POWER & MOBILITY

Impacts of injection pressure and timing on energy-assisted compression-ignition combustion with Gaussian-shaped ribbed piston bowl design

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Motivation

Problem:

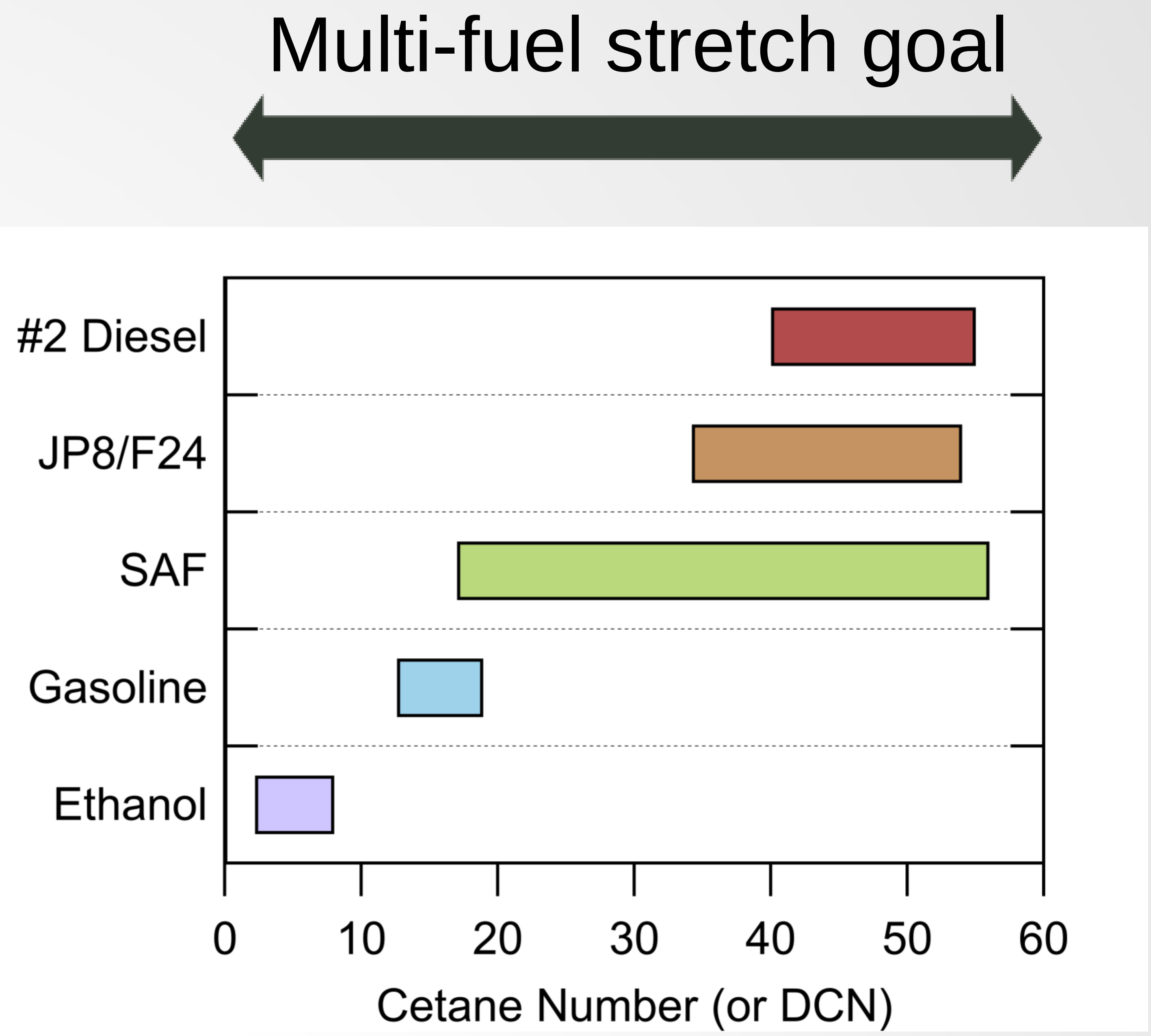
- Lack of cetane number specification for jet fuels and varying properties for accessible fuels
- Sustainable aviation fuels (e.g., alcohol to jet (ATJ)) have wide range of cetane numbers (CN) with some having CN < 20
- Long ignition delays for low cetane number fuels
- Small-bore compression-ignition (CI) engines operate at higher engine speeds
- Intake pressure (P) and temperature (T) decrease with increasing altitude, decreasing compressed gas P and T

Potential solution:

- Local energy deposition to control ignition, “Energy-Assisted Compression Ignition (EACI) using an Ignition Assistant”

Focus of this talk:

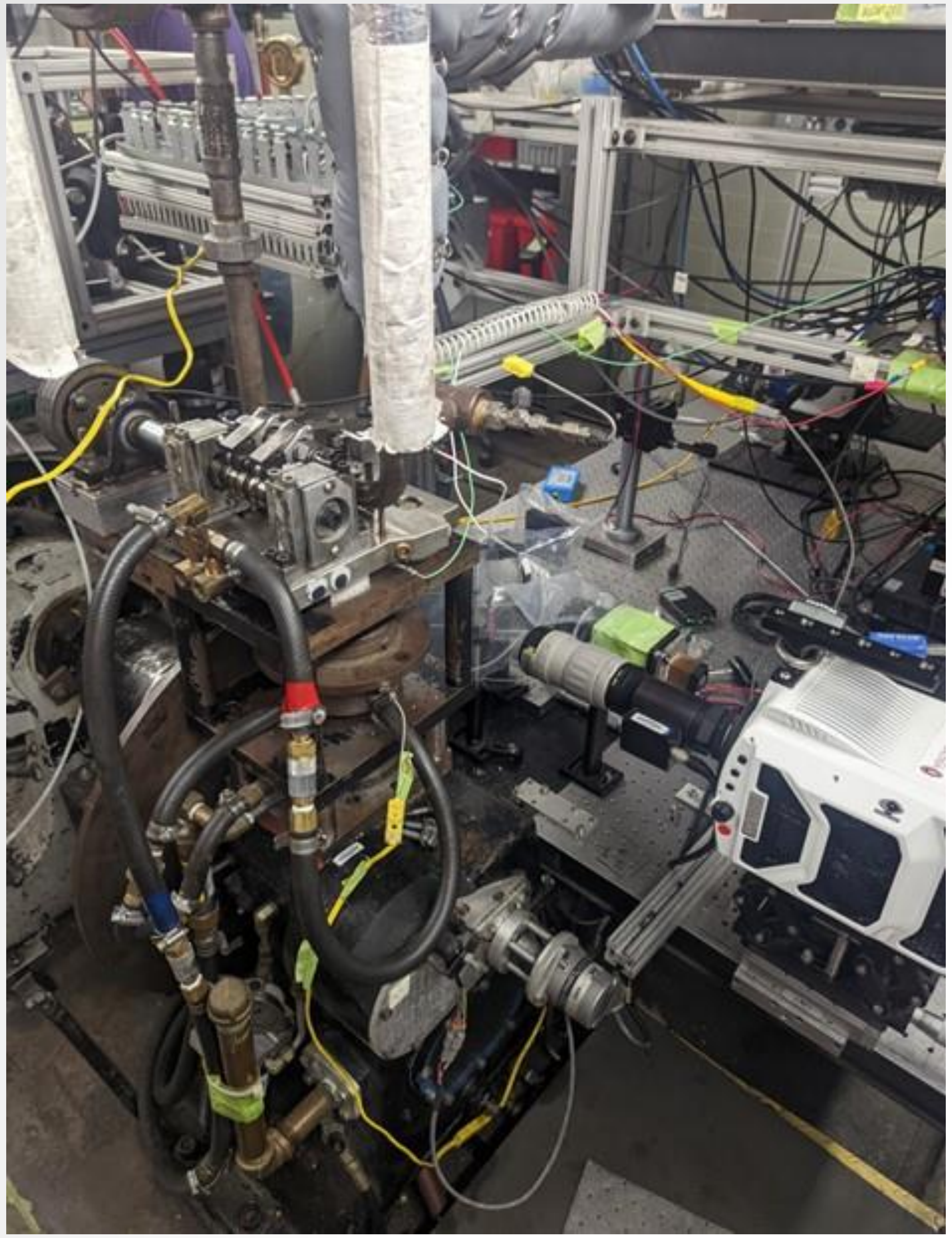
- Impact of injection pressure and timing to demonstrate the ability to potentially achieve EACI operation at more application-relevant engine speeds



Typical ranges of cetane numbers for fuels of interest from various source including [1]. Note range for ethanol is due uncertainty in its CN.

[1] PQIS, "Petroleum Quality Information System 2013 Annual Report," PQIS2013

Experimental Setup - Optical engine



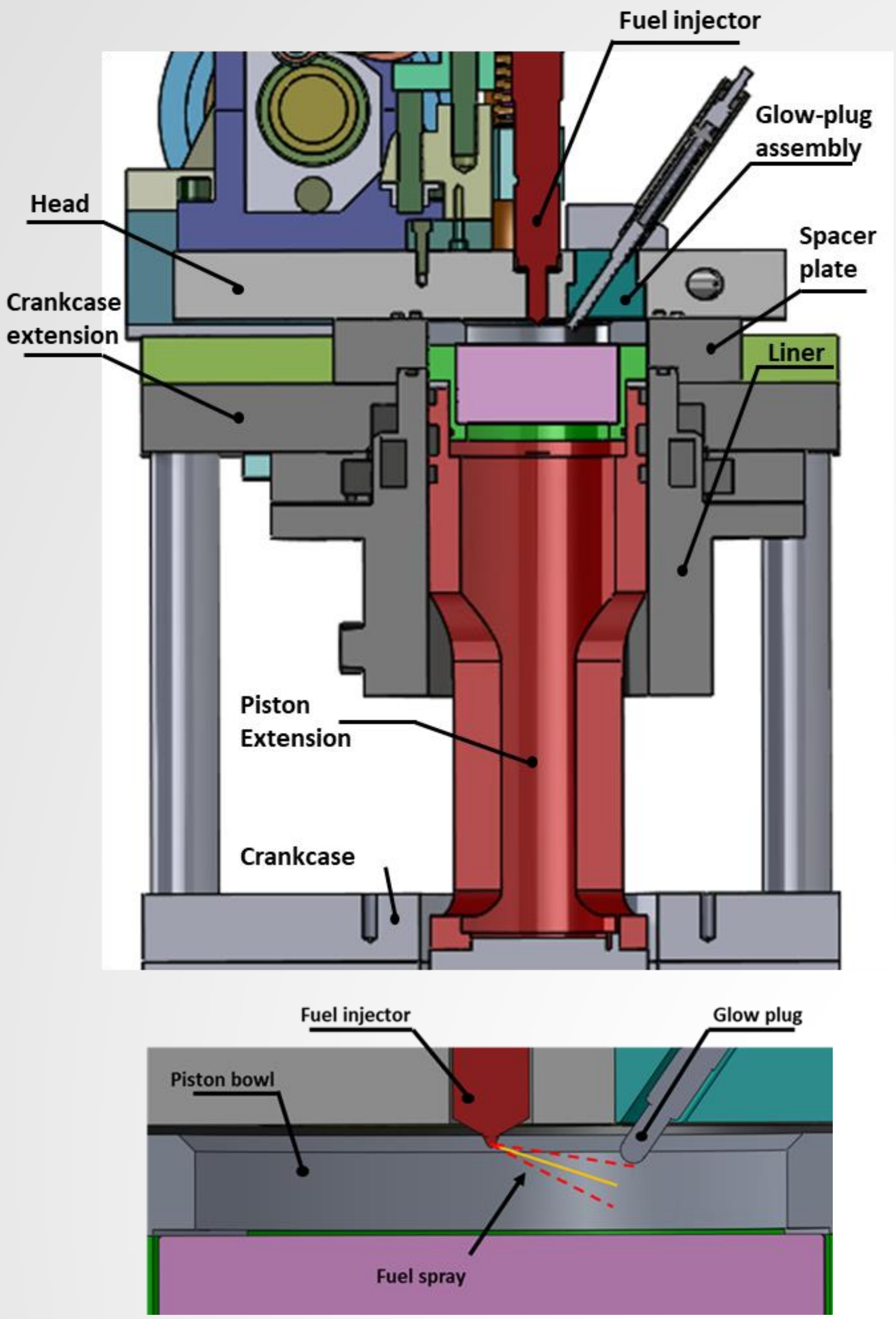
Picture of optical engine

Optical Engine Specifications	
Engine Type	Single-Cylinder Optical (0.4 ltr)
Bore [mm]	82.4
Stroke [mm]	76.2
Piston Window FOV [mm]	53.3
Geometric Compression Ratio	14.0:1
Connecting Rod Length [mm]	144.8
Swirl Ratio	0
Cycle	4-stroke
EVO [CAD]	164
IVO [CAD]	346
EVC [CAD]	-346
IVC [CAD]	-164

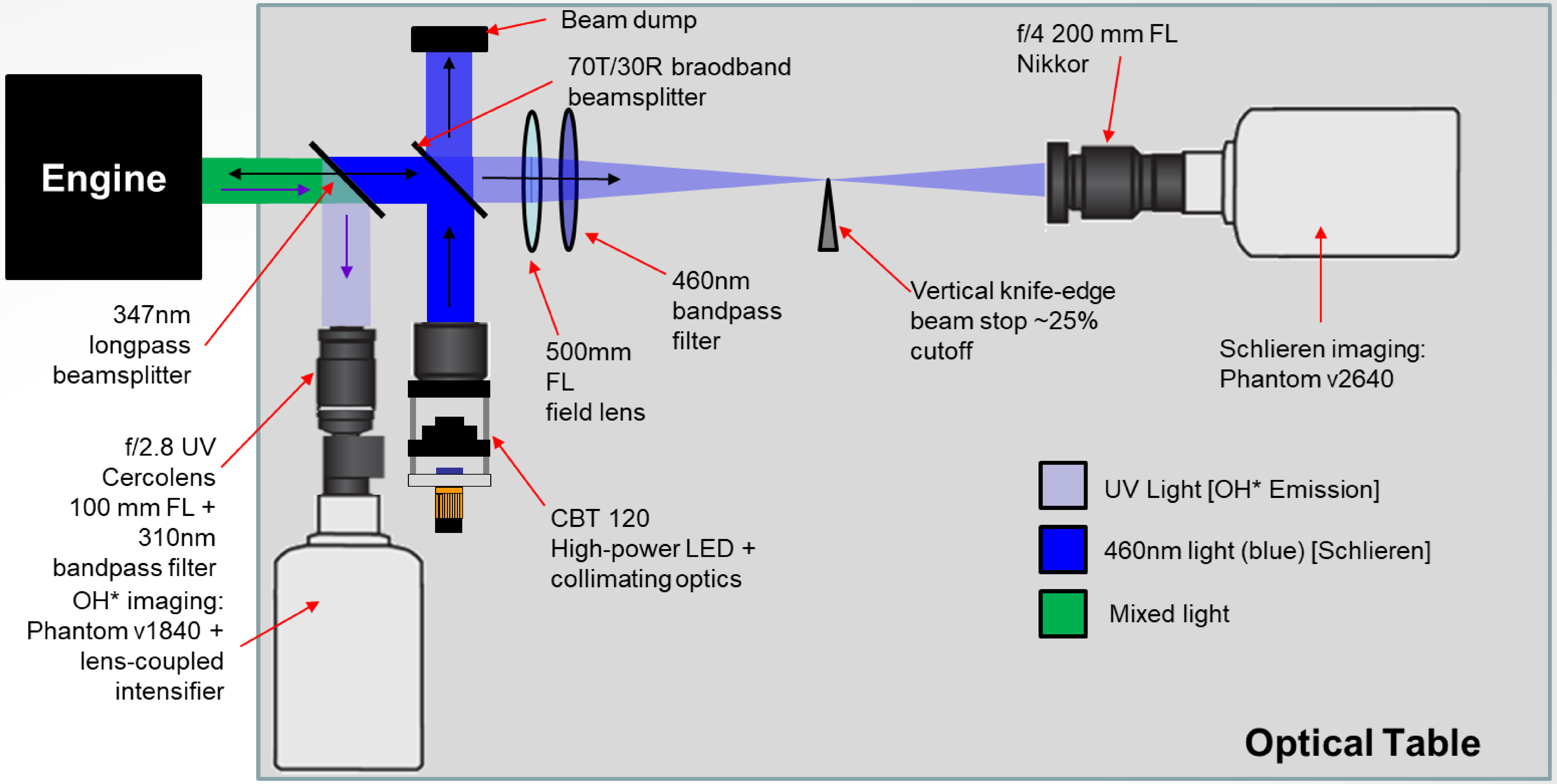
Experimental Setup - Imaging

OH Chemiluminescence Imaging
- Frame rate 8.8 kHz – 1.22 images per CAD
- 310 nm bandpass filter with 10-nm bandwidth

Schlieren Imaging
- Frame rate 28.8 kHz – 4 images per CAD



Section view of optical engine illustrating basic engine features and glow plug location in to combustion chamber



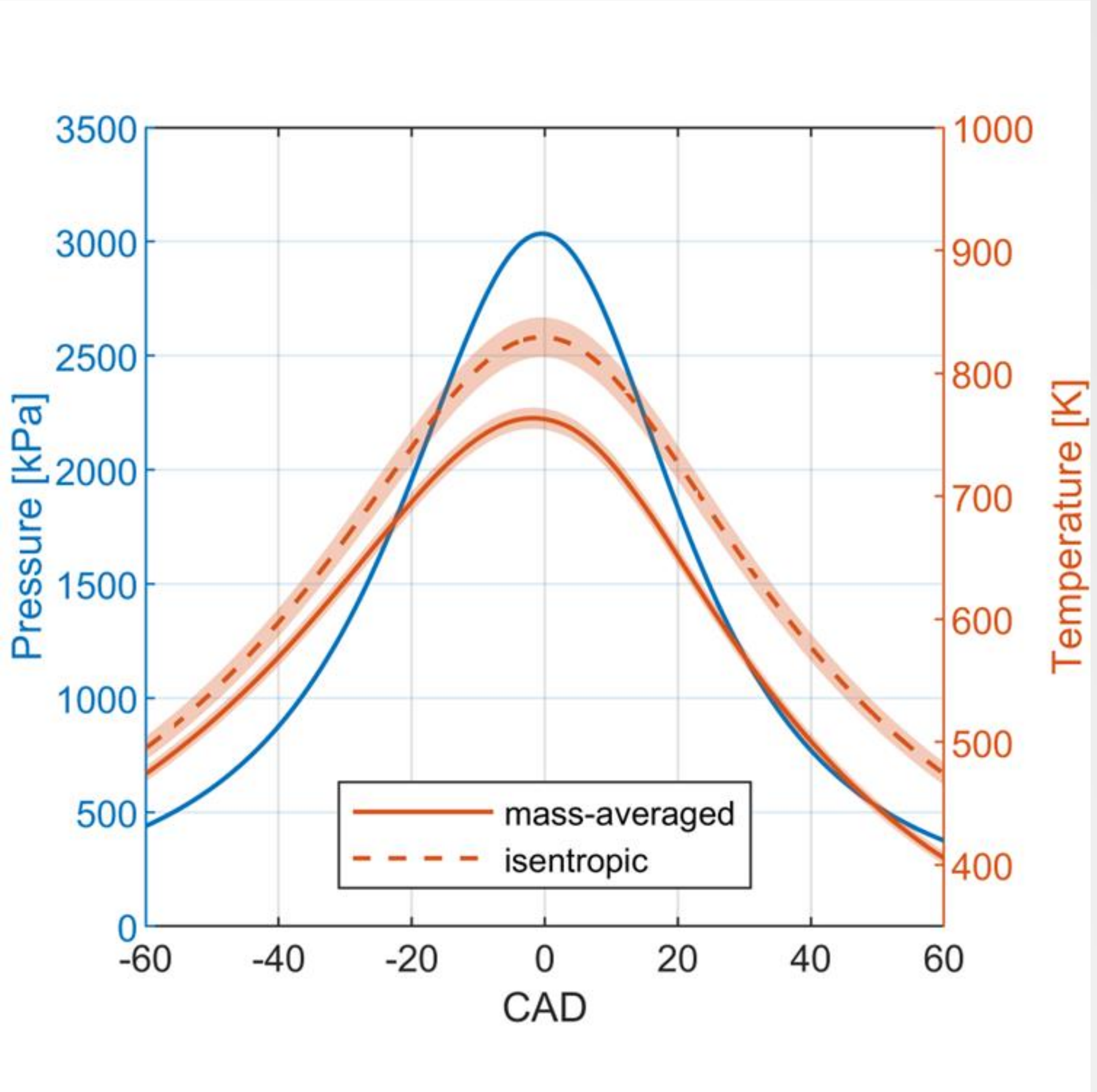
Experimental arrangement for the simultaneous OH chemiluminescence and schlieren high-speed imaging diagnostics shown relative to the engine location.

Experimental Setup – Parameters

Parameters	Units	Value
Engine speed	rpm	1200
Intake pressure	kPa	105
Intake temperature	K	301
Nominal TDC pressure	bar	30
Nominal TDC T. (mass-averaged)	K	750
Nominal TDC T. (isentropic)	K	825
Coolant temperature	K	323

Engine was fired at a skip-fire ratio of 9:1 for 100 cycles, yielding 10 fired cycles

- Images and pressure data acquired for 10 fired cycles



Average in-cylinder motored pressure and temperature (isentropic and mass-averaged). Shading correspond to 95 % confidence intervals based on systematic error and cycle-to-cycle variability

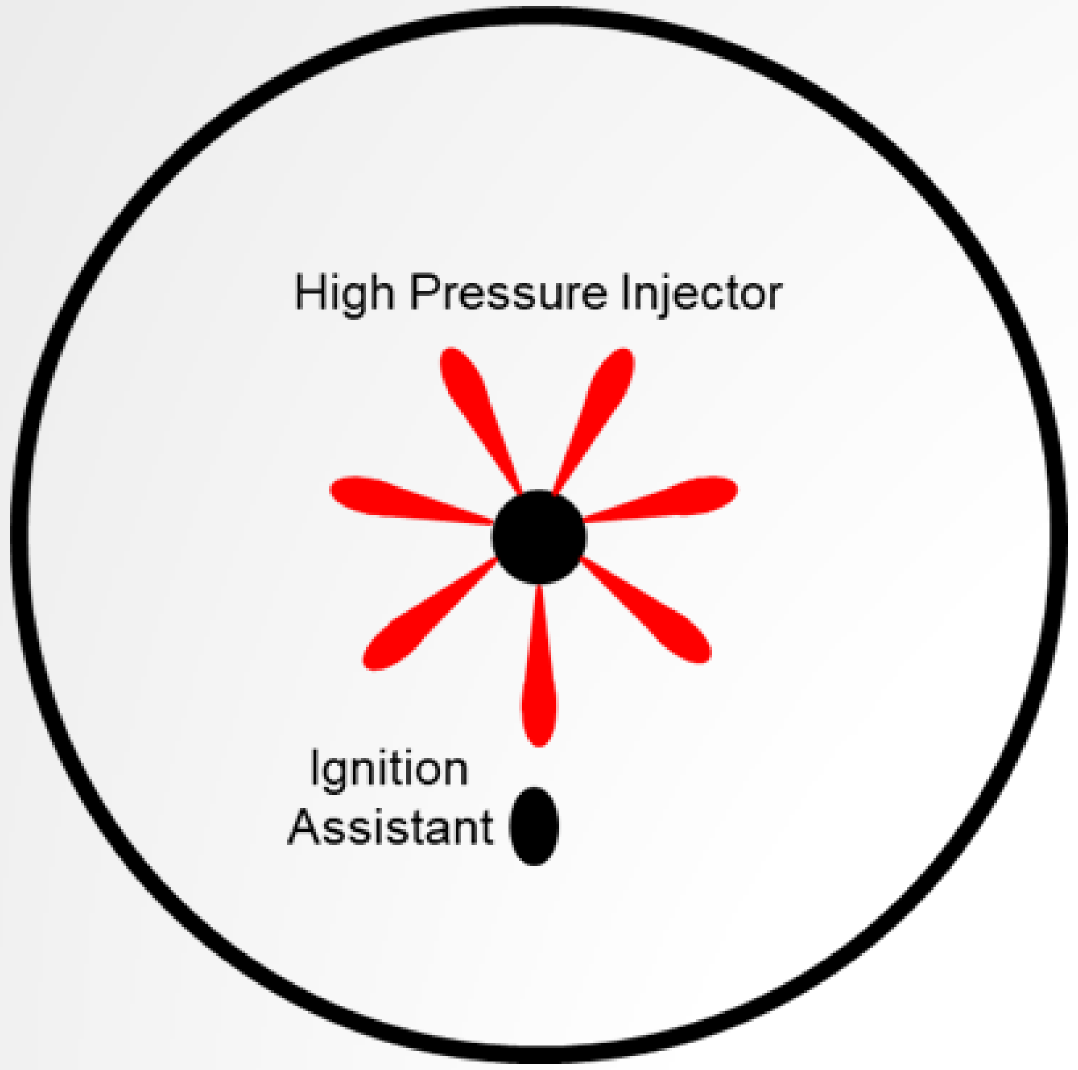
Experimental Setup – Actuators

Injector – Bosch CRIN 2.2

- 7 hole
- 140 µm orifices
- 144° included spray angle

Ignition assistant assembly

- Ignition assistant mount replicated positioning relative to injector for GM light-duty Euro IV 1.9-L diesel engine
- Ignition assistant: Beru CGP003



Schematic of fuel jet interacting with the IA

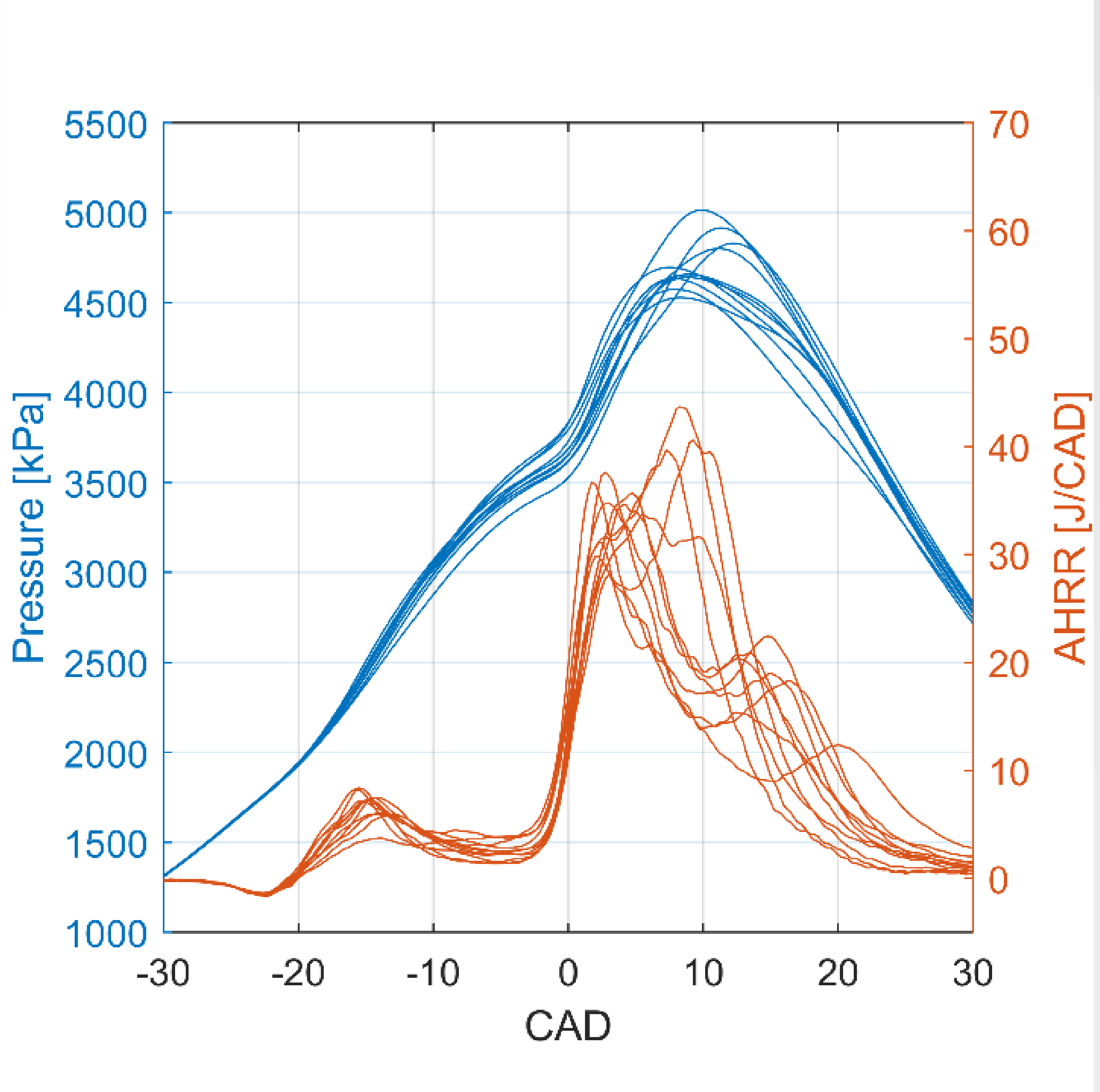
3D model of the modified ceramic glow plug used in the current work. The red line illustrates the path for the thermocouple installation

Background

Split-injection strategy achieves mixing-controlled combustion of low reactivity fuels (CN <20)

- Robust ignition of the first injection is required
  - Long injection dwells
  - High ignition assistant temperature
  - Large 1st injection mass
  - Moderate injection pressures
- Hot combusted gases from 1st injection positioned near the injector tip can enable rapid transition to mixing-controlled combustion of the second injection

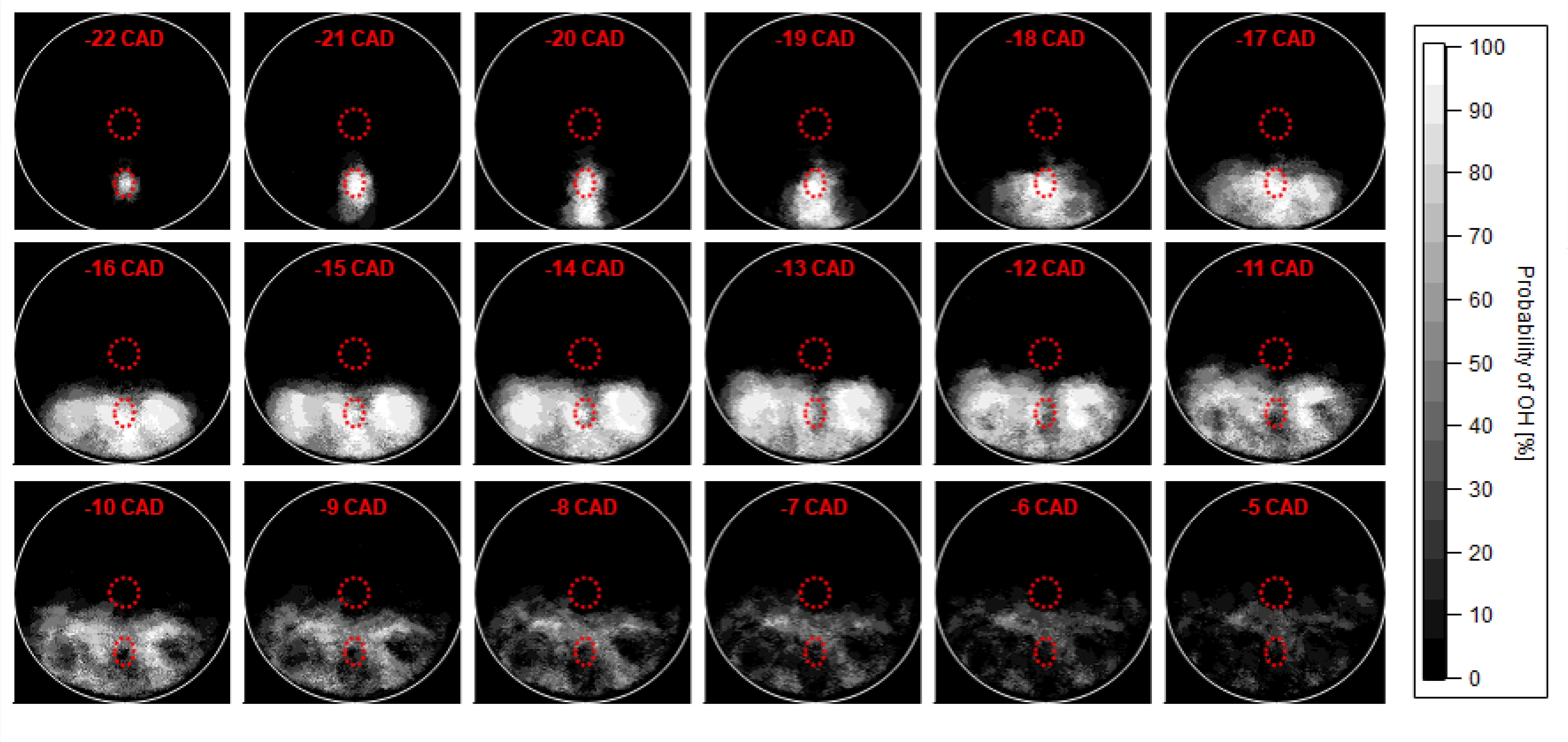
Fuel	1st Inj. Mass [mg]	1st Inj. SOI [CAD]	2nd Inj. Mass [mg]	2nd Inj. SOI [CAD]	Dwell [ms]	Inj. P. [bar]	IA T. [K]
CN 17	7.0	-26.75	7.0	-5	2.5	600	1450

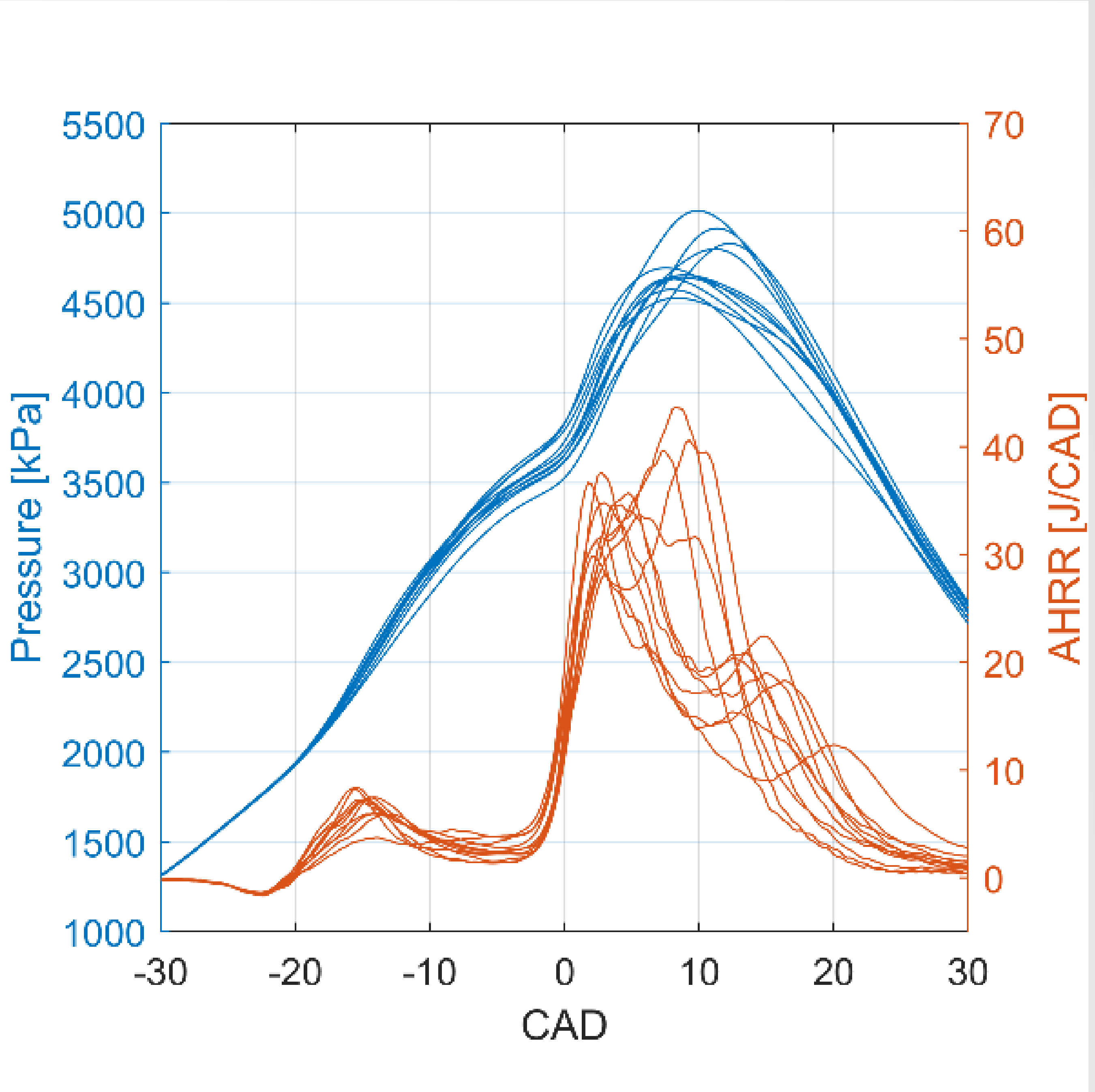


Individual cycle in-cylinder pressure and apparent heat release

Background

1st Injection Ignition and Combustion



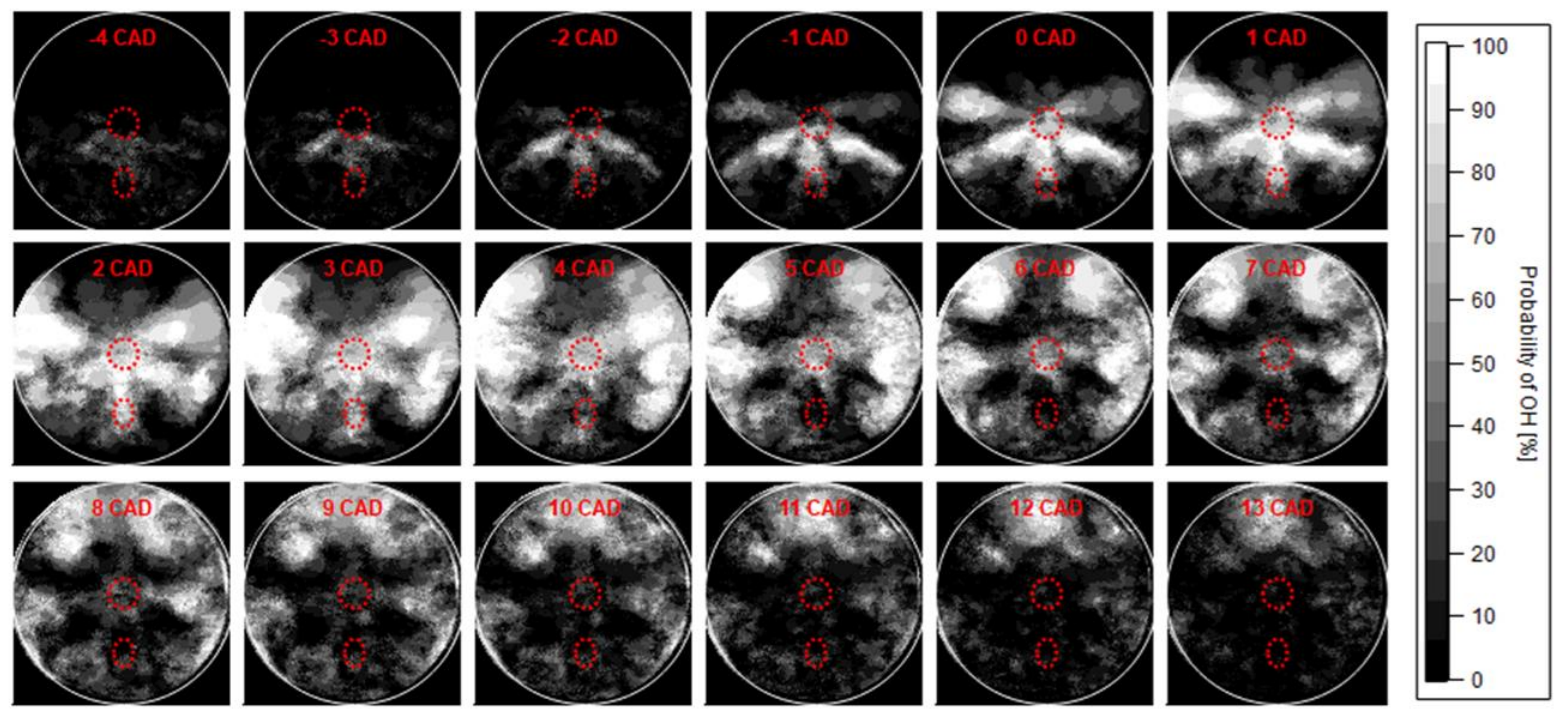


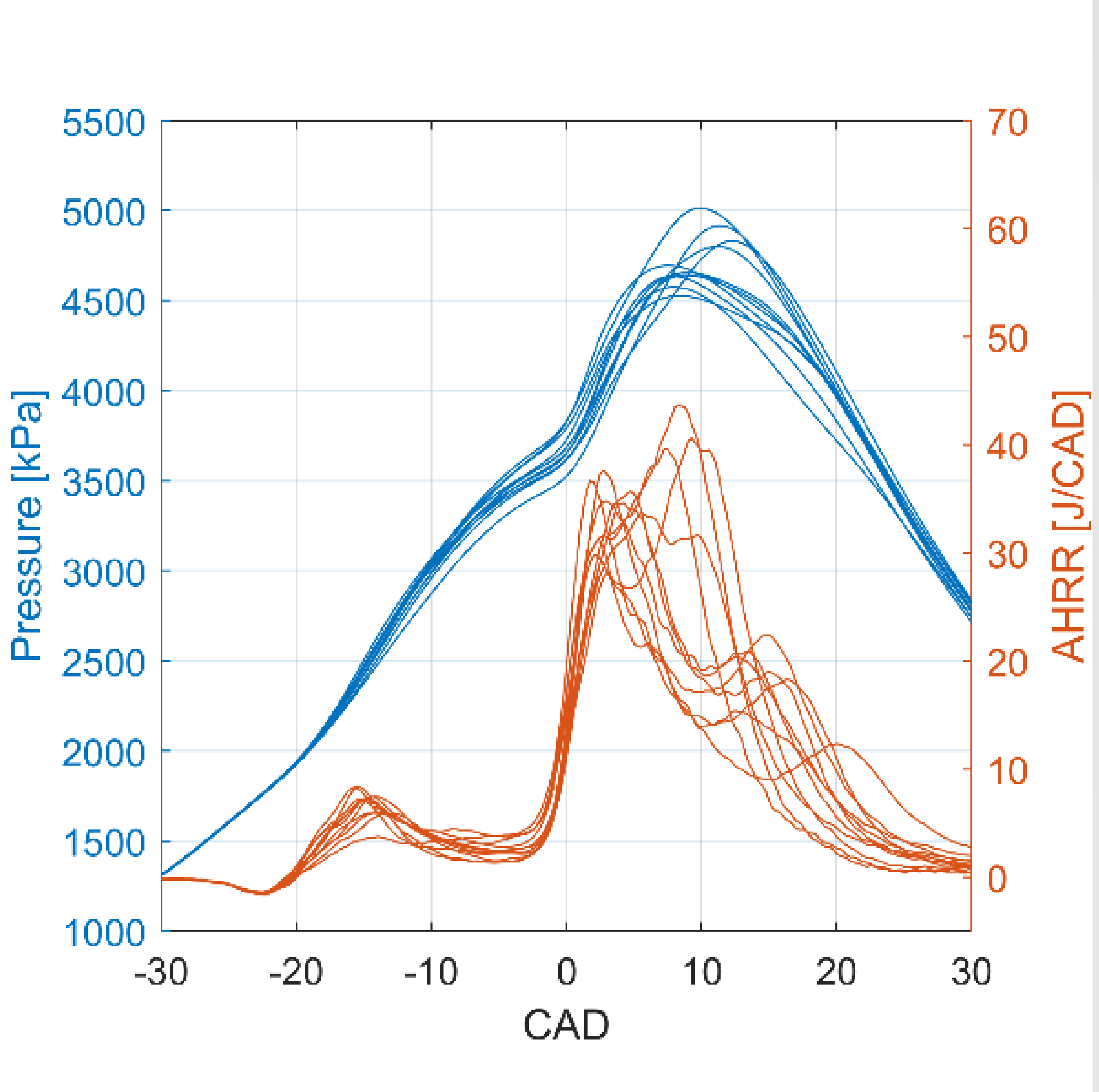
Fuel	1st Inj. Mass [mg]	1st Inj. SOI [CAD]	2nd Inj. Mass [mg]	2nd Inj. SOI [CAD]	Dwell [ms]	Inj. P. [bar]	IA T. [K]
CN 17	7.0	-26.75	7.0	-5	2.5	600	1450

- Rapid ignition of fuel jet directed at the ignition assistant (ID < 5 CAD)
- Azimuthal jet-to-jet propagation to about half of the fuel jets

Background

2nd Injection Ignition





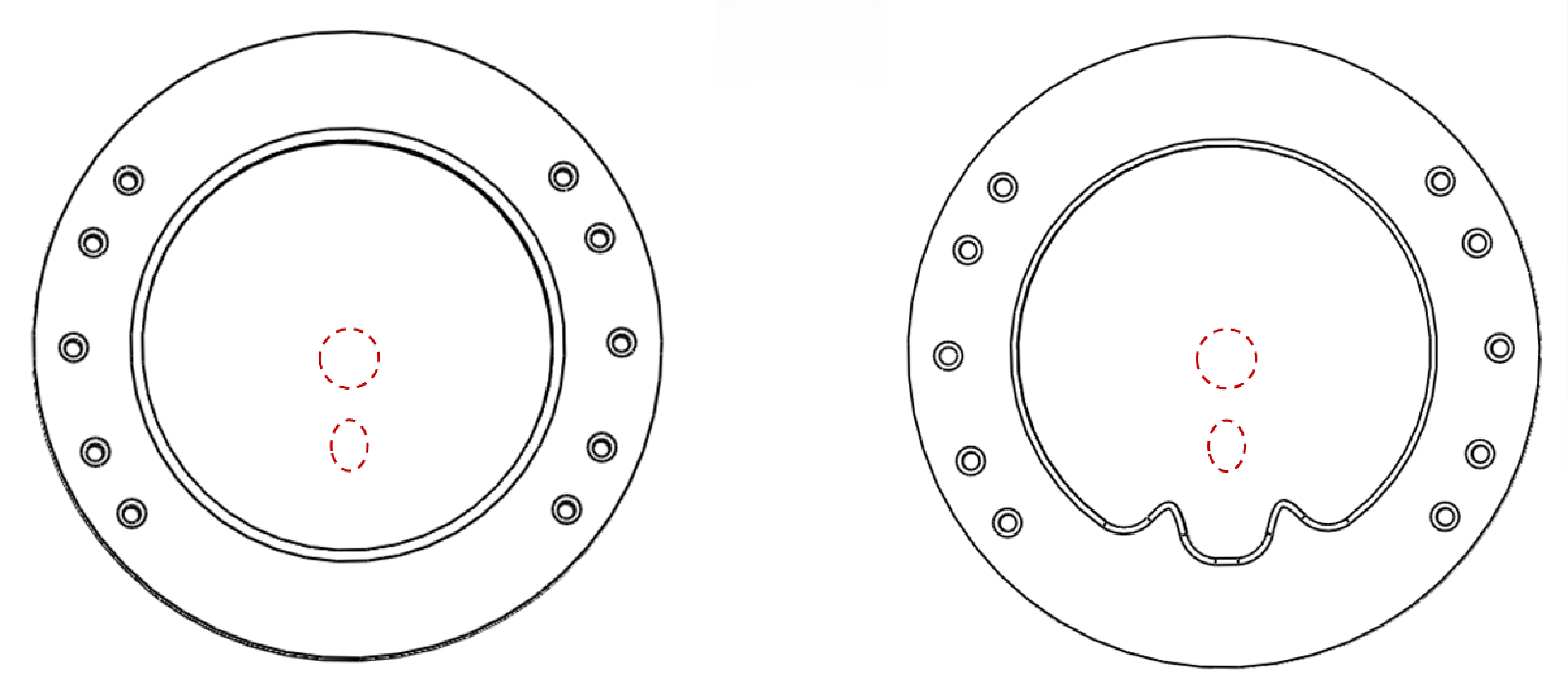
Fuel	1st Inj. Mass [mg]	1st Inj. SOI [CAD]	2nd Inj. Mass [mg]	2nd Inj. SOI [CAD]	Dwell [ms]	Inj. P. [bar]	IA T. [K]
CN 17	7.0	-26.75	7.0	-5	2.5	600	1450

- Mixing-controlled combustion of ~4-5 fuel jets
- Some jet-to-jet propagation
- Minimal end-gas autoignition of one remaining fuel jet

Background

Alternative piston bowl designs can increase the number of fuel jets experiencing mixing-controlled combustion and its repeatability

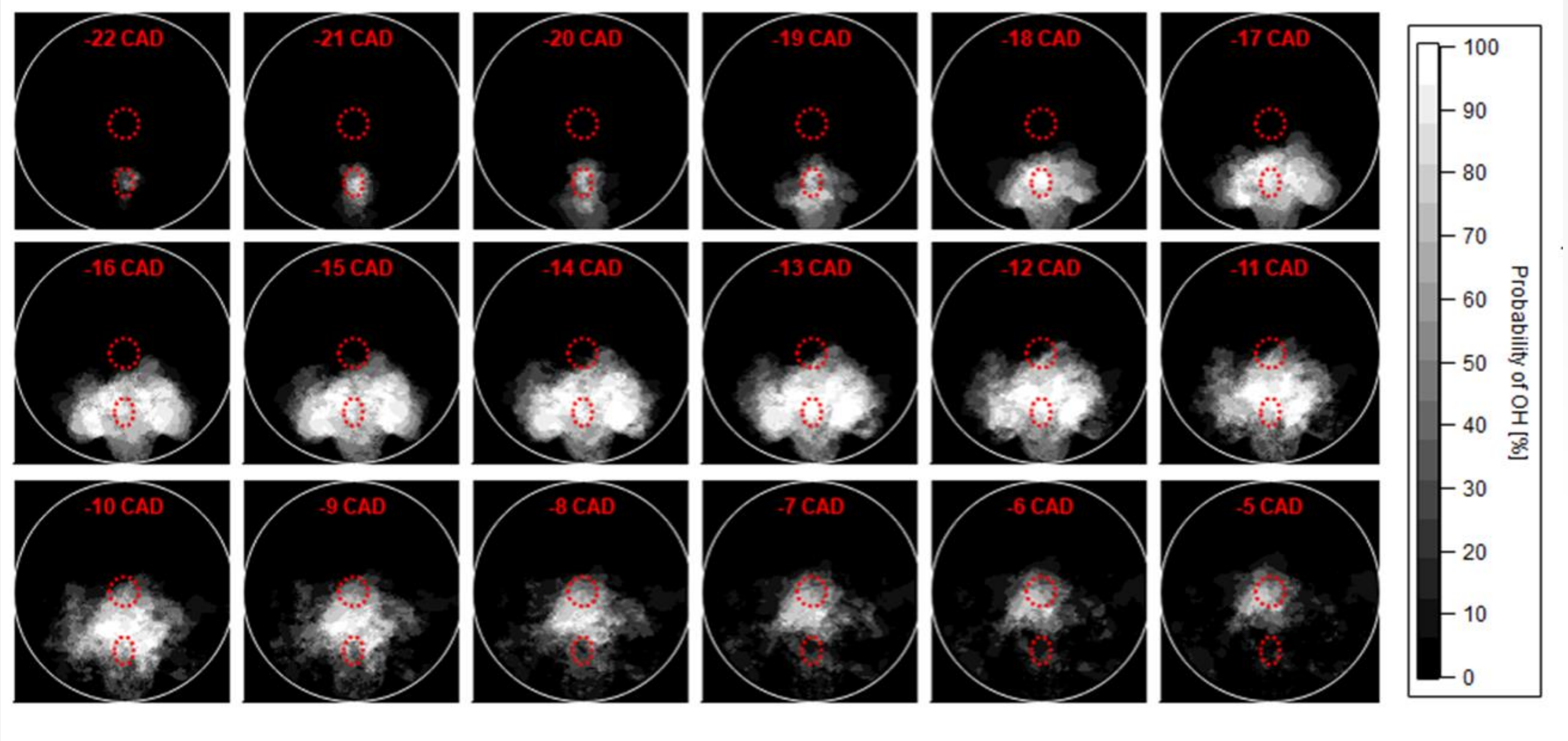
- Custom piston bowl designed with two Gaussian-shaped ribs added to relocate the hot burned gases from the 1st injection near the injector tip
- Hot combusted gases from the 1st injection positioned near the injector tip can enable rapid transition to mixing-controlled combustion of the second injection

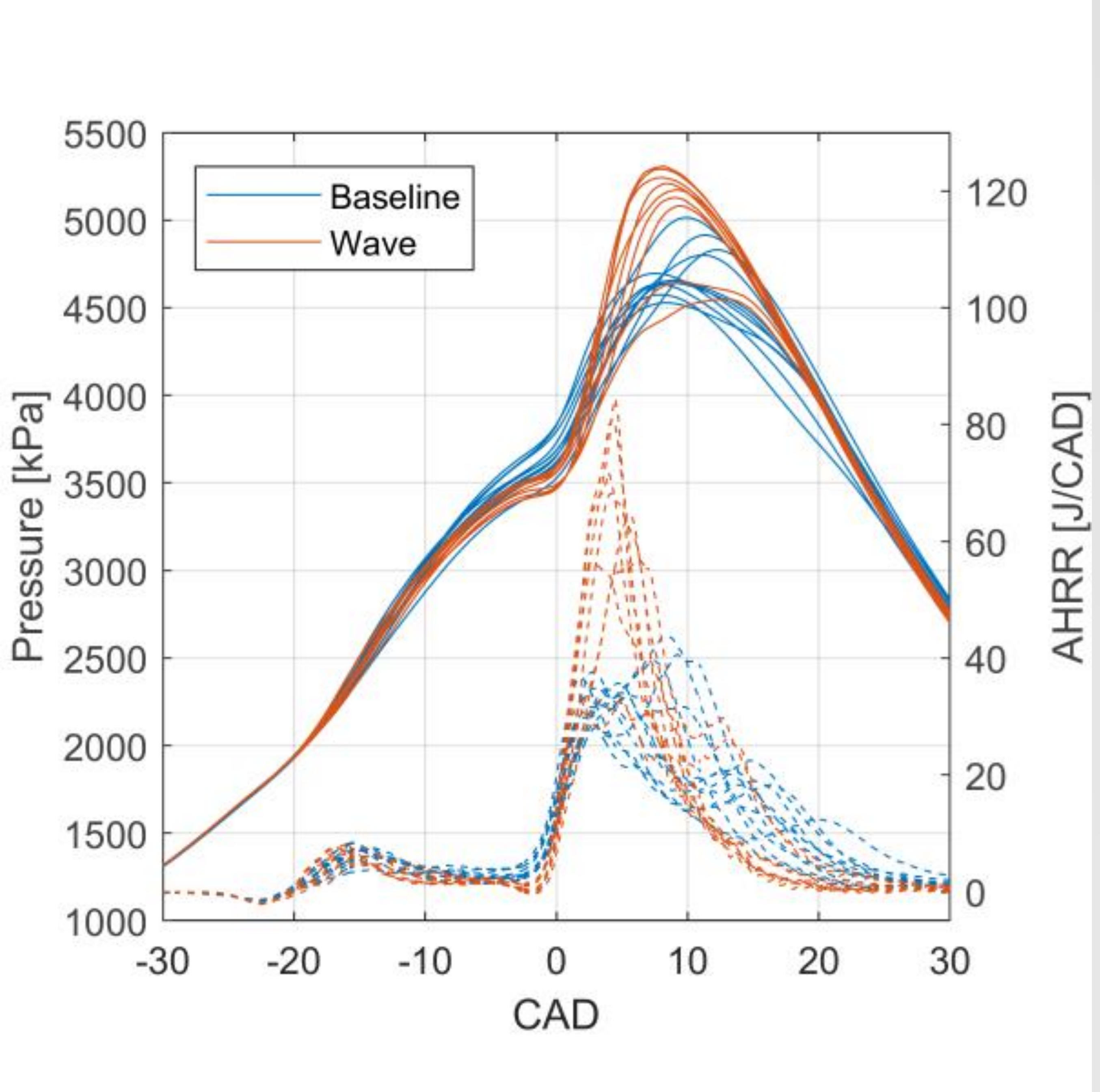


Schematic of the baseline, wave piston bowl designs

Background

1st Injection Ignition and Combustion (wave)



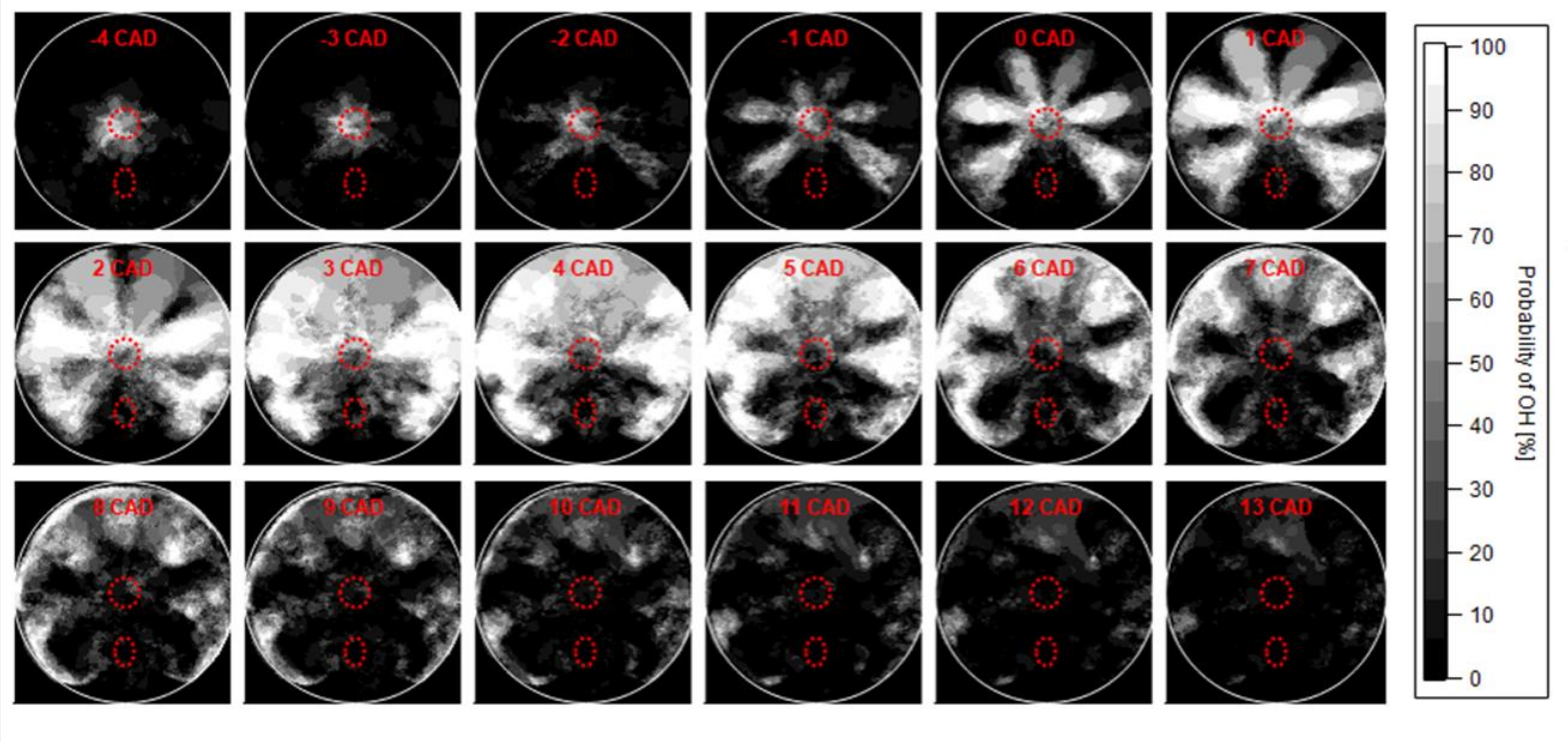


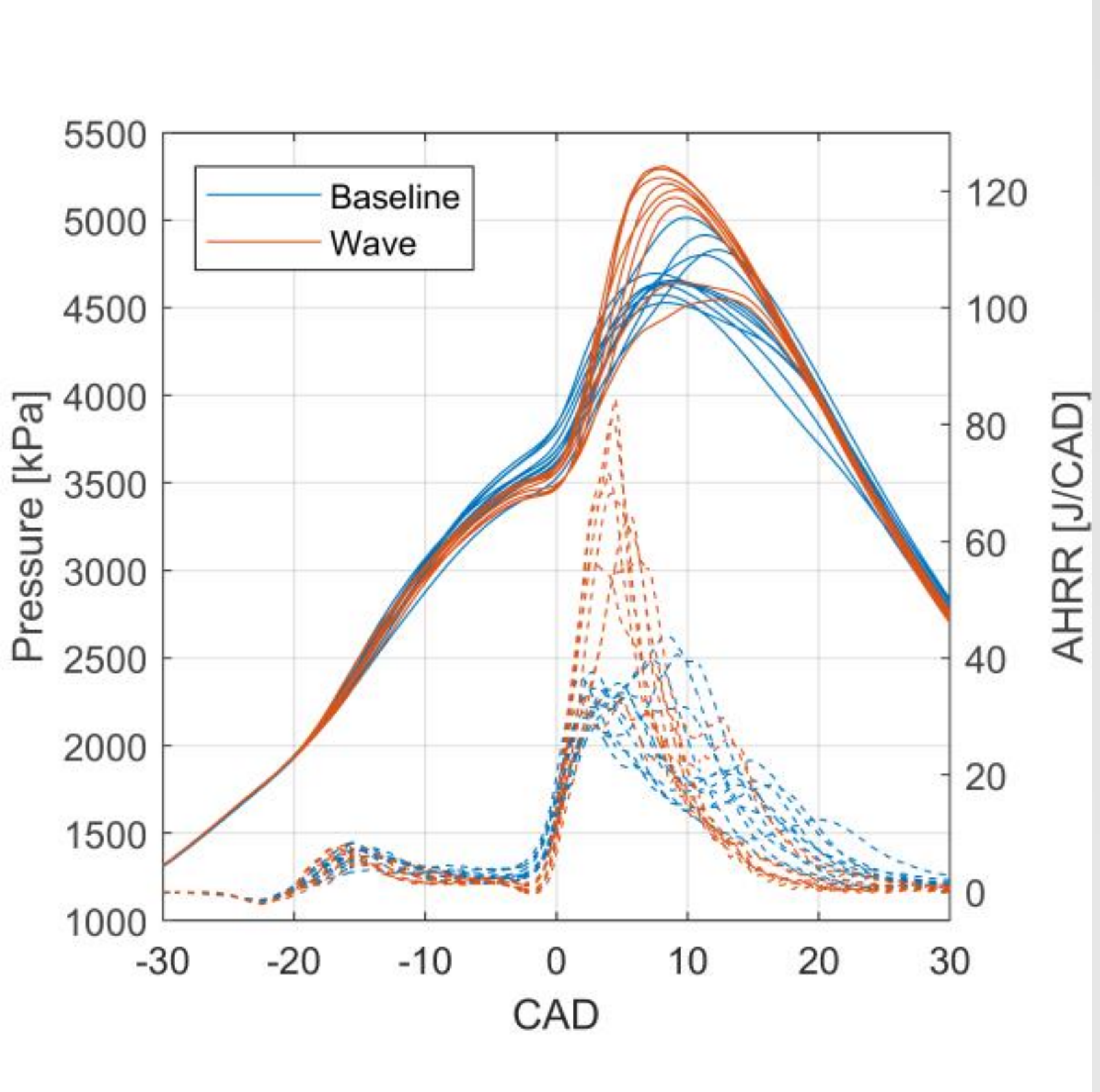
Relocation of 1st injection combusted gases can improve EACI combustion by increasing number of fuel jets experiencing mixing-controlled combustion

- Upward propagation and relocation of the fuel jet directed at the ignition assistant
- Some azimuthal jet-to-jet propagation

Background

2nd Injection Ignition (wave)





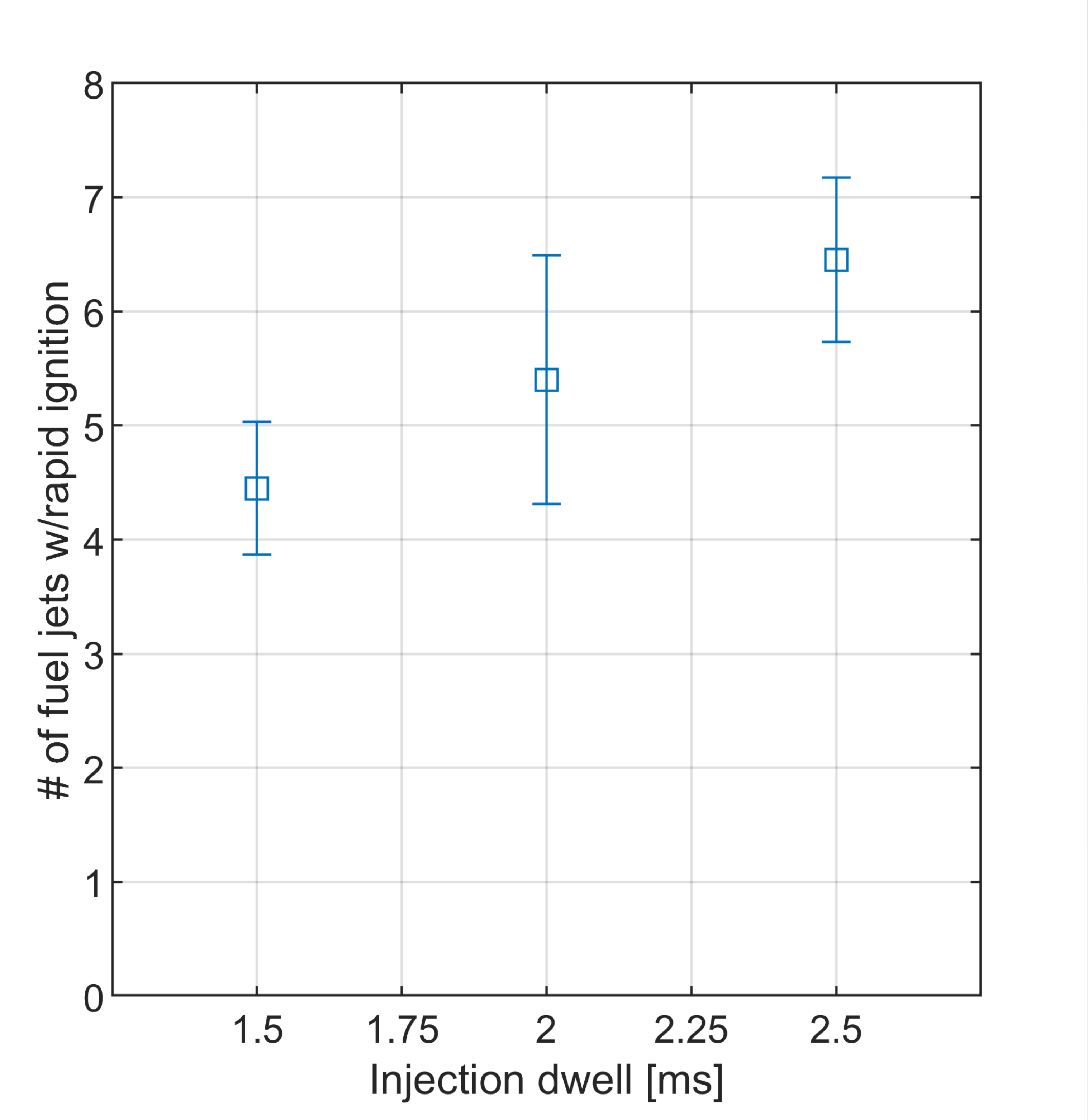
Hot combusted gases from the 1st injection positioned near the injector tip enable rapid transition to mixing-controlled combustion of the 2nd injection for all fuels

- Custom wave bowl increased the number of fuel jets experiencing mixing-controlled combustion
- No end-gas autoignition

Background

Decreasing injection dwell decreases the number of fuel jets experiencing mixing-controlled combustion

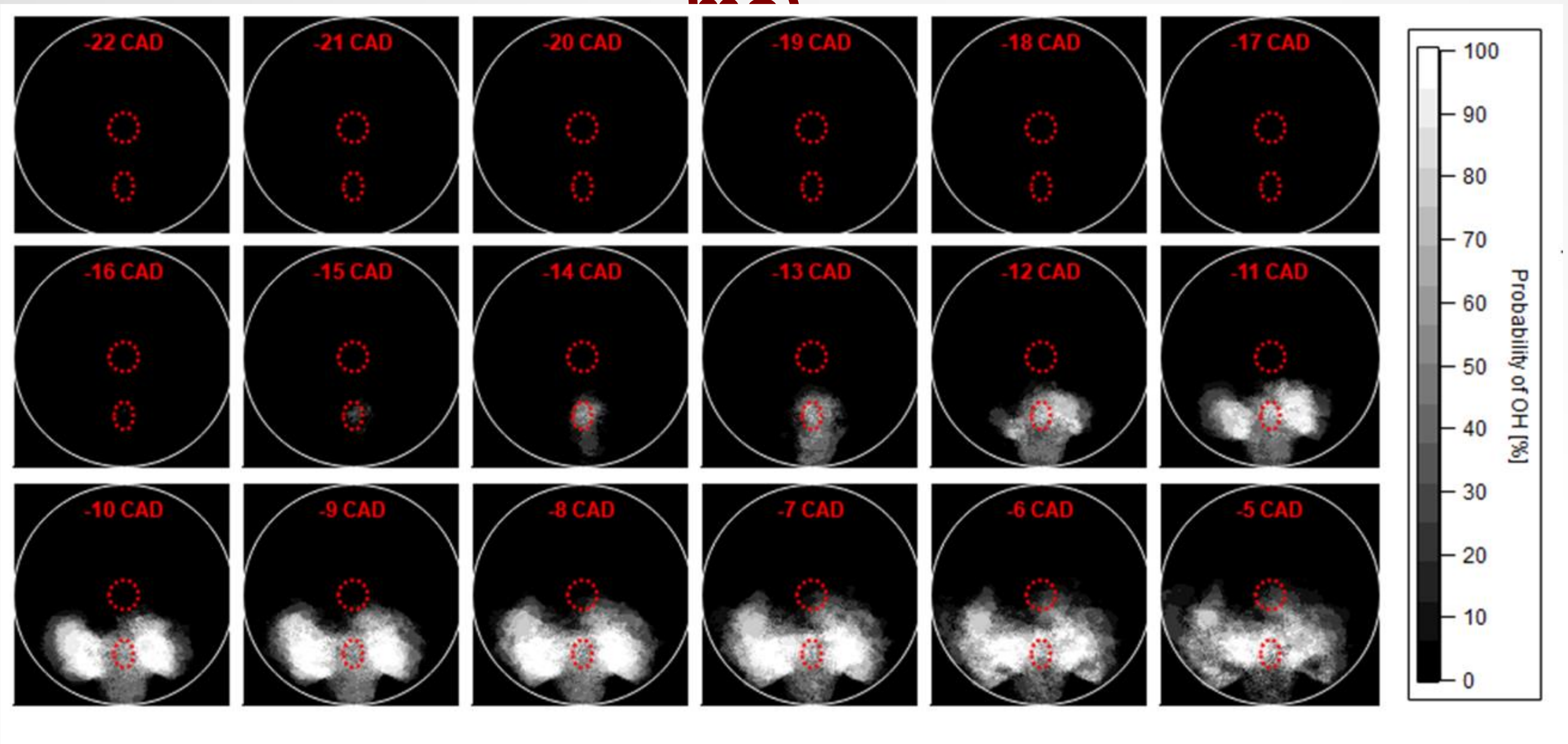
- Hot combusted gases from the 1st injection does not reach the injector tip enabling mixing-controlled combustion of all jets

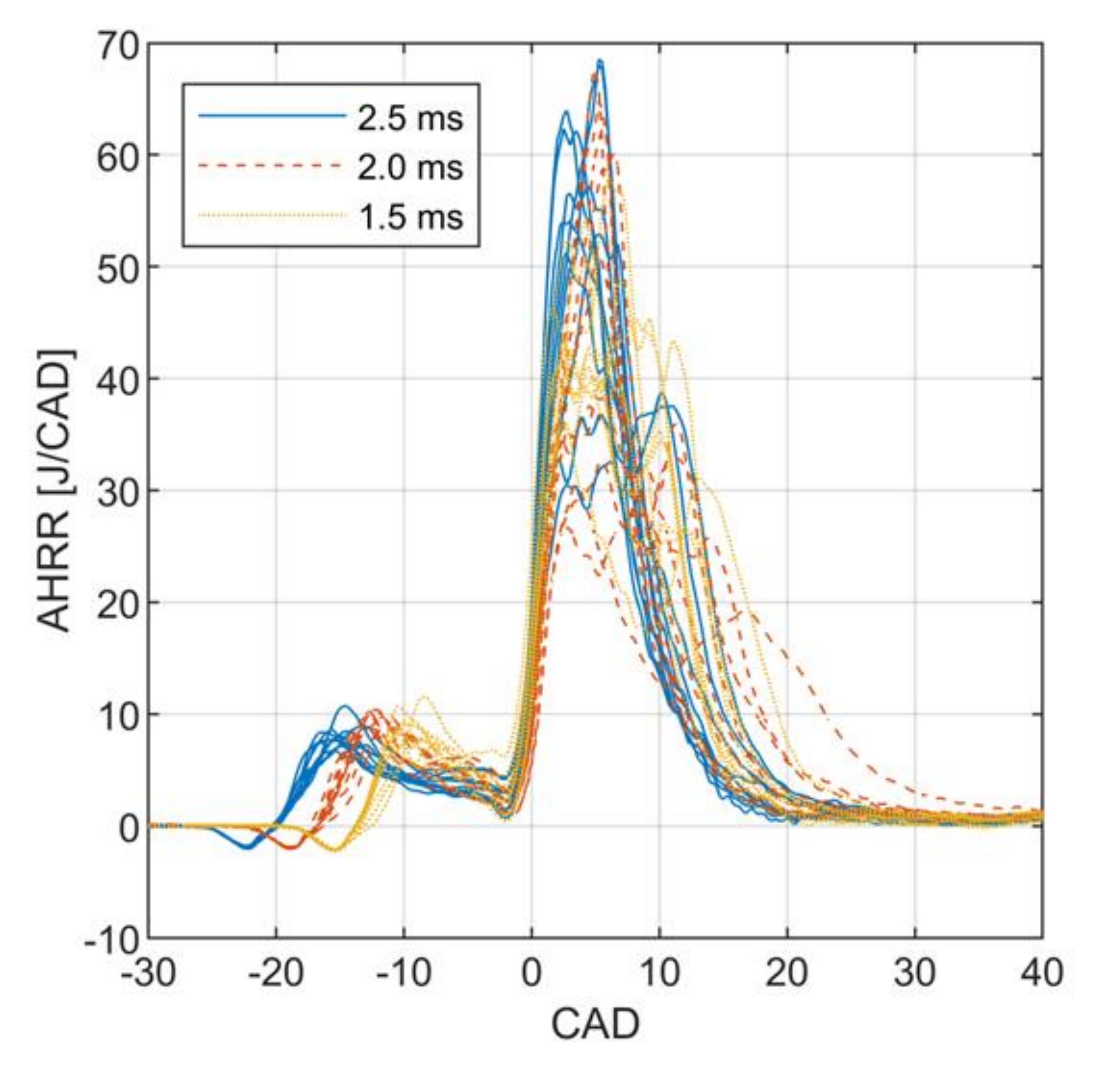


Number of fuel jets of the second injection with rapid ignition as a function of injection dwell for the narrow piston bowl. The error bands correspond to 95% confidence intervals based on cycle-to-cycle variability.

Background

1st Injection Ignition and Combustion (1.5 ms)

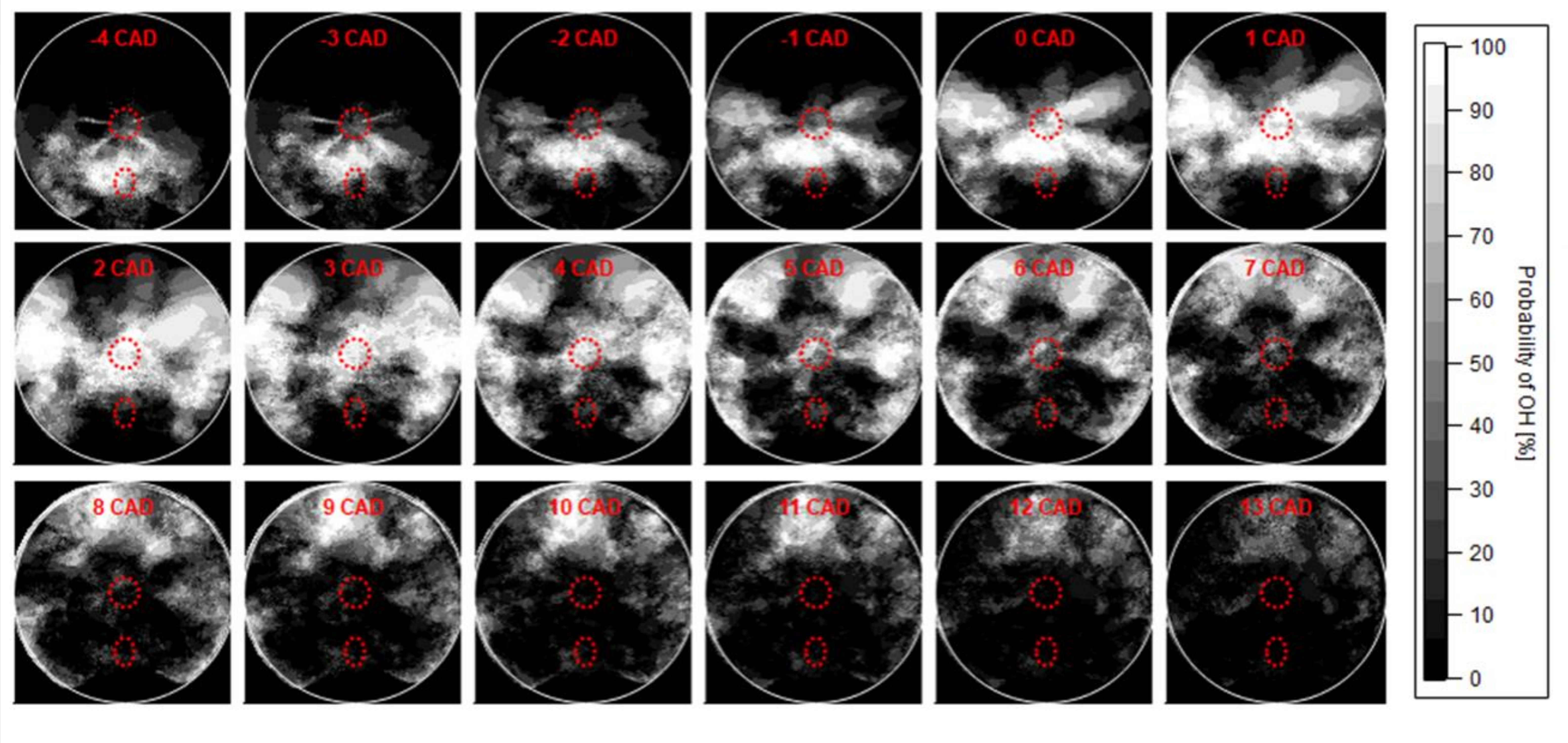


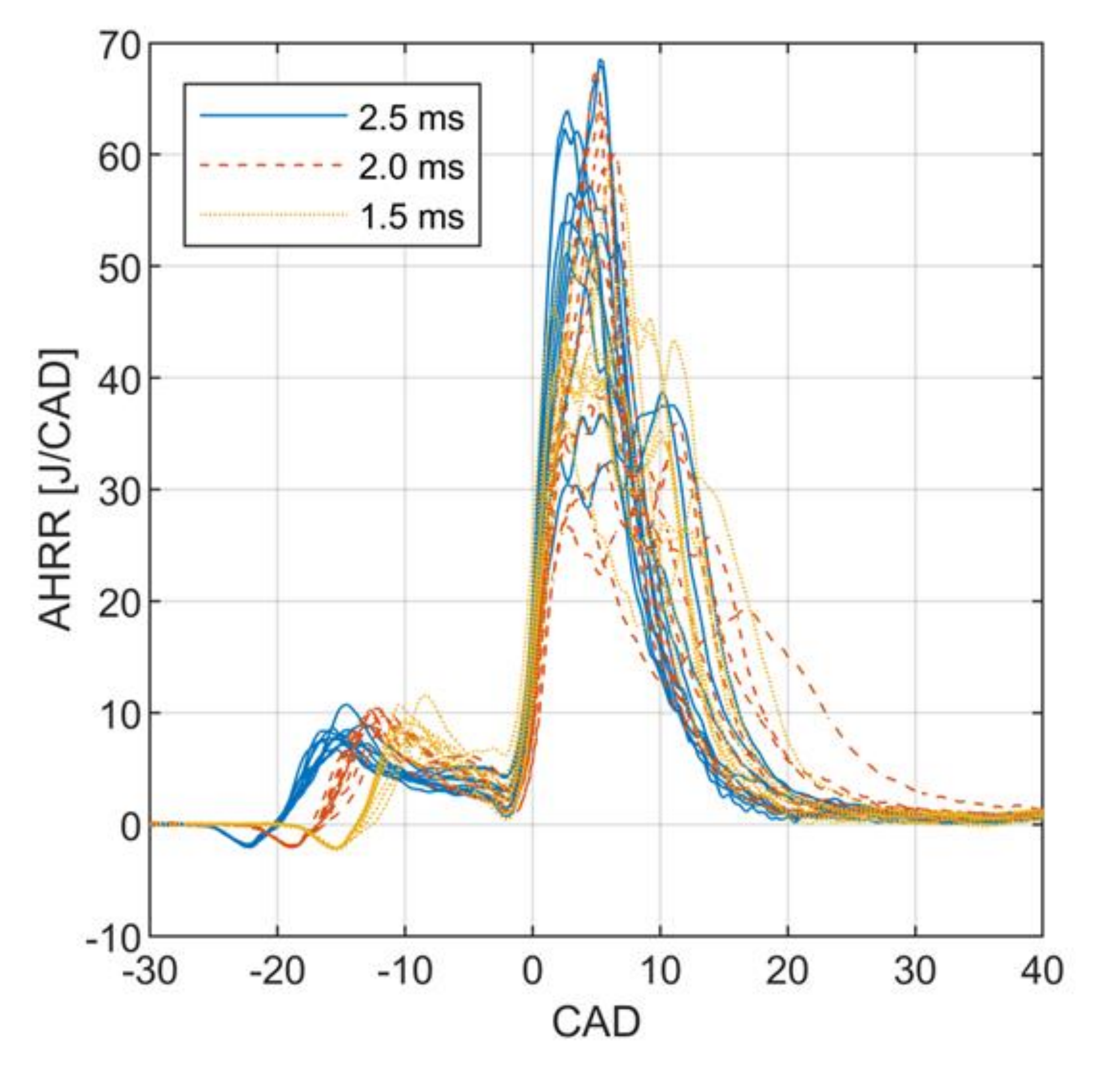


Relocation of 1st injection combusted gases did not reach the center of the combustion chamber close to the injector tip location

Background

2nd Injection Ignition (1.5 ms)





Hot combusted gases from the 1st injection positioned on the bottom of the injector tip enable rapid transition to mixing-controlled combustion of the 2nd injection for only 4 fuel jets

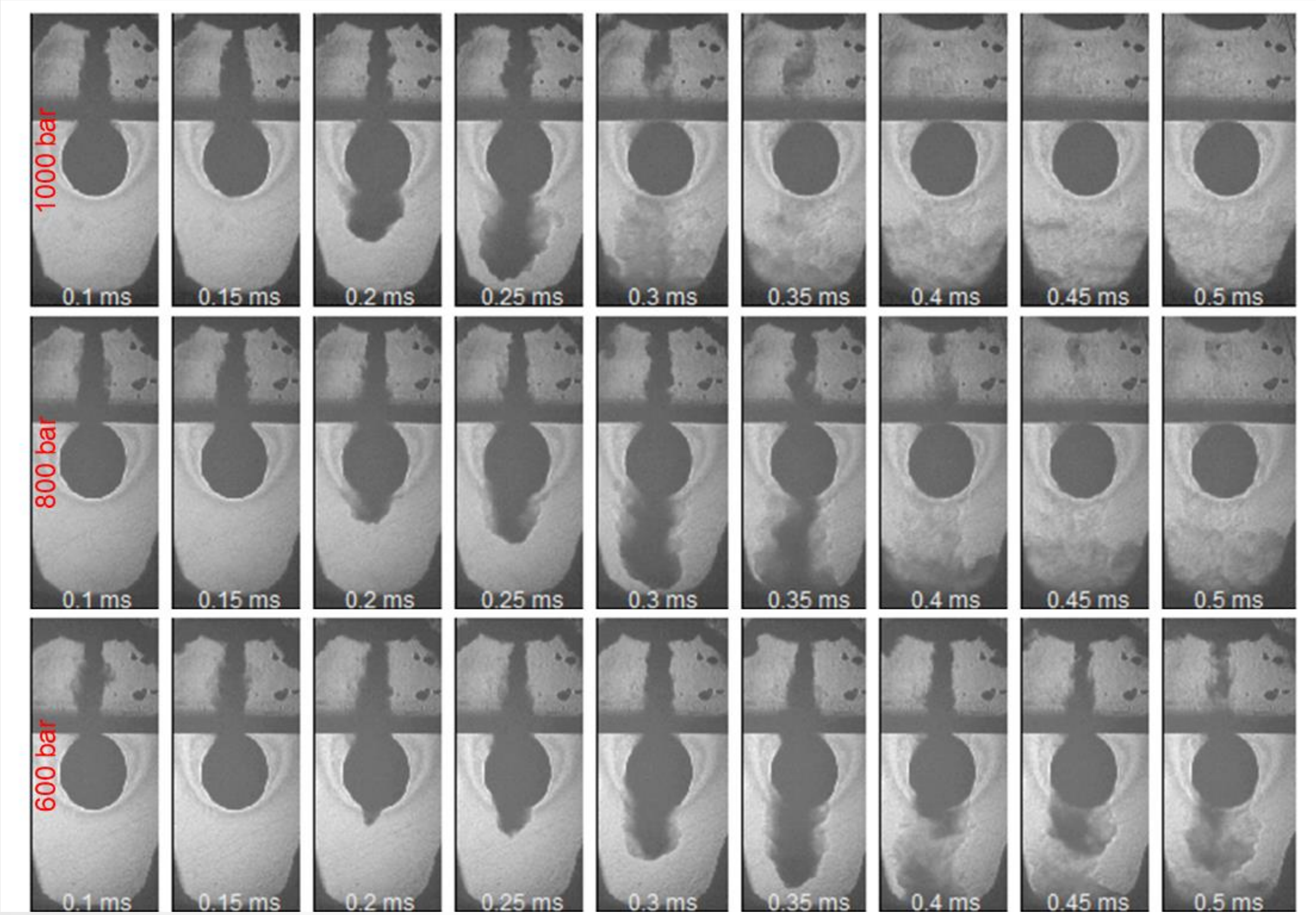
Results - Injection Pressure

Objective was to investigate how EACI split-injection strategies and alternative piston designs paired with higher injection pressures can enable mixing-controlled combustion of the 2nd injection for shorter dwell

- 1st injection studies for three hypothetical injection dwells (1.5, 2.0, and 2,5 ms)
- Three injection pressure (600, 800, 1000)
  - Injection pressures higher than previous experiments
- Higher injection pressures without alternative piston bowl leads to misfires of fuel jet in-line with ignition assistant
  - Fuel jet redirection from wave reduces misfires

Parameter	Units	2.5 ms	2.0 ms	1.5 ms
1st Inj. mass	mg	7	7	7
1st Inj. timing				
1000 bar	CAD	-26.25	-22.50	-19.00
800 bar	CAD	-26.50	-22.75	-19.25
600 bar	CAD	**-26.75**	-23.25	-19.75
2nd Inj. timing	CAD	-5	-5	-5

Results - Impacts on fuel jet inline W/ IA

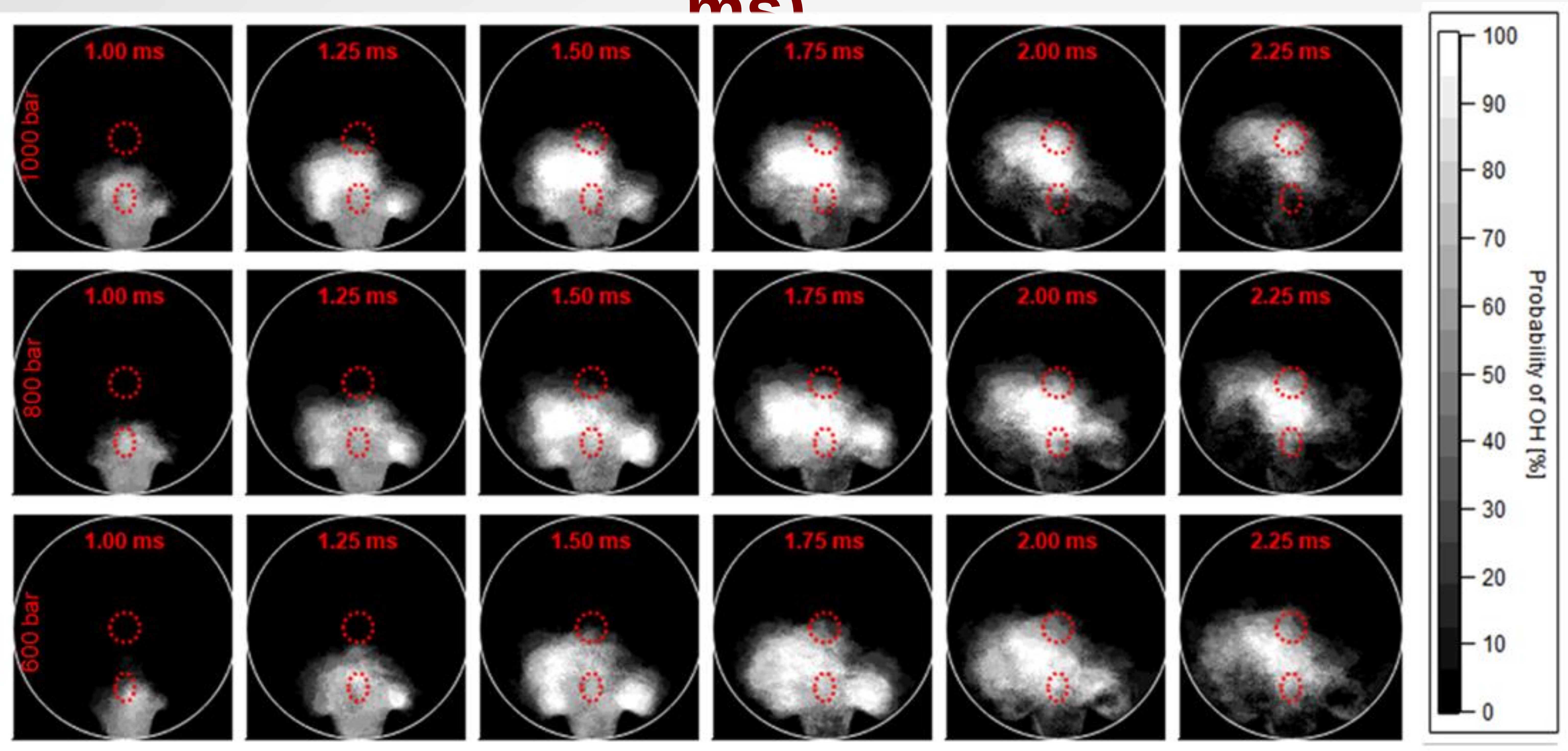


Schlieren images of the in-line fuel jet for all injection pressures, 1000 bar (TOP ROW), 800 bar (MIDDLE ROW), and 600 bar (BOTTOM ROW). For a 7.0 mg first injection with an injection dwell of 2.5 ms.

- **Residence time is critical for EACI hot surface ignition**
- **For all pressures, the fuel jet reaches the IA at the same time (0.10 ms)**
- **Injection duration for higher pressures are much shorter to achieve the same fuel mass**
- **1000 bar case the fuel jet is well past the IA by 0.30 ms , where for the 600 bar case the fuel is still in the vicinity at 0.50 ms**
- **Redirection for the wave piston bowl minimizes the residence time issue**
- **Redirected fuel mixture for the 1000 bar case reaches the IA at 0.5 ms**

Results – Relocation of hot gasses

1^{st} Injection Ignition and Combustion (2.5 ms)

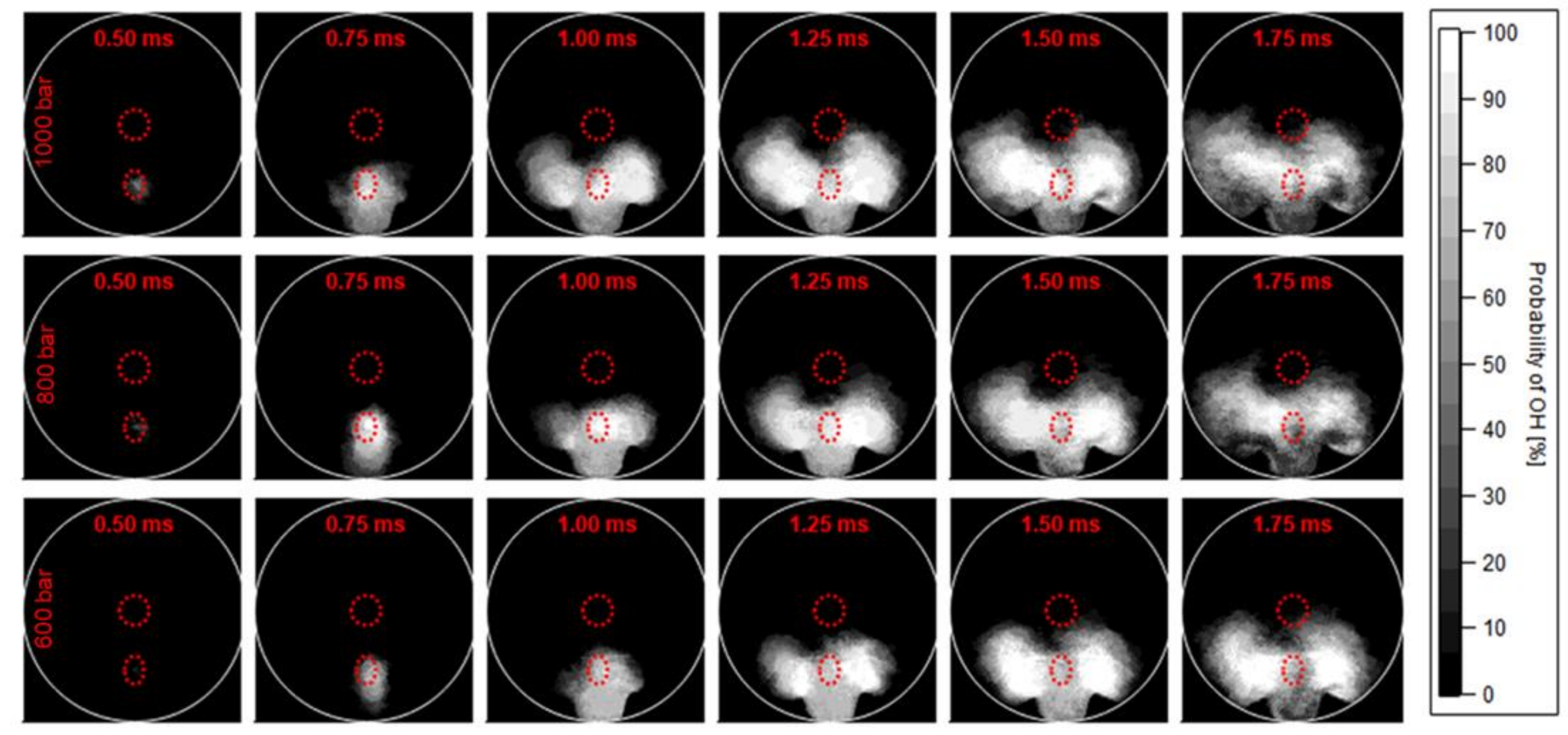


Ignition map images for time after first injection SOI with a dwell of 1.5 ms and injection pressure of 1000 bar (TOP ROW), 800 bar (MIDDLE ROW), and 600 bar (BOTTOM ROW).

- **Combustion is phased earlier with higher injection pressure**
  - **Faster azimuthal jet-to-jet propagation**
  - **Further propagation toward the injector**
- **Location of combusted gases is concentrated closer to the injector for the higher injection pressure**
- **At this 1^{st} injection timing for the 1000 bar case an injection dwell of 1.5-1.75 ms would produce similar 2^{nd} injection mixing-controlled results than a 2.5 ms dwell for the 600 bar case**

Results – Relocation of hot gasses

1st Injection Ignition and Combustion (1.5 ms)



Ignition map images for time after first injection SOI with a dwell of 1.5 ms and injection pressure of 1000 bar (TOP ROW), 800 bar (MIDDLE ROW), and 600 bar (BOTTOM ROW).

- Combustion is phased earlier with higher injection pressure
- Faster azimuthal jet-to-jet propagation
- Further propagation toward the injector
- At retarded injection timing relocation is still not ideal even with higher injection pressures
- Higher injection pressure relocated more gases close to the injector and would improve the number of 2nd injection jets going through mixing-controlled combustion

Key findings and conclusions

- A custom wave piston bowl design allows for EACI operation at higher injection pressure due to the piston wave features' redirection of the inline fuel jet
- At shorter injection dwells, higher injection pressure can be used to accelerate the combustion process
- Combustion propagation is highly dependent on in-cylinder conditions at SOI. As in-cylinder density at first injection SOI increases, less combustion is observed toward the center of the combustion chamber, and more azimuthal jet-to-jet propagation is observed

Questions?