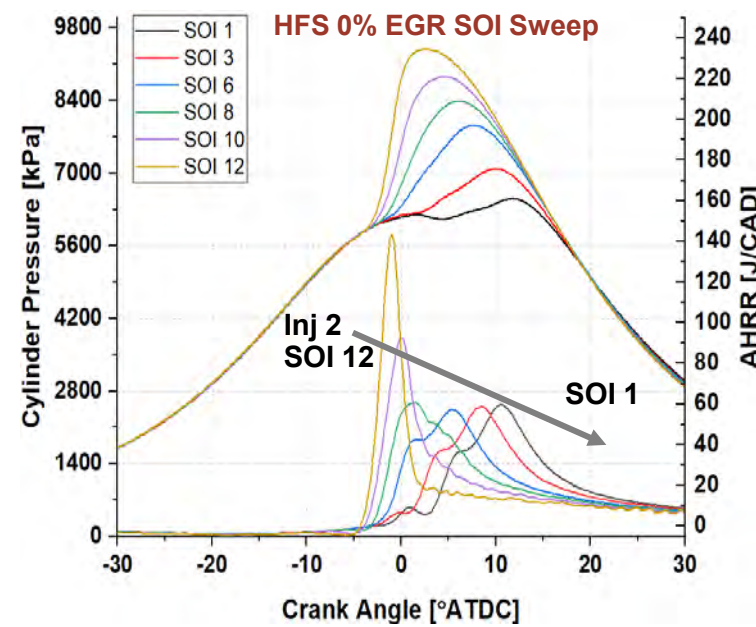


Engine Speed [RPM]	1200
Engine Load [IMEP_gross]	4.3 (target)
Intake/Exh Back Press [kPa]	1.12/1.31
Intake Manifold Temp [°C]	60



PFS

- Lack of control authority with Inj2 SOI with moderate boost levels
- Operable PFS range decreased with increased compression ratio compared to previous LD experiments [at MPRR limit]



HFS

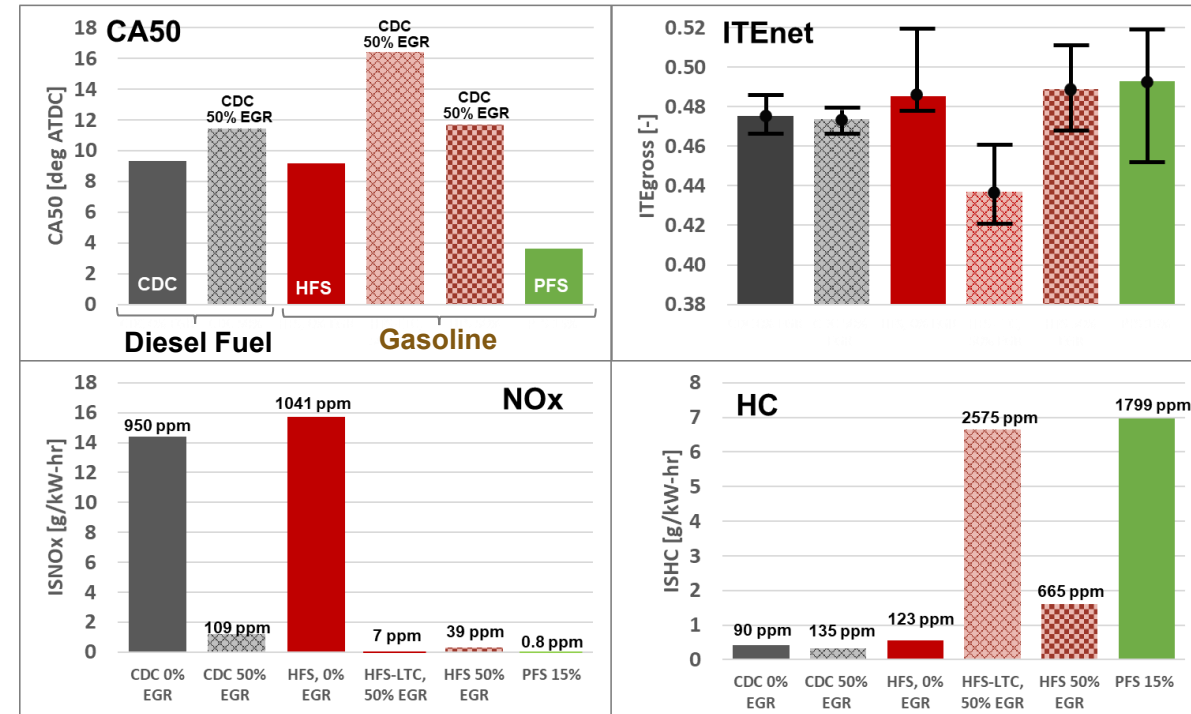
- Diesel-like control authority over combustion phasing with low FSN and high combustion efficiency
- Combustion phasing response with SOI timing still strong at 50% EGR levels required for LTC levels of soot/NOx

Single-Cylinder Experiments Bridge Previous Work to Multi-cylinder HD GCI Experiments

Current single-cylinder GCI experiments*

- **GCI injection strategies mapped successfully to MD engine**
- **HFS operation**
 - Improved combustion efficiency compared to previous work [back-up slide]
 - Improved ability to drive LTC with 87AKI gasoline (longer ignition delay) with MD combustion chamber and improved control over air handling
 - High load GCI demonstrated (not shown here) for HFS (not LTC)
- **PFS Operation**
 - High load operability reduced with higher compression ratio
 - Low load PFS improved combustion efficiency compared to previous work
 - 1-3 ppm NOx demonstrated

*Additional experimental results and details in 2021 Winter AEC presentation and upcoming SAE PFL paper



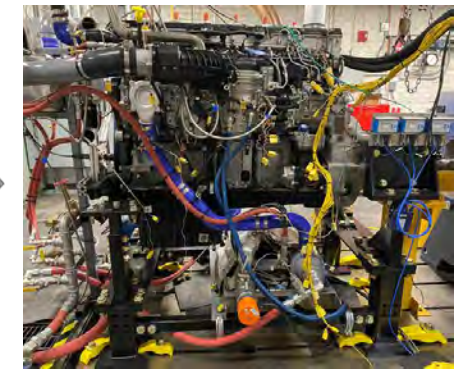
Comparison of selected 1200 rpm, 4.3 bar IMEPg, points across modes

Next challenges to be investigated Multi-cylinder GCI experiments**

- Load and speed limits for full map GCI
- Further investigation in load/speed impacts on control authority
- Engine system transient performance characteristics of GCI
- **Multi-cylinder experiments underway at time of reporting**



Single-Cylinder GCI



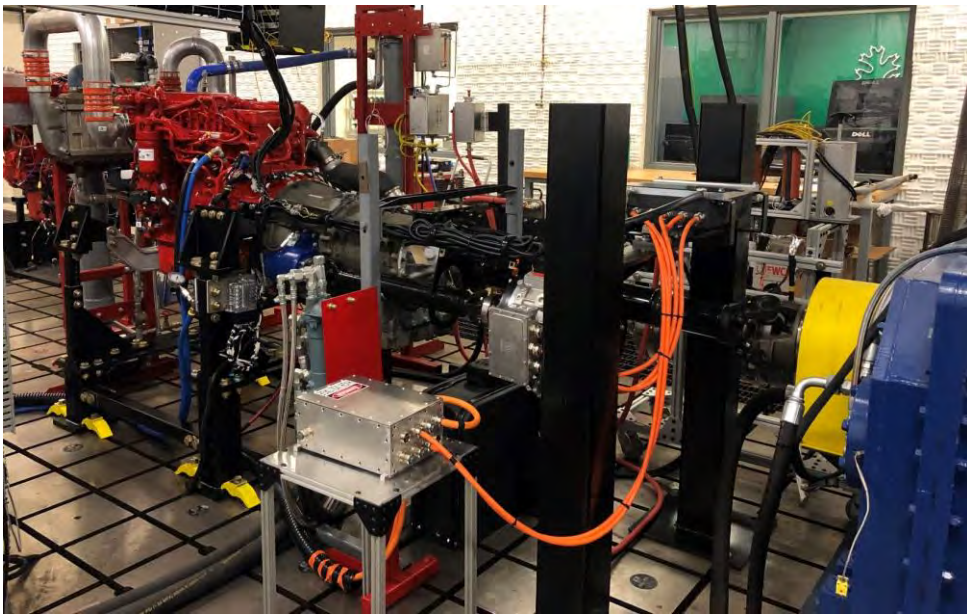
FY 21 Multi-Cylinder GCI

Task 4: Challenges Of Cold-start /Restart for Electrification of MD/HD Powertrains

Melanie Debusk, Scott Curran, Co-PI's [Chloe Lerin, Vicente Boronat, Brian Kaul, Dean Deter, Adian Cook]

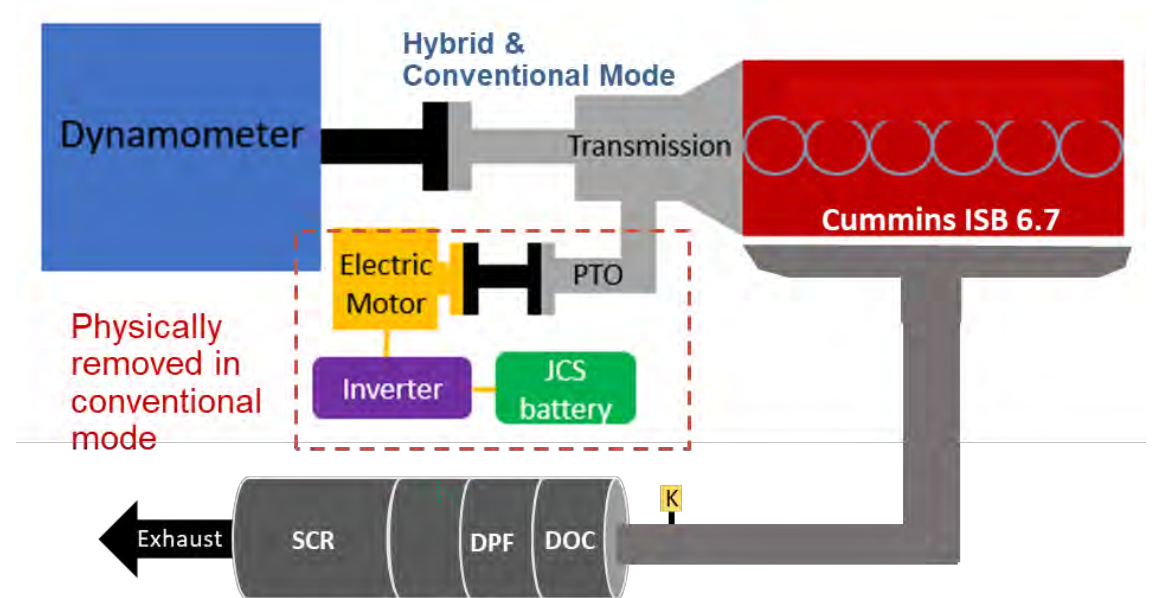
End-of-Project Goal: Provide combustion and emissions data sets, including restart scenarios, with hybrid truck architectures using advanced hardware-in-the-loop (HIL) laboratory.

Hardware-in-the-loop engine experiments



- **Transient MD/HD experiments hybrid/electric-capable heavy-duty powertrain laboratory**
- **Conventional, hybrid and start-stop combustion and emissions data sets over Heavy Heavy-Duty Diesel Truck (HHDDT) cycle**

Pre-production hybrid system with MD engine

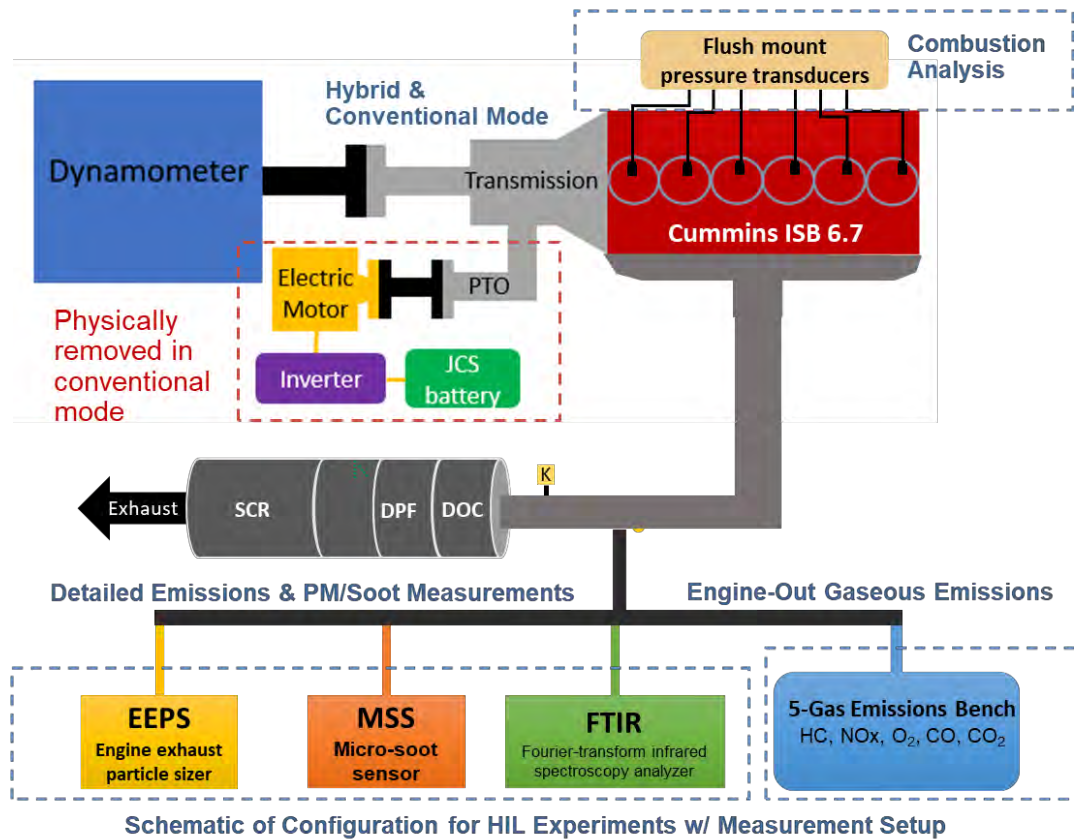


- **Cummins ISB 6.7L diesel engine (107 mm bore)**
 - Stock engine and engine controller + aftertreatment system
 - No changes to ECU for hybrid or start-stop
- **Pre-production parallel hybrid drive system***
 - From previous FOA project w/ Odyne Systems LLC + partners

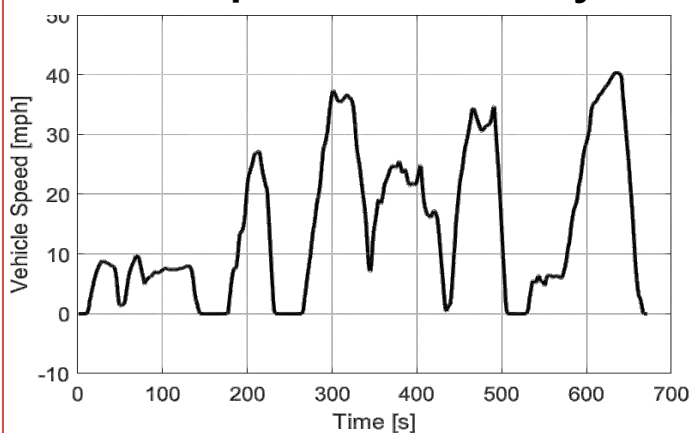
Extensive Combustion and Emissions Data Sets for Conventional and Hybrid Modes

Detailed Data Set Summary

Mode/Data	Combustion (all 6 cylinders)	Particle Number	Soot	NOx (NO + NO ₂)	THC + FTIR HC speciation	Fuel Consumption
Conventional	✓	✓	✓	✓	✓	✓
Hybrid	✓	✓	✓	✓	✓	✓
Stop/Start (SS)	✓	✓	✓	✓	✓	✓
Hybrid +SS	✓	✓	✓	✓	✓	✓



Transient portion HHDDT cycle



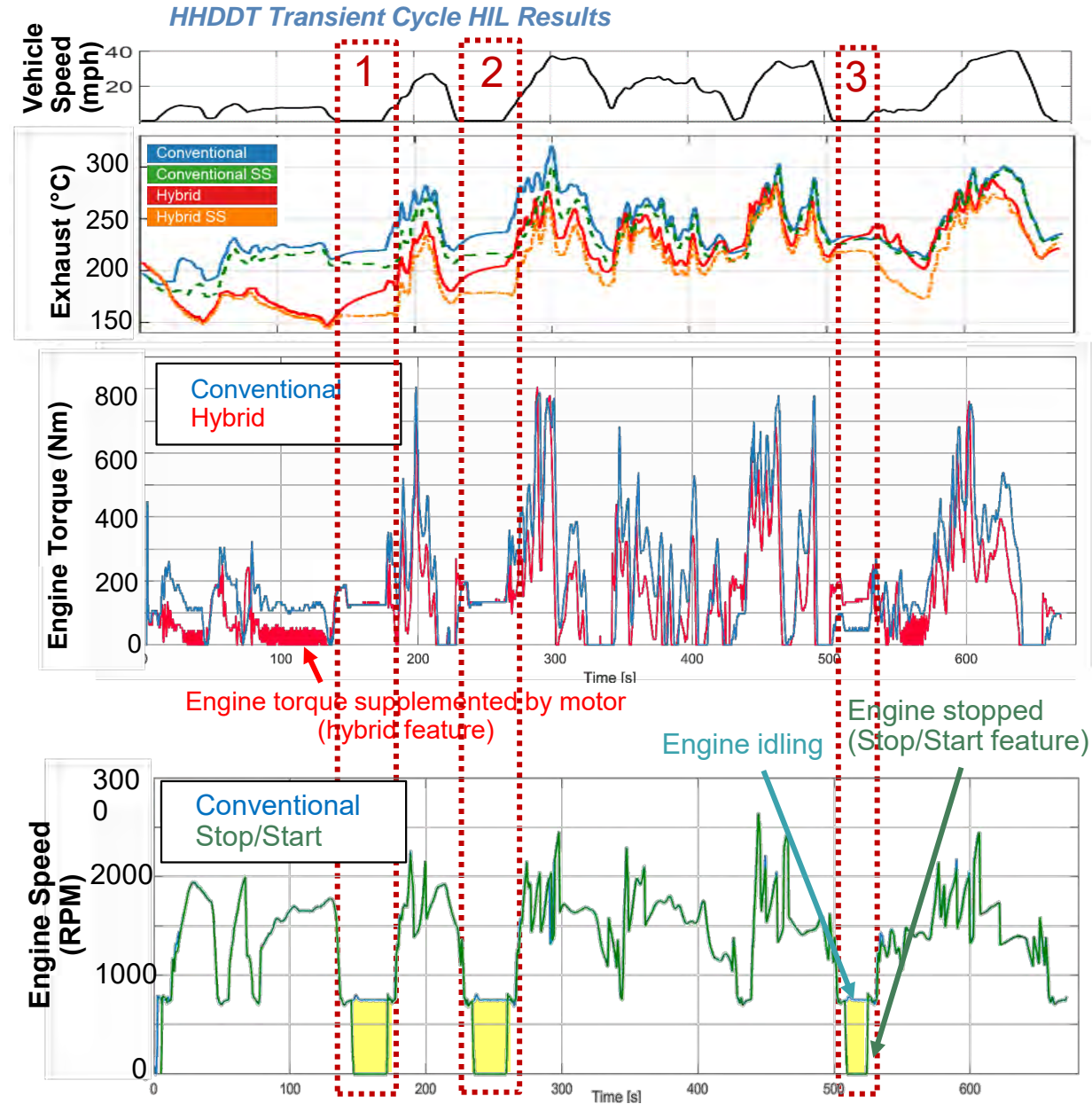
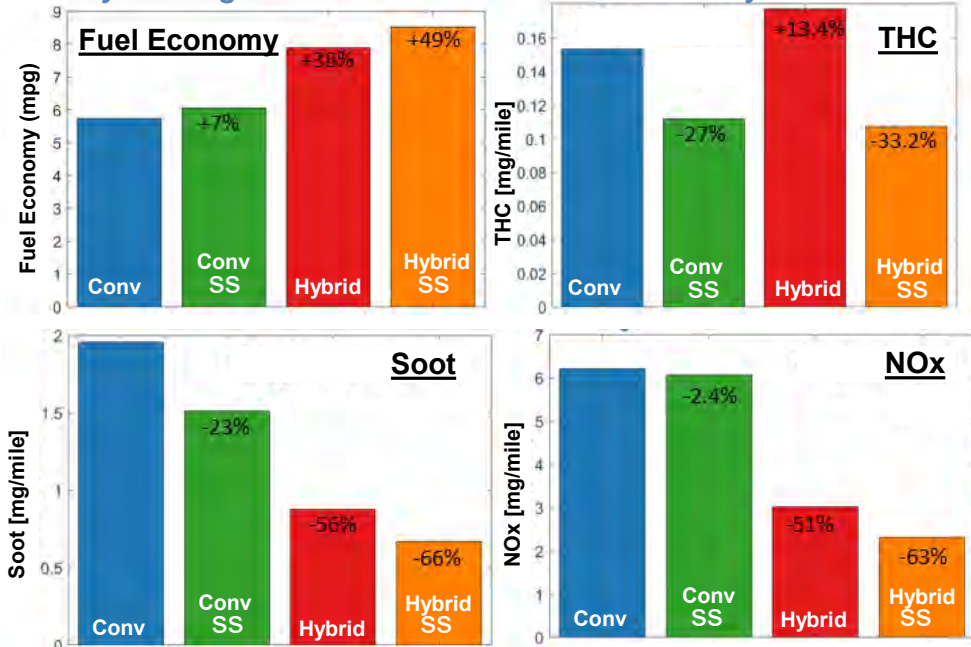
Parameters	HHDDT Transient
Duration [s]	668
Distance [mi]	2.85
Average Speed [mph]	15.4
Stops/mile	1.8
Max. Speed [mph]	47.5
Max. Acceleration [mph/s]	3.0
Max. Deceleration [mph/s]	-2.8
Percent Idle [%]	16.3

- Studied impact of different levels of electrification using 4 different medium-duty powertrain configurations
- Unique datasets containing combustion, emissions, and powertrain system data:
 - *Data sets are being made available*
- Publications in progress: 2021 ASME ICEF manuscript submitted

Conventional and Hybrid Modes With and Without Start/Stop have Trade-offs

- **Configuration impacts fuel demand**
 - Lower exhaust temperatures increase thermal management (TM) use to heat up catalysts = \uparrow fuel demand
 - Use of electric motor = \downarrow fuel demand
- **Net gain in fuel economy and lower NOx and soot emissions with exhaust temperature/fueling trade-offs**
 - SCR thermal management critical aspect.
 - Further optimization of the engine system is possible
- **Synergistic Benefits from combining Hybrid and Stop/Start (SS)**

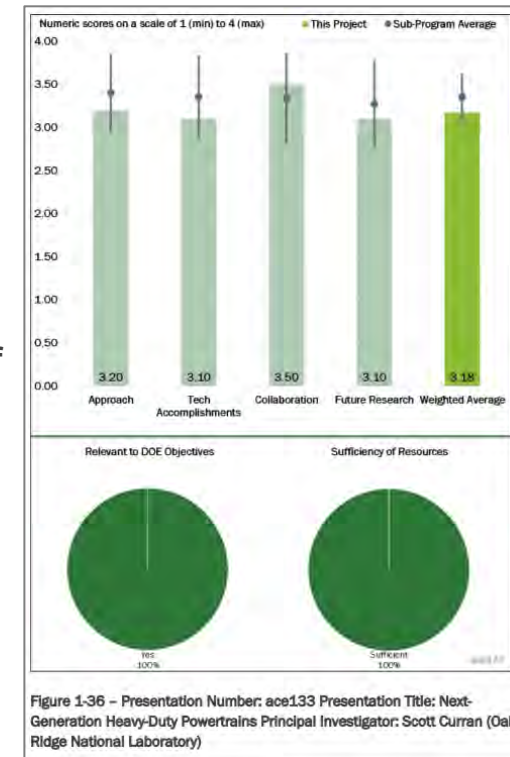
Cycle integrated values over HHDDT transient cycle distance



Responses to Previous Year Reviewers' Comments [2019 Reviewed]

- **Positive comments regarding scope, focus, coordination and engagement with stakeholders.**
- **Reviewers noted opportunities for improvements in task-to-task links**
 - Increased task-to-task links since FY 19 detailed in Collaboration slide
- **Task 1 focus on new diagnostics, different instruments are discussed, but not clear to the reviewer how these specific measurements are connected to key overall technical barriers and why they were chosen as key measurements of focus.**
 - The CRADA focuses on development and applications of advanced instrumentation to (1) identify origins and mitigate combustion variations and (2) address critical barriers to market penetration in collaboration with industry partners needs.
 - In-situ deployable temperature diagnostic in combination of diagnostic and neutron diffraction vital for CHT modeling
- **Task 2, the science application of neutron imaging was interesting, but not clear how development of high-fidelity models of injection hardware contributes to improved understanding of the combustion processes and improved efficiency**
 - The first phase of the project was to improve hydraulic models of MD-HD fuel injectors. The project scope as been modified due to feedback and budget changes to link neutron diagnostics via diffraction with Task 1 temperature probe using the “neutronic engine,”
- **Task 3, the discussion of which LTC strategies will be applied was not very clear to the reviewer, who stated that the range of concepts that could be employed is quite broad. For Task 3, Next Generation LTC Engines for MD and HD, the reviewer suggested not worrying about NOx emissions as much as understanding how to burn gasoline-like fuels in a HD engine.**
 - After reviewing feedback, Task 3 prioritized on translating previous experience with gasoline-like fuels in MD-HD engines. Focus on aspects of cyclic variability, low load performance and control authority over combustion phasing.
- **Task 4, Cold-Start and Restart for Electrification of MD and HD Powertrains, the reviewer said that the end goal of providing combustion and emissions data during restarts with electrified powertrains is likely very sensitive to the base-engine calibration and restart-operation strategy.**
 - This was valuable feedback. A pre-production prototype parallel hybrid system from a previous project was leveraged to provide real-engine system data sets that focused on the resultant changes to engine operation and not the calibration. These data sets will be made open to stakeholders.

Project was not reviewed in 2020 – last reviewed in 2019



Source| Vehicle Technologies Office 2019 Annual Merit Review Report

Collaborations and Coordination with Other Institutions

Leveraging collaborations:

- 21CTP, Advanced Engine Crosscut, IEA Combustion Task

15 Industry partners in the AEC MOU

- Meet two times a year to share information with industry partners
- Other national labs and University partners as well

Task specific collaborations include industry partners and task-to-task links

1: Advanced diagnostics + Cummins CRADA

- Cummins - Project Partner, Tim Lutz (CRADA Co-PI)
 - Joint measurement campaign at Cummins Technical Center
 - Validation of CHT models
 - Hardware/development support
- MAHLE Powertrain – in-cylinder diagnostic development - *Informal*
- Cummins SuperTruck-II Project – Diagnostic applications, J. Dickson (Co-PI) - *Informal*
- Univ. of Central Florida – Applied diagnostics, S.S. Vasu - *Informal*

2: Neutron imaging MD/HD components

- ECN for coordination of injector work, Lyle Pickett (SNL) provided diesel injector for tomography
- Office of Science BES user program
- ORNL Neutron Sciences – Hassina Bilheux, Ke An
- Leveraging PACE neutronic engine & previous neutron imaging project techniques and analysis tools
- *Subcontract with SwRI to design and build Neutronic Engine (PACE)*

3: Next generation MD/HD LTC engines

- Cummins – support for single cylinder engine platform + machining head for flush mount pressure transducers + technical support
- Daimler Trucks – support for multi-cylinder engine experiments
- ANL coordination for tasks
- Co-Optima MD-HD ACI/MCCI projects– leveraging SCE platform and sharing data
- CLEERS – Data sharing

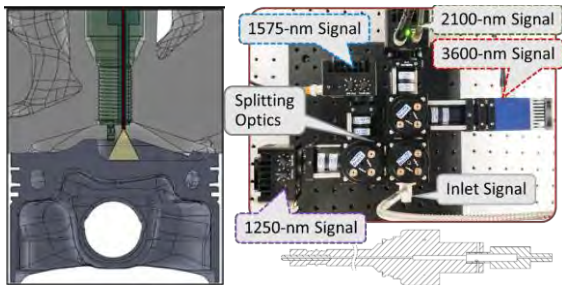
4. Cold-start and restart for electrified MD/HD

- Cummins support - machining head for flush mount pressure transducers on multi-cylinder engine
- Leverages pre-production hybrid system from previous FOA project with Odyne Systems LLC, NREL, and Allison Transmission
- Co-Optima data sharing (ASSERT)
- ORNL VSI HIL laboratory team
- CLEERS – Data sharing

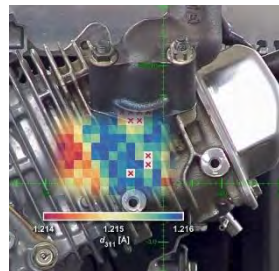
Task-to-task collaborative links, including leveraging shared engine research platforms, advanced laboratories, specialized emissions characterization tools, and advanced combustion diagnostics [details in Approach – Slide 5]

Challenges and Barriers and Proposed Future Research (remainder of FY 21)

Task	Challenges/ Barriers	FY 21 Proposed Future Research* (selected)
1: Advanced diagnostics + Cummins CRADA	Advance fundamental understanding to improve predictive models and future engine design	<ol style="list-style-type: none"> 1. Comparison of measured T with CHT modeling and two-color method 2. Apply diagnostic (side looking and forward probe) for measurements on the Cummins ISB MD engine [FY 21 Q4 Milestone] 3. Campaign on development engine at Cummins Tech Center
2: Neutron imaging MD/HD components	Develop fundamental data sets using x-ray and neutron diagnostics	<ol style="list-style-type: none"> 1. Analysis of all materials used in optical probe + associated instrumentation 2. Verify operation of the Task 1 optical probe in the neutronic engine during off-beam testing [FY 21 Q4 Milestone] 3. Design of calibration and comparison experiments for T diagnostics
3: Next generation MD/HD LTC engines	Overcome technical barriers for achieving high-load operation and addressing low stability	<ol style="list-style-type: none"> 1. Cyclic variability analysis with single-cylinder engine data set 2. Load and speed limits for full map GCI using multi-cylinder platform [FY21 Q3 Milestone] 3. Load/speed impacts on control authority using multi-cylinder [FY 21 Q4 milestone]
4: Cold-start and restart for elect. MD/HD	Address lack of understanding of cold-start and restart emissions for electrified MD/HD truck applications	<ol style="list-style-type: none"> 1. Analysis and reporting on data sets for combustion, FTIR and PM data sets



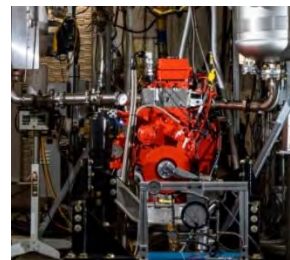
Surface Temp Diagnostic



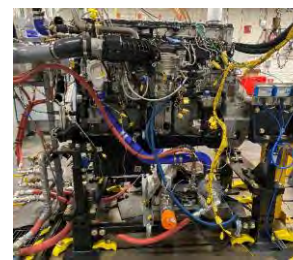
Diffraction: Neutronic Engine



Imaging: MD/HD Components



Single- & Multi-Cylinder GCI Engines



Multi-cylinder MD/HD Engine + Hybrid Drive

*Disclaimer: Any proposed future work is subject to change based on funding levels.

ACE133 Summary

- **Relevance**

- Advance the foundational knowledge base for the next generation of MD/HD engine systems to increase engine efficiency and reduce engine-out emissions

- **Approach/Strategy**

- Task 1: Advanced in-cylinder temperature diagnostics including Cummins CRADA
- Task 2: Neutron diagnostics of MD/HD engine system components
- Task 3: GCI SCE/MCE experiments for next generation LTC engines for MD/HD vehicles
- Task 4: Hybrid powertrain/combustion experiments for electrification of MD/HD powertrains

- **Technical Accomplishments**

- Task 1: Milestone met for temp. diagnostics
- Task 2: Build up of MD/HD injector neutron imaging
- Task 3: SCE experiments complete [summary paper submitted], MCE experiments underway
- Task 4: Rich experimental hybrid and conventional data sets completed, [summary paper focused on emissions submitted]

- **Collaboration and Coordination**

- Tech Teams, 21CTP, AEC, Adv. Engine CrossCut and National lab partners
- Cummins CRADA, Daimler Trucks, ECN,

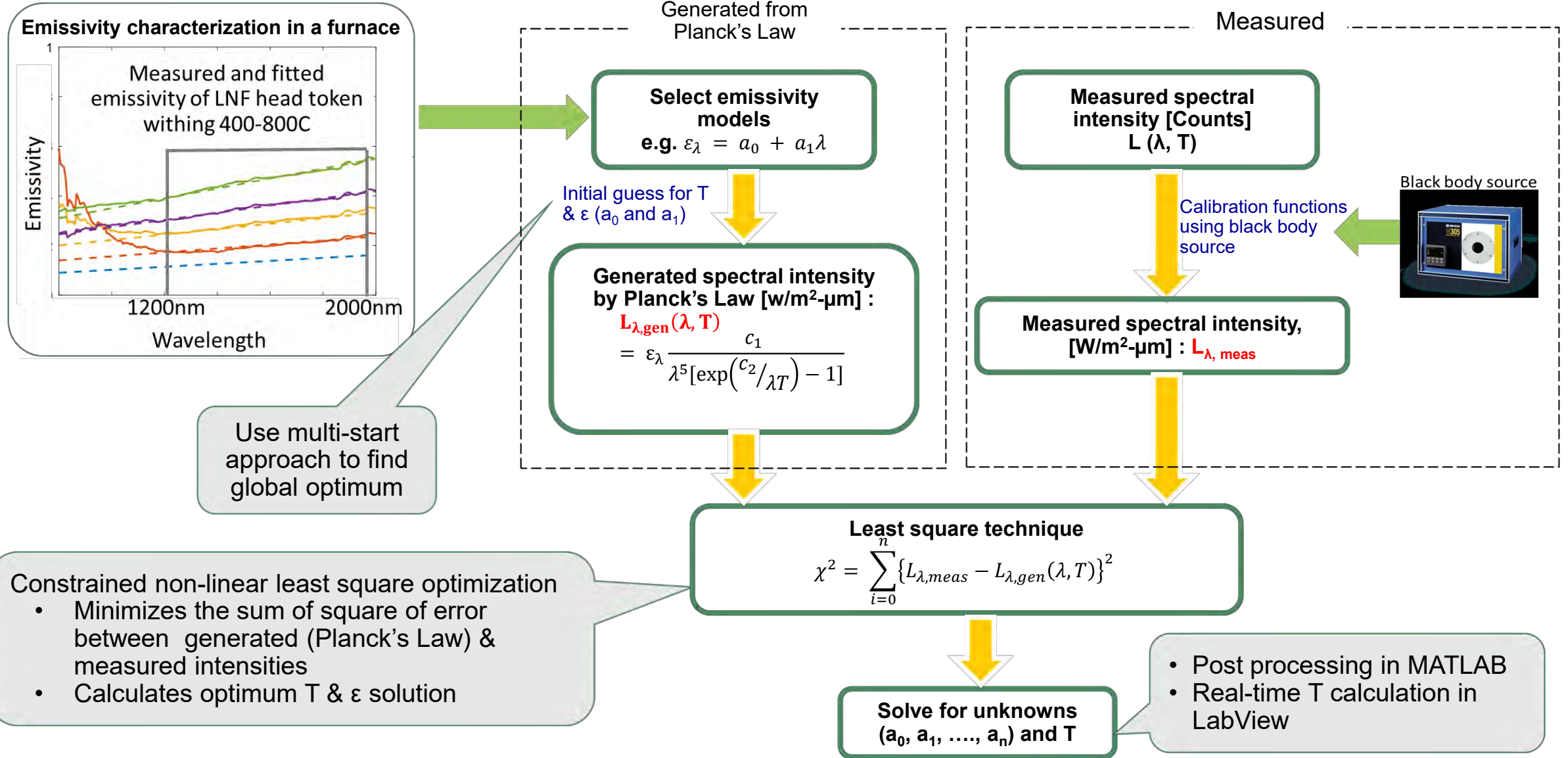
- **Proposed future work***

- Complete FY 21 plans to advance goals for each of the 4 tasks

Technical Backup Slides

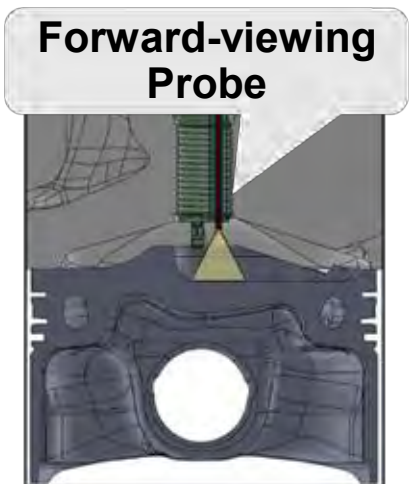
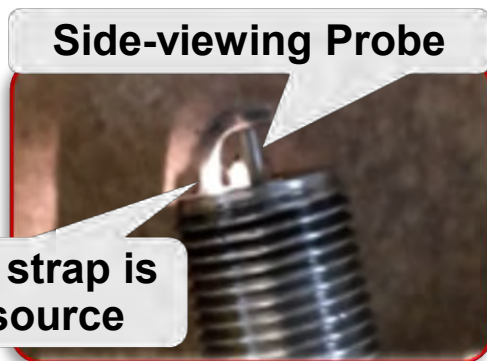
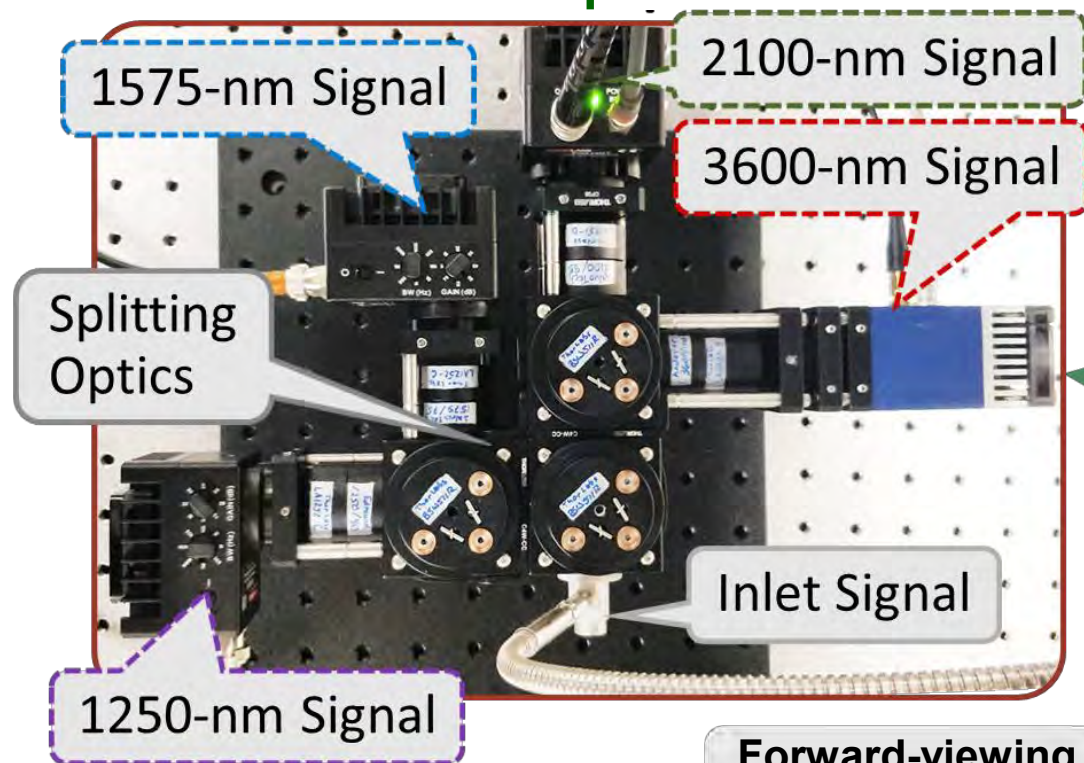
Task 1: MRT (Multi-spectral Radiation Thermometry) to solve for temperature

- Simultaneously solves for surface emissivity(ϵ) and temperature (T)

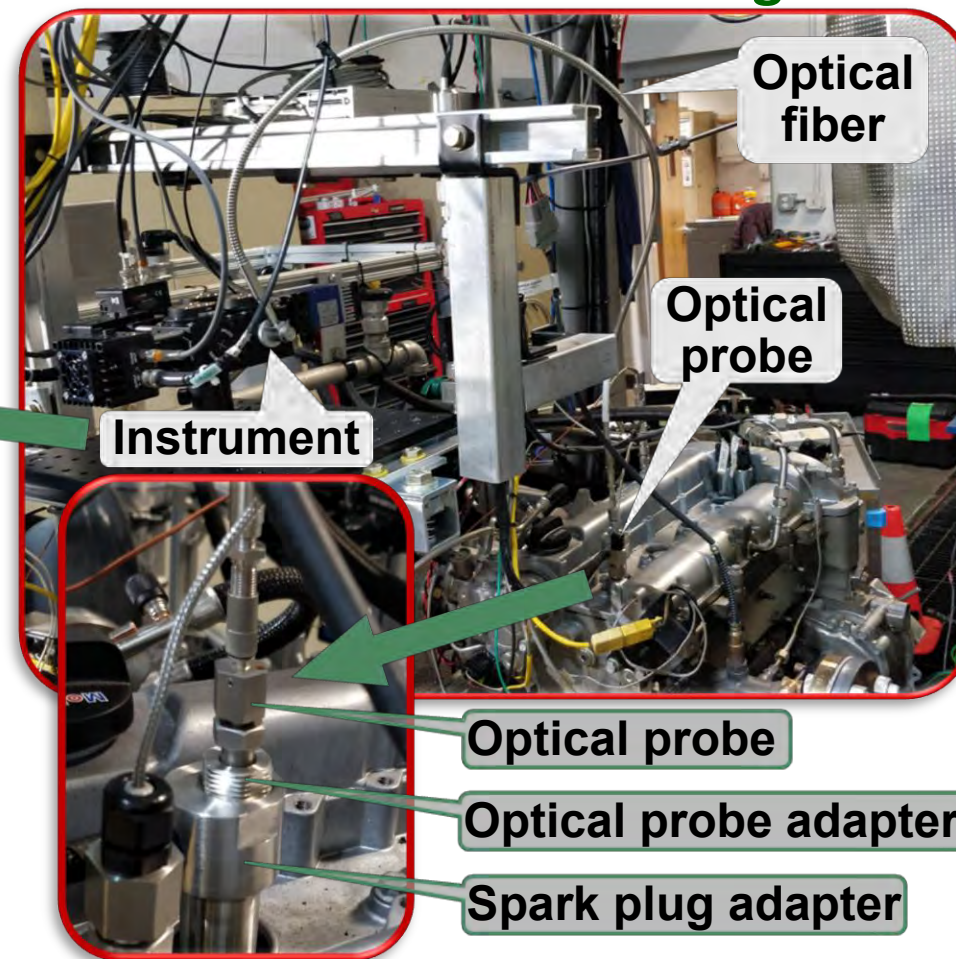


Task 1: In-Cylinder Surface-Temperature Diagnostic Demonstrated on GM LNF Engine

Instrument Setup



Instrument in GM LNF engine

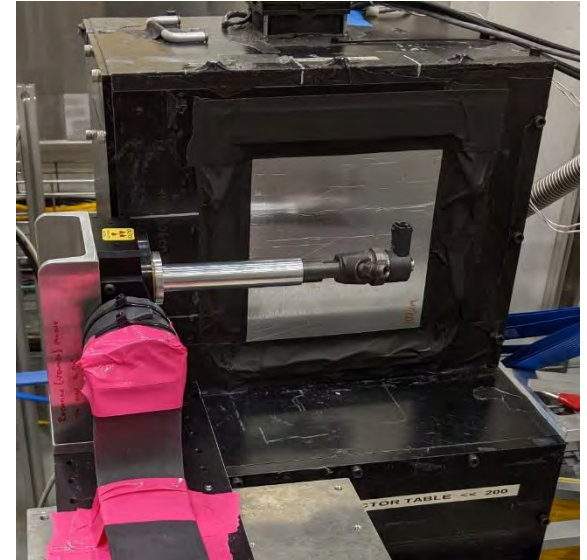
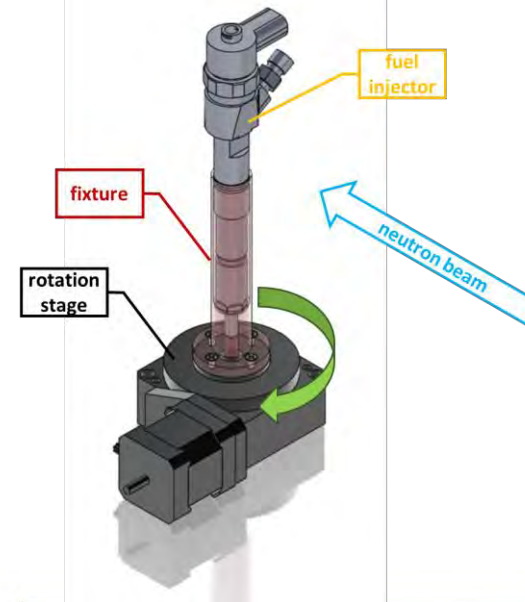


- 5bar IMEP, 2000 RPM
- 20kHz measurement rate: 0.6 CAD at 2000 RPM
- Low soot expected at measured conditions
 - IC Engine PM T >1500 C (Block et al., 1988, Comb & Flame)

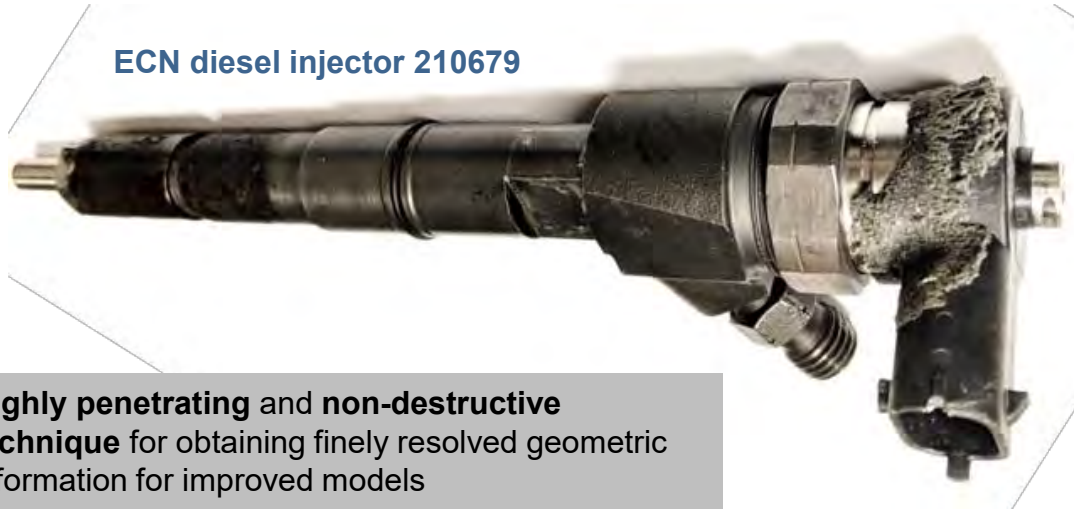
Task 2: Neutron Computed Tomography Scan of Diesel Injector Completed at HFIR

- **ECN injector 210679 provided by Lyle Pickett (SNL)**
 - Injector too tall to fit in front of detector due to horizontal shelf
 - developed custom Al fixture and 90° bracket for rotation stage to rotate about horizontal axis
- **Performed two-part scan to capture entire region of interest**
- **1250 projections (~21 hr) for each scan**
- **Good contrast, all internal features visible**

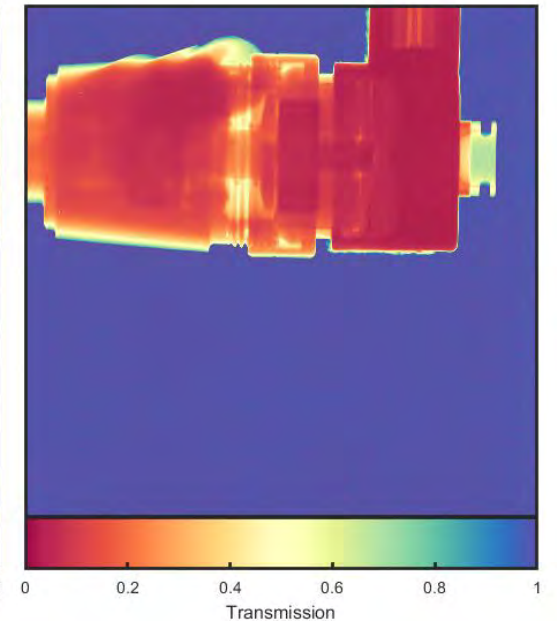
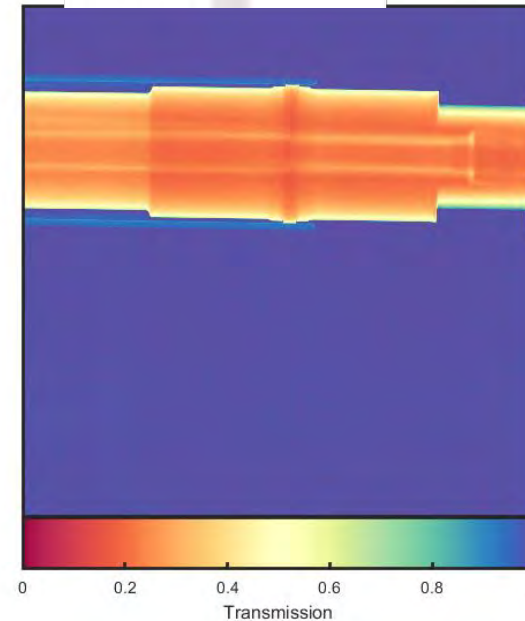
Neutron imaging sample environment



ECN diesel injector 210679

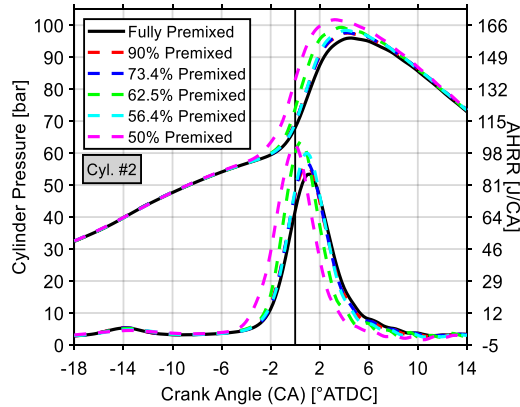


Highly penetrating and non-destructive technique for obtaining finely resolved geometric information for improved models



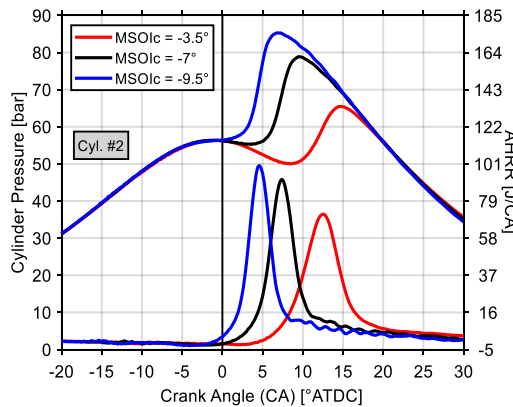
Task 3: MD-HD LTC Project Background

Current Study builds on previous ORNL GCI experiments using LD platform

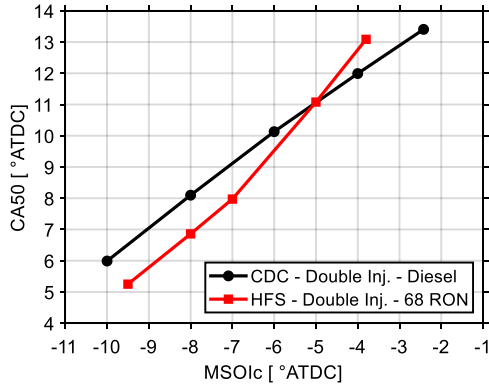


J. GT&P 2015 <https://doi.org/10.1115/1.4030281>
 IJER 2016 <https://doi.org/10.1177/1468087415621805>
 ICEF 2016 <https://doi.org/10.1115/1/ICEF2016-9459>
 ECS&T 2019 <https://doi.org/10.1007/s40825-019-00122-5>
 ICEF 2020 <https://doi.org/10.1115/ICEF2020-2929>

Combustion timing controllability results for PFS operation with the 68 RON gasoline at 2000 rpm, 4 bar BMEP.



Combustion process for double injection HFS using the 68 RON gasoline with 27% EGR at 2000 rpm, 4 bar BMEP and varying the injection timing.

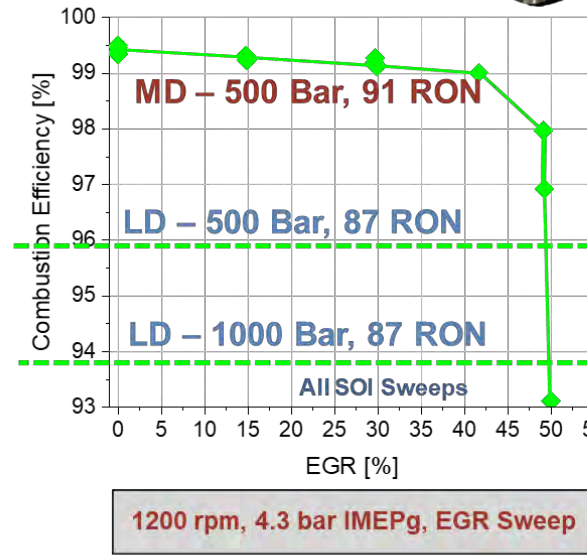


Combustion control authority of CDC vs. HFS-GCI with 68 RON gasoline using a double injection strategy with 27% EGR at 2000 rpm, 4 bar BMEP.

Task 3: Improved HFS Comb Eff. with MD platform compared to GCI previous results using 87mm bore engine

MD SCE GCI Platform

Bore/Stroke [mm]	107/124
Comp. Ratio [-]	20.0
Displacement [L]	6.7/1.12
Swirl Ratio [-]	~1.5



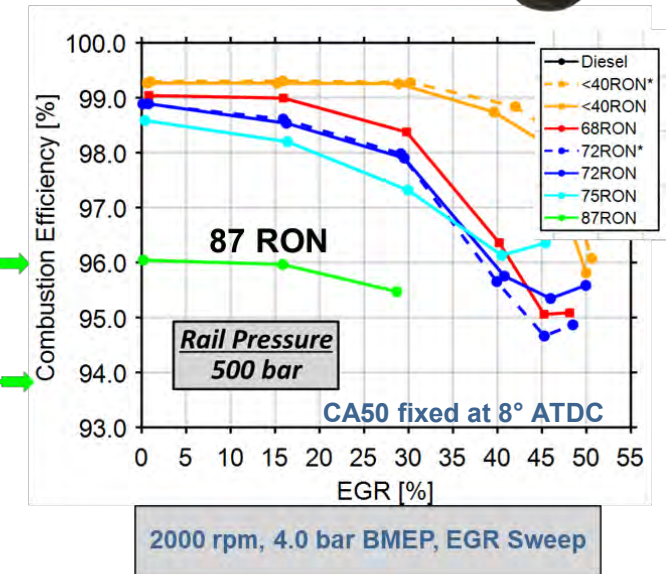
[1] Dempsey et al., <https://doi.org/10.1115/ICEF2020-2929>

FY 20/21 107 mm Bore MD Platform

- Higher Compression Ratio
- Lower swirl for better stratification control,
- Better stroke/bore for improved HT
- Increased injector to surface distances

87mm Bore GCI MCE [1]

Bore [mm]	87/90
Comp. Ratio [-]	16.5
Displacement [L]	1.9/0.47
Swirl Ratio [-]	2.0-5.0



Previous 87mm bore GCI platform

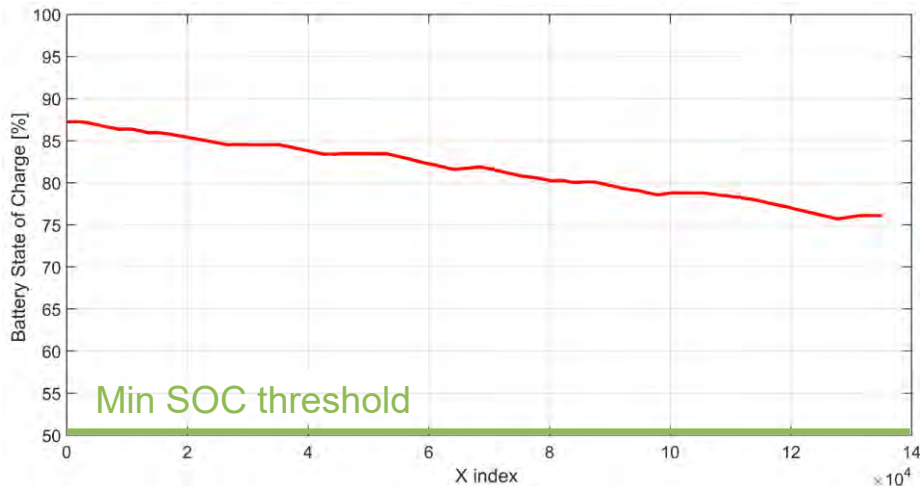
- LD engine: additional charge motion furthered issues of overmixing with higher octane gasolines with longer ignition delays [1]
- Limitations with air handling system for high EGR operation
 - Limited in-cylinder O₂ at high EGR levels [Phi approaching 0.8]

Task 3: Hybrid Configuration

Key Characteristics in Engine Operation

Hybrid mode takeaways:

- Engine load shifted during hybrid operation/ emissions + fuel consump. diff
- Difference in TM strategy leads to increased engine torque demand (and fueling)



TM: Thermal Management (for SCR)

*Temperature location: upstream of canister

