AEC001: Heavy-Duty Low-Temperature and Diesel Combustion & Heavy-Duty Combustion Modeling

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FY 2010 DOE Vehicle Technologies Program Annual Merit Review
Advanced Combustion Engine R&D/Combustion Research
8:30 – 9:00 AM, Tuesday, May 10, 2011

Sponsor: **U.S. Dept. of Energy, Office of Vehicle Technologies**

Program Manager: **Gurpreet Singh**

Heavy-Duty Combustion Project Overview

Timeline

- Project provides fundamental research that supports DOE/ industry advanced engine development projects
- Project directions and continuation are evaluated annually

Barriers

- Inadequate understanding of fuel injection, mixing, thermodynamic combustion losses, combustion/ emission formation processes
- Inadequate capability to accurately simulate these processes.

Budget

- Project funded by DOE/VT:
  FY10-SNL/UW: \$660/115K
  FY11-SNL/UW: \$700/115K

Partners

- University of Wisconsin
- 15 industry partners in the AEC MOU
- Project lead: Sandia (Musculus)

Heavy-Duty In-Cylinder Combustion Objectives

Long-Term Objective

Develop improved understanding of in-cylinder LTC spray, combustion, and pollutant-formation processes required by industry to build cleaner, more efficient, heavy-duty engines

Current Specific Objectives:

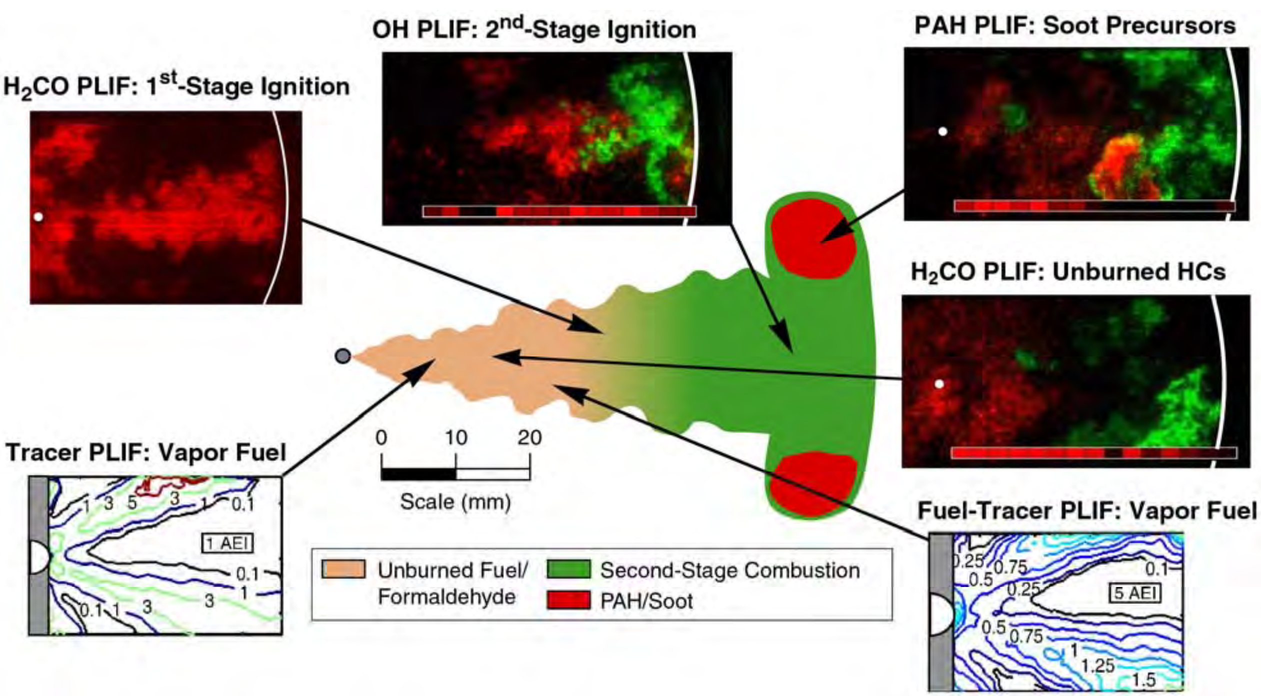
1. SNL - Quantify oxidation of piston-bowl soot remaining from main injection by narrow included-angle post-injections
2. SNL+UW – Characterize RCCI combustion using high-speed imaging diagnostics
3. SNL+UW - Define the in-cylinder conditions that govern flame propagation / distributed autoignition combustion modes
4. UW - Compare multi-mode combustion model predictions to measurements of combustion propagation

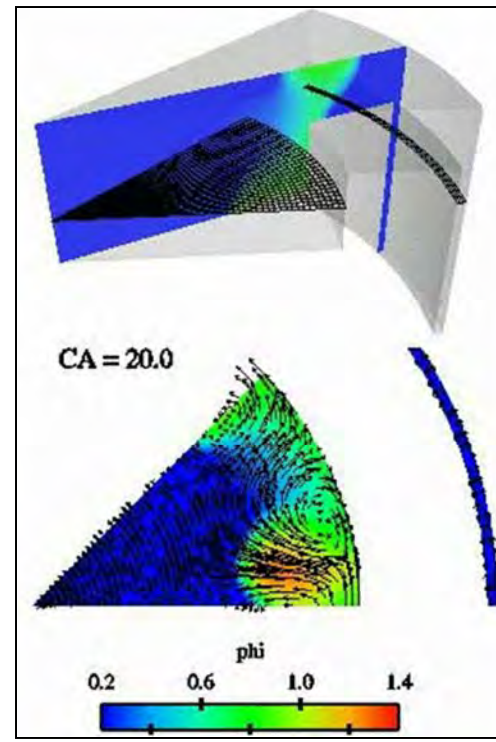
Heavy-Duty In-Cylinder Combustion Milestones

1. (SNL+UW) Demonstrate dual-fuel system in SNL heavy-duty optical engine.
2. (SNL+UW) Characterize combustion propagation for high-efficiency dual-fuel RCCI.
3. (UW) Compare multi-mode combustion model predictions to measurements of combustion propagation

Approach: Optical Imaging and CFD Modeling of In-Cylinder Chemical and Physical Processes

- Combine planar laser-imaging diagnostics in an optical heavy-duty engine with multi-dimensional computer modeling (KIVA) to understand LTC combustion
- Transfer fundamental understanding to industry through working group meetings, individual correspondence, and publications





Collaborations

- All work has been conducted under the Advanced Engine Combustion Working Group in cooperation with industrial partners
  - Cummins, Caterpillar, DDC, Mack Trucks, John Deere, GE, International, Ford, GM, Daimler-Chrysler, ExxonMobil, ConocoPhillips, Shell, Chevron, BP, SNL, LANL, LLNL, ANL, ORNL, U. Wisconsin
- New research findings are presented at biannual meetings
- Tasks and work priorities are established in close cooperation with industrial partners
  - Both general directions and specific issues (e.g., UHC for LTC, soot in higher load conditions)
- Industrial partners provide equipment and support for laboratory activities

Accomplishments (19 slides)

- Accomplishments for each of the four current specific objectives below are described in the following nineteen slides

<u>Current Specific Objectives:</u>

① **SNL – Quantify narrow included-angle post-injections oxidation of piston-bowl soot from the main injection.**

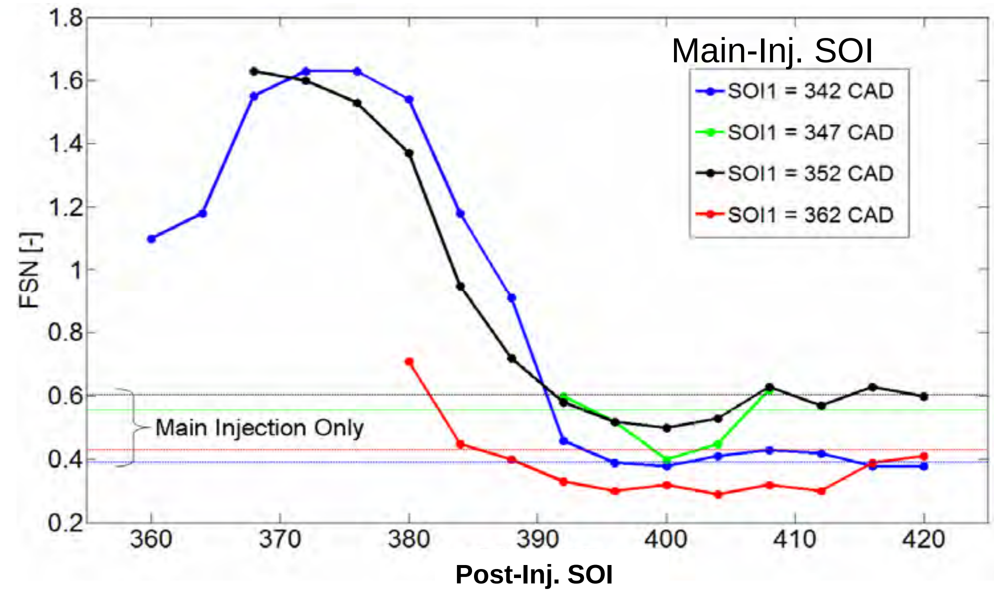
② **SNL+UW – Characterize RCCI combustion using high-speed imaging diagnostics**

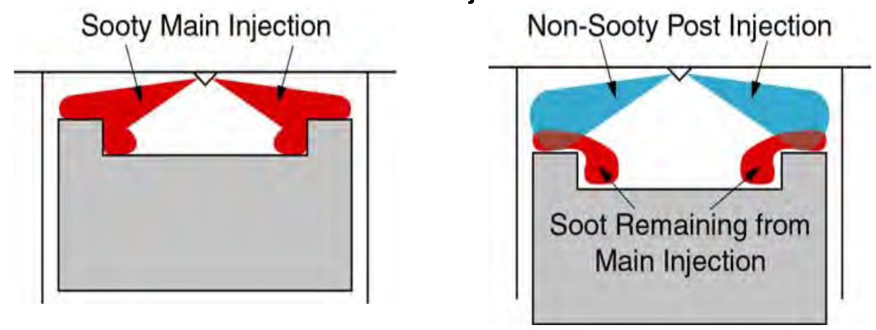
③ **SNL+UW – Define the in-cylinder conditions that govern flame propagation / distributed autoignition combustion modes.**

④ **UW – Compare multi-mode combustion model predictions to measurements of combustion propagation**

① Previous data showed how post injections oxidize squish-soot, but bowl-soot remains

- 2009 Peer Review: post-injection soot oxidation.
- 2009 data showed that with a constant main injection, adding a post increases soot at small dwell, but decreases soot at larger dwell.
- Wide-angle (154) injector: soot is split between bowl and squish
- A late post-injection oxidizes soot, but only in the squish region.
- **Most soot, in the piston bowl, is not affected by post injection.**

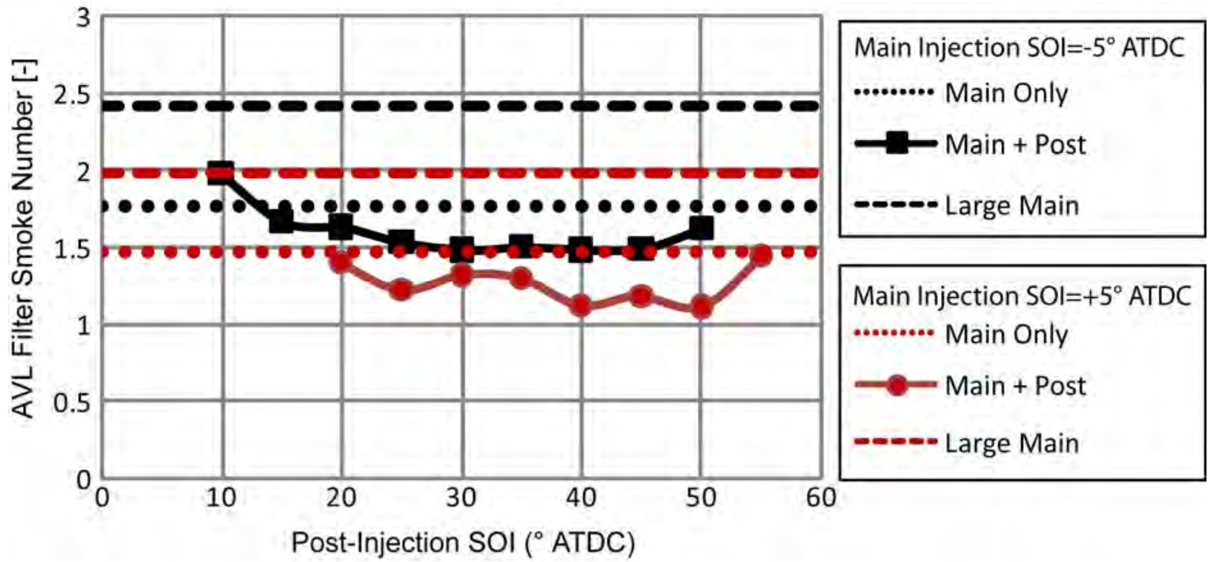


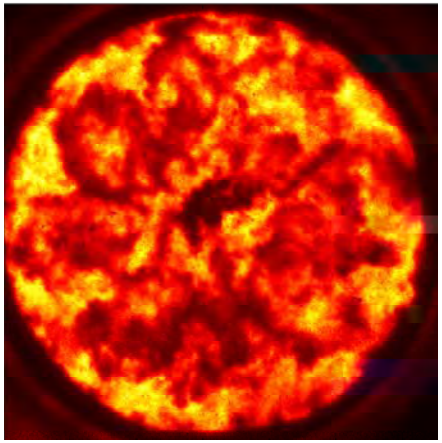


How well can piston-bowl soot from the main injection be oxidized by post-injection into the bowl (narrow-angle inj.)?

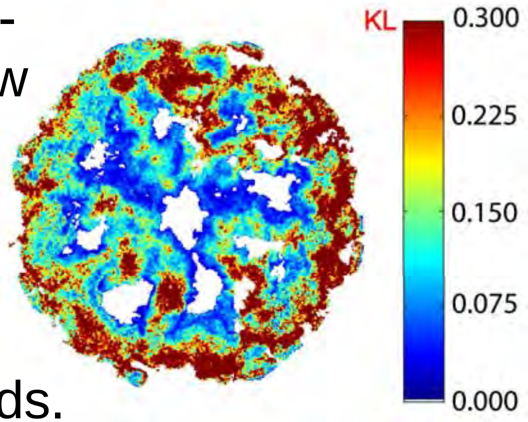
① Post-injections with narrow-angle provide similar soot-reduction as with wide-angle

- Narrow-angle (124°) injector yields much more exhaust soot (FSN 1.5 vs. 0.6)
- Post injection reduces soot, but only modestly (similar to 154°)



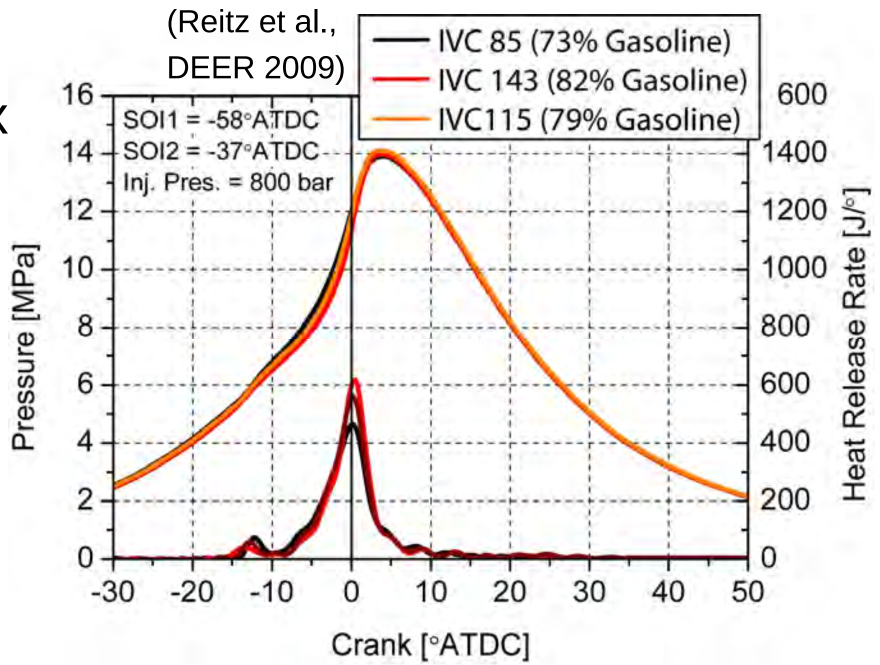


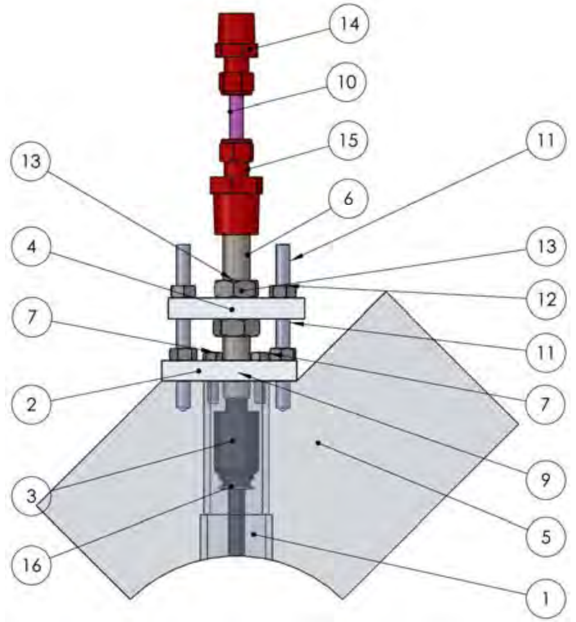
- Soot luminosity images show post-injection impinging on bowl-window and disturbing bowl-soot
  - Can significantly affect 2-color measurements
- In-cylinder 2-color KL data: considerable scatter, no clear trends.



② Developed new GDI system to expand capabilities to dual fuels, premixed charge

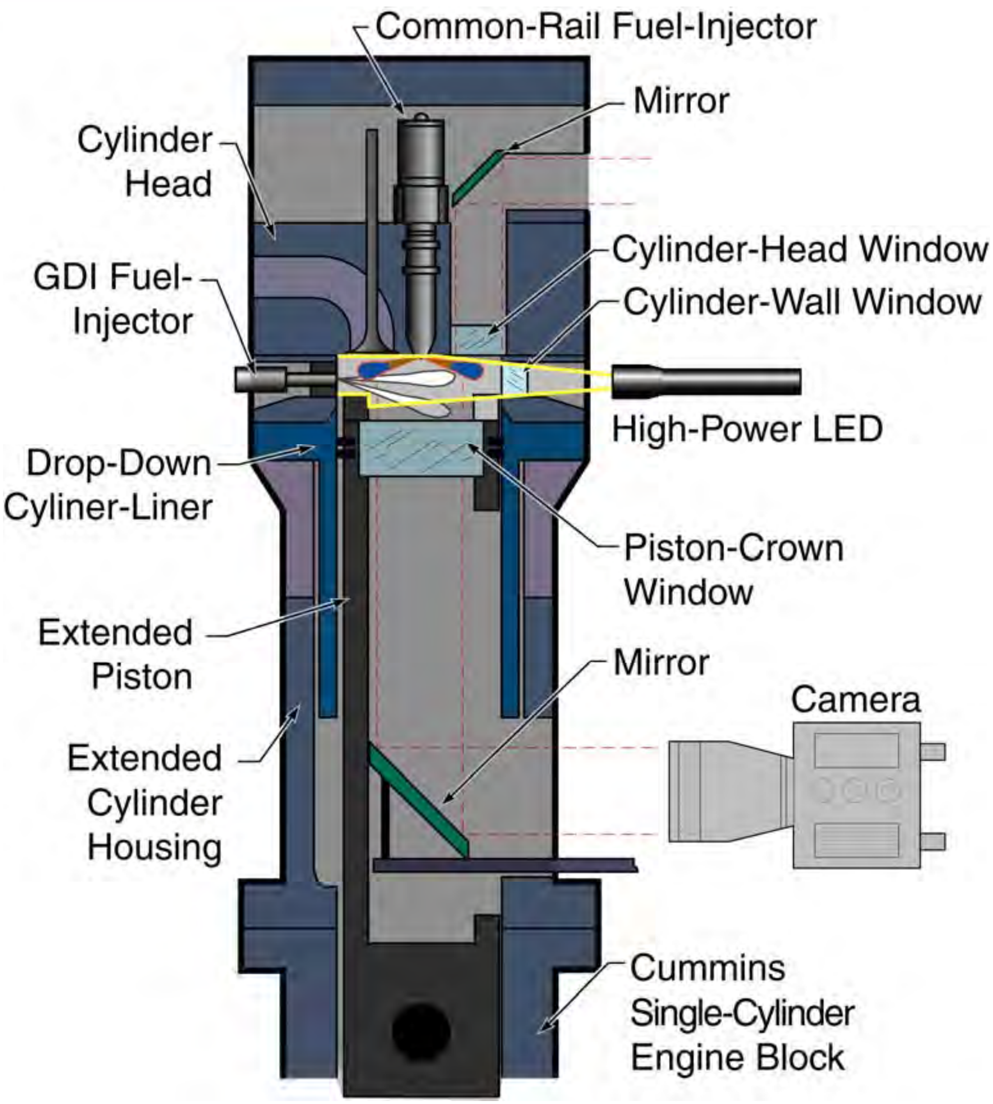
- U. Wisc. (Reitz et al.) has shown mid-load iη_{th}> 50% at 2010 PM/NOx in-cyl. with dual-fuel gasoline/diesel
- Presents both a modeling challenge and a diagnostic opportunity
  - Both distributed autoignition and flame propagation are possible.



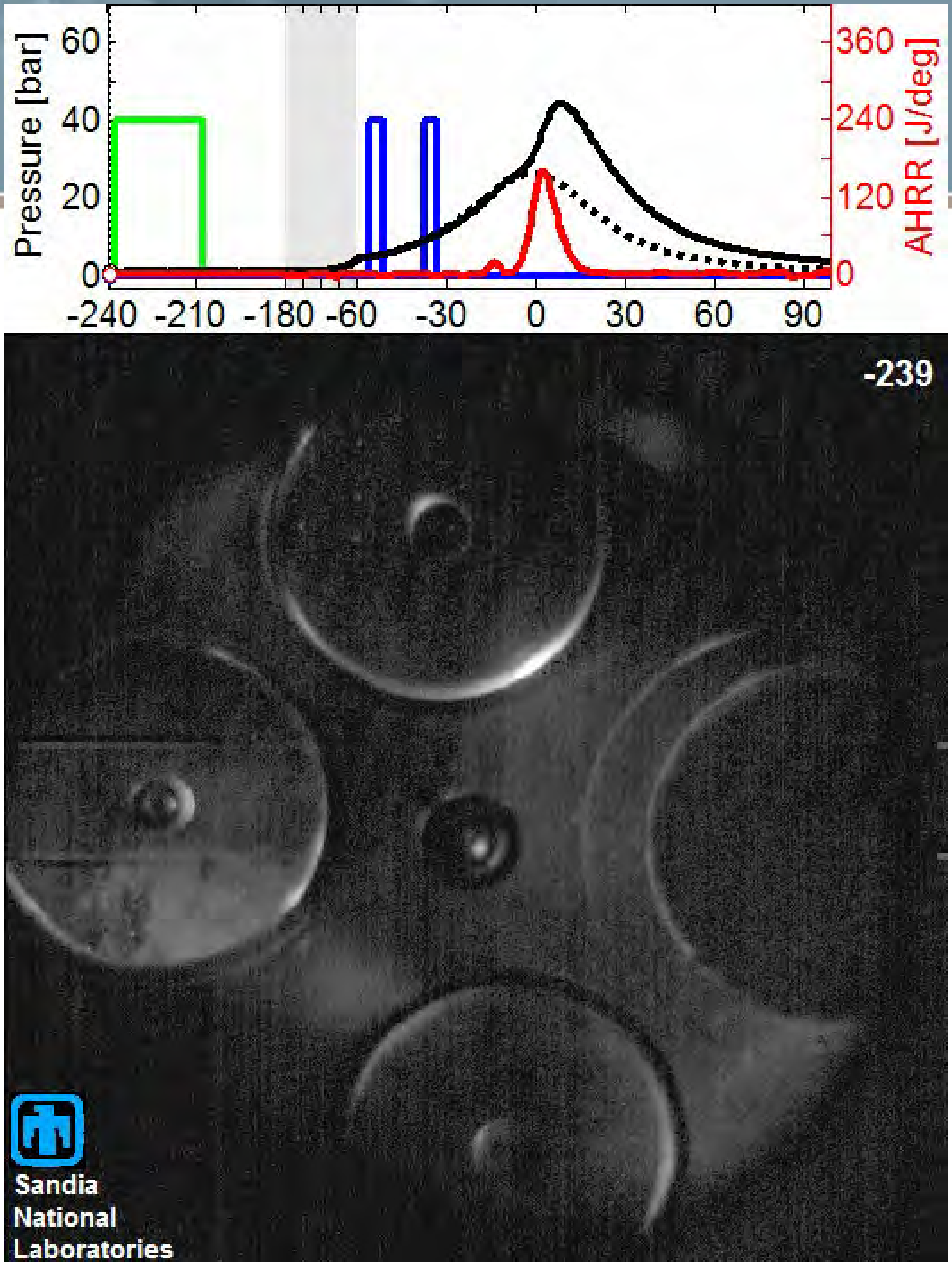


- GDI side-injector system for gasoline fuels designed and installed in optical engine.
- UW modeling student (Sage Kokjohn) to visited Sandia for 8 months in FY2010/11
  - Optical diagnostic study of flame propagation / autoignition to improve model fidelity

② Central Common-Rail + side-mounted GDI enable dual-fuel (RCCI) capability



- Bosch GDI (100 bar) mounted in place of side-window
  - Premixed charge of gasoline-like fuel
- 8-hole production Cummins XPI common-rail fuel injector (300-1600 bar) in cylinder head
  - Direct injection of diesel-like fuel
- Sprays illuminated using CW high-power LED white-light source through side-windows



② LTC: RCCI with n-heptane & iso-octane

- No EGR
- GDI from top of view, CR in center
- High gain: cool flame visible, no soot

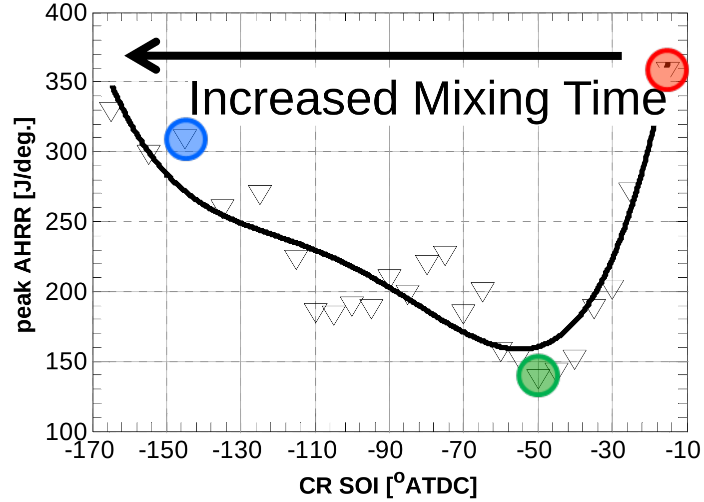
Fuel (net)	PRF64 (ϕ=0.42)
Intake	21% O_2 (EGR)
Load	4.3 bar IMEP
Intake T	90°C
Intake P	1.15 bar
GDI SOI	-240° ATDC
CR SOI	-57°, -37° ATDC
Speed	1200 rpm
Engine r_C	10.75
Window	100 mm diam
Framing	7200 fps
Gain	500
Filter	500 nm SWP

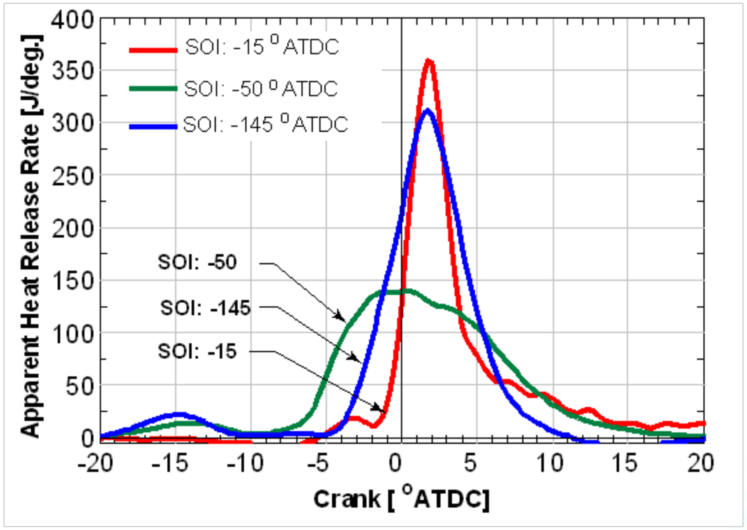
② RCCI: Fuel reactivity and ϕ stratification are important for managing peak heat release rate

- Common-rail (n-heptane) SOI timing sweep creates range of equivalence ratio (ϕ) and reactivity stratification
- CA50 held constant at 2° ATDC by adjusting intake temperature
- Minimum peak AHRR: SOI= -50° ATDC
- Higher AHRR at both earlier and later SOI

Operating Conditions

Engine speed	1200 rpm
Gross IMEP	4.2 bar
Intake temperature	73 to 100 °C
Intake pressure	1.1 bar abs.
Inlet oxygen concentration	21 vol. %
CR SOI	-165 to -15° ATDC
GDI SOI	-240° ATDC
n-heptane mass (CR)	36%
iso-octane mass (GDI)	64%
Premixed equivalence ratio	0.27
Overall equivalence ratio	0.42



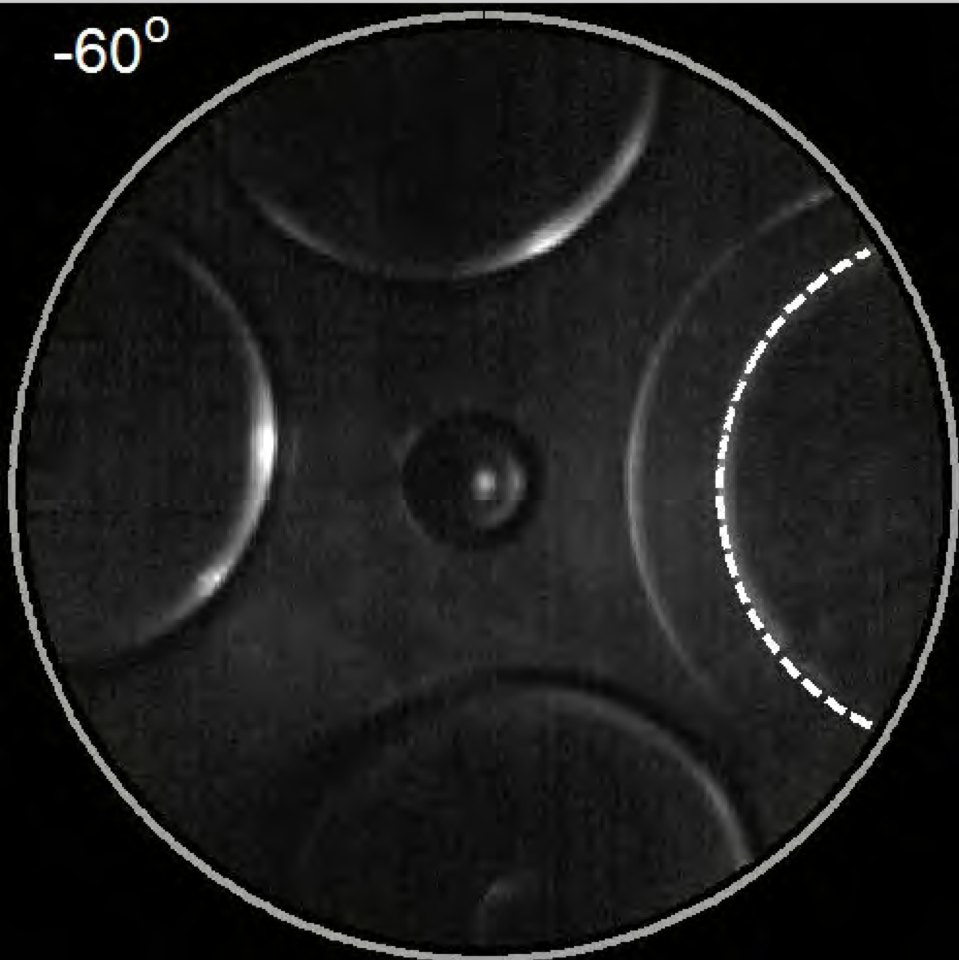


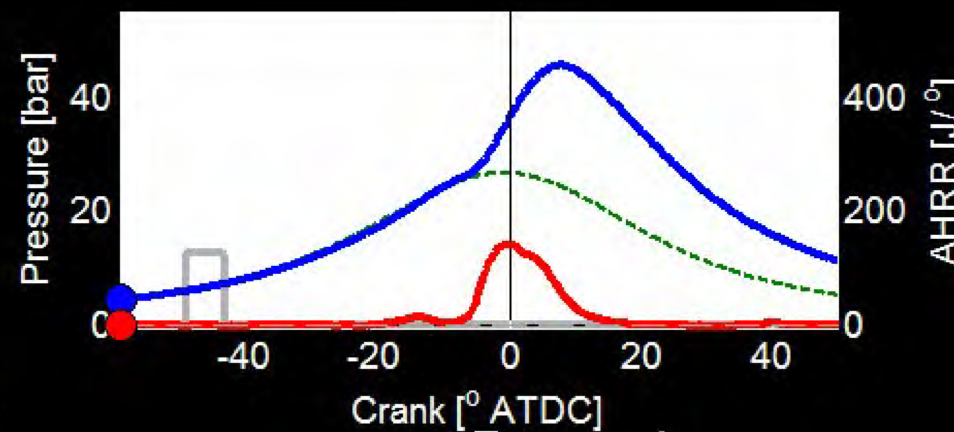
*See back-up slide for still-image summary

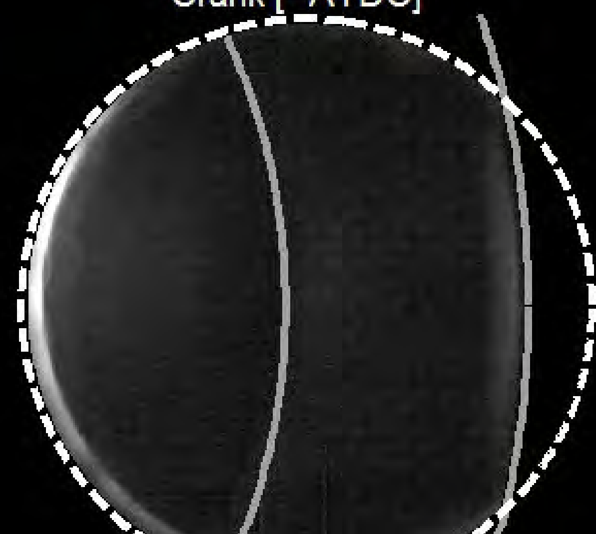
② Mid-range SOI (-50ÁATDC) ignites in squish and burns gradually to center of cylinder

- Likely moderate fuel reactivity and concentration gradients at ignition

CR SOI:	**-50° ATDC**
Intake Temperature:	92° C
Global equivalence ratio:	0.42



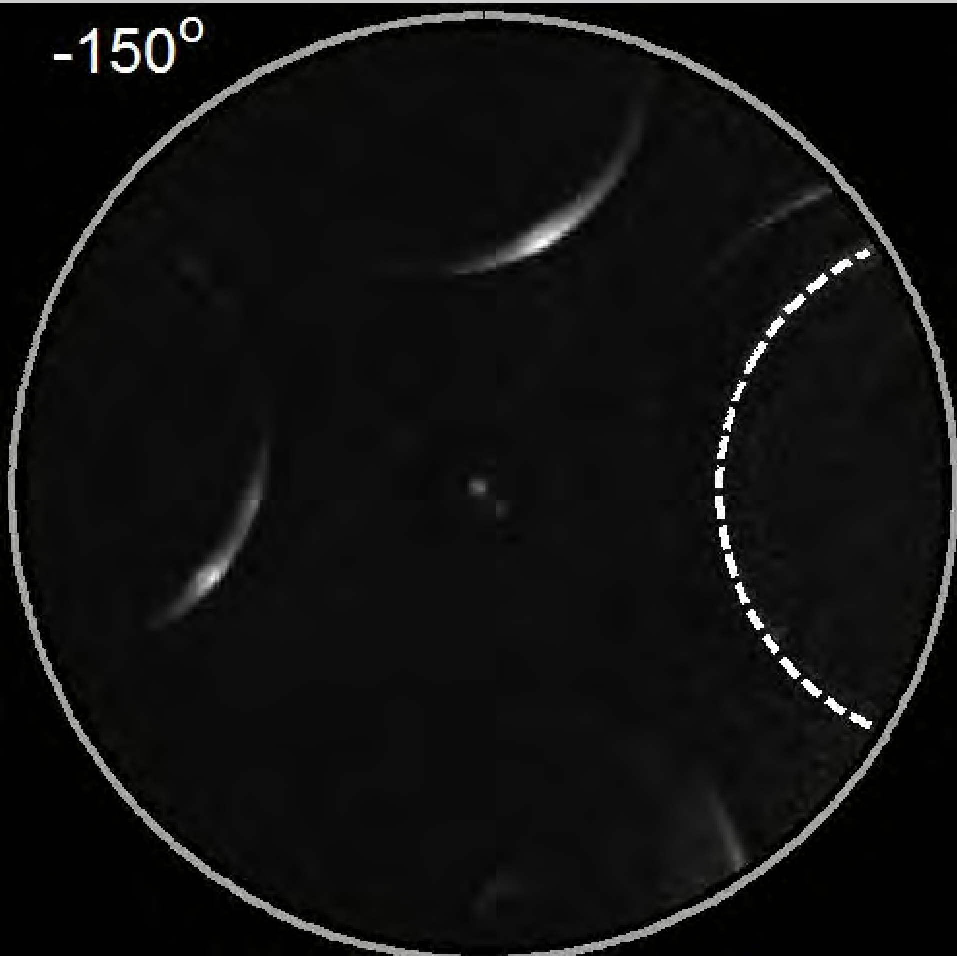


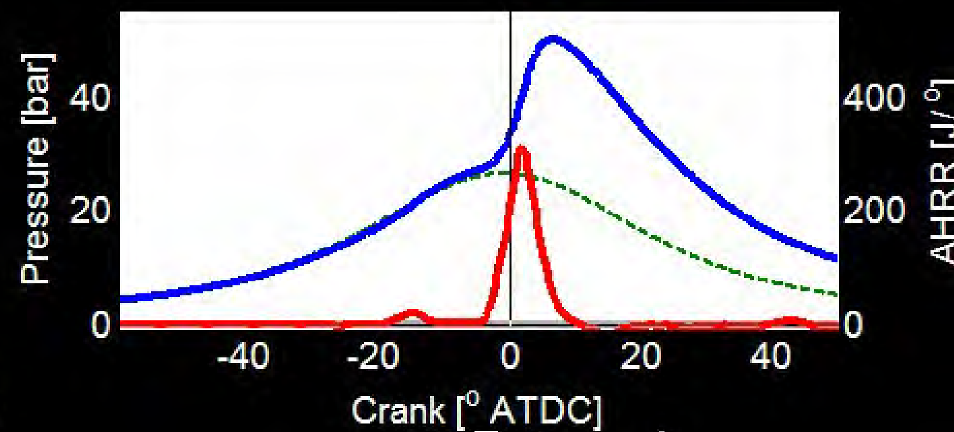


② Early SOI (-145ÁATDC) ignites in pockets throughout chamber and burns quickly

- Likely low fuel reactivity and concentration gradients at ignition (HCCI-like)

CR SOI:	**-145° ATDC**
Intake Temperature:	93° C
Global equivalence ratio:	0.42

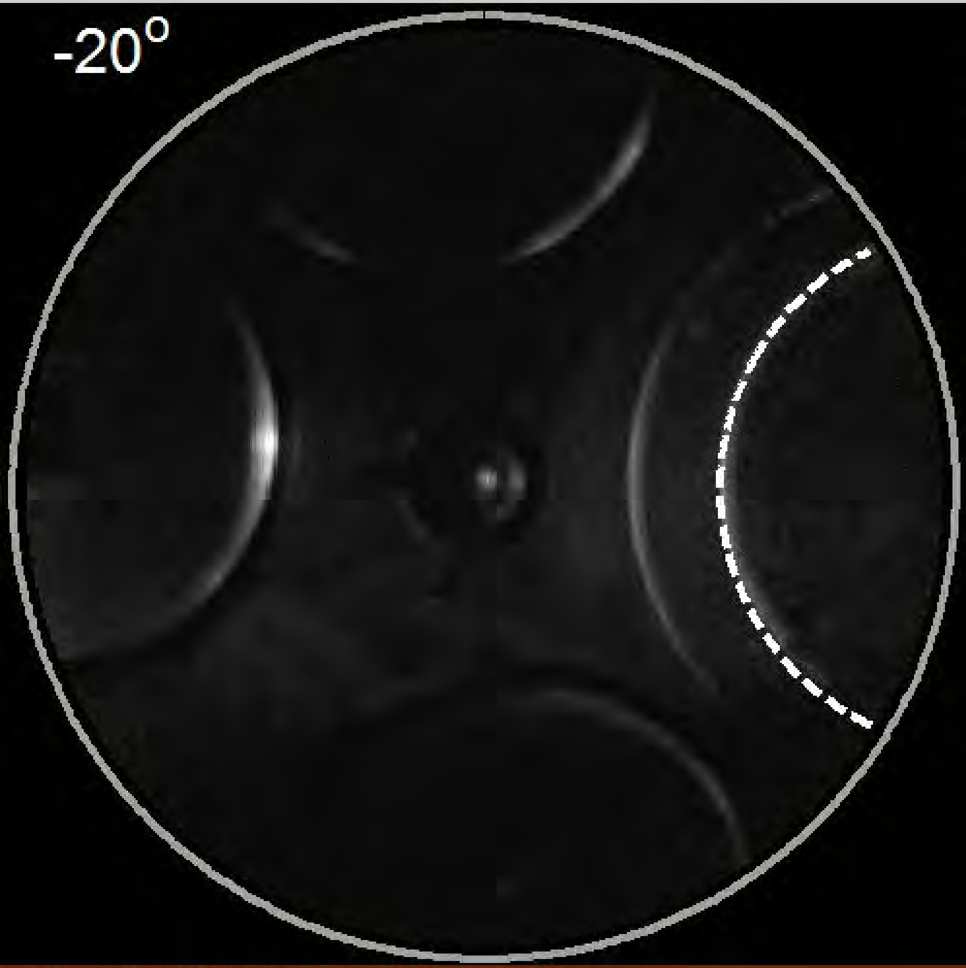


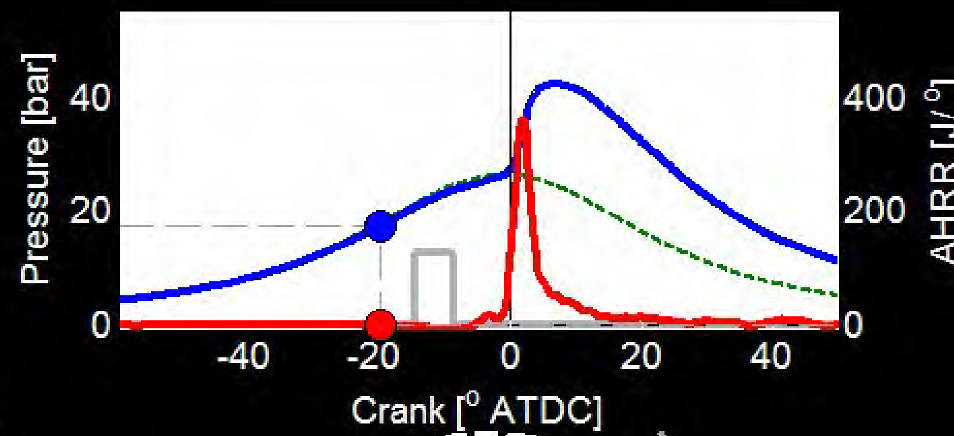


② Late SOI (-15° ATDC) ignites in jets (premixed burn), some mixing-controlled combustion

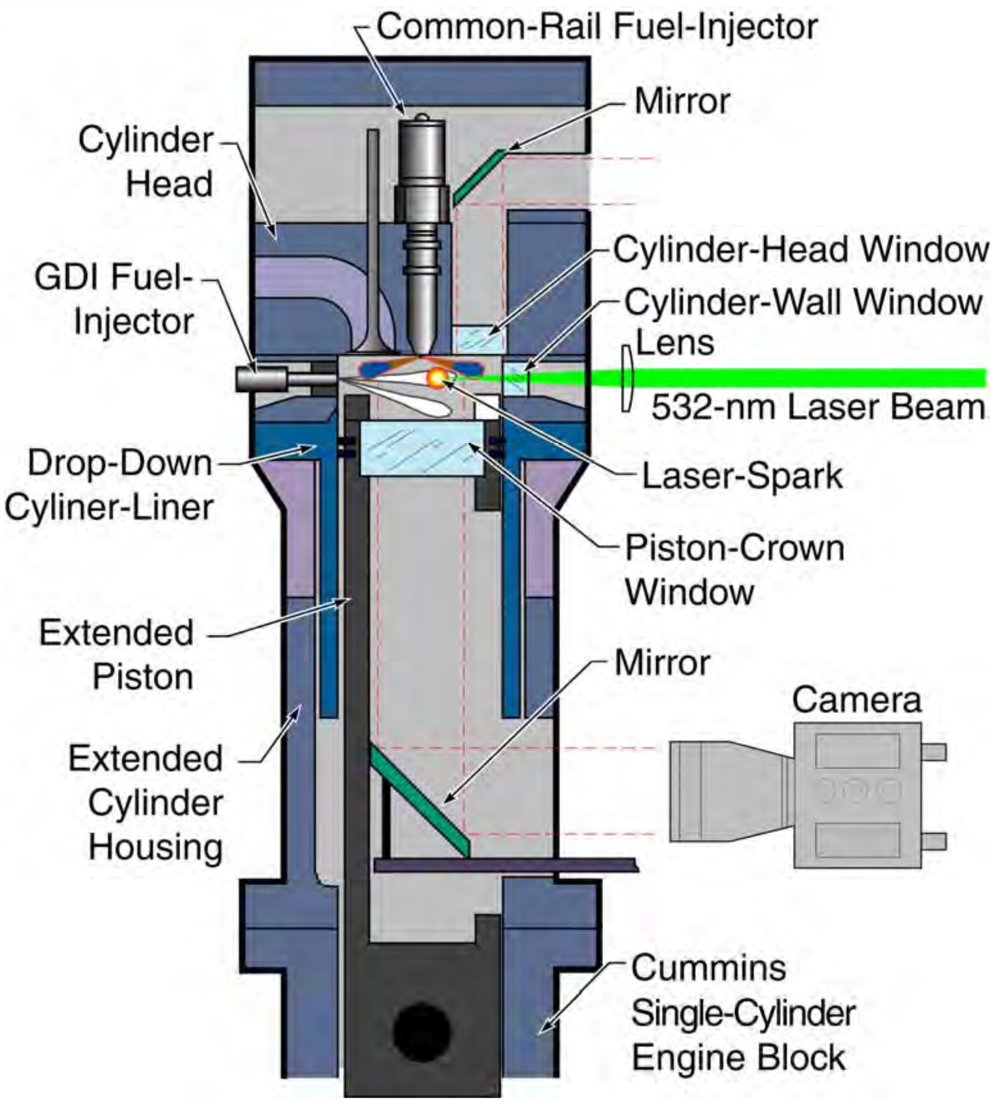
- Likely strong reactivity and concentration gradients with rich jet mixtures (diesel-like)

CR SOI:	-145° ATDC
Intake Temperature:	85° C
Global equivalence ratio:	0.42



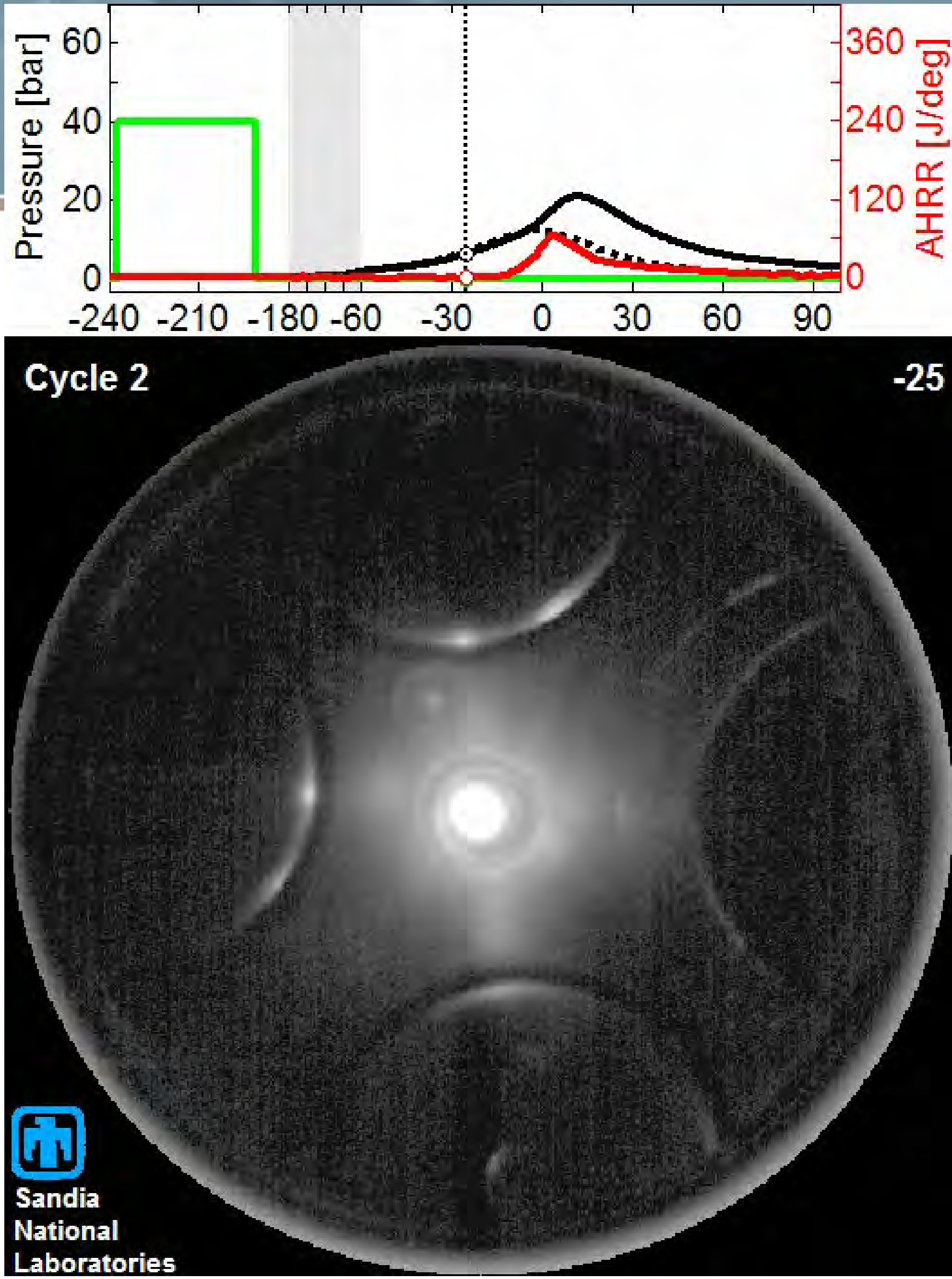


③ Focused high-power laser beam pulse creates positionable plasma for spark ignition



- Focused laser beam (~100 mJ) creates plasma (spark)
  - Can probe ignitability of mixtures to explore combustion regimes (flame propagation/distributed autoignition)
- Multiple combustion modes achievable
  - Spark Ignition
    - For study of known flame propagation regime
  - HCCI
    - For study of known distributed autoignition regime
  - RCCI
    - Combustion strategy where both autoignition and distributed autoignition are possible

*See back-up slide for still-image summary



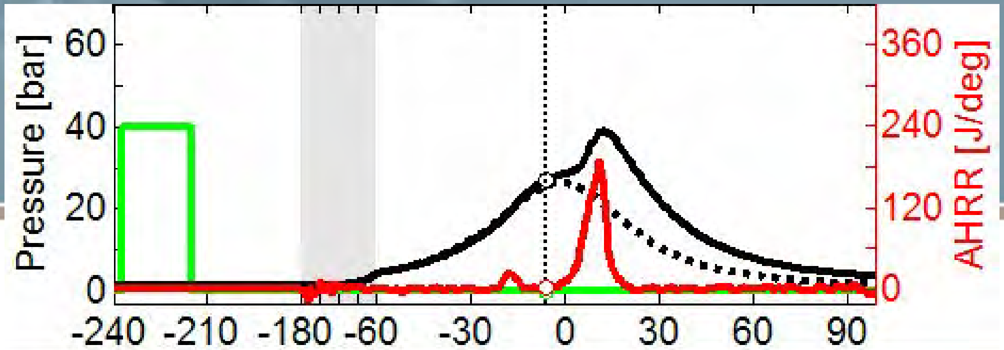
③ HTC: Conventional Spark-Ignition

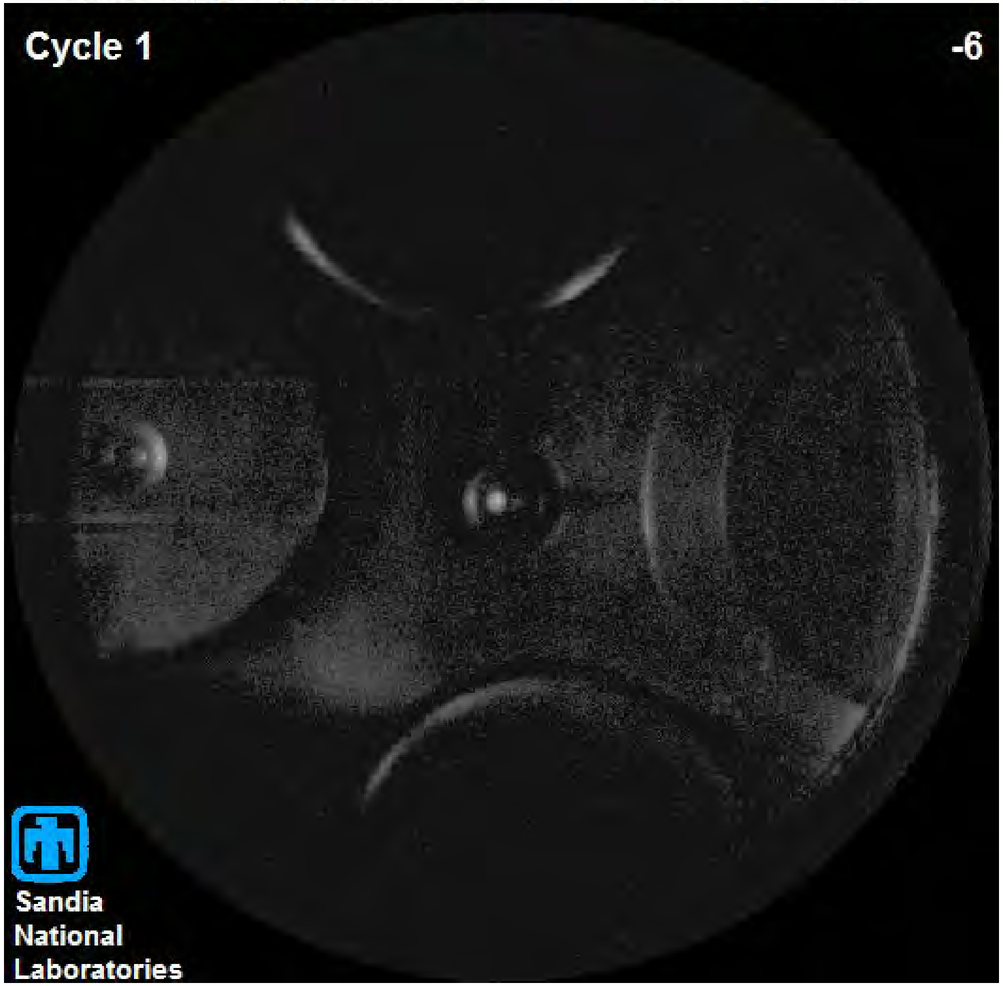
- GDI only, throttled, near stoich.
- Laser spark at center
- High-speed chemiluminescence

Fuel	iso-octane (ϕ=0.95)
Intake	21% O_2
Load	4 bar IMEP
Intake T	30°C
Intake P	~0.5 bar
Spark	-25° ATDC
Speed	1200 rpm
Engine r_C	10.75
Window	100 mm diam
Framing	7200 fps
Gain	300
Filter	500 nm SWP

*See back-up slide for still-image summary

③ LTC: HCCI with n-heptane & iso-octane

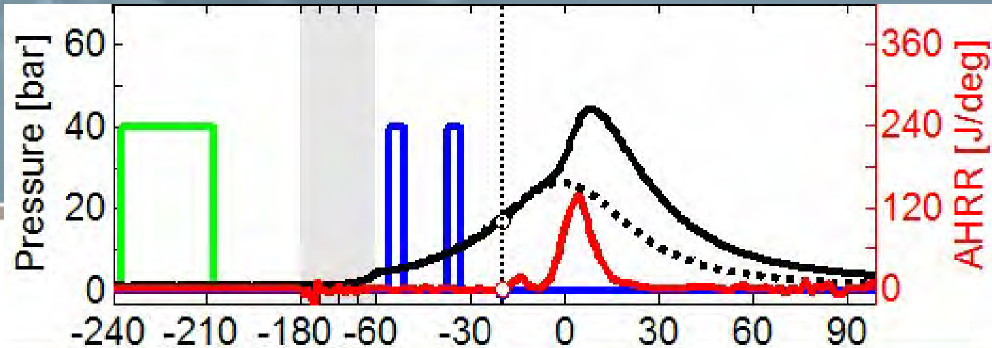


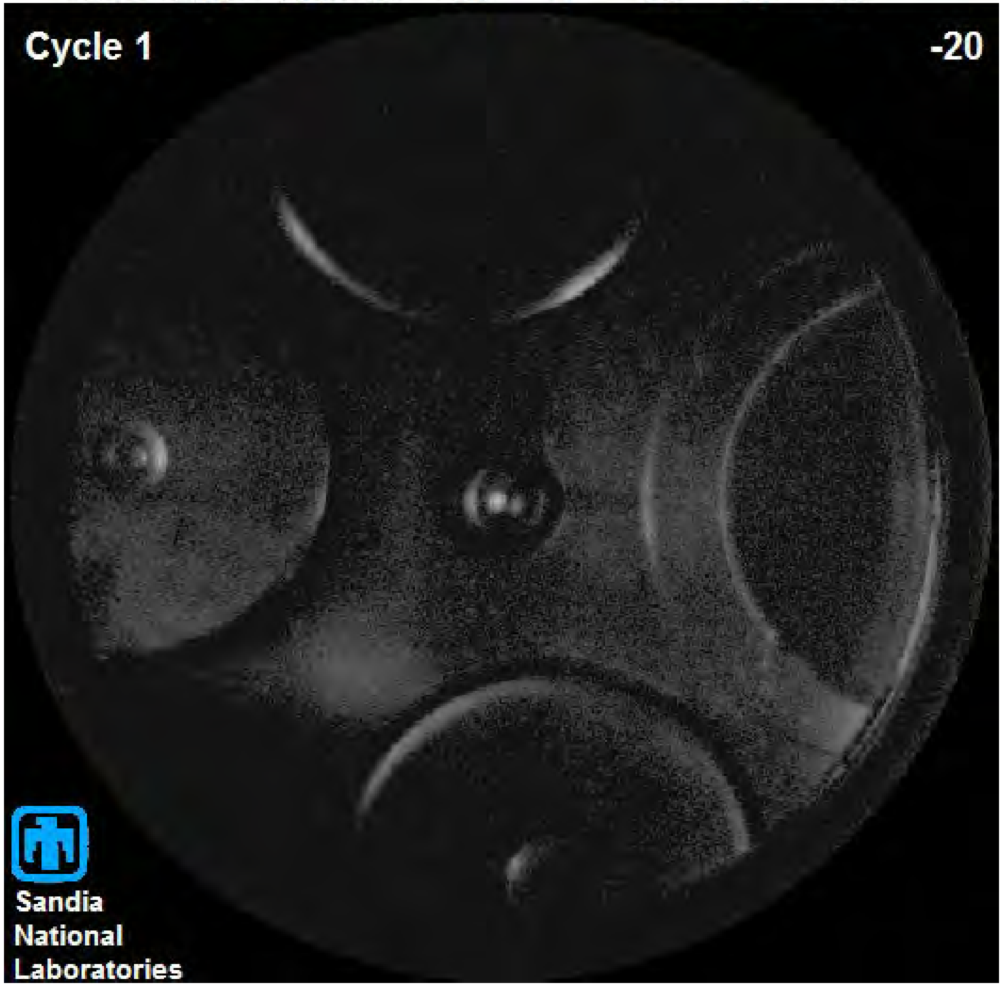


- Subsequent fuel-tracer PLIF shows GDI fuel (iso-octane) is not very uniform

Fuel	PRF57 (ϕ=0.35)
Intake	21% O_2 (EGR)
Load	3.7 bar IMEP
Intake T	90°C
Intake P	1.15 bar
GDI SOI	-240° ATDC
CR SOI	-345° ATDC
Speed	1200 rpm
Engine r_C	10.75
Window	100 mm diam
Framing	7200 fps
Gain	500
Filter	500 nm SWP

*See back-up slide for still-image summary



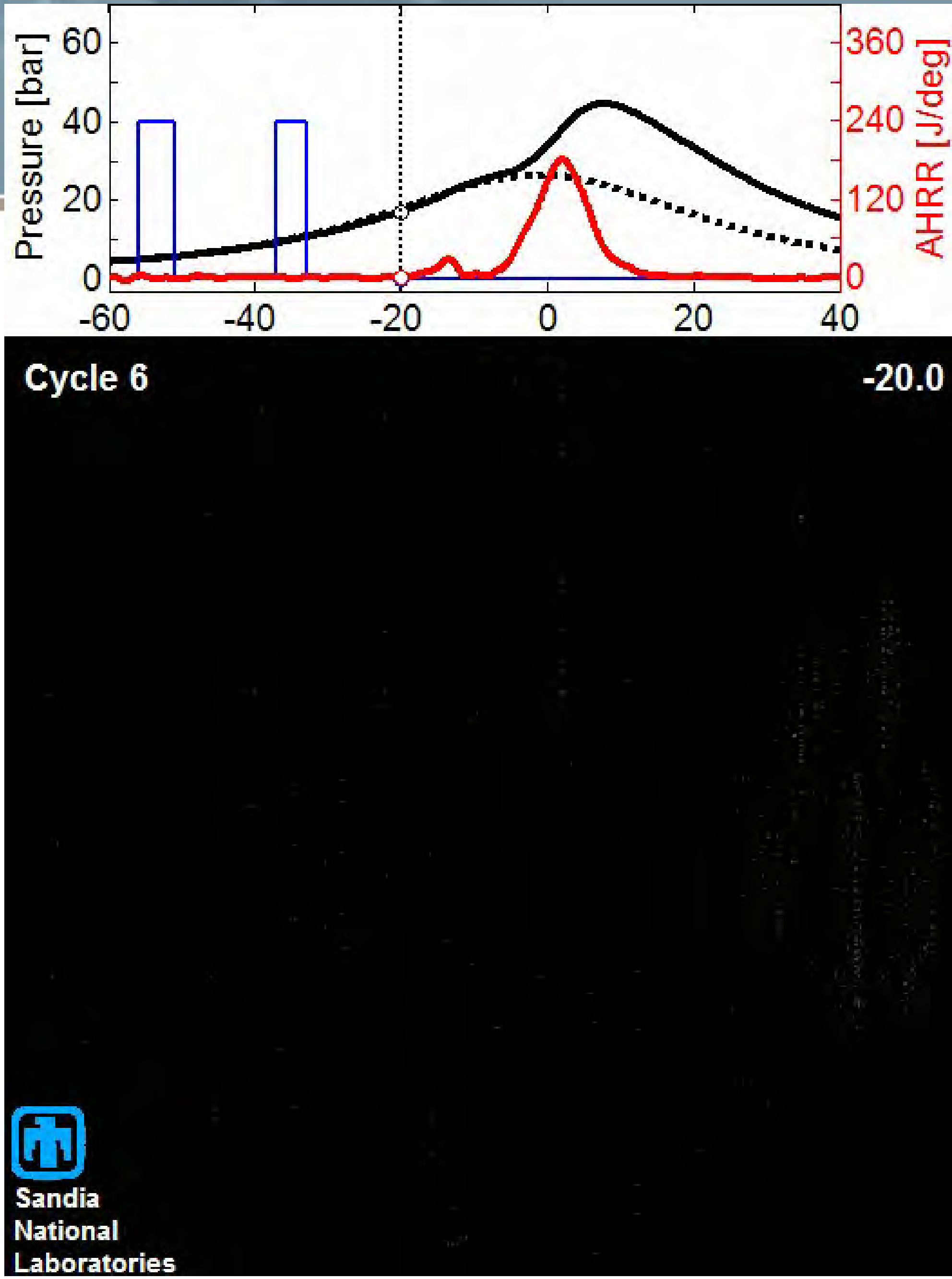


③ LTC: RCCI with n-heptane & iso-octane

- No EGR
- GDI from top of view, CR in center
- High gain: very little soot, cool flame

Fuel (net)	PRF64 (ϕ=0.42)
Intake	21% O_2 (EGR)
Load	4.3 bar IMEP
Intake T	90°C
Intake P	1.15 bar
GDI SOI	-240° ATDC
CR SOI	-57°, -37° ATDC
Speed	1200 rpm
Engine r_C	10.75
Window	100 mm diam
Framing	7200 fps
Gain	500
Filter	500 nm SWP

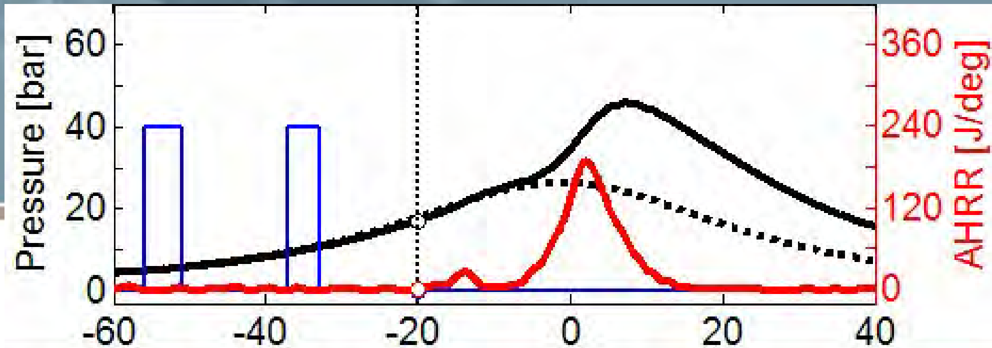
③ Laser-spark to define combustion regimes



- Just before SOC, Laser spark in center of cylinder
- Center mixture does not support flame propagation

Fuel (net)	PRF64 (ϕ=0.42)
Intake	21% O_2 (EGR)
Load	4.3 bar IMEP
Intake T	90°C
Intake P	1.15 bar
GDI SOI	-240° ATDC
CR SOI	-57°, -37° ATDC
Engine r_C	10.75
Window	100 mm diam
Framing	7200 fps
Gain	500
Filter	500 nm SWP

③ Laser-spark to define combustion regimes

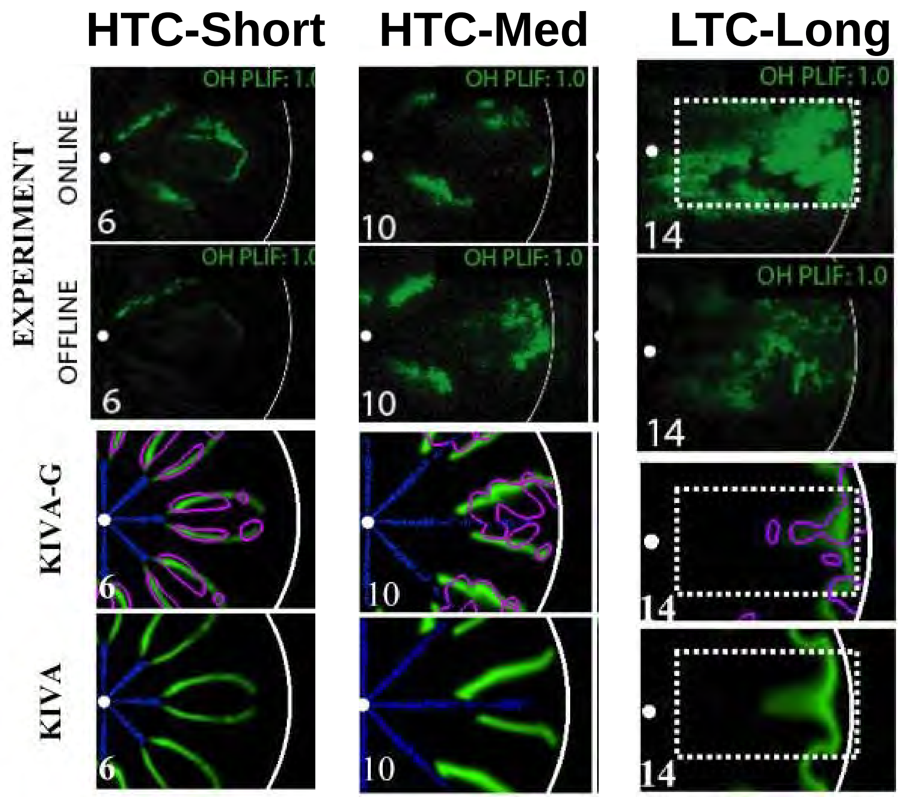


- Just before SOC, Laser spark near piston bowl
- Bowl-edge mixture often supports flame propagation

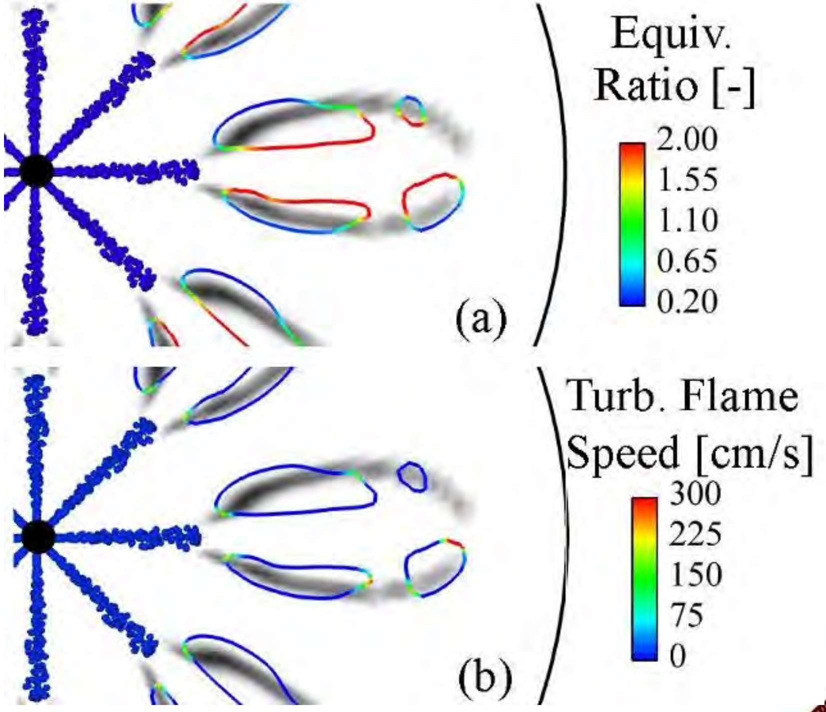
Fuel (net)	PRF64 (ϕ=0.42)
Intake	21% O_2 (EGR)
Load	4.3 bar IMEP
Intake T	90°C
Intake P	1.15 bar
GDI SOI	-240° ATDC
CR SOI	-57°, -37°ATDC
Engine r_C	10.75
Window	100 mm diam
Framing	7200 fps
Gain	500
Filter	500 nm SWP

④ Models: flame propagation required to capture lift-off edge-flame, kinetics sufficient otherwise

- For both conventional diesel and LTC, combustion structure is virtually identical with (KIVA-G) or without (KIVA) flame propagation submodels (kinetics models are sufficient)

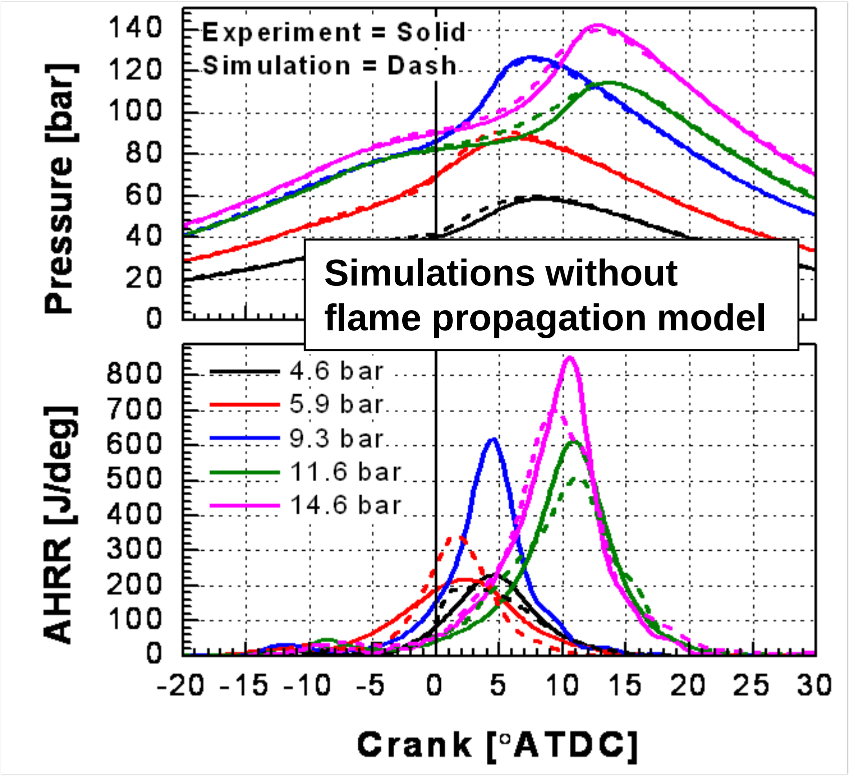


- Flame propagation sub-models are required to capture triple-flame structure at the lift-off location.
- Only non-negligible flame speed is in nose-like structure in near-stoichiometric region at lift-off length.

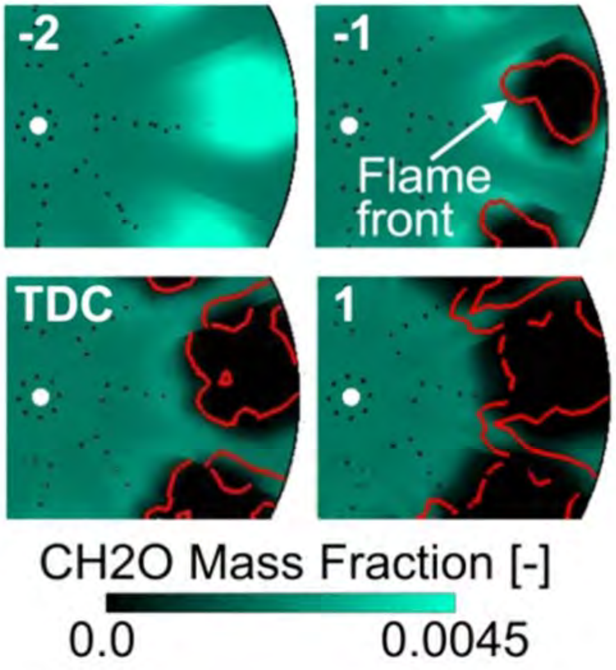


④ Models: RCCI mostly distributed autoignition, but some flame propagation locally

- For simulations of a heavy-duty engine at many RCCI conditions, the global combustion characteristics can be captured without consideration of flame propagation.



- Models predict that most of RCCI combustion is dominated by distributed auto-ignition, though flame propagation is important in some regions, depending on local conditions (e.g., equivalence ratio)

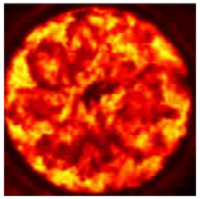


Future Plans: High-efficiency dual-fuel experiments and modeling, LTC soot, and multiple injections

- Probe in-cylinder mixing and combustion processes of high-efficiency dual-fuel operation
  - Build a fundamental understanding of in-cylinder processes that contribute to improved efficiency.
  - Incorporate insight and validation data from optical experiments exploring transitions from distributed autoignition to flame propagation to improve model fidelity
- Explore multiple-injection efficiency and emissions
  - Quantify emissions and efficiency improvements across wide parameter space to identify critical requirements
  - Use laser diagnostics (fuel-tracer, formaldehyde, and OH PLIF) to understand governing in-cylinder mechanisms
- Build understanding of in-cylinder LTC soot and PAH
  - Use multiple laser wavelengths and high-temporal-resolution imaging/spectroscopy to track PAH growth and conversion to soot

Heavy-Duty Combustion and Modeling Summary

Improved understanding of in-cylinder LTC spray, combustion, and pollutant-formation to help industry build cleaner, more efficient, heavy-duty engines

① 

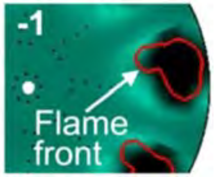
(SNL) Narrow-angle injection: higher soot than wide-angle, but similar post-injection oxidation

② 

(SNL+UW) New GDI enables RCCI, high-speed imaging shows heat release affected by reactivity gradients

③ 

(SNL+UW) Laser-spark ignition probe combustion regimes for understanding and model development

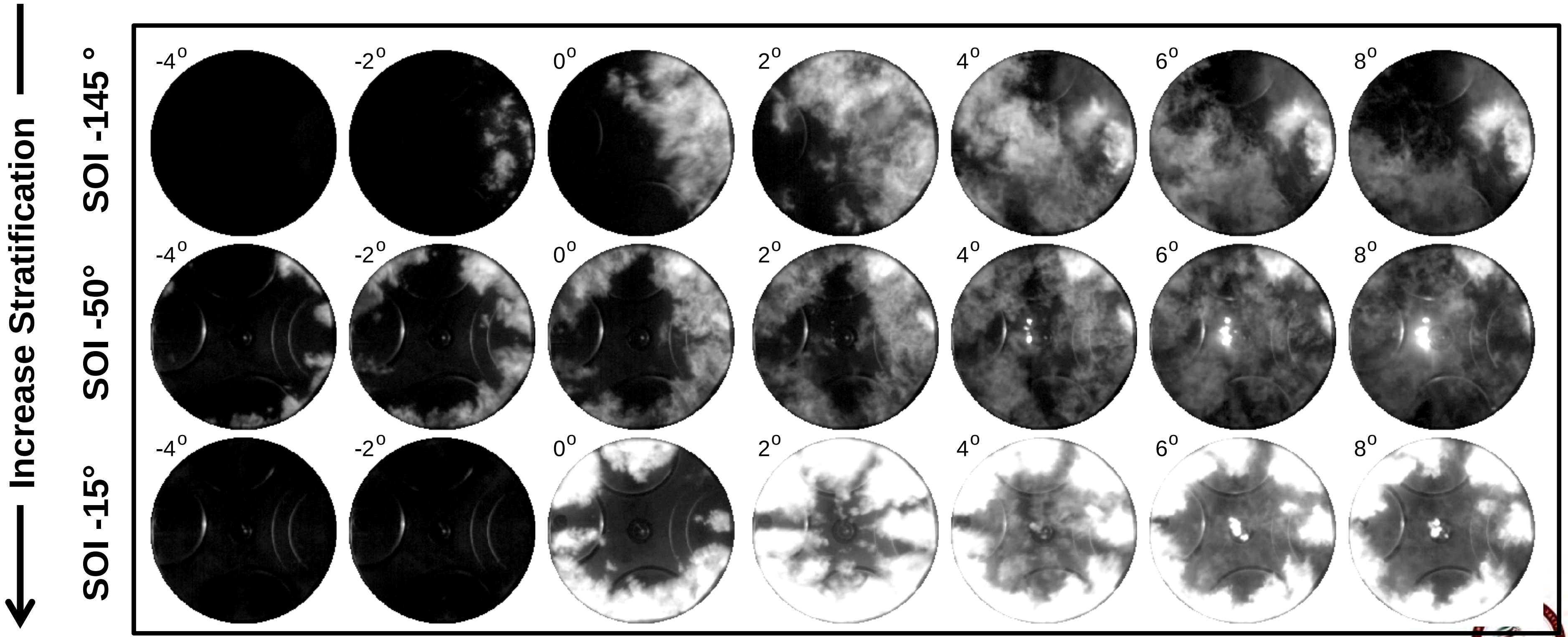
④ 

(UW) Models predict most combustion dominated by kinetics, but flame propagation important locally

Technical Back-Up Slides

② Summary: Fuel reactivity and ϕ stratification important for managing peak heat release rate

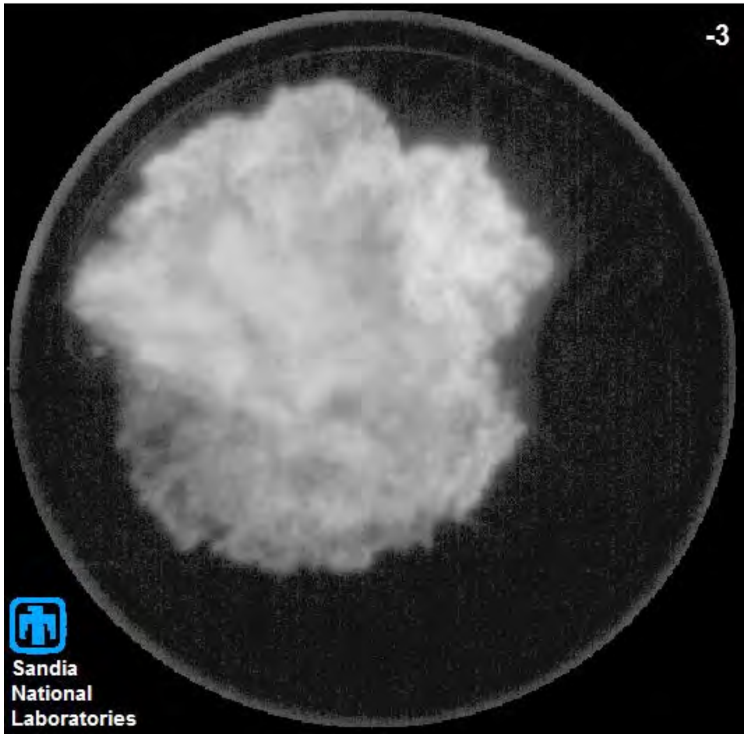
- Over- or under-stratification results in rapid energy release.
- Early SOI: Low reactivity & concentration gradients (HCCI-like)
- Mid-range SOI: Moderate reactivity & concentration gradients (RCCI)
- Late SOI: Strong gradients with rich jet mixtures (diesel-like)



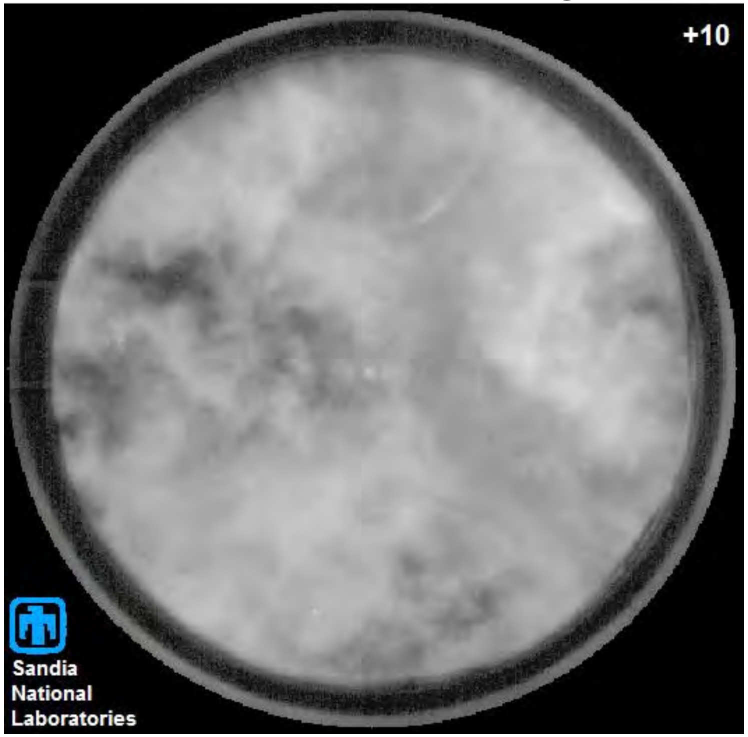
③ With dual-fuel injection and laser ignition, multiple known combustion modes achievable

- Combustion regimes for RCCI and other LTC (and conventional) strategies may span from flame propagation to distributed autoignition
  - Can be important for both modeling and high-efficiency operation
- Defined combustion regimes provide reference for optical diagnostics

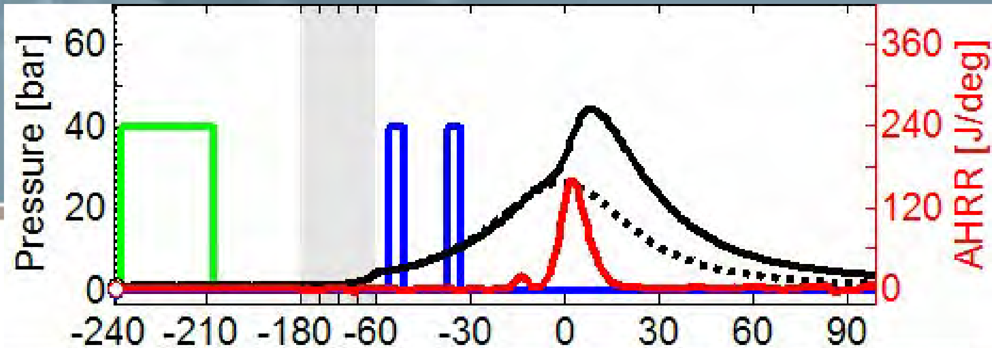
Spark Ignition: Flame Propagation



HCCI: Distributed Autoignition



② Dual-Fuel Injection (GDI+CR)



- GDI sprays (100 bar) are first, entering at top of field of view
  - Creates premixed charge of iso-octane (PRF 100)
- Common-rail sprays (600 bar) occur in two injections, emanating from centrally located injector in cylinder head
  - Direct injection of n-heptane (PRF0)
- Gives overall PRF=64
- Sprays illuminated using CW high-power LED white-light source through side-windows