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Progress Report: Bowl Geometry Impact on Mixture Formation

Steve Busch, Kan Zha

Sandia National Laboratories

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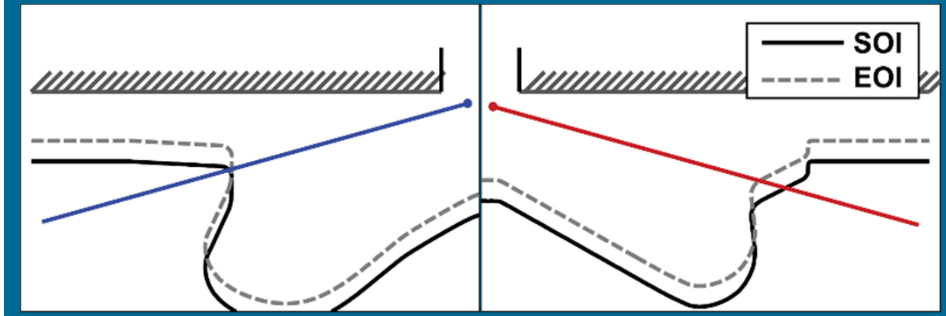
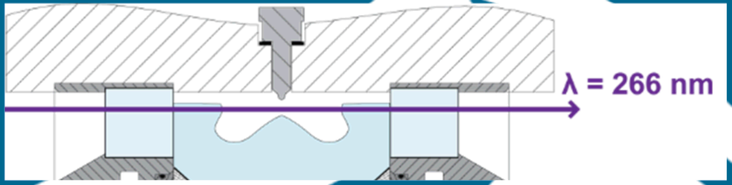
Outline

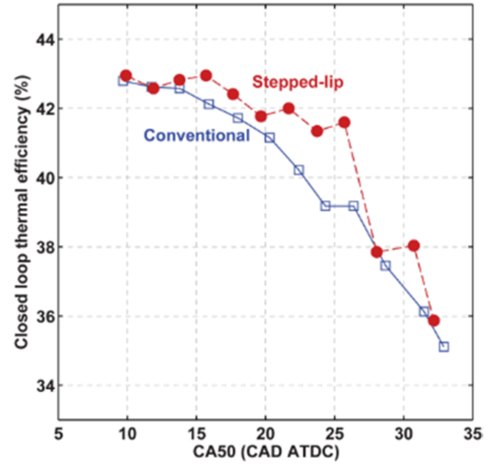
- State of knowledge and open questions
  - Early injection PCCI (LTC): mixture formation
  - Conventional diesel combustion: late-cycle mixing
- Experiments and analysis techniques
  - Fuel tracer PLIF
  - High speed liquid scattering imaging (in progress)
- Results
  - Three injection timings; three spray targeting cases
  - Differences in mixture formation processes; implications for combustion efficiency
- Ongoing experimental studies

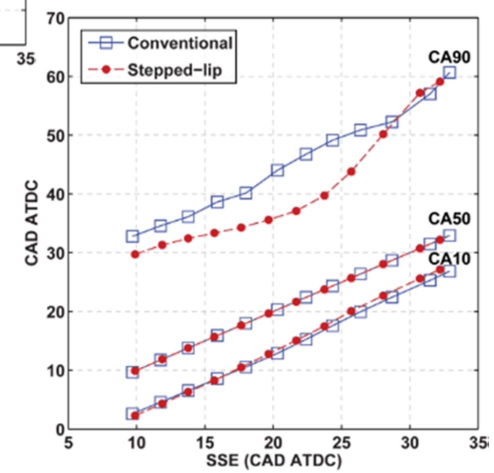


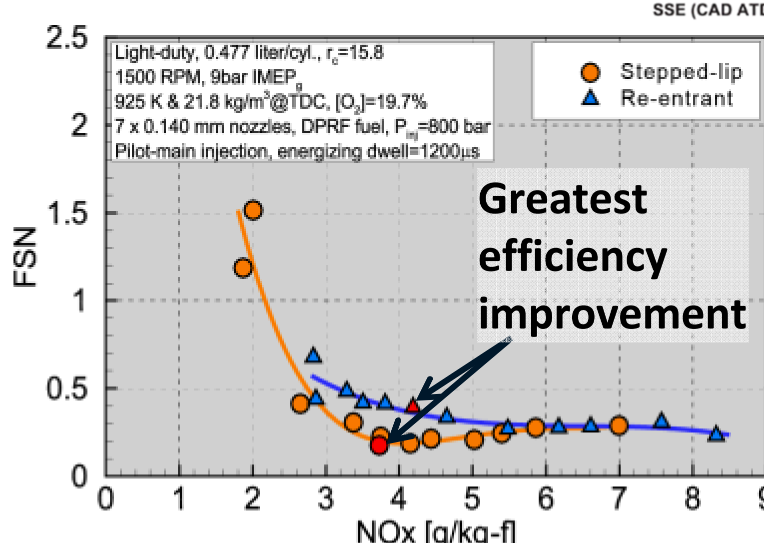


State of knowledge: performance and emissions

- **Conventional diesel combustion with a single pilot injection (CDC)**
  - The stepped-lip piston yields higher thermal efficiency for some injection timings
  - Efficiency gains appear to be most closely associated with faster late-cycle heat release (analysis ongoing)
  - Stepped-lip efficien ... coincide with reduced so ... NO ... issions
- **Open qu**
  - ... anisms gov ... hes ... provements in ef ... and emissions?
  - Ca ... sms be u ... k thermal ef ... while ... cing soot and ... ons?



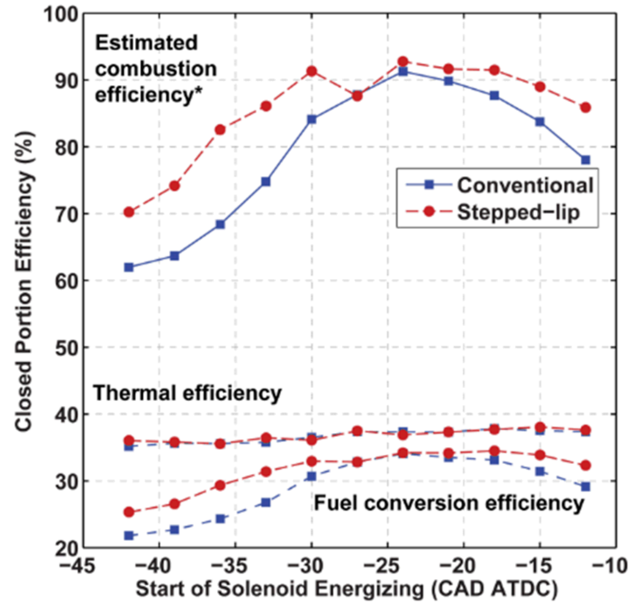




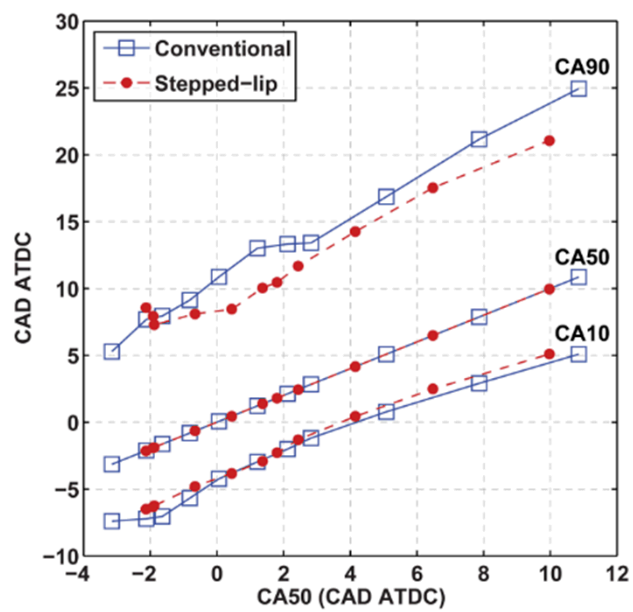
State of knowledge: performance and emissions

- **Early injection, PPCI combustion (LTC)**
  - Peak fuel conversion efficiency is slightly higher with the stepped-lip geometry
  - Efficiency gains with the stepped lip piston are most closely associated with improvements in combustion efficiency
  - Mixture formation with the stepped-lip bowl is less sensitive to injection timing
  - Late-cycle heat release appears to be slightly enhanced w... the stepped-lip bowl
    - For this pred... ...ixed combusti... the ther... effici... ...emen... is mini...

- ...on
  - ...hat difference... ...obser... in th... mixture f... ...cess tha... ...ences in c... ...stic...

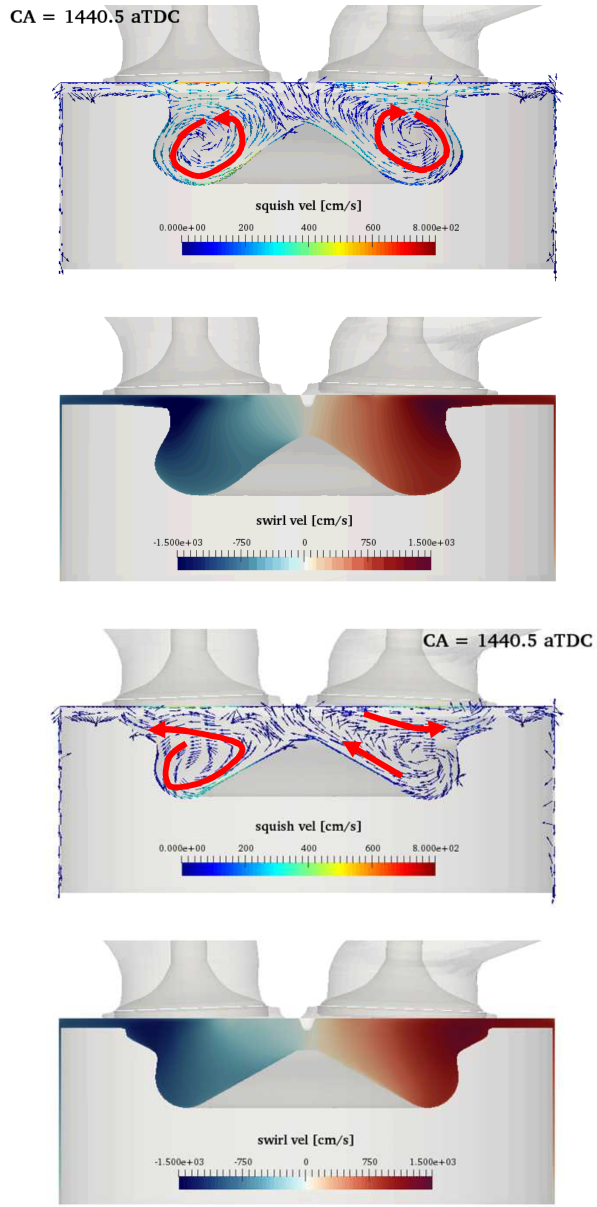


*estimated from energy balance



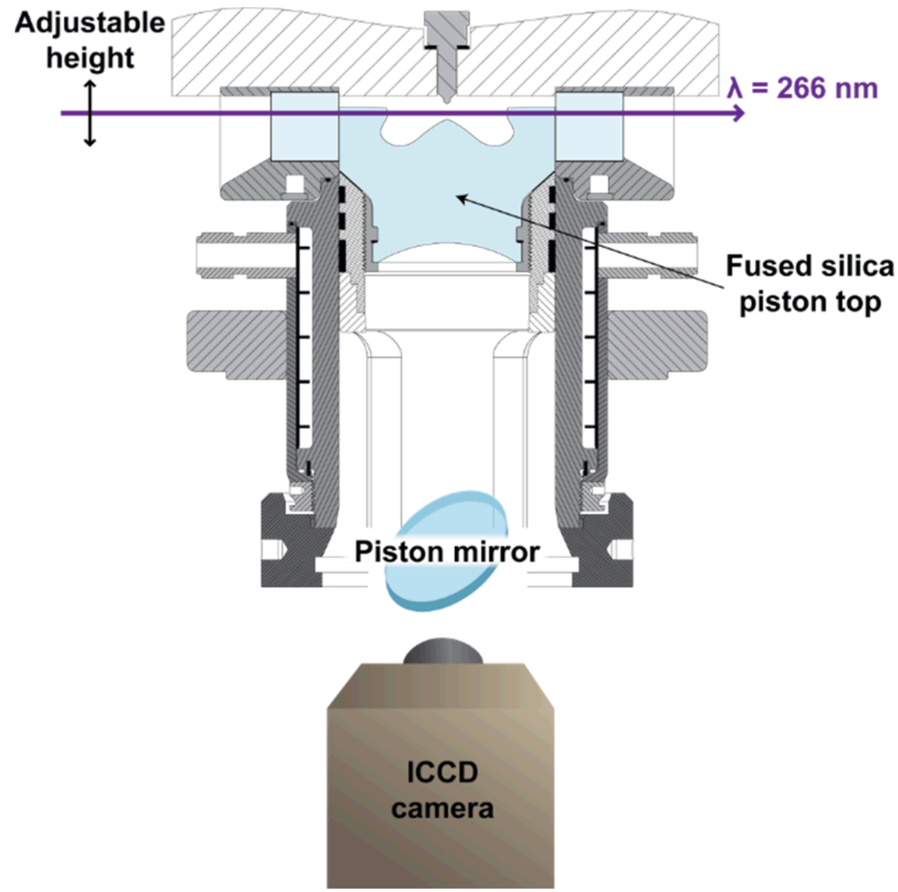
State of knowledge: bowl geometry impact on in-cylinder motored flow

- **Conventional re-entrant bowl geometry**
  - Interactions between swirl and squish create a toroidal vortex in the bowl
- **Stepped-lip bowl geometry**
  - Expected squish / reverse squish velocities are half as fast as for the conventional bowl
  - Reverse squish flow during the early expansion stroke is c ser to ideal for the stepped-lip bowl – h l to be an inertial effect
  - Higher degre thal asy try in near-TD ne flo tructu th ventional
- **ion**
  - How do differe w beh r impact mation



Experimental setup: fuel tracer PLIF

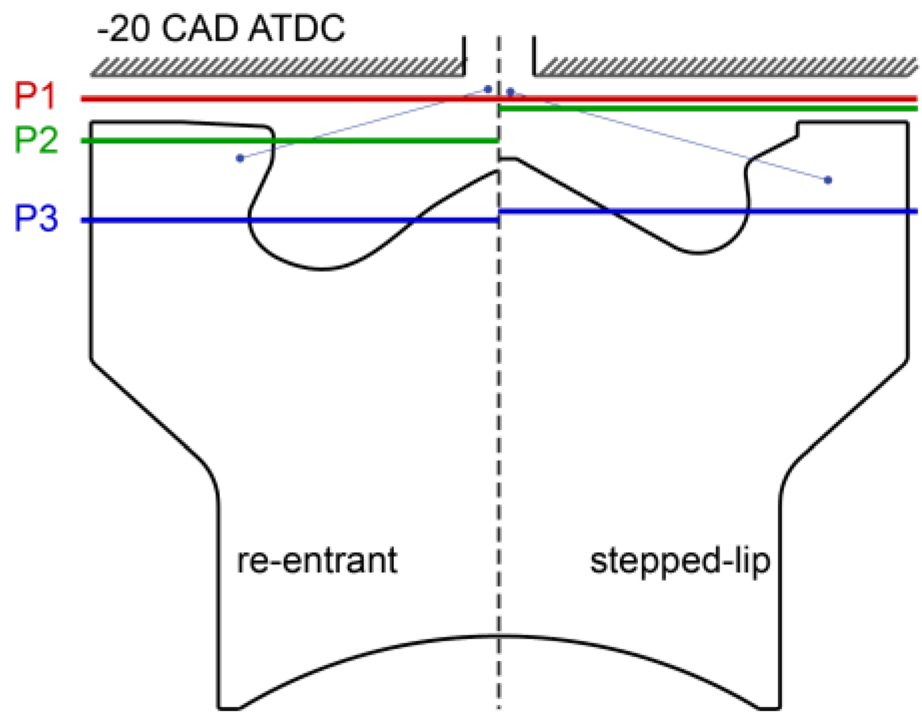
- **Engine operation**
  - 1500 rpm; motored operation (0% O_2)
  - Fuel: 42 vol% n-hexadecane + 58 vol% heptamethylnonane
  - Tracer: 0.5 weight% 1-methylnaphthalene
  - Swirl ratio: 2.2
  - Skip-fired (1 fired : 4 skipped)
- **Fluorescence illumination source**
  - Nd:YAG, 4th harmon… 66 nm)
  - ~ 30 mJ/pulse (rel… ity measured for c… t)
  - Laser sh… s < 1 m
- **Imaging through piston**
  - … + ICCD camer… = 15)
  - Nikon UV-105 l…
  - WG-2… ter



Bore x stroke	82 mm x 90.4 mm
Compression ratio	15.8:1
Valves	4
Injector type	Solenoid
Holes	7 x 139 µm
ks	1.5/86
Included Angle	149°

PLIF imaging plane locations

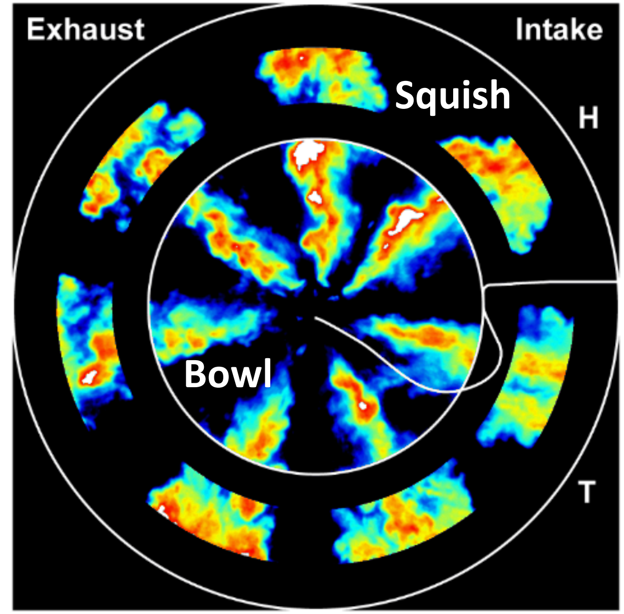
- **Plane 1 (position relative to piston and engine changes with crank angle)**
  - Halfway between piston top and cylinder head
- **Plane 2 (moves with piston)**
  - Conventional piston: passes through bowl rim
  - Stepped-lip piston: 1.4 mm above the piston top to minimize reflection
    - Passing a laser [illegible]et through the step region is [illegible]ble
- **Plane 3 (moves with piston)**
  - Conventi[illegible]m be[illegible]w pis[illegible]top
  - St[illegible] mm bel[illegible]n top
- **Distortion correction via a semi-automated, ray tracing based routine**
- **Iterative computation of fuel concentration**



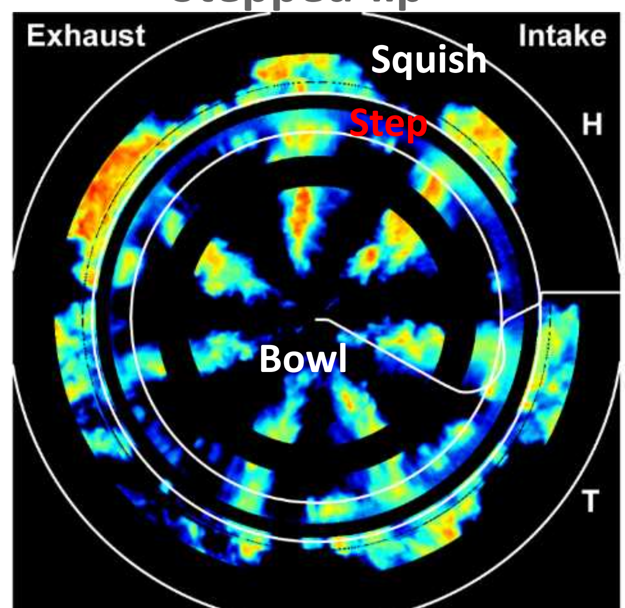
Sample PLIF result images

- **Conventional piston**
  - The region above the bowl is fully visible
  - Only a portion of the squish region is visible
- **Stepped-lip piston: more complex distortion correction than with the conventional bowl**
  - Dramatic change in … owl profile radius of curvature at bott… …f pip severely degrades image q…
  - The region in… …bove the… …wl is split int… …s (sho… at rig…
  - … …ble above … …ext at right)
  - A limited amou… …matio… … availabl… … region

Conventional

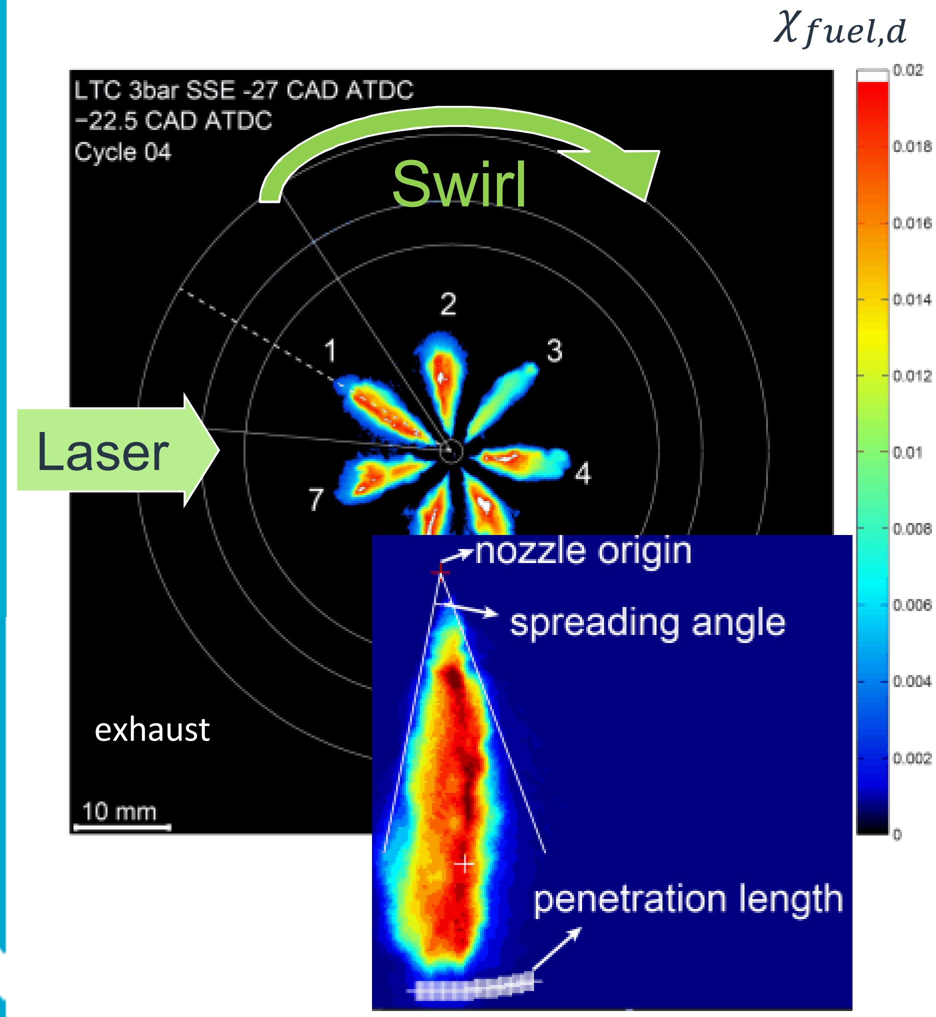


Stepped-lip



Spreading angle and penetration length quantification

- Background subtraction:
  - Background reflection problems are mitigated by subtracting a constant from each image
- Spreading angle and penetration length calculation using ECN script (Siebers, SAE Paper 960034).
  - Since measurements were not taken perpendicular to th… axis, calculated "spreading angle" … ection on the field-of-vie…
- Calculati… …ned for … lum… f… cycles (χ_f …).



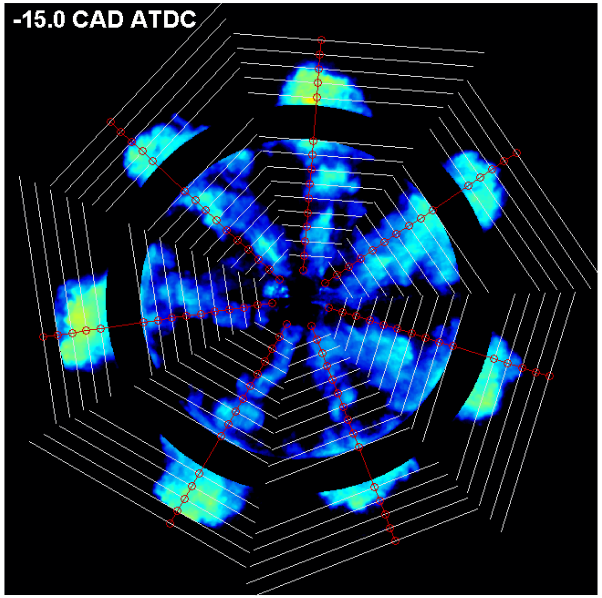
Spray structure characterization

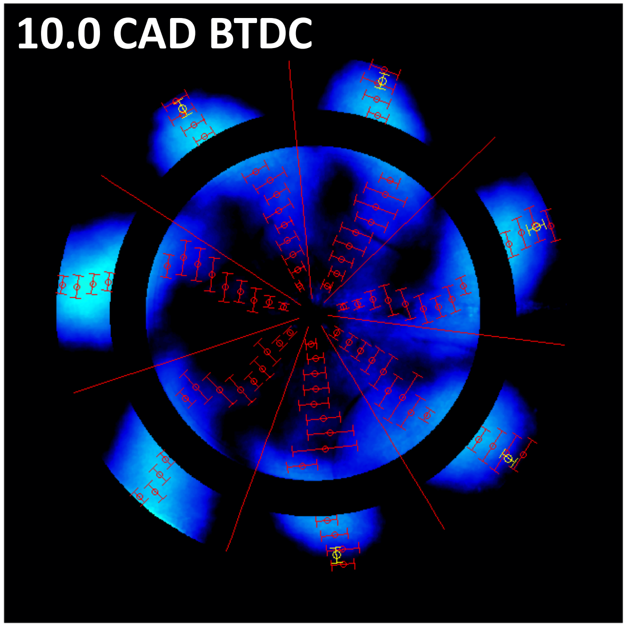
- Fuel concentration-weighted centroid evaluated along multiple profiles (shown as white lines) across each jet

- Ensemble average provides simplified representation of jet structure, insight into how jets are deflected by swirl

- Angular deviation fro ... xes can be plotted as a functio ... adi ... r different crank a ...

- Th ... ll be appli ... o CF ... a ... ples-to-apples ... ison ...

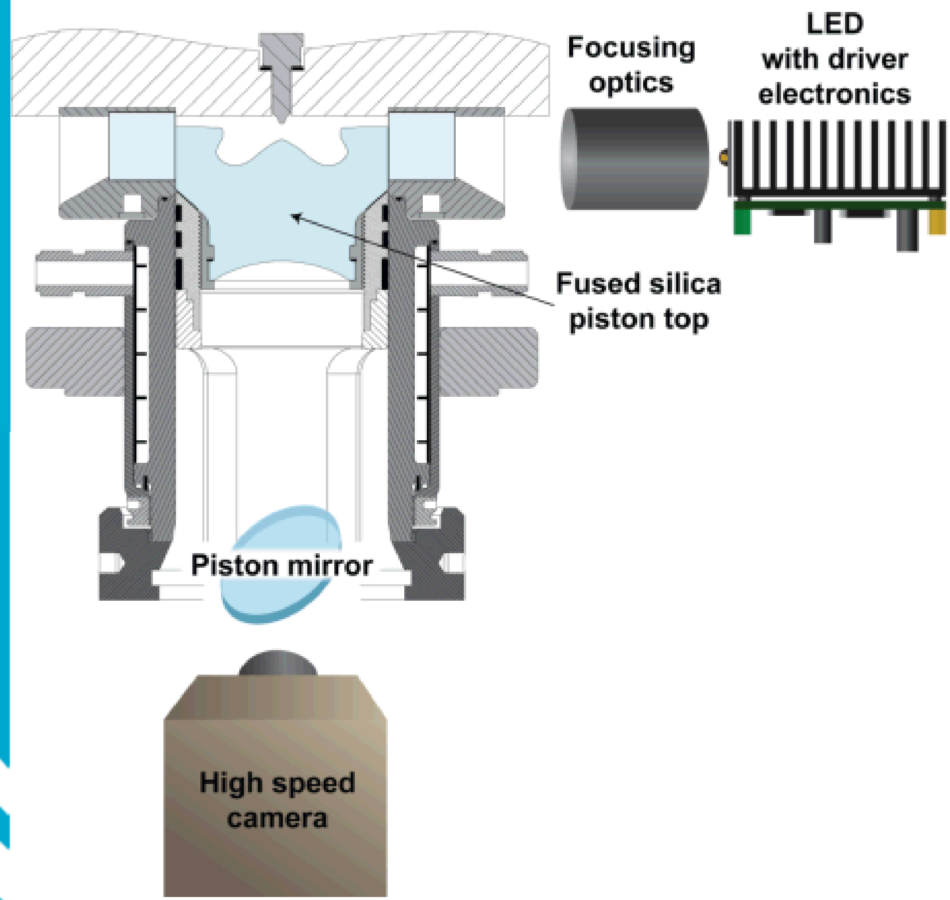




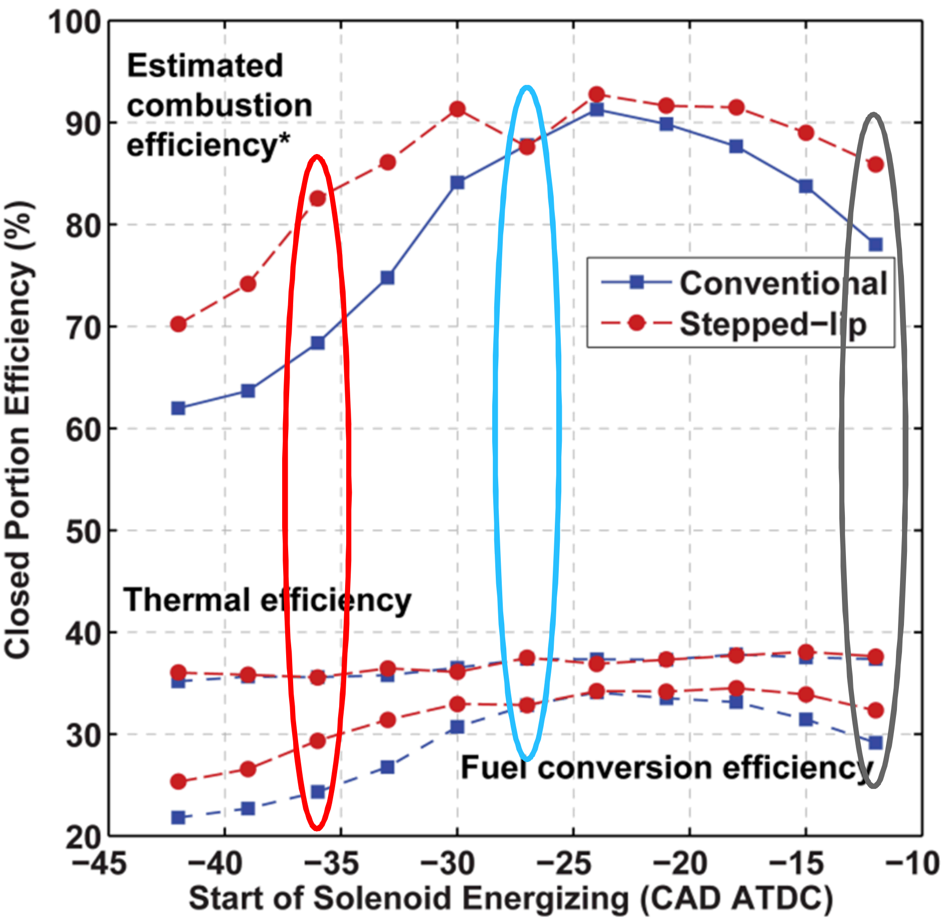
CRF

Experimental setup: high speed fuel injection imaging (in progress)

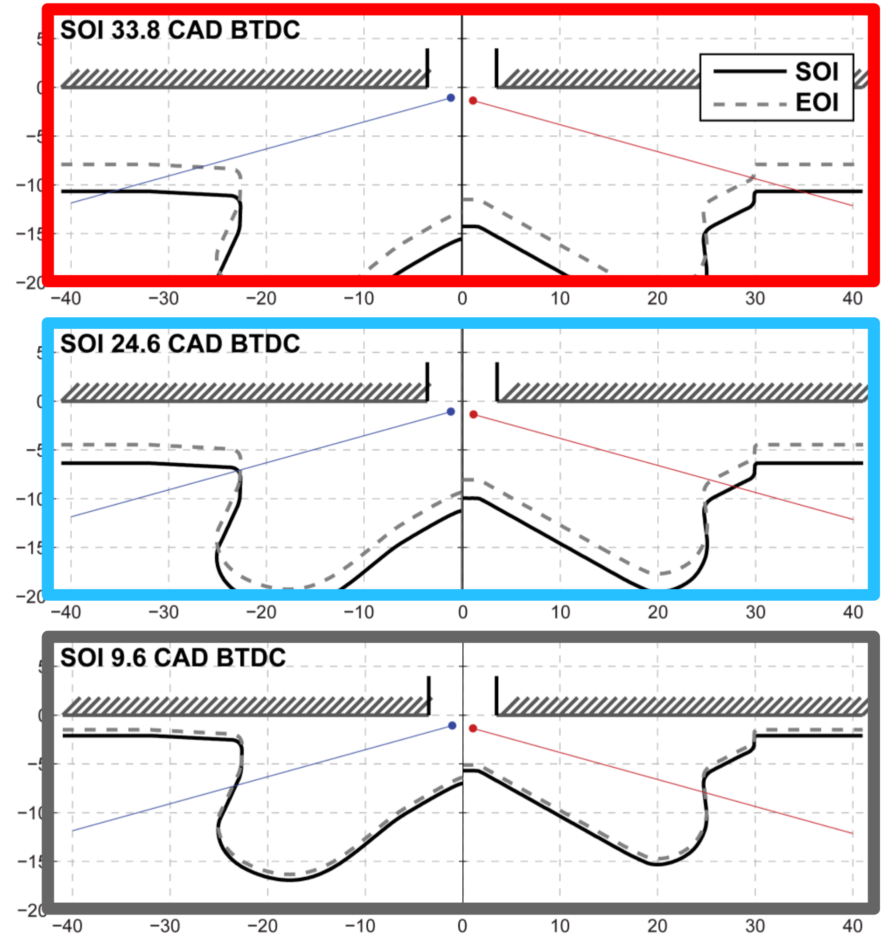
- **Engine operation**
  - 1500 rpm; motored operation (0% O_2)
  - Fuel: 42 vol% n-hexadecane + 58 vol% heptamethylnonane
  - Swirl ratio: 2.2
  - Skip-fired (1 fired : 4 skipped)
- **Elastic scattering Illumination source**
  - Illumination through side window
  - High-energy pulsed ...ad-die LED, 3μs pulses
  - Non-uniform ill... ...on
- **Imaging through piston**
  - Ph... ...onochro... ...MOS
  - ...ate: 40 kfps
  - ...225 CAD resol... ...500 ...m)
  - Image siz... ...xels



Early injection PCCI – spray targeting for three injection timings of interest

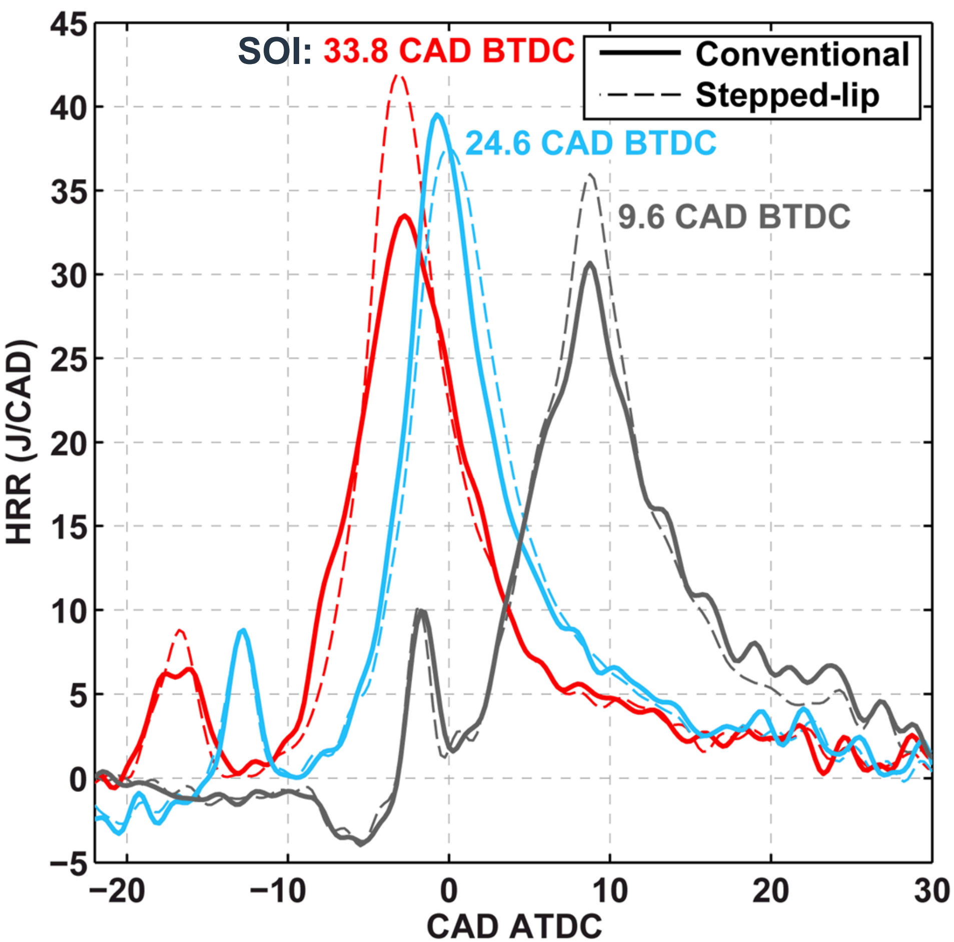


*estimated from energy balance



Heat release comparison: PCCI operation

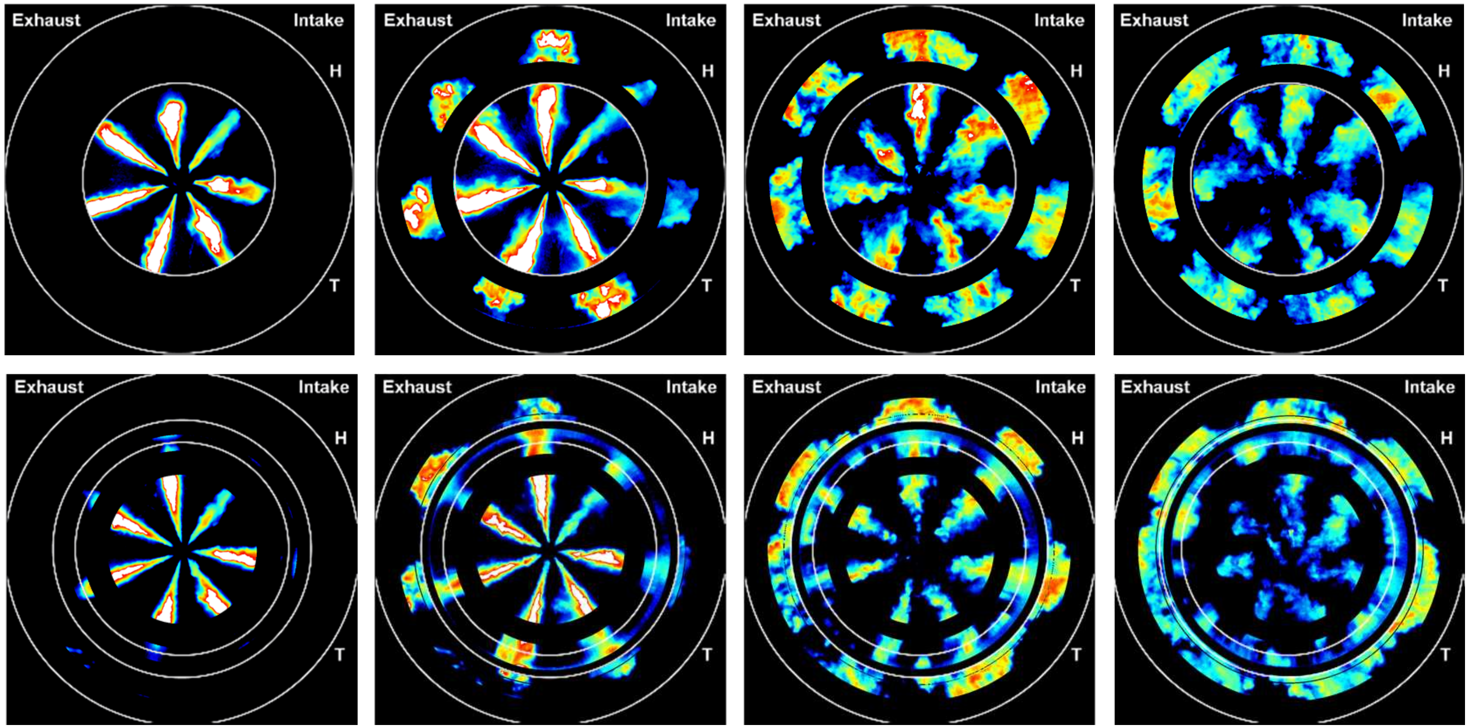
- **Early SOI: 33.8 CAD BTDC**
  - Most prominent differences during second stage (high temperature) heat release
  - Can differences in the mixture fraction distribution be determined at the start of heat release that could explain the more robust combustion?
- **Intermediate SOI: 24.6 CAD BTDC**
  - Similar heat release profiles, but heat release is slightly advanced with the conventional piston bowl
  - How do spray targeting effects impact the mixture formation process?
- **Late SOI: 9.6 CAD BTDC**
  - Differences are observed during the second stage heat release and in the later stage of combustion (15-25 CAD ATDC)



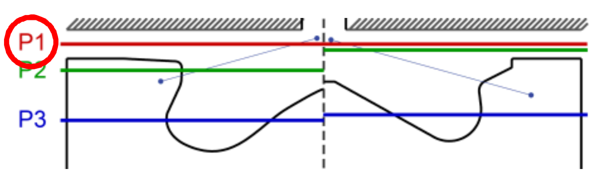
Mixture formation processes compared: SOI 33.8 CAD BTDC (Plane 1)

Single cycles

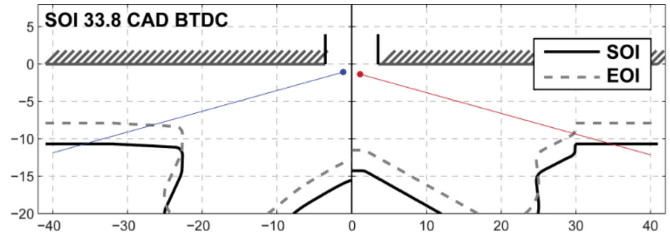
	30 CAD BTDC	27.5 CAD BTDC	25 CAD BTDC	22.5 CAD BTDC
Conventional				
Stepped-lip				



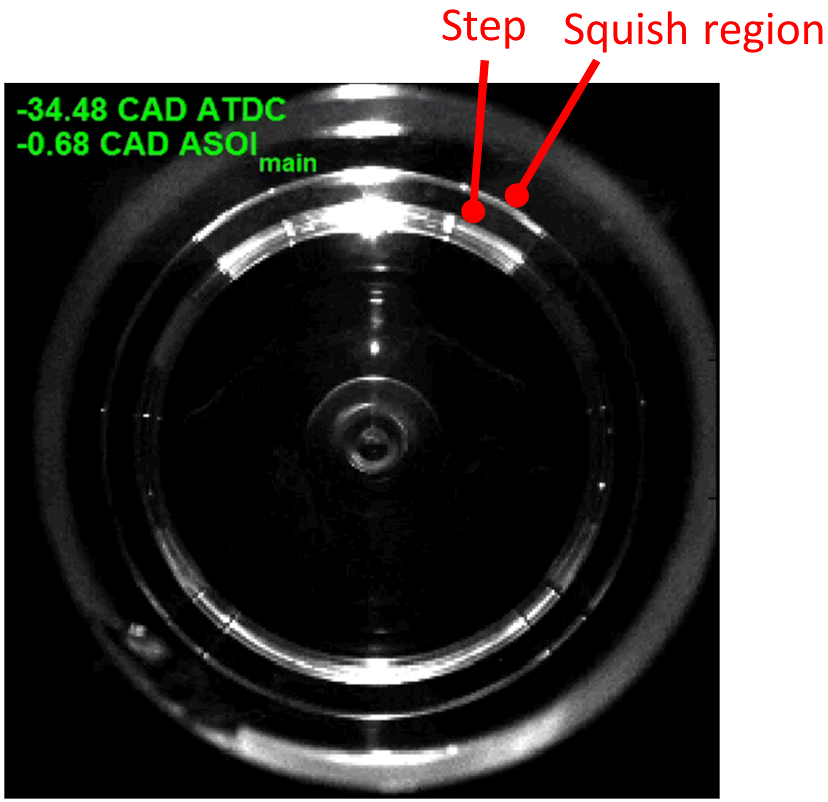
Fuel reaches bowl rim	SL: Interaction with step	SL: Jets begin to interact with one another	Conventional: jets not merged



Interaction between spray and piston step: SOI 33.8 CAD BTDC



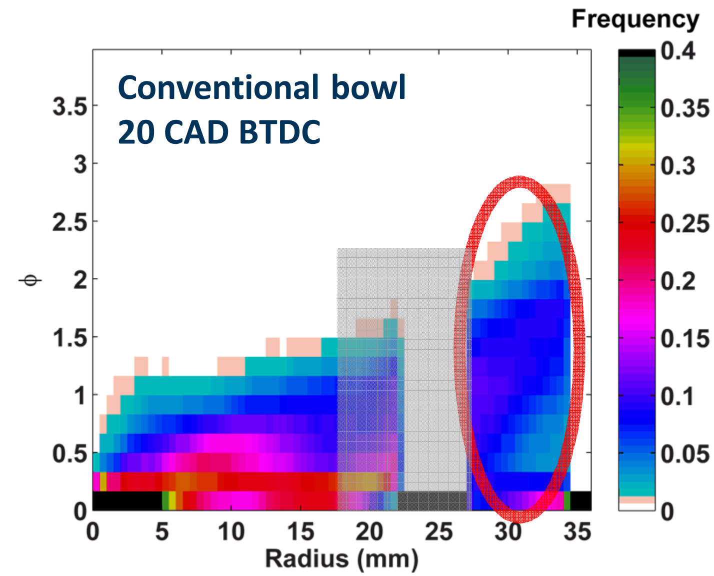
Conventional piston video coming soon…

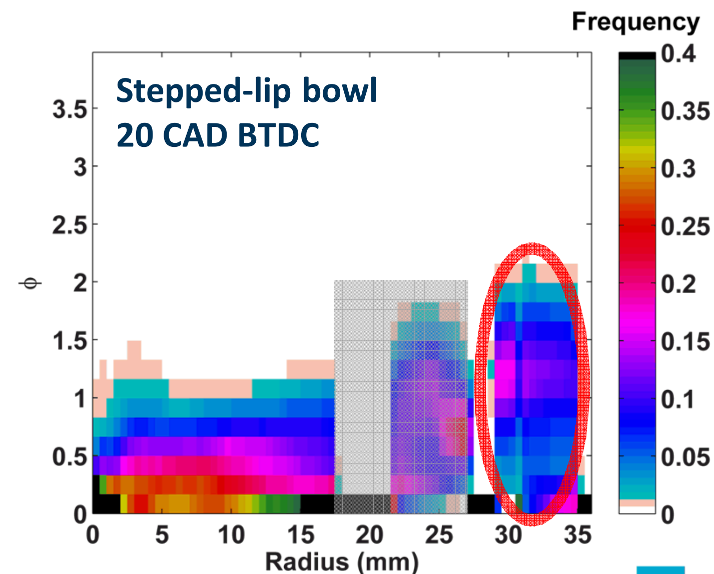


Single cycle video; 40 kfps

Mixture distribution at start of low-temperature heat release; SOI 33.8 CAD BTDC

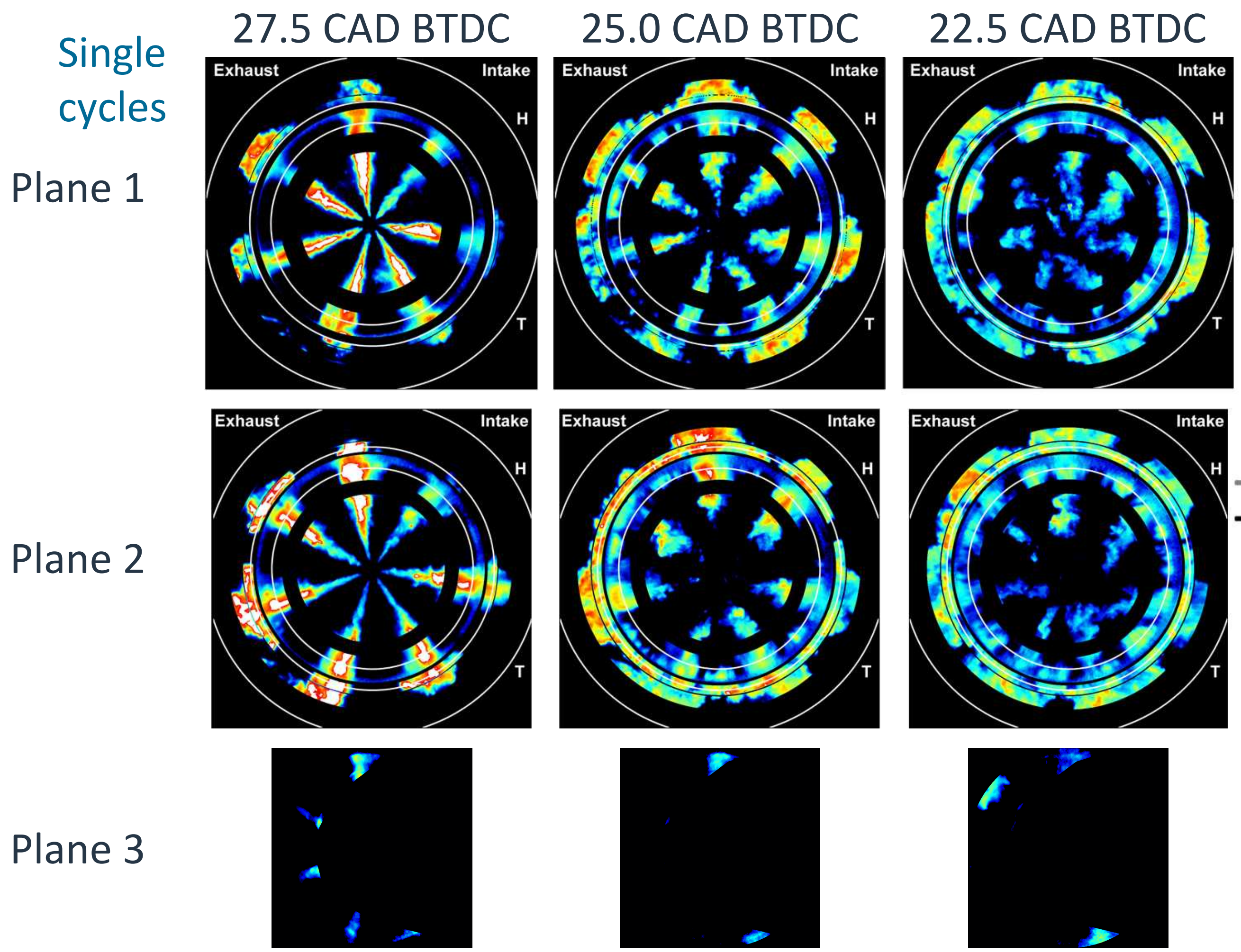
- Fuel-air equivalence ratios are binned as a function of radius for each of 50 measured cycles
- Equivalence ratio distributions are shown as a phi-R heat map at the start of low-temperature heat release
- Comparisons are not possible for radii between ~17-26 mm
- Differences near a radius of 30 mm
  - Narrower and richer fuel/air ratio distribution with the stepped-lip bowl
  - Interaction between the fuel jets and the step may act to reduce overmixing and thereby sources of lean CO emissions
- Differences in the bowl are more difficult to interpret
  - Leanest equivalence ratios are most susceptible to background interference

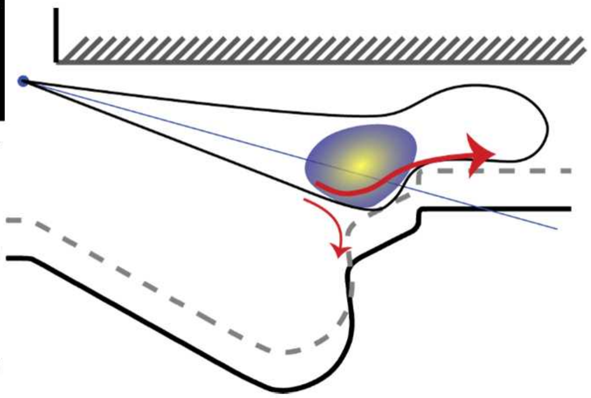


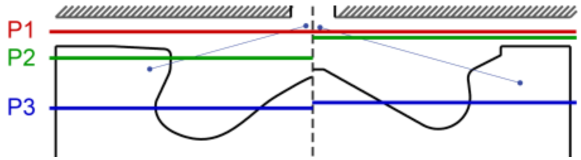


Interaction between spray and piston step: SOI 33.8 CAD BTDC

Single cycles







Interaction between spray and piston step: SOI 33.8 CAD BTDC

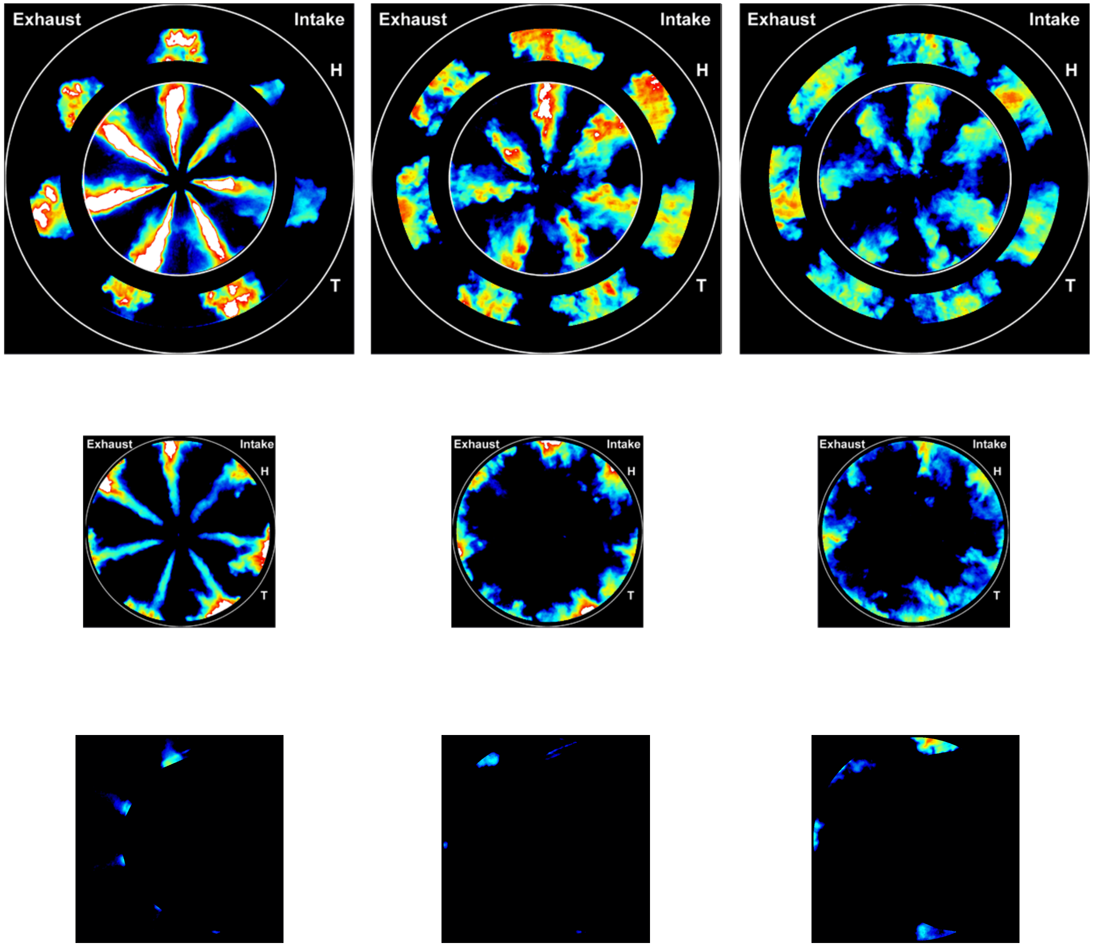
Single cycles

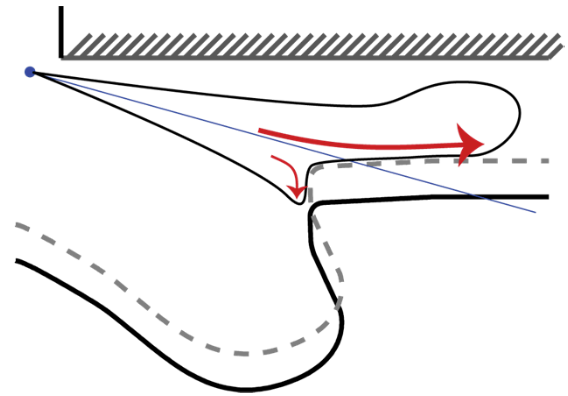
27.5 CAD BTDC | 25.0 CAD BTDC | 22.5 CAD BTDC

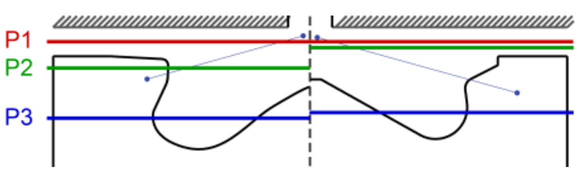
Plane 1

Plane 2

Plane 3







Recap: early injection PCCI (SOI 33.8 CAD BTDC)

- Spray targeting considerations: fuel jets impact primarily on squish regions of pistons and are deflected towards the liner
  - Significant penetration into the piston bowls is not expected
  - Stepped-lip piston: some interaction with the step is expected

- Jets interact with the step of the stepped-lip piston
  - Interactions between liquid fuel and the step appear stronger on the exhaust side
  - Fuel impinges on the step and is deflected tangentially; radial penetration is impeded; jet heads merge with the stepped-lip piston but not with the conventional bowl
  - Start of low-temperature heat release: richer conditions exist above the stepped-lip bowl near a radius of 30 mm than above the conventional bowl
  - This mechanism may hinder over mixing and improve combustion efficiency

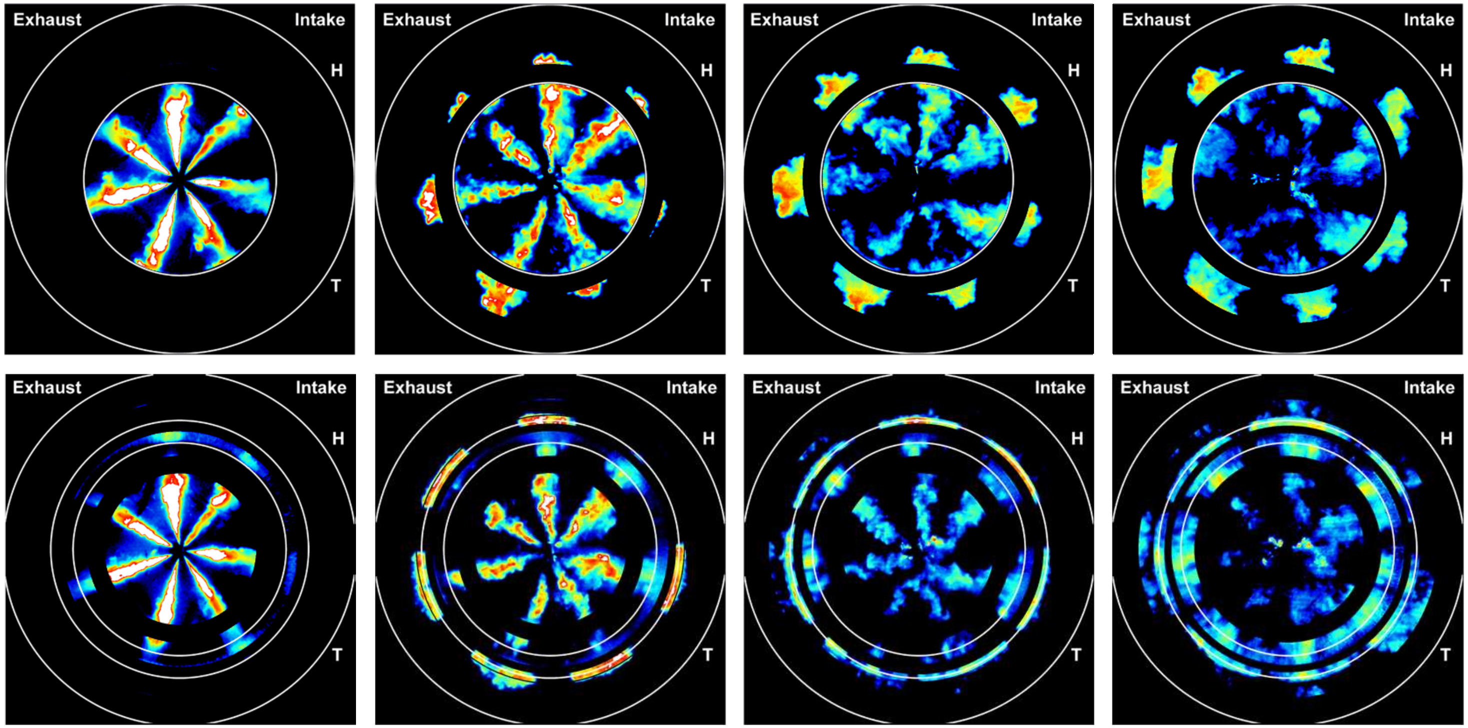
Mixture formation processes compared: SOI 24.6 CAD BTDC (Plane 1)

Single cycles

20 CAD BTDC | 17.5 CAD BTDC | 15 CAD BTDC | 12.5 CAD BTDC

Conventional

Stepped-lip

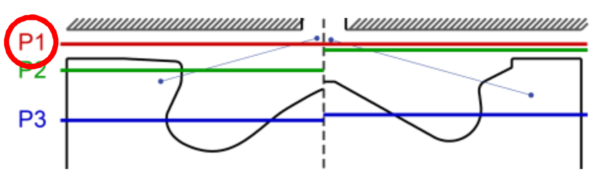


Fuel reaches bowl rim

SL: no penetration into squish region

Conventional: slow penetration into squish region

SL: fuel in outer portion of squish region

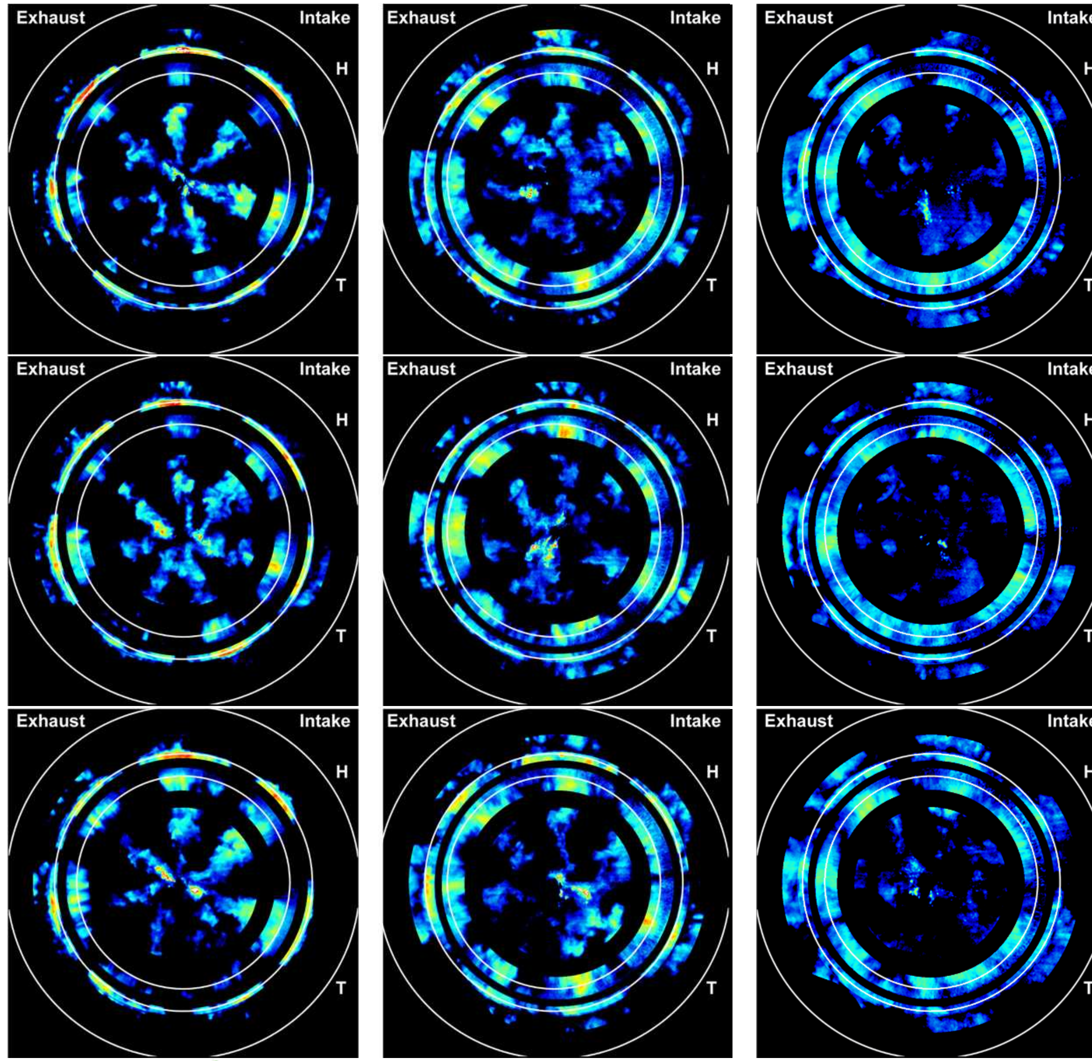


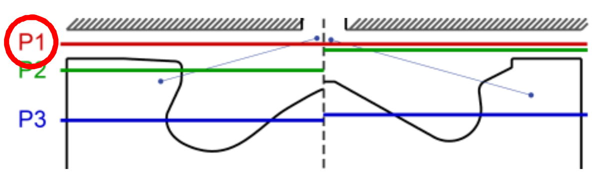
Interaction between spray and piston step: SOI 24.6 CAD BTDC

- 15.5 CAD BTDC: fuel first observed at outer edge of visible area
- 12.5 CAD BTDC: fuel in outer squish regions appears to have moved inward
- 10.0 CAD BTDC: inward progression has continued

Single cycles

15.0 CAD BTDC | 12.5 CAD BTDC | 10.0 CAD BTDC





Mixture formation with the stepped-lip bowl: SOI 24.6 CAD BTDC

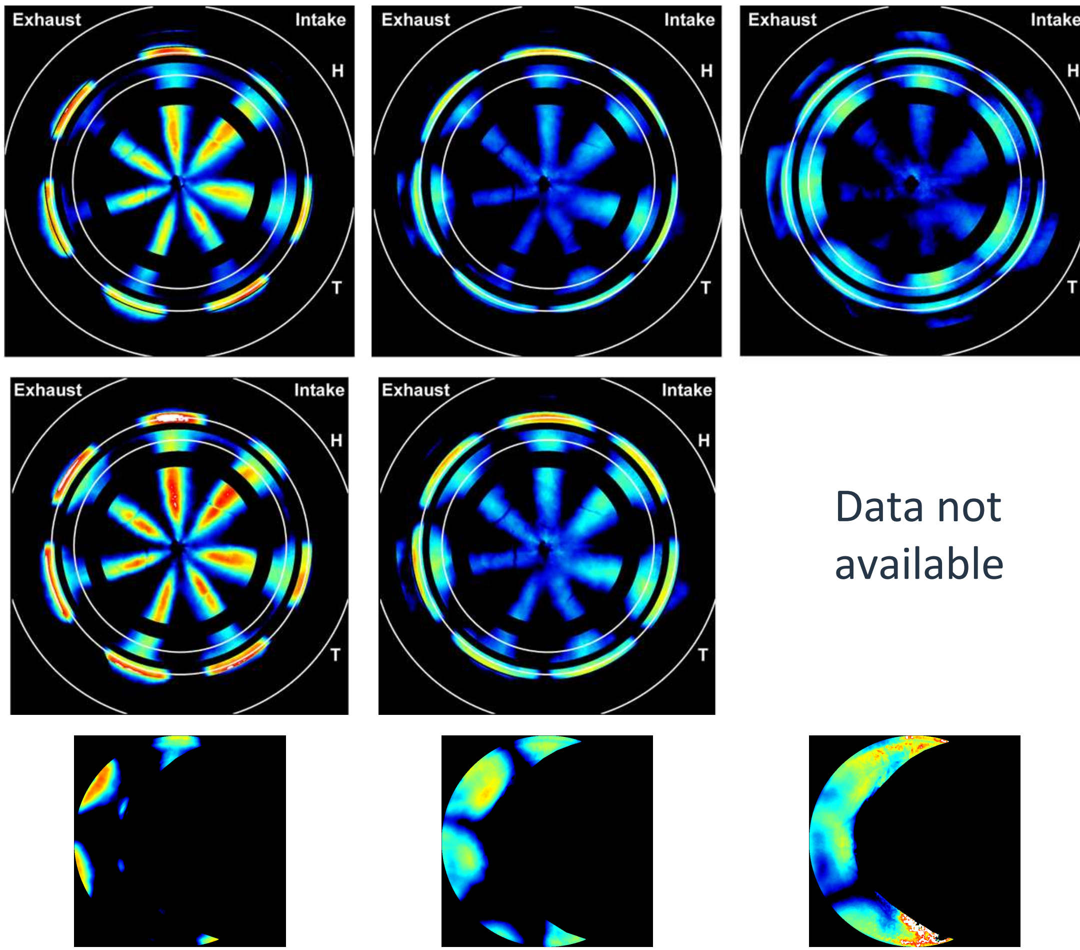
Ensemble average

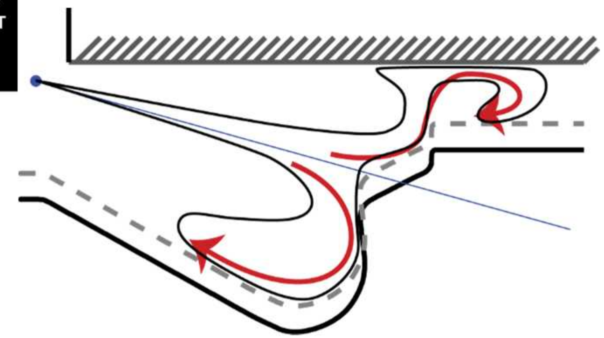
17.5 CAD BTDC | 15.0 CAD BTDC | 12.5 CAD BTDC

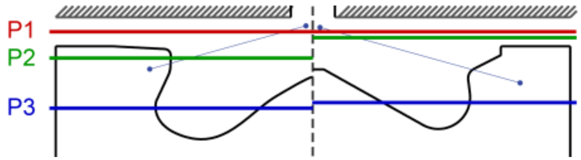
Plane 1

Plane 2

Plane 3

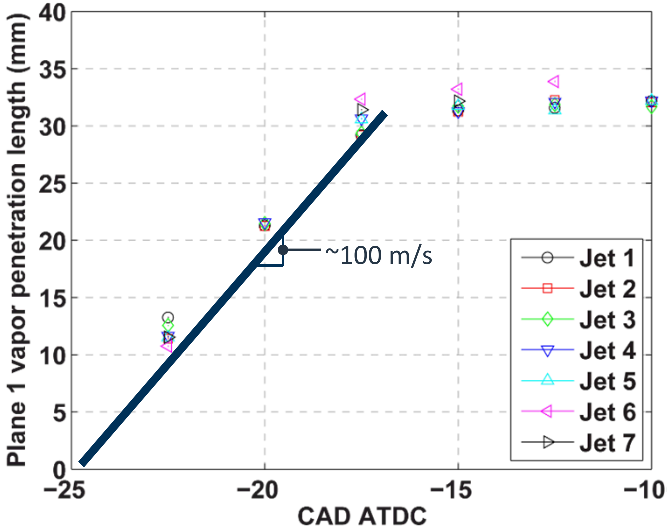


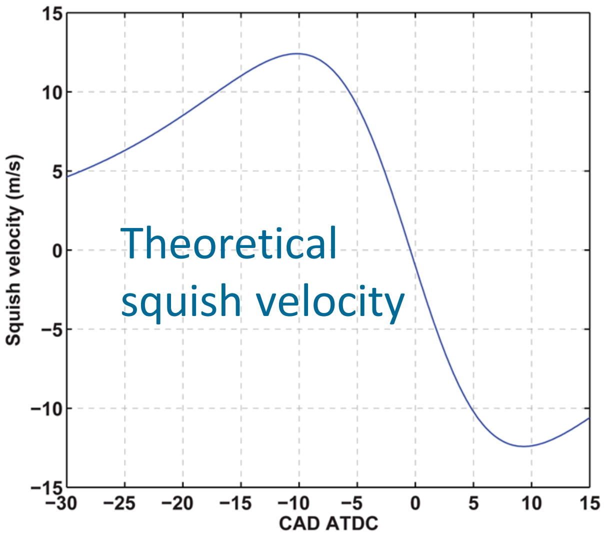




Vapor penetration: conventional bowl, SOI 24.6 CAD BTDC

- Vapor penetration levels off after 17.5 CAD BTDC
- Squish velocity and increasing density impede the outward penetration of the sprays
  - This may limit over mixing and maintain high combustion efficiency





Mixture formation with the conventional bowl: SOI 24.6 CAD BTDC

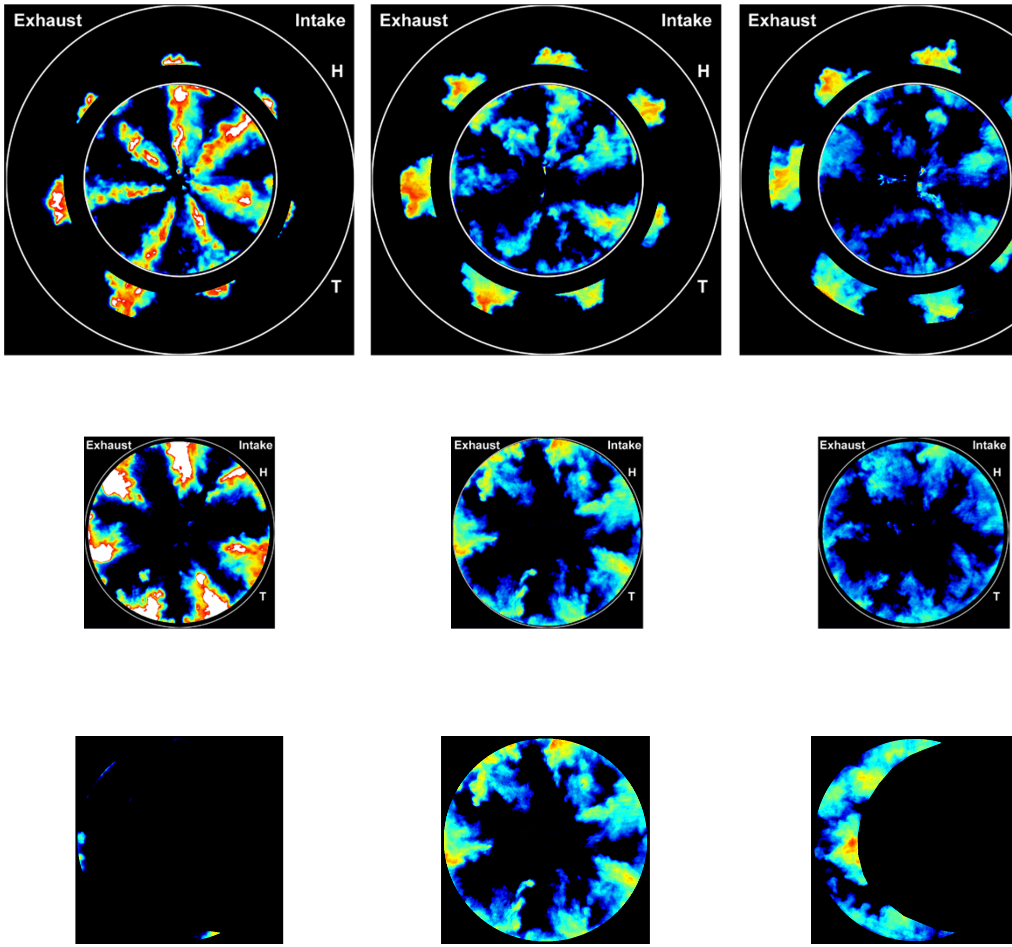
Single cycles

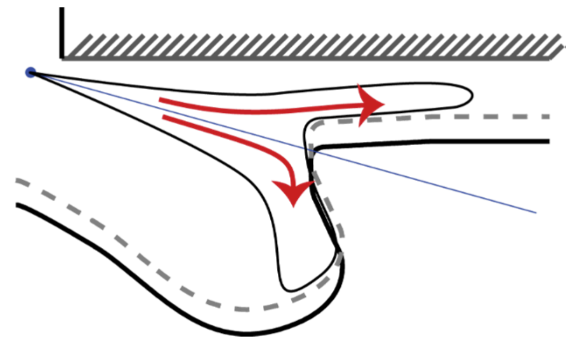
17.5 CAD BTDC | 15.0 CAD BTDC | 12.5 CAD BTDC

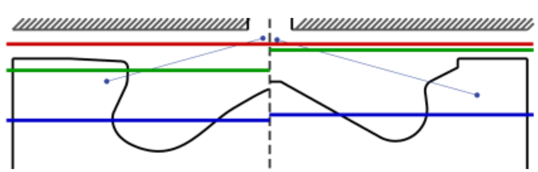
Plane 1

Plane 2

Plane 3

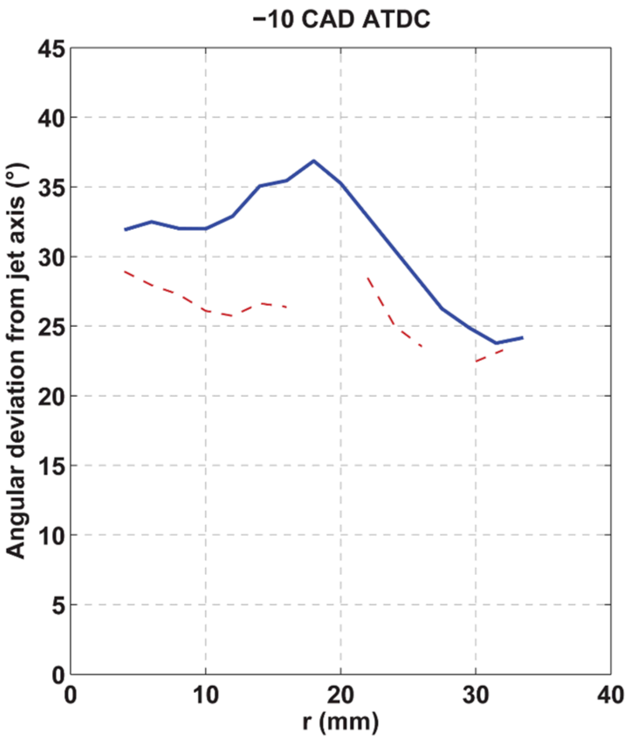




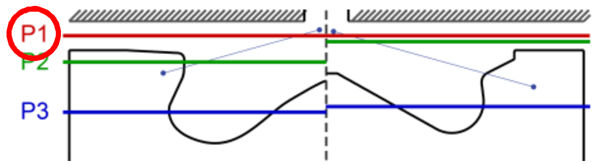


Spray-swirl interactions: SOI 24.6 CAD BTDC

- Average jet deflection by swirl is larger with the conventional piston after 17.5 CAD BTDC
- Swirl amplification is known to be greater with the conventional piston
- Angular momentum is redistributed differently by the squish flow for each piston geometry
- Impact on mixing and combustion is not yet well understood



Average deflection over all jets



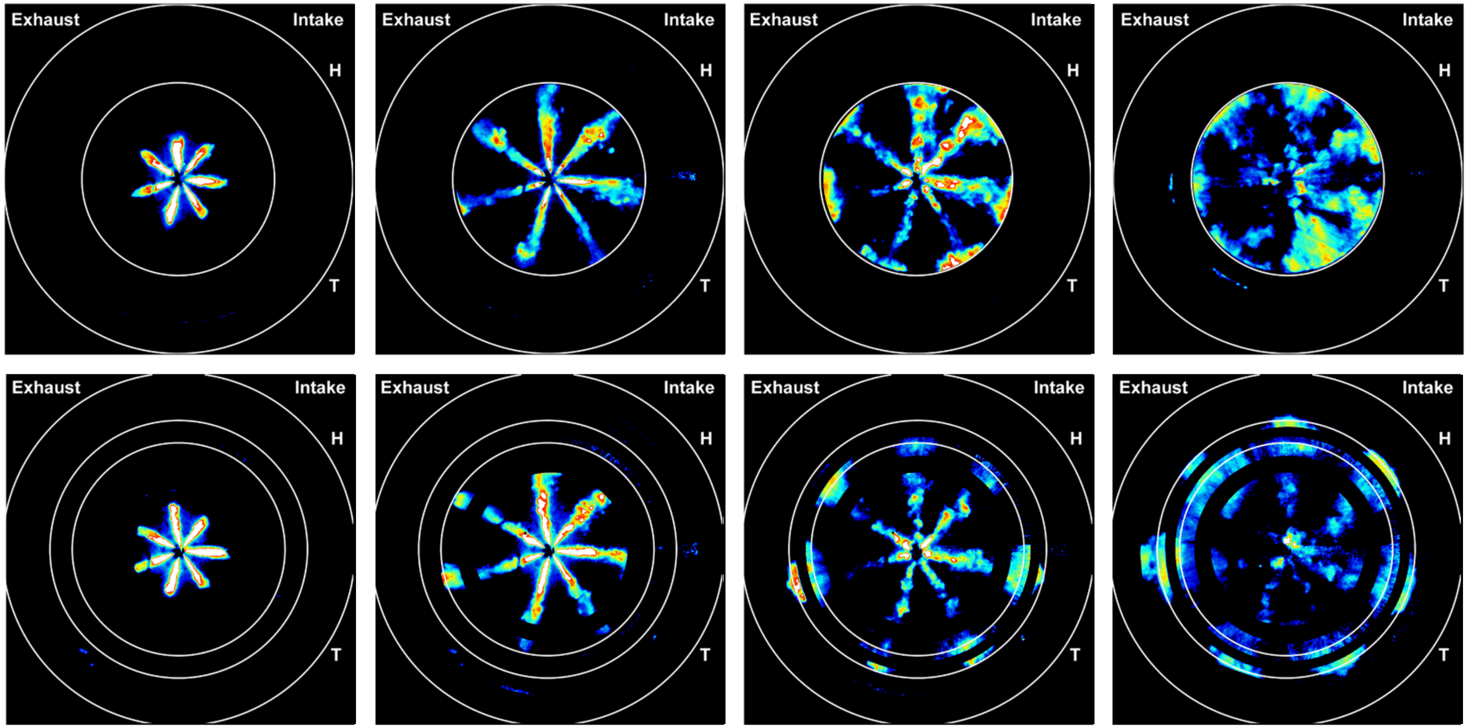
Recap: intermediate injection PCCI (SOI 24.6 CAD BTDC)

- Spray targeting considerations: fuel jets impact primarily on bowl rim (conventional bowl) or step region (stepped-lip bowl)
- Conventional bowl
  - Fuel jets penetrate into the squish region, but progress is likely hindered by squish flow; jets are also directed downward into the bowl
  - The jets are more affected by swirl flow than for the stepped-lip bowl
  - More fuel is present in the bowl than for the early injection case
- Stepped-lip bowl
  - Penetration into squish region is impeded as fuel is redirected upward at the step's outer rim
  - Mixture moving inward from the outer portion of the squish region is consistent with a toroidal vortex that forms as a result of interactions with the piston bowl, cylinder head, and possibly the bore wall
    - This is evidence of a mixing mechanism that does not exist with the conventional piston bowl
  - Jets do not merge above the bowl rim as with the early injection case
  - More fuel is present in the bowl than for the early injection case
- Despite differences in mixture preparation, both pistons perform similarly at this condition

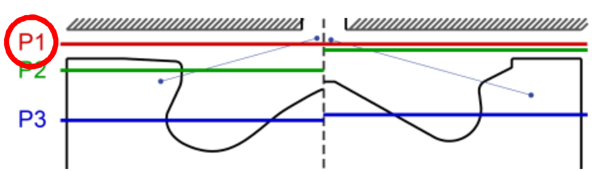
Mixture formation processes compared: SOI 9.6 CAD BTDC (Plane 1)

Single cycles

	7.5 CAD BTDC	5.0 CAD BTDC	2.5 CAD BTDC	TDC
Conventional				
Stepped-lip				

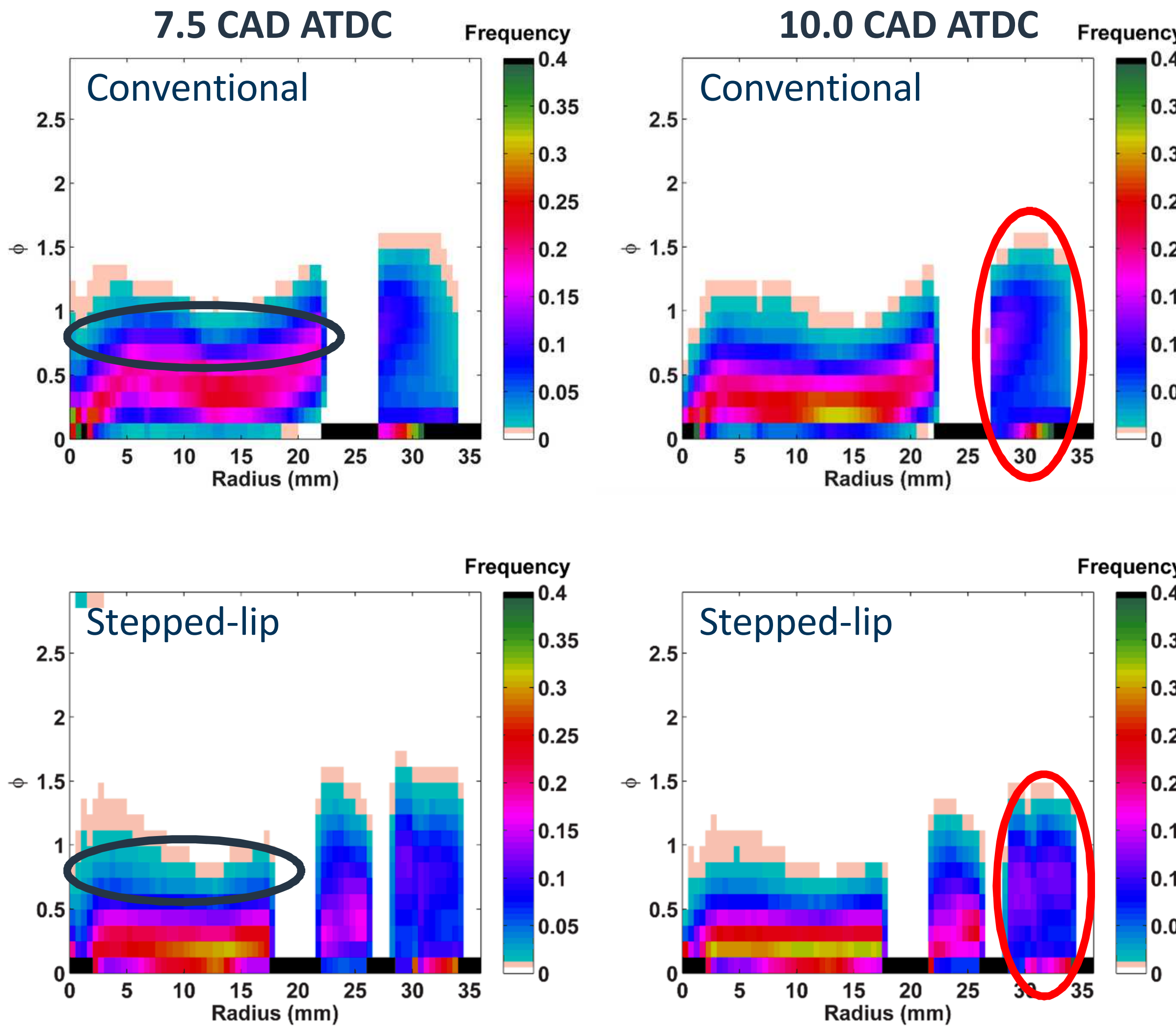


Shortly after SOI	Jets reach bowl rims	SL: small amounts of fuel above the step	Near start of high-temperature heat release; little mixture in squish region



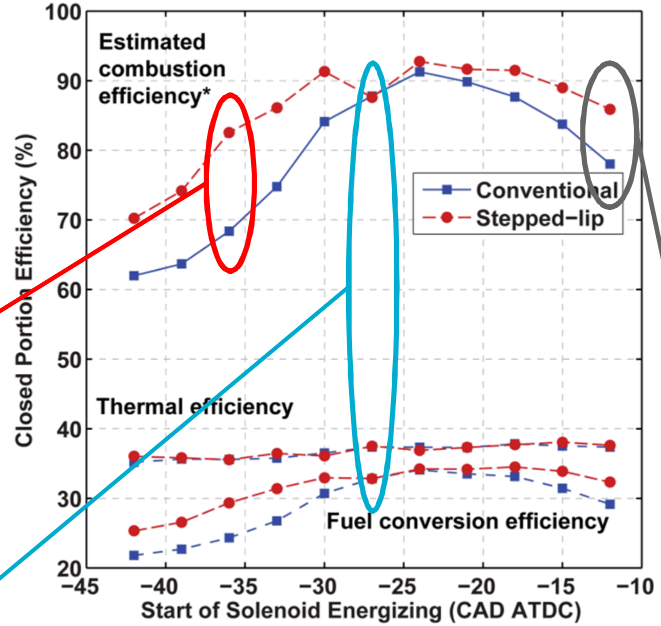
Behavior after TDC: SOI 9.6 CAD BTDC (Plane 1)

- Mixtures above the conventional bowl are richer than above the stepped-lip bowl (black ellipses)
- Richer mixture penetrates further into the squish region with the stepped-lip bowl (red ellipses)
  - Counterintuitive based on how we expect the reverse squish flow to behave
- Richer mixtures in the squish region could better promote CO oxidation and complete combustion with the stepped-lip bowl
- Further research is needed



Summary: theories about mixture formation and combustion efficiency for early-injection PCCI operation

- Piston step acts to spread jets tangentially
- Richer, narrower fuel/air mixture distribution near the stepped-lip bowl rim
- Likely cause of improved combustion efficiency



*estimated from energy balance

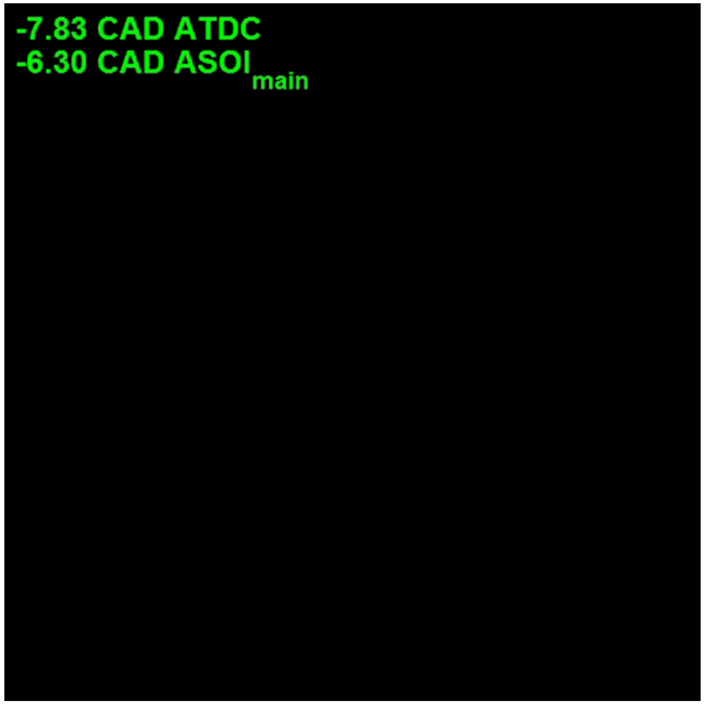
- Richer mixtures observed in the squish region with the stepped-lip bowl after TDC
- This could promote complete combustion, but the mechanism is unclear

- Conventional bowl: strong squish flow impedes fuel jet penetration into squish region
- Stepped-lip bowl: formation of a toroidal vortex: a mixing mechanism not observed with the conventional bowl
- Comparable performance despite mixture formation differences

CRF

Ongoing studies

- High-speed Mie scattering: characterizing liquid lengths, understanding interactions with piston geometry
- Conventional diesel combustion: desire to understand late-cycle turbulent mixing behavior
- High-speed natural lu... imaging
  - Where and wh... rich, ... combustio... e?
  - Ca... differe... flow ... e combus... g...
    - Combustion i... ocimetry
- Comp... D



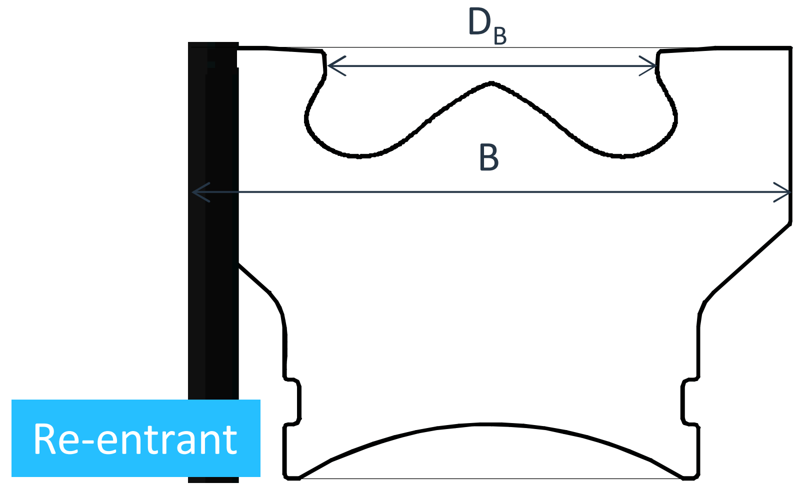
Thank you for your attention

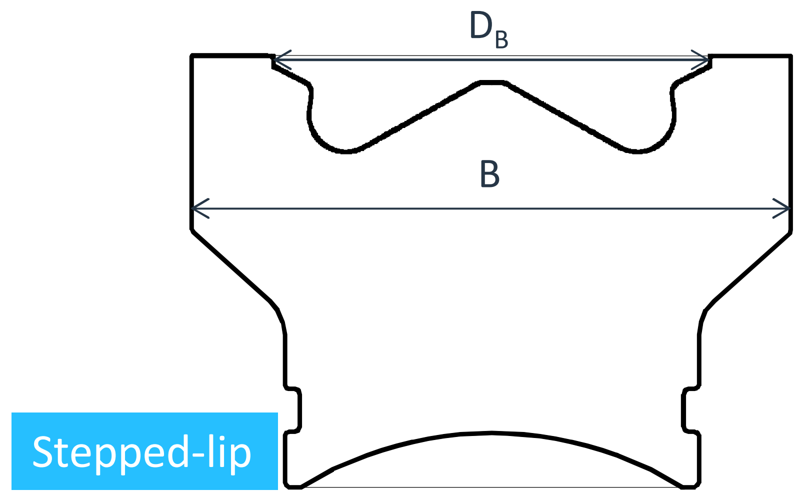
Questions?

Backup slides

SNL optical piston bowl geometries

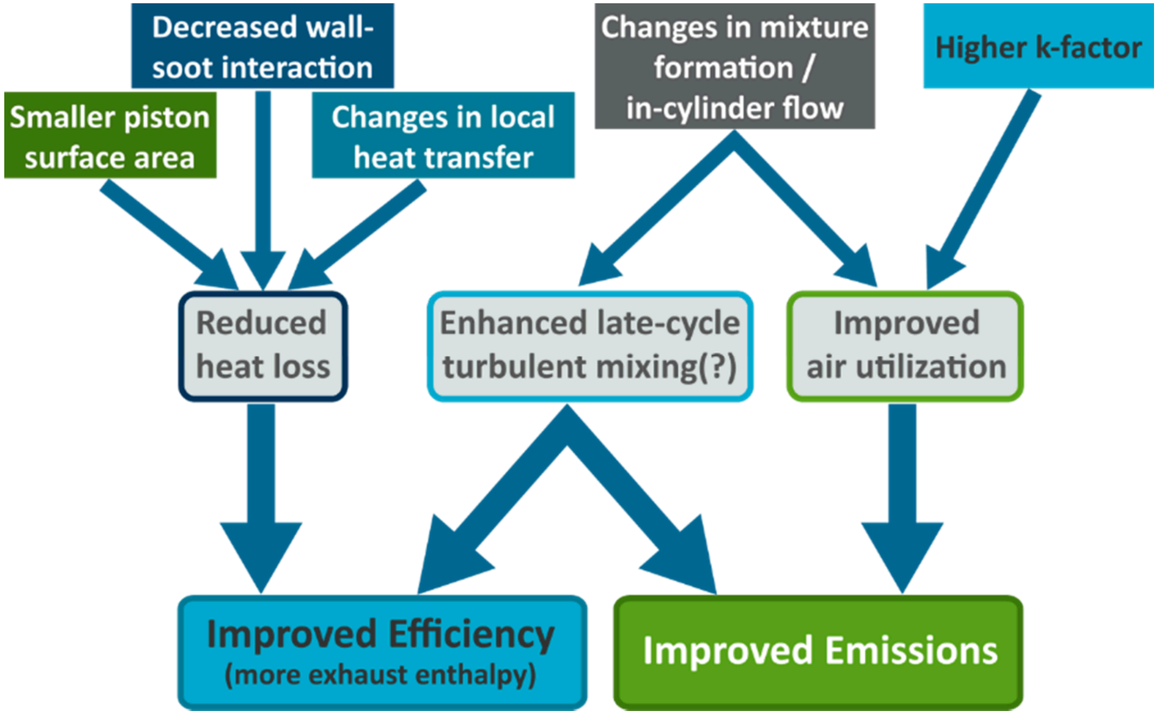
- Two fused silica pistons with identical:
  - Bowl volume = 0.028 L
  - Squish height = 1.35 mm
  - Compression ratio = 15.8:1
  - No valve cut-outs
- Different bowl geometries result in different bowl-to-bore ratios:
  - Re-entrant: D_B/B = 0.55
  - Stepped-lip: D_B/B = … 73
- Surface area of stepp… …wl is ~10% less than for the c… …ional b… …l
- Injector ti… …n is se… …sed … rec… …s from OE… …rs



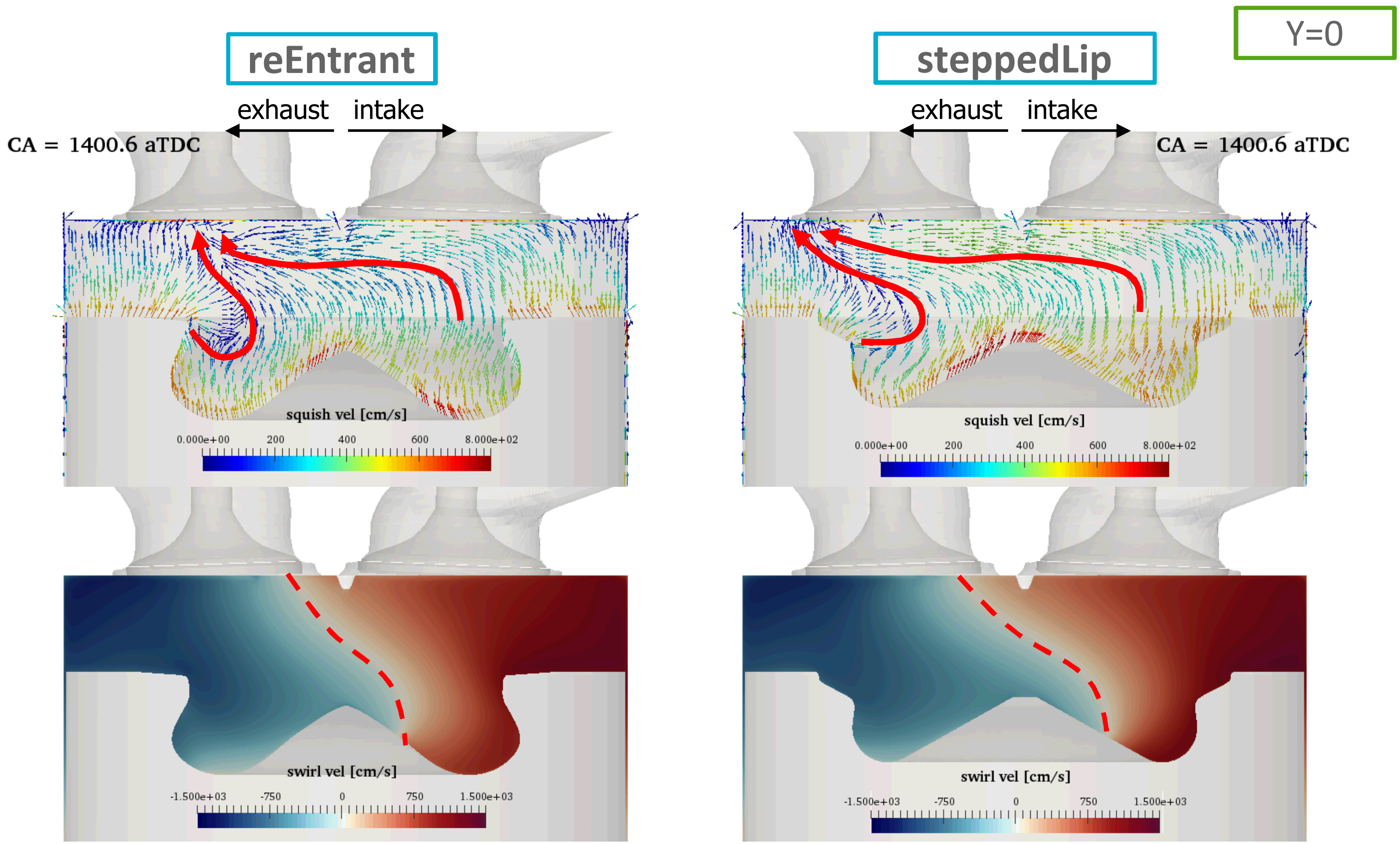


Understanding efficiency and emissions advantages with stepped-lip pistons

- The mechanisms responsible for these advantages are not well documented
- Limitations and drawbacks of stepped-lip pistons are not well understood
  - Spray targeting sensitivity
  - High speeds/loads
  - Others?
- Ultimate goal
  - Understand how piston geometry can be optimized to improve efficiency and reduce emissions



RE vs. SL Flow comparison: Rs=2.2, CR=16.1, CA = -40 aTDC



squish motion appears in reEntrant, not yet in steppedLip

First stub of squish behavior appears at the step's rim