ACS001: Heavy-Duty Low-Temperature and Diesel Combustion & Heavy-Duty Combustion Modeling

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FY 2017 DOE Vehicle Technologies Office Annual Merit Review
Advanced Combustion Engine R&D/Combustion Research
11:00 – 11:30 AM, Tuesday, June 6, 2017

Sponsor: **U.S. Dept. of Energy, Vehicle Technologies Office**
Program Managers: **Leo Breton, Gurpreet Singh**

ACS001

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ACS001 Overview: Heavy-Duty Low-Temperature and Diesel Combustion & Heavy-Duty Combustion Modeling

Timeline

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

Barriers

From 2013 US DRIVE Adv. Comb. & Emission Tech. Team Roadmap:

- Inadequate understanding of LTC control technologies, esp. for mixed-mode
- LTC aftertreatment integration
- Impact of future fuels on LTC

Budget

- Project funded by DOE/VTO:
  FY16-SNL/UW: $720k/$113k
  FY17-SNL: $580k
  ($490k planning level)
  FY17-UW: $113k

Partners

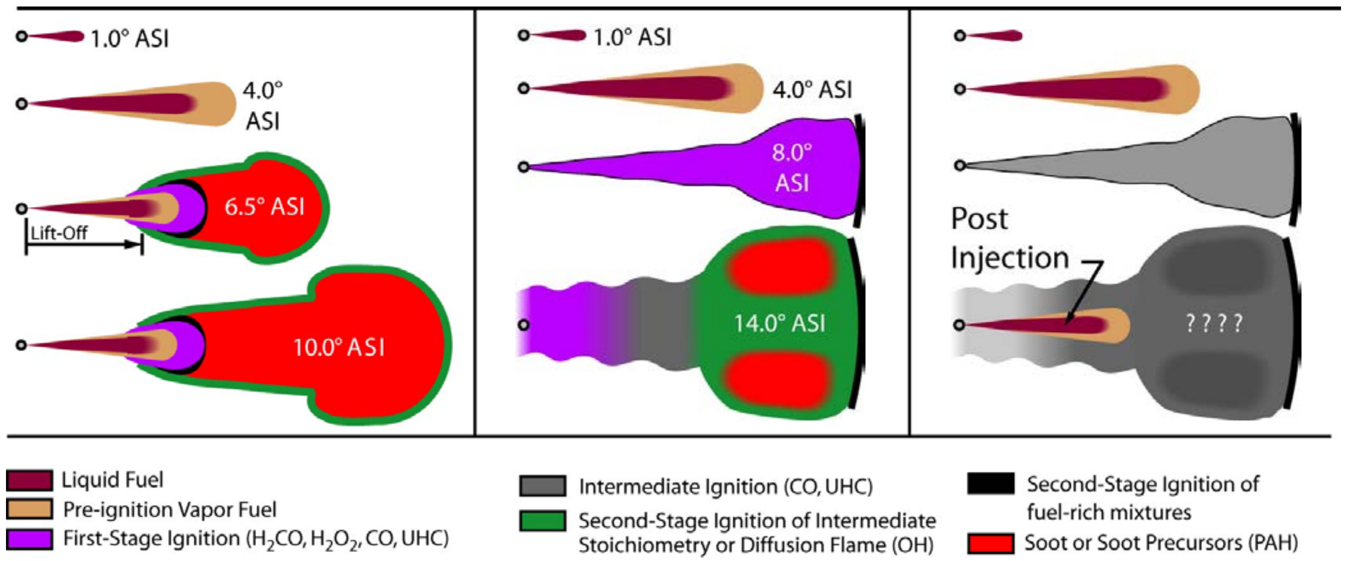
- U. of Wisconsin, Cummins, Delphi, Convergent Science, Lund University
- 16 AEC MOU industry partners
- Project lead: Sandia (Musculus)

ACS001 Relevance/Objectives: Heavy-Duty In-Cylinder Combustion

Long-Term Objective

Develop the science base of in-cylinder spray, combustion, and pollutant-formation processes for both conventional diesel and LTC that industry needs to design and build cleaner, more efficient engines

1997: **Conventional Diesel** (Single Injection)	2012: **LTC Diesel** (Single Injection)	2013+: **Multiple Injection** (Conventional & LTC)



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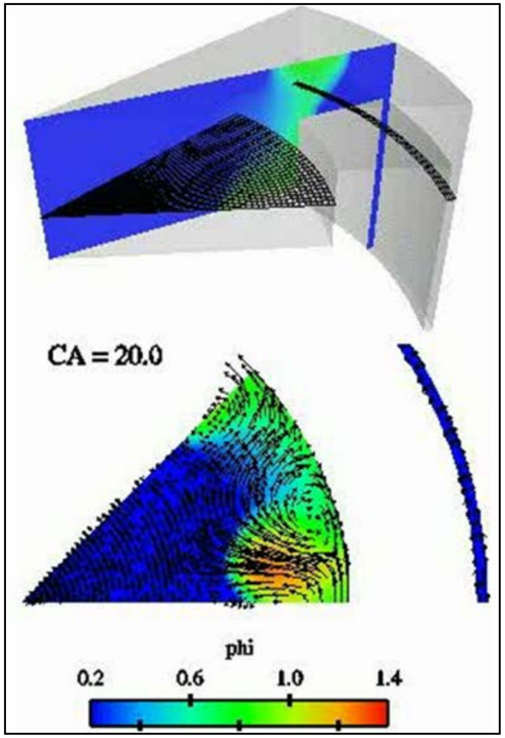
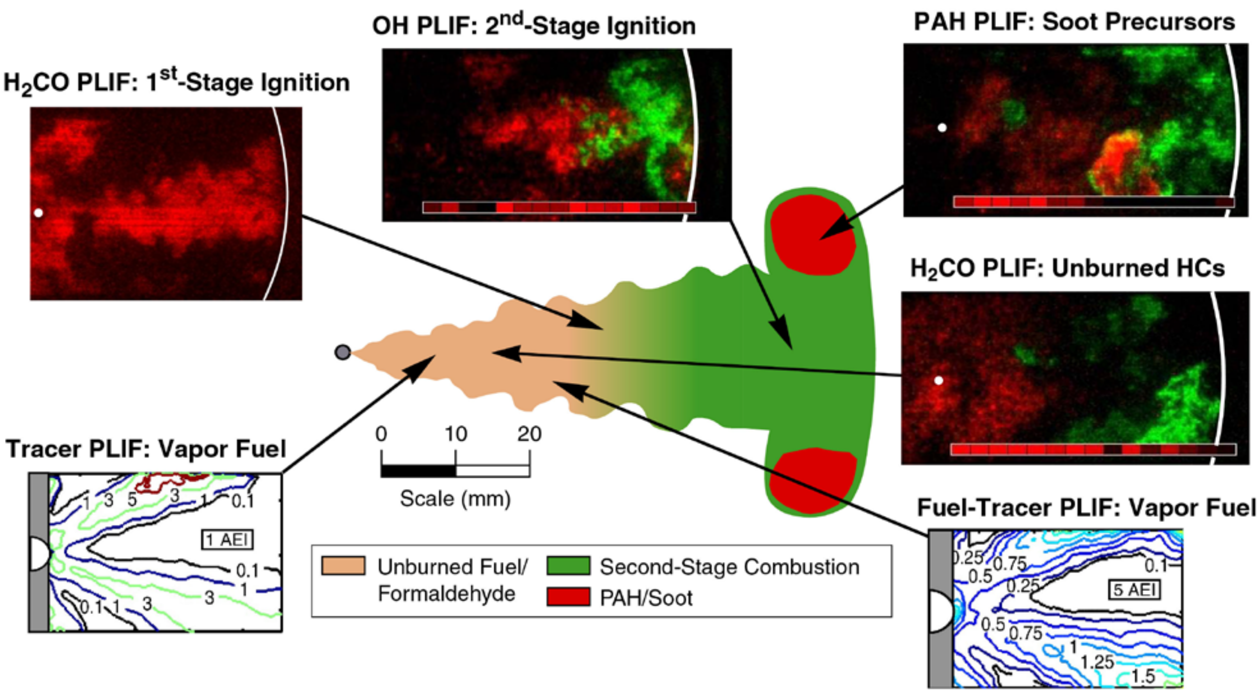
Current Milestones/Objectives:

- SNL – Develop and apply an optical heat transfer diagnostic (postponed)
- SNL – Measure dependencies of soot/precursor formation
- UW & SNL – Complement experimental soot and spray data

ACS001 Approach/Strategy: Optical imaging & CFD modeling of in-cylinder chemical/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





ACS001: 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
- Industrial/University partnerships support laboratory activities
  - FY2017: Delphi – heavy duty injection system
  - FY2017: DOE/NSF proposal on soot/precursor modeling with UW//Convergent Science
  - FY2017: Collaborations/visits with Lund University

Responses to Previous Years Reviewers' Comments

Comment: *"Additional bigger-picture materials pointing to the desired progress directions and connections would have helped."*

Response: This year's presentation synthesizes results from multiple annual review presentations and includes a brief literature review and industry perspective to provide an improved big-picture view.

Comment: *"Concern begins to arise that some details of the findings/conclusions are engine-specific."*

Response: This year we put our findings in the context of a wide range of literature studies to better indicate how this research fits into results across a range of engines.

Comment: *"Thermal imaging for vapor penetration is very interesting and would like to see more development and validation of the technique to understand it better."*

Response: The modeling work this year has suggested new opportunities for IR diagnostics for more quantitative soot imaging, and we have plans to apply these diagnostics in the future.

Comment: *"[Consider] uncertainty quantification (UQ) and sensitivities for the simulation models, including not just the model-form uncertainty inherent in the three models presented, but also the myriad input coefficients to those models."*

Response: This is of great interest to us as well, and we'll strive to incorporate UQ in future modeling work.

Comment: *"There is an unusually good balance of experimental and computational approaches within the project."*

Response: This has been a productive approach that we will continue to follow.

ASC001: Technical Accomplishments & Progress

- Accomplishments are described in the following 17 slides

Current Milestones/Objectives:

SNL – Develop and apply an optical heat transfer diagnostic (postponed)

SNL – Measure dependencies of soot/precursor formation

UW & SNL – Complement experimental data, improve computer modeling of ignition in residual jets

OEMs have adopted post-injections combustion strategies for both emissions & efficiency benefits

DAIMLER

"Daimler Trucks ushers in a new era: the launch of the Mercedes-Benz OM 470x, under the name "Blue Efficiency Power", heralds the arrival of a completely redesigned range of heavy-duty engines that sets a new benchmark in so many ways. … ***A post-injection ensures the almost complete combustion of the particulates***." (Daimler, Mannheim, Mar 18, 2011)

SCANIA

"As the first heavy vehicle manufacturer, Scania introduced Euro V engines utilizing exhaust gas recirculation (EGR) and no exhaust gas aftertreatment. … A pilot injection is used to reduce noise, and ***a post-injection to reduce soot and NOx emissions***."
(http://www.dieselnet.com/news/2007/09scania.php)

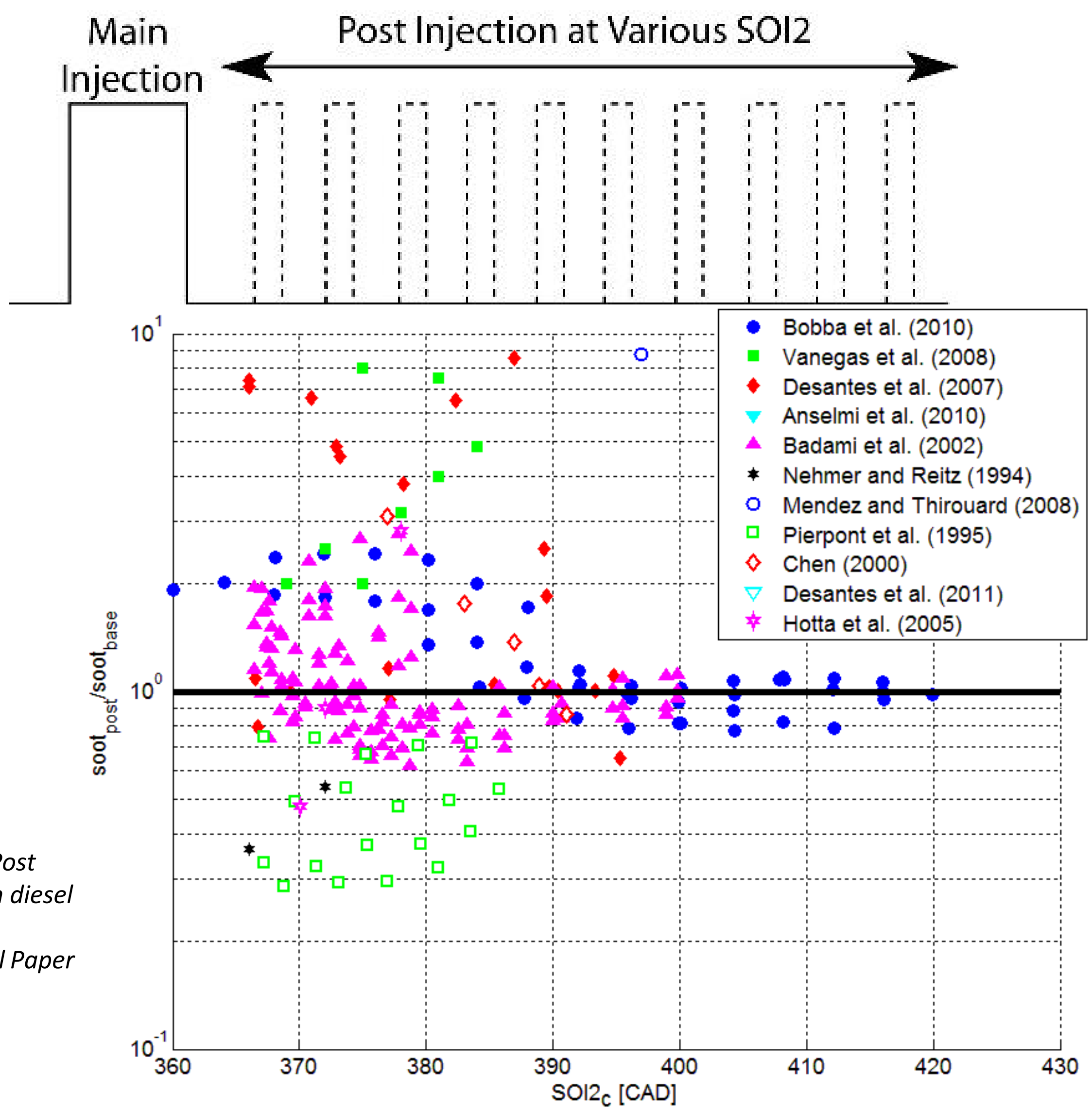
CATERPILLAR®

"Caterpillar has demonstrated Tier 3 compliance on an ACERT mid-range industrial Cat 3126 engine, with HC+NOx below 2.8 g/bhp-hr and PM below 0.08 g/bhp-hr (the Tier 2 PM standard is 0.15 g/bhp-hr). … ***Multiple injections allow the use of a late "post-injection" event for PM control***, which can allow further injection timing retard for NOx control."
(http://www.dieselnet.com/news/2001/11epa.php)

RENAULT

"Laguna will be premiering the Renault-Nissan Alliance's new 2.0 dCi engine, a 1995 cc unit featuring up-to-the-minute diesel engine technologies. … ***The post-squirts sustain the main injection combustion, to burn off soot and thus bring down pollutant emissions before the exhaust gases have even left the combustion chamber***."
(http://www.renault.co.ir/html/%23Agu-Newsletter/Engine-en.php)

Reported soot reduction performance varies widely among literature studies



O'Connor J, Musculus MPB, "Post injections for soot reduction in diesel engines: a review of current understanding " SAE Technical Paper 2014-01-1255

Studies have identified three mechanisms of soot reduction by post injections, despite little evidence

Enhanced Mixing

- The post injection enhances mixing of fuel and air to suppress soot formation and/or soot and air to enhance soot oxidation
- Fluid mechanic effect

Increased Temperature

- Additional heat release from the post-injection fuel raises chamber temperatures
- Increased temperature enhances soot oxidation

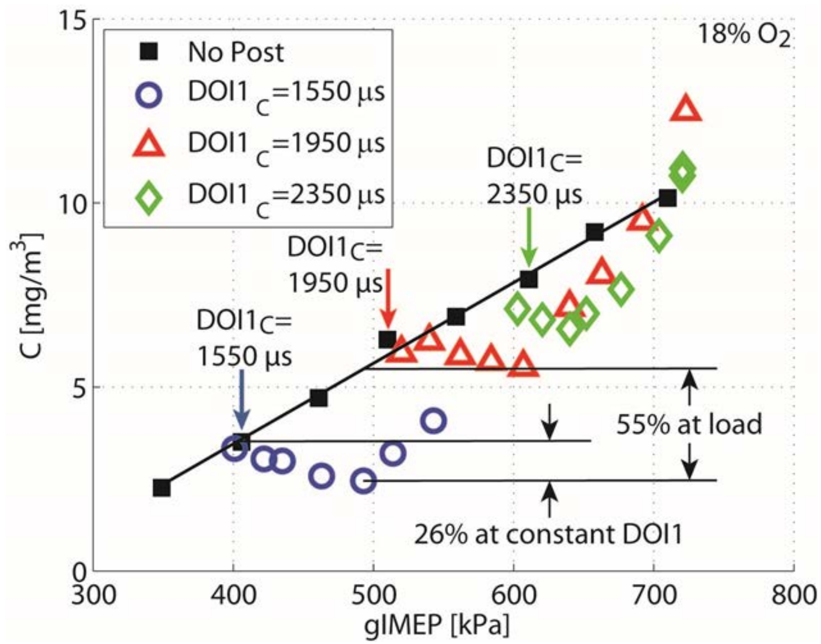
Injection Duration Effects

- Net soot increases non-linearly with injection duration
- Shorter main + post yields less soot than longer main injection
- Minimal enhanced oxidation, just less soot exhausted at a given load

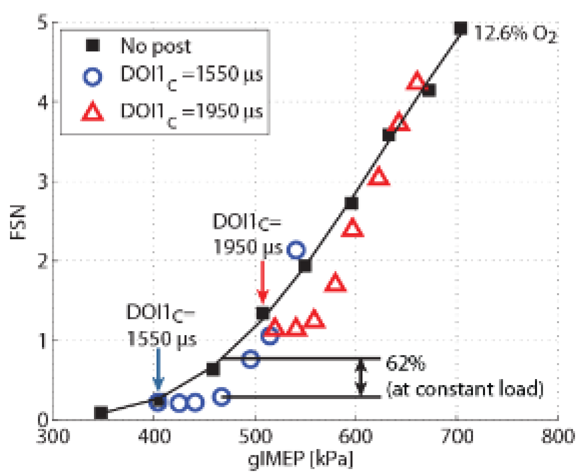
O'Connor J, Musculus MPB, "Post injections for soot reduction in diesel engines: a review of current understanding " SAE Technical Paper 2014-01-1255

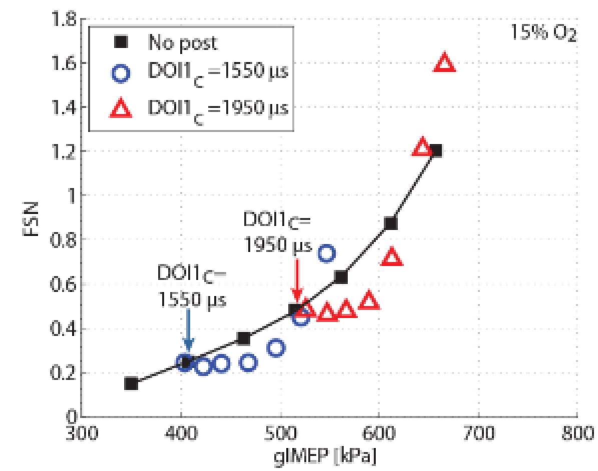
2013 AMR: Injection duration & EGR affect post-injection soot reduction, dwell unimportant

- At 20-30% EGR (18% intake O_2), close-coupled post-injections can reduce soot
- Example: 500 kPa gIMEP
  - 55% reduction at constant load (practical perspective)
  - 26% reduction at constant DOI1 (fundamental perspective)
    - Can't be just duration effect



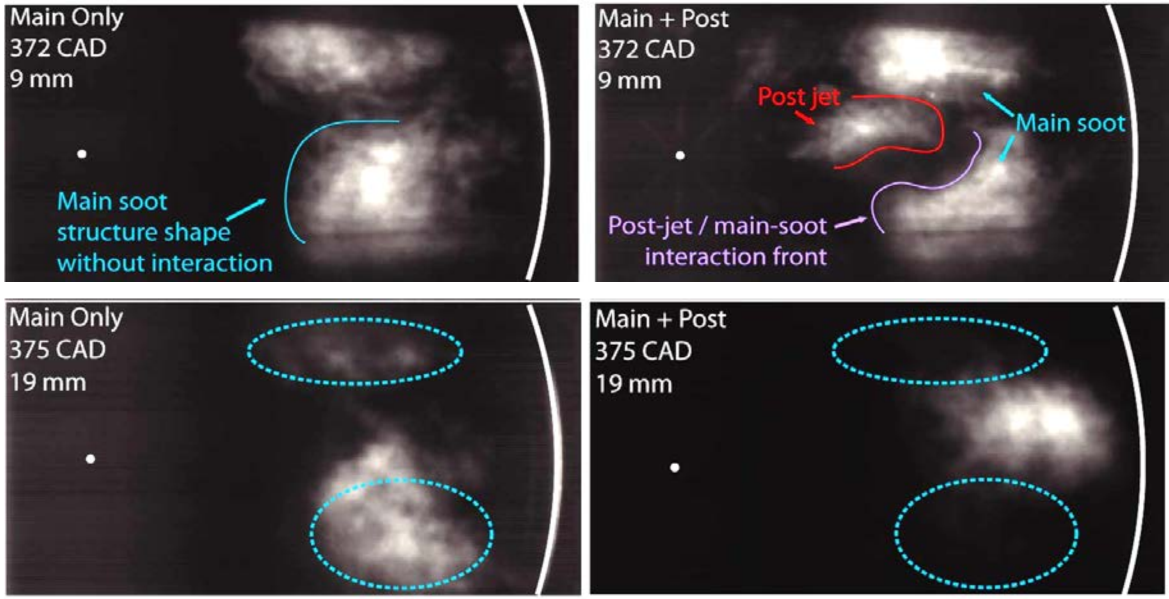
- At higher EGR, post injections are also effective
- Dwell between main and post injection has little effect for conditions tested





2014 AMR: Soot PLII shows first clear evidence of post jet interacting with main-injection soot

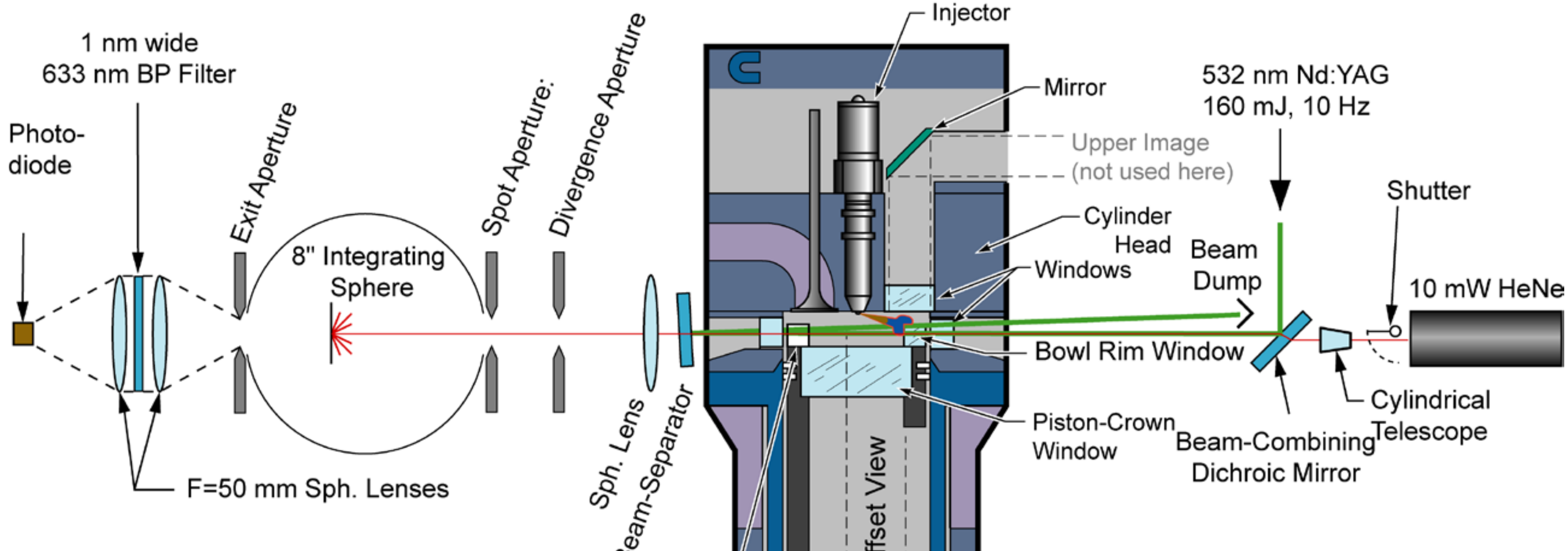
- Post injection alters the shape of the main-injection soot cloud, by disrupted formation, enhanced oxidation, and/or displacement
- Main-injection soot is oxidized / formation is suppressed later in the interaction event



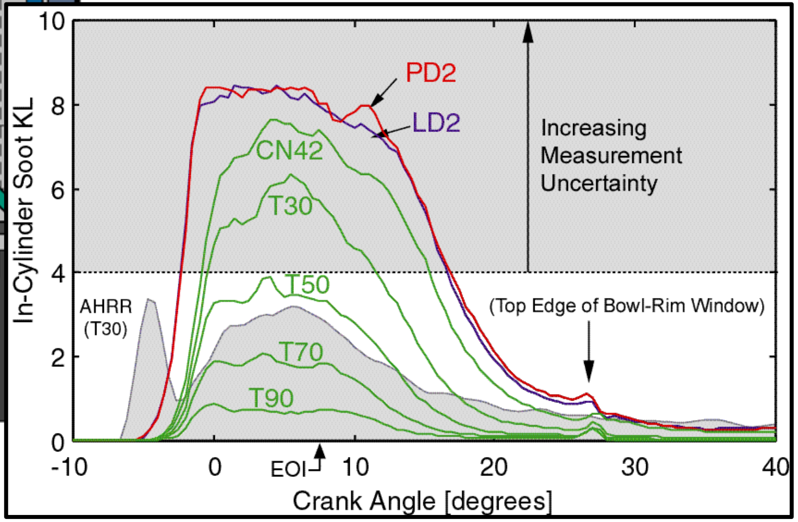
- Soot-PLII imaging illustrates post-main interactions and unambiguous changes to soot distribution, but cause-effect is still unclear
  - Increased temperature aiding oxidation?
  - Quantitative validation of soot models? (total soot vs sheet only)

We need a quantitative imaging diagnostic with temperature data

2002 AMR: quantitative soot by laser-extinction limited to single line-of-sight (due to beam steering)

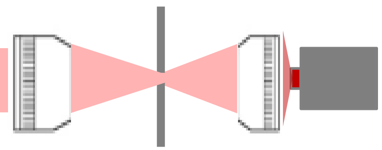


- Integrating sphere required to capture all of the extinction beam steered by in-cylinder density gradients during combustion
- Complicated setup provides quantitative soot extinction (KL), but only along one line of sight (no imaging)

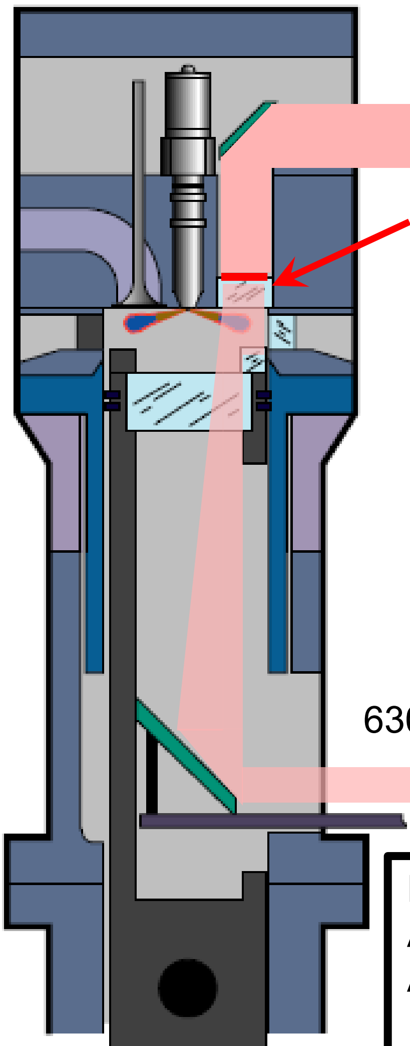


2012 AMR (Pickett/Skeen-Sandia): Diffuse back-illuminated (DBI) for quantitative soot imaging

- By using diffuse light, beam steering effects are largely negated, thereby allowing soot extinction to be measured.[1]



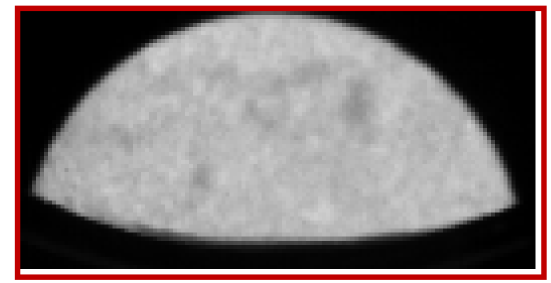
632 +/- 20 nm LED
~ 12 µJ/pulse
(~ 4 W peak, 3 µs pulse)
62.5 kHz



Engineered diffuser (10°)

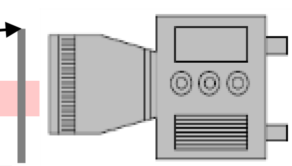
$$\frac{I_{LED\ on} - I_{LED\ off}}{I_{LED\ on,\ no\ soot}} = \exp(-KL)$$

K ~ soot volume fraction (f_v)
L ~ optical path length
KL ~ soot mass along path



128 x 64 array

630 nm bandpass filter (10 nm FWHM)



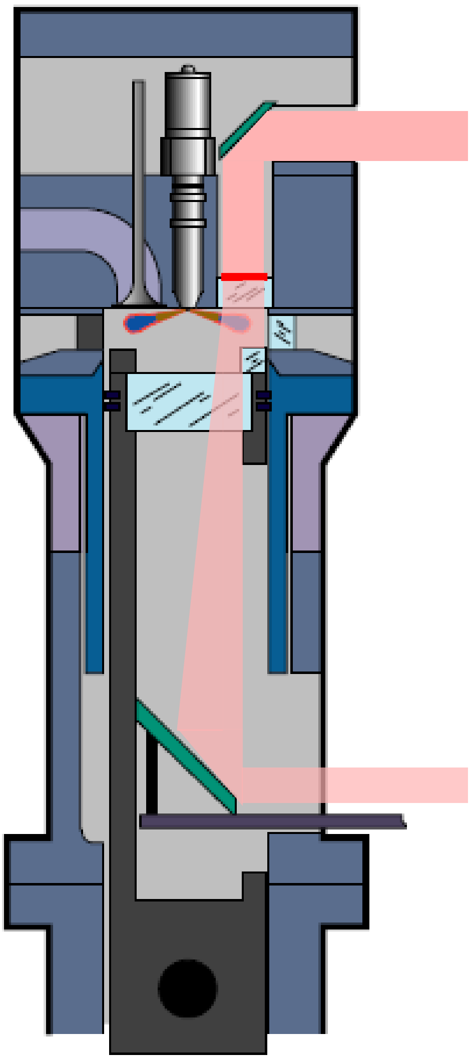
DBI camera
Phantom 7.3 (14-bit) monochromatic CMOS camera
1 µs exposure time
125 kHz frame rate

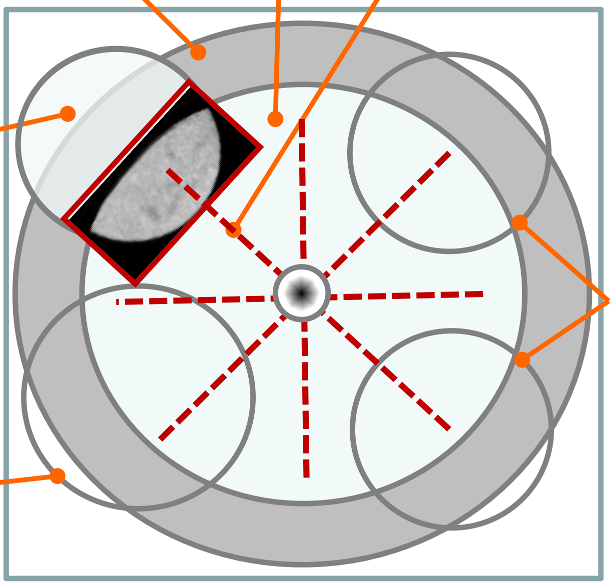
Diffuser: θ = 10º
Acceptance angle: ω ~ 4°
Anticipated beam steering[2] : α ~ 3°
Criteria: θ ≥ (α + ω) is satisfied[1]

[1] Manin, J. et al, SAE Int. J. Engines 6(4), 2013

[2] Musculus, M., and Pickett, L. M., Combust. Flame 141(4), 2005

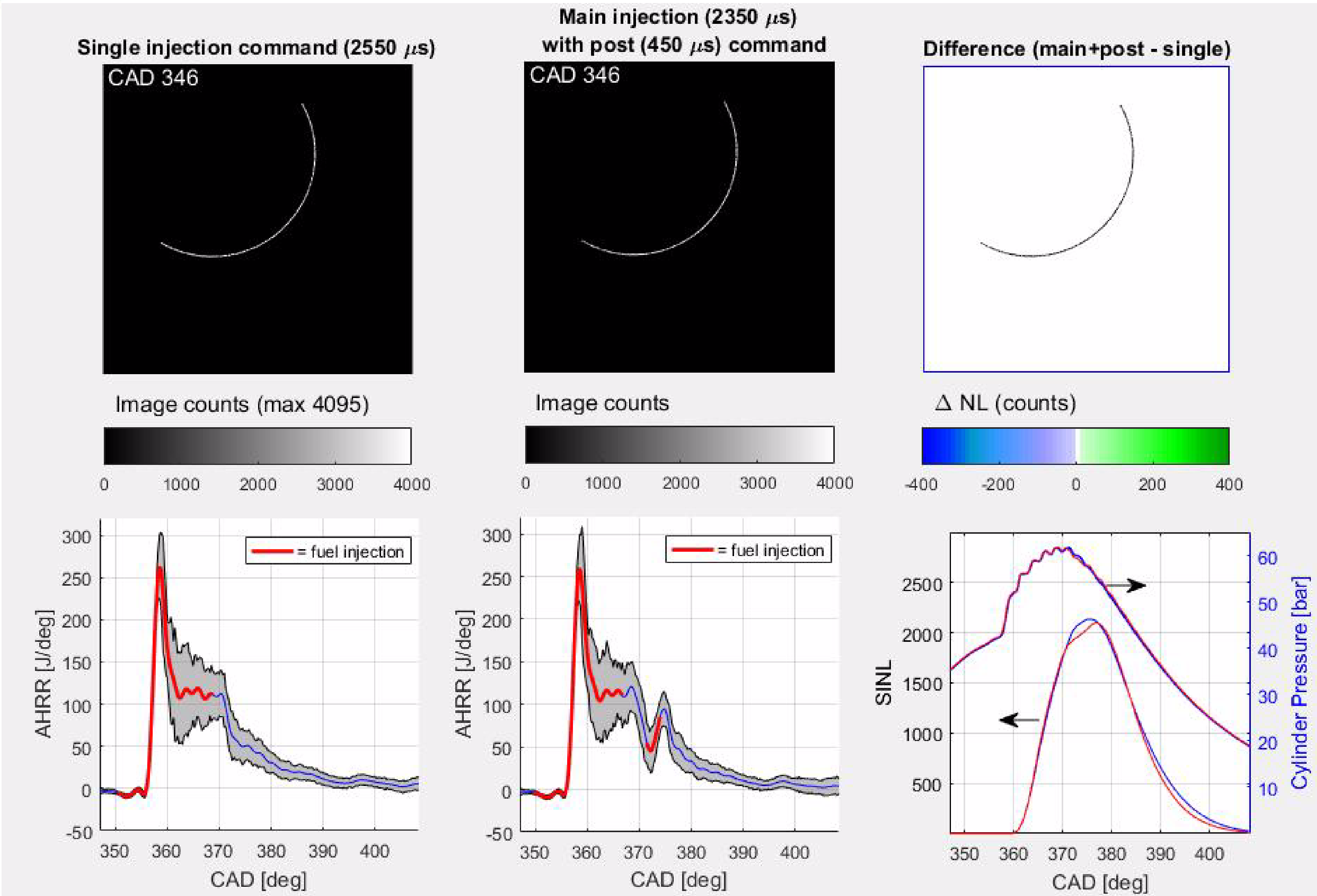
DBI field of view is limited to optical pass-through region, near bowl-rim for one jet in upper-left corner





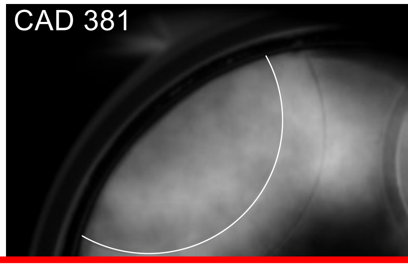
Cylinder head – *Looking from below*

Soot natural luminosity (NL) imaging is simple to acquire, but by itself is not quantitative on soot

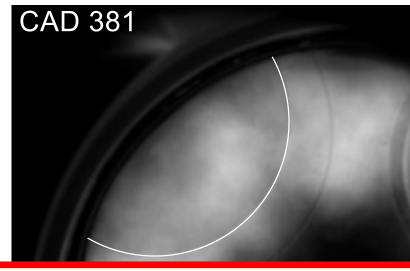


NL intensity changes slightly with a post-injection, but cause could be soot temperature, or f_vL, or both

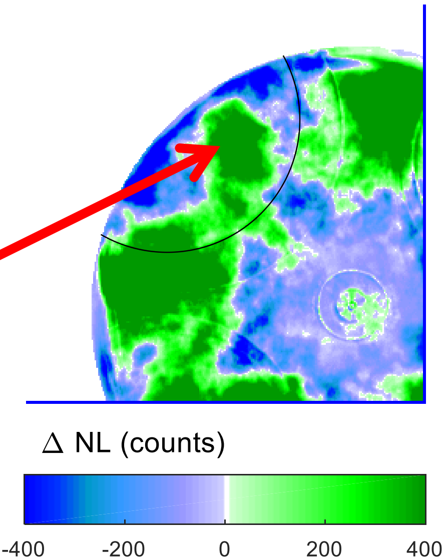
Single injection command (2550 μs)

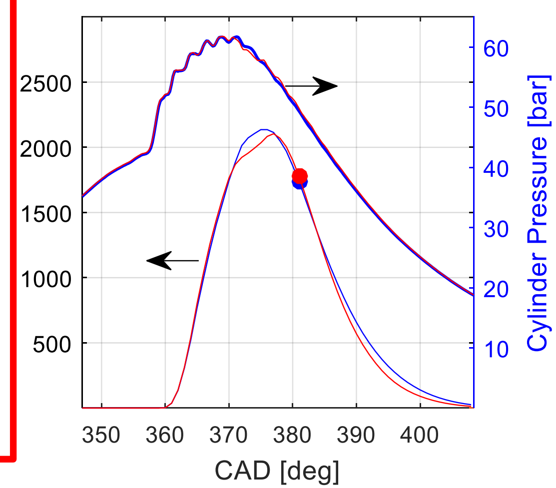


Main injection (2350 μs) with post (450 μs) command



Difference (main+post - single)



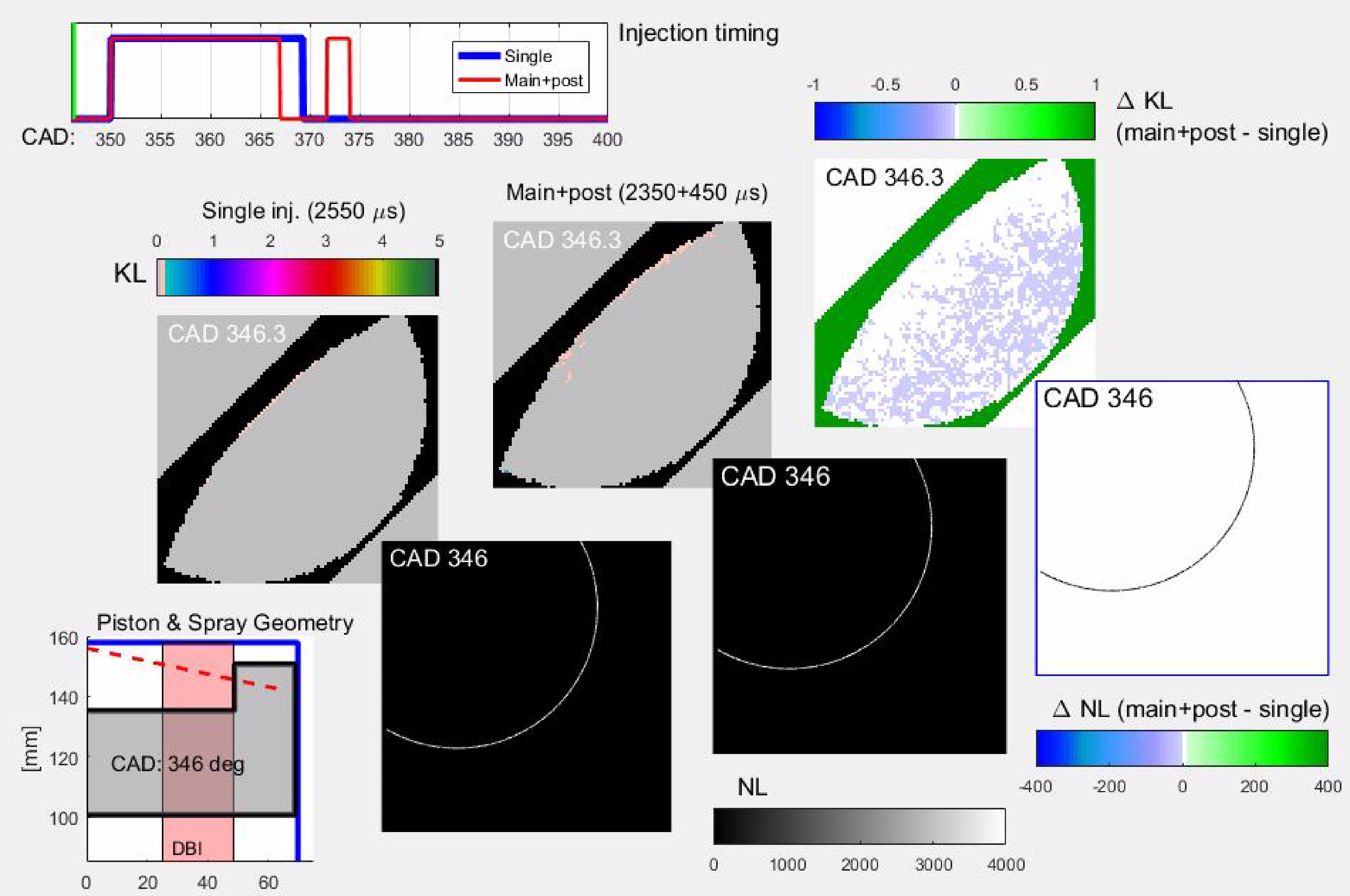


- When a post injection is added, the local NL either increases (green) or decreases (blue)
- NL = f(temperature, volume-fraction-length f_vL)
  - Increased NL could be higher soot f_vL or higher temperature or both
  - Decreased NL could be reduced soot f_vL or lower temperature or both
- Problem: “one equation, two unknowns”
  - Two-color method provides two equations, but two-color f_vL is biased to closest, highest temperature soot (see 2004 AMR)
- **DBI imaging has no soot temperature bias**

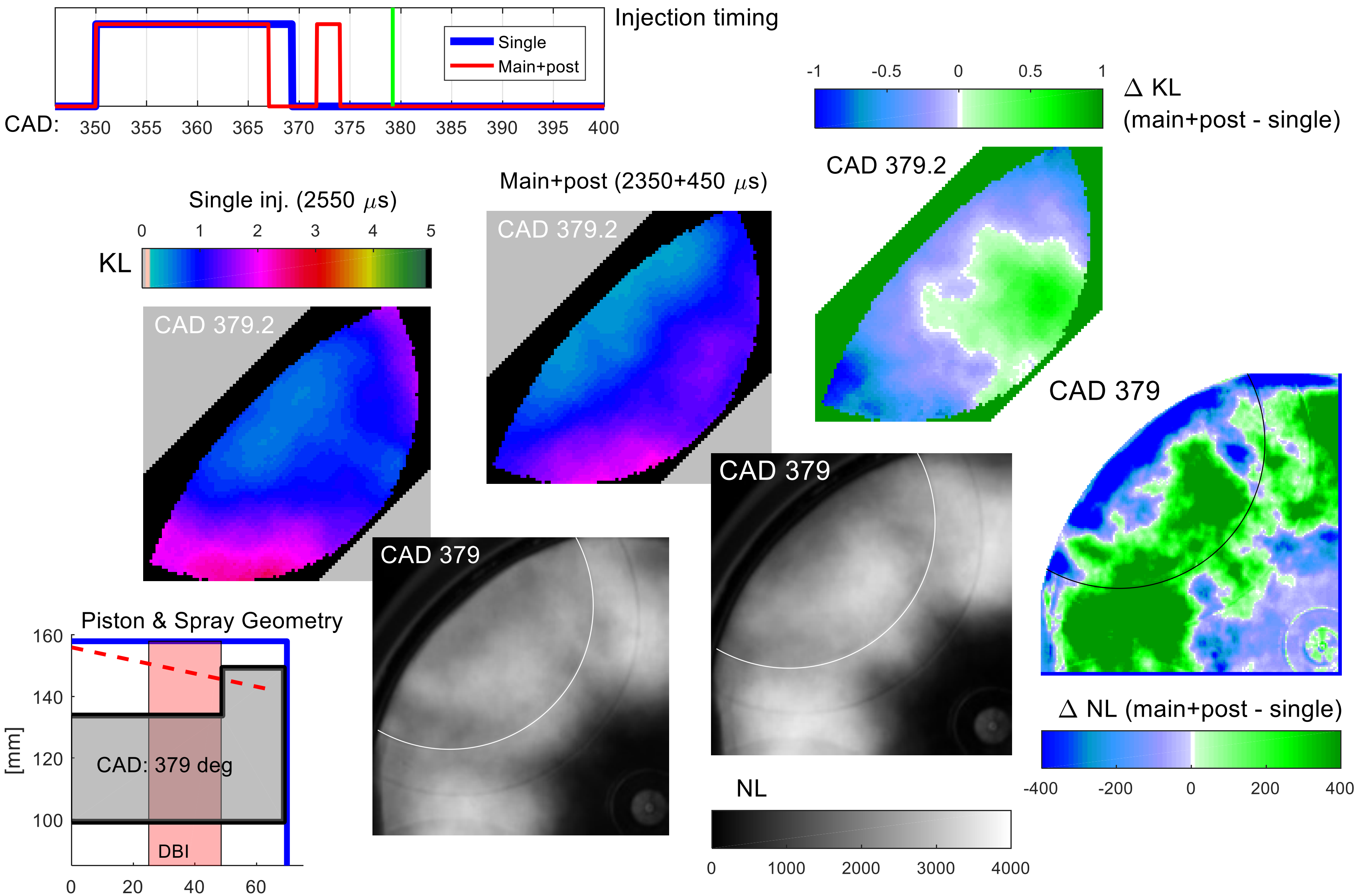
CAD [deg]

CAD [deg]

Simultaneous NL and DBI imaging provides complementary soot temperature and KL ($f_v L$) data



DBI imaging: post-injection increases soot in jet, consistent with PLII, but now is quantitative (KL)



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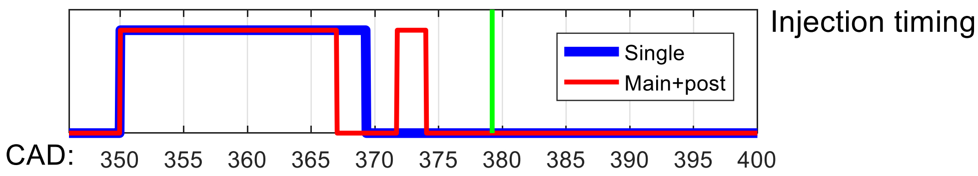
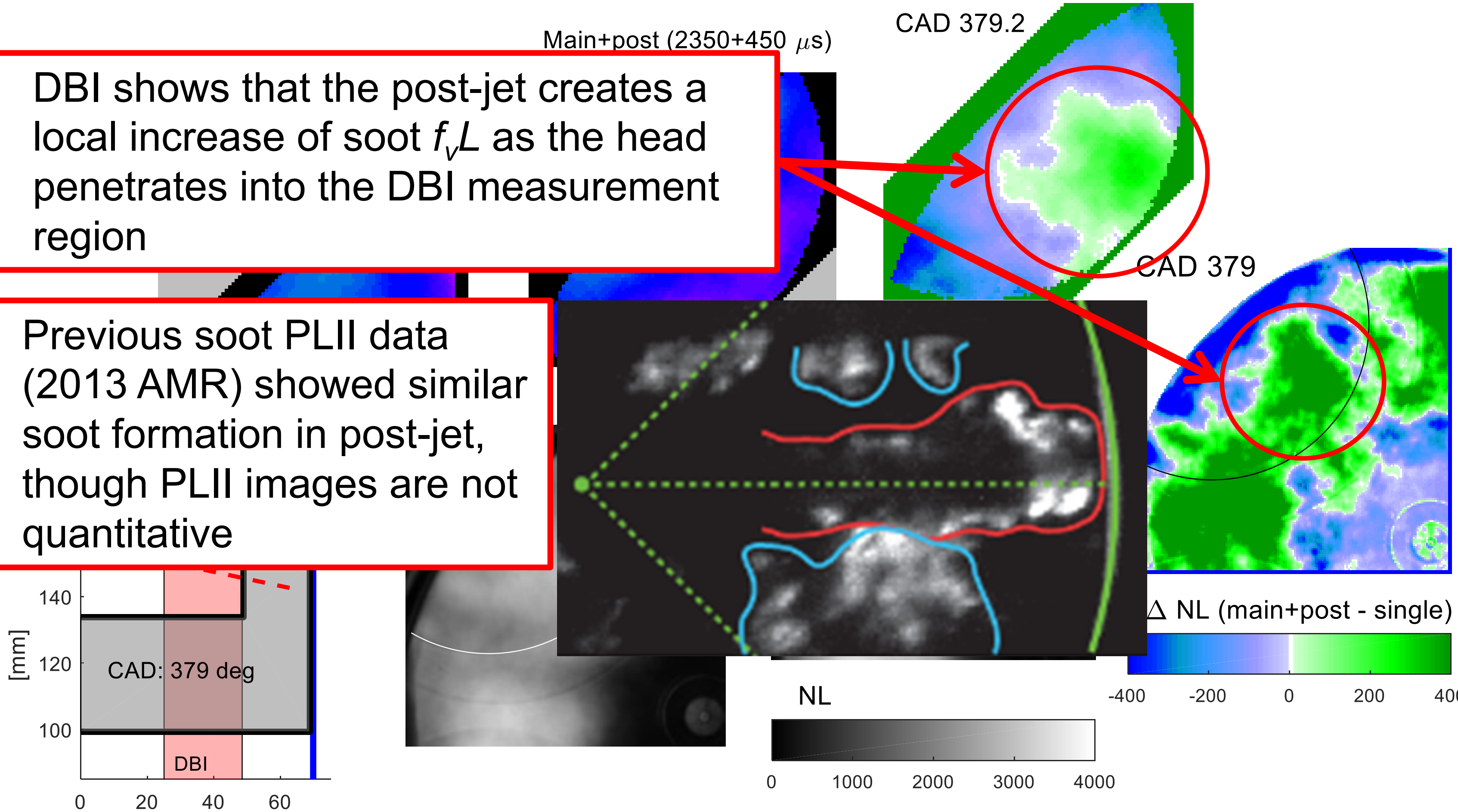
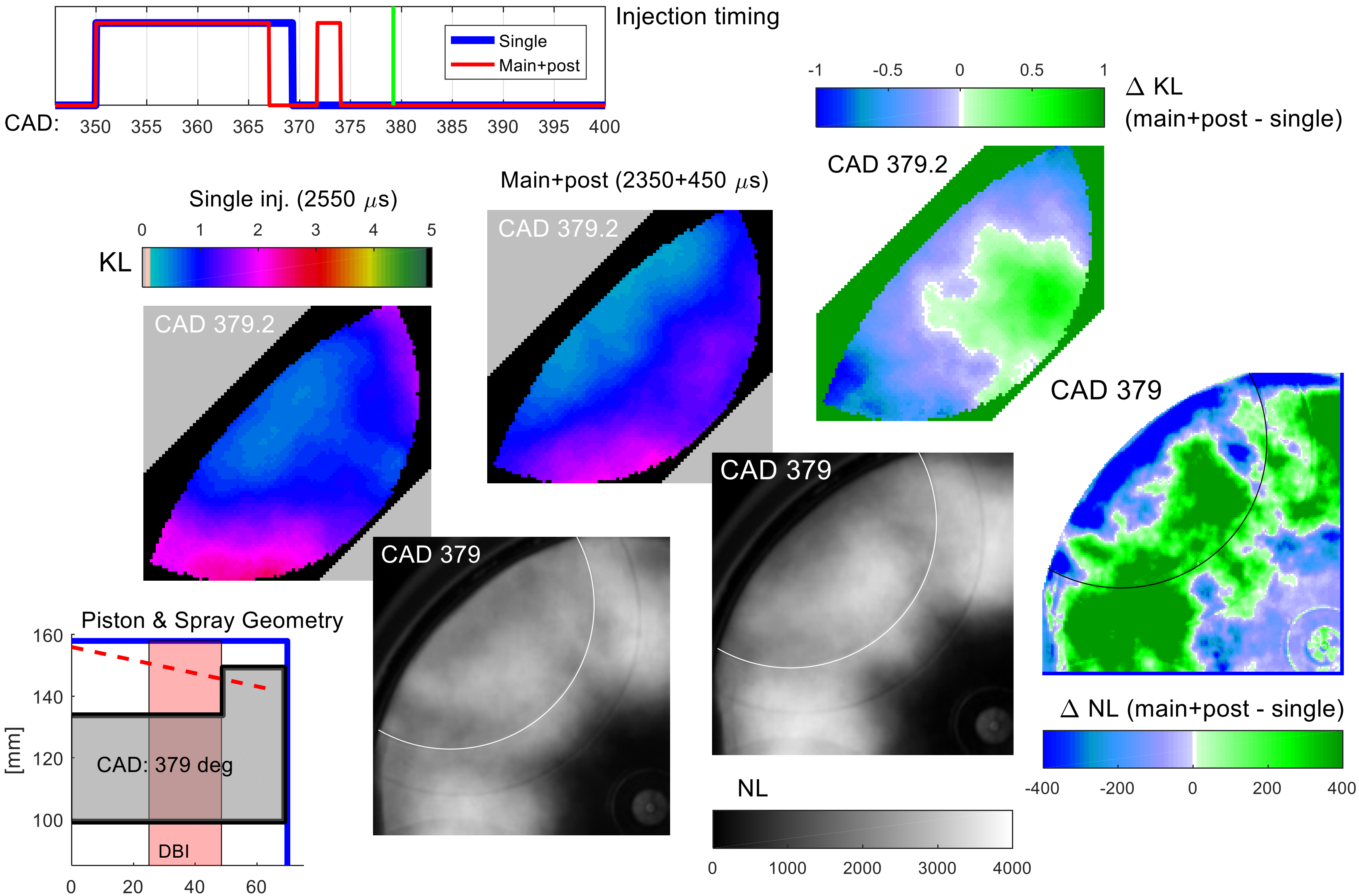


- DBI shows that the post-jet creates a local increase of soot $f_v L$ as the head penetrates into the DBI measurement region

- Previous soot PLII data (2013 AMR) showed similar soot formation in post-jet, though PLII images are not quantitative



DBI (KL) + NL imaging: first clear evidence of post-injection soot oxidation by increased temperature



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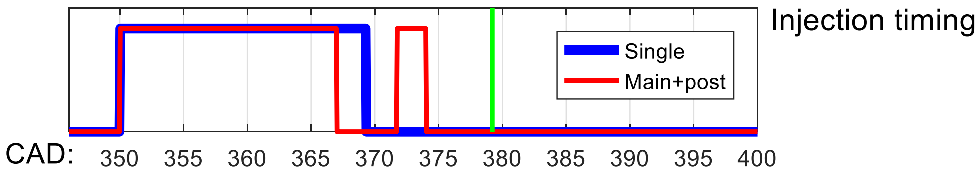
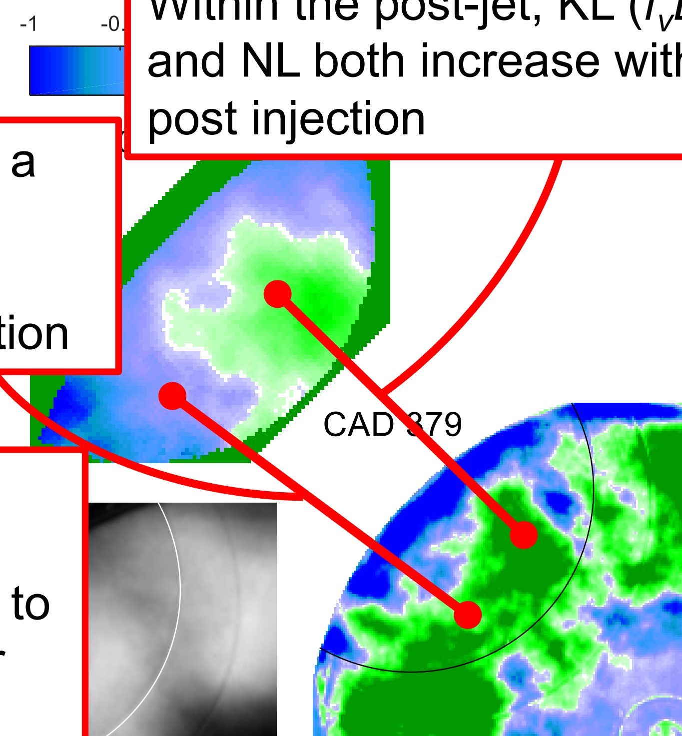
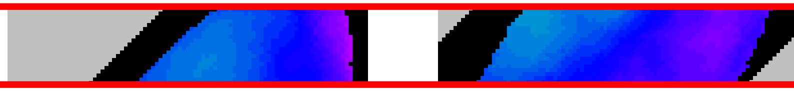


Within the post-jet, KL (f_vL) and NL both increase with post injection

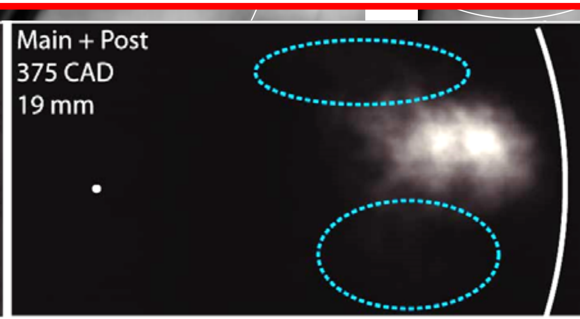


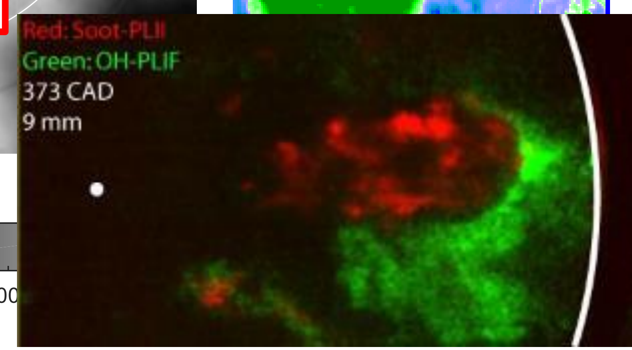
To the side of the post-jet, KL (f_vL) decreases with a post injection, while NL increases.

→ If NL = f(f_vL,T), then the post injection must increase T locally, which should aid soot oxidation

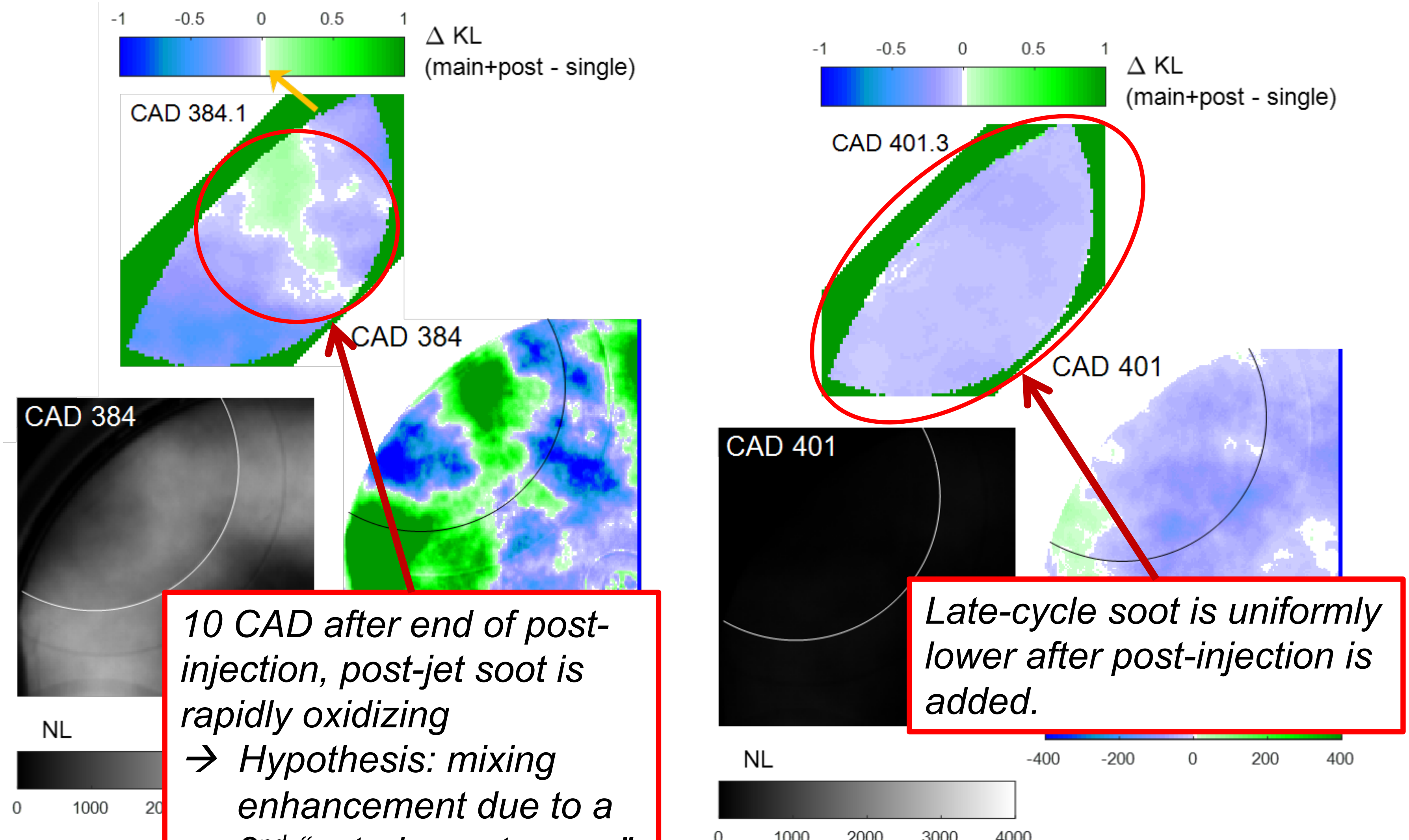


Consistent with previous soot PLII (2014 AMR) showing decreased soot to side of post-jet within laser sheet, and increased OH PLIF signal (green) to side of sooty jet (red). OH is a strong soot oxidizer typically formed in high-temperature regions.





Post-injection soot is oxidized later in the cycle, potentially due to 2nd entrainment wave (mixing)



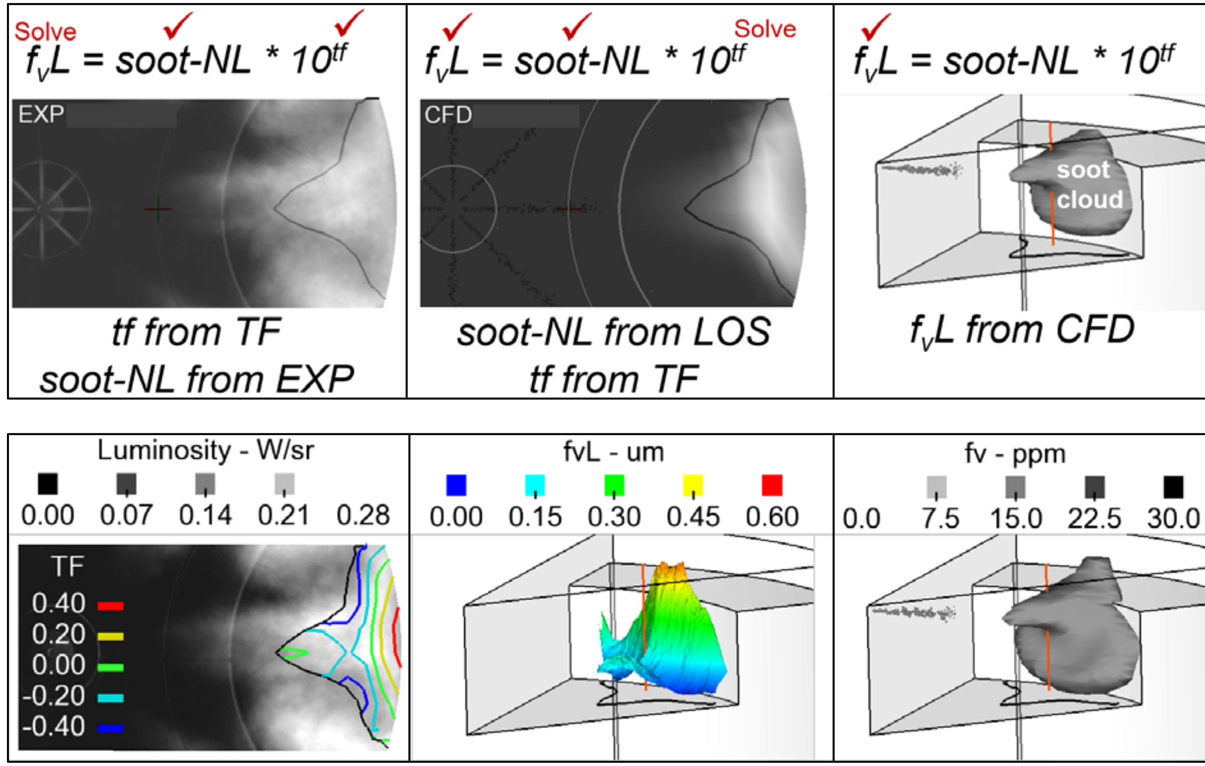
10 CAD after end of post-injection, post-jet soot is rapidly oxidizing

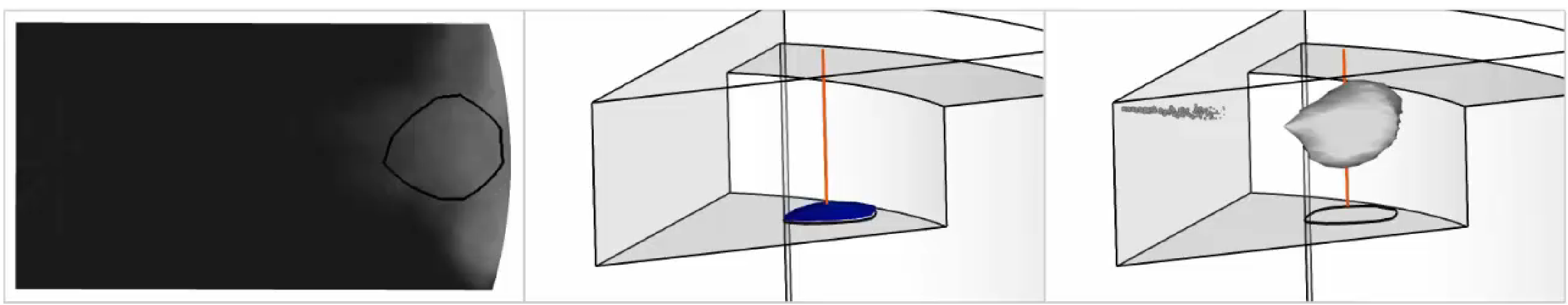
→ *Hypothesis: mixing enhancement due to a 2nd "entrainment wave."*

Late-cycle soot is uniformly lower after post-injection is added.

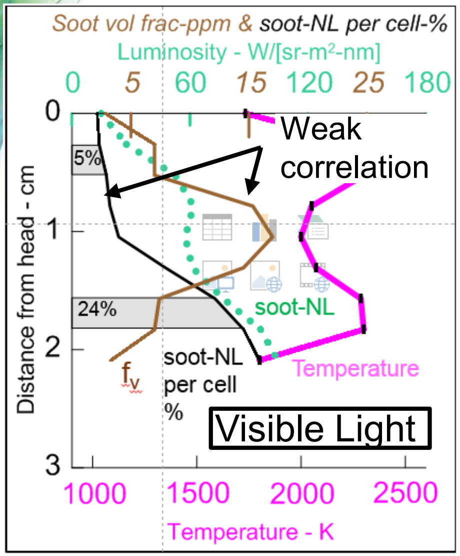
UW Modeling: Compute NL from predictions, find transfer function to convert experiment NL to f_vL

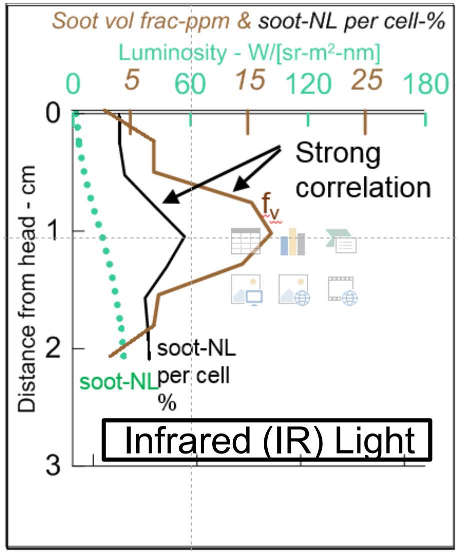
- Goal: Develop rule-of-thumb transfer function to interpret NL imaging in terms of f_vL
- First row: soot-NL gives reasonable representation of f_vL in downstream jet
- Second row: Transfer function transposes experimental image into f_vL surface that correlates well with predicted soot cloud
- Third row: Correlation holds over space and time



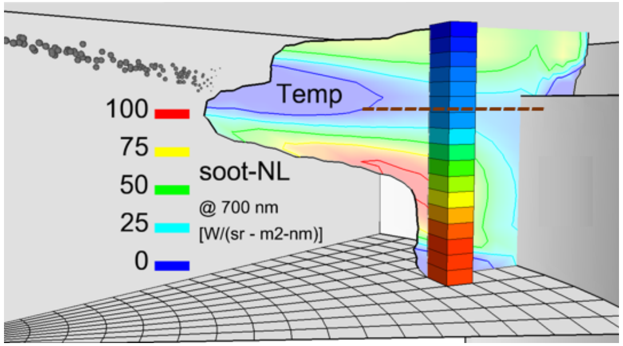


UW Modeling: computed NL predicts that infrared (IR) NL imaging will better represent soot f_vL

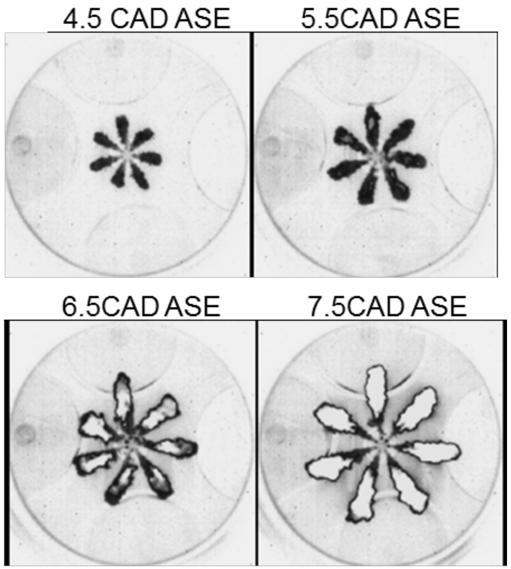




- *T* & f_v vary along line of sight (L)
- Visible-light: local f_v weighting of soot in NL signal is non-uniform
  - –Signal trapping: closer soot weight (24%) more than distant soot (5%)
  - –Temperature: bias to hot soot
  - –Weak *f_v↔NL correlation*, so complicated NL↔f_vL trans. func.
- IR: local weighting of soot f_v in NL signal is more uniform
  - –Less signal trapping, so close and distant soot have similar weighting
  - –Lower temperature bias in IR
  - –More uniform NL→f_vL trans. func.
- 3500 nm IR imaging has already proven useful for vapor fuel penetration imaging (2015 AMR)
  - –Future experimental work will compare DBI & IR soot imaging



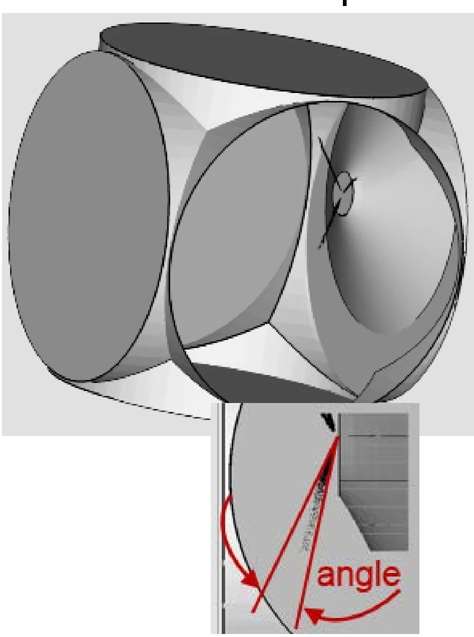
2015 AMR: simple IR imaging of hot fuel vapor jet spreading/penetration

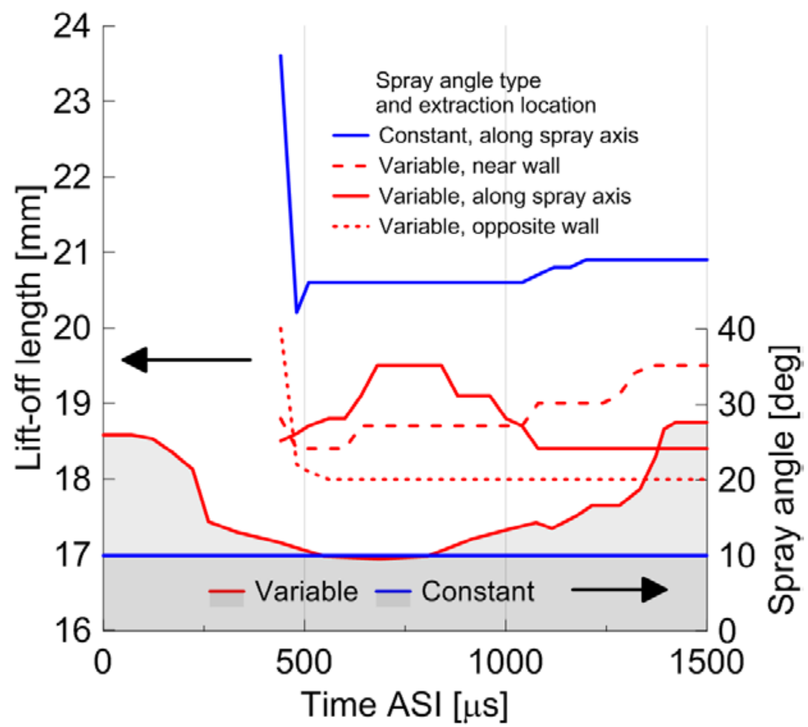


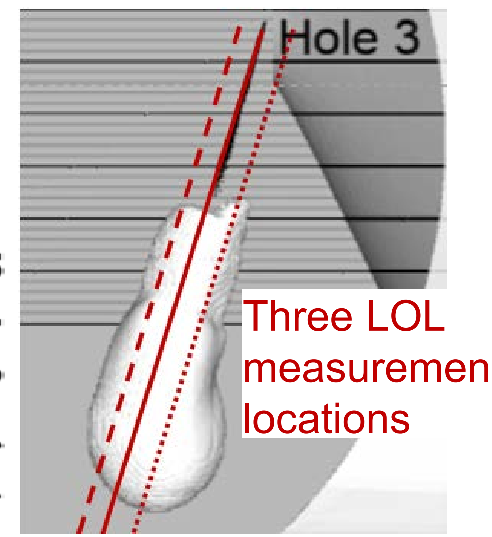
UW Modeling: Understand apparent spray angle effects on lift-off length (LOL) in const. vol. vessel

- Experiments: 3-hole Spray B angle & LOL fluctuate more than single-hole Spray A
  - –Do spray-angle dynamics affect LOL? Exp'ts: Comparison to constant angle not possible
- Approach: Simulate Spray B w/ both constant & varying spray angle (from meas.)
  - –Models predict greater variation of LOL for dynamic spray angle
  - –Magnitude of LOL variation depends on LOL measurement location
  - –Models also predict longer LOL for constant spray angle

Simulate VSL & 3 plumes





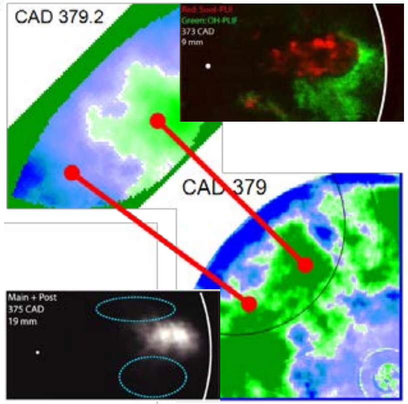


Remaining Barriers/Future Plans: Multi-injection conceptual model, heat-transfer, improve models

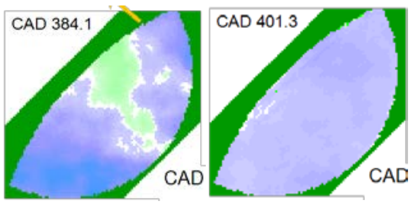
- Continue building a conceptual-model understanding of multiple-injection processes for both conventional diesel and LTC
  - Multi-injection schedules (pilot, post, split) deployed by industry
  - Identify mechanisms and critical requirements (injector rate-shaping, dwell, duration, etc.) to improve emissions and efficiency
  - Continue to develop IR imaging tools to provide new insight not previously available with visible and ultraviolet diagnostics
- Determine how in-cylinder processes affect efficiency across range of combustion modes and in-cylinder geometries
  - Correlate in-cylinder temperature and heat transfer across combustion modes to efficiency
- Gain fundamental insight from both experiments and models
  - Continue to refine 3-D analysis tools and apply them to end-of-injection mixing/ignition processes, multiple injections, heat transfer

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

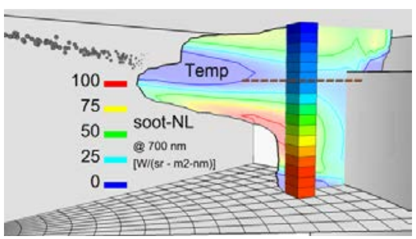
Summary: ACS001 – Heavy-Duty Low-Temperature and Diesel Combustion & HD Combustion Modeling



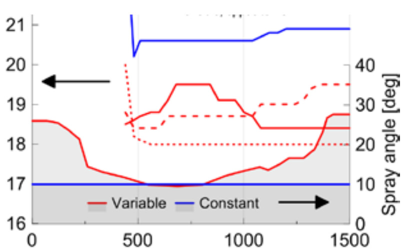
(SNL) New combined diffuse background illumination (DBI) and natural luminosity (NL) imaging technique shows first clear evidence of post-injection soot reduction by increased local temperatures, strengthening suggestions from 2014 AMR soot PLII and OH PLIF imaging data



(SNL) Quantitative soot DBI imaging shows late-cycle reduction of soot in post-jet, consistent with increased mixing from a 2nd entrainment wave, a new fluid-mechanic effect that was described in 2008 AMR



(UW) Developed soot volume fraction ($f_v L$) ↔ NL transfer function to aid interpretation of NL images; analysis suggests using IR for better soot imaging



(UW) For ECN: Modeling of Spray B using fluctuating spray angle observed in experiments increases lift-off length variations compared to constant injection, aiding interpretation of data from experiments