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Sandia Hydrogen-Fueled Internal Combustion Engine Research

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Sponsor: DOE Office of FreedomCAR and Vehicles Technologies Program
Program Managers: Gurpreet Singh and Kevin Stork

Boeing Visit
Sandia National Laboratories, Livermore, CA
December 6, 2005.

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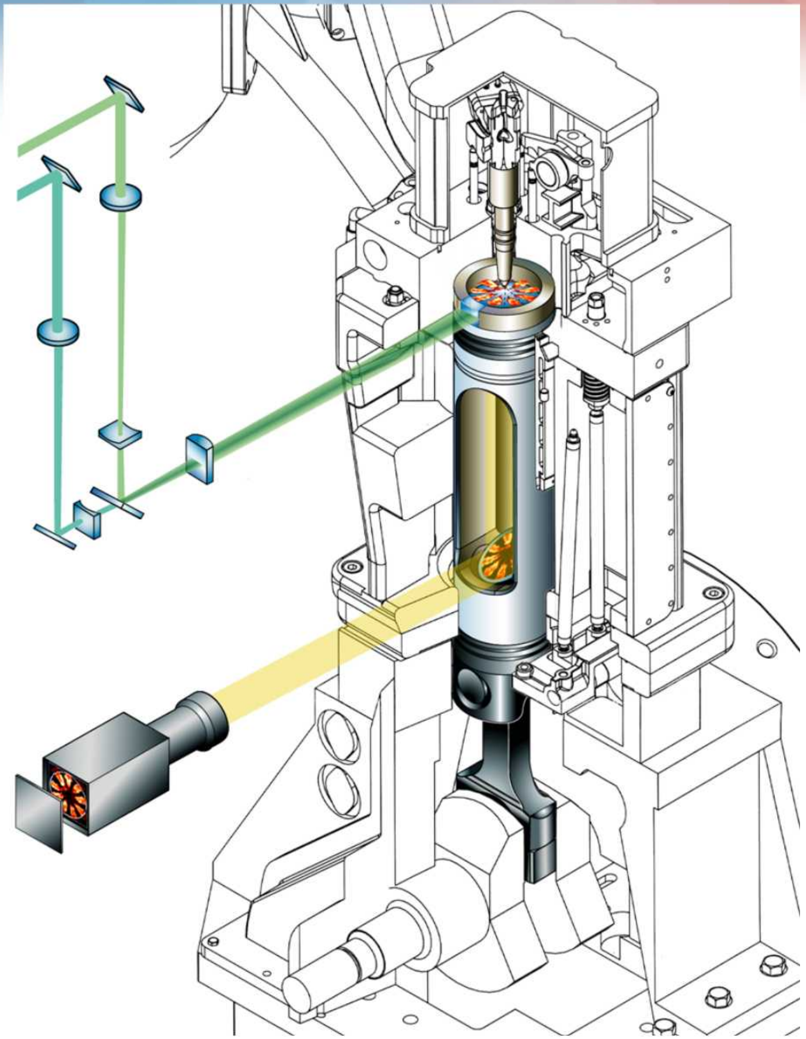
Research Approach of the Engines Group

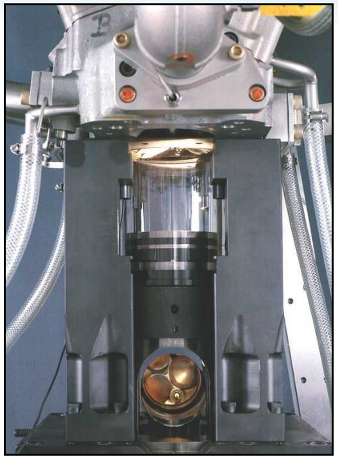
Mission:
Conduct fundamental research to understand critical in-cylinder engine processes.



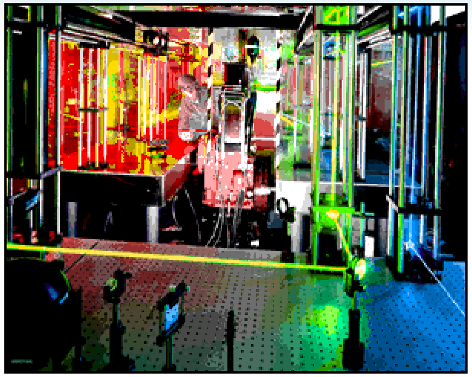
Approach:
- Laser based optical diagnostics
- Realistic engine conditions
- Realistic engine geometries with

Optical access through:
- Pistons
- cylinder liner
- spacer plates
- exhaust ports

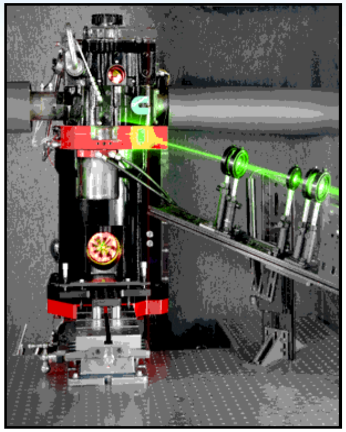
Engine Combustion Research Projects



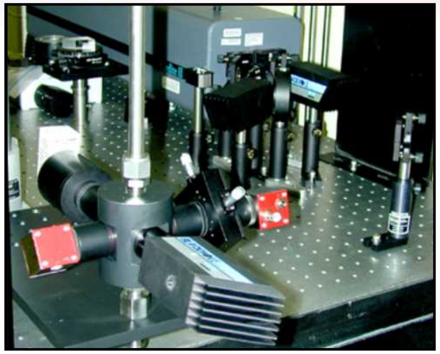
Automotive HCCI



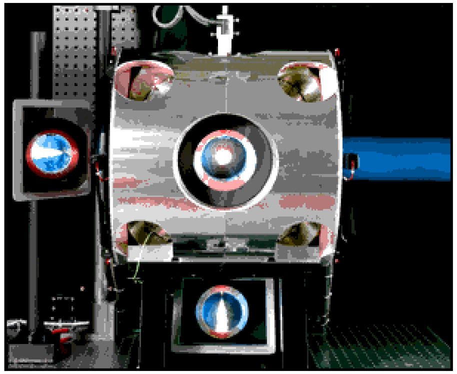
Fuels



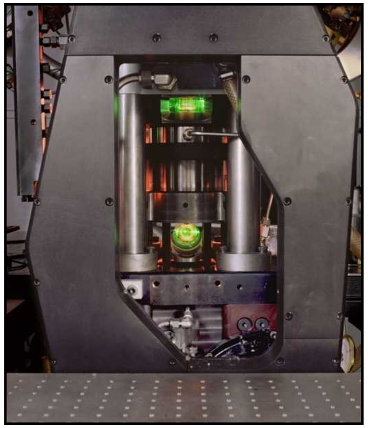
Heavy-duty



PM diagnostics

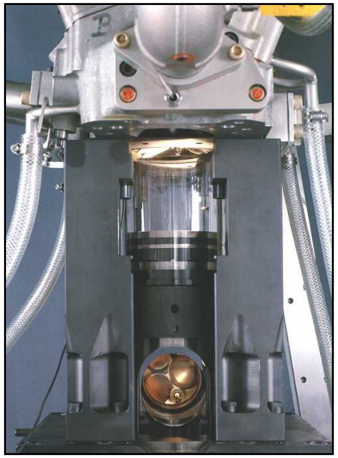


Diesel/LTC



HSDI

HCCI Fundamentals



H_2ICE

H_2ICE Project Overview

- **H_2ICEs are part of DOE's transitional strategy towards a hydrogen economy.**
  - technology is available today and economically viable in the near-term.
  - fewer constraints concerning H_2 storage compared to fuel cells.
    - relative ease of a dual-fuel option (H_2/gasoline).
    - amenable to high temperature metal hydrides.
    - impurities are a non-issue.

- **DOE's near-term goals for the H_2ICE:**
  - peak brake thermal efficiency (BTE) ≥ 45%.
  - Tier2/bin5 emissions or better (NO_x ≤ 0.07g/mile).
  - power densities greater than present-day gasoline engines.

- **Research is required to resolve technical barriers to meet these goals.**
  - fundamental research of in-cylinder combustion and transport processes.
  - NO_x emissions and control.
  - investigate advanced H_2ICE concepts and related technical issues:
    - <u>pressure boosting</u> (preignition, CR effects, heat transfer, etc)
    - <u>direct-injection</u> (in-cylinder mixing, injector durability, etc)

- **Project is relatively new (December 2003)**

Interactions

- Sponsor: DOE Office of FreedomCAR and Vehicles Technologies Program

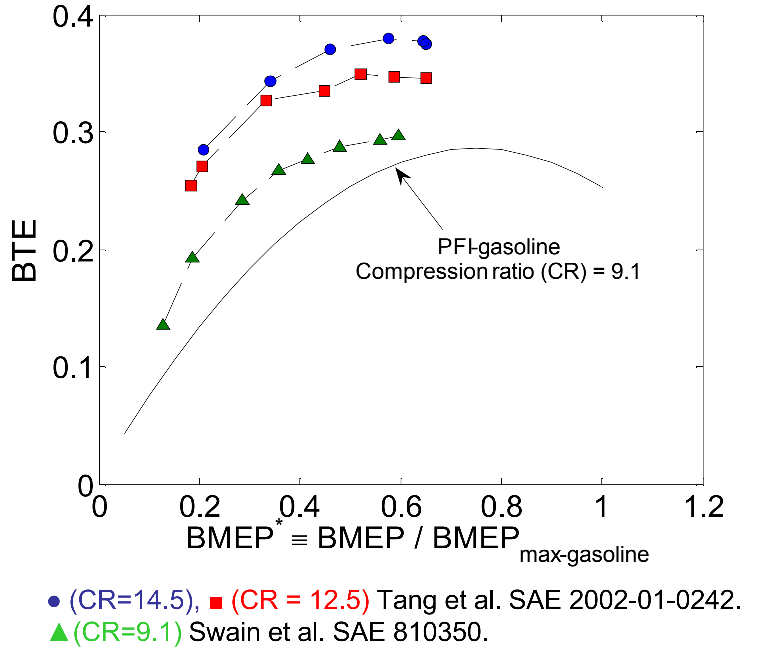
- Project is conducted in close collaboration with Ford Motor Company (only FreedomCar partner with a clear interest in H_2ICEs).

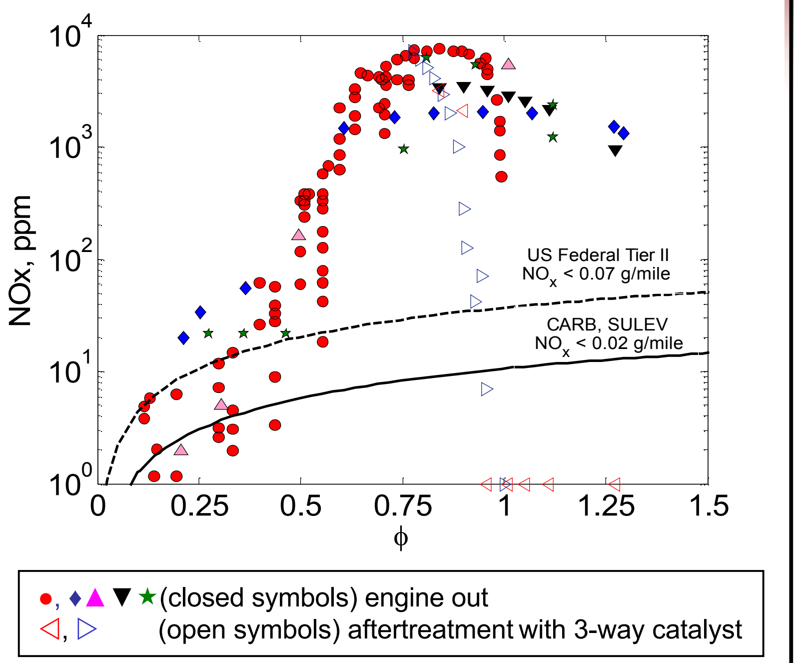
- Collaborate within the European Research Project HyICE (Optimizing Hydrogen Powered Engines) through a non-disclosure agreement.

U.S. HyICE Partners

European HyICE Partners

Present day H_2ICEs





Compared to gasoline-fueled ICEs, present day H_2ICEs have:

- higher thermal efficiencies.
- lower power densities.

Can operate with near-zero emissions:‡

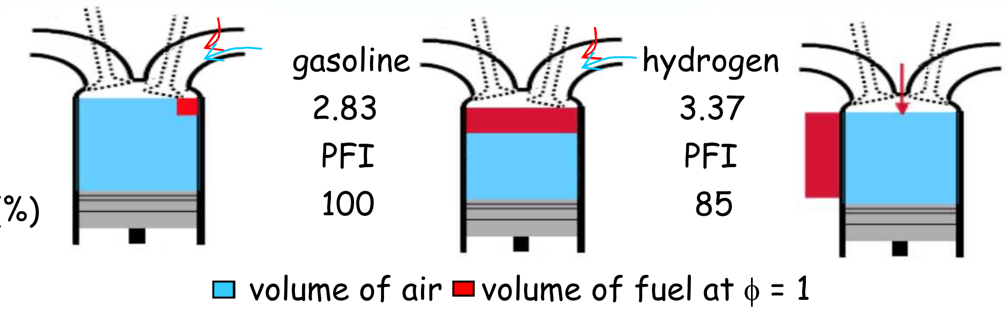
- operate ultra-lean (ϕ < 0.45).
- operate at stoichiometry (ϕ = 1) with aftertreatment.

‡NO_x is essentially the only non-zero air pollutant emission from a H_2ICE.

Motivation (Need for Advanced H_2ICEs)

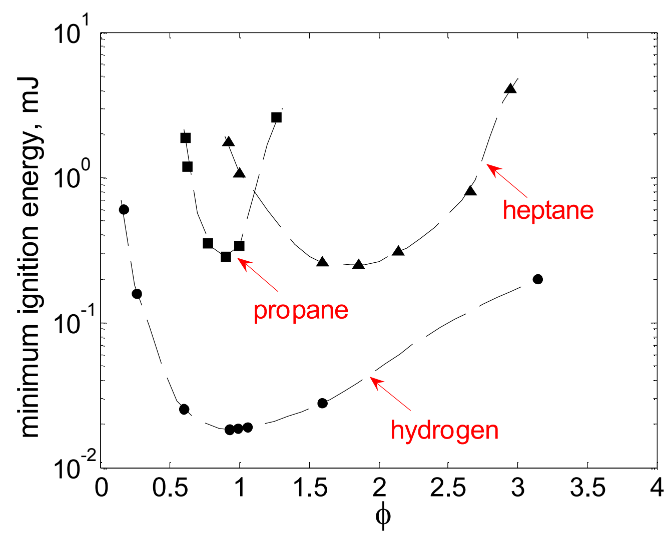
1. Improve power density relative to conventional port-fuel-injection (PFI).

fuel	gasoline	hydrogen	hydrogen
heat of combustion (MJ/kg of air at ϕ =1)	2.83	3.37	3.37
Mixing	PFI	PFI	DI
Power related to gasoline (%)	100	85	115



2. Minimize undesired combustion (preignition and backflash).

- H_2 is predisposed to pre-spark combustion (i.e., preignition from engine hot-spots).
- Difficult to operate a PFI-H_2ICE near ϕ = 1 without preignition problems (further reduction in peak-power).



Some Advanced H_2ICE Options

- **Pressure-boosted-H_2ICE (turbocharging/supercharging of intake air)**
- **Liquid-hydrogen-fueled-H2ICE (hydrogen stored onboard as a liquid)**
- **Direct-injection-H_2ICE (H2 injected after intake valve closing (IVC))**
  - improves maximum power (no displacement of intake air).
  - minimize preignition events with late injection (less time for combustible mixture to preignite).
  - increased degrees of freedom (multiple injection, start of injection (SOI), among others).
- **H_2ICE-electric hybrid (H2ICE in parallel or series with an electric motor)**
- **Super-advanced-H_2ICE (combination of advanced H2ICE options)**

Approach

■ **Establish a state-of-the-art laboratory to investigate in-cylinder H_2ICE combustion and emissions processes.**

• increase efficiencies • increase power output • decrease emissions

■ **Focus is direct injection of H_2 in cylinder (DI-H_2ICE).**

– most promising advanced H_2ICE concept (i.e. many degrees of freedom).

■ **Use optical diagnostics in-cylinder to build a detailed understanding of H_2ICE mixing, combustion and emissions processes.**

– OH* chemiluminescence: flame development, flame speed, preignition, knock and qualitative measure of local ϕ.

– planar laser induced fluorescence (PLIF): quantitative measure of local ϕ and in-cylinder NO_x formation.

– particle image velocimetry (PIV): in-cylinder fluid motion effects and hydrogen jet development.

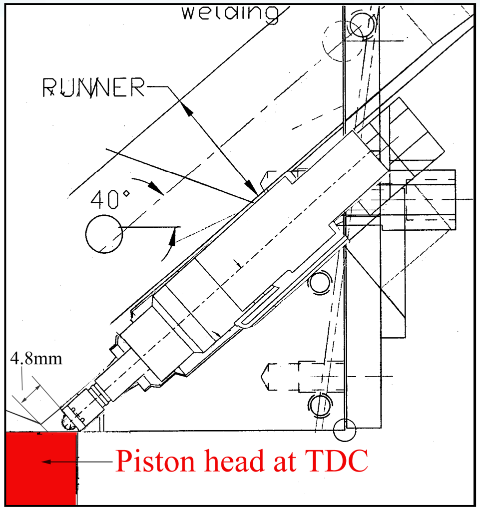
■ **Couple experiments with Large Eddy Simulations (LES).**

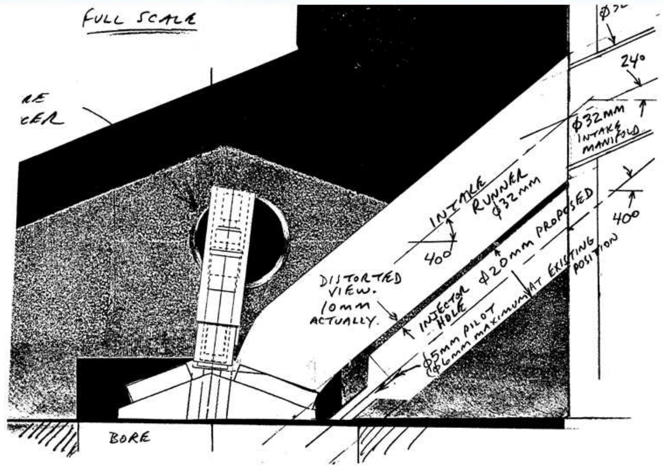
– improved understanding of fundamental physics.

Sandia H_2 Research Engine

- GM single-cylinder head
  - 4 valves, central spark plug
  - CR: 9.1 (flat piston)
- Sandia drop down optical cylinder
  - interchangeable quartz liner
  - interchangeable quartz piston
- Hydrogen fueling
  - pre-mixed (in progress)
  - port fuel injection (PFI)
  - side direct injection (DI)

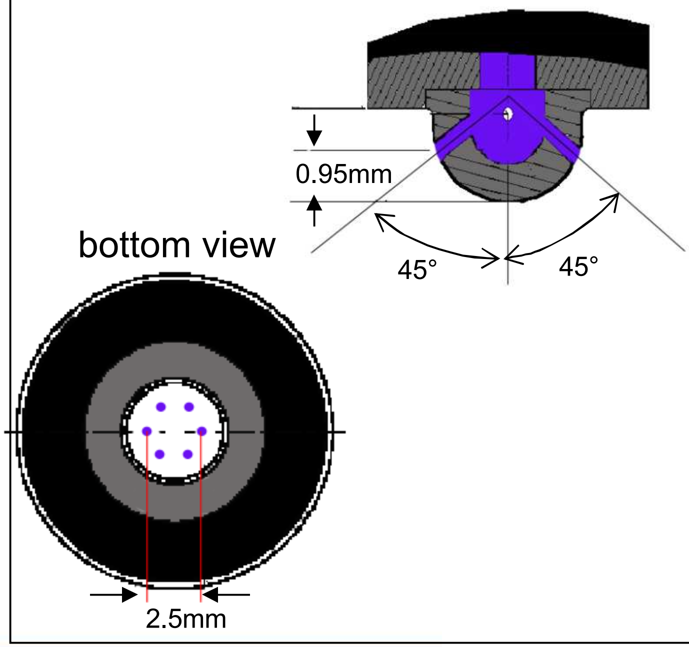
H_2 In-cylinder Direct Injection

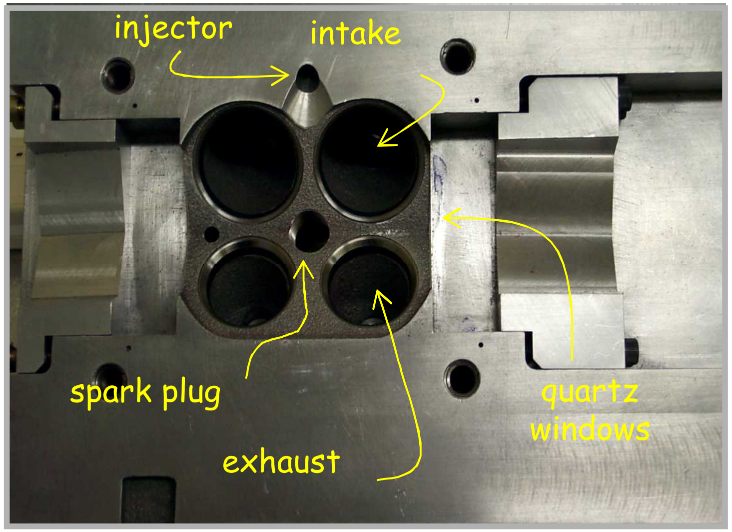




Injector-tip

- tip, 4mm diameter spherical-cap
- six hole, D = 0.56mm
- separation = 1.31mm
- jet angles 45° wrt to injector axis





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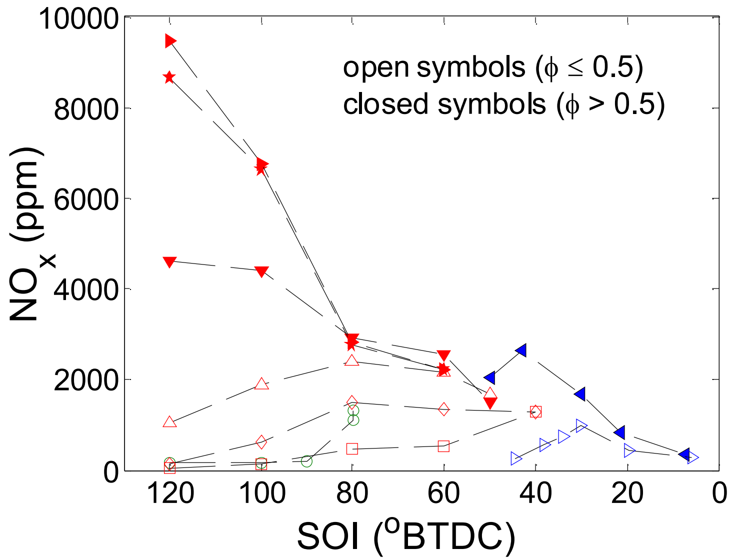
DI-H_2ICE Technical Challenges

- **Hardware: high-pressure high-flow H_2 injector (durability issues).**
  - Westport Innovations (experimental prototype)
  - working pressures: 100 – 2200 psi / flow rates: 0.2 – 4.5 g·s^{-1}

- **Mixing:**
  - maximum mixing times (SOI at IVC) **20–4 ms** over speed range 1000–5000 rpm.
  - preignition is minimized with late injection (post IVC) but **mixing times are reduced**.
  - optimization of the many degrees of freedom: (SOI, duration, pressure, multiple, etc..).
  - effect of mixture inhomogeneities is non-trivial (see figure below).

Engine-out NO_x concentration verses SOI from various studies.

- NO_x concentration increases with retard of SOI in some data sets, and decreases in others.



Similar effects on BTE, therefore it is critical to develop a knowledge base of in-cylinder transport processes.

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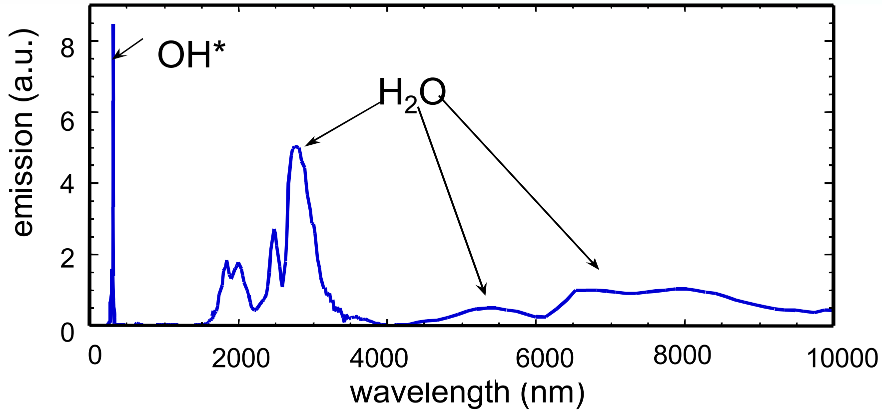
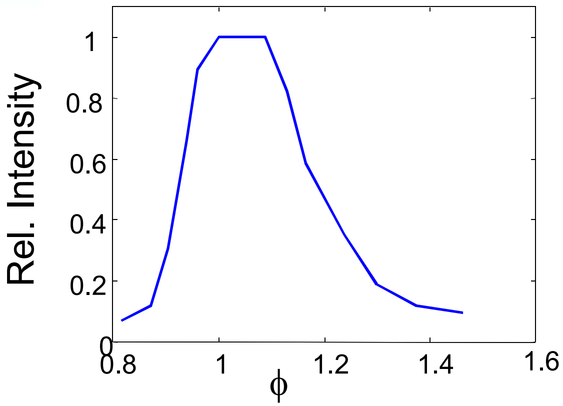
OH* Chemiluminescence

Emission spectra of a hydrogen-air flame
(courtesy of B. Patterson & B. Schefer)



Y. Ikeda et al.,
SAE 2001-01-0919



- **OH* is a combustion intermediary that tracks heat-release (i.e. flame front) and does not require external excitation.**
- **OH* has a unique emission spectra.**
- **OH* intensity correlates with fuel/air ratio (Q: can we extrapolate a line-of-sight averaged local ϕ).**

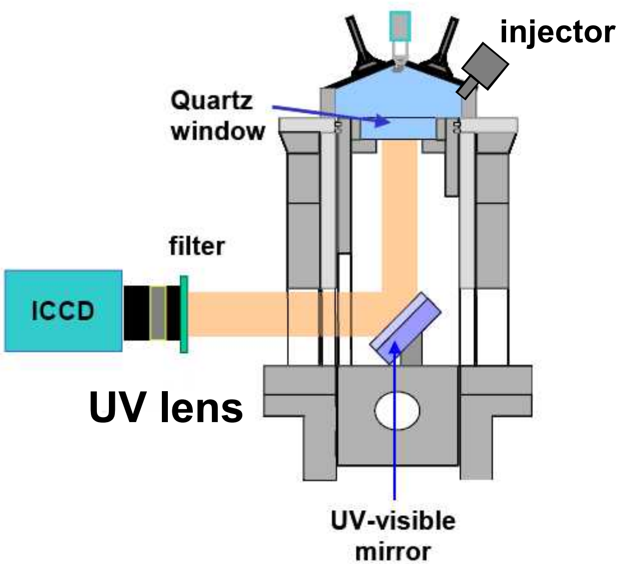
OH* Chemiluminescence in a DI-H_2ICE

Investigate

- In-cylinder mixing and flame development for various injection strategies.
- How does mixture formation at combustion affect IMEP and cycle variability.
- Qualitative measure of in-cylinder local ϕ.

Operating point: 800 and 1200 rpm, MAP ≈ 50kPa, $\phi \approx 0.6$, Coolant T = 80 ºC.
Burst Fired Scheme: 12 total cycles, 9 motored and 3 fired consecutively.
Imaging: Acquired on 3rd fired cycle with 10-20 images acquired per CAD.

experimental setup

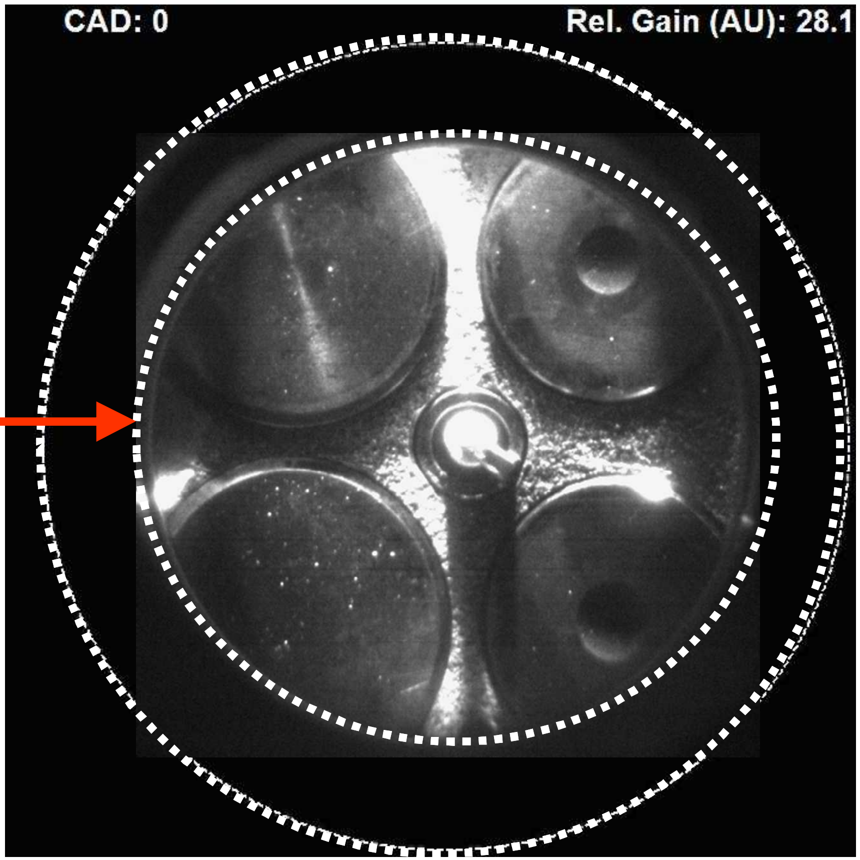


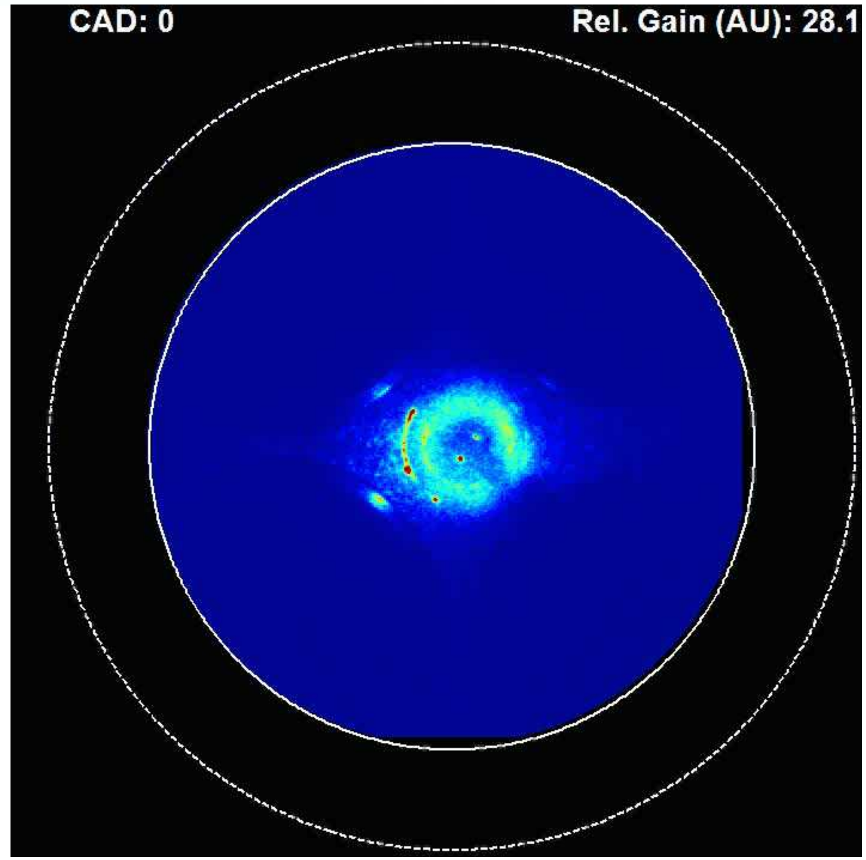
Case (SOI/EOI)	Description
(1) 270/240	"pre-mixed" $0.45 < \phi < 0.95$
(2) 110/80 Pinj = 20 bar	early injection low-pressure
(3) 110/101 Pinj = 100 bar	early injection high-pressure
(4) 60/30 Pinj = 20 bar	late injection low-pressure
(5) 39/30 Pinj = 100 bar	late injection high-pressure

OH* Movies (Ensemble Averaged)

Inner circle: quartz piston, d = 65.5 mm
Outer circle: cylinder bore, d = 85.9 mm

Case 1: SOI270/EOI240
"premixed" inject during intake stroke

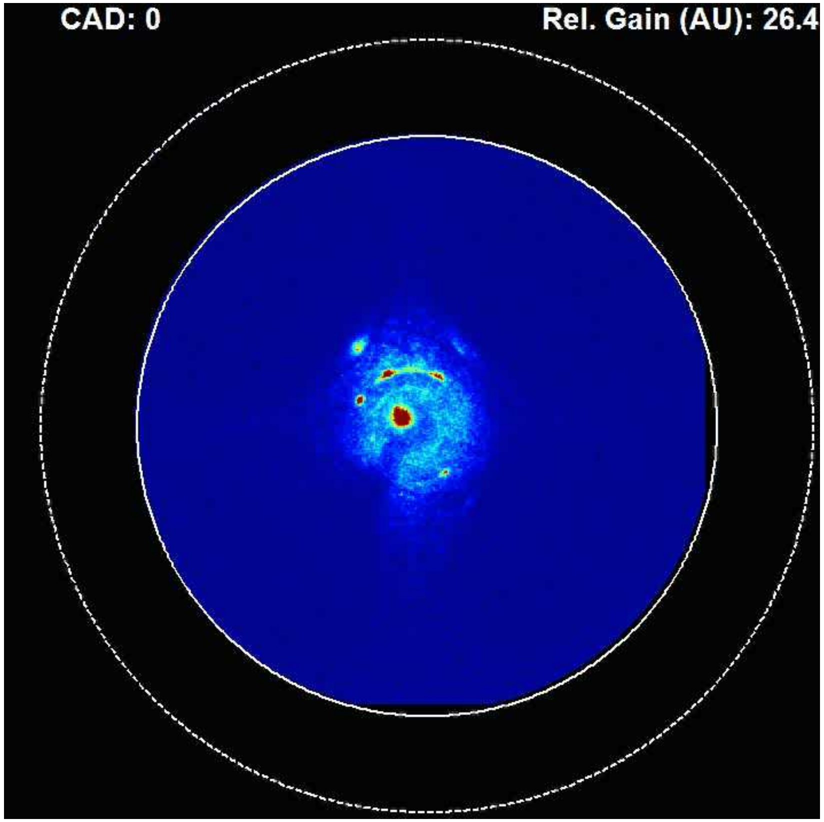




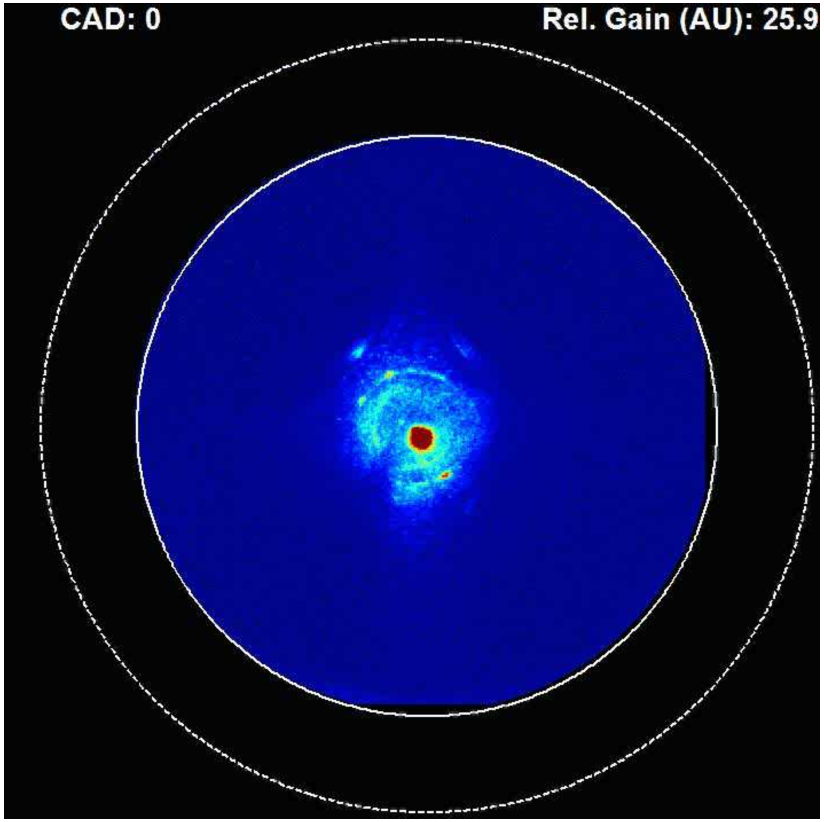
location of H_2 injector

OH* Movies for DI-H2ICE (Ensemble Averaged)

Case 2: SOI110/EOI80
early-injection, Pinj = 20 bar

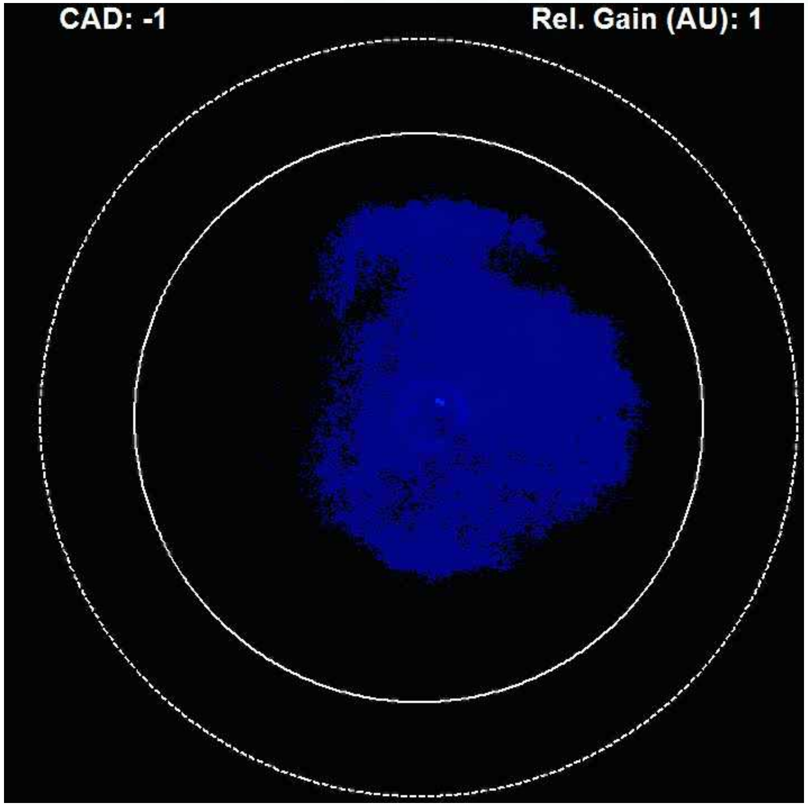


Case 3: SOI110/EOI101
early-injection, Pinj = 100 bar

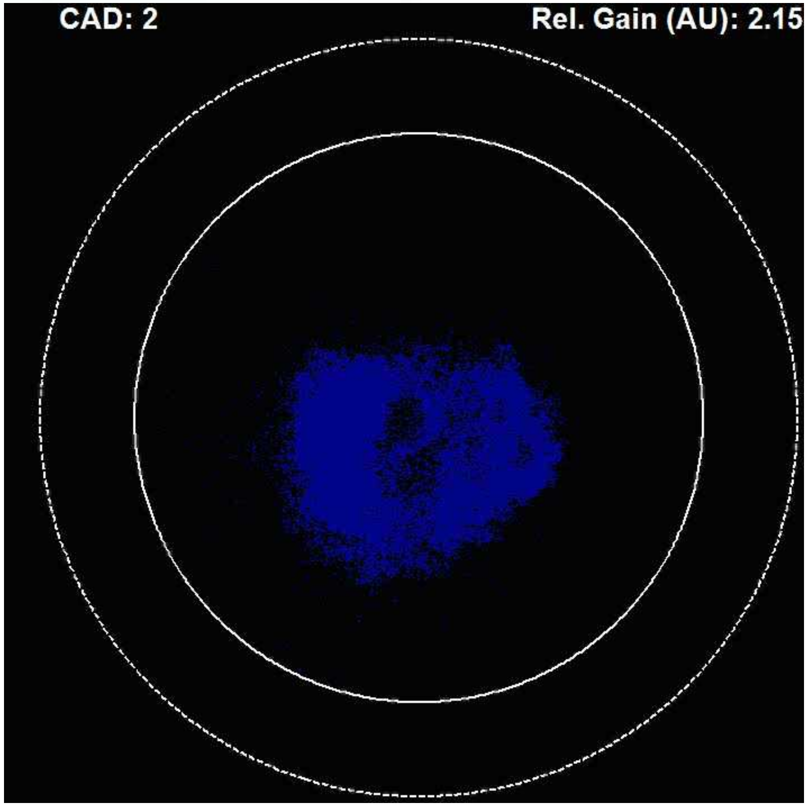


OH* Movies for DI-H2ICE (Ensemble Averaged)

Case 4: SOI60/EOI30
late-injection, Pinj =20 bar



Case 5: SOI39/EOI30
late-injection, Pinj=100 bar



NOTE: Cycle-to-cycle OH* intensity is widely variable for late injection (see next slide). Interpretation of the ensemble average is not straightforward.

MODELING WILL HELP INTERPRETATION

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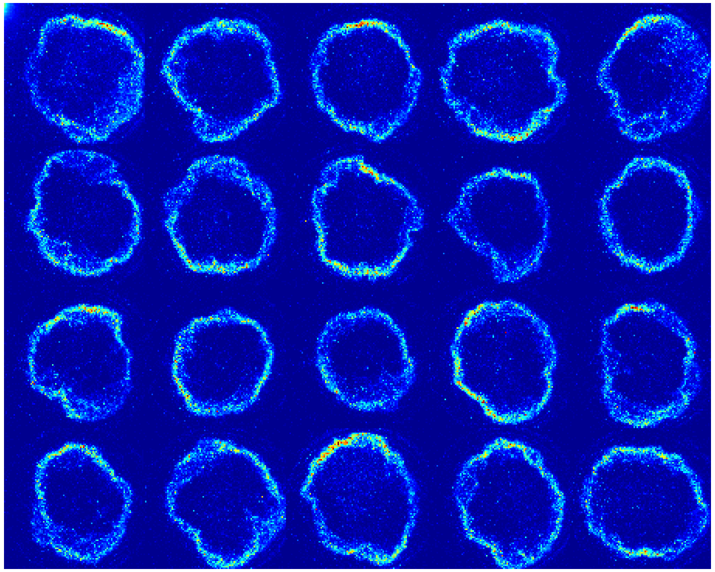
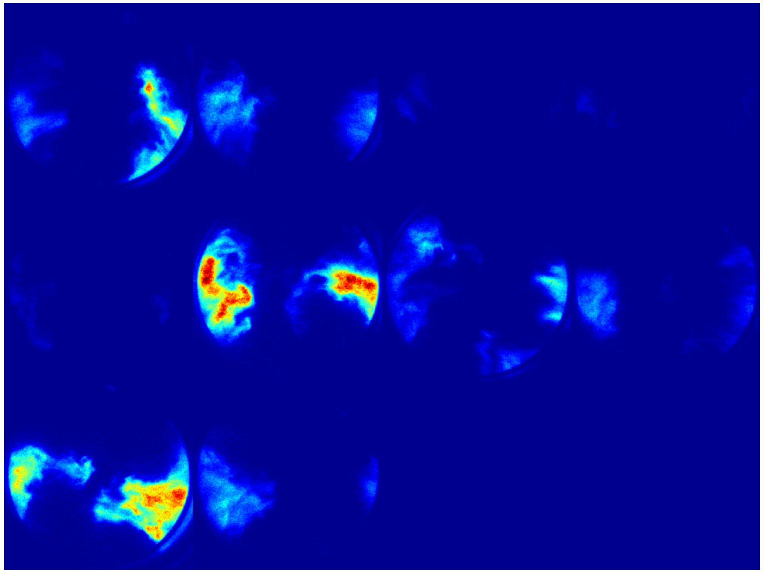
Cycle-to-Cycle Variability

Case 1 (20 Images at 8 CAD):
"premixed", low-pressure, GAIN = 20



Case 5 (10 Images at 12 CAD):
late-injection, high-pressure, GAIN = 1



CASE	SOI/EOI	IMEP	COV_{IMEP}
1	270/240	200 kPa	1.1%
2	110/80 (LP)	238 kPa	1.7%
3	110/101 (HP)	234 kPa	1.7%
4	60/30 (LP)	231 kPa	2.4%
5	39/30 (HP)	235 kPa	1.4%

- "Premixed" case is extremely consistent.
- Case 5 is widely variable.
  - importance of a few cycles
- Only small differences in COV_{IMEP}.
  - high flame speed of hydrogen

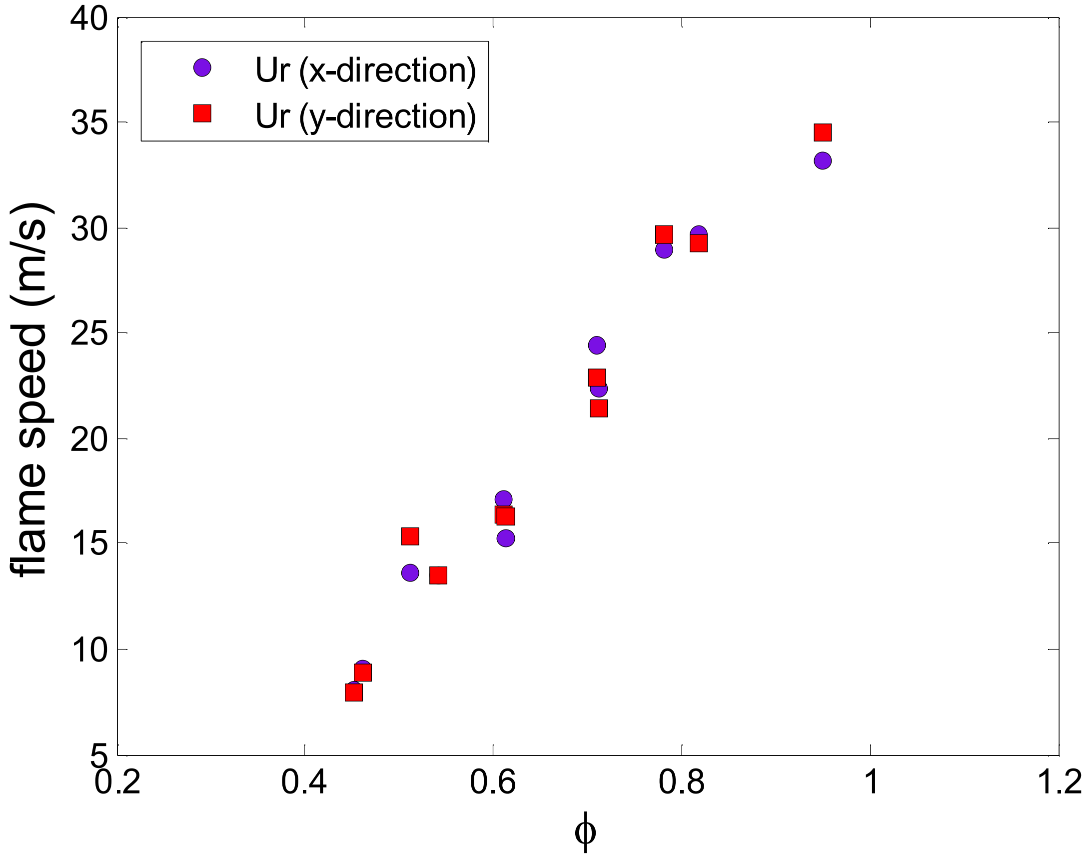
Quantitative OH* Chemiluminescence

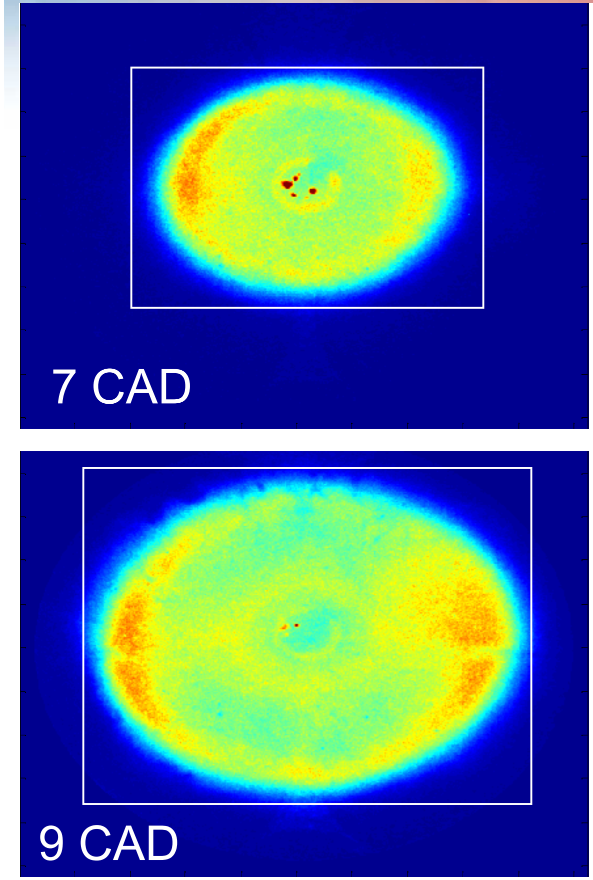
- **Qualitative OH* chemiluminescence provides valuable information.**
  - assessment of mixture formation and injection variables
  - cycle-to-cycle variability

- **Quantitative OH* chemiluminescence provides more information.**
  - measure of flame speed
  - measure of local equivalence ratio

Next few slides introduces some preliminary work done on quantitative OH* chemiluminescence

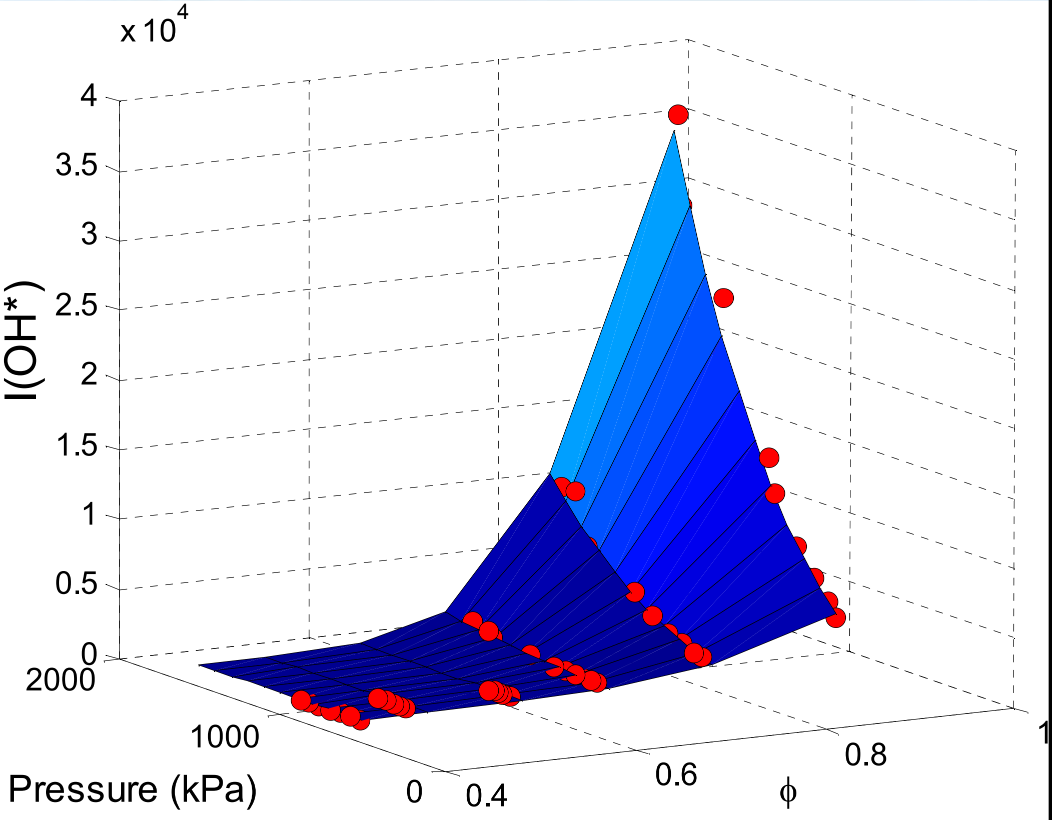
Measure of Average Flame Speed





$$\text{flame speed} = \frac{\Delta\,\text{bounding box}}{\Delta\,\text{CAD}} = \frac{dx}{dt} = \left(e.g.\frac{56\ \text{pixels} \times 133\,\mu\text{m per pixel}}{2.78\times10^{-4}\,s} \right) = 26.8\ \text{m/s}$$

Empirical Function Form of I(OH*)



From "premixed" data where ϕ, *P* and *I(OH*)* are known (●), using non-linear least squares regression we find:

$$I(OH^*) = AP^B \exp(CP^D \phi)$$

then

$$\phi = \frac{\ln\left(I(OH^*)/AP^B\right)}{CP^D}$$

uncertainty $\pm$ 6%

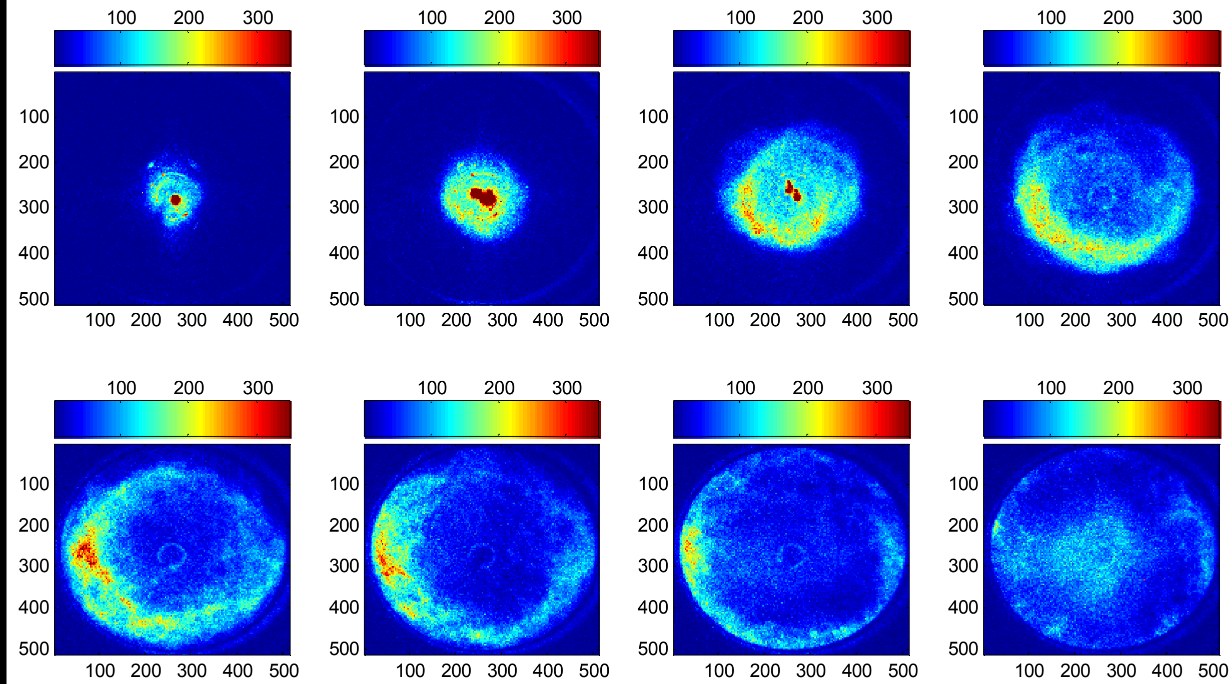
From I(OH*) and P we can gain a semi-qualitative measure of local ϕ.

Early direct injection

ϕ_{global} = 0.56

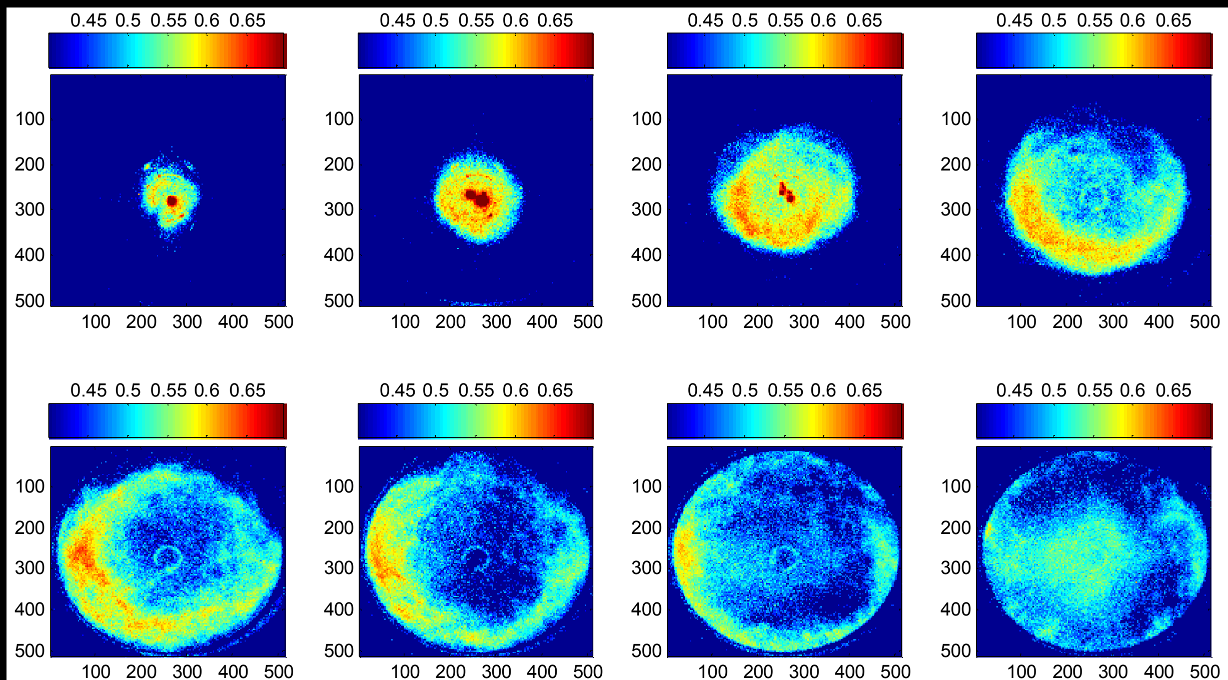
Intensity Images at CAD:

0, 2, 4, 6, 8, 10, 12, 14



Corresponding Inverted ϕ images at CAD:

0, 2, 4, 6, 8, 10, 12, 14



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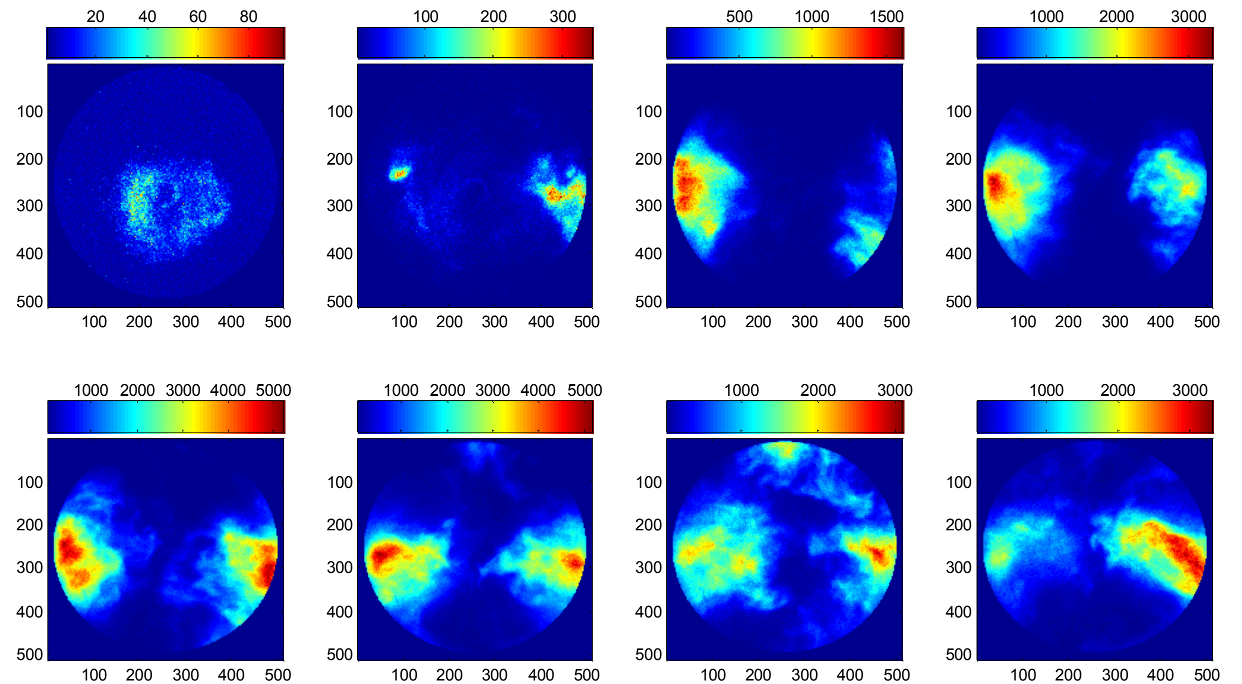
Late direct injection

$\phi_{global} = 0.56$

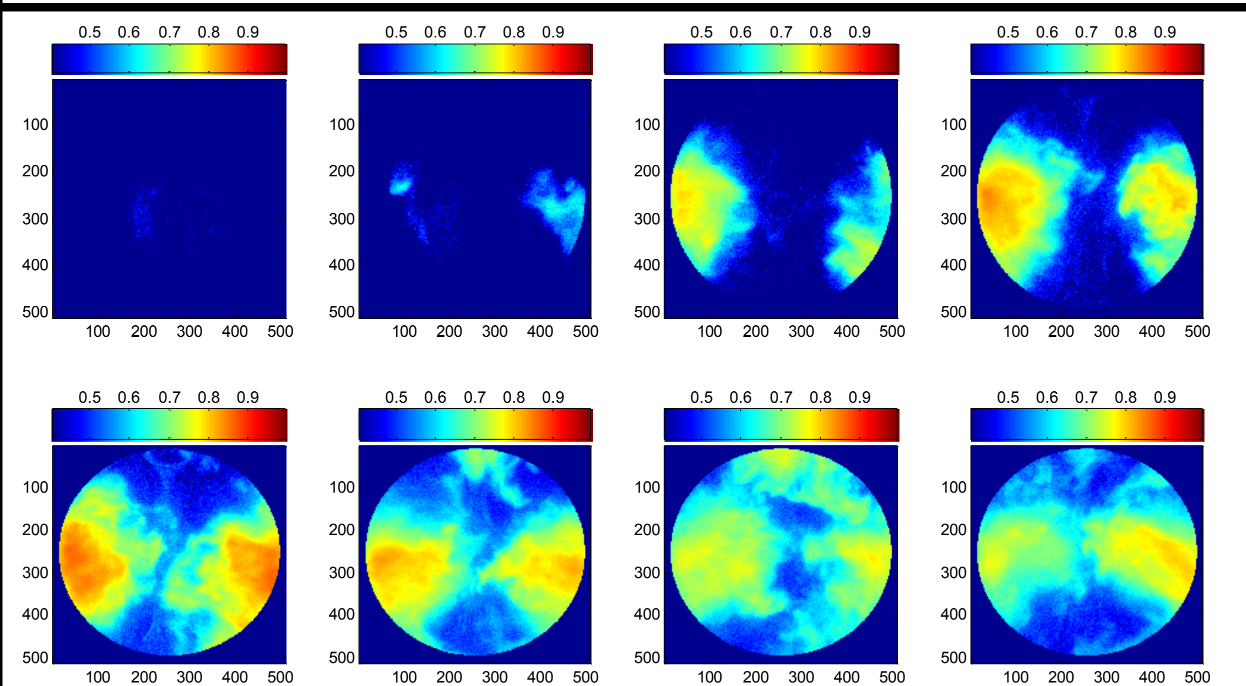
Intensity Images at CAD:

2, 4, 6, 9, 12, 16, 20, 24



Corresponding Inverted ϕ images at CAD:

2, 4, 6, 9, 12, 16, 20, 24



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Future Plans

- **Primary focus remains to develop a fundamental understanding of in-cylinder H_2-air mixing processes and the evaluation of various DI strategies.**

- **Diagnostics to be used:**
  - Particle Image Velocimetry (PIV) ⇒ in-cylinder velocity vectors.
  - Planar Laser Induced Fluorescence (PLIF) ⇒ pre-combustion local ϕ.
  - Chemiluminescence imaging ⇒ combustion/post-combustion local ϕ.

- **Implementation of a NO_x emissions bench:**
  - time averaged emissions measurements (many cycles)
  - investigate methods to measure cycle-resolved NOx emissions (assumption is that a few cycles are responsible for producing high time-averaged NO_x emissions).

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