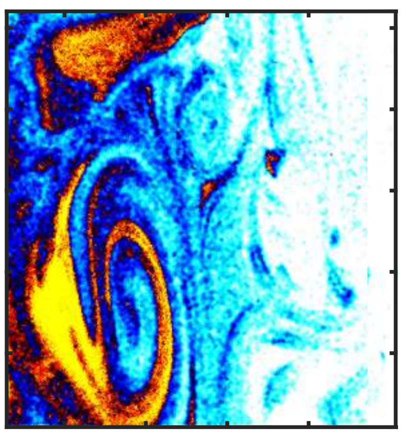
A new experimental database for the investigation of soot in a model scale swirled combustor under perfectly premixed rich conditions



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B. Franzelli

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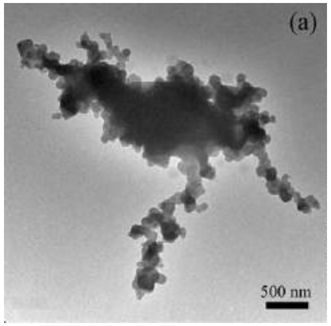
cnrs EM2C Air Liquide creative oxygen CentraleSupélec

Introduction

1) Soot are dangerous and harmful:
- Environment[2]
- Human health[3]



TEM images of a soot particle [1]

2) **But** crucial role of soot in industrial burners
- Thermal radiation of soot is highly effective for glass or metal melting in large industrial applications

Need for a better comprehension of soot production with precise modeling that requires quantitative data for validation

But there are numerous difficulties:
- Experimentally: numerous small particles with high intermittency; optical properties not perfectly known and highly dependent on fuel and operating conditions
- Numerically: multi-physics and multi-scale phenomenon

[1] Li, W., & Shao, L. (2009). Transmission electron microscopy study of aerosol particles from the brown hazes in northern China. ***J. Geophys. Res. Atmos***, *114*(D9).

[2] T.C Bond et al. (2013) Bounding the role of black carbon in the climate system: A scientific assessment. ***J. Geophys. Res. Atmos***., 118, 5380–5552,

[3] Pascal M et al. (2016) Impacts de l'exposition chronique aux particules fines sur la mortalité en France continentale et analyse des gains en santé de plusieurs scénarios de réduction de la pollution atmosphérique ***Santé publique France***

Introduction

Numerous studies already exist on soot characterization:

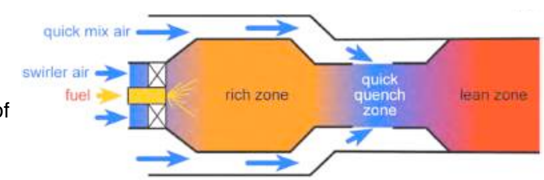
- A) Laminar diffusion flame[1]/good predictability[1]
- B) Laminar premixed flame[2]/good predictability[3]
- C) Turbulent diffusion flame[4]/difficult challenge (f_v)[5]

A B C

- D) **Turbulent premixed flame:** still no experimental and only one numerical (LES) study on turbulent premixed sooting flame [6]

But this configuration present several advantages:

- No air/fuel mixing effect → direct study of effects such as equivalence ratio or turbulence on soot production
- Perfectly premixed condition is better for numerical validation
- Rich-Quench-Lean industrial concept for NOx reduction



[1] Smooke, M., et al, 2005. Soot formation in laminar diffusion flame. ***Combust. Flame***, 143 (4), pp. 613–628.

[2] Betrancourt, C. et al,2017. Investigation of the size of the incandescent incipient soot particles in premixed sooting and nucleation flames of n-butane using LII, HIM, and 1 nm-SMPS. ***Aerosol Sci. Technol.***, 51 (8), pp. 916–935.

[3] Abid, A.D., et al (2009). Quantitative measurement of soot particle size distribution in premixed flames–the burner-stabilized stagnation flame approach. ***Combust. Flame*** 156.10 : 1862-1870.

[4] Geigle, K. P.et al, 2011. Experimental analysis of soot formation and oxidation in a gas turbine model combustor using laser diagnostics. ***J. Eng. Gas Turbines Power***, 133 (12).

[5] Rodrigues, P. et al (2018). Coupling an LES approach and a soot sectional model for the study of sooting turbulent non-premixed flames. ***Combust. Flame***, 190, 477-499.

[6] El-Asrag, H. et al (2007). Simulation of soot formation in turbulent premixed flames. ***Combust. Flame***, *150*(1-2), 108-126.

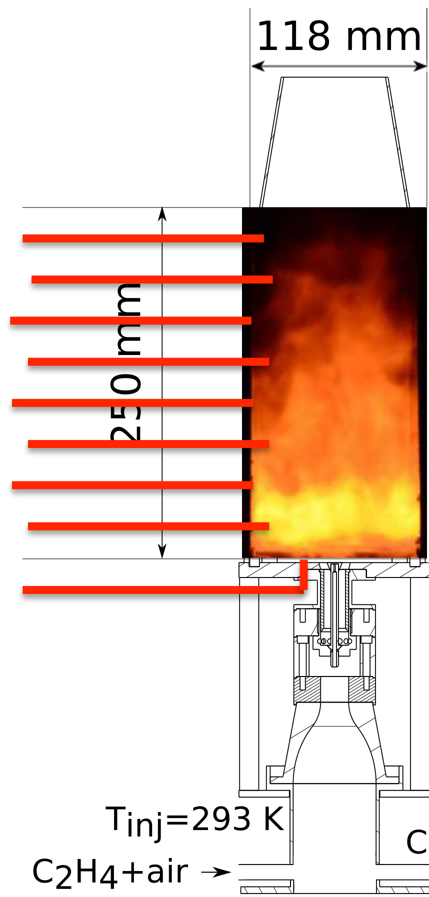
Context

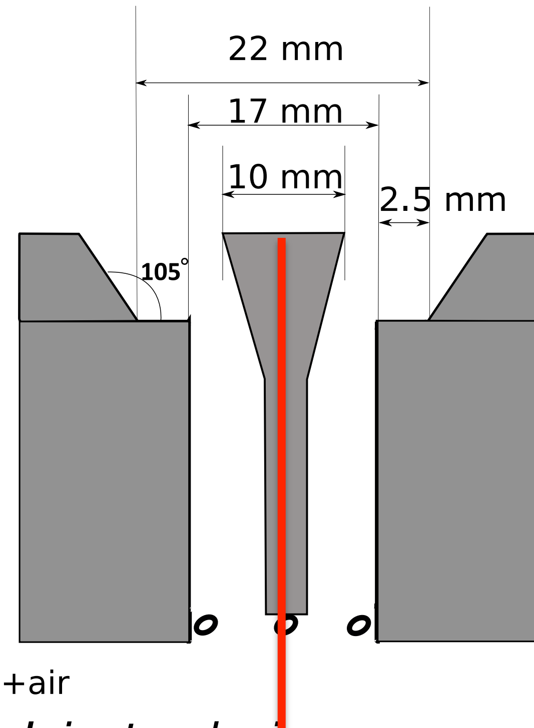
1) EM2Soot configuration
2) Laser Induced Incandescence for soot volume fraction measurements
3) Study of a specific sooting point (15 kW, $\phi=2.1$)
4) Effects of operating conditions on soot production

EM2Soot configuration

Characteristics:

- Perfectly premixed (ethylene/air) swirled flame
- Quartz confinement
- 12 thermocouples for wall and gas temperature measurements





Injector design

Several challenges:

- Stabilization of a rich premixed swirled flame with a new injector design
- Important role of the combustion chamber temperature (issue for repeatability)
- Fast blackening of quartz (< 2 min)
- Relatively low soot volume fraction (detection issues)

Context

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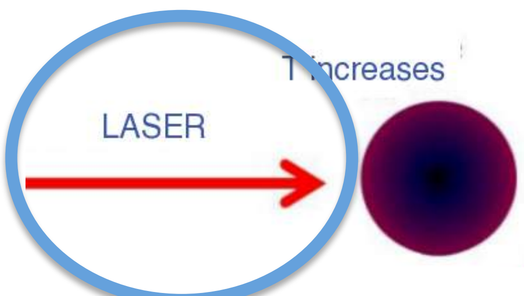
Laser Induced Incandescence (LII) Emission

I) LII: principle of measurement
Discovered by chance in 1984 by Melton, allows to measure quantitatively the volume fraction of soot

Laser Induced Incandescence (LII):

- Non intrusive, quantitative measurements of soot volume fraction $f_v = k.I_{LII}$
- Based on Planck's law applied to heated soot particles by a short intense laser shot



Laser Induced Incandescence (LII) Emission

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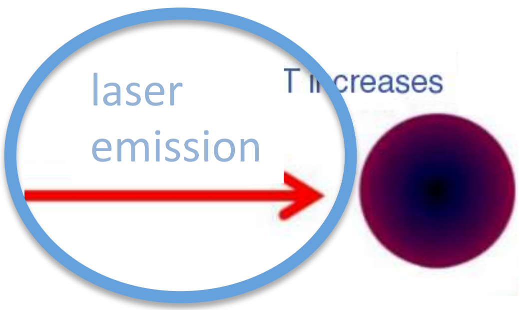
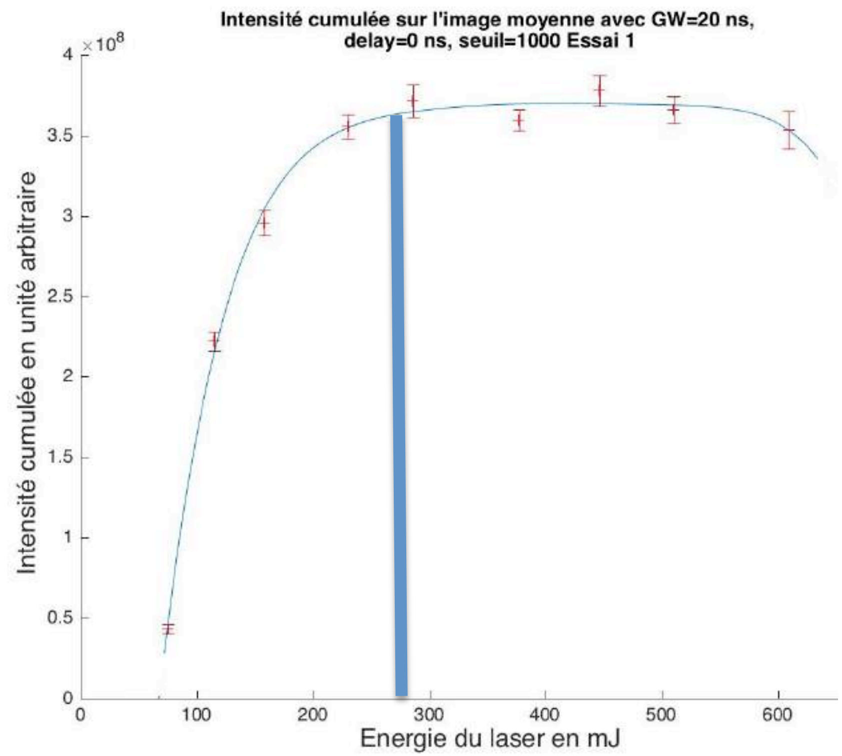
Discovered by chance in 1984 by Melton, allows to measure quantitatively the volume fraction of soot



Existence of a plateau where the signal is independent of the laser energy.



Evolution of LII signal at 1064 nm fonction of laser energy

Laser Induced Incandescence (LII) reception

I) LII: principle of measurement
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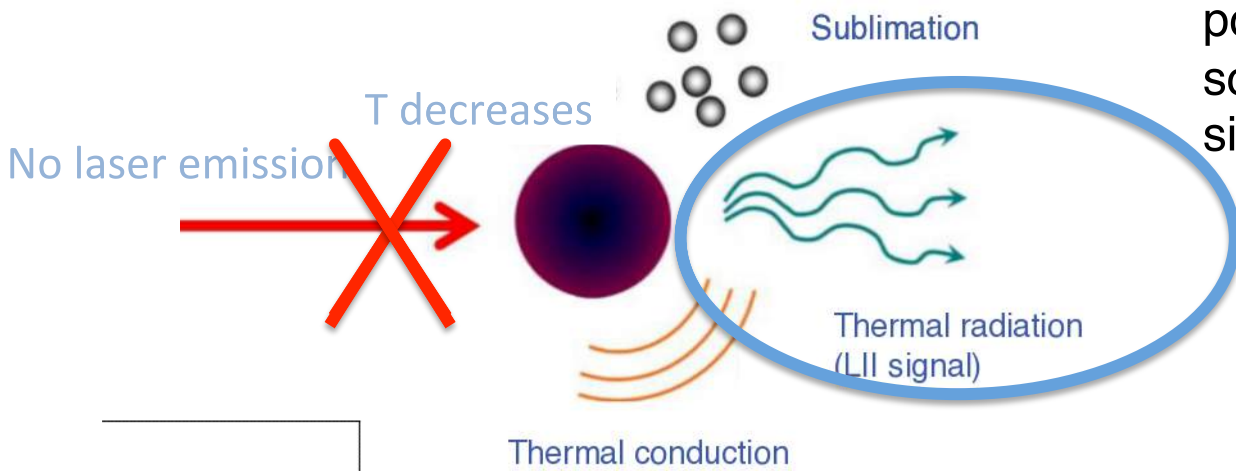
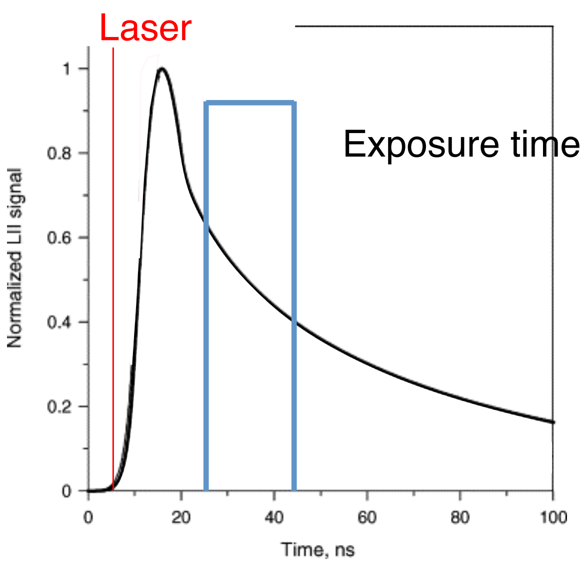


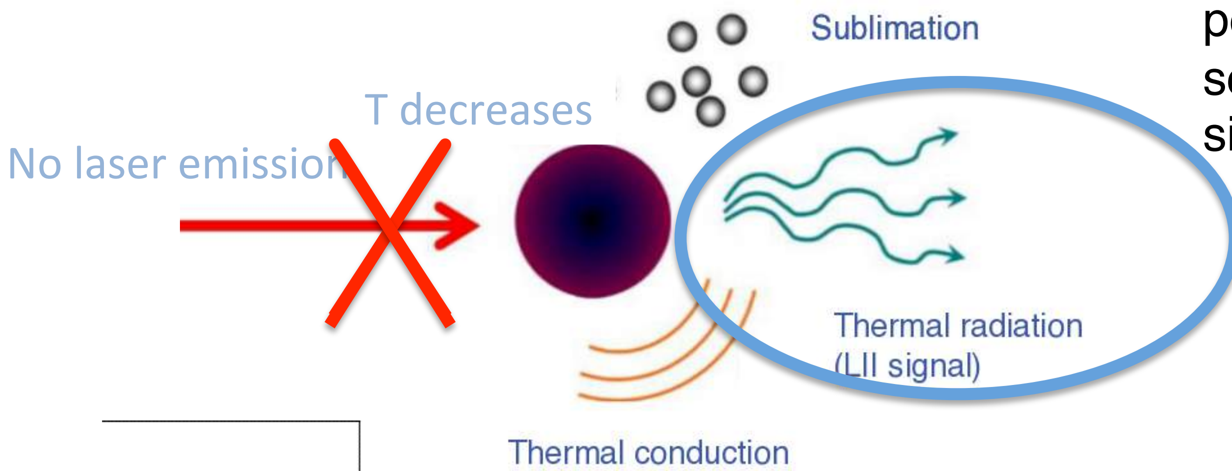
At high energy, possible sublimation of soot particles and signal decay



Exposure time very often between 20 and 100ns

I) LII: principle of measurement

Discovered by chance in 1984 by Melton, allows to measure quantitatively the volume fraction of soot



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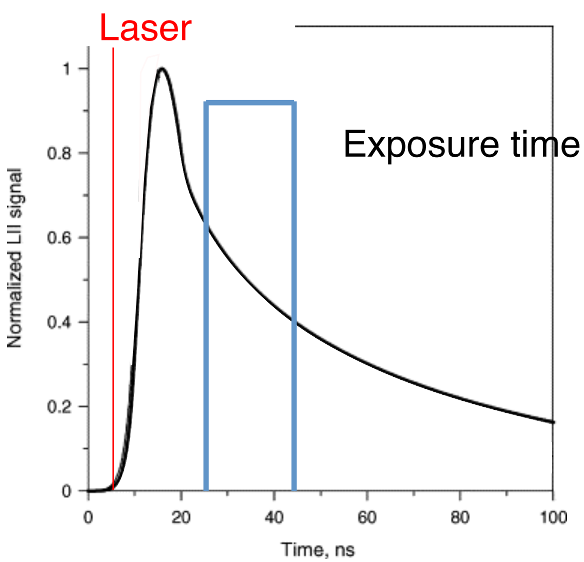

Exposure time very often between 20 and 100ns

External calibration required !

Calibrated by emission/absorption technique (MAE[2]: Modulated Absorption Emission) with evaluation of the error[3] and thorough comparison between MAE and LII on a laminar case[4]:

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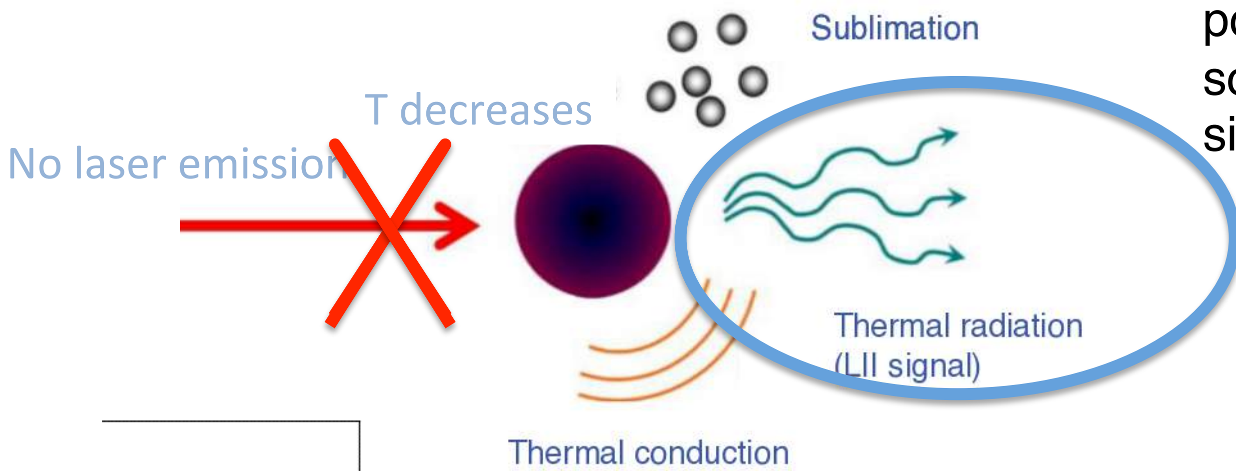

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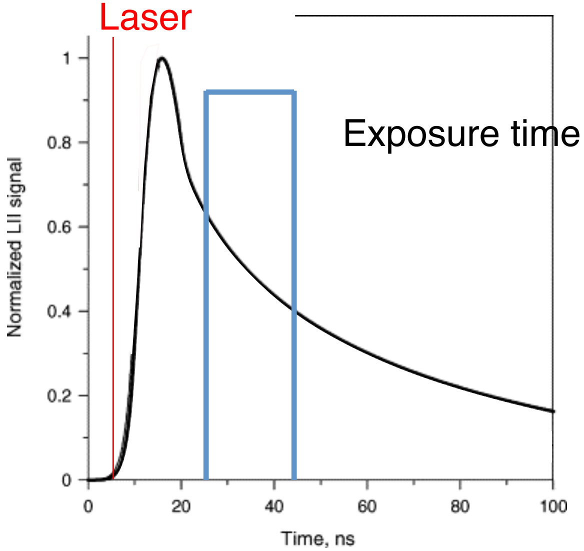


Exposure time very often between 20 and 100ns

External calibration required !

Calibrated by emission/absorption technique (MAE[2]: Modulated Absorption Emission) with evaluation of the error[3] and thorough comparison between MAE and LII on a laminar case[4]:

Optical properties of soot E(m) = 0,38 classically between 0,15 and 0,45

Experimental setup for Laser Induced Incandescence

LII: Quantitative measurements of soot volume fraction f_v

Laser:

Nd:Yag λ=1064 nm, f=10 Hz, F=0.45 J/cm^2

Camera:

PIMAX 3: Gate Width: 100 ns

Gate delay: 0 ns

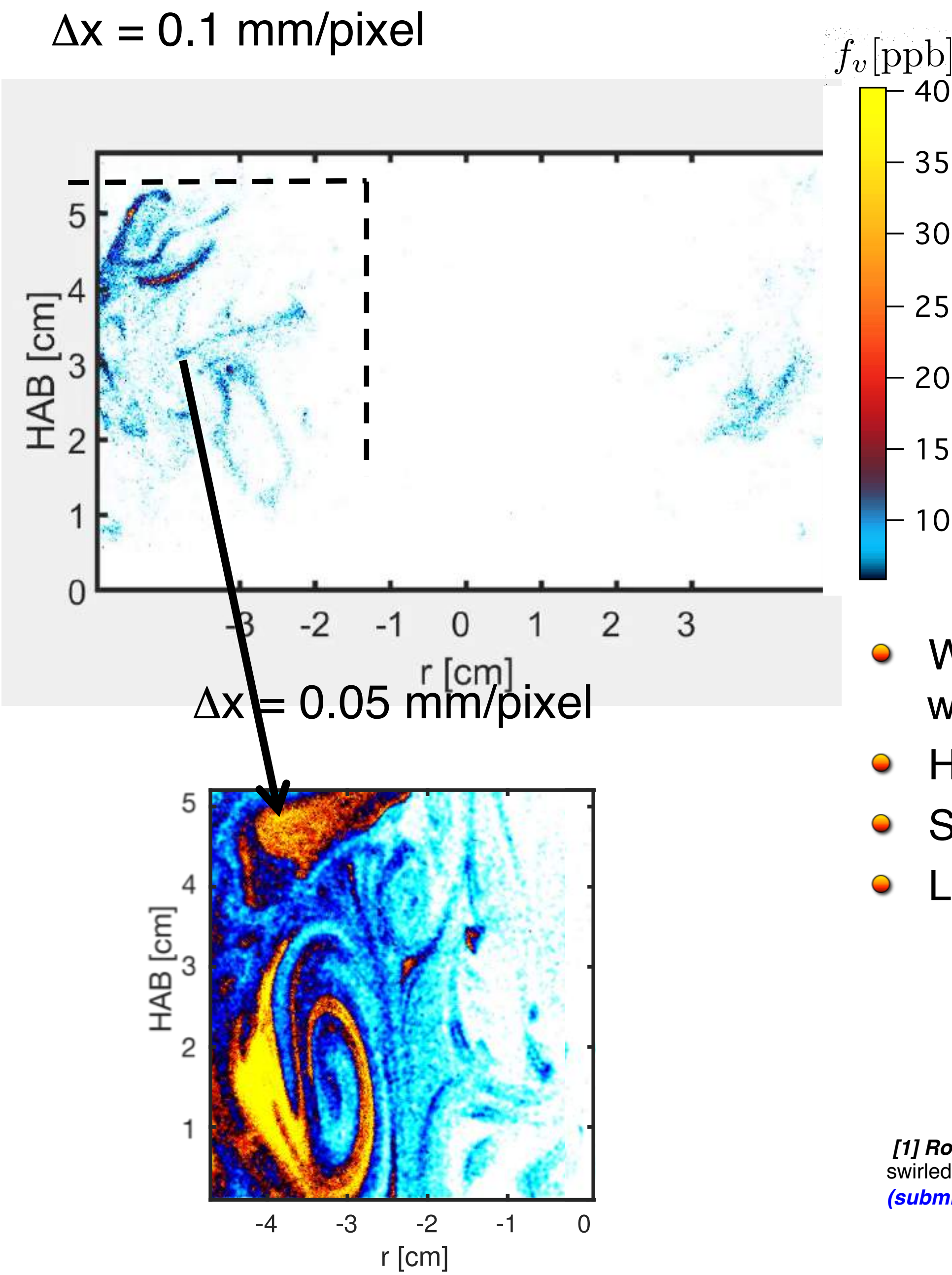
Filter:

Δλ= 400-450 nm for LII detection

Context

1) EM2Soot configuration
2) Laser Induced Incandescence for soot volume fraction measurements
3) Study of a specific sooting point (15 kW, $\phi = 2.1$)
4) Effects of operating conditions on soot production

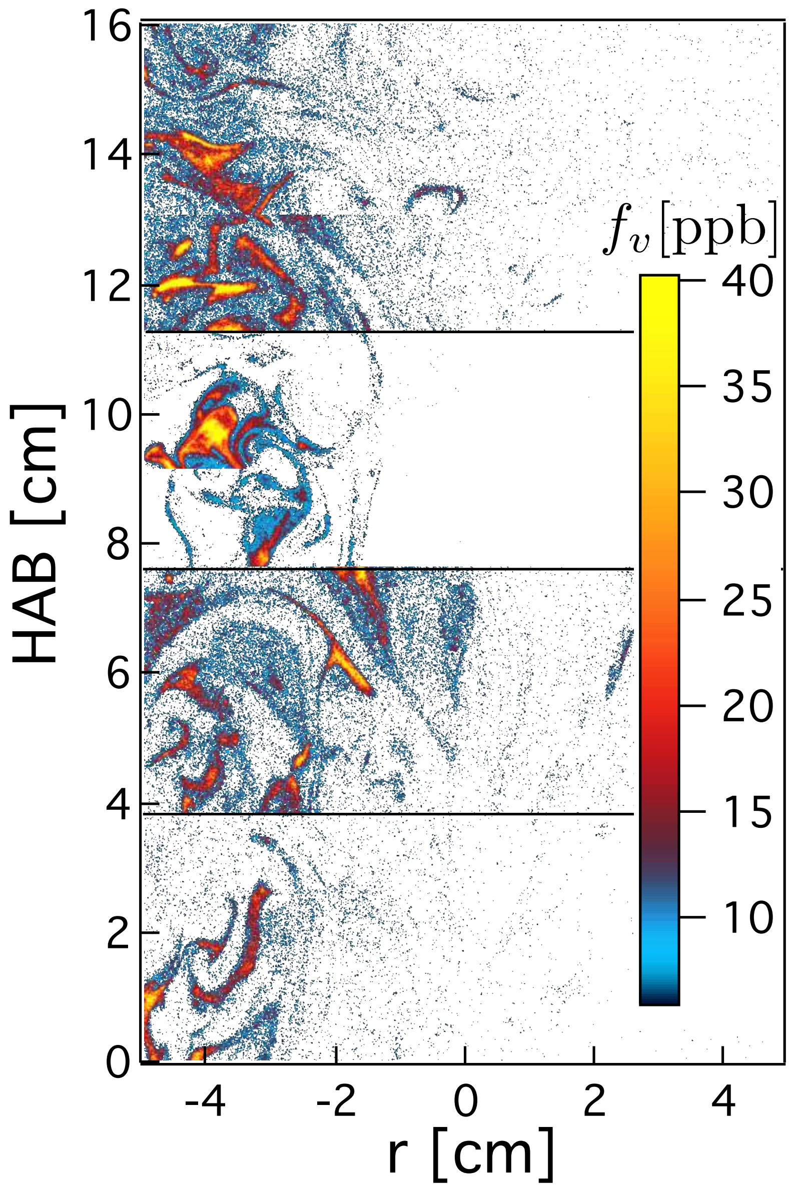
Study of a specific sooting point [1] (15 kW, $\phi=2.1$)



- Wrinkled filament of soot visible along the wall with large-scale soot structure
- High temporal and spatial intermittency
- Strong interaction with turbulent eddies
- Ligamentary structure (thickness ≈ 1 mm)

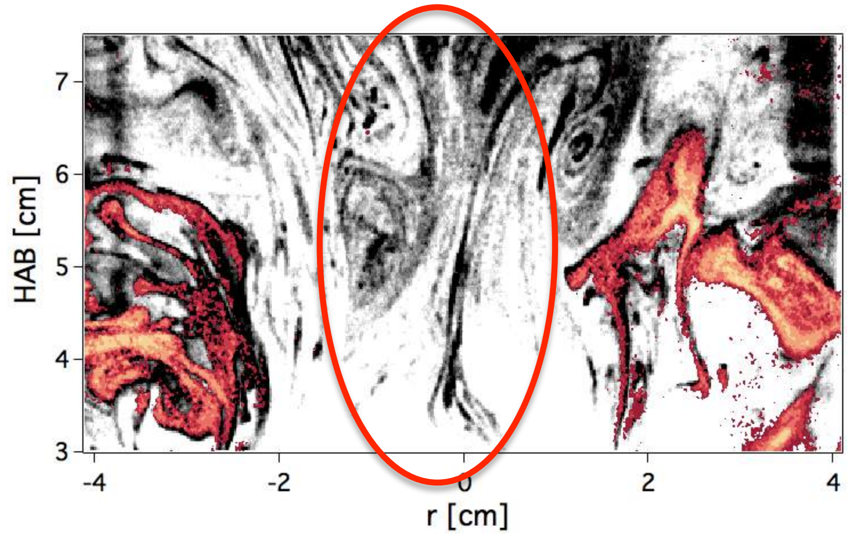
[1] Roussillo, M. et al., 2018. "Experimental investigation of soot production in a confined swirled flame operating under perfectly premixed rich conditions". ***Proc. Combust. Inst (submitted)***

Study of a specific sooting point (15 kW, ϕ=2.1)



LII signal (soot volume fraction) is mainly detected close to the wall

But.... Light scattering signal in the middle is detected



Simultaneous LII (red)/light scattering (black) experiments at 532 nm

Soot is also present in the central region, two possibilities:

- ***Small number of large particles***
- ***Big number of nuclei***

Context

1) EM2Soot configuration
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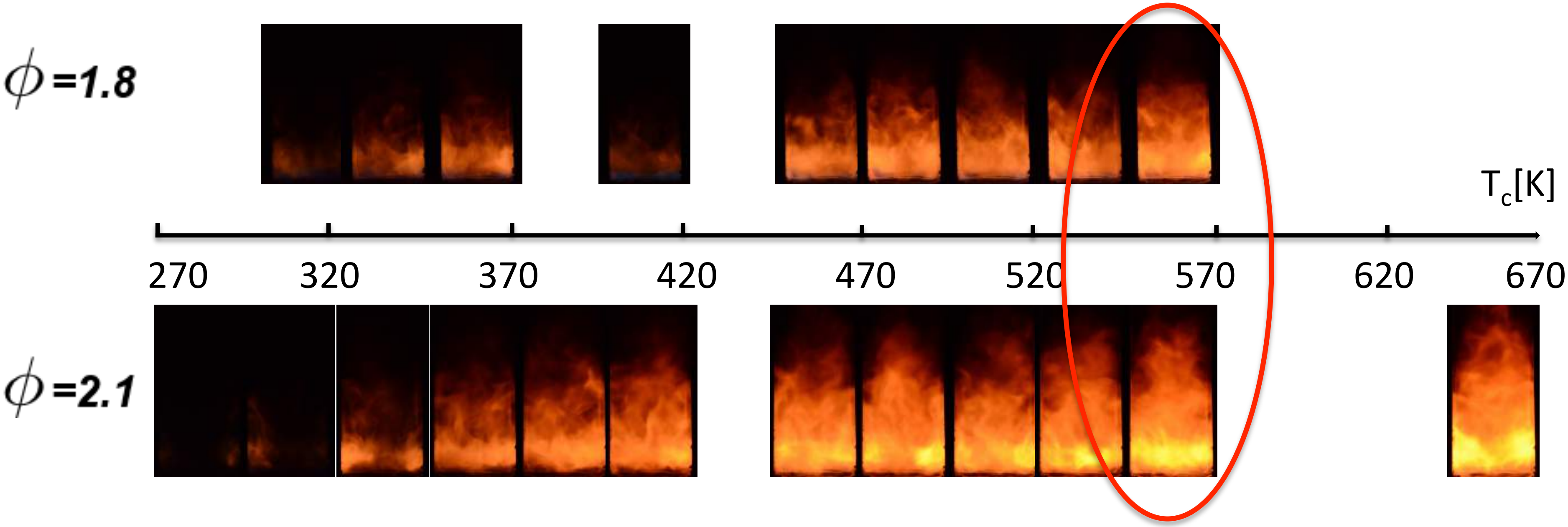
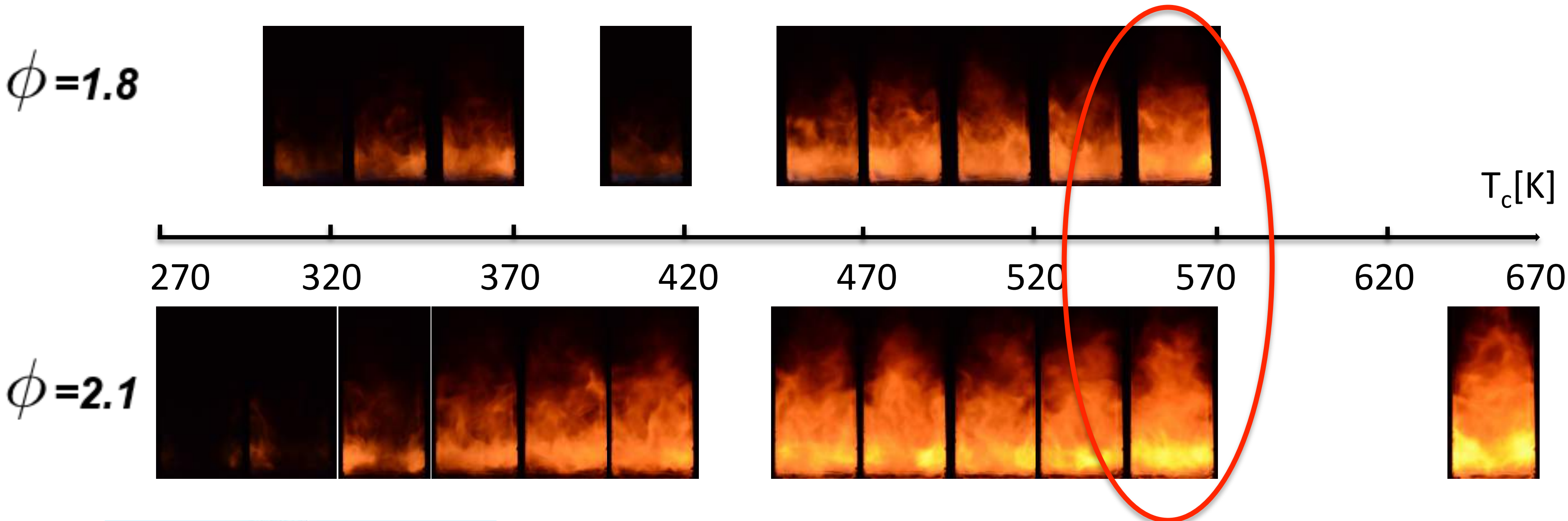
Effect of wall temperature[1]



- Strong effect of walls temperature on soot production both qualitatively and quantitatively

[1] Roussillo, M. et al, 2018. "A new experimental database for the investigation of soot in a model scale swirled combustor under perfectly premixed rich conditions".
ASME 2018

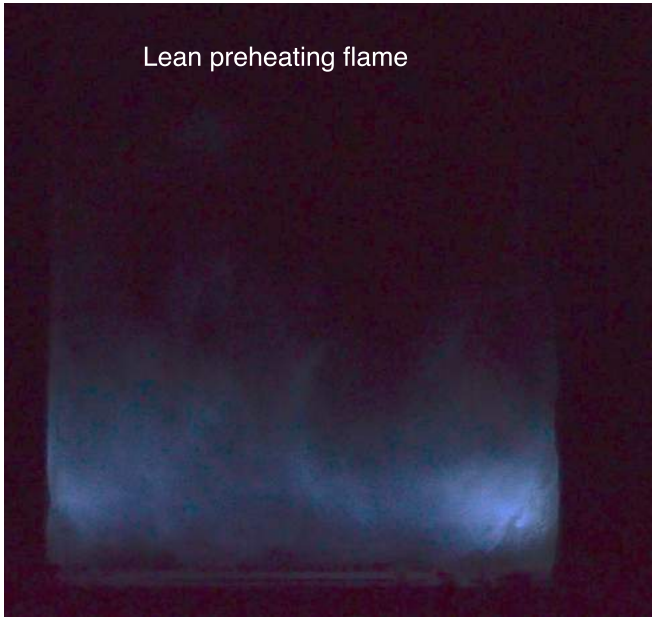
Effect of wall temperature[1]

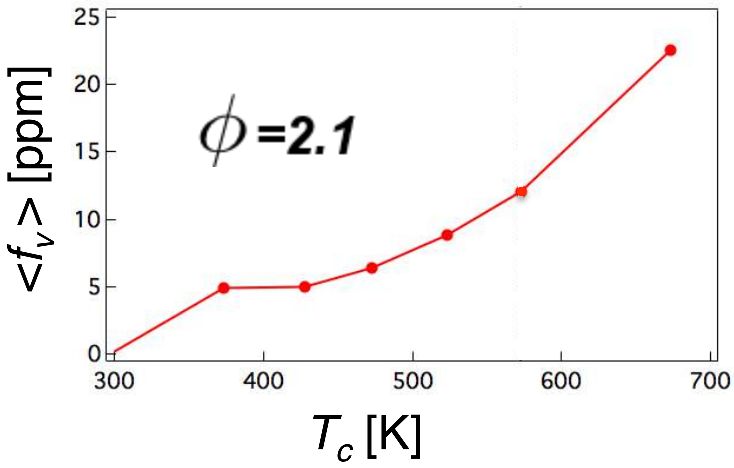


- Strong effect of walls temperature on soot production both qualitatively and quantitatively
- Preheating with a lean flame: T_c=570 K

[1] ***Roussillo, M. et al,*** 2018. "A new experimental database for the investigation of soot in a model scale swirled combustor under perfectly premixed rich conditions".
ASME 2018

Effect of wall temperature[1]



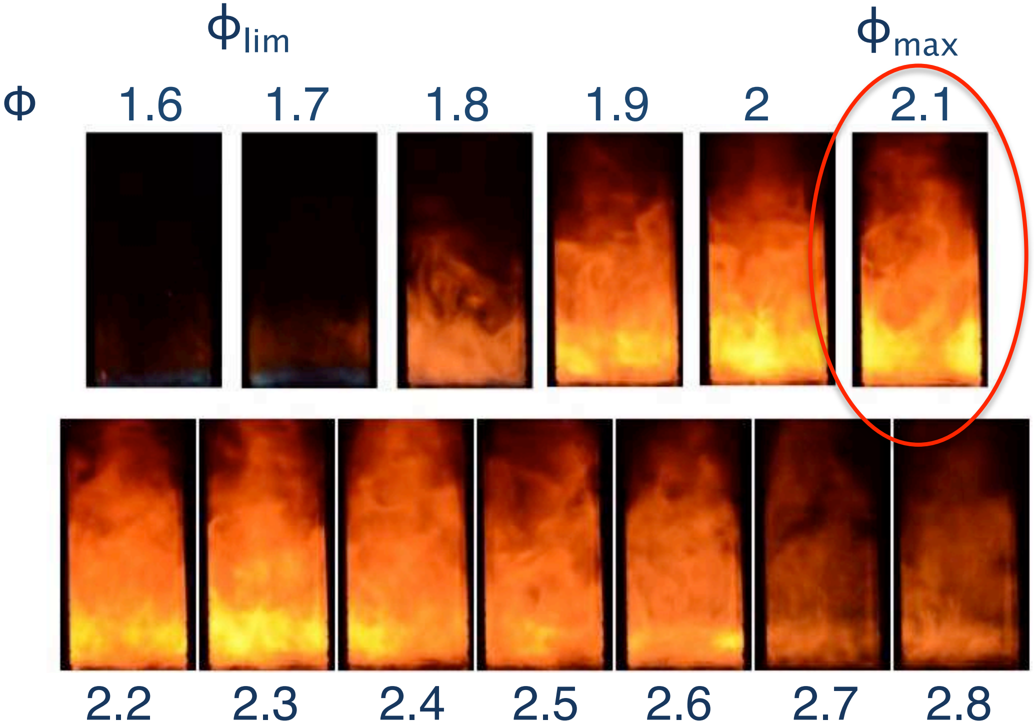


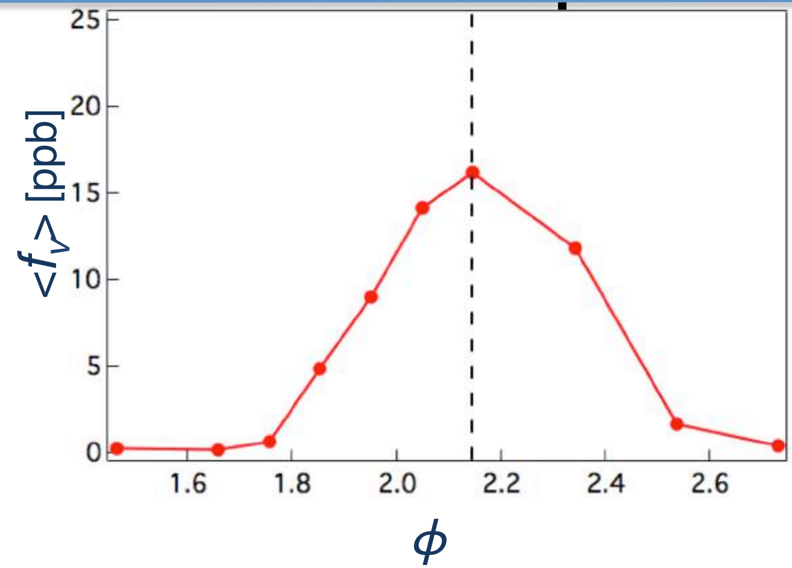
Preheating with a lean flame: T_c=570 K

- repeatability
- sufficient soot production
- quasi-steady thermal state during experiments with ΔT= 15 K

[1] Roussillo, M. et al, 2018. “A new experimental database for the investigation of soot in a model scale swirled combustor under perfectly premixed rich conditions”. ***ASME 2018***

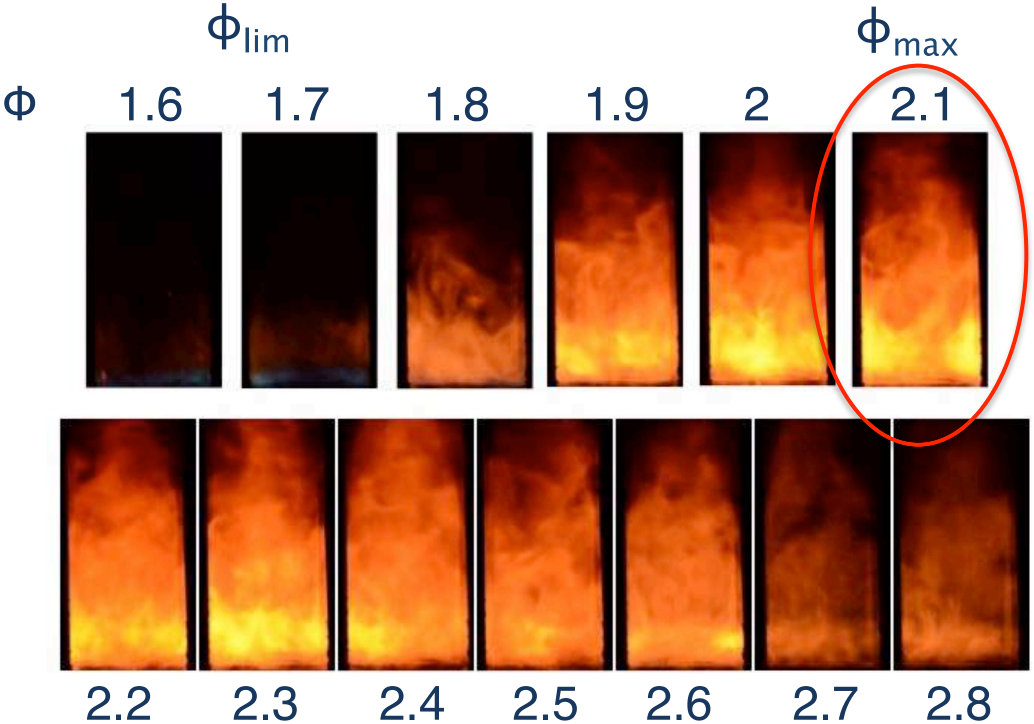
Effect of equivalence ratio and flame power

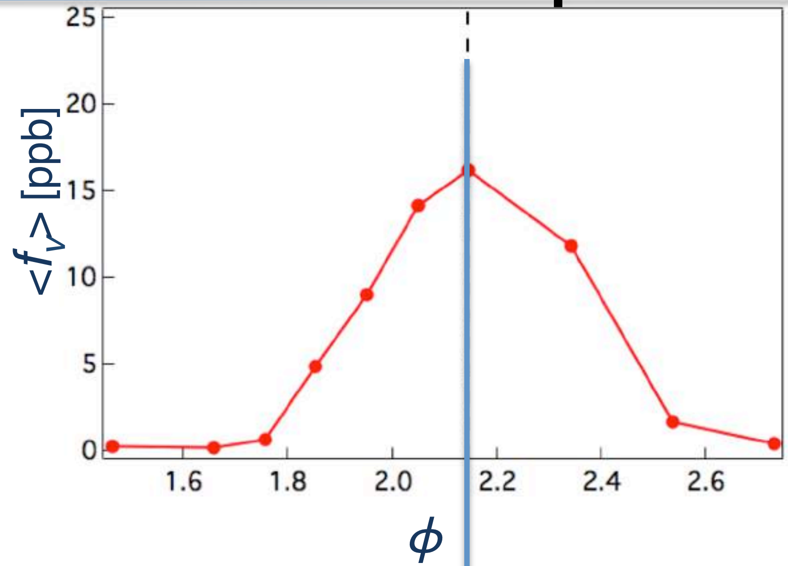


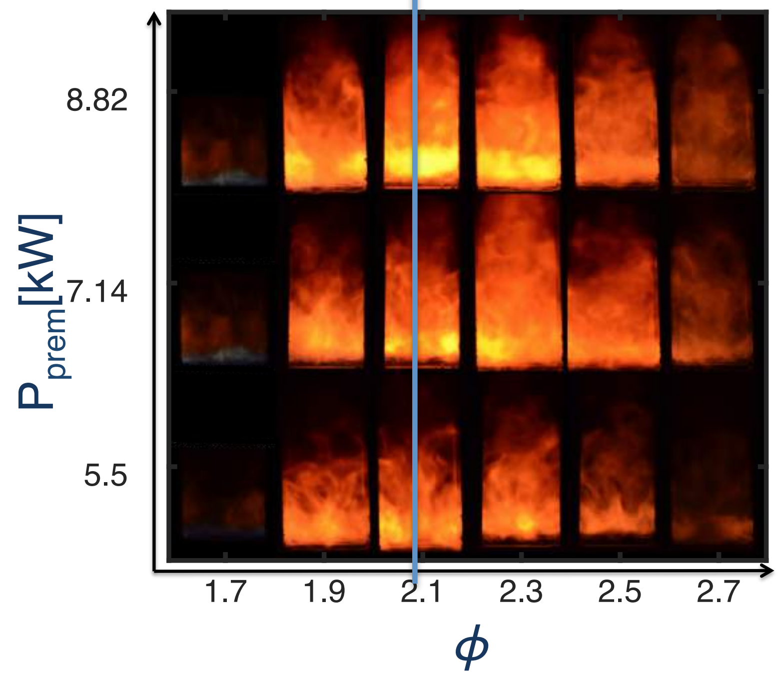


- A critical equivalence ratio for maximum soot production close to 2.1 is measured

Effect of equivalence ratio and flame power







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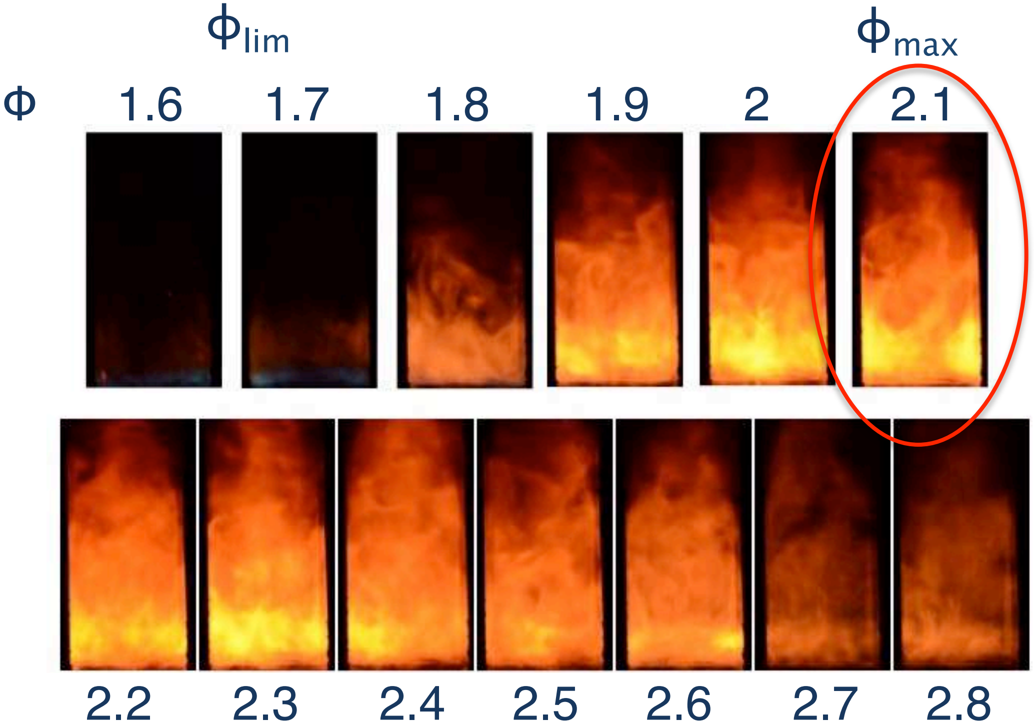
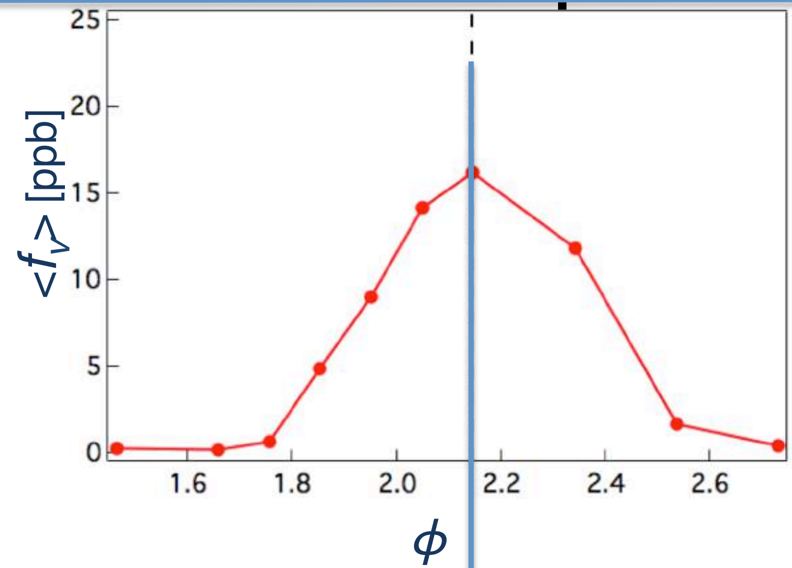
Effect of equivalence ratio and flame power

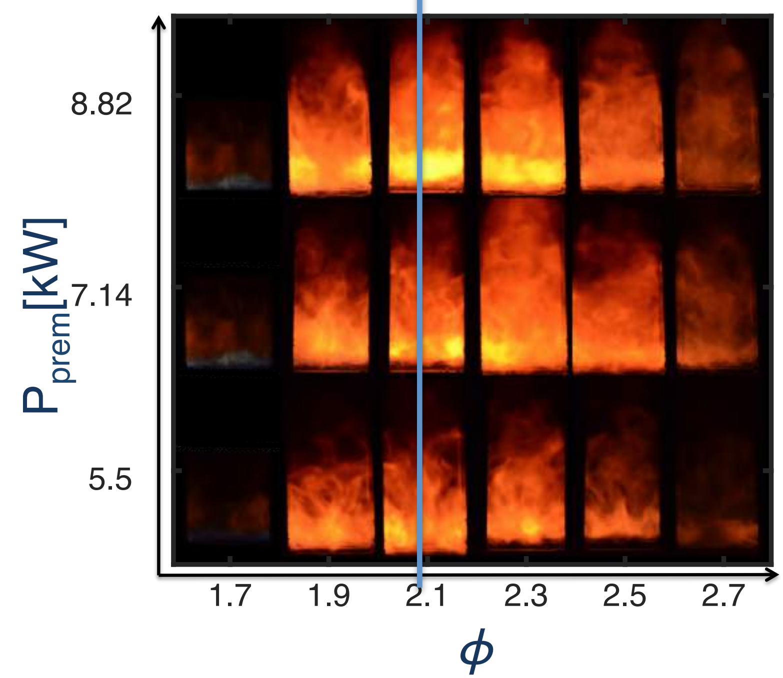




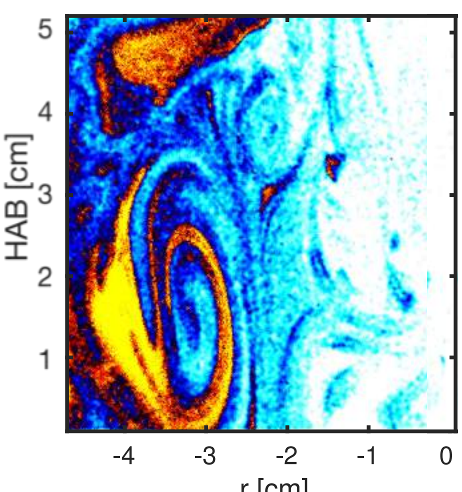
- A critical equivalence ratio for maximum soot production close to 2.1 is measured
- Fair agreement between LII and visual aspect of flame evolution with the equivalence ratio

  Soot production increases with power
- Scalable for all studied powers

  Important effect of the injector design/confinement on ϕ_{lim} and ϕ_{max}



Conclusion



- First quantitative measurements of soot in turbulent premixed sooting flames
- High correlation between quartz temperature and soot production was highlighted
- Soot volume fraction is measured only along the wall but soot particles are present everywhere in the burner
- Effects of equivalence ratio and flame power on soot production have been discussed

Future work:

- New confinement to measure LII signal along the wall
- Temperature measurement by LIP
- Slightly different injector to modify the injector and chamber aerodynamic
- PIV measurements
- Simulations

ACKNOWLEDGMENT

Support from G.Legros and J.Bonnety (UPMC) for the LII calibration through the MAE technique is gratefully acknowledged. This study is supported by the Air Liquide, CentraleSupelec and CNRS Chair on oxycombustion and heat transfer for energy and environment and by the OXYTEC project, grant ANR-12-CHIN-0001 of the French Agence Nationale de la Recherche.

Thank you for your attention

Any questions ?

Paris Saclay University 60 000 students
CentraleSupelec 4 000 stendents
120 000m2

EM2C 4500 m2
44 lab
100 staff

Nomenclature

Rich premixed condition, two flames are present

Exhaust flame

$$P_{exh} = \dot{m}_{exhaust\ fuel} PCI_{C_2H_4}$$

Premixed flame

$$P_{prem} = \dot{m}_{fuel}^{stochio} PCI_{C_2H_4}$$

$P_{tot} = P_{ex} + P_{prem}$

EM2Soot is fully characterized by ϕ and P_{prem}

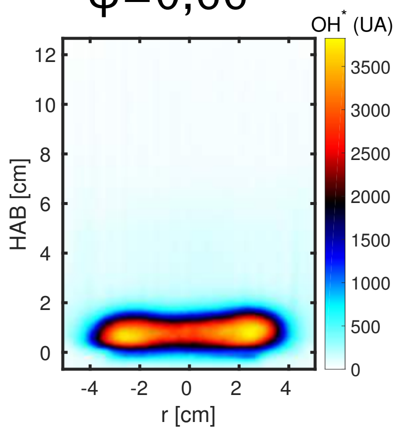
$$\phi = \frac{P_{tot}}{P_{prem}}$$

Effect of wall temperature

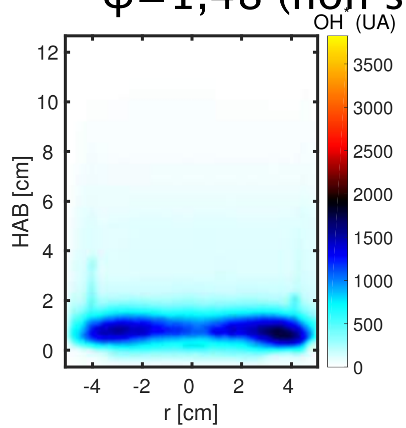
As soot production is extremely linked with the temperature of preheating, a working method had to be implemented:

Information on the flame reaction zone OH

ϕ=0,66

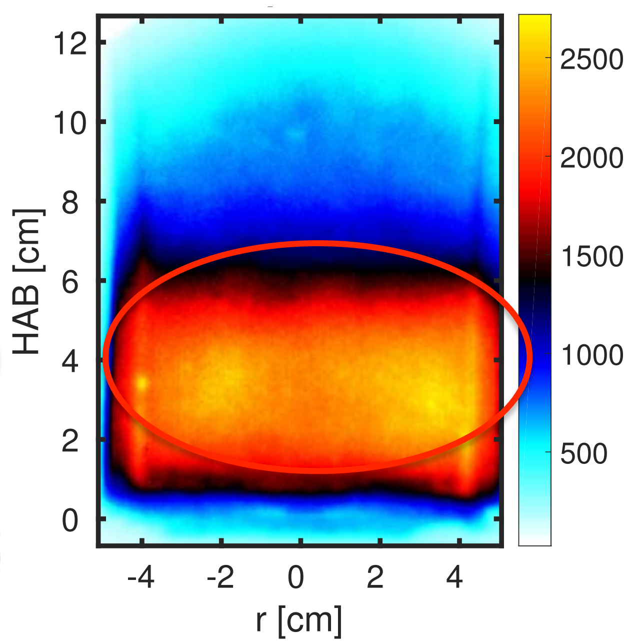


ϕ=1,48 (non sooting)



Reaction zone close to the injector backplane with this injector design[1]

ϕ=1,7 (sooting)



OH detection is no longer possible due to black body radiation of naturally heated soot particle and low OH concentration for rich conditions[2]

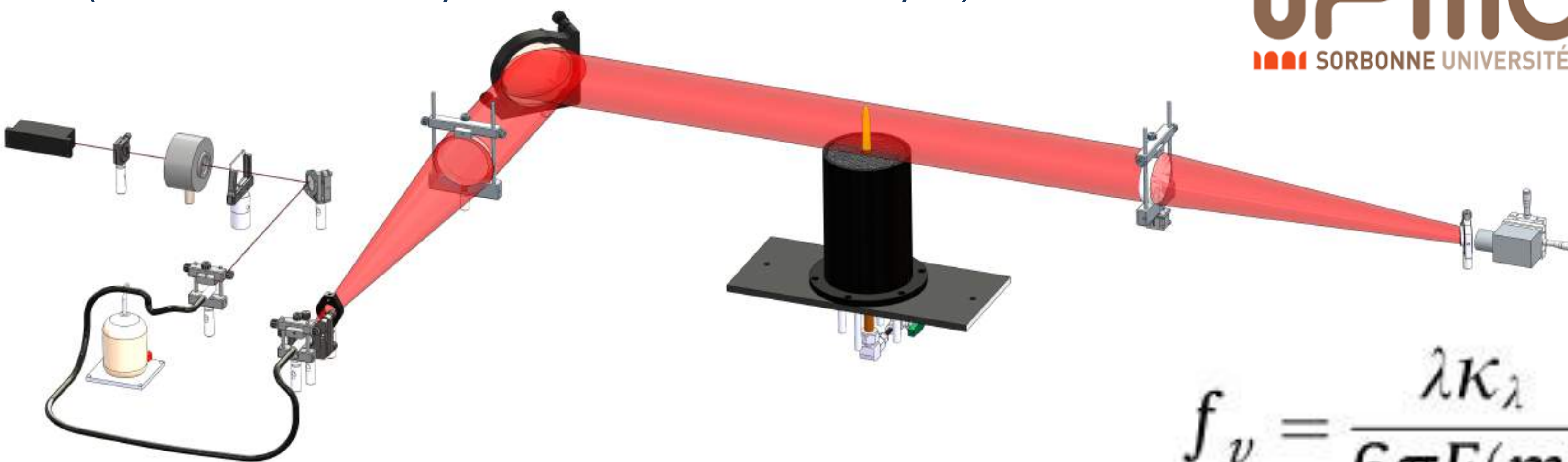
Hypothesis: Reaction zone remains the same for non-sooting and sooting flames

[1]* Jourdaine, P et al** "Effect of quarl on N2 -and CO2 -diluted methane oxy-flames stabilized by an axialplus-tangential swirler". ***In ASME Turbo Expo 2016: Turbomachinery Technical Conference and Exposition

***[2]* Panoutsos, C.et al.**, 2009. "Numerical evaluation of equivalence ratio measurement using OH *and CH chemiluminescence in premixed and nonpremixed methane–air flames". **Combust. Flame**,* 156 (2), pp. 273–291

MAE [1] on a laminar configuration [2]

MAE [4] (Modulated Absorption Emission Technique):

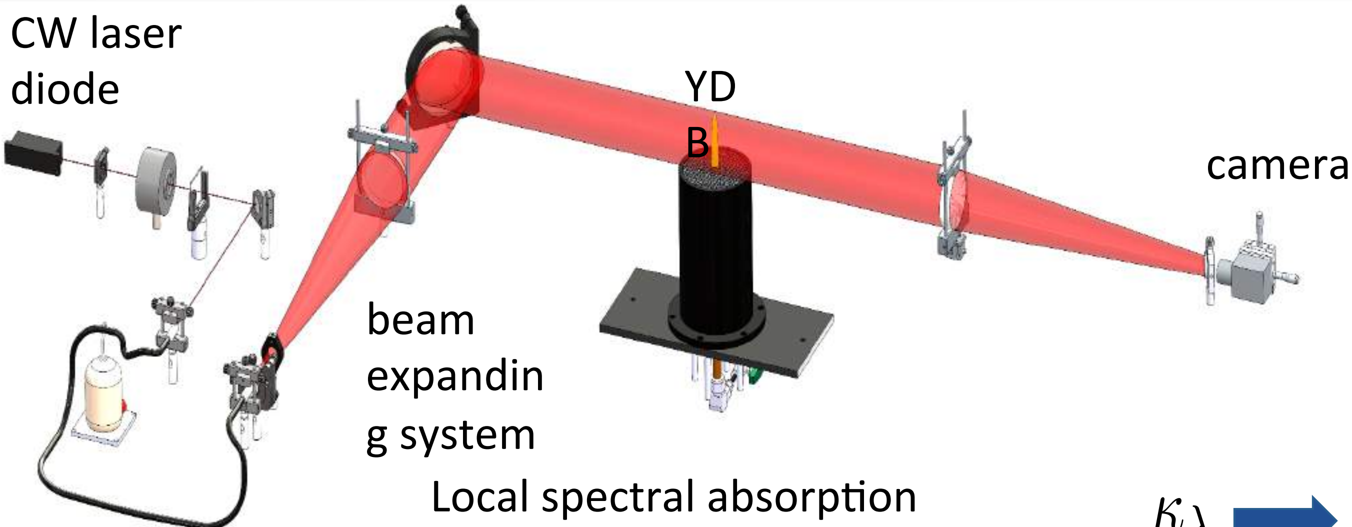


$$f_v = \frac{\lambda K_\lambda}{6\pi E(m)}$$

- Measurements of f_v and T in laminar axisymmetric flames based on absorption measurements
- Non-applicable in turbulent flames (cf deconvolution process)
- Main sources or errors linked with the high variability of E(m)

[1] Legros, G et al.(2015). Simultaneous soot temperature and volume fraction measurements in axis-symmetric flames by a two-dimensional modulated absorption/emission technique. *Combustion and Flame*, *162*(6), 2705-2719
[2] Franzelli, B. et al., 2018. "Muti-diagnostic soot measurements in a laminar diffusion flame to assess the ISF database consistency*".*
Proc. Combust. Inst

MAE [1] on a laminar configuration [2]



Local spectral absorption coefficient from incoming energy with-w/o laser/flame:

$$\kappa_\lambda \rightarrow f_v = \frac{\lambda \kappa_\lambda}{6\pi E(m)}$$

Operating conditions

$\lambda = 645\mathrm{nm}$ $E(m) = 0.38$

Filter $645 \pm 2\mathrm{nm}$

Line-of-sight measurements
In-house deconvolution

Uncertainties

Factor 2: E(m)

2.5% (Santoro flame)

- Measurements of f_v and T in laminar axisymmetric flames based on absorption measurements
- Non-applicable in turbulent flames (cf deconvolution process)
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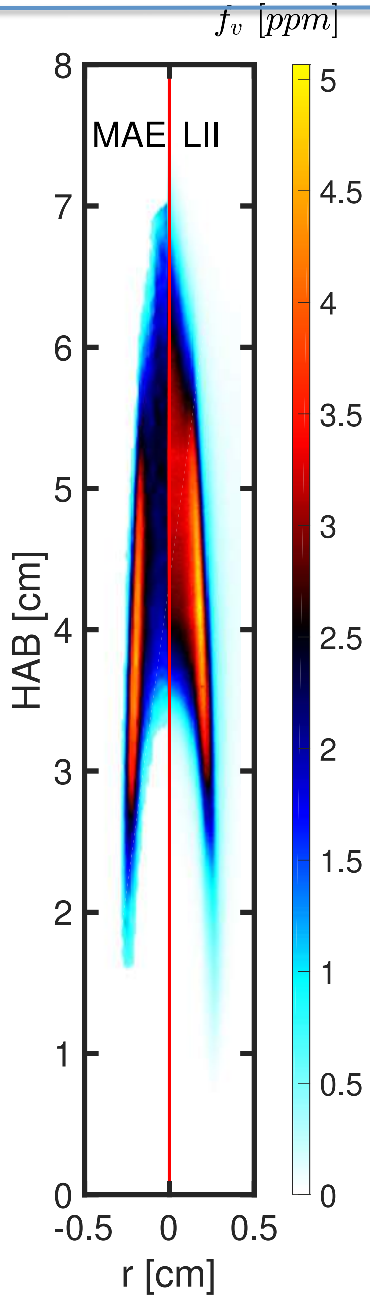
[1] Legros, G et al.(2015). Simultaneous soot temperature and volume fraction measurements in axis-symmetric flames by a two-dimensional modulated absorption/emission technique. *Combustion and Flame*, *162*(6), 2705-2719
[2] Franzelli, B. et al., 2018. "Muti-diagnostic soot measurements in a laminar diffusion flame to assess the ISF database consistency". ***Proc. Combust. Inst***

Calibration of LII with MAE [1] on a laminar configuration [2]



Calibration is carried out by comparing LII and MAE measurements in the wings of the flame in order to neglect:

- LII self-absorption
- MAE errors along the r=0 axis due to the deconvolution process

How intermittency affects results interpretation

Soot is a highly intermittent phenomenon[1,2]:

Intermittency index

$$\Omega(x,y) = 1 - \frac{1}{N_t}\sum_{t=1}^{N_t}\mathcal{I}(x,y,t)$$

with $\mathcal{I}(x,y,t) = \begin{cases} 0 & \text{if} \quad f_v(x,y,t) < \epsilon \\ 1 & \text{if} \quad f_v(x,y,t) \geq \epsilon \end{cases}$

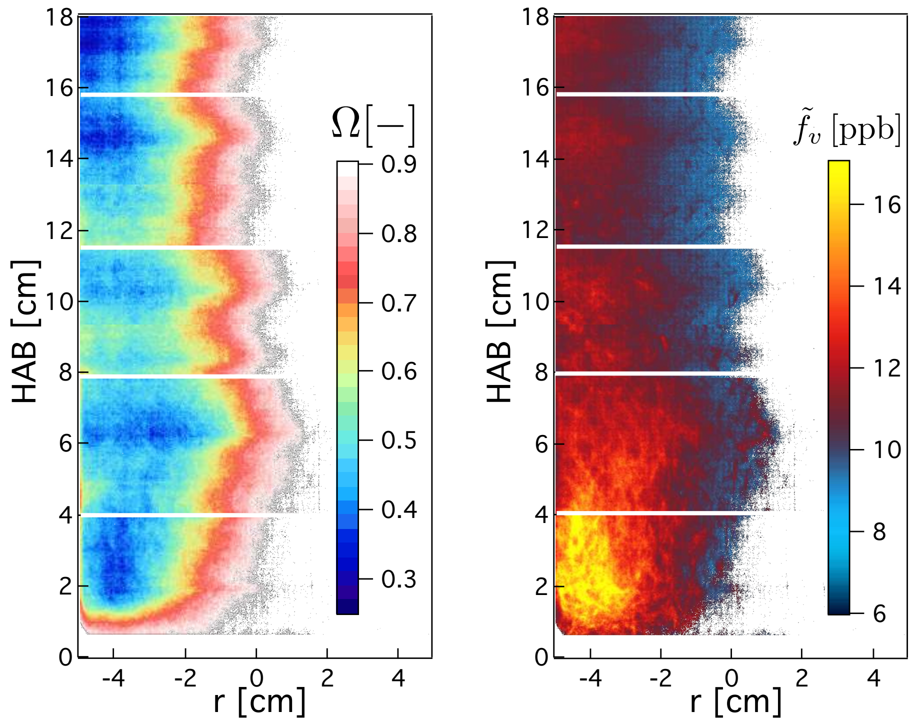
Weighted mean to take into account the intermittency index

$$\widetilde{f_v}(x,y) = \frac{\sum_{t=1}^{N_t} f_v(x,y,t) I(x,y,t)}{\sum_{t=1}^{N_t} I(x,y,t)}$$

Low intermittency

ε=7.5 ppb

Medium intermittency



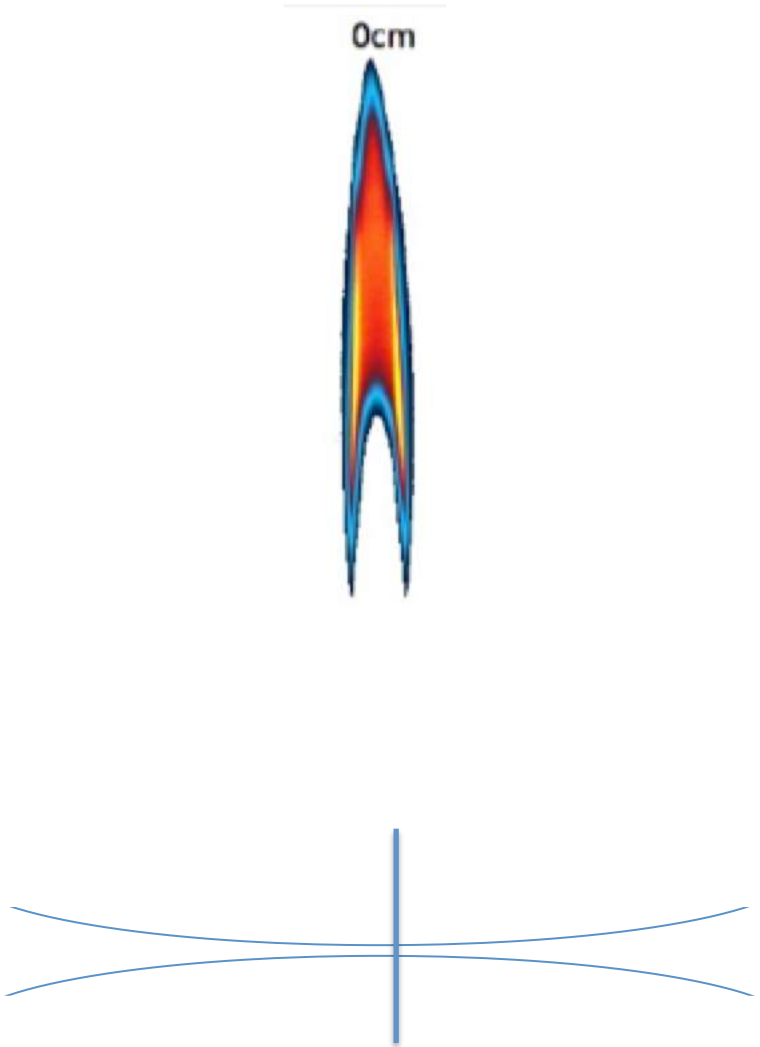
Higher weighted mean in the lower region

[1]*Qamar, N. H. et al* (2009). Soot volume fraction in a piloted turbulent jet non-premixed flame of natural gas. ***Combust. and Flame***, 156(7), 1339-1347.

[2] *Roussillo, M.et al.*, 2018. "Experimental investigation of soot production in a confined swirled flame operating under perfectly premixed rich conditions". ***Proc. Combust. Inst. (submitted)***

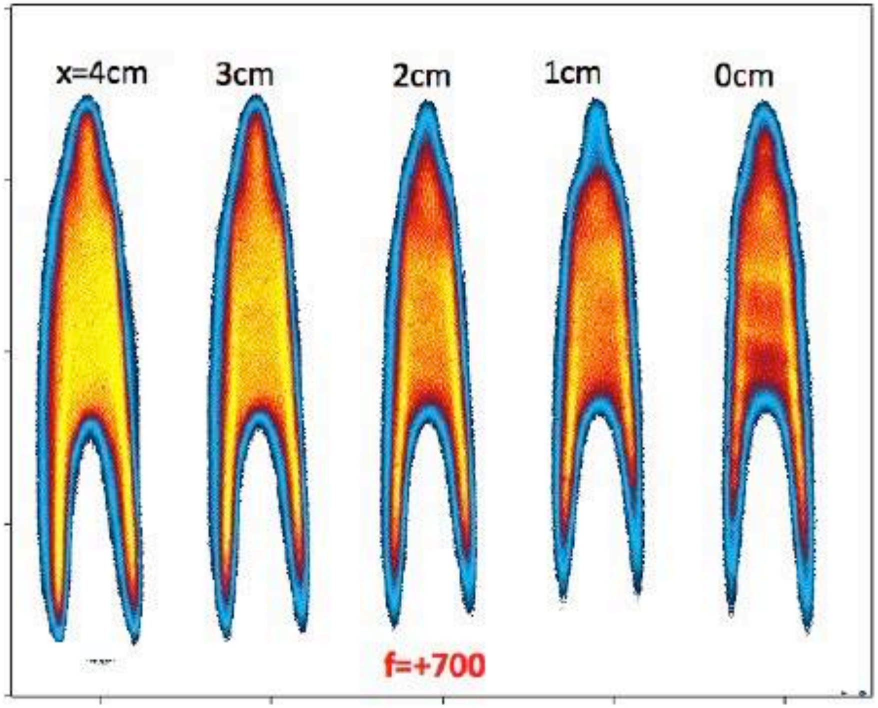
Effect of focal length on LII measurements

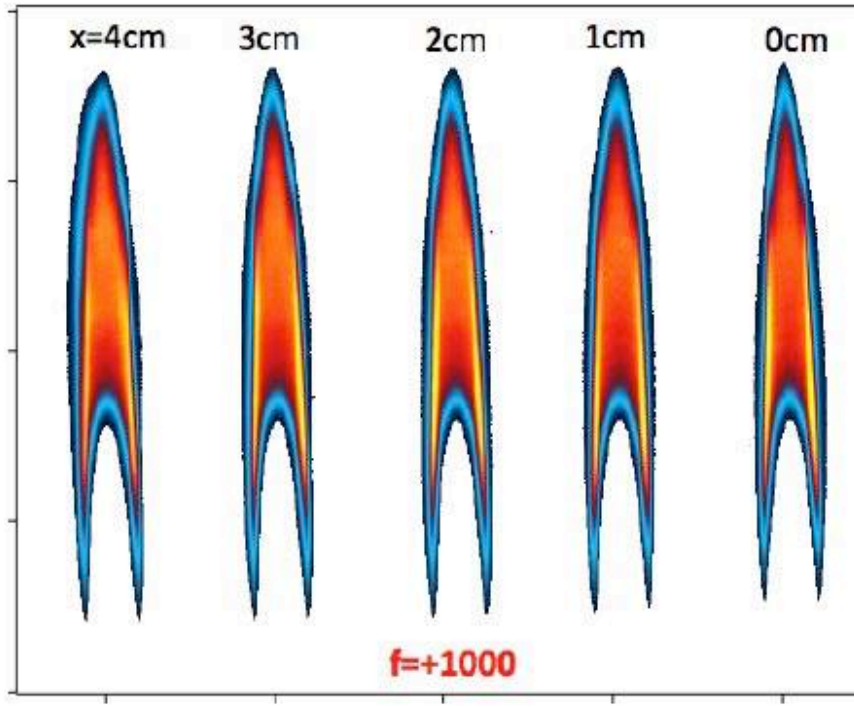
f=700 mm

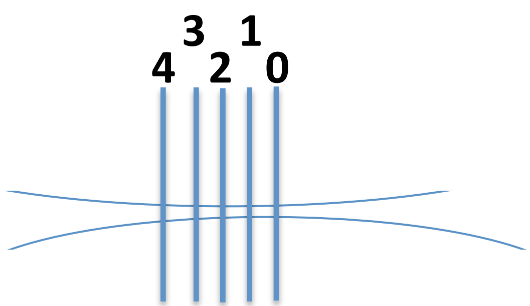


f=1000 mm

Effect of focal length on LII measurements

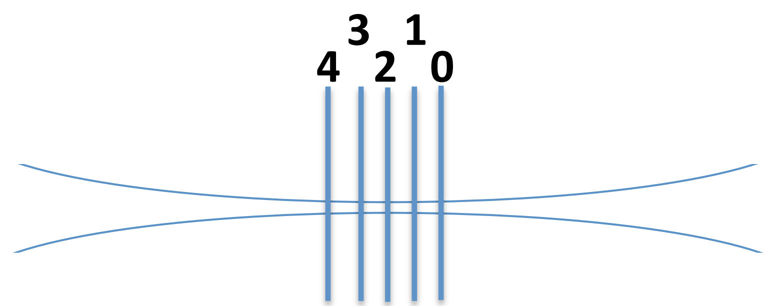






Focus point=0

f=700 mm

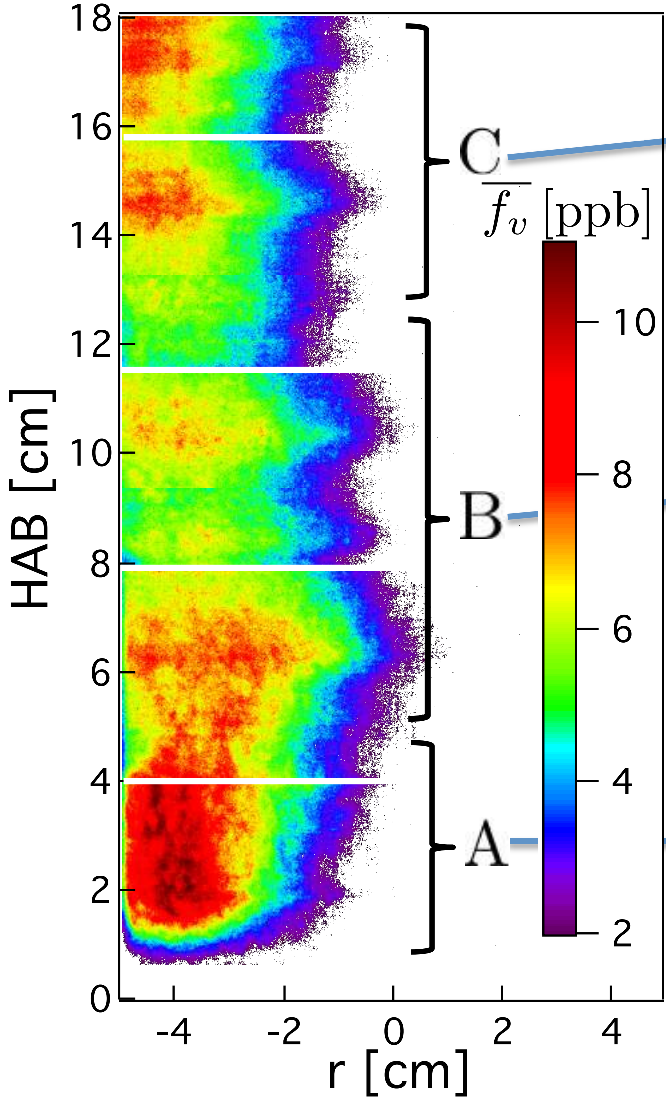


Focus point=0

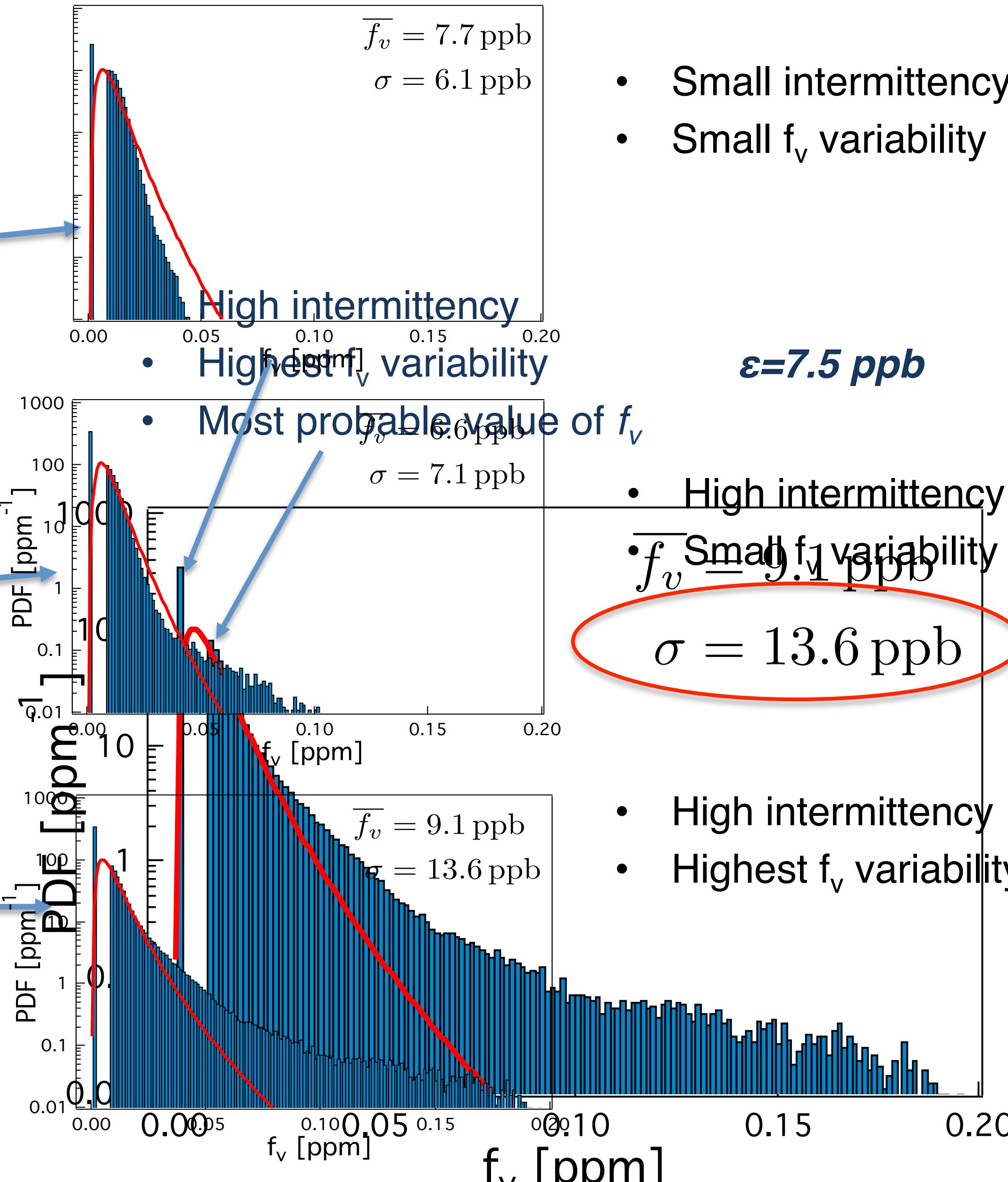
f=1000 mm

Intermittency affects results interpretation

Mean soot volume fraction distribution is monotonic along HAB?



Mean soot volume fraction from 300 uncorrelated images



- Small intermittency
- Small f_v variability

- High intermittency
- Highest f_v variability
- Most probable value of f_v

ε=7.5 ppb

- High intermittency
- Small f_v variability

- High intermittency
- Highest f_v variability

Intermittency affects results interpretation

Weighted mean to take into account the intermittency index I

$$\widetilde{f}_v(x,y) = \frac{\sum_{t=1}^{N_t} f_v(x,y,t) I(x,y,t)}{\sum_{t=1}^{N_t} I(x,y,t)}$$

$$\mathcal{I}(x,y,t) = \begin{cases} 0 & \text{if } \; f_v(x,y,t) < \epsilon \\ 1 & \text{if } \; f_v(x,y,t) \geq \epsilon \end{cases}$$

ε=7.5 ppb

Intermittency has a major impact on soot production➔ weighted mean f_v has a monotonic behaviour along HAB (mean f_v is non-monotonic)