COMBUSTION RESEARCH FACILITY

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Effect of close pilot spacing on combustion and emissions

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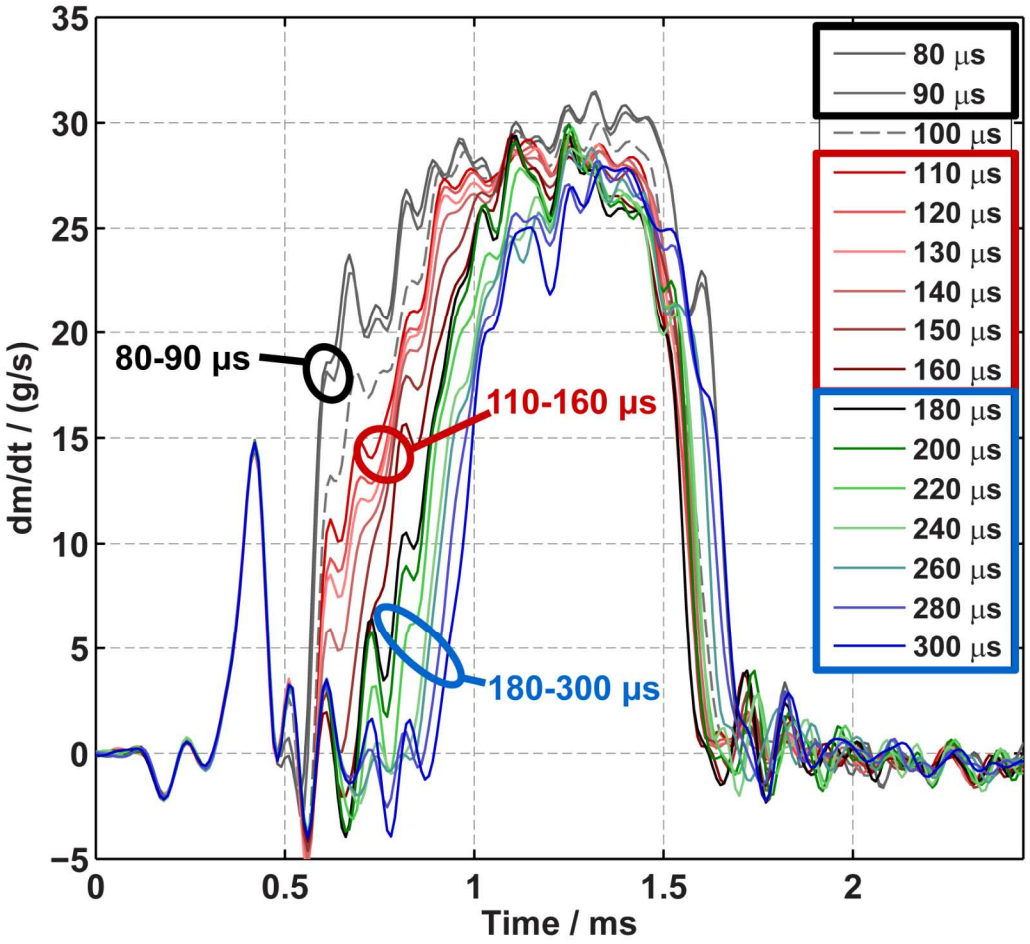
Progress Report Outline

- HDA measurements
  - 800 bar rail pressure
  - Verification of various injection regimes with changing dwell time
- Development of liquid scattering measurement technique
  - Pulsed LED illumination system
  - High speed imaging
  - Automated image de-warping
- Initial high speed spray imaging results
  - Confirmation that technique works
- Next steps

HDA Measurements at 800 bar rail pressure, constant energizing time

- Similar trends at other rail pressures
- Three different regimes as before
- Selected dwell times for optical analysis
  - 300 µs
  - 140 µs
  - 90 µs
  - (single injection)

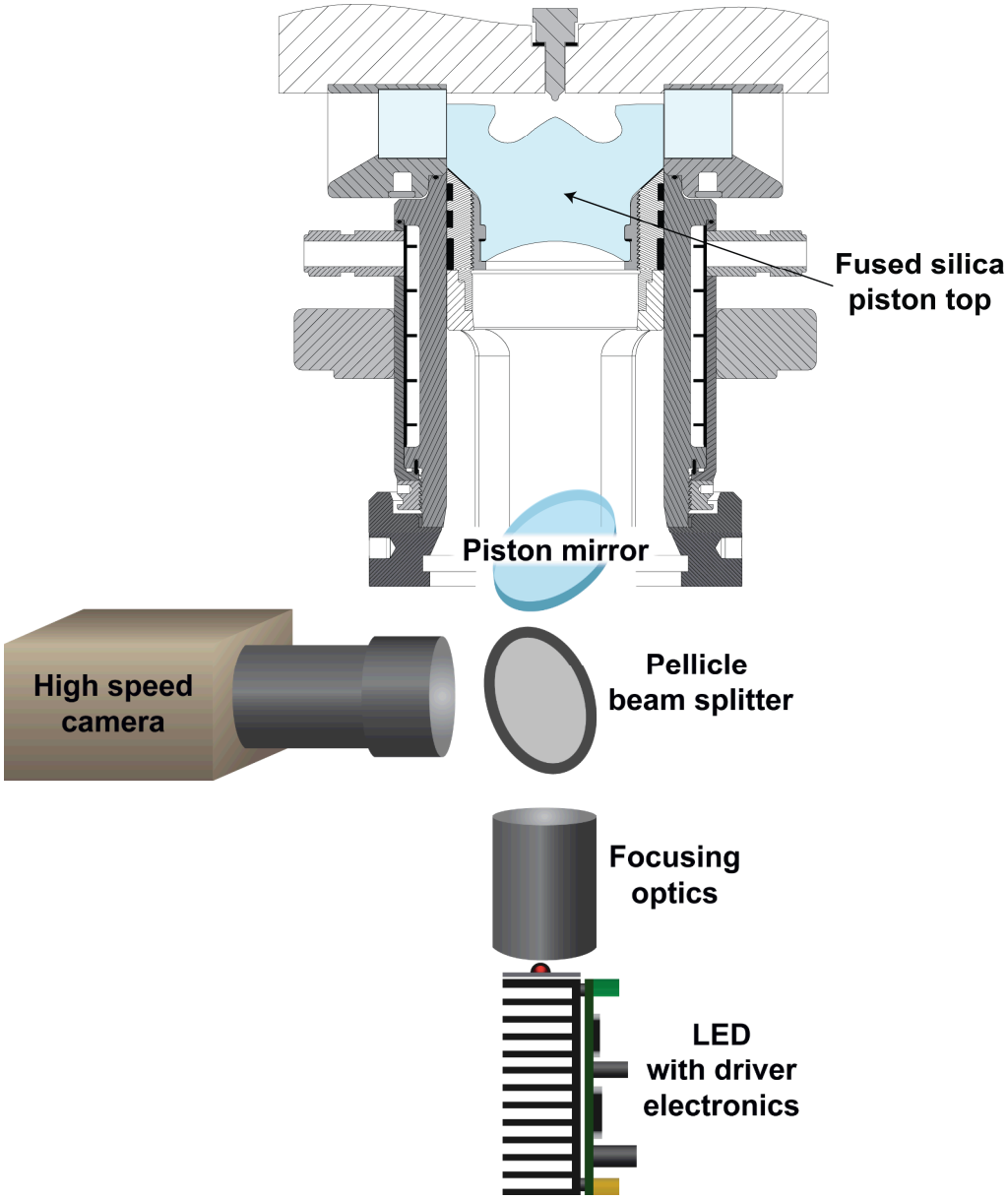


Requirements for a high speed Mie scattering measurement technique

- Objective: high-speed imaging of fuel injection events
  - Validation of HDA data via liquid penetration rate analysis
  - Information about injection process with changing dwell time
- Elastic scattering from fuel droplets
  - Need high intensity, short pulse illumination source
  - Frame rate: 20 kHz or higher to resolve behavior between pilot and main injection events
- Pulsed LED illumination
  - Short pulse duration
  - High intensity
  - High repetition rate
- Observation with high speed camera

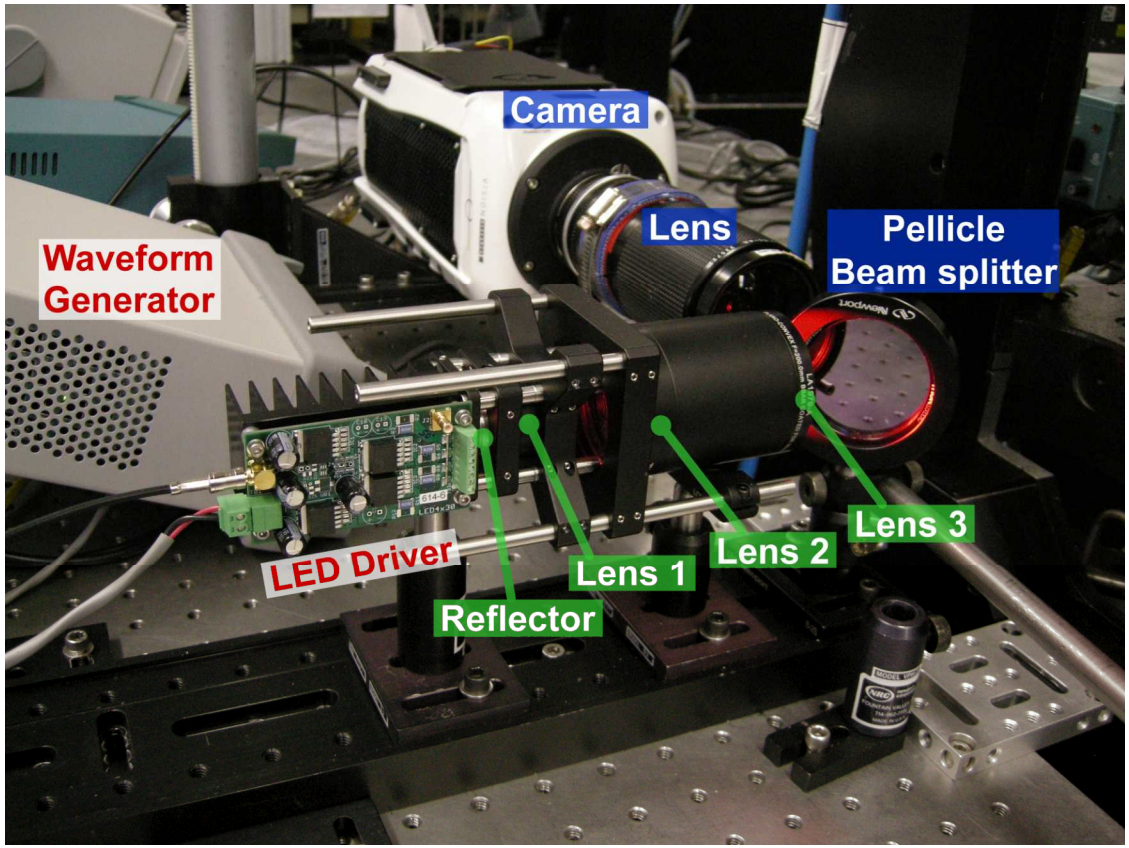
High speed Mie scattering setup

- Imaging and illumination through the bottom of the piston
- Pellicle beam splitter
  - Thin (~2 µm) nitrocellulose membrane
  - Eliminates problems with second surface reflections
  - Problems with vibration and air currents
- Optics necessary to couple as much LED light into the cylinder as possible



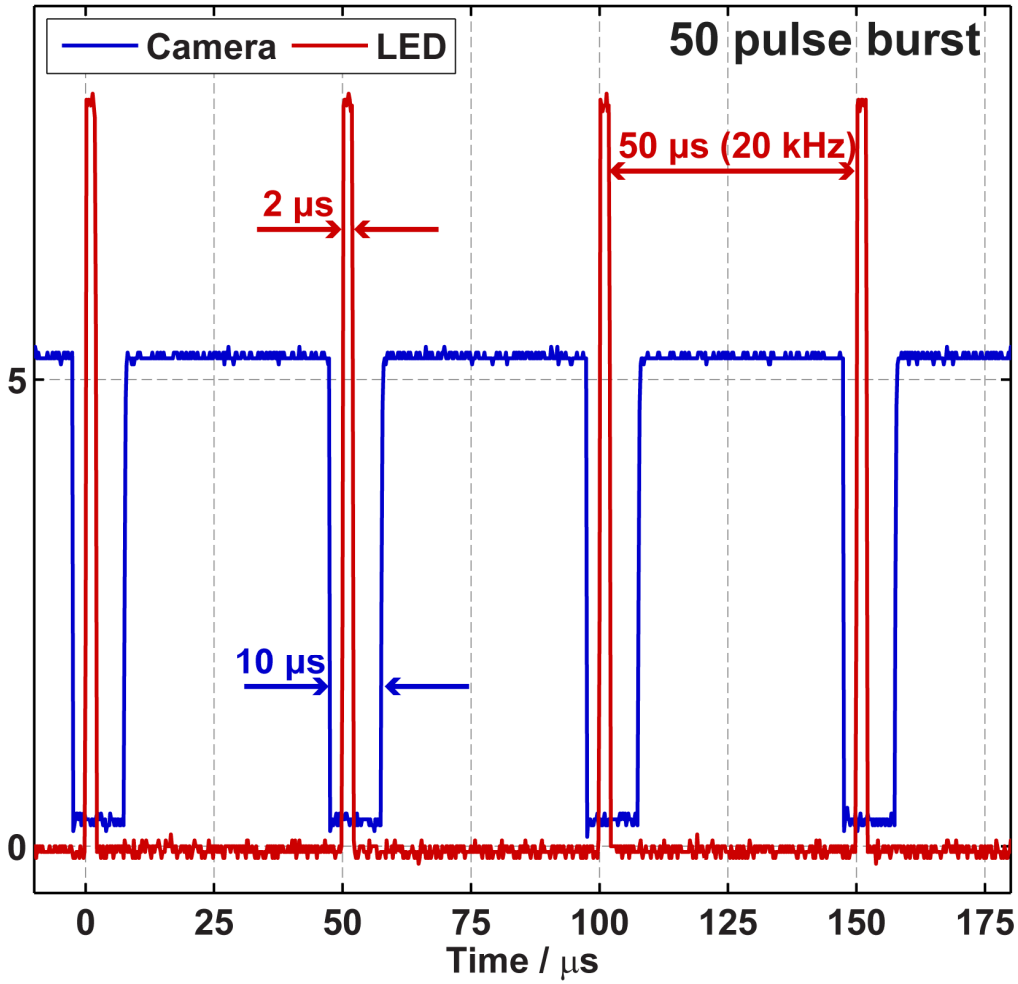
LED system

- High-output pulsed red LED
  - Pulse width <= ~2 µs
  - Peak current ~50 A
- Reflector and lenses to couple light into engine
- Pellicle beam splitter allows illumination and observation through the piston



Measurement timing

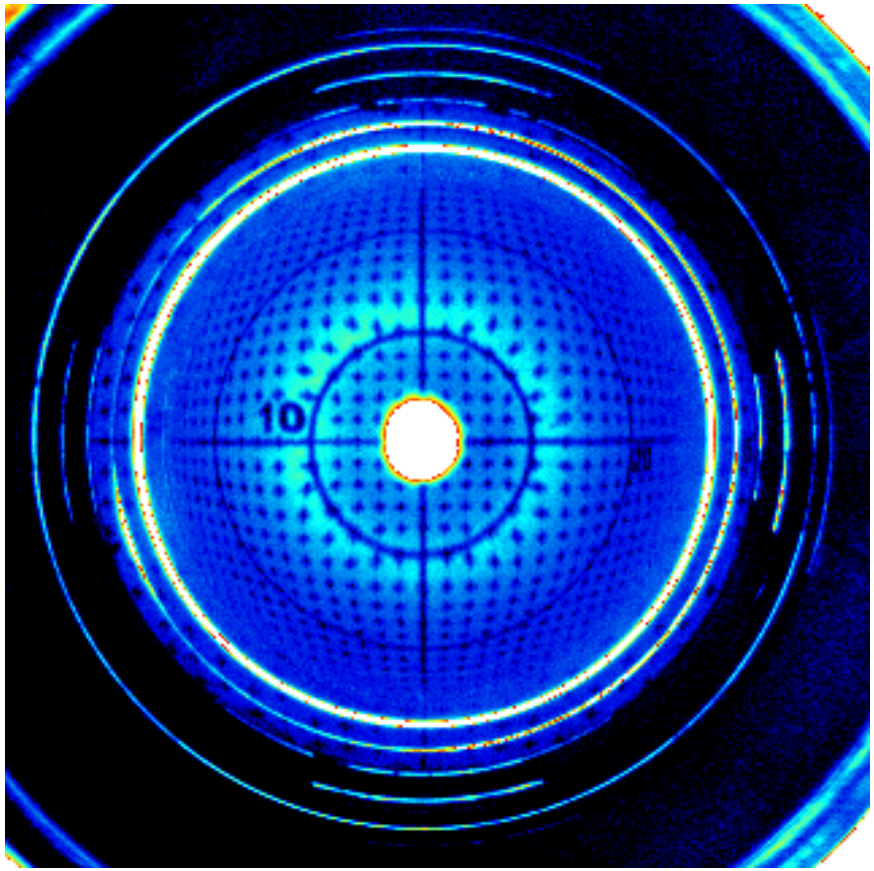
- Camera and LED are synchronized with a waveform generator
- 20 kHz, 50 pulse bursts
  - Starts at SOE
  - ~0.5 CAD resolution
  - 10 µs exposure duration
  - 2 µs LED pulse width, 3 µs delay



Imaging challenges

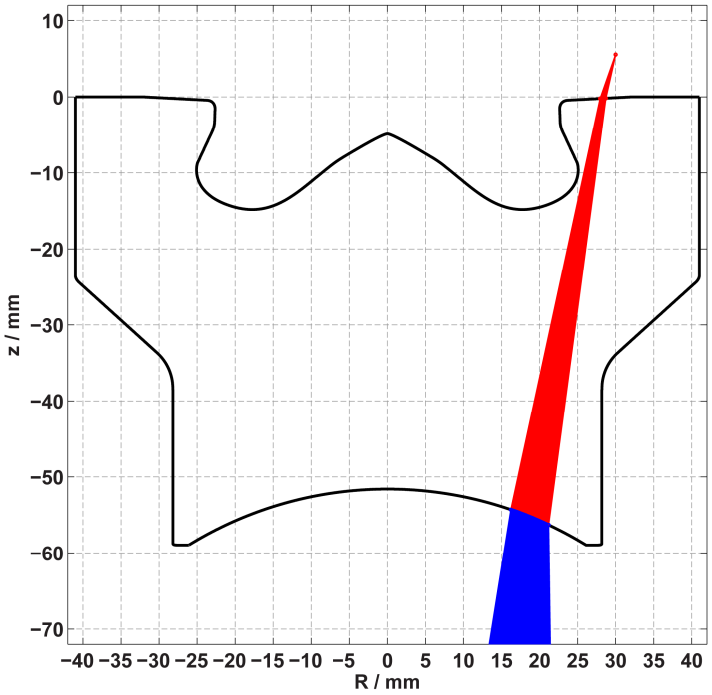
- Area of interest: inside the piston bowl
- Image warping (known issue)
  - Changes with crank angle
- Uneven illumination due to piston shape
  - Ø2 mm saturated region in the middle of the image
  - Illumination pattern changes with crank angle
  - Intensity correction outside center of image should be possible

Calibration target with stationary engine



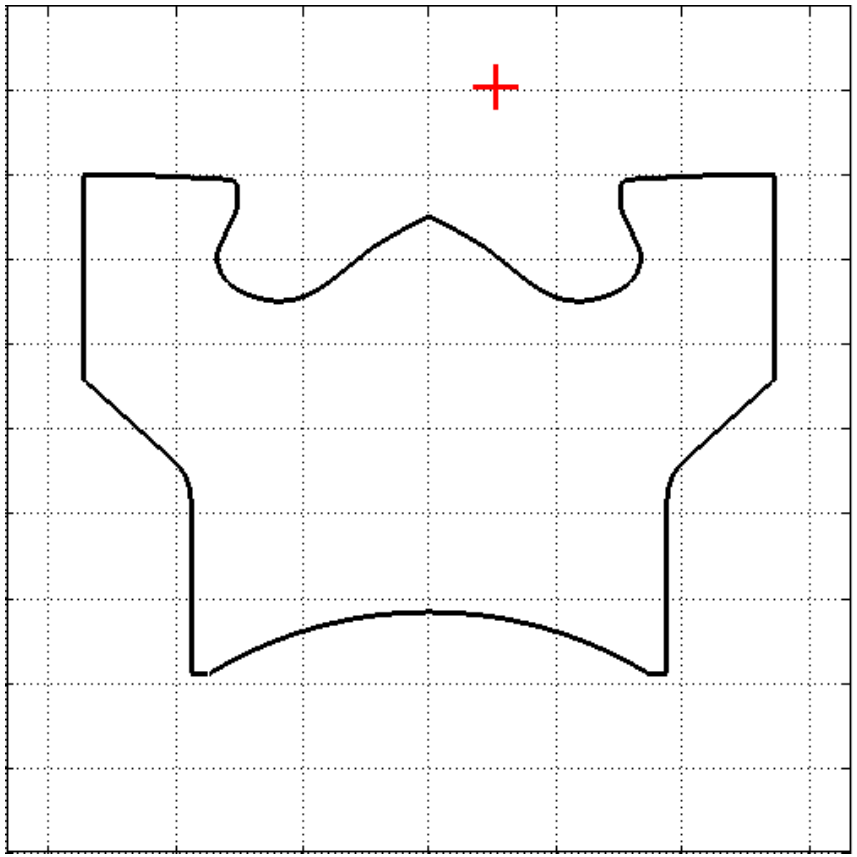
Automated image de-warping

- De-warping images by hand is time consuming
  - For high speed imaging spanning multiple crank angles, would likely lead to repetitive stress injuries
- A new image de-warping approach has been developed based on ray tracing



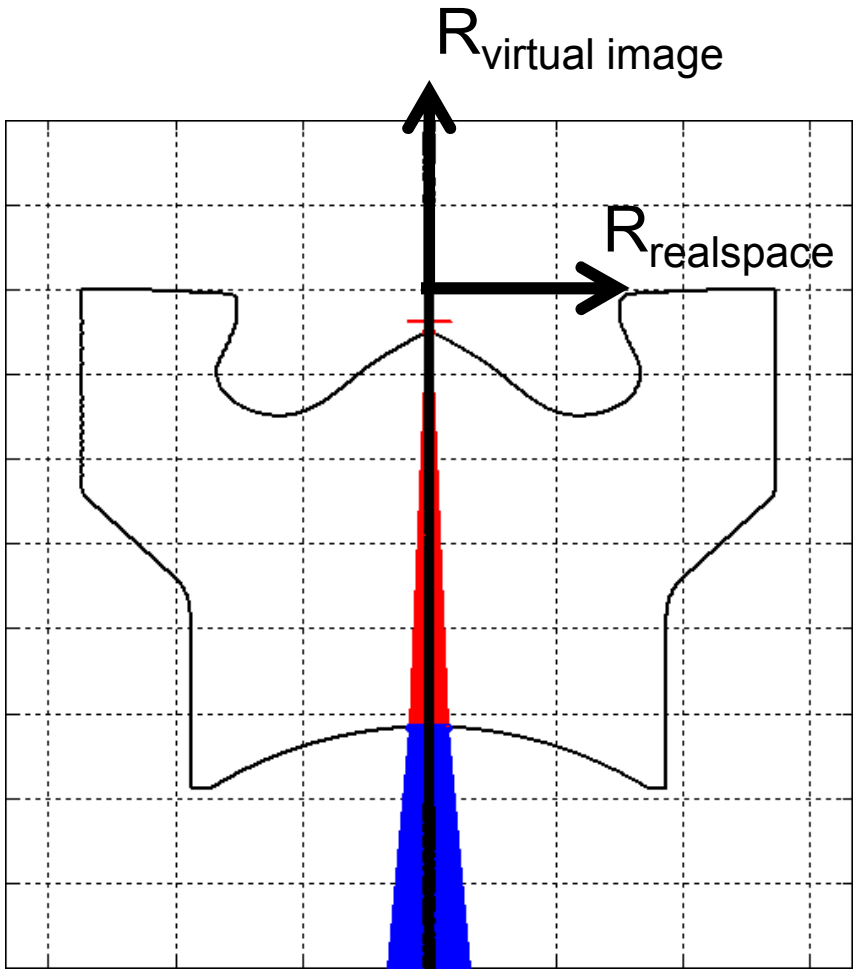
Ray tracing approach

- Rays start above piston at a given point and propagate through the piston
- Virtual image forms where the exiting rays intersect
- Any ray can be traced in this manner
- Only the rays that reach the mirror can be seen by the camera
- The point in real space is mapped into a virtual image point

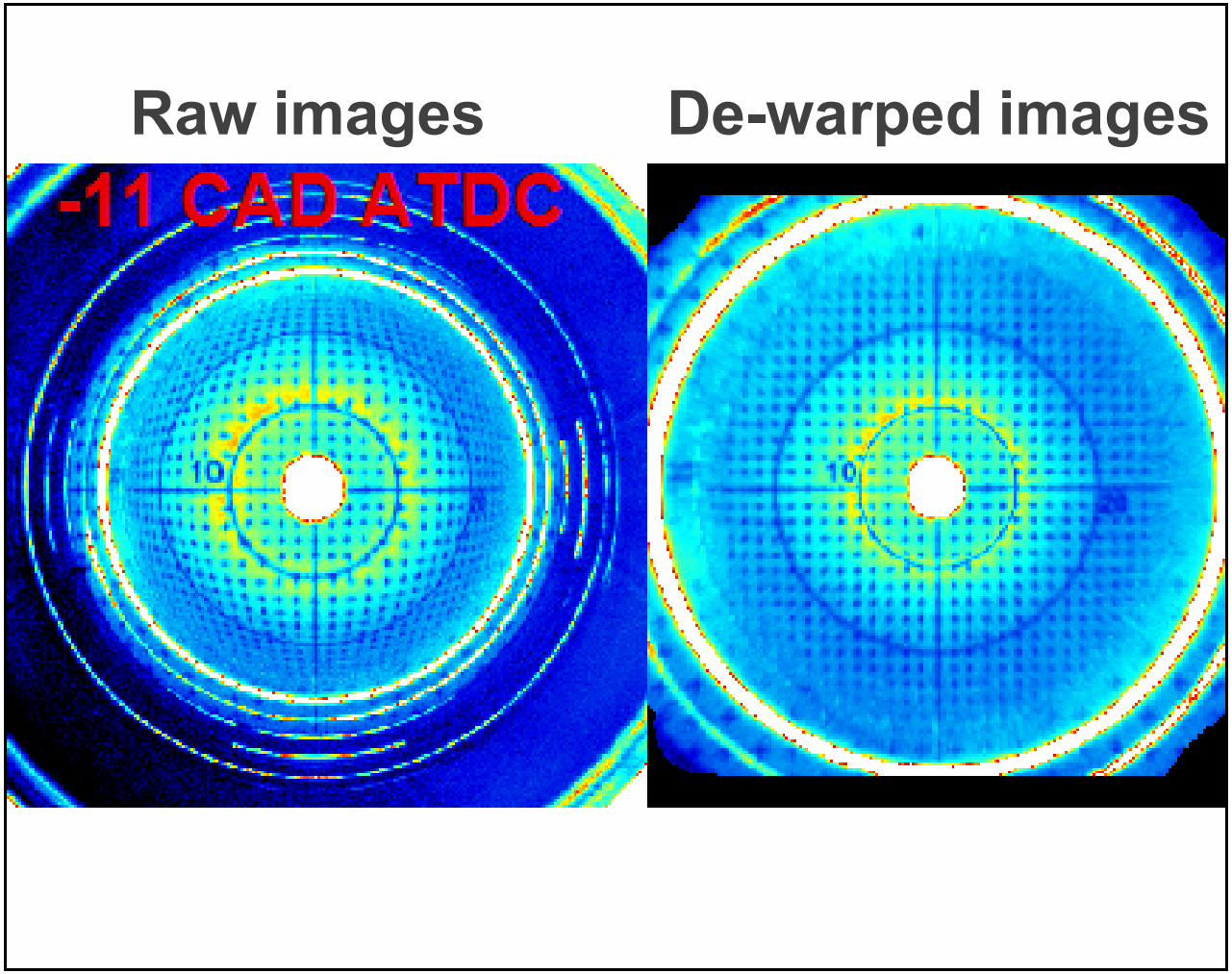


Ray tracing approach

- For a given crank angle and plane in real space (5 mm below the head)
  - Perform ray tracing for many radial positions
  - Determine mapping function between real space and the virtual image
- Radial mapping functions are used to de-warp images taken at a known crank angle



Testing the ray tracing approach



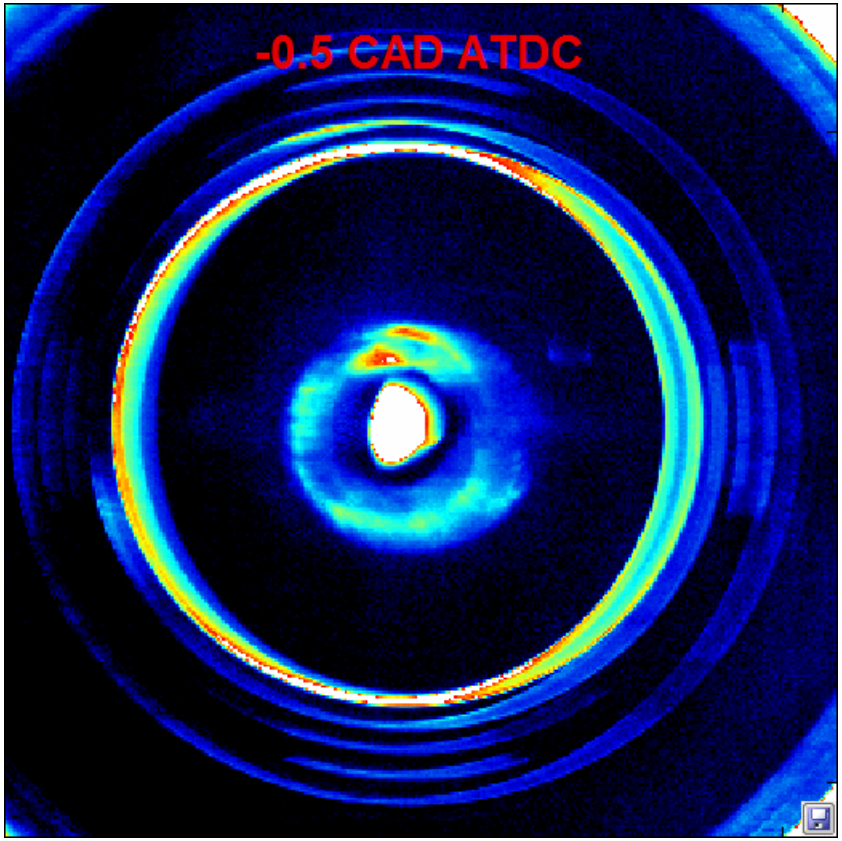
Engine operating conditions

Injection train	[-]	Single	Dwell 300	Dwell 140	Dwell 90
Eng. speed	[rpm]	1500			
Rail Press.	[bar]	800			
Boost pressure	[kPa abs]	155			
Intake temp.	[°C]	80			
SOE_{pilot}	CAD BTDC	2	6.6	4.1	3.5
Q_{pilot}	[mg/str]	-	~1.45		
$t_{pull\ up,\ pilot}$	[µs]	-	250	250	250
$t_{hold,\ pilot}$	[µs]	-	60		
Dwell time	[us]	-	300	140	90
SOEmain	CAD BTDC	5.2	1.1	0	-0.1
Q_{main}	[mg/str]	25.9	23.5	22.6	23
$t_{pull\ up,\ main}$	[µs]	250			
$t_{hold,\ main}$	[µs]	545	472	327	285

- Motored operation (air replaced with N_2)
- Same injection schedules as were used in fired operation

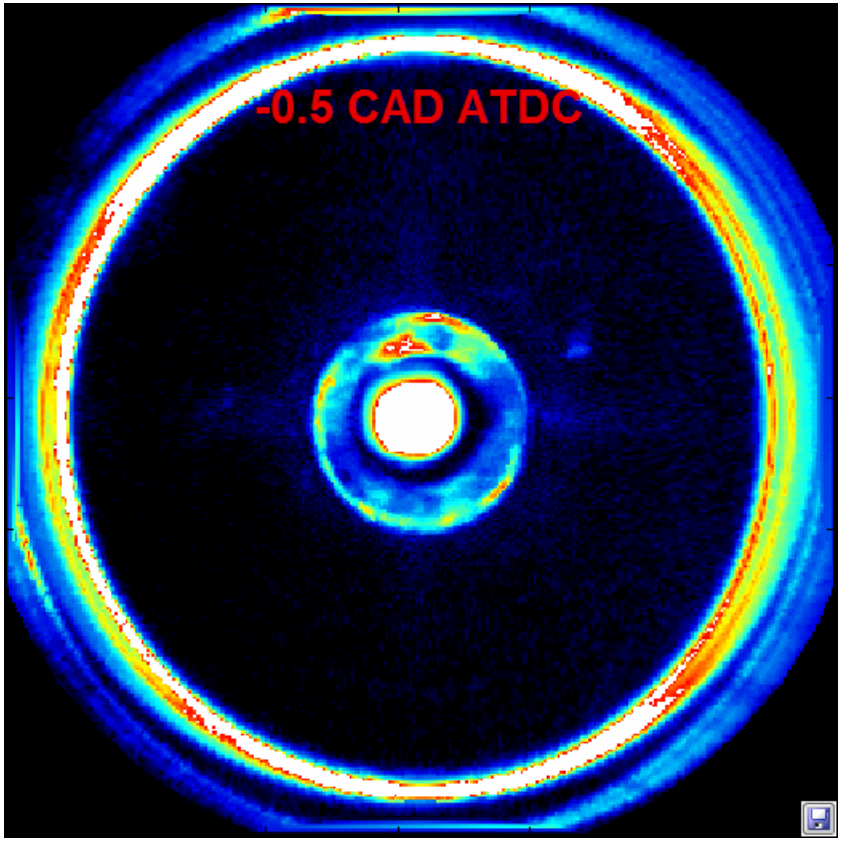
Initial results: raw images

- Good
  - LED illumination bright enough to see the spray
  - 20 kHz frame rate okay
- Bad
  - Images shift and are blurry
  - Result of vibration of beam splitter membrane
  - De-warping and background subtraction not optimal
  - No data at injection tip
- Solution: different beam splitter



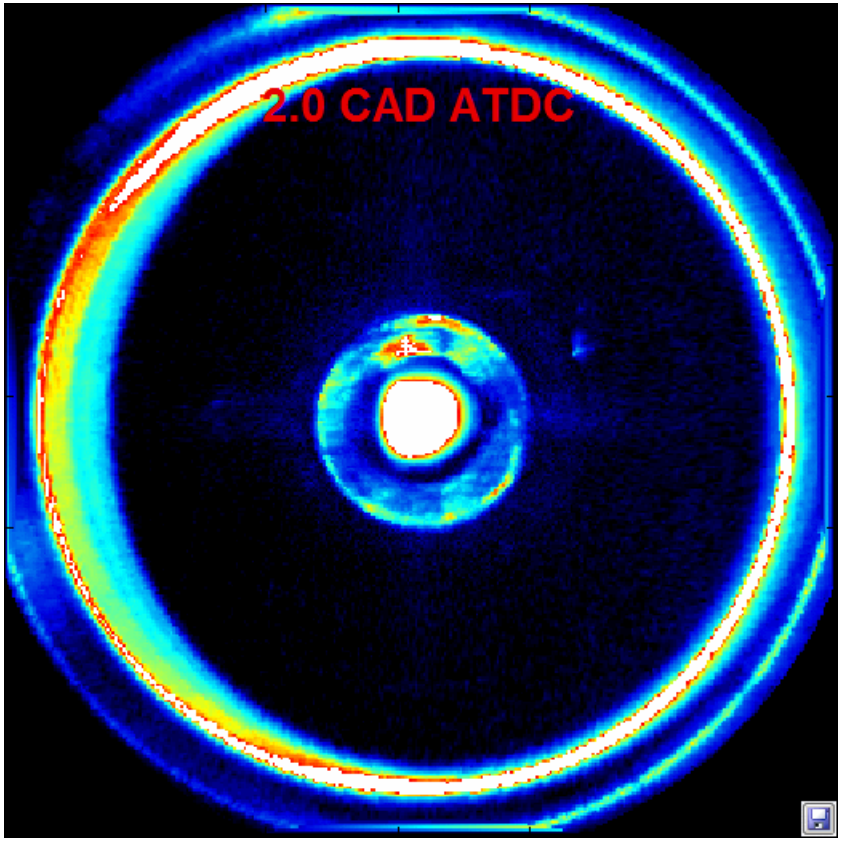
Initial results: dwell 300 µs

- Single “best” cycle in terms of imaging problems
- Two separate injection events
  - Separated by ~ 8 frames (~400 µs)
  - Corresponds well with HDA measurements



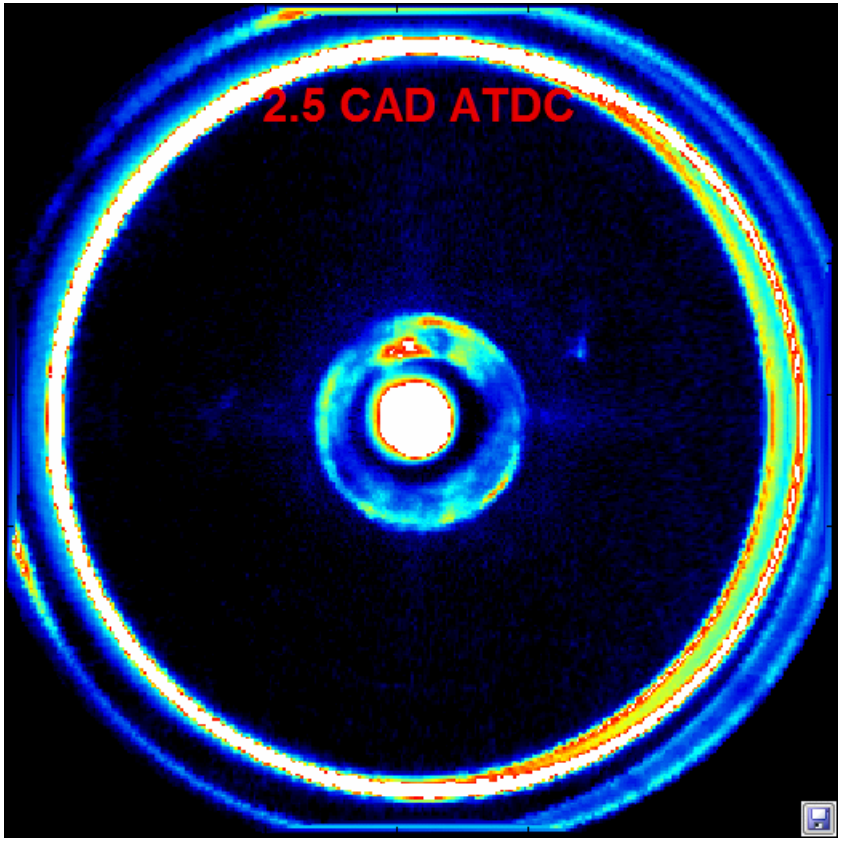
Initial results: dwell 140 µs

- Minimum combustion noise
- Two separate injection events
  - <= 1 frame separation (<= 50 µs)
- Seems to correspond roughly with HDA measurements



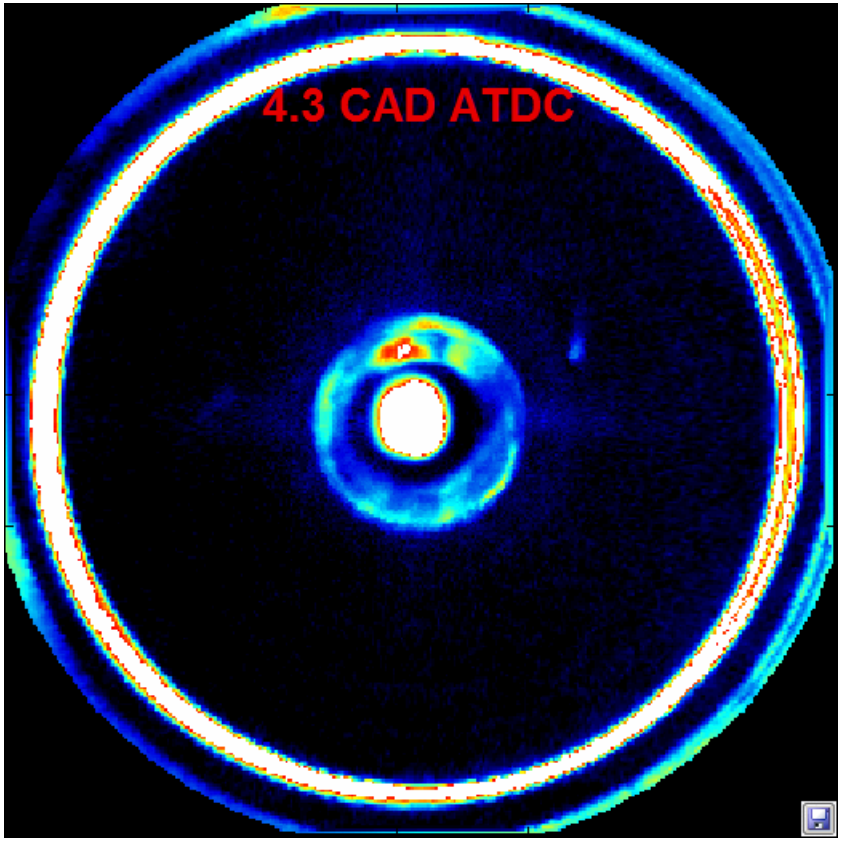
Initial results: dwell 90 µs

- No clear separation between injection events
- Need for higher measurement frequency
  - Camera: should be able to image at 40 kHz
  - LED: unsure if safe operation is possible at 40 kHz; this will be tested



Initial results: single injection

- Single injection will serve as a reference case



Summary

- Injector behavior at 800 bar is consistent with data at 500, 750, and 1000 bar
  - Dwell times of 300, 140, and 90 µs will be investigated optically
- Setup of high speed Mie scattering experiment
  - Pulsed LED illumination
  - Imaging through the bottom of the piston
  - 20 kHz frame rate
- Automated image de-warping algorithm functional
- Problems with the beam splitter should be resolved very soon
- Reliable data should be available in a couple weeks
- An engine may not be the best facility to perform these measurements
  - For more reliable quantitative results, testing in an injection chamber may be desirable (exploring collaborative efforts)

Next steps

- Improve beam splitter setup, repeat measurements
- Attempt to image at 40 kHz (depends on LED)
  - Better resolution of spray tip penetration
  - Improved imaging of dwell behavior
- Further development of image processing techniques
  - Intensity correction, background subtraction
  - Calculate penetration rates
- Compare with HDA data, interpret in context of mixture formation and combustion noise
- Plan next steps

THANK YOU!

QUESTIONS?

High speed Mie scattering imaging setup