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High-Speed Imaging of Catalyst Heating Operating Strategies in an Optical Diesel Engine

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Abstract

Previous thermodynamic and emissions measurements with catalyst heating operation in a direct-injection diesel engine were performed for a broad range of injection strategy calibrations. These studies provide a basis for understanding how post injections influence heat release and pollutant emissions, but more detailed investigations will be necessary to provide understanding into the mixture formation, ignition, combustion, and pollutant formation processes under these conditions. In this work, high-speed optical and infrared imaging techniques are applied to provide an introductory overview of the fuel injection, spray penetration, and combustion processes. As a result of the relatively cool intake and coolant temperatures, the pilot injection does not reach second-stage ignition. Both the pilot and main injections are observed to be largely confined to the piston bowl. Thus, the incomplete combustion of this mixture is a significant contributor to unburned hydrocarbons in the exhaust. Post injections that are early enough to be at least partially targeted into the bowl can interact directly with these species, which may help ignite the post injection. The post injection, in turn, is a source of additional momentum and turbulence, and its combustion supports the oxidation of these incomplete combustion products. As the post injection is retarded, its interaction with the bowl is decreased. For post injections starting at 30 CAD ATDC, almost no interaction with the bowl is observed, and heat release occurs without natural luminosity. Increasing the mass ratio of post fuel to main fuel leads to faster penetration into the squish region and persistent natural luminosity in the squish region. Initial measurements with oxygenated compounds indicate that both ethers and alcohols act to decrease unburned hydrocarbon emissions. However, for late post injections when fuel reactivity may be expected to play an important role in achieving robust ignition of post injections, the heat release associated with the post injection is relatively insensitive to fuel composition. Ongoing analysis of optical data is expected provide further insight into this phenomenon.

Acknowledgements

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  - Kan Zha (Sandia)
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  - Tim Gilbertson (Sandia)

Outline

First optical measurements of catalyst heating operation

– Motivation / objectives

– Optical engine setup and operation

– Image processing

– Experimental results

– Summary

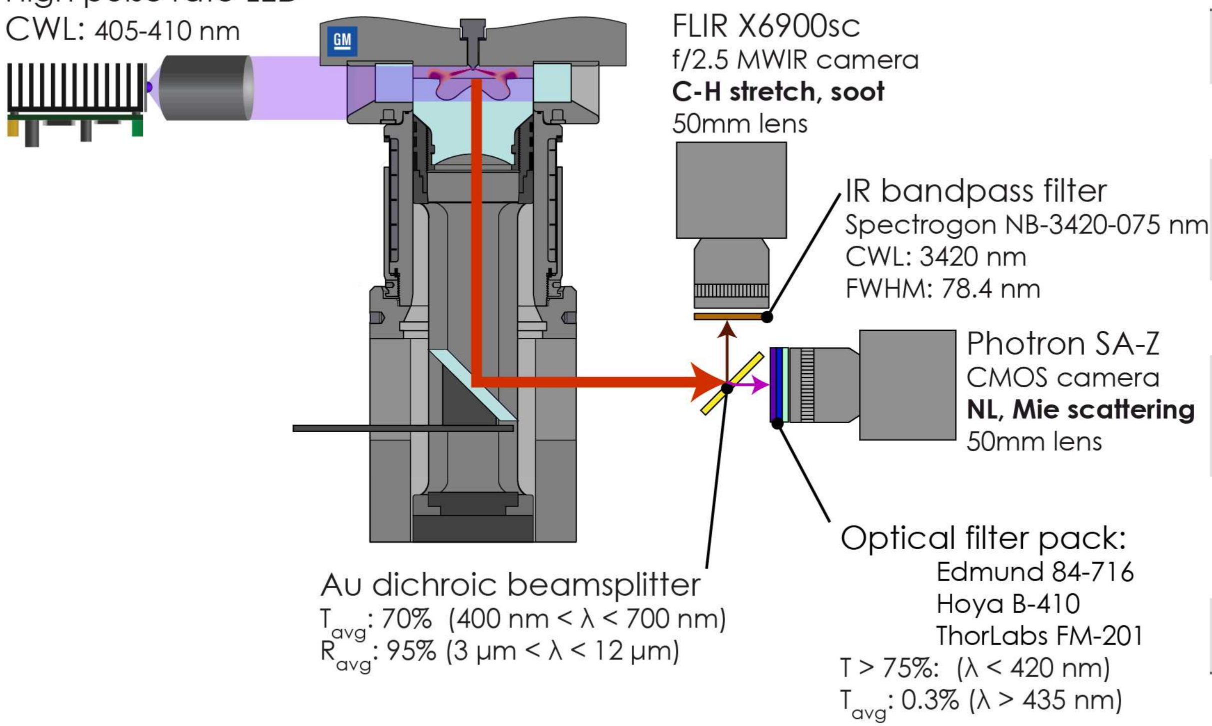
Motivation / objectives of optical experiments: provide initial in-cylinder insights into catalyst heating operation

Analysis of thermodynamic and emissions measurements has yielded questions about in-cylinder phenomena during catalyst heating operation

- Ignition, combustion and pollutant formation processes
- Initial high-speed imaging studies: vapor-phase fuel and natural luminosity
  - With/without post injection
  - Post injection timing
  - Post/main split
- Impacts of oxygenated fuel blends (CoOptima)
  - Octanol
  - Dibutyl ether
  - OME blend

Optical engine setup

2.25 kfps IR imaging
(4 CAD @1500 rpm)



9 kfps NL imaging
(1 CAD @ 1500 rpm)

Valves	4
Bore/stroke (mm)	82.0/90.4
Geometric compression ratio	15.8:1
Piston material	Fused silica
Injector	Fast-acting solenoid
Nozzle hole exit diameter (μm)	7 x 139
Included angle (°)	149

Optical engine operation

Engine speed (rpm):	1500
Coolant temperature (°C):	31
Intake temperature (°C):	49
Intake flow rate (g/s):	8.51
Intake composition (mole fraction):	O_2: 18.7%; CO_2: 1.1%; N_2: 79.2%
Swirl ratio (-):	2.2
Rail pressure (bar):	500
Fuel (baseline):	Cert diesel, CN = 43.9
Firing mode:	4 skip – 1 fire

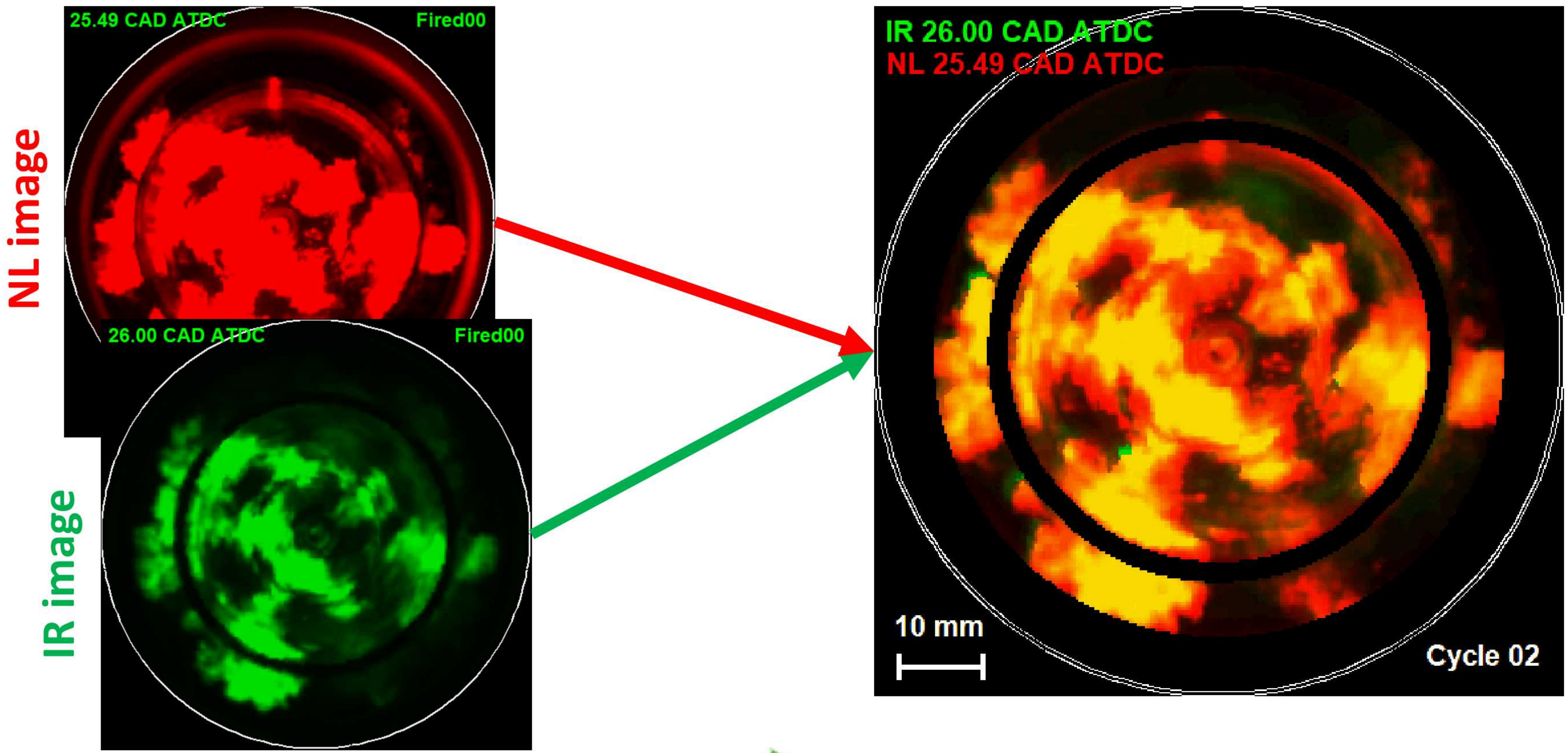
Injected Mass (mg)				Start of injection (CAD ATDC)								Results in this presentation
Total	Pilot	Main	Post	Pilot	Main	Post						
7	2	5		-15	TDC							2-5
9	2	5	<-2->	-15	TDC	10(A)	14(B)	18(C)	22(D)	26(E)	30(F)	2-5-2C
9	2	3	<-4->	-15	TDC	10(A)	14(B)	18(C)	22(D)	26(E)	30(F)	2-3-4A, 2-3-4C,2-3-4F

CRF

Image processing

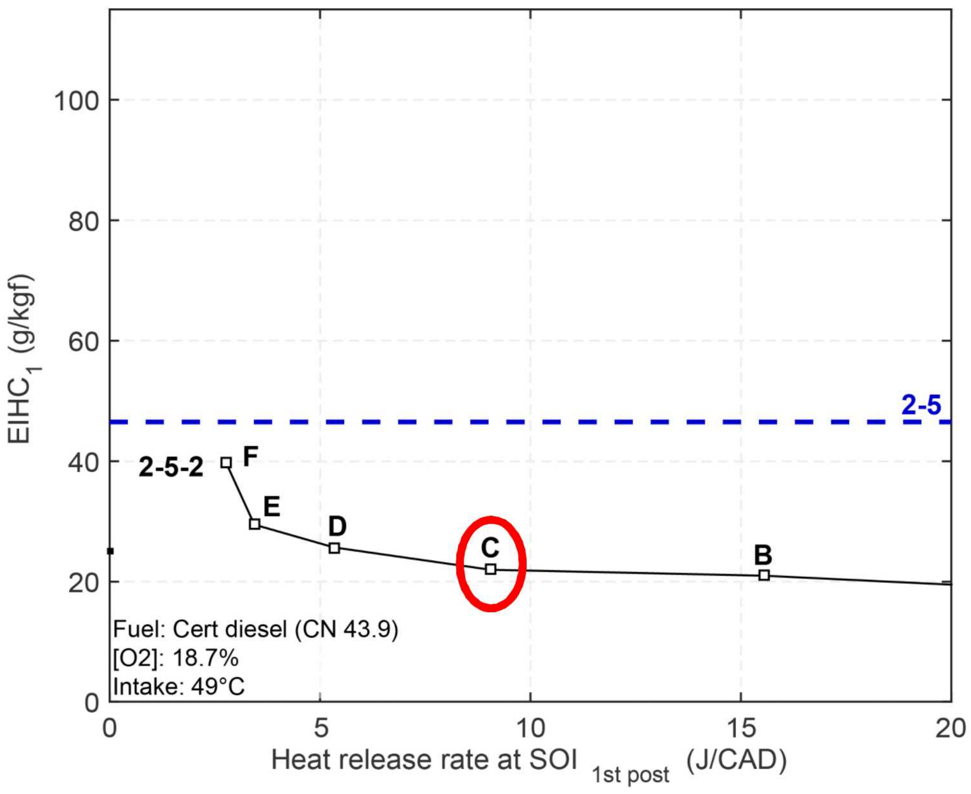
- Background subtraction, automated distortion correction
- Superimpose **NL** and **IR** images
- Today's results: 20-cycle ensemble average images

Superimposed NL and IR image



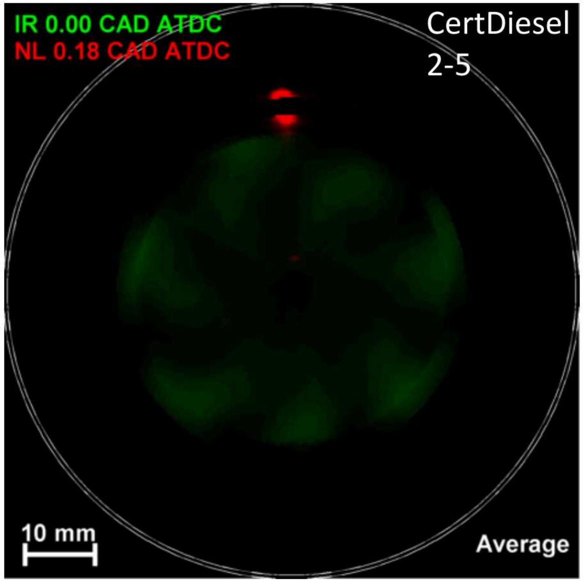
Results: post injections can reduce UHC emissions

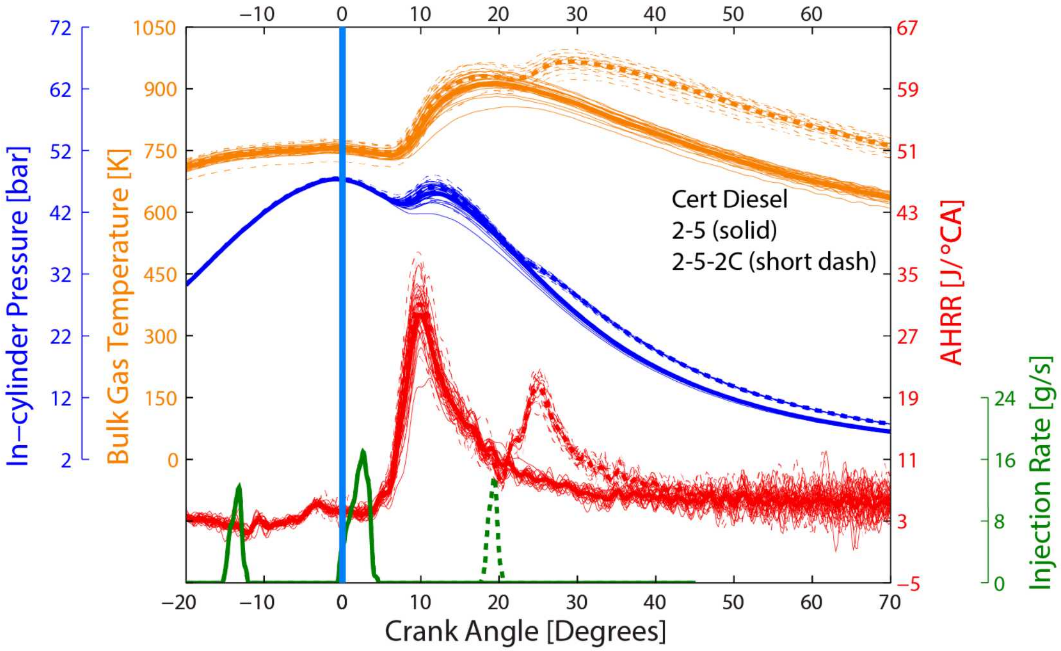
- With 5 and 7 mg main injection quantities, adding a post injection decreases unburned hydrocarbon emissions
- Open questions:
  - How/where are the UHCs forming with the pilot and main injections?
  - What is the post injection doing to help oxidize them?
- Comparison: 2-5 vs. 2-5-2C

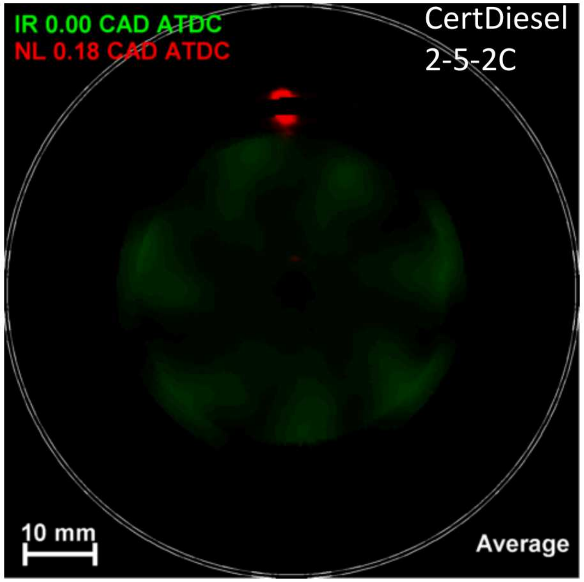


Results: comparison of 2-5 and 2-5-2C before main injection

- IR signal consistent with C-H stretch from pilot fuel vapor is observed only within the bowl
- No visible NL signal detected from the pilot injection before main injection
- Small amount of heat release from pilot before main injection starts

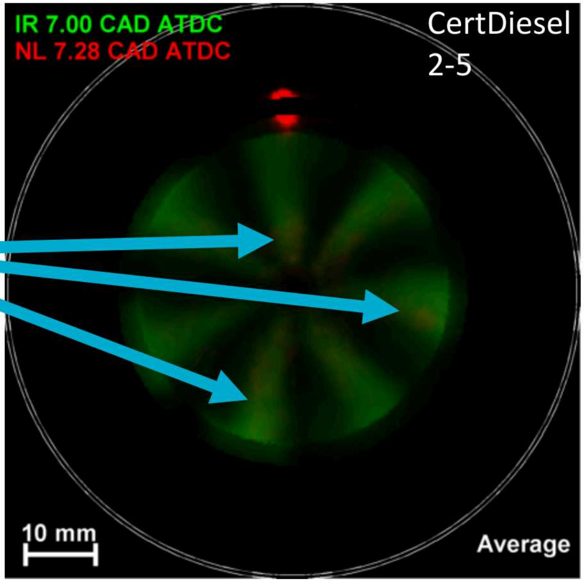


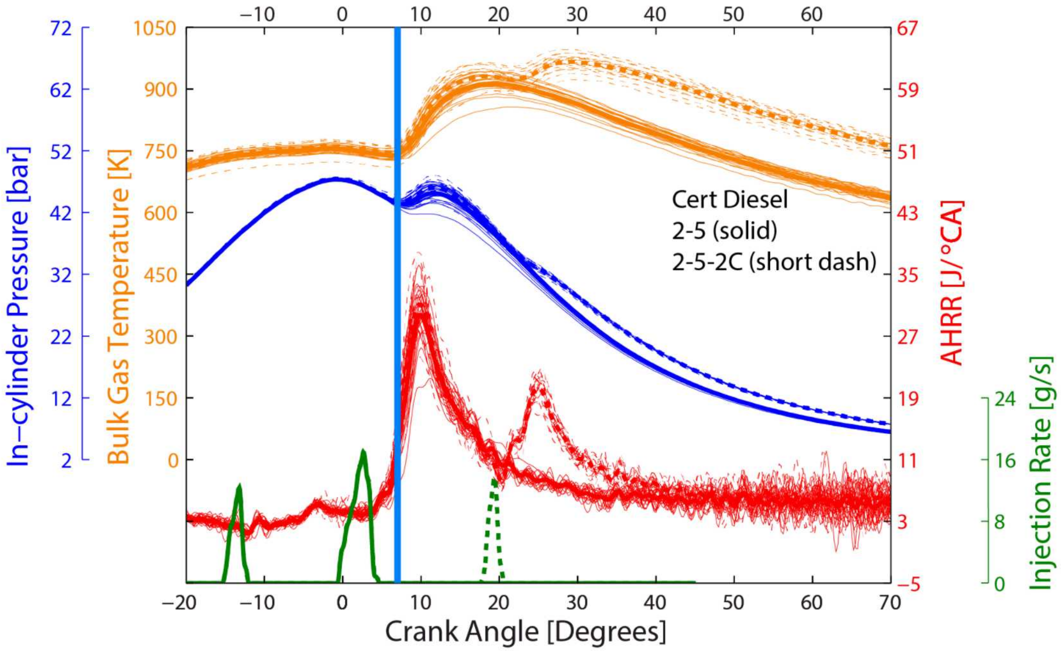


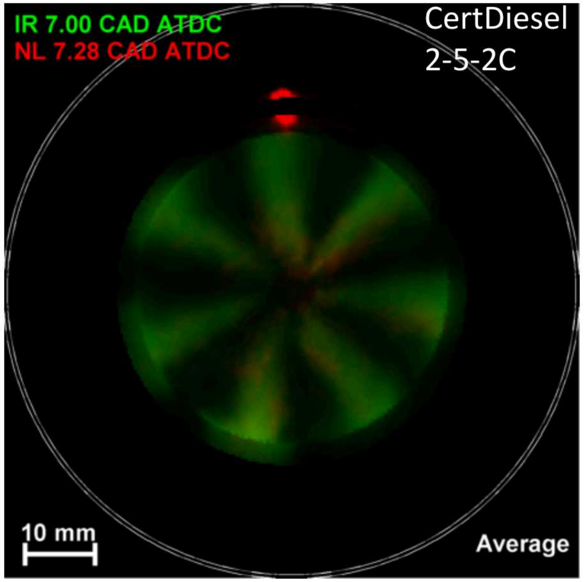


Results: comparison of 2-5 and 2-5-2C after main injection

- IR signal from the main injection remains in bowl; spray structure is repeatable as high-temperature ignition occurs
- NL signal begins to appear in and around some of the spray plumes as high-temperature heat release begins

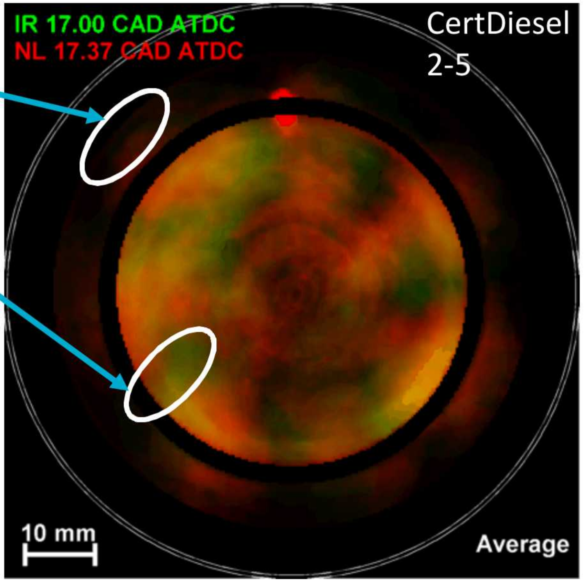


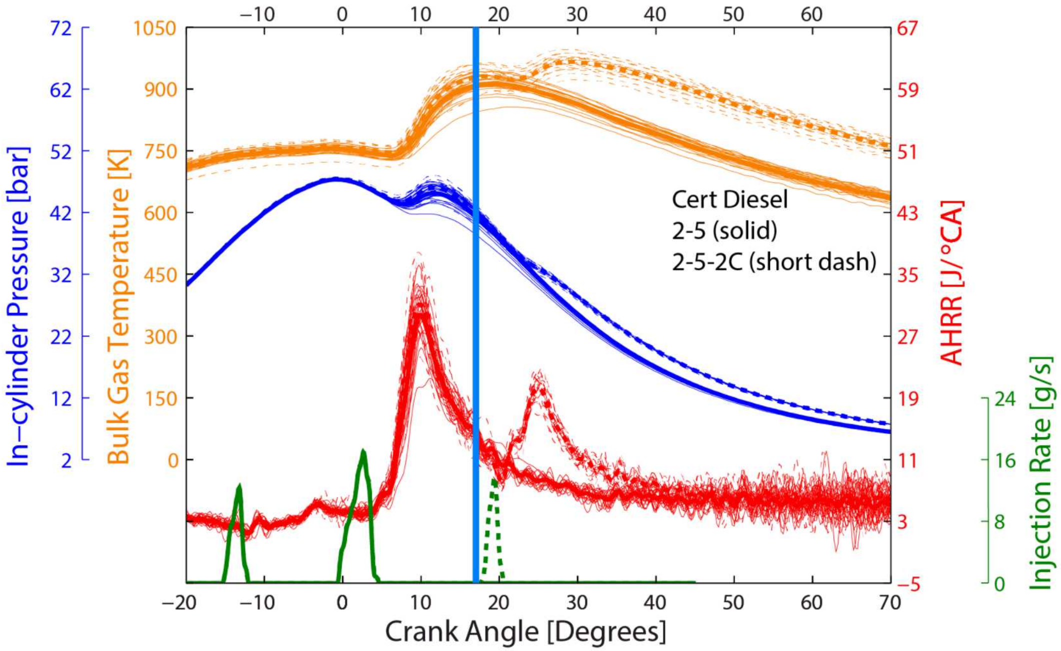


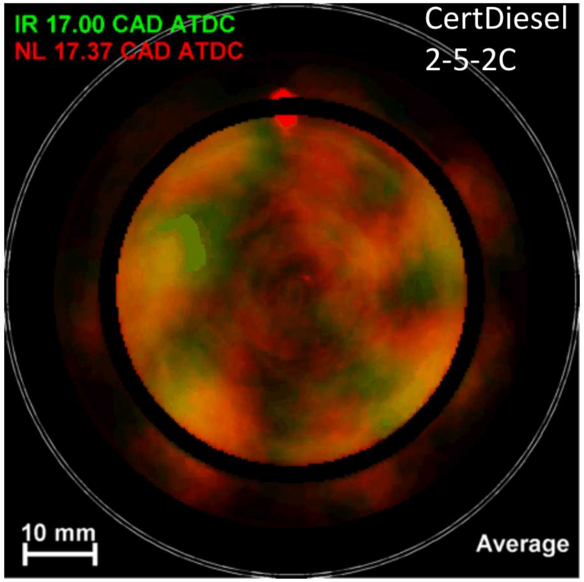


Results: comparison of 2-5 and 2-5-2C before post injection

- NL and IR are visible in the bowl and begin to penetrate outward into the squish region
- IR signal observed in the bowl between spray plumes
  - Consistent with un- or partially-burned fuel – C-H stretch
  - Potential source of unburned hydrocarbons
  - Hypothesis: over-lean mixture in the bowl fails to react to completion
- No appreciable differences between 2-5 and 2-5-2-C, yet

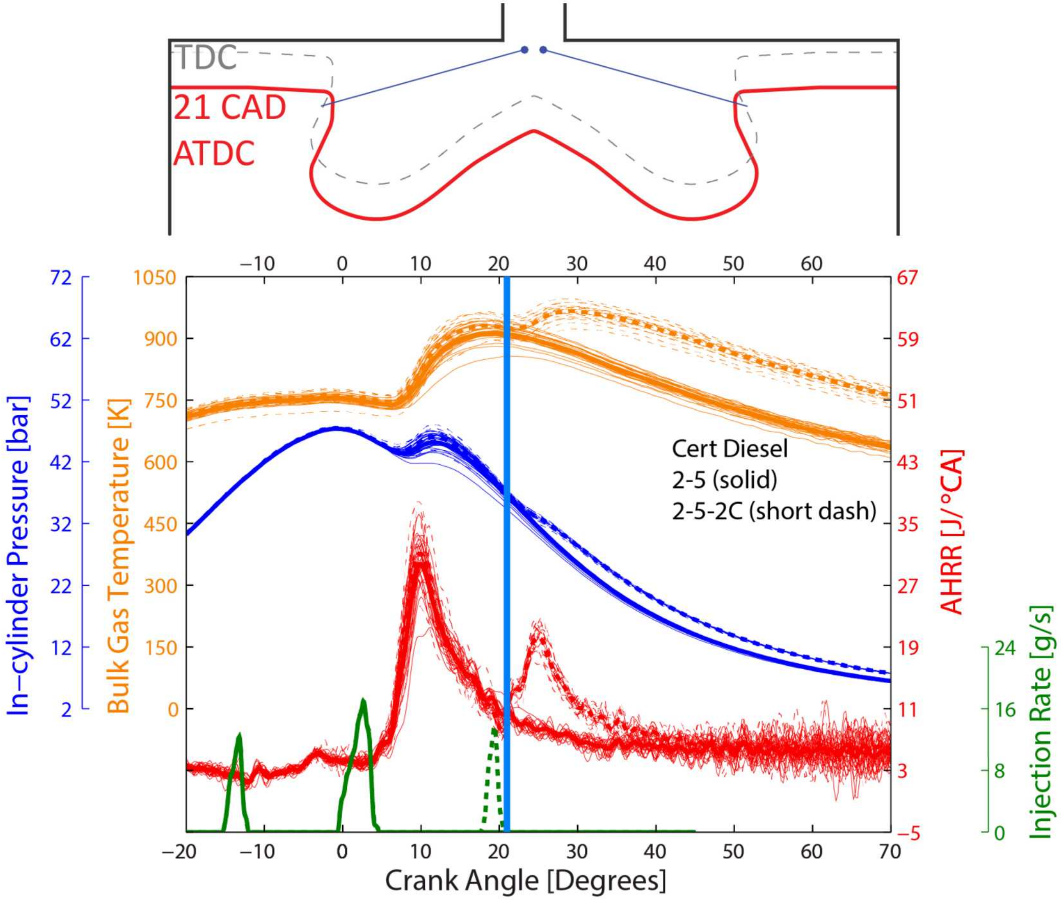


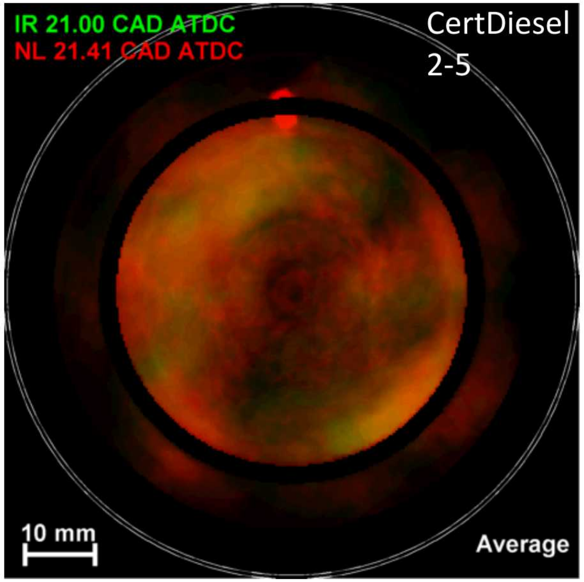


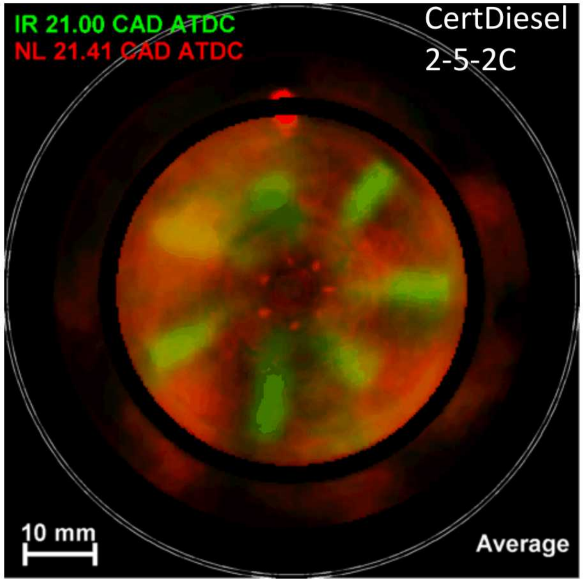


Results: comparison of 2-5 and 2-5-2C after post injection

- Post injection is targeted at corner of bowl rim
  - Expected interactions with bowl contents and squish region
- New IR signal is visible for each of the post injection spray plumes before post heat release starts

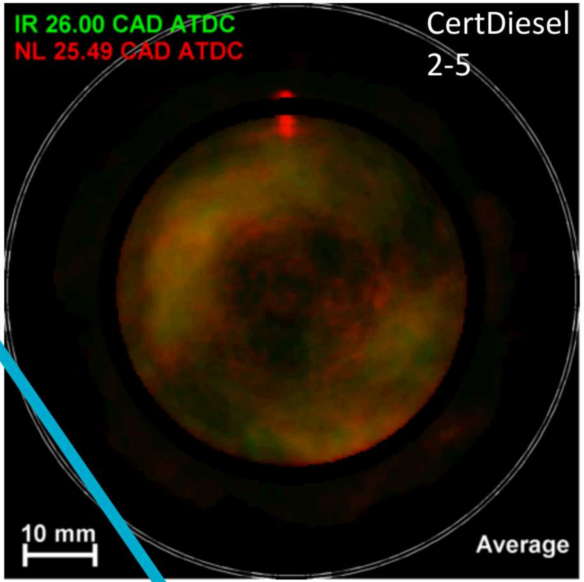


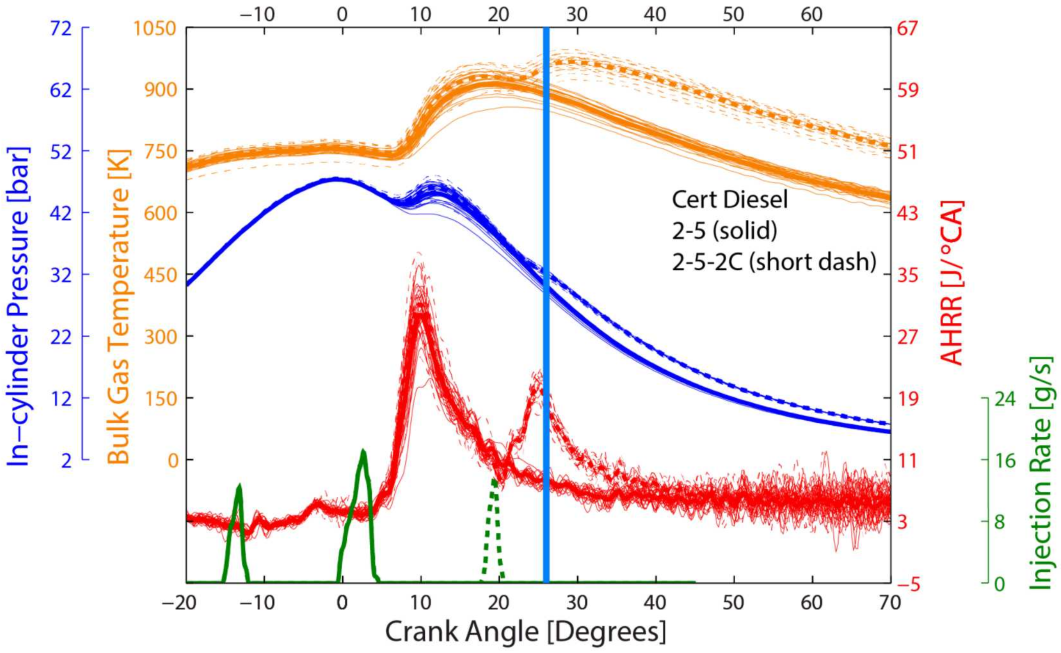


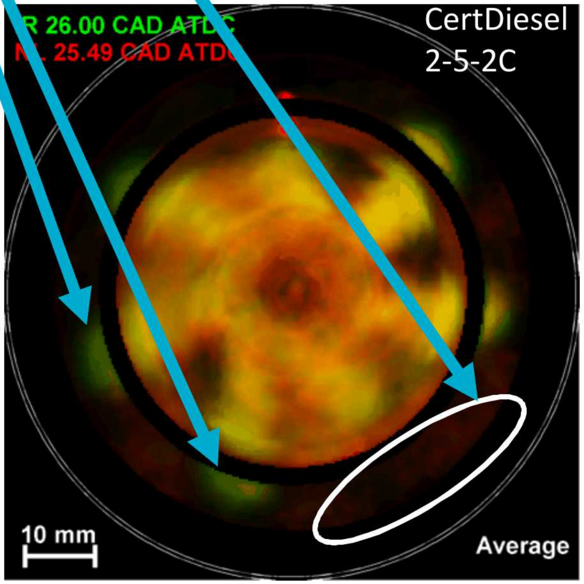


Results: comparison of 2-5 and 2-5-2C during post combustion

- Increased NL signal in the bowl during post combustion
- NL from main combustion persists in the squish region
- Post injection penetrates into squish region, often in between regions where main combustion NL is observed

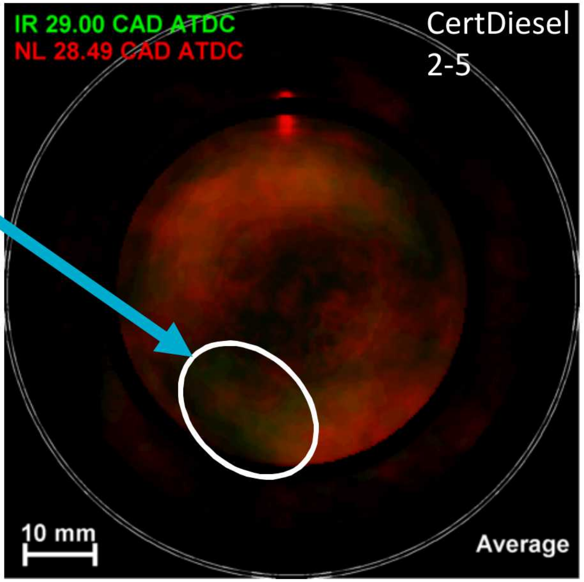


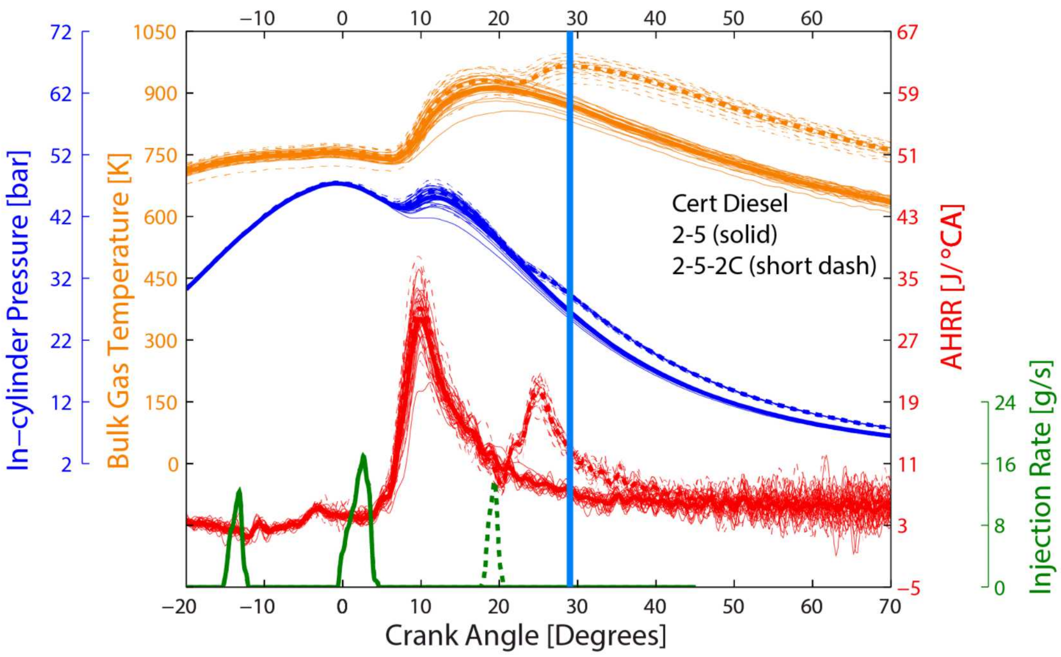


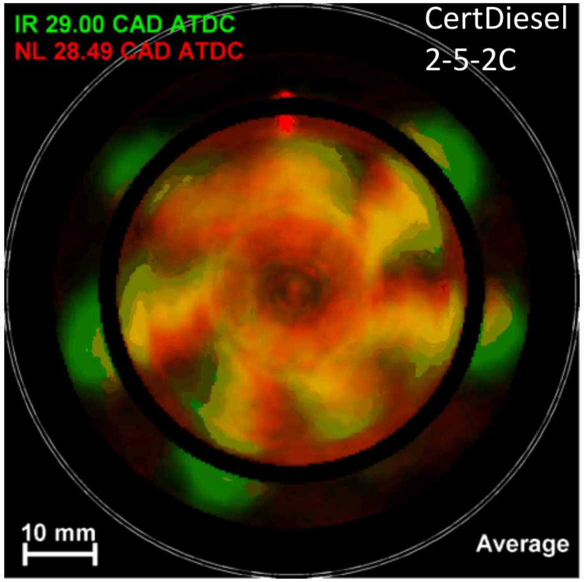


Results: comparison of 2-5 and 2-5-2C near end of post combustion

- Regions of IR signal are observed in the bowl, in the absence of NL signal
  - May indicate hydrocarbons in the bowl that fail to reach second-stage ignition
- Post injection continues to penetrate into squish region
  - IR signal is visible, but new NL is not observed

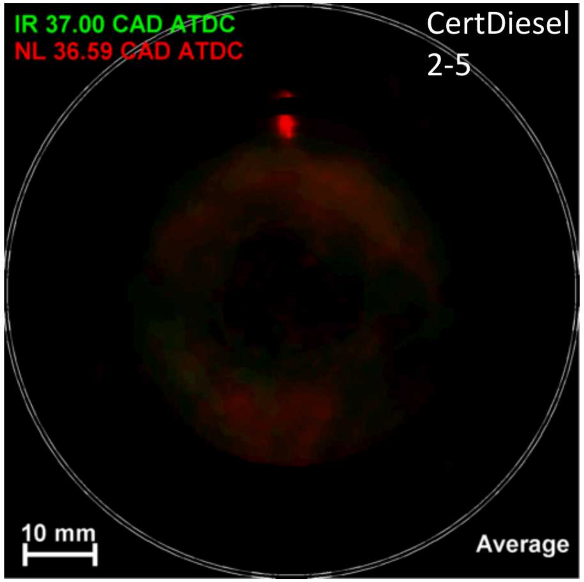


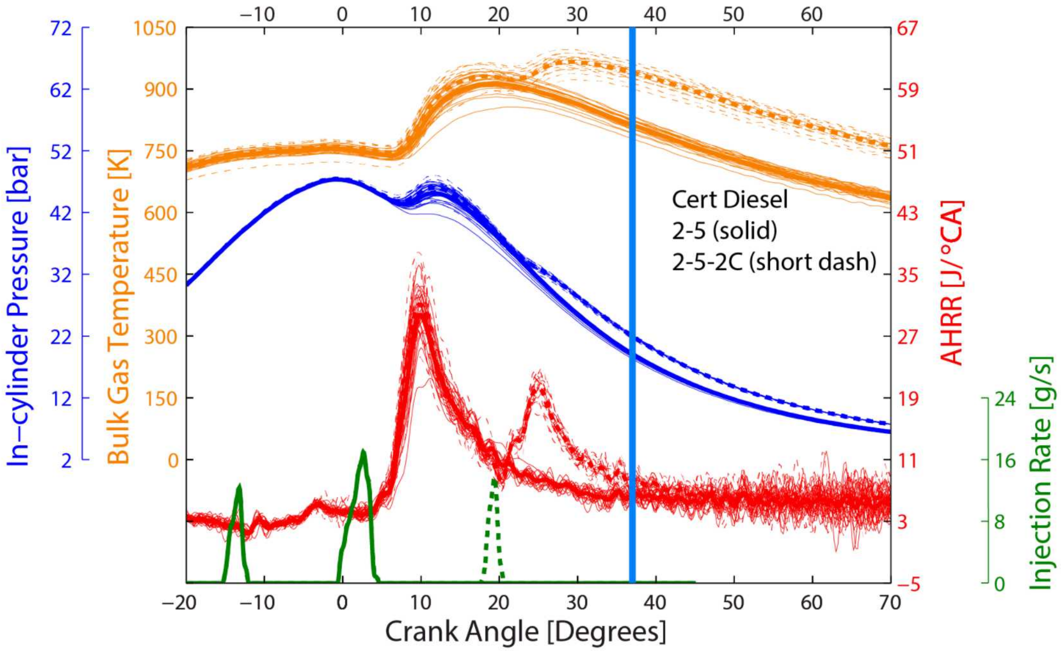


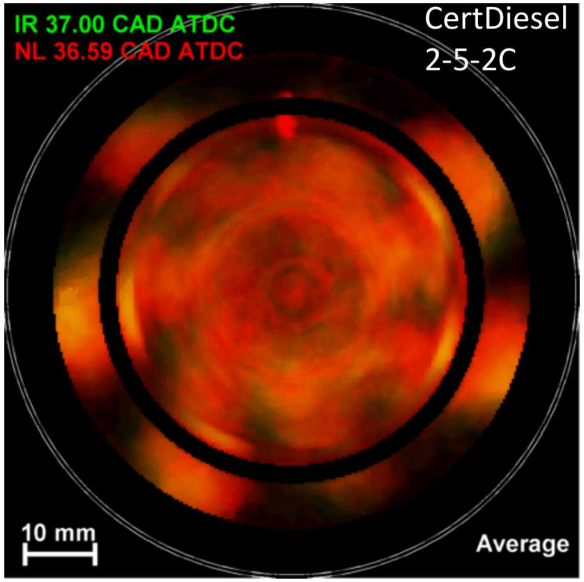


Results: comparison of 2-5 and 2-5-2C after end of post combustion

- NL and IR signals persist in the bowl after post heat release has finished
- NL appears very late in the post injection plumes in the squish region
  - Soot formation occurs without appreciable heat release, well after most of the high-temperature post injection combustion







Recap: 2-5 vs. 2-5-2C

- The pilot does not reach high-temperature ignition before the main injection begins

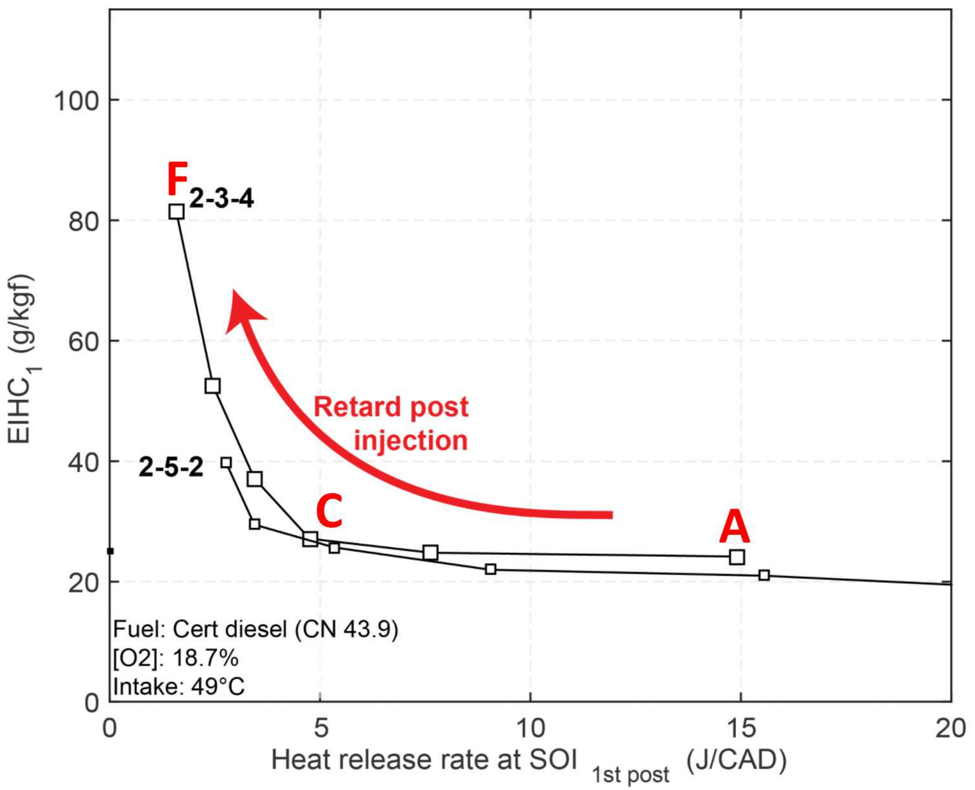
- High temperature heat release occurs after the end of the main injection
  – Combustion of main and/or pilot mixture takes place primarily in the bowl
  – Residual IR in bowl in absence of NL: evidence of UHCs?

- Post injections can interact with both the bowl and with the squish region
  – Combustion of the post injections in the bowl may help oxidize unburned hydrocarbons from the pilot and the main injections
  – Swirl transports the combusting main injection plumes in the squish region such that the post injections may not interact directly with them
  – Post injections can form soot as high-temperature reactions are ramping down

Results: changing post injection timing

- UHC emissions trends depend more on post injection timing than on injection strategy calibration for a given total fuel quantity
- Open questions:
  - How does the timing of the post affect its ignition and combustion?

- Comparison: 2-3-4A vs. 2-3-4C vs. 2-3-4F



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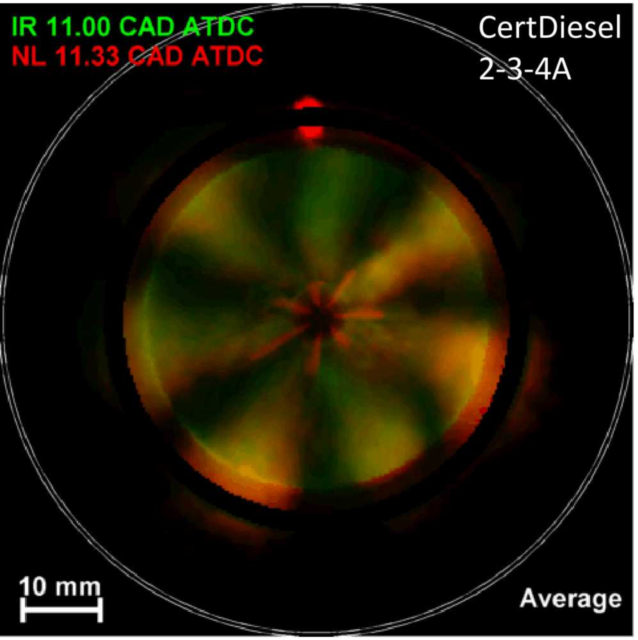
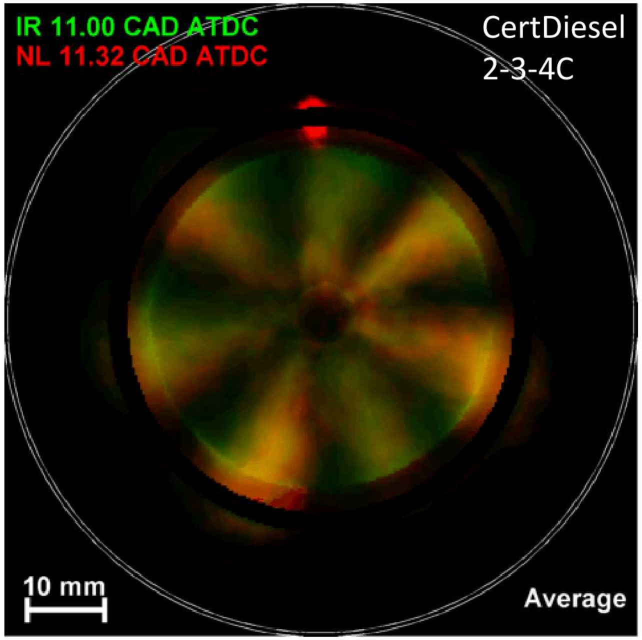
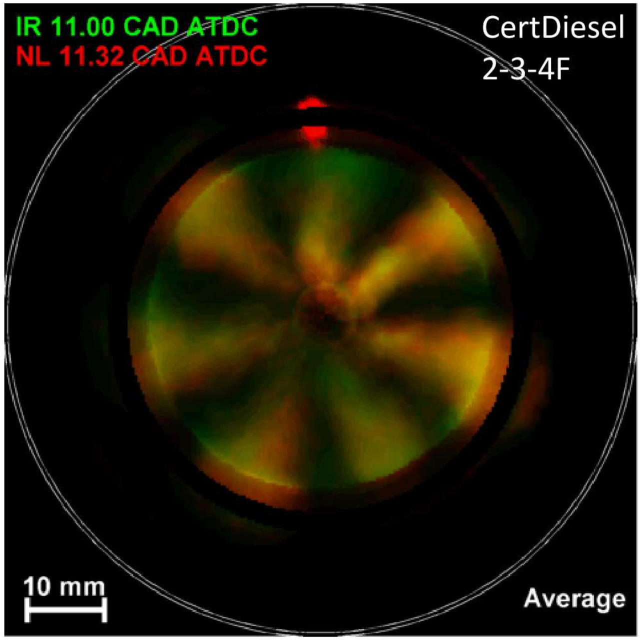
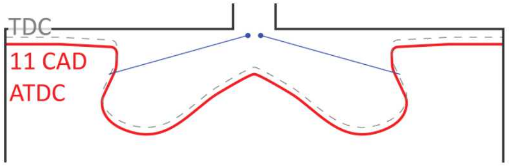
Results: Comparison of 2-3-4 A, C, and F

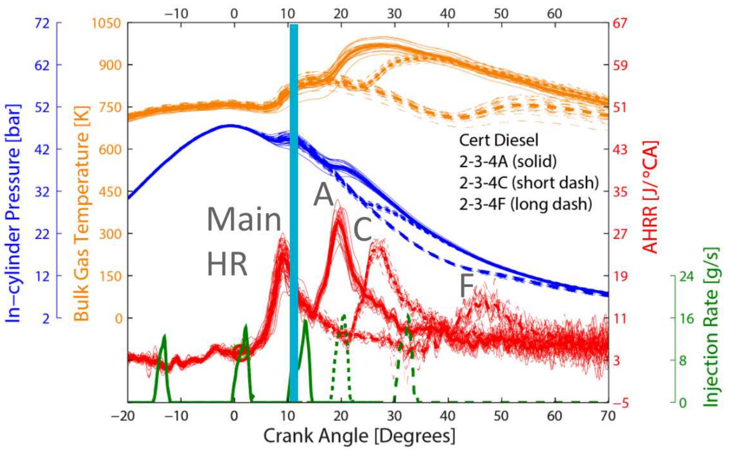




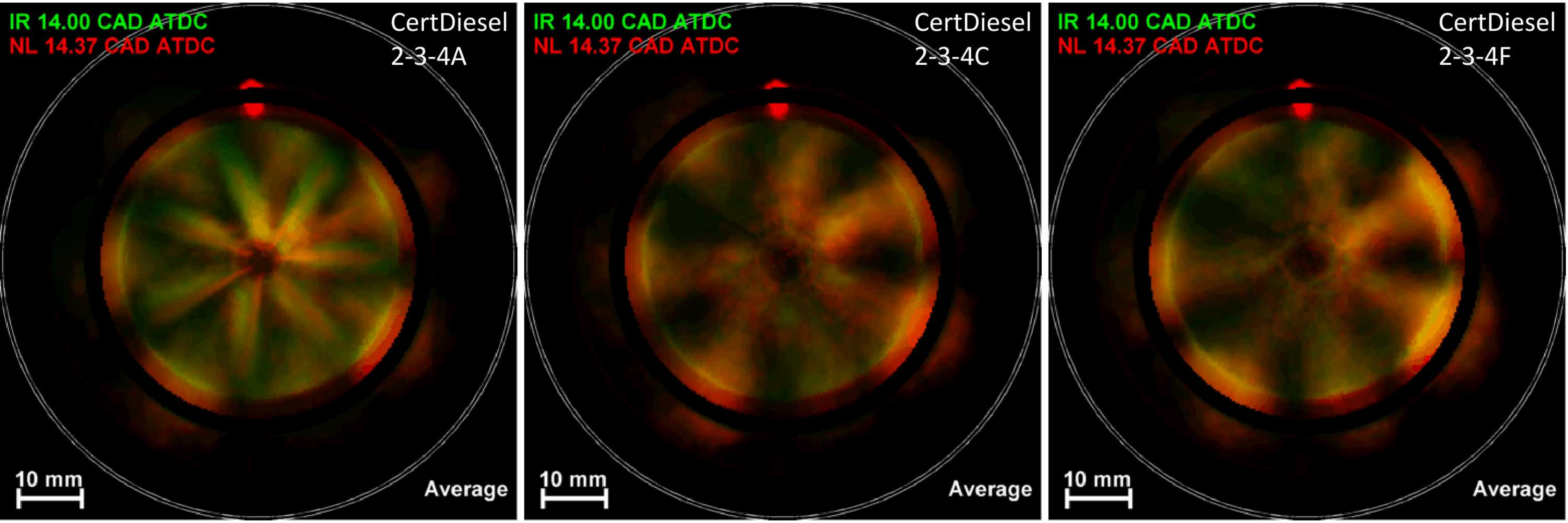


- Start of post “A”
  - High temperature heat release from main and pilot is ongoing

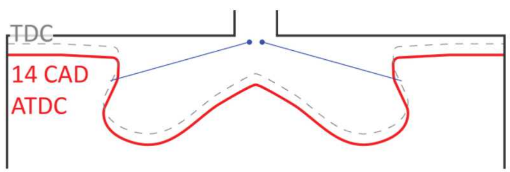


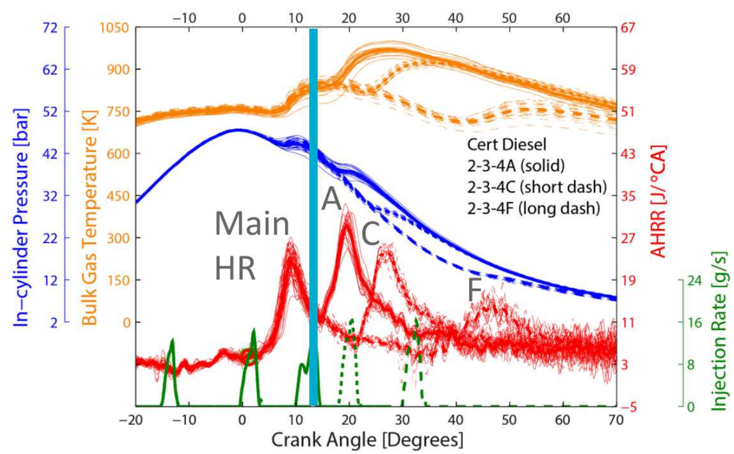


Results: Comparison of 2-3-4 A, C, and F

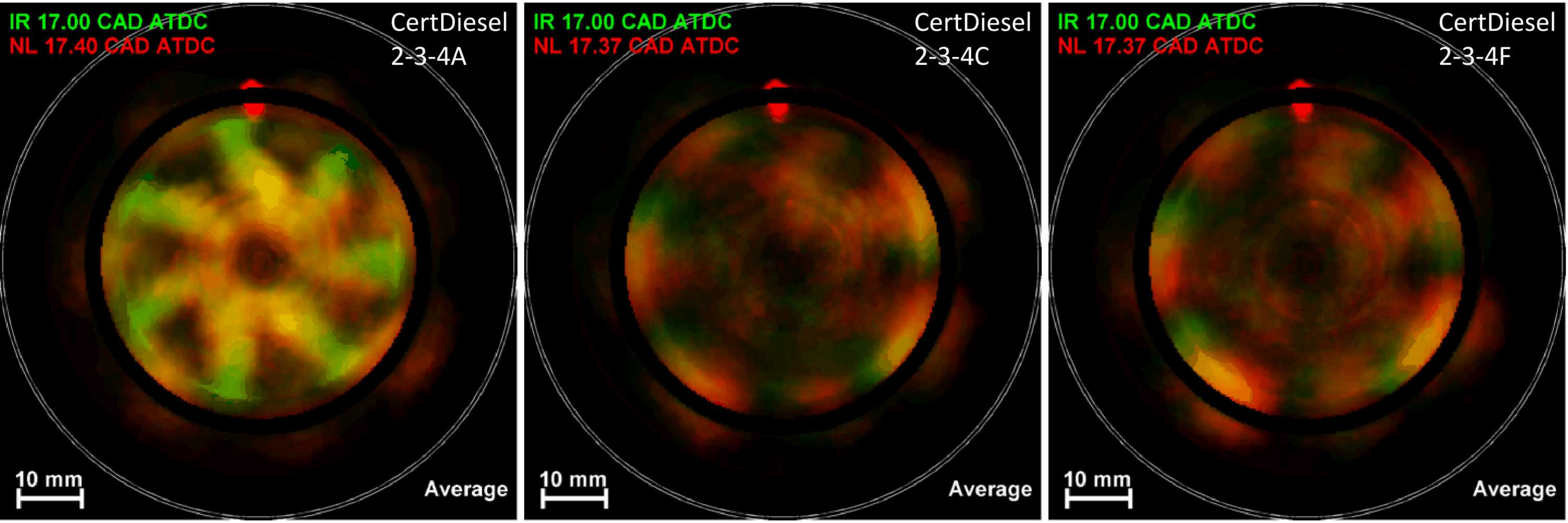


- End of post "A", before start of post heat release
  - Post injection is targeted below bowl rim, in between residual main spray
  - Liquid (red) and vapor (green) are visible in the bowl

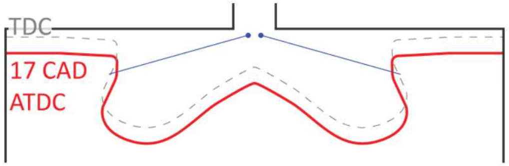


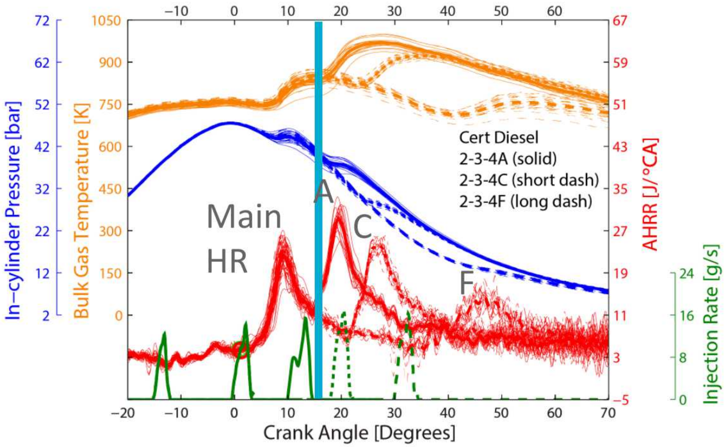


Results: Comparison of 2-3-4 A, C, and F

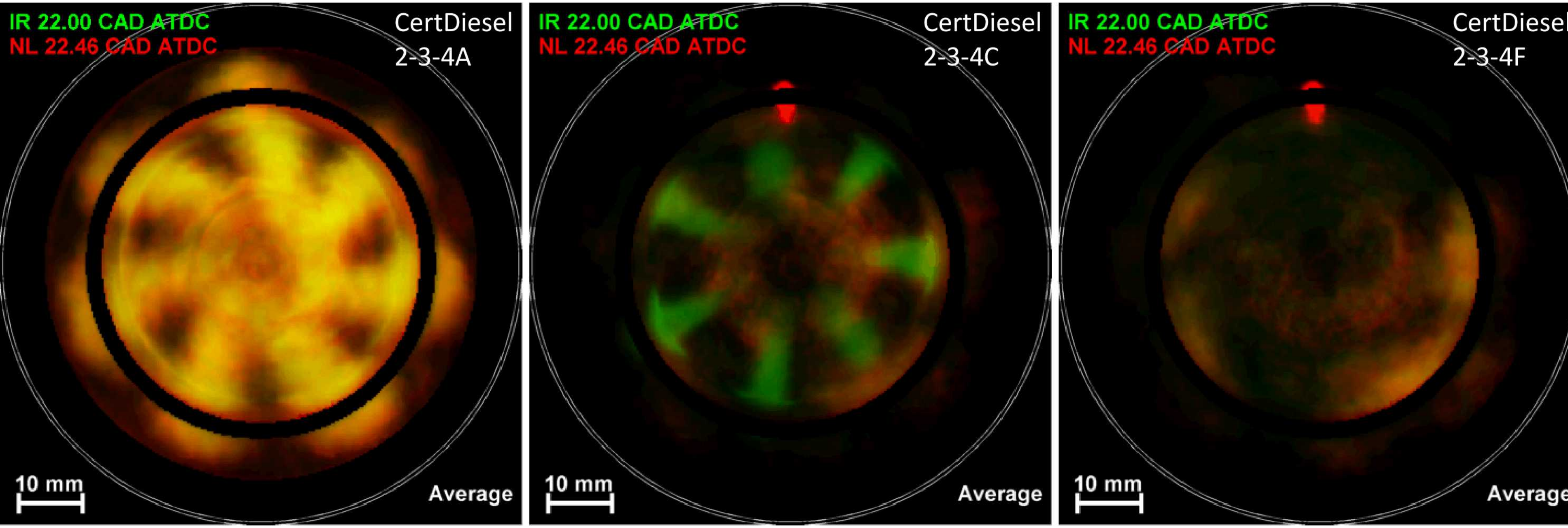


- Start of heat release for post "A"
  - NL signal increases in bowl
  - Fuel vapor without NL is visible in the outer portions of the bowl

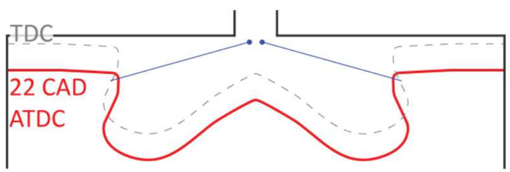


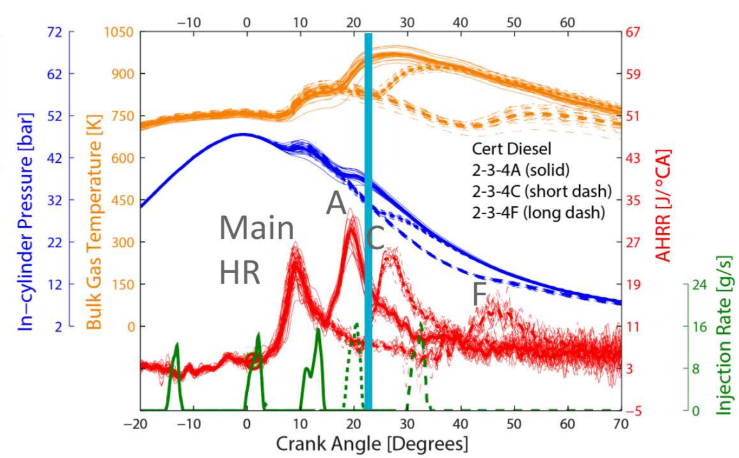


Results: Comparison of 2-3-4 A, C, and F

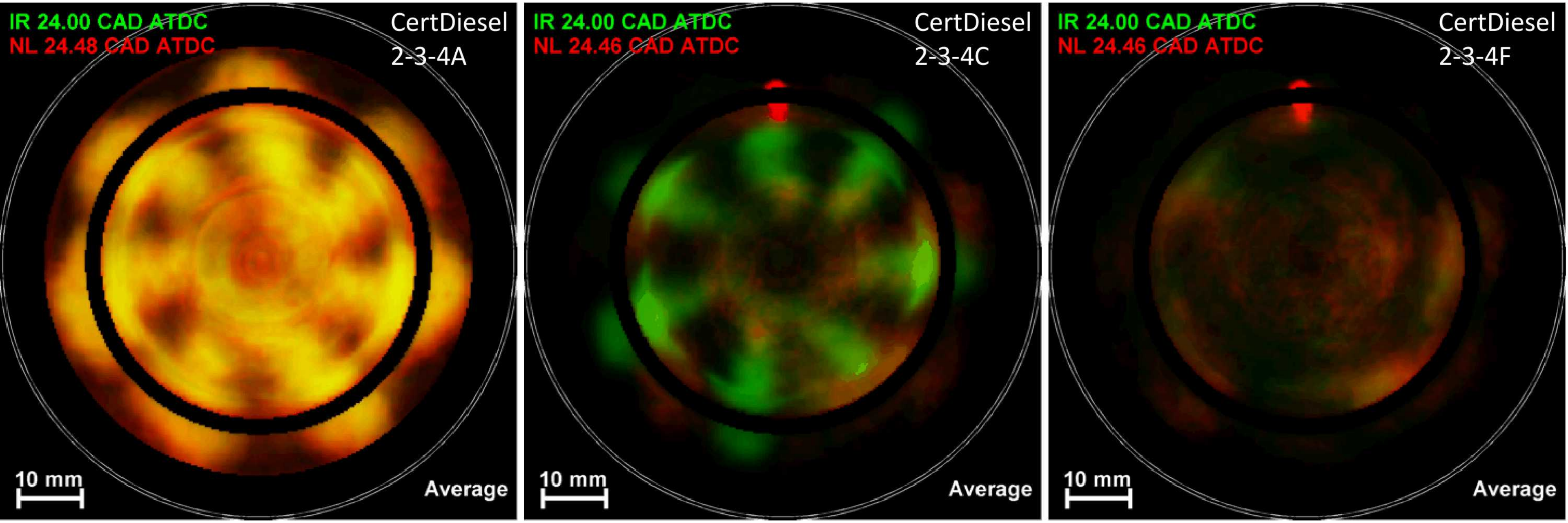


- Post "A" continues to burn
  - NL and IR signals overlap
- End of post "C", start of post heat release
  - Sprays targeted at bowl rim, at main mixture clouds
  - Residual NL remains in center, outer regions of bowl

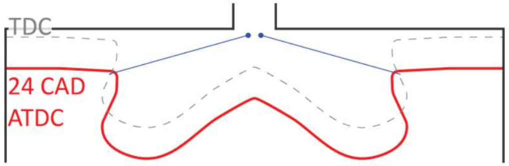


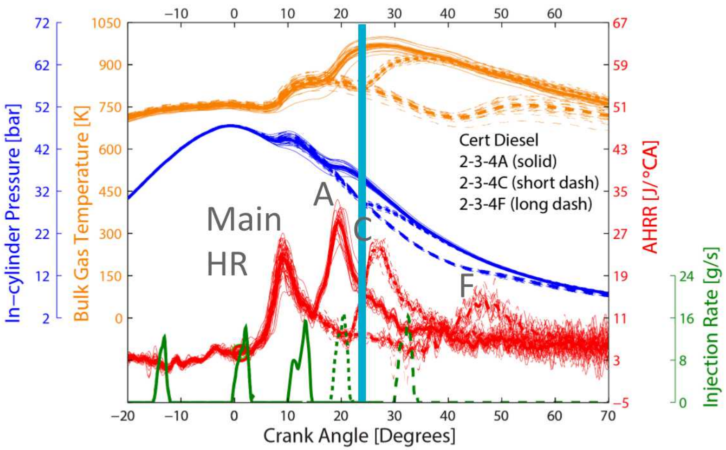


Results: Comparison of 2-3-4 A, C, and F

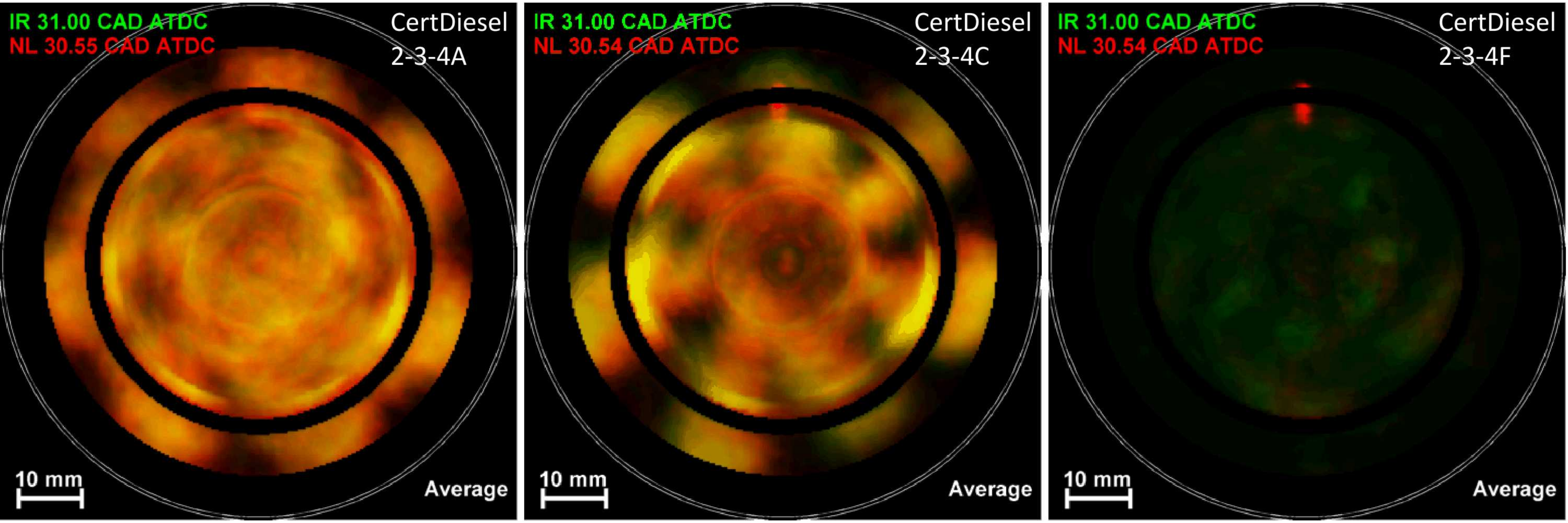


- Post "A" continues to burn
- Post "C" has started to burn
  - NL increases in outer regions of bowl
  - Post injection sprays begin to penetrate into squish region

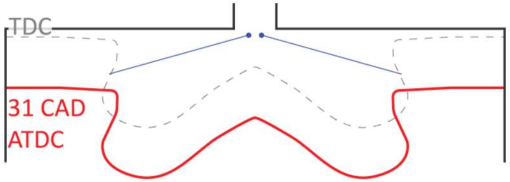


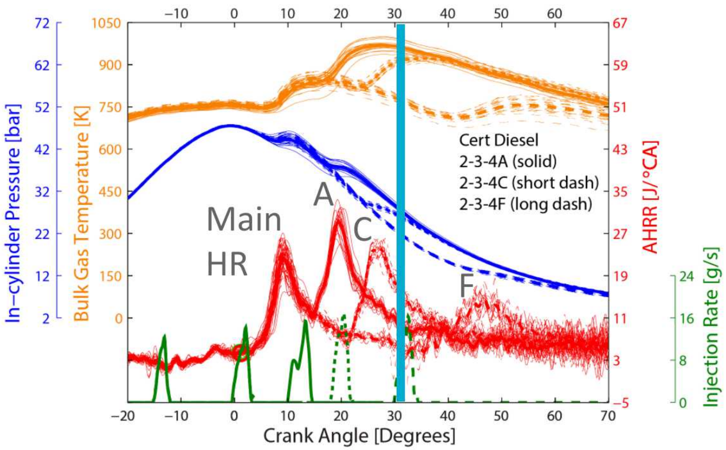


Results: Comparison of 2-3-4 A, C, and F

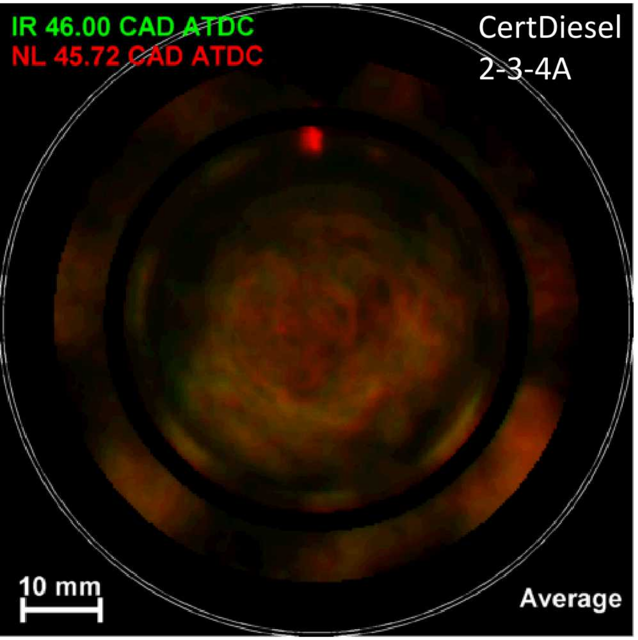


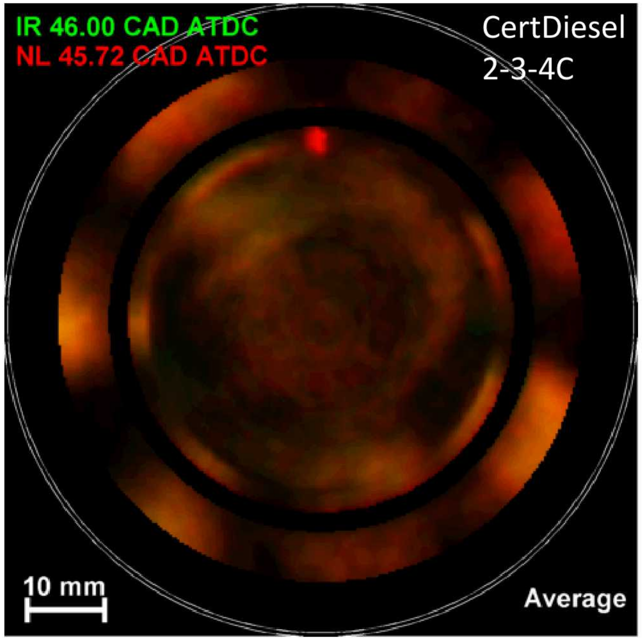
- Post “A” nearly finished burning
- Overlap of NL and IR with Post “C”
- Post “F” begins
  - Sprays targeted at squish region
  - Very dim residual NL/IR signals are observed

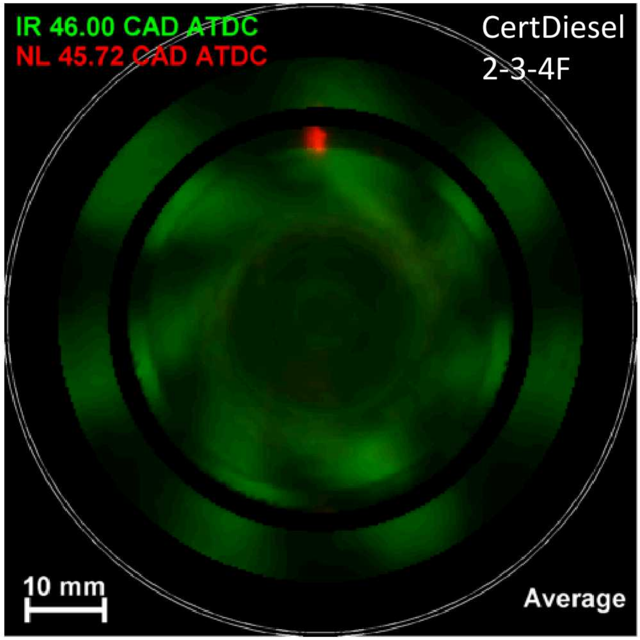




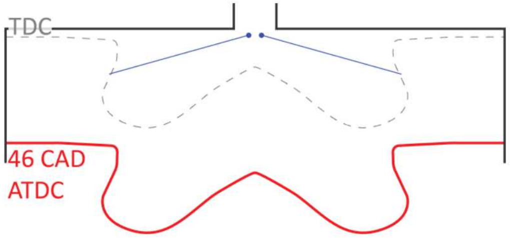
Results: Comparison of 2-3-4 A, C, and F

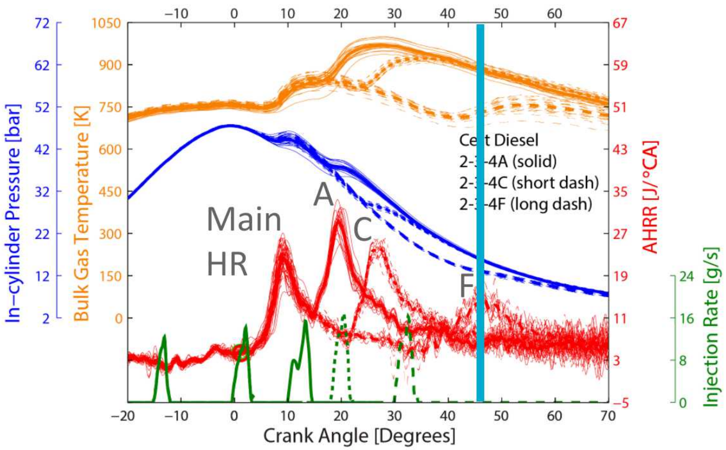






- No appreciable heat release for posts "A" & "C"
  - NL and IR remain in bowl and squish
  - Brighter NL in squish for post "C"
- Peak of "F" heat release
  - No NL observed
  - Meaning of IR signal unclear





Recap: changing post injection timing

- Early post injections
  - Interact strongly with mixture in the bowl, but can reach the squish region
- Intermediate injections
  - Burn in the bowl, but interact to a greater extent with the squish region
- Late post injections
  - Heat release occurs without NL
  - Likely no direct interaction with bowl contents

Results: comparison of pilot/main split ratio

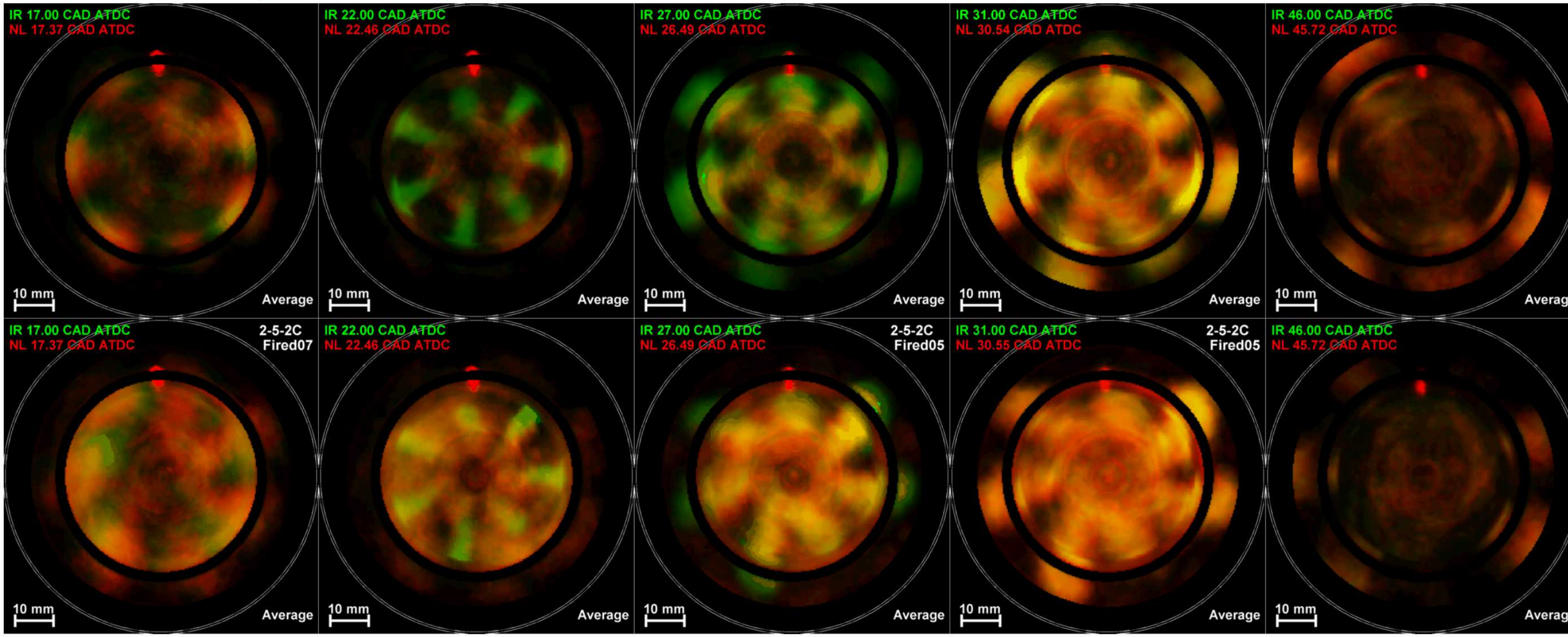
Top: 2-3-4C (9 mg total, SOI_{post} = 18 CAD ATDC)

Bottom: 2-5-2C (9 mg total, SOI_{post} = 18 CAD ATDC)

Shortly before SOI_{post} | Post injection | Squish region penetration

2-3-4C

2-5-2C



2-5-2C: brighter NL in bowl before SOI_{post}

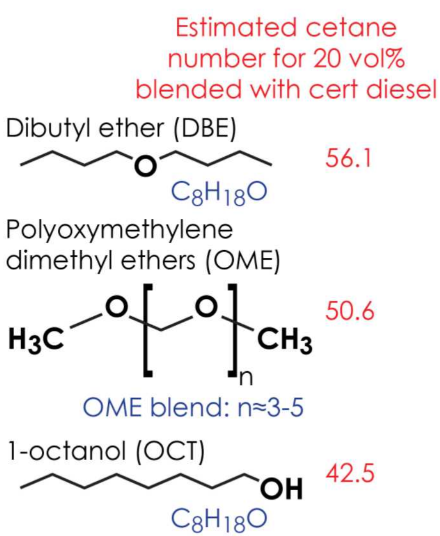
2-5-2C: NL remains in bowl after post injection ends, supports post ignition

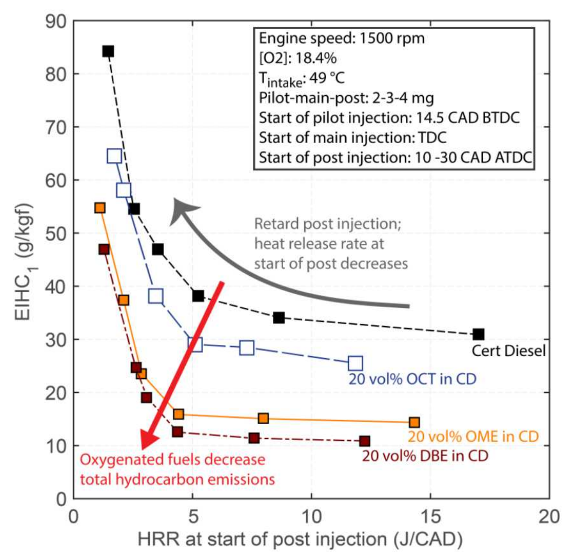
2-3-4C: Faster squish region penetration due to longer post injection

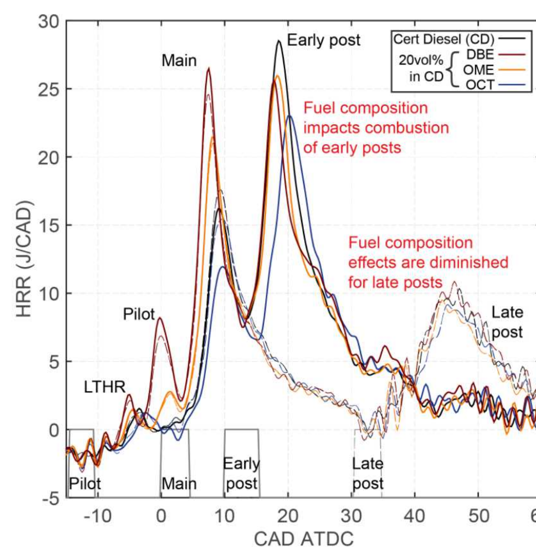
2-3-4C: More NL remains in squish region and in bowl

Results: effects of oxygenate blends

- Three oxygenates splash blended with cert diesel at 20 vol%
  - OME blend, di-butyl ether, and 1-octanol splash blended with cert diesel
- Oxygenated additives can significantly reduce total hydrocarbon emissions
  - Ethers do this more effectively than 1-octanol
- Oxygenated additives affect the ignition and combustion of the pilot and main injections, but the impact on the post combustion depends on post injection timing
  - The combustion of late post injections is not significantly affected by post injection timing
  - Limited evidence: changing fuel composition may not promote robust ignition of late posts
- Analysis of IR/NL images is ongoing







Summary: insights from initial analysis of optical data

- Combustion of the pilot and main is incomplete; partially burned products are left primarily in the bowl

- Early post injections have a strong interaction with the bowl contents and can therefore effectively oxidize incomplete combustion products
  - Pilot/main combustion helps ignite post in the bowl
  - Post injection promotes turbulent mixing, increases temperatures
  - Increasing fuel reactivity promotes ignition of all injections; successful pilot ignition is associated with robust main combustion and post ignition

- As post injections are retarded, their interaction with the bowl contents is diminished
  - Bulk heating of the charge due to post combustion may not be sufficient to help oxidize UHCs in the bowl
  - Later posts may encounter cooler charge in the squish region and do not appear to burn robustly

Thank you for your attention

Questions?

Results: effects of oxygenate blends

- DBE
  - Higher reactivity promotes earlier, more robust main combustion, faster penetration into squish region due to combustion-driven expansion
- Octanol: small impact on reactivity and combustion evolution

2-3-4C