SAND2020-6793PE

Fundamental Advancements in Pre-Chamber Spark Ignition and Emissions Control for Natural Gas Engines: In-Cylinder Optical Imaging

Mark P. B. Musculus, Rajavasanth Rajasegar, Zheming Li, Dalton Carpenter
Sandia National Laboratories, California

José Maria Garcia Oliver
CMT - Universitat Politècnica de València, Spain

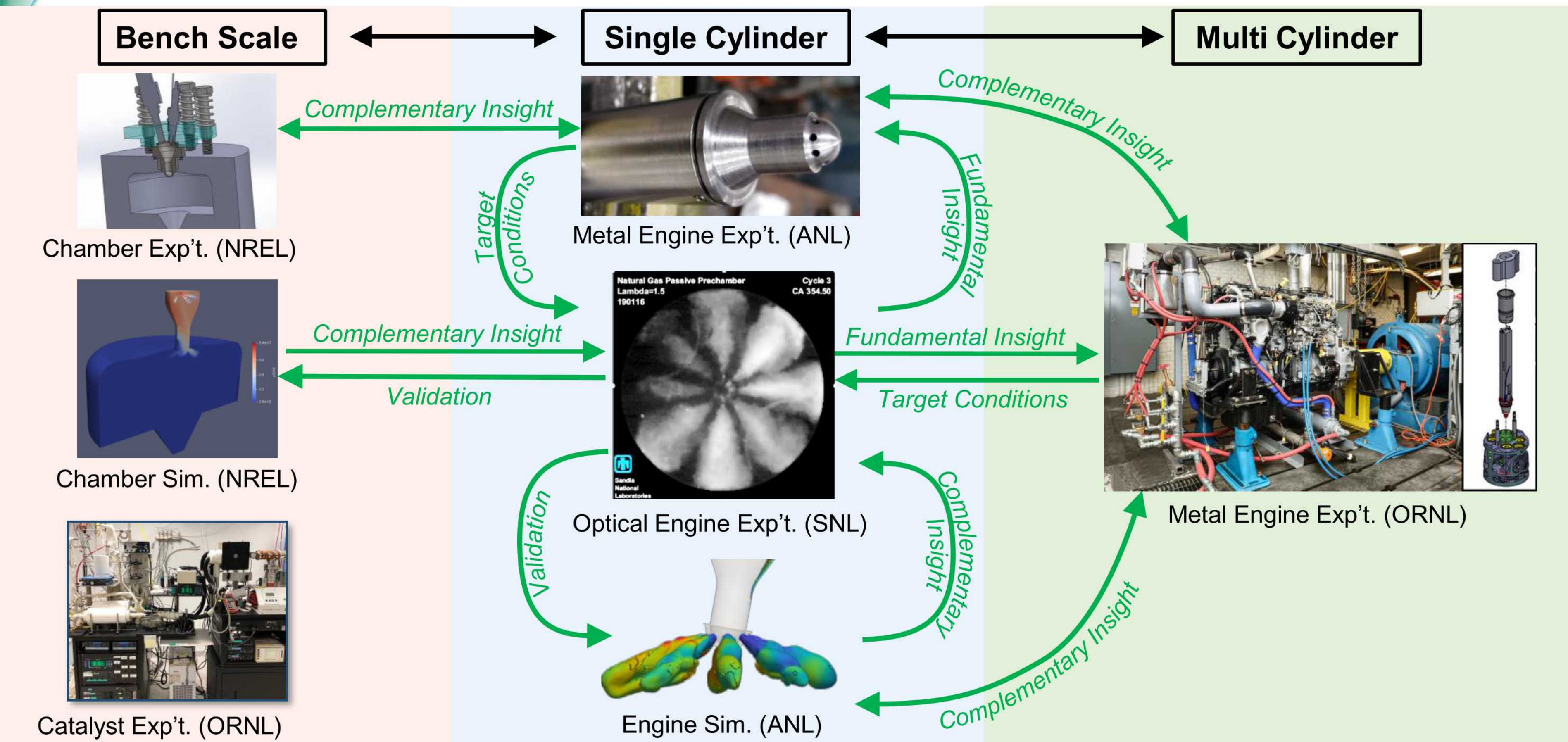
Yoichi Niki
Nat. Inst. Maritime, Port, Aviation Tech., Japan

Advanced Engine Crosscut Team Meeting
USCAR– Southfield, Michigan
November 14, 2019

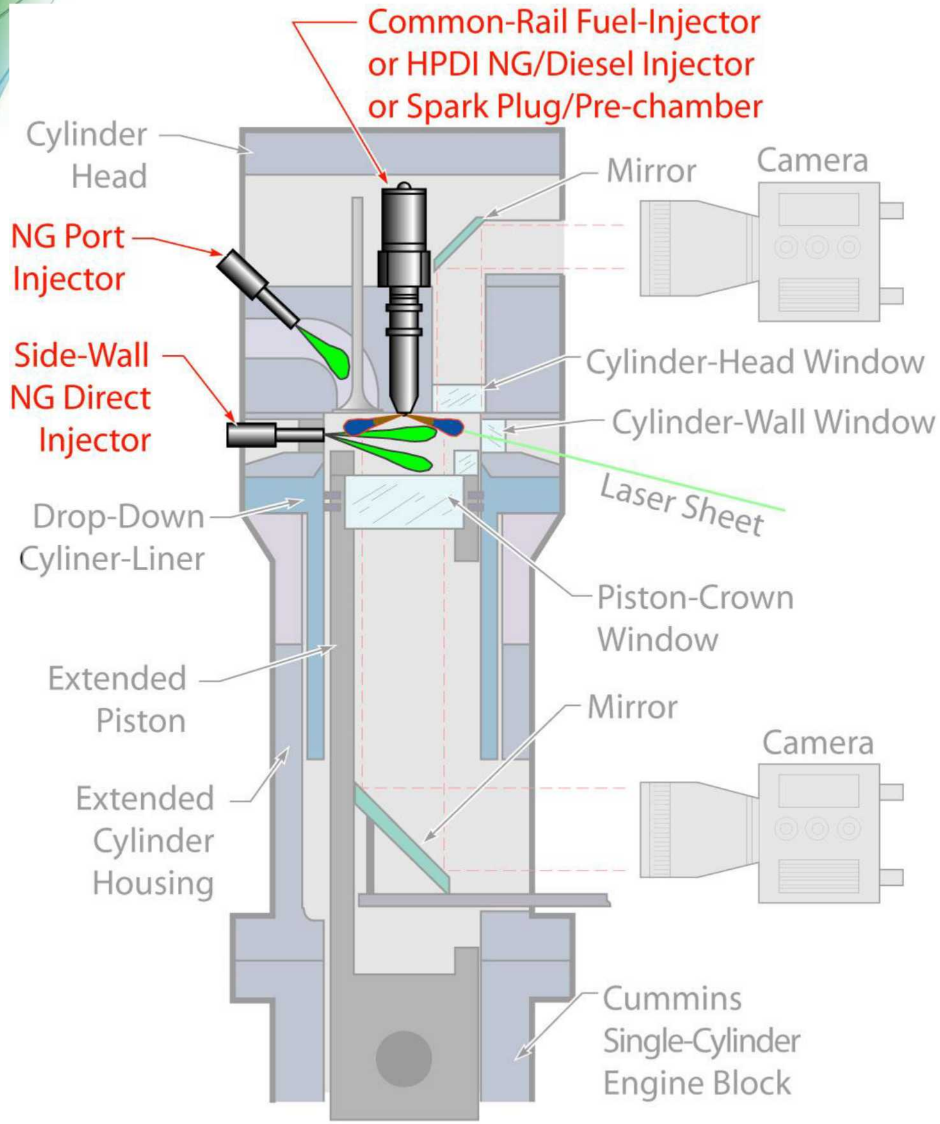
Sponsor: US DOE Vehicle Technologies Office
Program Managers: Kevin Stork, Gurpreet Singh, Michael Weismiller

This research was sponsored by the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE). Optical engine experiments were conducted at the Combustion Research Facility, Sandia National Laboratories, Livermore, CA. Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Integration across 4 nat'l labs connects fundamental experiments & modeling to practical hardware



SNL (B1-B3): Modify HD optical engine with active natural gas pre-chamber for fundamental mixing & combustion data



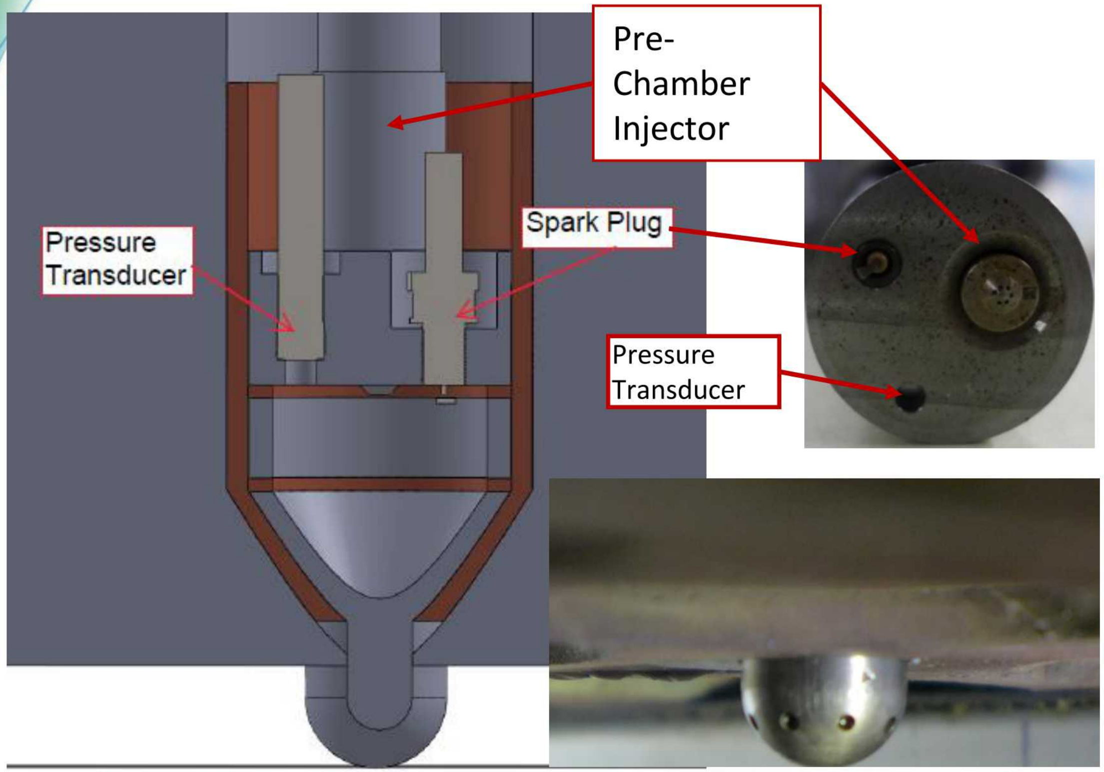
SNL Task Statement (B1-B3 / $750k): Adapt a PCSI module to a HD optical single-cylinder engine and use laser/imaging diagnostics for the ignition-jet as it emerges from the pre-chamber, mixes with and ignites the premixed main-chamber gases, and subsequently drives the progression of main-chamber combustion, whether flame propagation or sequential autoignition

- **B1** (Inadequate science base / simulation tools)**:** Provide phenomenological and quantitative data including ignition-jet penetration rates, spatial and temporal progression of intermediate combustion species to identify modes of ignition and combustion, and/or sources of combustion inefficiency in the late cycle

  Also use optical data to validate **NREL** and **ANL** simulations and aid interpretation of **ORNL** metal-engine data so that together the labs can develop a conceptual-model description of PCSI

- **B2** (EGR/lean limits), **B3** (hot-spot pre-ignition): Use conceptual model and fundamental understanding as basis that will provide a fundamental basis for developing operating strategies and hardware to mitigate barriers B2 & B3

HD optical engine modified to add fueled natural gas pre-chamber for fundamental mixing & combustion data



1st generation pre-chamber
- 3% of main-chamber volume
- Number of holes: 8
- Hole size: 1.6 mm
- Included angle: 130°
- Nozzle plane parallel to cylinder head
- Tip protrusion: 10.6 mm below the fire deck
- Fueling: GDI injector
- Pressure: uncooled piezoelectric
- Spark plug: miniature "Rimfire"

Pre-chamber injector abbreviations:
- SSE: Start of Solenoid Energizing
- ESE: End of Solenoid Energizing
- DSE: Duration of Solenoid Energizing

SNL (B1-B3): Unfueled pre-chamber performance verified for lambda sweep, main-chamber direct injection

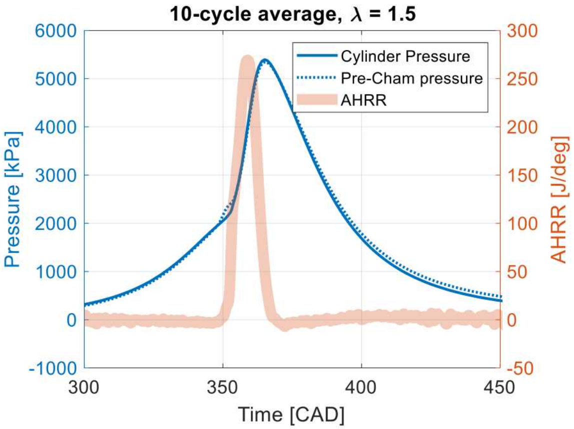
- Relatively low engine speed of 600 RPM due to main-chamber direct injector capacity limit
- Main chamber injection only (pre-chamber unfueled); 100 bar NG injection pressure
  - Main-chamber injection of ~20-25ms duration (DSE) during intake stroke (40 CAD SSE)
  - Target load of 5 bar IMEPg, naturally aspirated, no EGR

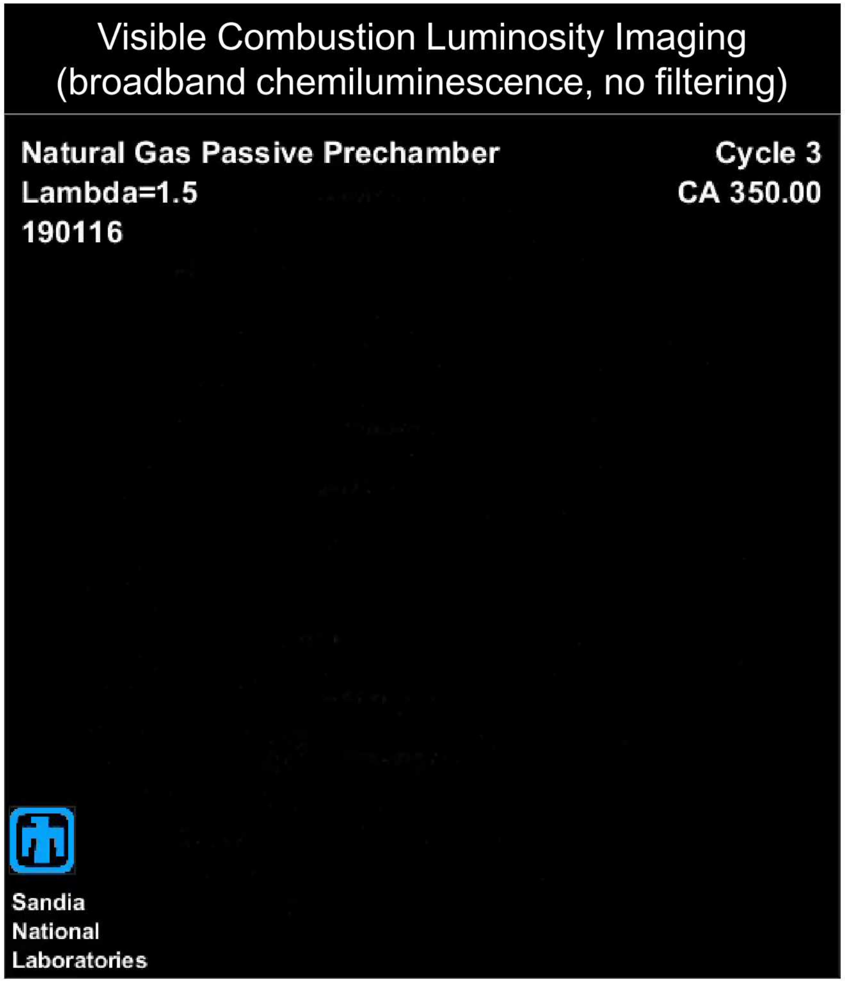
Global λ	IMEPg [kPa]	COV of IMEPg [%]	Intake T [C]	Intake P [bar]	Spark [CAD]	SSE [CAD]	DSE [ms]
1.5	543	1.7	80	1.03	343	40	24.60
1.6	515	2.2	84	1.03	340		22.90
	519	2.3	79	1.03	342		
	521	1.5	80	1.02	343		
	523	1.9	86	1.03	344		
1.7	492	1.9	80	1.03	337		21.88
	512	2.0	80	1.02	342		
	507	1.9	73	1.02	343		
1.8 (2/10 misfires)	365	60.6	78	1.02	343		20.73
1.9 (6/10 misfires)	142	166	80	1.01	343		19.69

For stable (low COV) λ=1.5 passive pre-chamber, combustion imaging shows cycle-to-cycle variations

<u>Operating conditions</u>

- Speed: 600 RPM
- Spark: 343 CAD
- Lambda: 1.5
- IMEPg: 543 kPa
- IMEPg COV: 1.7%

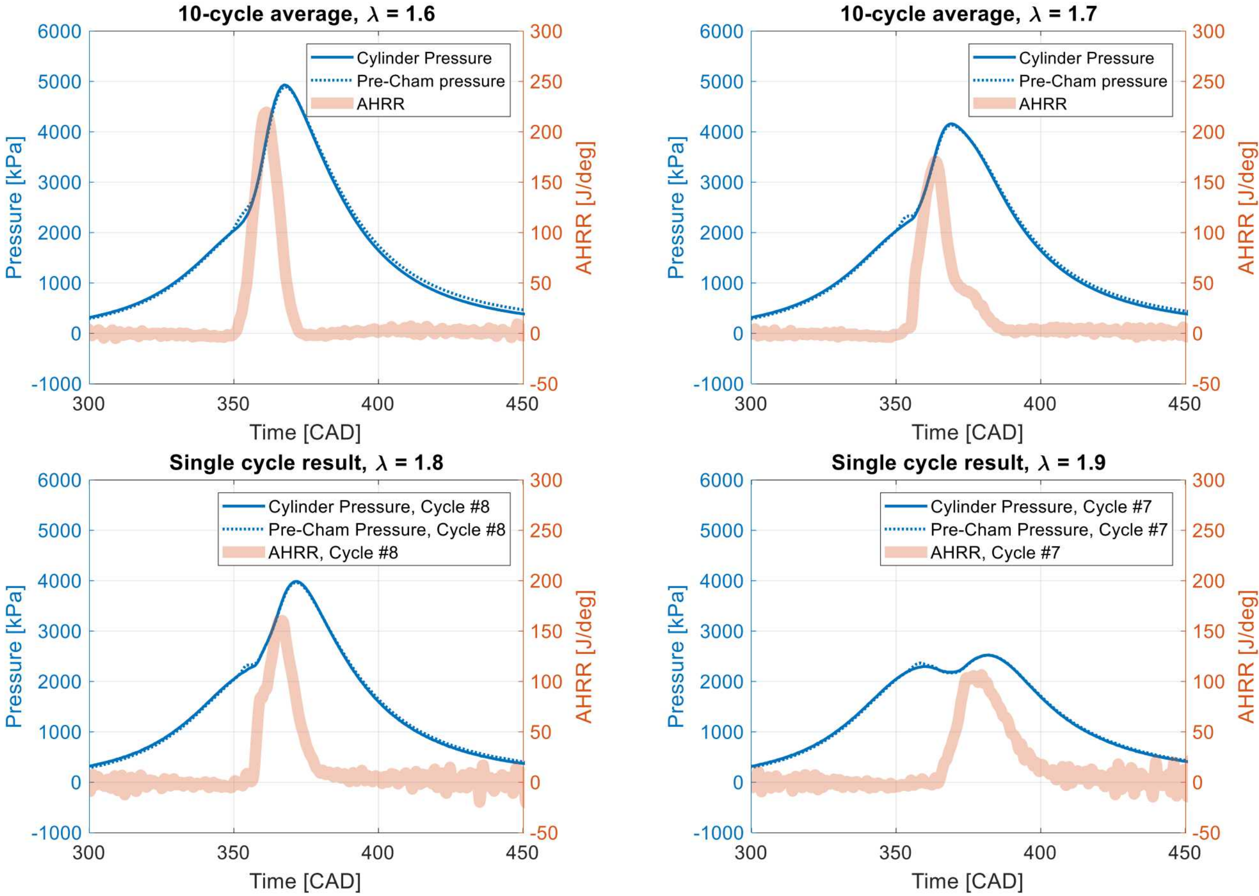




- Pre-chamber pressure rises above main-chamber pressure after spark, indicating ignition
  - Later pressure differences may be partly due to thermal effects on uncooled transducer
- Large cycle-to-cycle variation in timing of individual jet ignition and luminosity of pre-chamber jets
  - Early luminosity fluctuates on-and-off in some jets

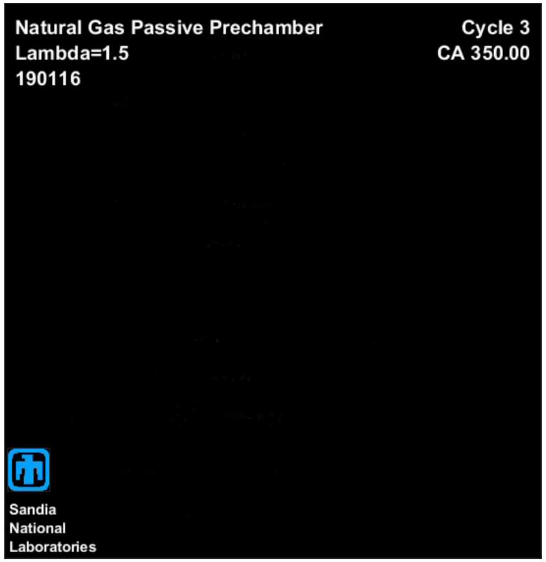
As unfueled pre-chamber is swept to leaner conditions, combustion duration & misfires increase (const. spark timing)

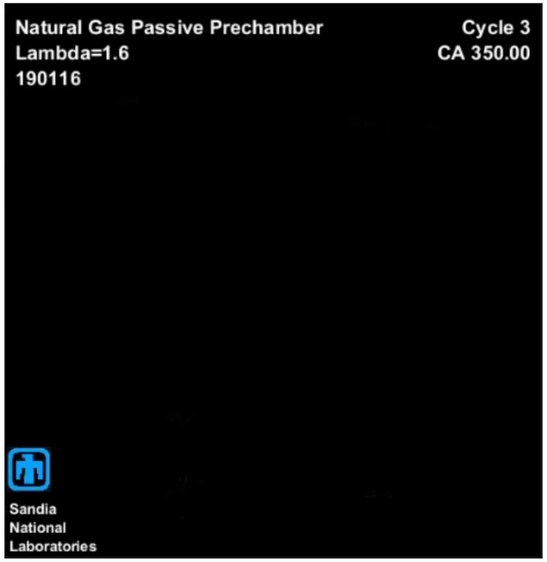
- Unfueled pre-chamber
- Intake T & P held constant
- Main-chamber injection DSE varied
- With constant 343 CAD spark timing, combustion duration increases and combustion becomes less stable for λ>1.7
- At λ=1.9, both pre-chamber and main-chamber combustion is greatly retarded, and 60% misfires

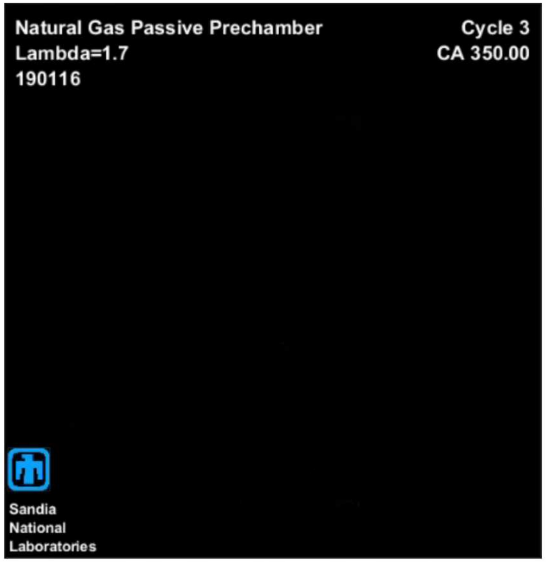


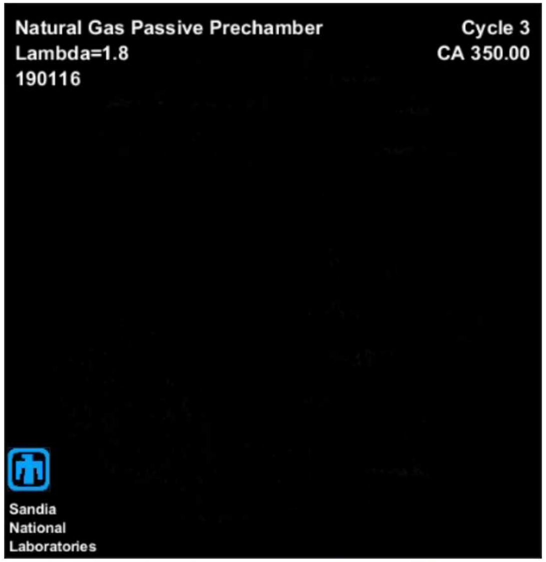
Imaging: increasing jet-to-jet & cycle-to-cycle variability, non-luminous pre-chamber jets w/ ignition delay at leanest mixtures

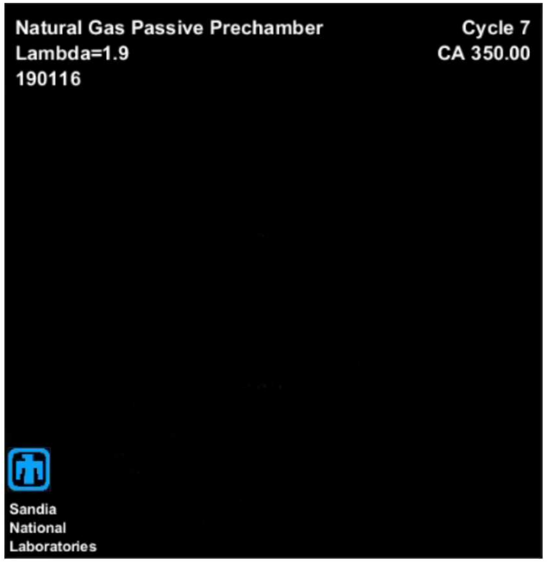
- Identical camera settings
- As with AHRR & pressure rise, combustion luminosity is weaker with increasing λ
- At λ>=1.7, no consistent luminosity from pre-chamber jets before main-chamber ignition
  - Transition of ignition mechanism from actively burning jets to diesel-like ignition delay



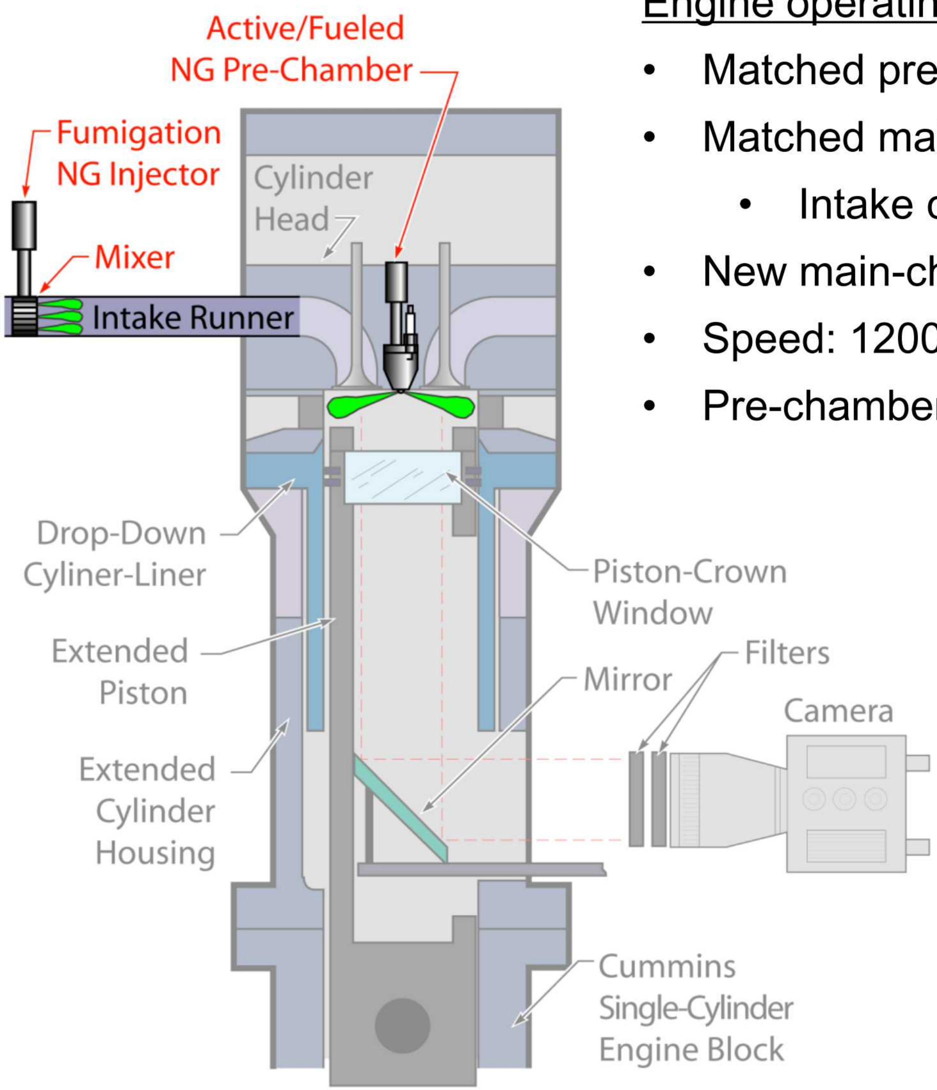








Second round of optical experiments use common pre-chamber design (ANL, NREL, SNL) and target operating conditions



Engine operating conditions:

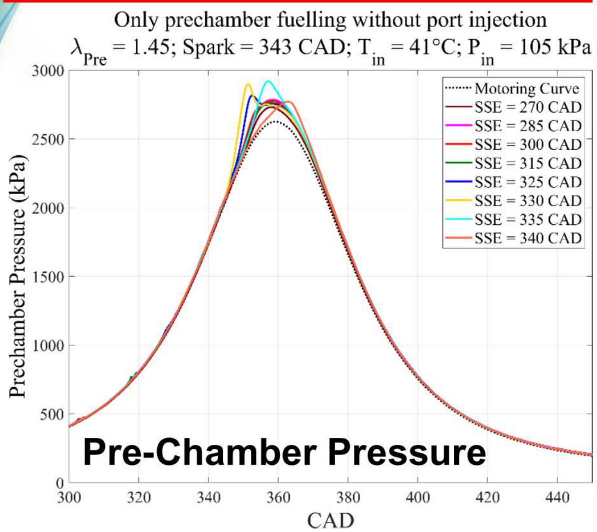
- Matched pre-chamber design (from ANL, NREL also)
- Matched main-chamber conditions at spark:19bar, 730K
  - Intake conditions: 1.05bar, 314K
- New main-chamber fueling: fumigation in intake runner
- Speed: 1200 rpm
- Pre-chamber spark timing: 343 CAD

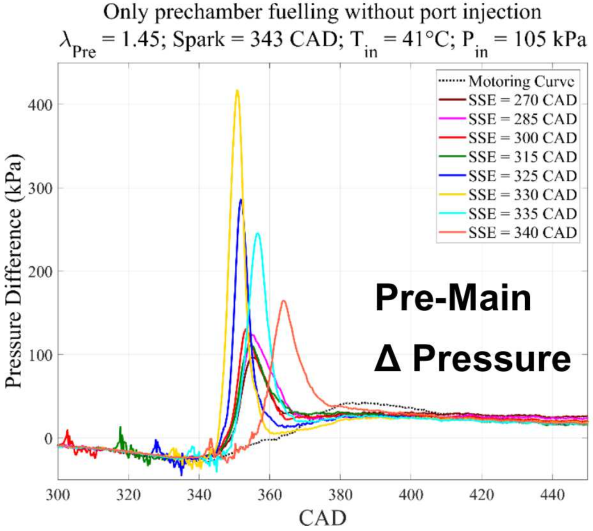
Parameter sweeps:

- Prechamber-only fueling
  - SSE 270-240 CAD at λ_{pre} = 1.45
  - λ_{pre} 0.61-1.84 at SSE = 270 CAD
  - λ_{pre} 0.75-1.65 at ESE = 337 CAD
- Unfueled pre-chamber
  - λ_{main} 1.5-1.7
- Fueled pre-chamber
  - λ_{pre} 0.49-1.65 at λ_{main} = 1.65
  - λ_{main} 1.65-2.60 at λ_{pre} = 0.93

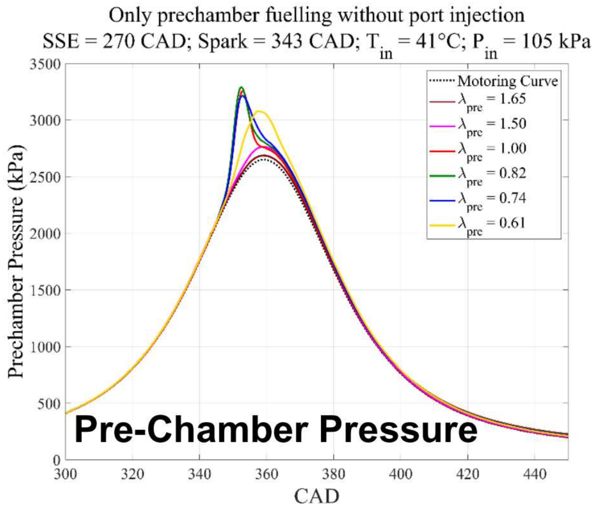
Pre-chamber-only fueling (no main-chamber fuel/ignition): measure/model jet penetration, flame emergence, fuel leakage

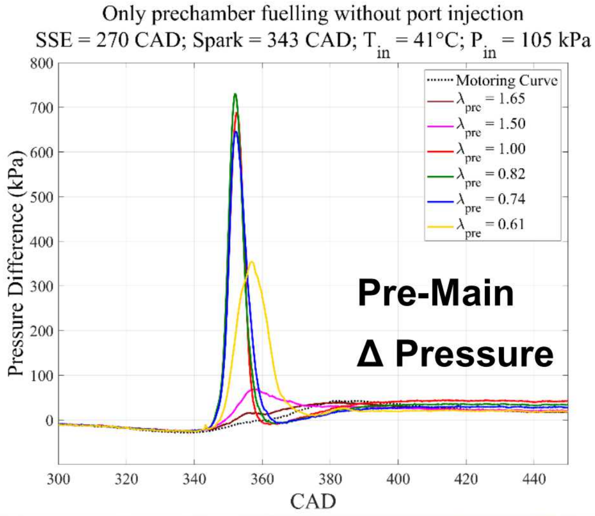
SSE 270-240 CAD at λ_{pre} = 1.45



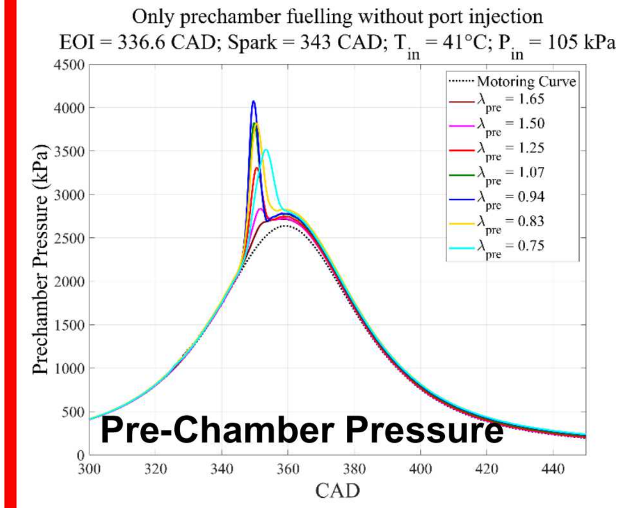


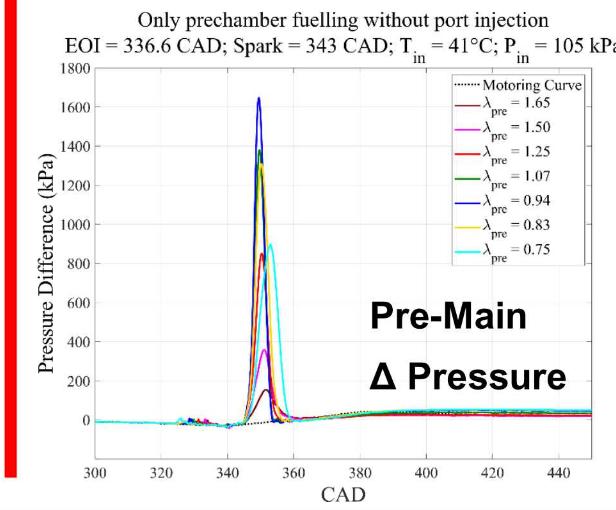
λ_{pre} 0.61-1.84 at SSE = 270 CAD





λ_{pre} 0.75-1.65 at ESE = 337 CAD

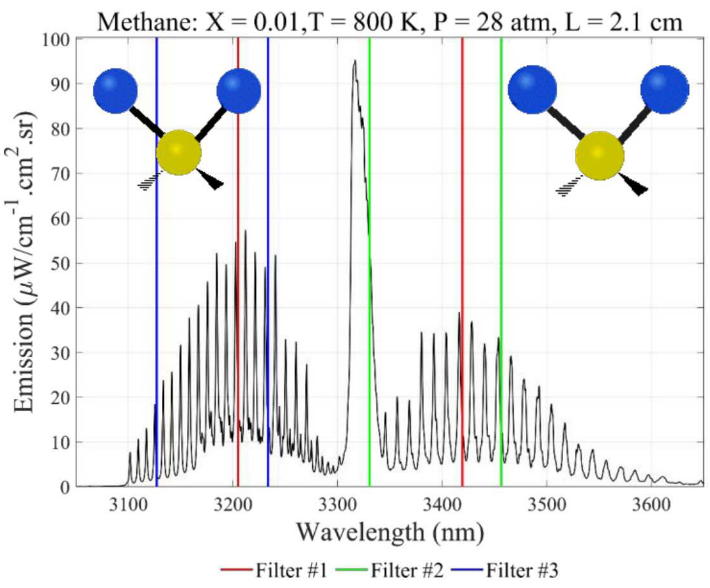




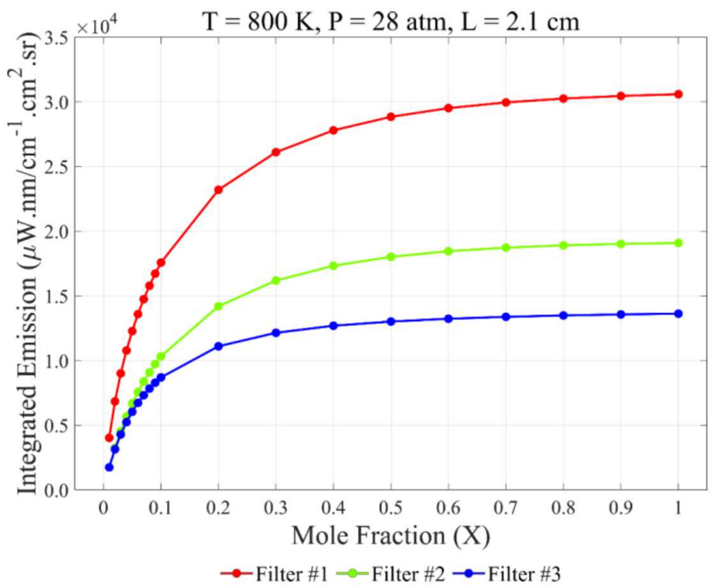
Infrared (IR) emission imaging: combustion or compression-heating increases vibration of C-H bonds in hydrocarbons

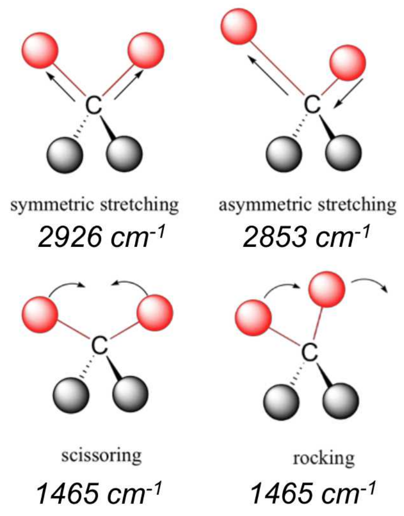
- All hydrocarbons, including natural gas components (methane, ethane, ethylene, acetylene, propane, etc.) emit in the infrared near 3.3 μm (3000 cm^{-1}) due to thermally excited vibration of C-H bonds, or "C-H stretch"
- Emission is strong enough for imaging when heated by compression to ~700 K or more, providing a means to quickly and easily detect hot in-cylinder fuel
  - IR emission signal is strongly dependent on temperature, and begins to saturate approaching stoichiometric natural gas, so IR intensity must be interpreted with care

HITRAN based Simulated Emission Spectrum



Integrated Emission Intensities for Quantification

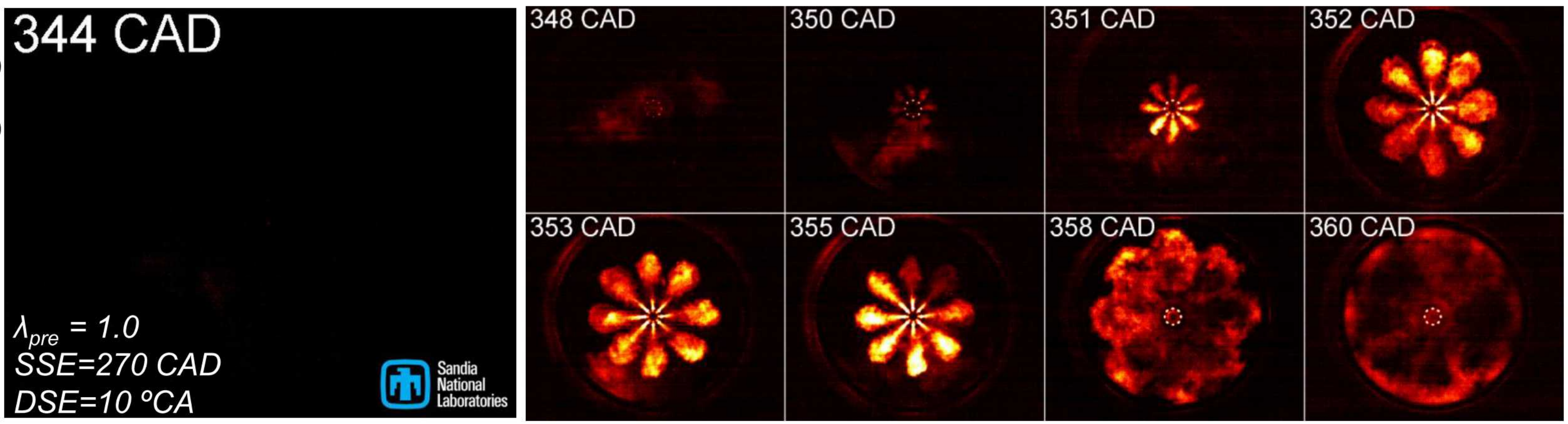


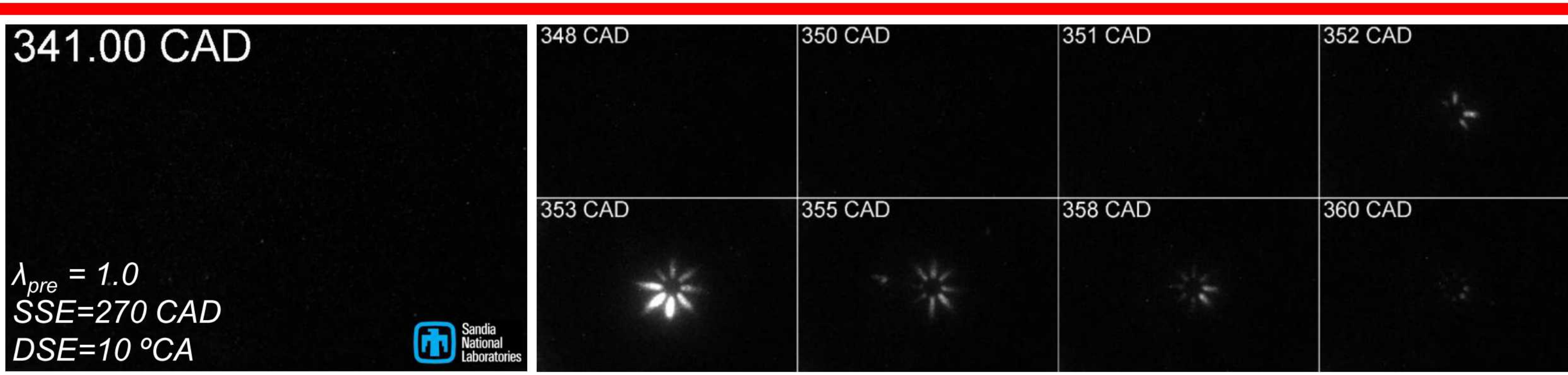


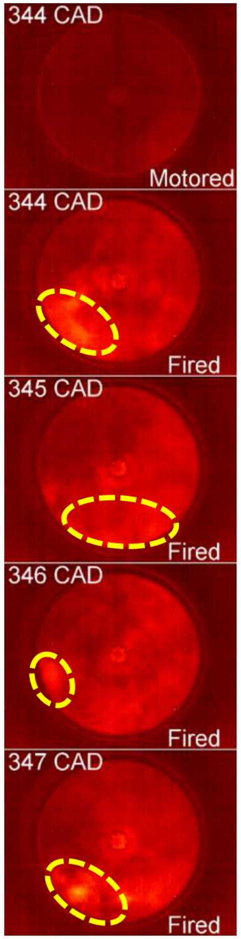
Pre-chamber-only fueling, stoichiometric: unburned fuel-jet precedes burning jet, evidence of fuel leaking from pre-chamber

- After spark at 343 CAD, infrared images show weakly-emitting fuel jets emerging by 350 CAD as pressure in the pre-chamber rises due to combustion
- Broadband chemiluminescence first appears at 352 CAD, indicating that the propagating flame inside the chamber has reached the nozzles
- Pre-chamber fuel "blobs" leak into main chamber; none for motored cycles

Infrared Imaging



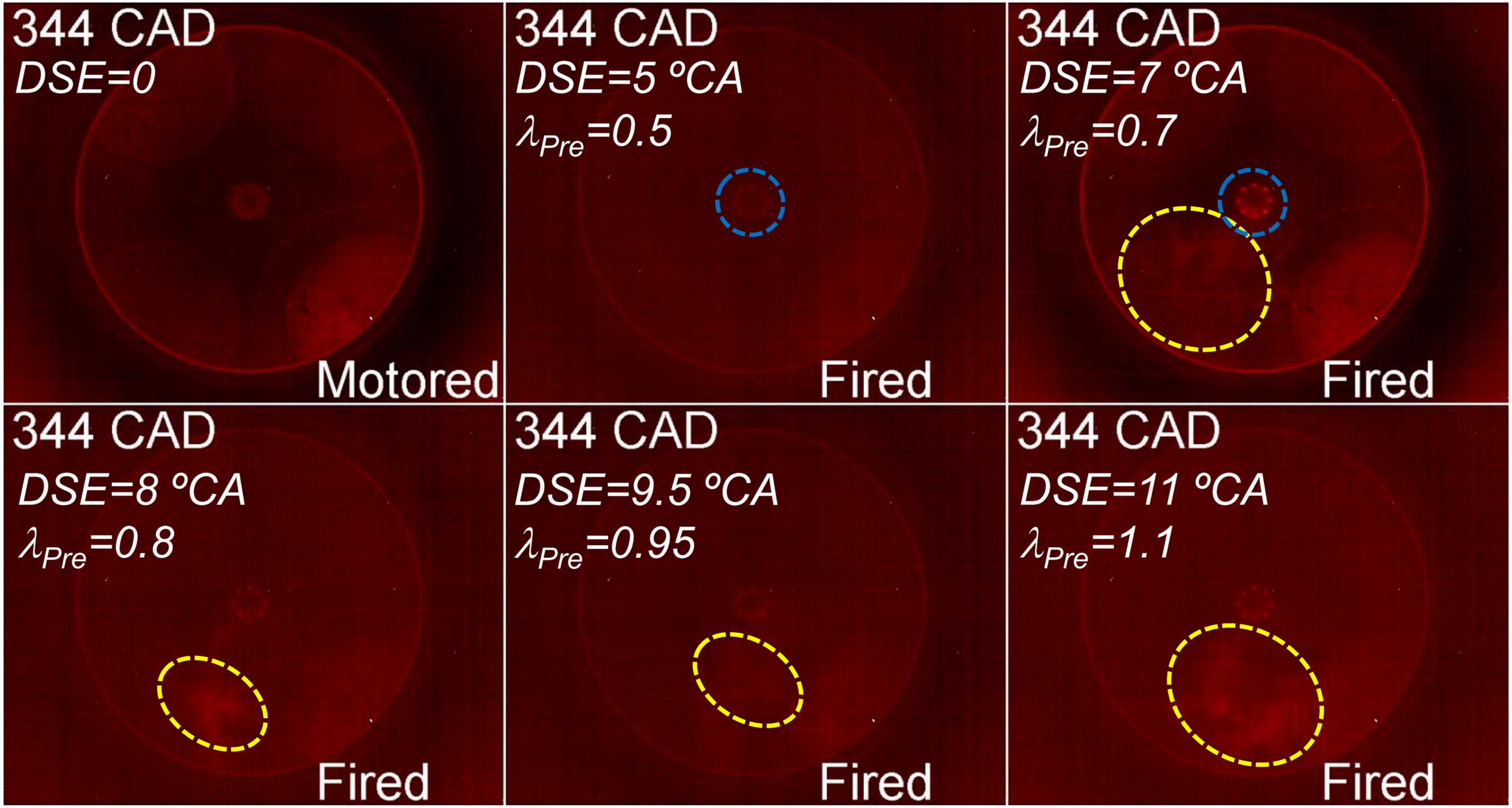




IR images of fuel leakage

IR emission imaging reveals fuel loss from pre-chamber before spark, increasing with λ_{Pre} (longer pre-chamber injections)

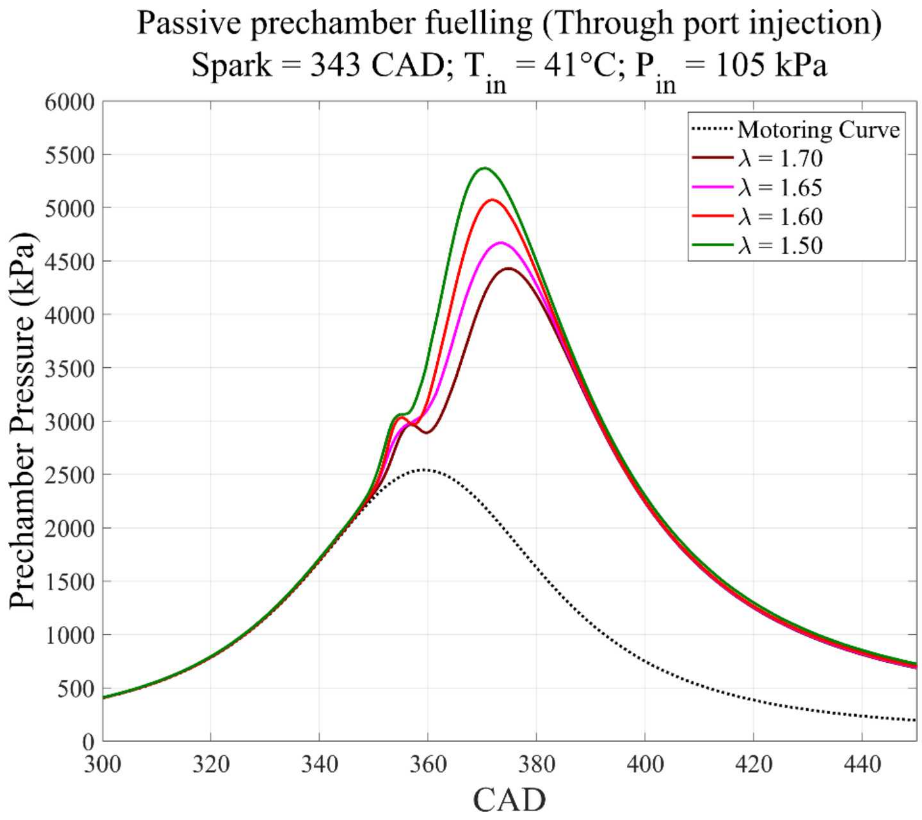
- IR emission from hot fuel inside the prechamber shines through the nozzles (blue circles)
- As DSE is increased, weak IR emission from fuel "leaks" from pre-chamber (yellow circles)



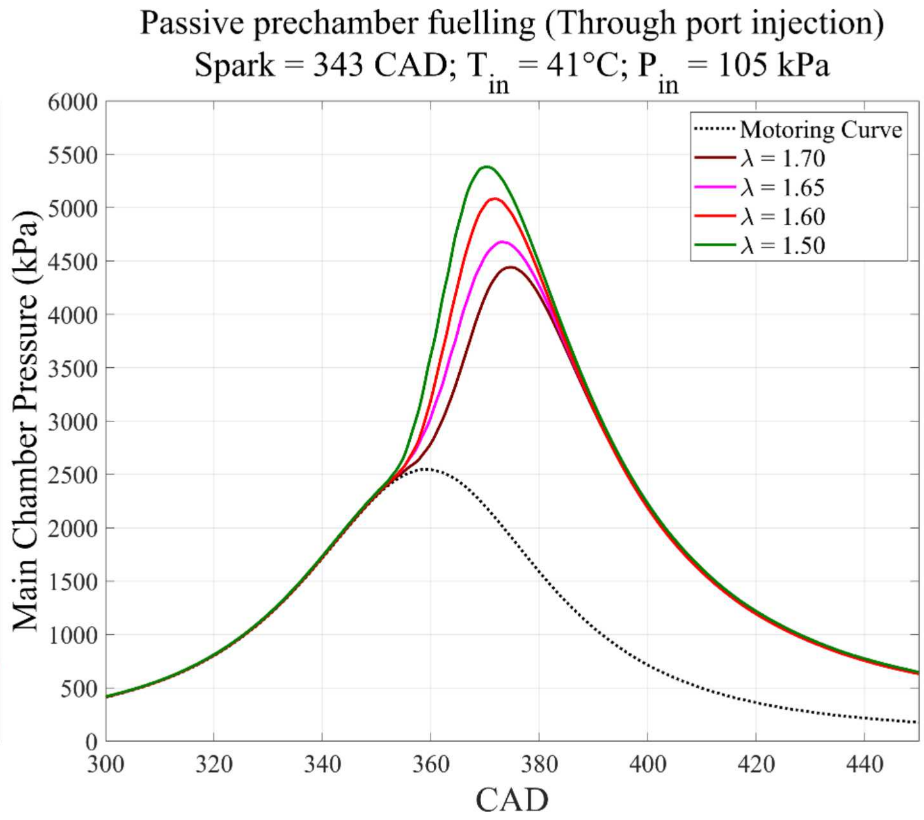
Unfueled pre-chamber, λ=1.5-1.7 sweep: combustion duration increases at constant spark timing

- After spark at 343 CAD, pre-chamber and main-chamber pressure rise rate and peak pressure decrease with increasing λ_{main}

Pre-Chamber Pressure

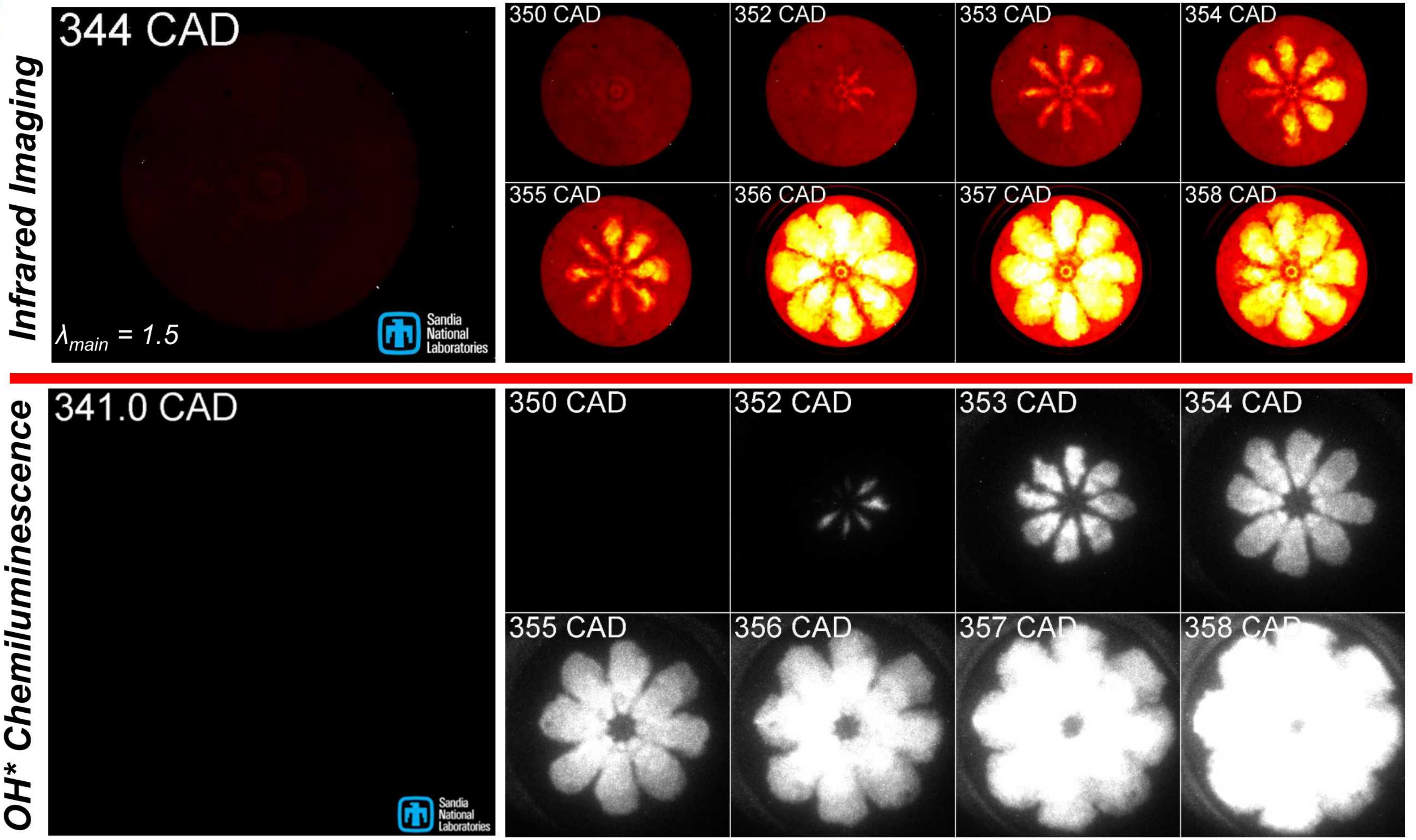


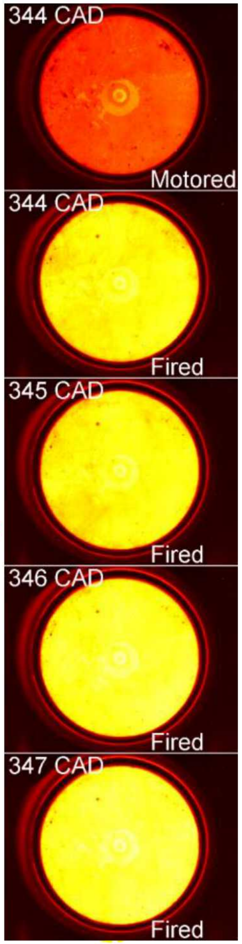
Main-Chamber Pressure



Unfueled pre-chamber, $\lambda_{Main}=\lambda_{Pre}=1.5$: burning jets ignite main-chamber within 1 CAD after emerging from pre-chamber

- Burning IR jets emerge by 352 CAD (unburned $\lambda=1.5$ jet into $\lambda=1.5$ main likely not visible)
- OH* chemiluminescence also appears at 352 CAD, main-ignition by 353 CAD
- IR imaging shows main fuel relatively well mixed (sensitive to temperature though)

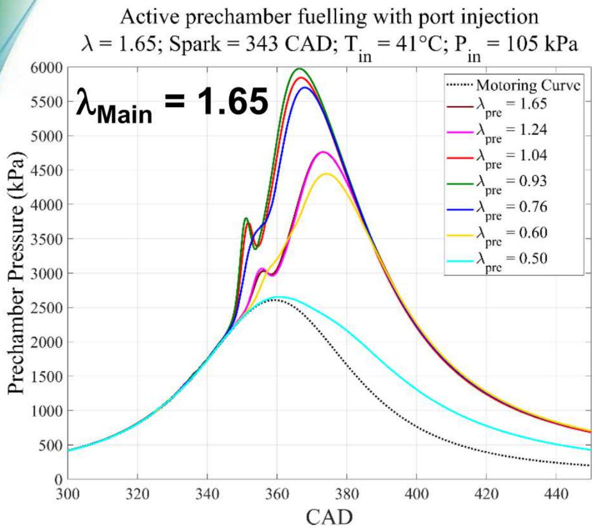




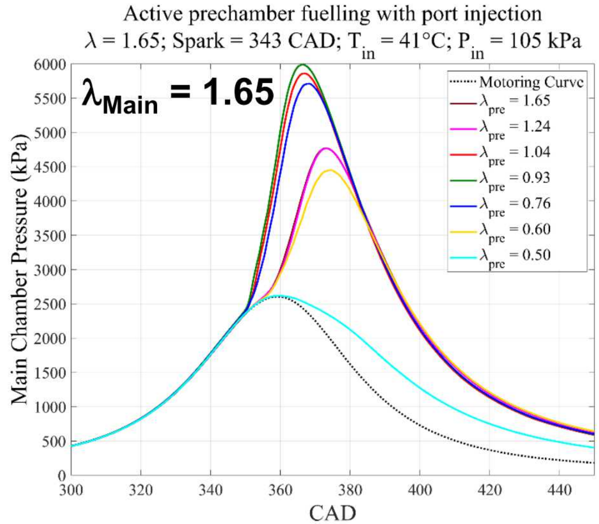
IR images of main fuel

Fueled pre-chamber sweeps: λ_{Pre} = 0.49 to 1.65 at λ_{Main} = 1.65 is fastest at λ_{Pre} = 0.93; use λ_{Main} = 1.65 to 2.60 at λ_{Pre} = 0.93

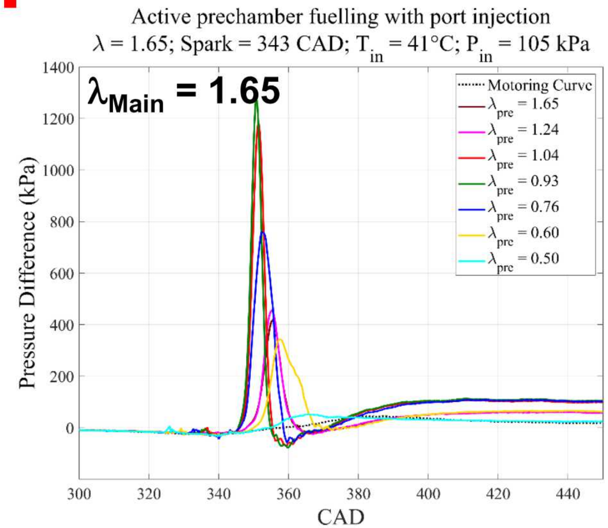
Pre-Chamber Pressure

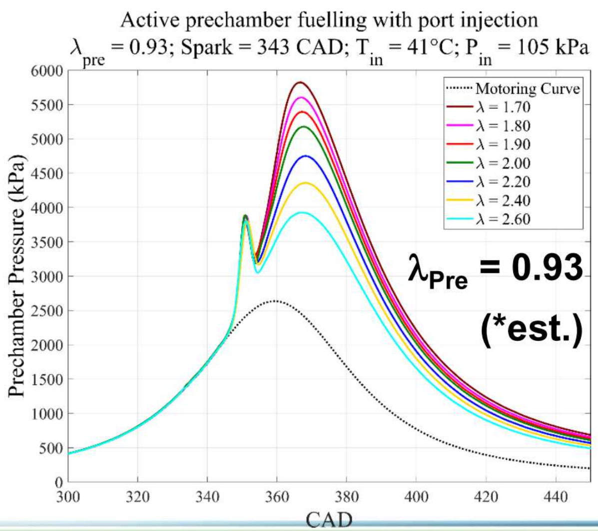


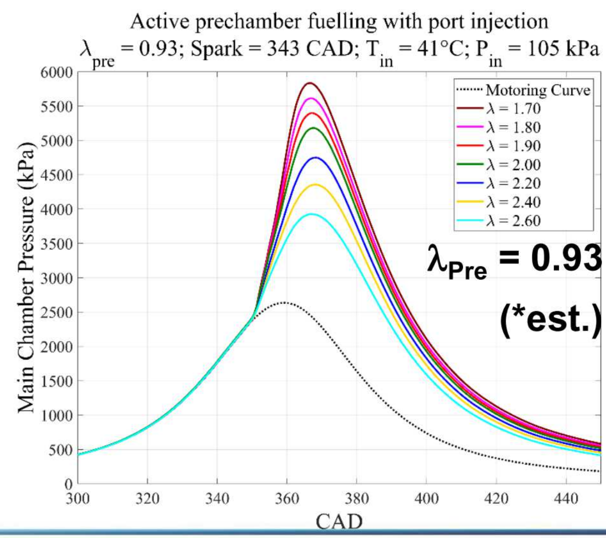
Main-Chamber Pressure

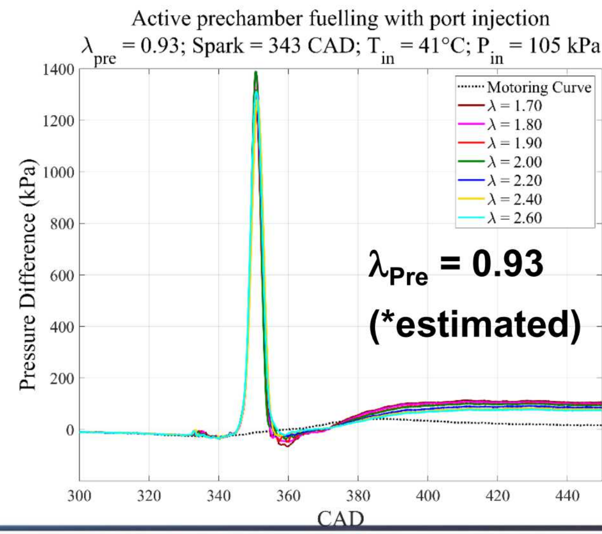


Pre-Main Δ Pressure



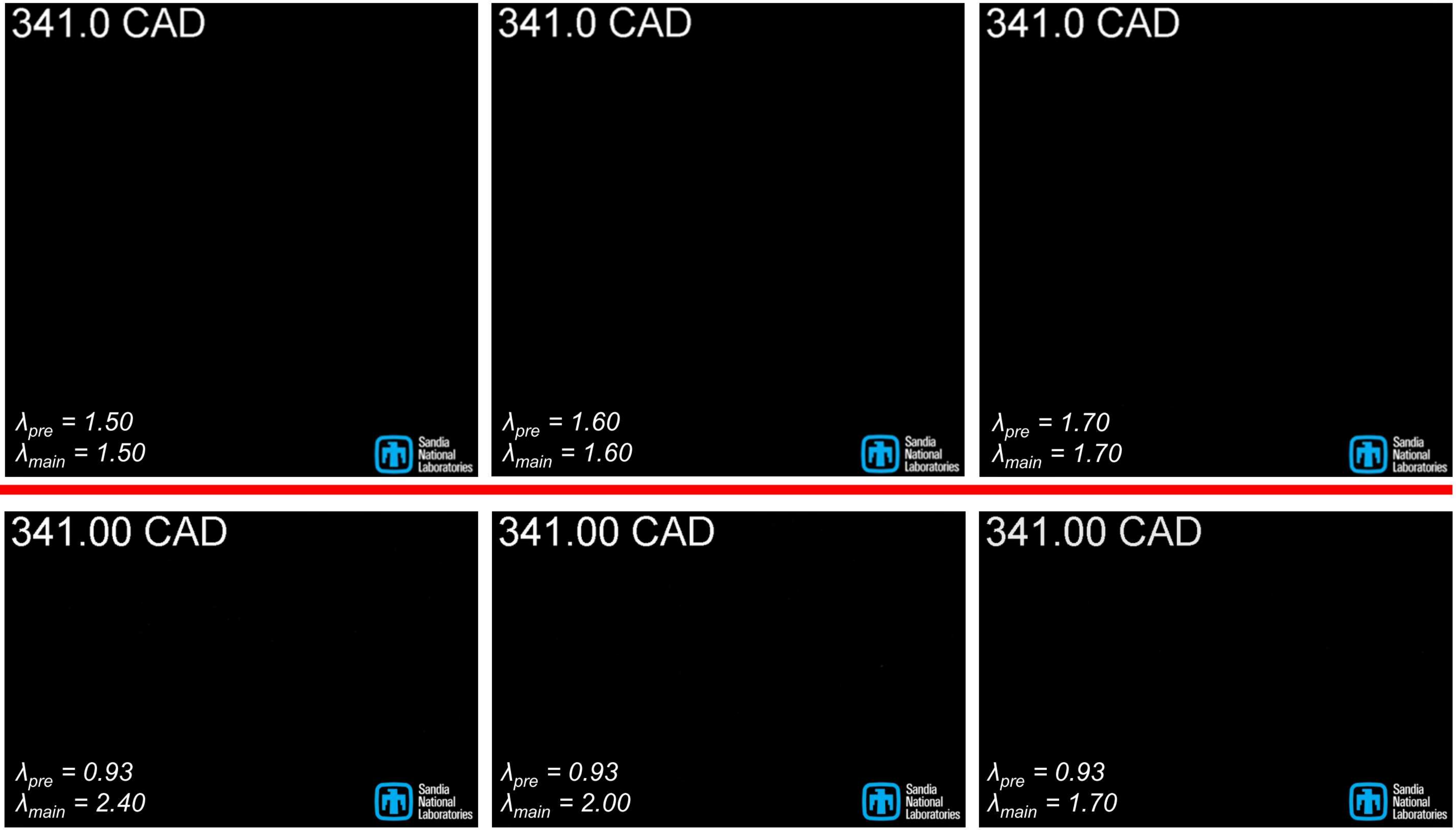






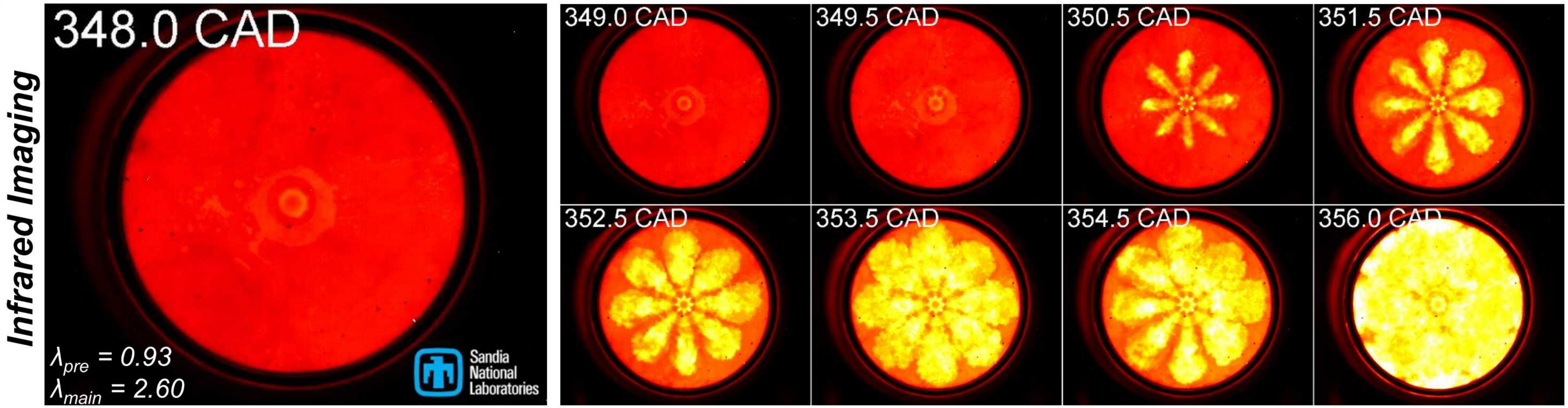
Unfueled pre-chamber misfires for $\lambda_{Pre} = \lambda_{Main} > 1.70$; $\lambda_{Pre} = 0.93$ pre-chamber extends lean limit beyond $\lambda_{Main} = 2.40$

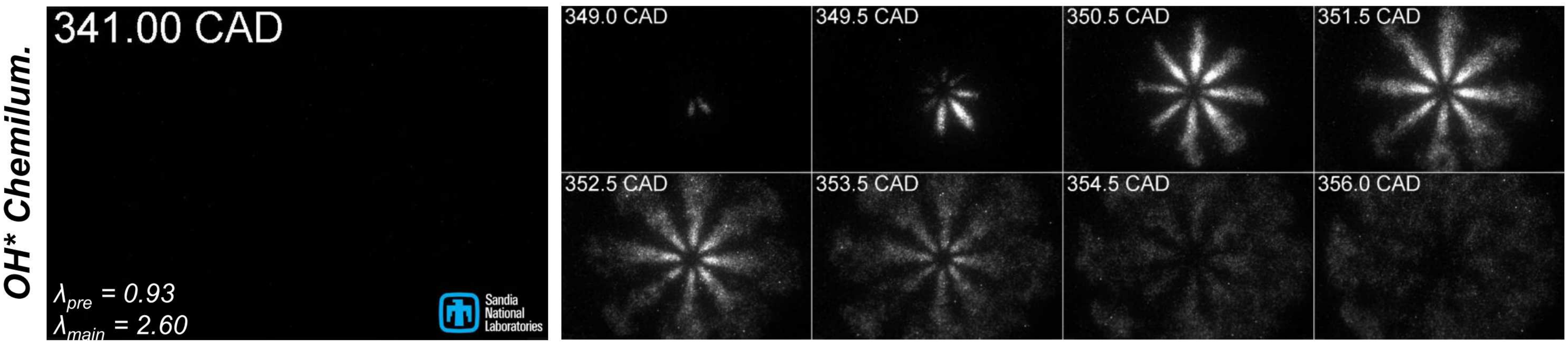
- At λ_{Main}=1.70, OH* chemiluminescence images throughout main chamber are much more luminous for fueled (λ_{Pre} = 0.93) than unfueled (λ_{Pre}=1.70) pre-chamber



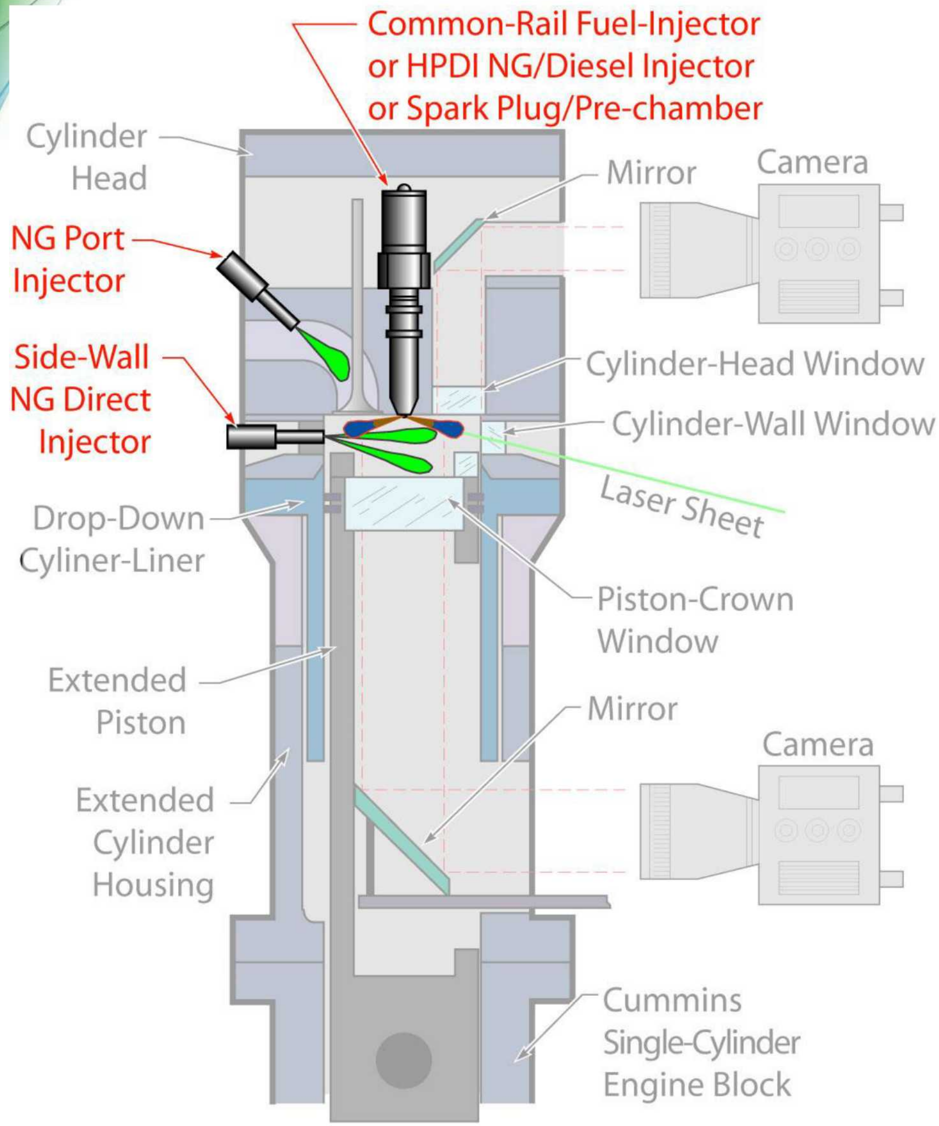
Fueled pre-chamber, λ_{Pre} = 0.93, λ_{Main} = 2.60: distinct flame propagation not apparent in OH* chemiluminescence

- Cycle-to-cycle variability in main-chamber ignition for IR images (not due to pre-chamber)
  - OH* images are from single cycle; IR image sequence assembled from one per cycle
- IR and OH* show progression of combustion through main chamber, but flame not distinct





Future work for HD optical engine with active natural gas pre-chamber for fundamental mixing & combustion data



Next Steps:

1. Complete design and fabrication of third-generation pre-chamber assembly with automotive-scale spark plug, improved sealing, and improved clamping
2. Gather engine performance and combustion imaging data along the EGR dilution and/or lean-mixture limits to characterize the in-cylinder processes affecting stability and efficiency
3. Utilize other laser/imaging diagnostics to measure additional in-cylinder quantities
   a) Infrared and/or fuel-tracer imaging for penetration/spreading-angle of reacting and/or non-reacting pre-chamber jets
   b) Combustion radical chemiluminescence and/or fluorescence imaging for ignition/combustion location and mode of propagation

Back-Up Slides

Comparison between fueled and unfueled prechamber at λ_{Main}=1.70

Unfueled Prechamber: $\lambda_{Main} = \lambda_{Pre} = 1.70$

Fueled Prechamber: $\lambda_{Main} = 1.70$; $\lambda_{Pre} = 0.93$