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Equivalence Ratio and Flame Structure Measurements in an LP Aero-engine Injection System under Relevant Operating Conditions

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Context and objectives

- Pollutant emissions** : first-order parameter in the design of aircraft engines.
 - ACARE: 50% CO₂ reduction*, 80% NO_x diminution* (Vision 2020) *Compared to 2000
 - Implies fuel consumption reduction and combustion efficiency improvement.
- Innovative engine technologies using state-of-the-art injection technology such as **Lean Premixed (LP)** have been designed to meet future requirements.
- An understanding and modelling of the various physical and chemical phenomena and their interactions in the combustion chambers are required to design these innovative injection systems.
 - Nowadays, only global pollutant emissions are measured.
 - What happens inside the combustion chamber?

The industrial chair PERCEVAL goal is to develop and apply laser-based diagnostics for acquiring in-situ quantitative concentrations in aeronautical combustion chambers.

OH-PLIF analysis

- Absorption correction and quantitative analysis on mean OH-PLIF images**

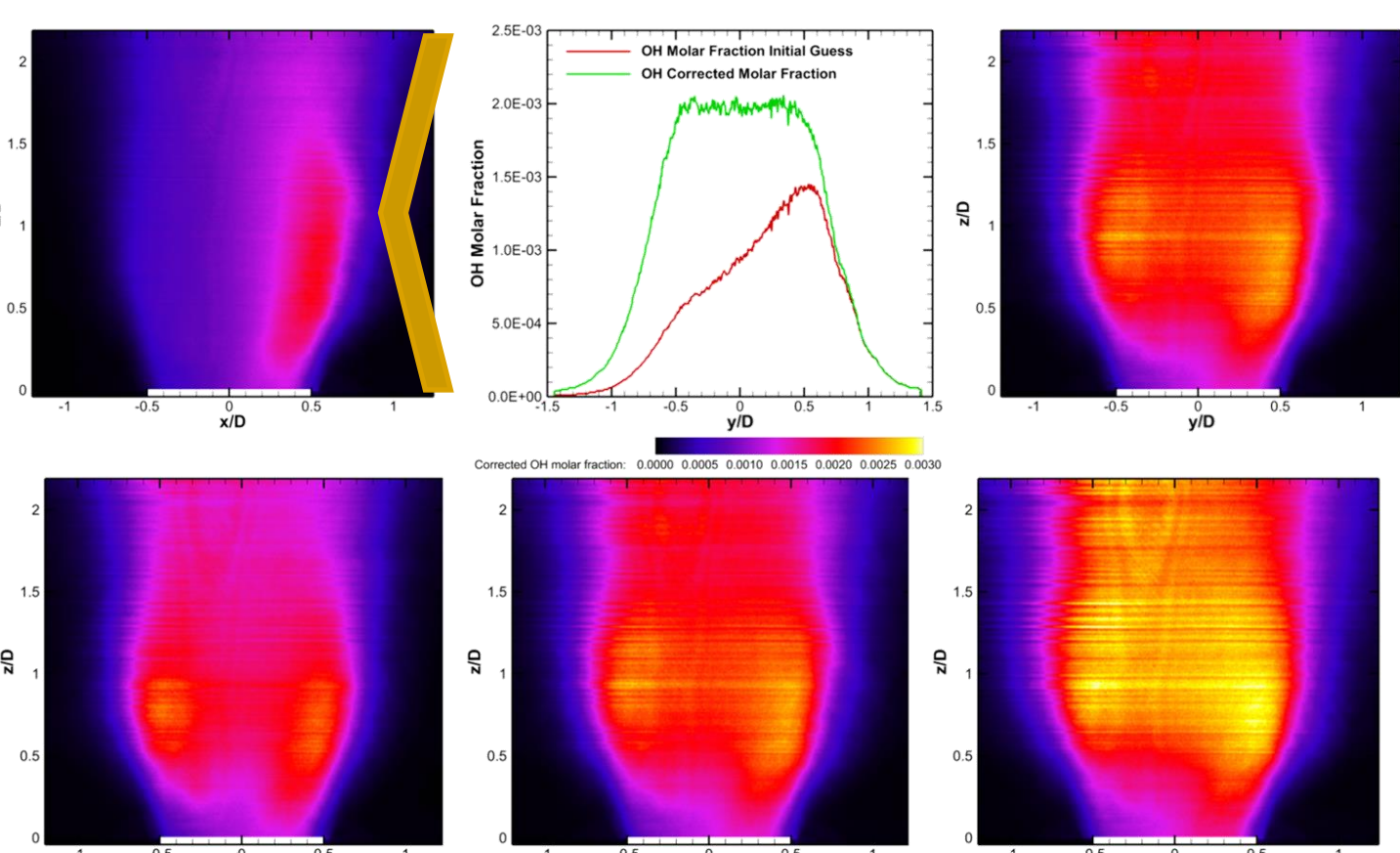
- Homogeneous OH distribution inside burned gases
- Symmetrical flame
- Strong absorption of laser

$$[OH] = [OH]_{initial} \cdot e^{-k_{abs} \cdot x \cdot \frac{P}{Lo_T}}$$

$$k_{abs} = \sigma_{abs} \cdot [OH]_{initial}$$

$$X_{OH} = [OH] / Lo_T$$

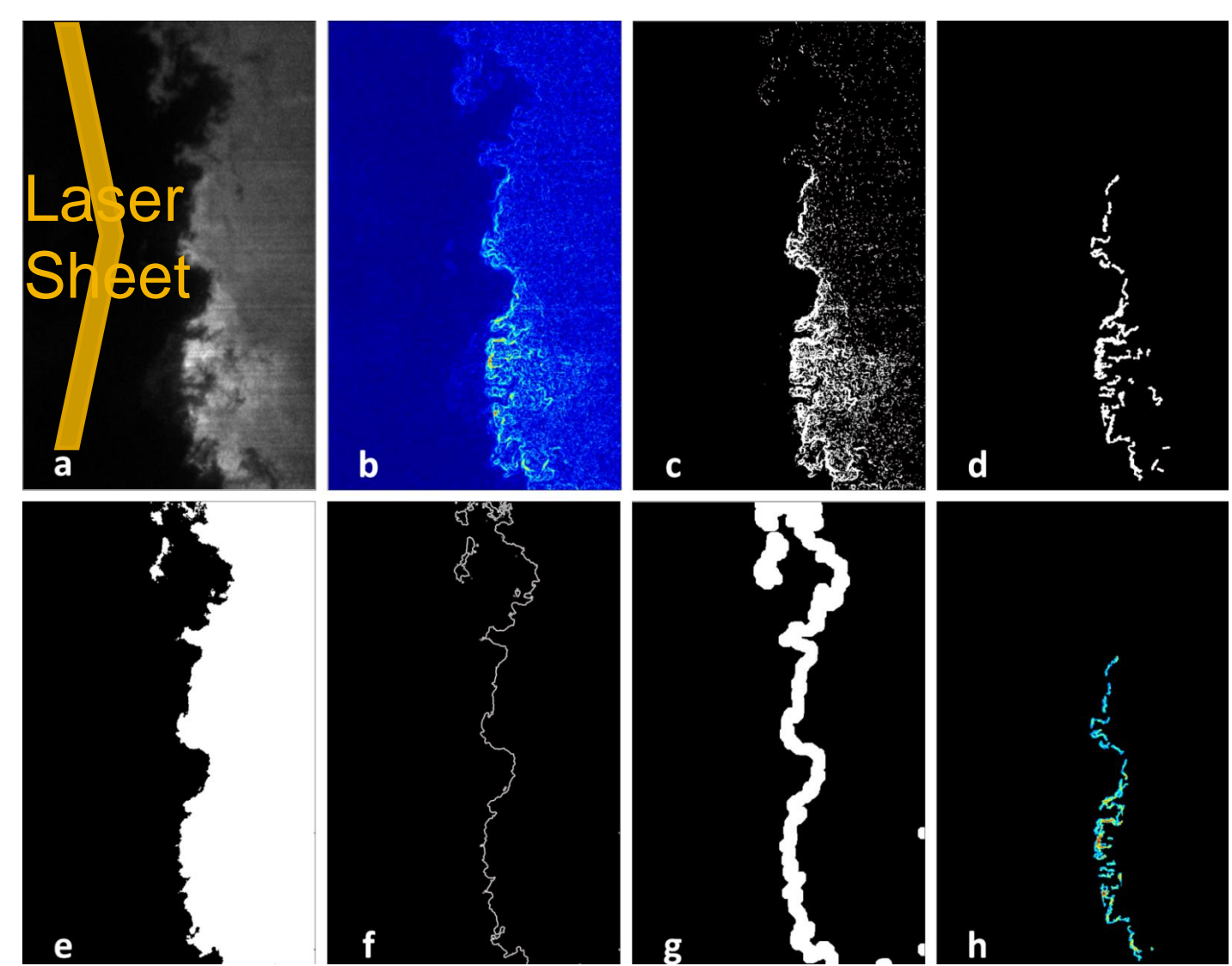
Lo: the Loschmidt number density (molecules.cm⁻³)



Top: OH Mole fraction before (left) and after (right) absorption correction, (center) OH mole fraction line profile at $z = 1.5D$
 Bottom: Corrected OH Mole fraction under $P = 0.83$ MPa, $T_{in} = 670$ K at FAR = 38% (left), 42% (center) and 46% (right)

- Flame position and thickness δ extraction from gradient on OH-PLIF images**

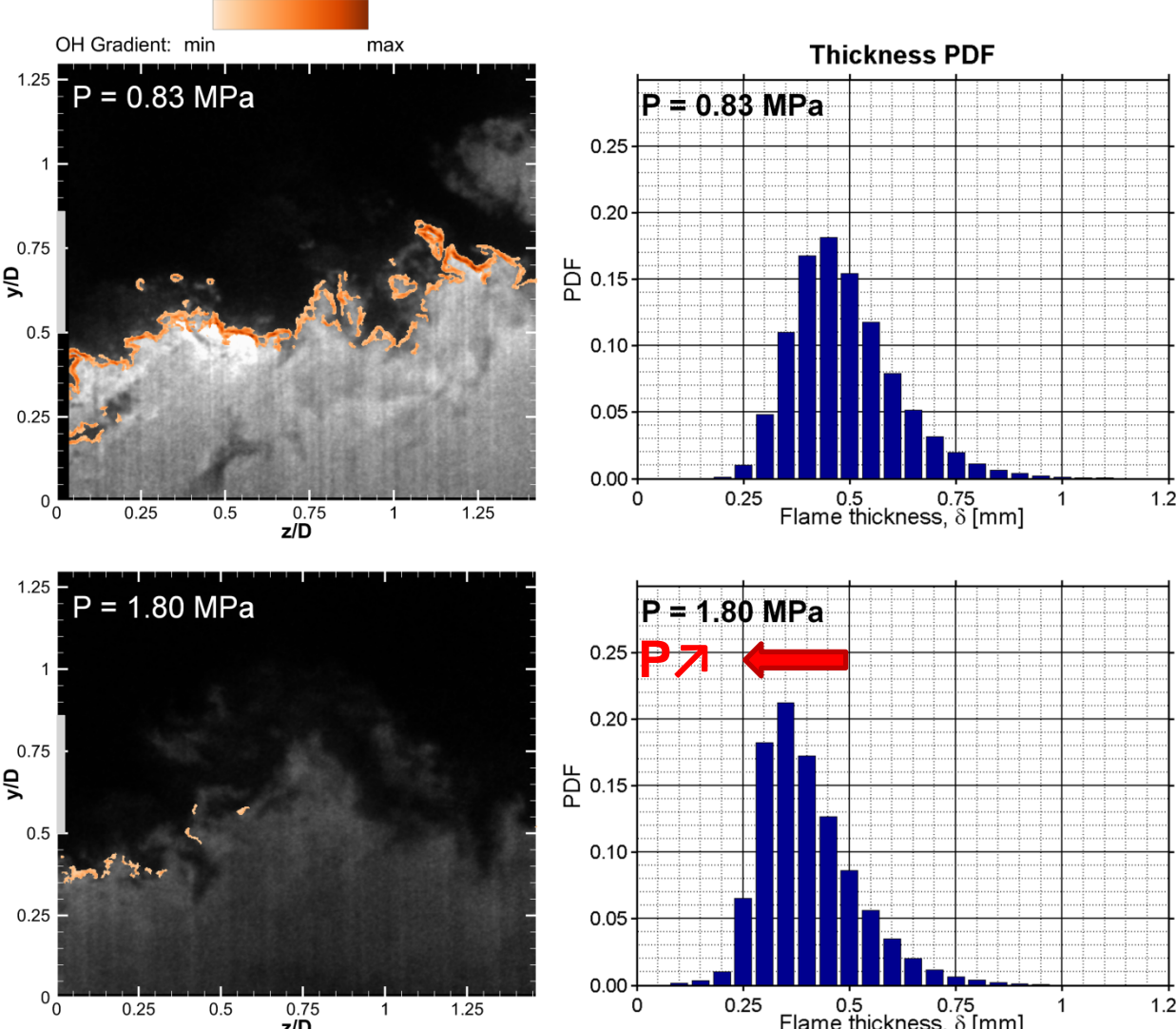
- OH gradient = accurate marker of the flame position according to the study of SADANANDAN[3]



Flame position extraction methodology based on the work of J. APELOIG [4] on an instantaneous OH-PLIF image at $P = 0.83$ MPa, FAR = 42%.

- Reaction zone position and flame thickness dependency with pressure**

- Reaction zone is stabilized inside the injection system
- Less reaction zone detected at high pressure → Flame more compact
- Flame thickness decreases with pressure as expected



(Left) Reaction zone position overlaid with corrected OH-PLIF images and (Right) Flame thickness Probability Density Function deduced from 500 OH-PLIF images at $P = 0.83$ MPa and $P = 1.80$ MPa.

→ The analysis of the absorption of the laser energy and OH-PLIF gradient enables to have a deep understanding of the flame stabilization and gives access to quantitative values to compare the injection system behavior when changing the operating conditions.

Experimental set-up

- HERON combustion facilities** (High prEssure facility for aeRO-eNginE combustion):

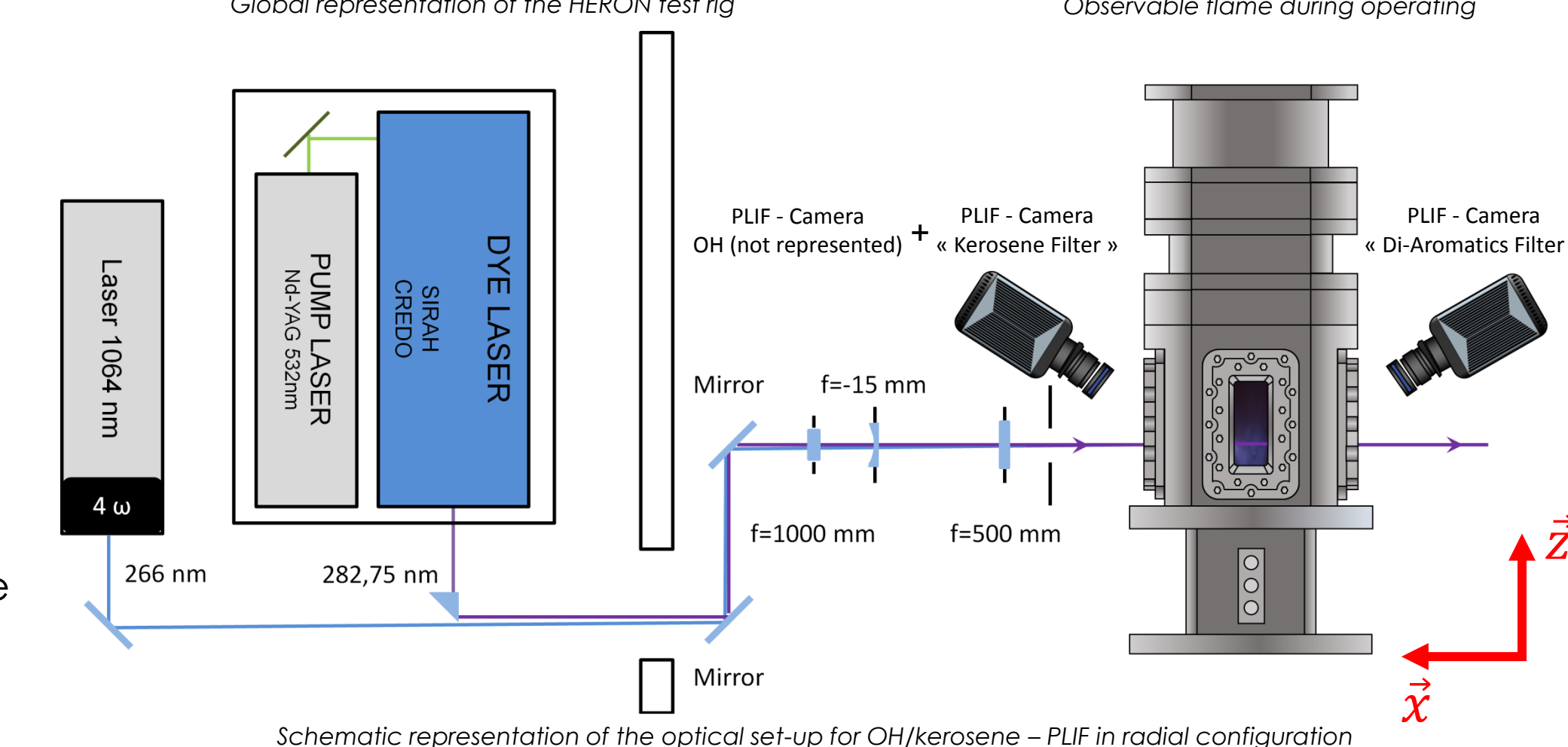
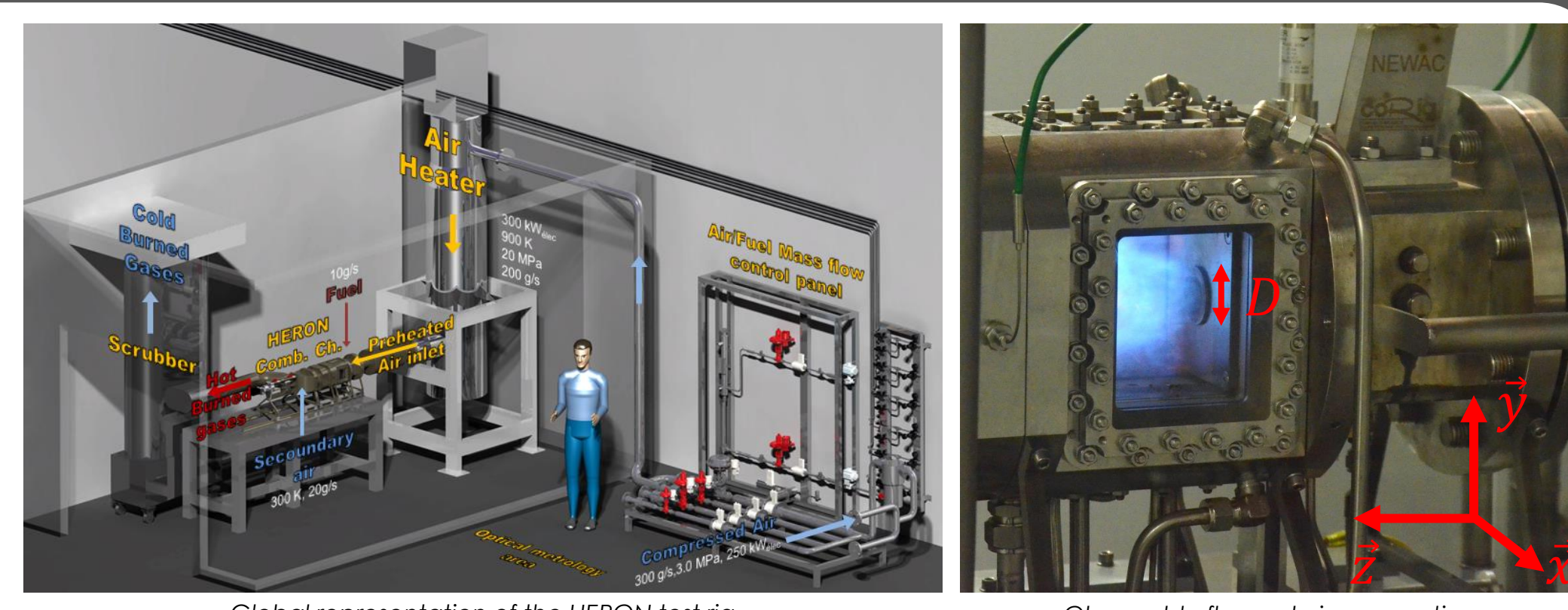
- High Pressure: 0.1 – 2.0 MPa
- Preheated air inflow: 300 – 900 K
- Large optical access for laser based measurements
- Single SAFRAN HE LP injector
- Liquid fuel: Commercial Jet-A1 (TOTAL) → 10 g/s

- Operating conditions**

- At $T_{air\ inlet} = 670$ K → $P = 0.41 - 1.8$ MPa
- At $P = 0.83$ MPa → $T = 550 - 700$ K

- Simultaneous laser based measurements**

- OH - PLIF Measurements: Flame Structure
 - Excitation: Nd-YAG with tunable dye laser (Sirah) $\lambda = 282.75$ nm ($Q_1(5)$, $A^2\Sigma^+ \leftarrow X^2\Pi$), 26 mJ/pulse
 - Collection: Narrow band-pass filter centered at 315nm ± 10nm
- Kerosene - PLIF: Equivalence Ratio measurements
 - Excitation: quadrupled Nd-YAG (4 ω), 266 nm, 60 mJ
 - Collection: simultaneous 2 spectral windows "Global Kerosene" and "Di-Aromatics" fluorescence
- Collection: 3 emCCD Pi-Max4 camera (Roper Instruments) 3 Hz, mounted with a 100 mm, f/2.8 UV-Cerco lens.



Kerosene-PLIF analysis

- Quantitative analysis methodology**

$$S_{fluor} = \eta_D \cdot \frac{\Omega}{4\pi} \cdot V \cdot N_1^0 \cdot \sigma_v \cdot \phi \cdot \frac{I_{laser}}{h\nu_L} \cdot \phi = \frac{A_{21}}{A_{21} + Q_{21}}$$

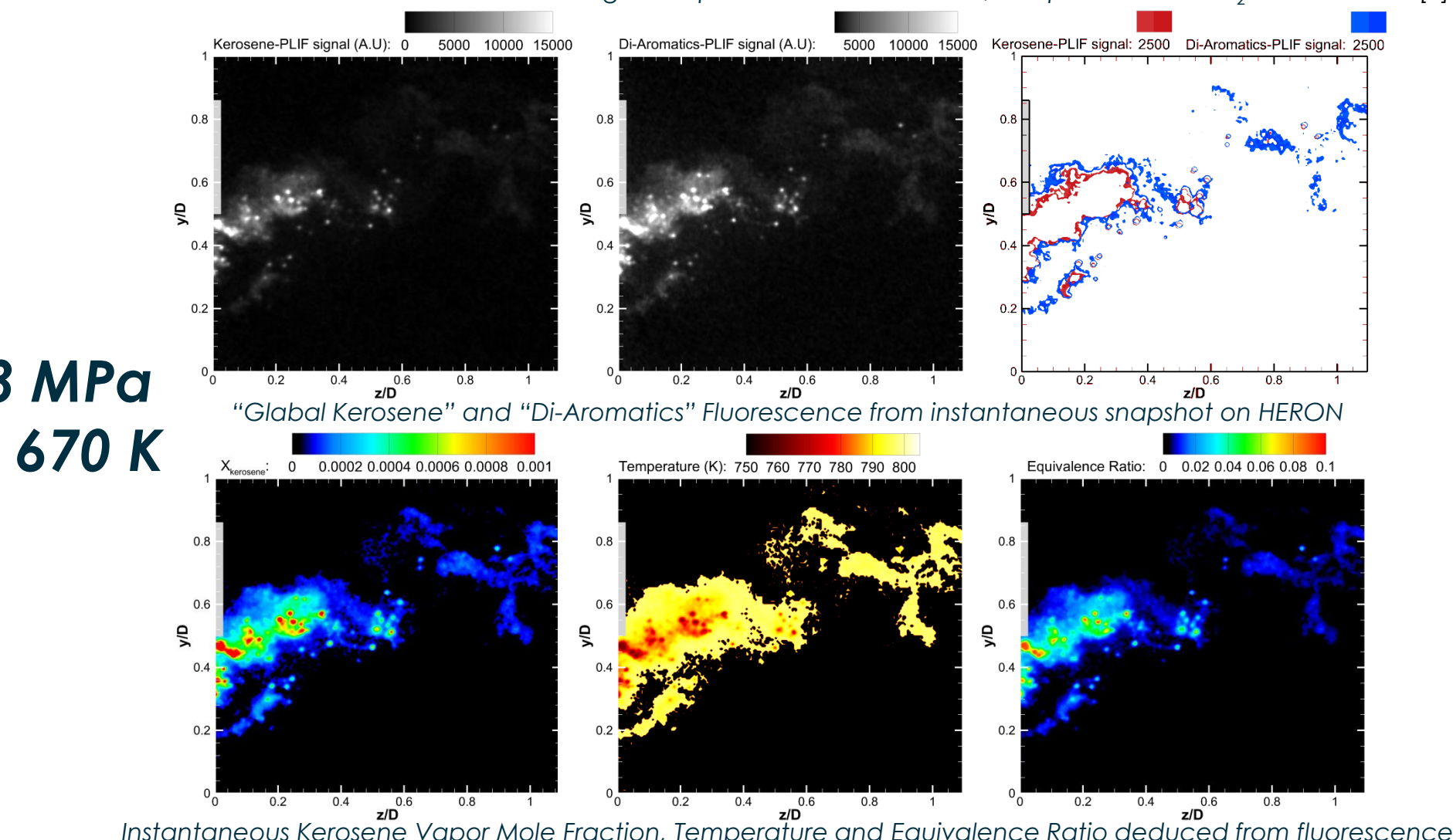
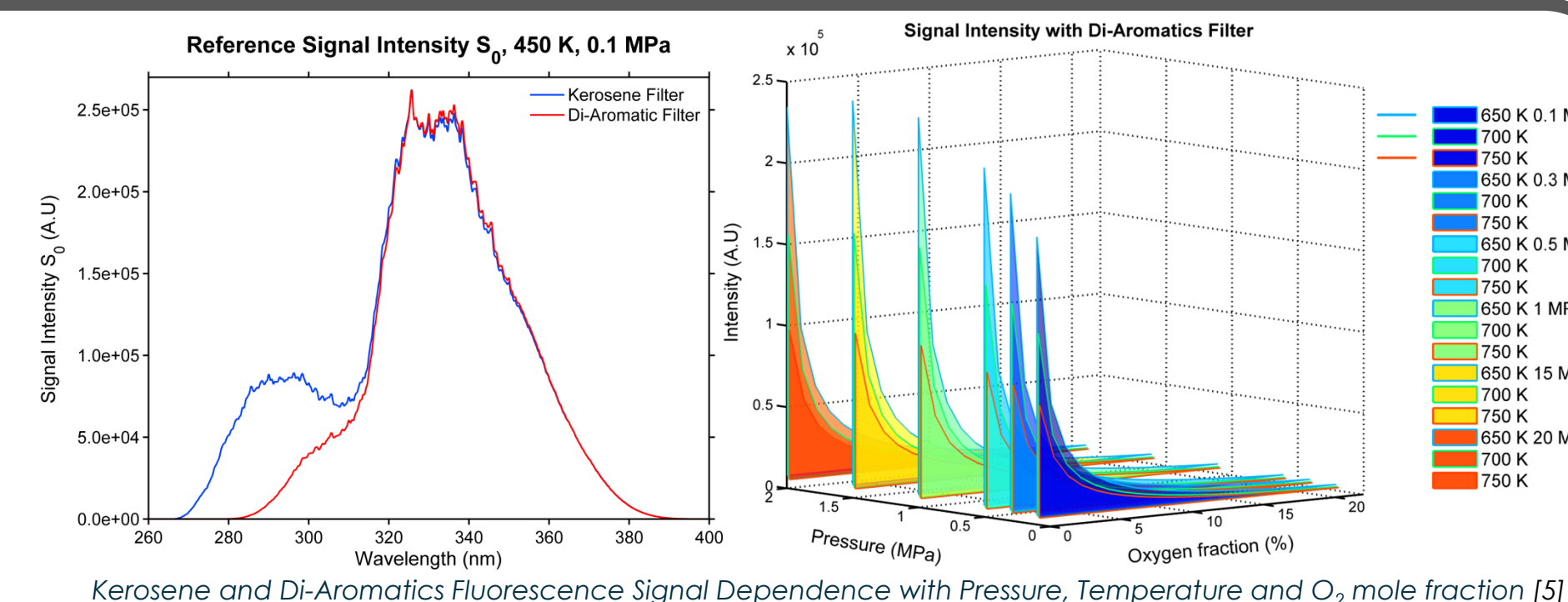
- Two spectral channel fluorescence detection
 - Mono-Aromatics: [260 - 320] nm
 - Di-Aromatics: [300 - 400] nm

$$\begin{cases} S_{kero\ measure} = K_{kero} \cdot P \cdot [x_{kero}] \cdot \frac{S_{kero}(T, P, O_2)}{T} \\ S_{di-aro\ measure} = K_{di-aro} \cdot P \cdot [x_{diaro}] \cdot \frac{S_{di-aro}(T, P, O_2)}{T} \end{cases}$$

- Knowledge of kerosene fluorescence in high pressure and high temperature from B.ROSSOW [5] → $S(T, P, O_2)$
- Calibration measurements of the optical set-up → K
- Resolution of the non-linear system

- Application on HERON test rig**

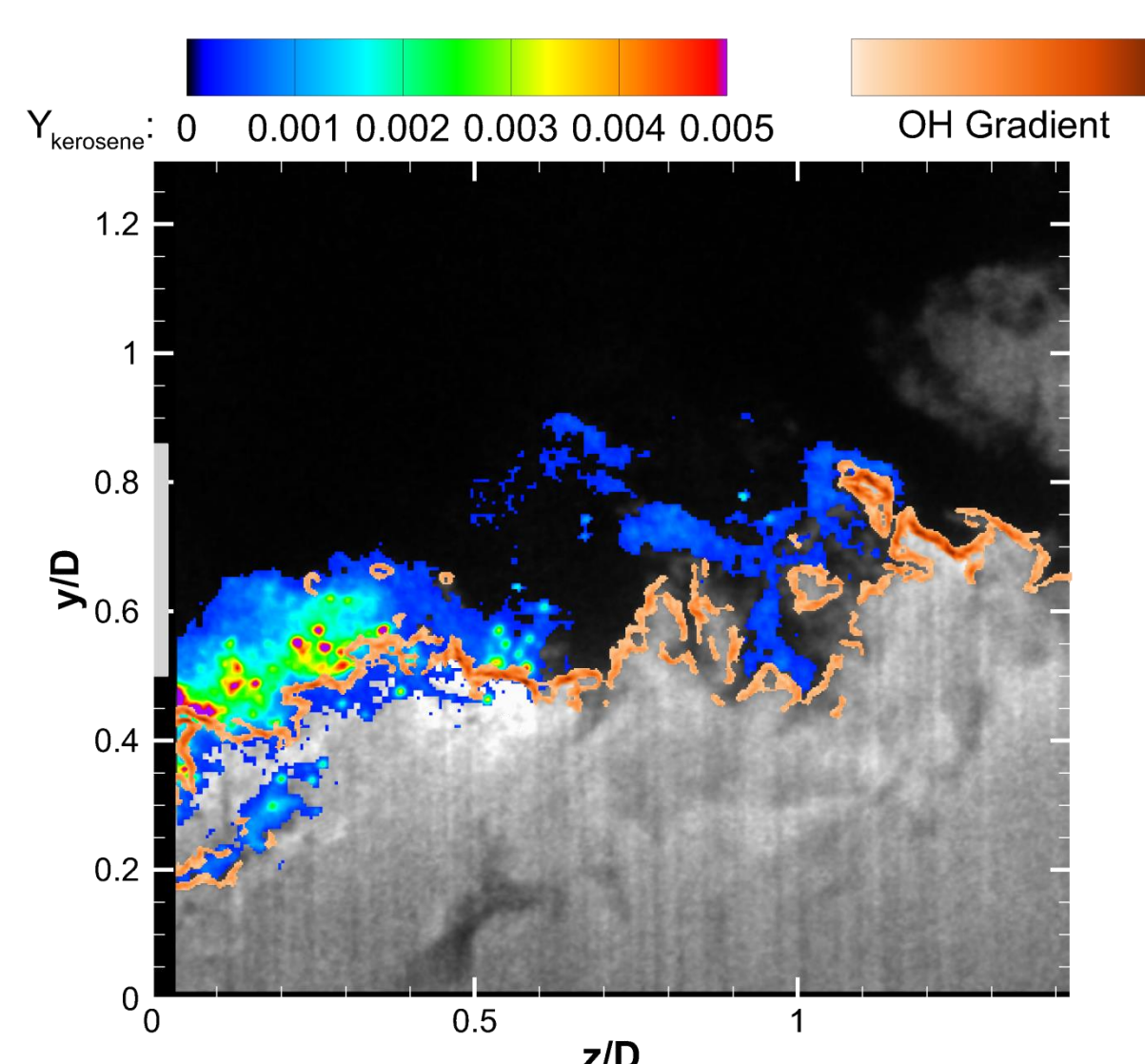
- Accurate Kerosene and Di-Aromatics signal correspondence
- Vapor temperature close to the inlet air temperature (670 K) → Validation of the resolution code
- Low kerosene mass fraction and equivalence ratio → Most of the kerosene burn inside the LP injection system



Flame topology and kerosene distribution

- Simultaneous analysis of OH/kerosene fields**

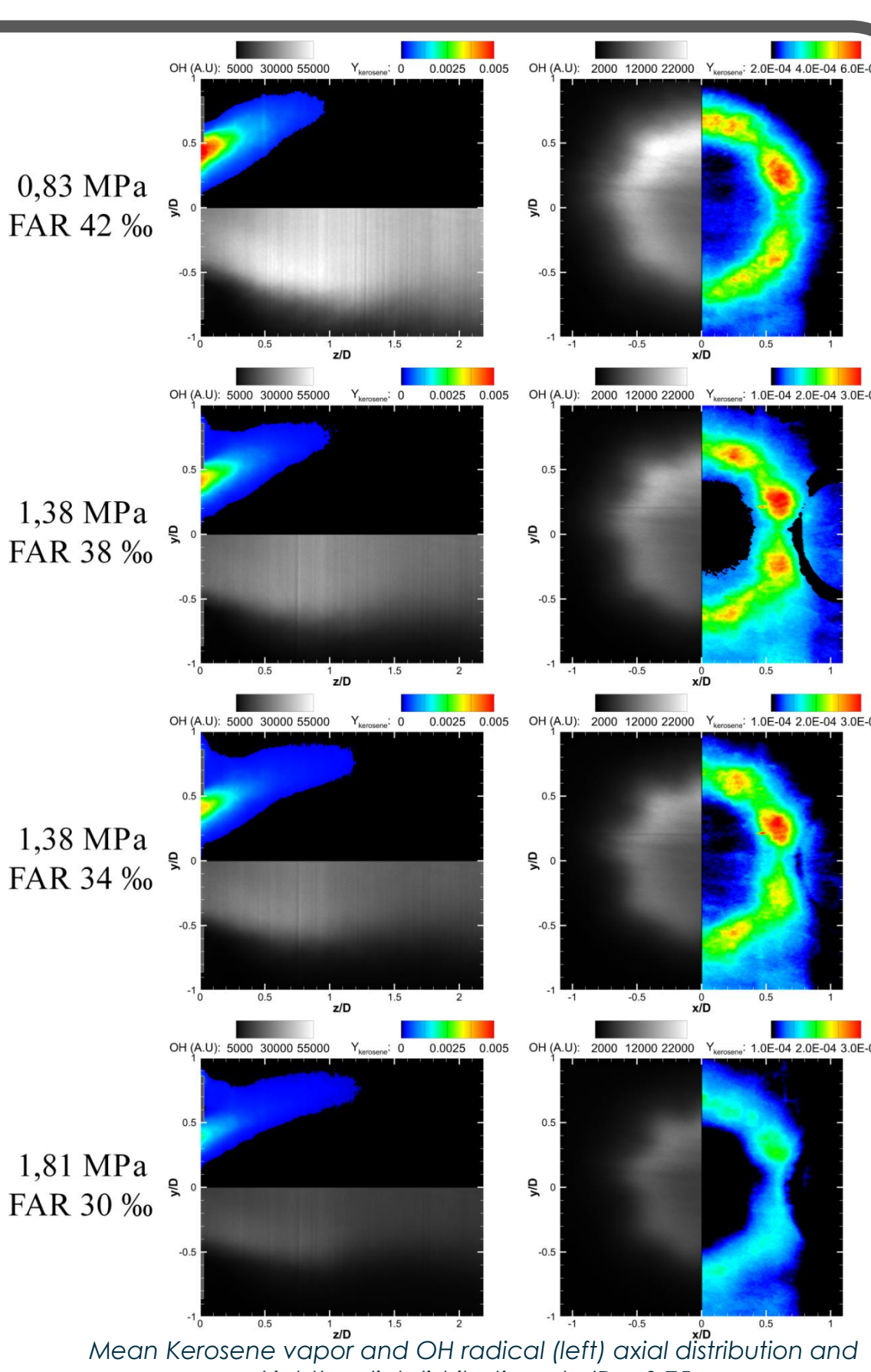
- Strong correlation between kerosene vapor distribution, flame position and reaction intensity



- Mean OH and kerosene distribution**

- OH and kerosene mean field are analyzed in two optical configurations → axial and radial.
- As expected from the OH distribution, most of the kerosene is consumed inside the injection system
- Kerosene vapor mass fraction decreases when increasing the pressure → combustion occurs upstream
- Non-uniformity of the kerosene distribution shown by radial measurements à $z/D = 0.75$ → "Memory" of the injection process

→ The joint analysis of kerosene and OH spatial distribution in radial configuration gives new insight on the comprehension of the operating of the injection system and will help in the design of new systems.



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Conclusions and prospects

- OH-PLIF and Kerosene-PLIF have been simultaneously applied inside an aeronautical combustion burner.
- Flame Topology and fuel/air mixing process have been quantitatively analyzed for relevant gas turbine operating conditions with an LP injection system running with Jet-A1.
 - Flame is stabilized inside the injection system and this behavior is stressed by increasing the pressure inside the combustor.
 - The kerosene mass fraction indicated that most of the fuel is consumed inside the injection system
 - Deep and exclusive understanding of the injection system + Data base for LES code validation.
- Global pollutant emissions as a function of pressure and FAR is measured at the exit of the burner.
 - NO-PLIF is currently performed simultaneously with OH-PLIF.
 - CO-PLIF in development and will be applied in the HERON facility to understand how pollutants are locally formed inside the burner with innovative aeronautical injection systems.