

Optical Technologies for Diagnostics and Control of Combustion Processes Dynamics

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Outline of Presentation

Motivation of work

- Combustion problems of CCS derived fuels.

Flame radiant energy strategy

- Diagnostics, monitoring and control of combustion.

Fields of application

- Identification of thermo-acoustic instabilities.
- Analysis of flameless oxy-combustion of coal-water slurry.
- Monitoring and control of combustion instabilities.
- Anemometry

Combustion Problems of CCS Derived Fuels

CCS derived fuels contain H₂: **syngas**, and, in general, **“hydrogen blends”**.

- H₂ tends to **enhance flame stability**, i.e.,
 - the laminar flame speed increases
 - the ignition delay time decreases
 - the flammability limits enlarge.

□ Designers tend to use **even more leaner mixtures** to reduce NO_x.

□ Design requirements and changes in composition **enhance flame dynamics** with respect to natural gas (thermo-acoustic instabilities, flashback, Lean Blow-Off, localized extinctions and reignitions, ...), while acceptable operation of **GT** requires **“weak” dynamics**.

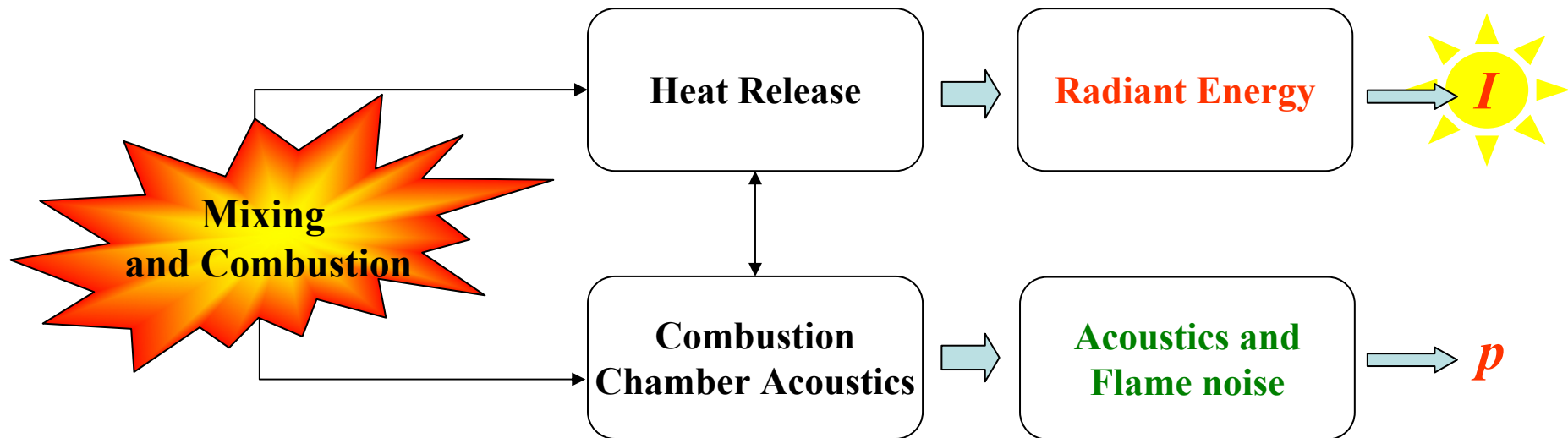
□ “Hydrogen blends” like syngases have **lower LHV** with respect to natural gas.

□ Designers have to **increase the fuel mass flow rate**, and hence its injection velocity, to obtain a certain power.

□ CCS derived fuels come from different sites and have **different composition**.

Real time diagnostics, monitoring and control is required in CCS derived fuels combustors, especially in GTs.

Radiant Energy, Chemical Kinetics and Turbulence



- *Radiant energy I* is due to electronically excited molecules produced by oxidation reactions and which emit light relaxing to lower energy states.
- *Intensity of light emitted* is proportional to the production rate of some molecules \Rightarrow chemiluminescence directly related to **chemical reaction rate** and **heat release rate**.
- *Turbulence* affects mixing and combustion, then radiant energy. **In what dynamical way?**

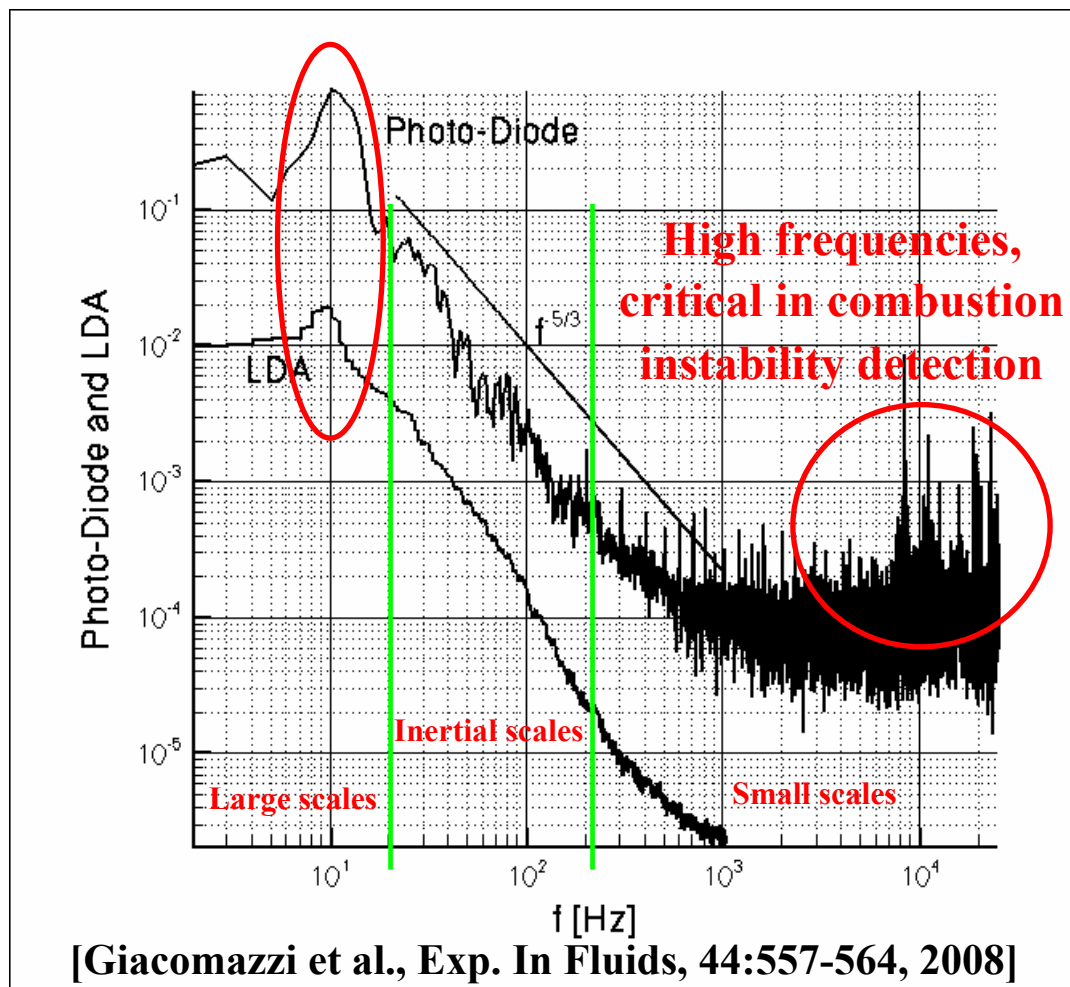


We propose to sample flame radiant energy (e.g., by means of photo-diodes or photomultipliers) for **monitoring flame stability and LBO**.

Radiant Energy Spectrum and Turbulence

Time averaged spectrum (60 spectra of 1 s sampled at 50 kHz) of **flame radiation** shows:

- **Inertial decay**: $f^{-5/3}$ as in turbulence dynamics, found in different combustors (also found by other researchers by means of photo-multipliers looking at OH).
- **High frequency energy peaks**: due to fast **chemical** reactions **or** unphysical **noise**?



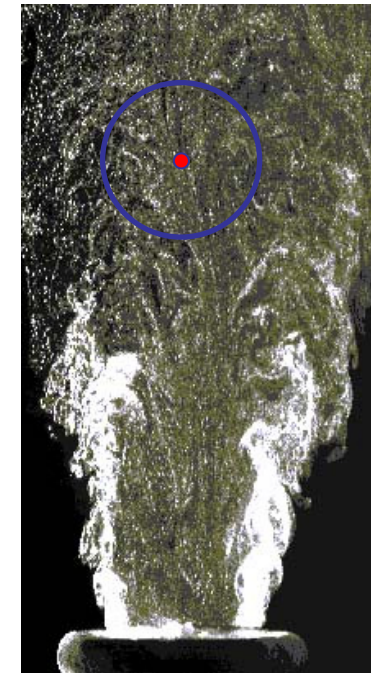
CH_4 / Air Premixed flame

$\text{Re} = 12755$ on L_{bluff}

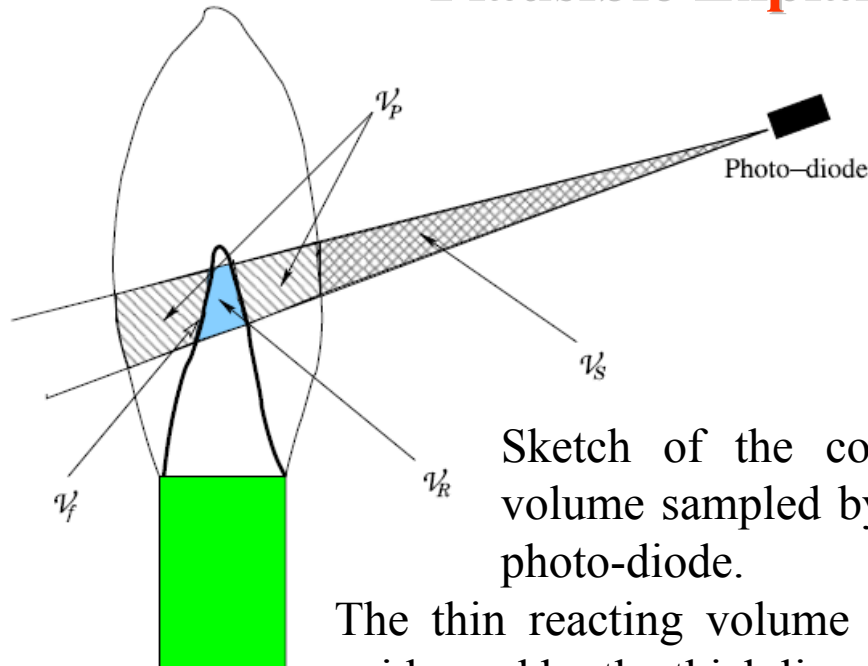
$\Phi = 0.8$

Photo-Diode has a wider sampling region

LDA has a small sampling volume



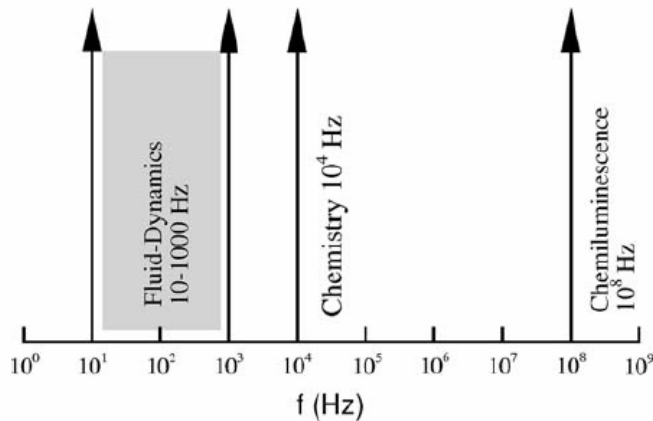
Plausible Explanation of the Scaling



Sketch of the control volume sampled by the photo-diode.

The thin reacting volume V_f is evidenced by the thick line.

V_P is the emitting volume of hot products, V_R is the cold, nonemitting volume of reactants, and V_S is the transparent surrounding space.



$$\overline{I}(t) = \int_{\lambda_1}^{\lambda_2} \left[S_f I_{\text{ch}} + \mathcal{A}_P I_{\text{th}}|_{\mathcal{A}_P} + S_f I_{\text{th}}|_{S_f} \right] d\lambda.$$

$$\overline{I}(t) \approx \underbrace{\int_{\lambda_1}^{\lambda_2} S_f(t) \sum_{\text{rad}=1}^{N_{\text{rad}}} i_{\text{rad}} \gamma_{\text{rad}}^*(T_f) Y_{\text{rad}}(t) d\lambda}_{\overline{\Phi}_{\text{ch}}}$$

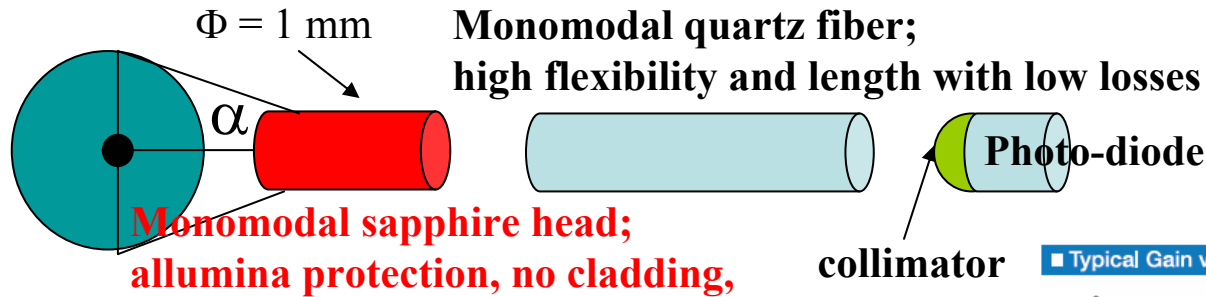
$$+ \underbrace{\int_{\lambda_1}^{\lambda_2} [\mathcal{A}_P I_{\text{th}}(\overline{T}, \lambda) + S_f(t) I_{\text{th}}(T_f, \lambda)] d\lambda}_{\overline{\Phi}_{\text{th}}}$$

$$\overline{I}(t) \approx S_f(t) \sum_{\text{rad}=1}^{N_{\text{rad}}} i_{\text{rad}} \gamma_{\text{rad}}^*(T_f) Y_{\text{rad}}(t) \delta(\lambda - \lambda_{\text{rad}}) + \overline{\Phi}_{\text{th}},$$

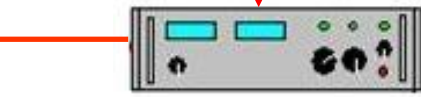
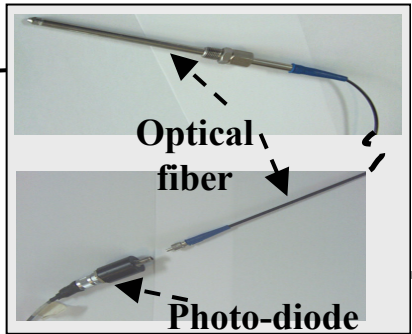
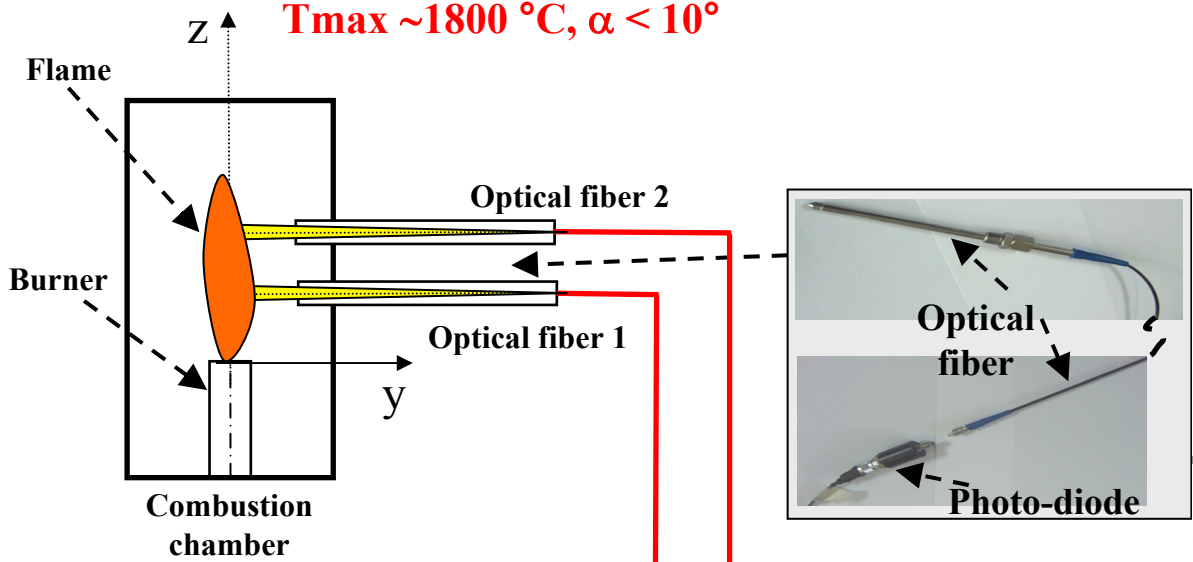
$$\frac{D\overline{I}}{Dt} \approx \left[\sum_{\text{rad}=1}^{N_{\text{rad}}} i_{\text{rad}} \gamma_{\text{rad}}^*(T_f) Y_{\text{rad}} \delta(\lambda - \lambda_{\text{rad}}) + \int_{\lambda_1}^{\lambda_2} I_{\text{th}}(T_f, \lambda) d\lambda \right] \frac{DS_f}{Dt}$$

[Giacomazzi et al., Exp. In Fluids, 44:557-564, 2008]

ODC (Optical Diagnostics of Combustion)

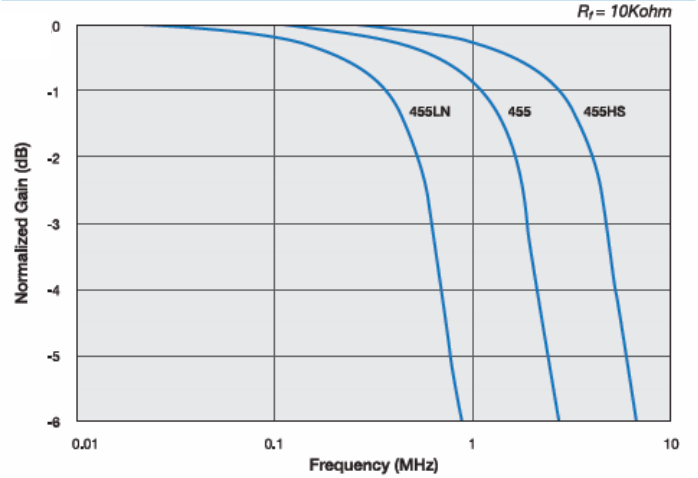


**ENEA's Patent
 2004**

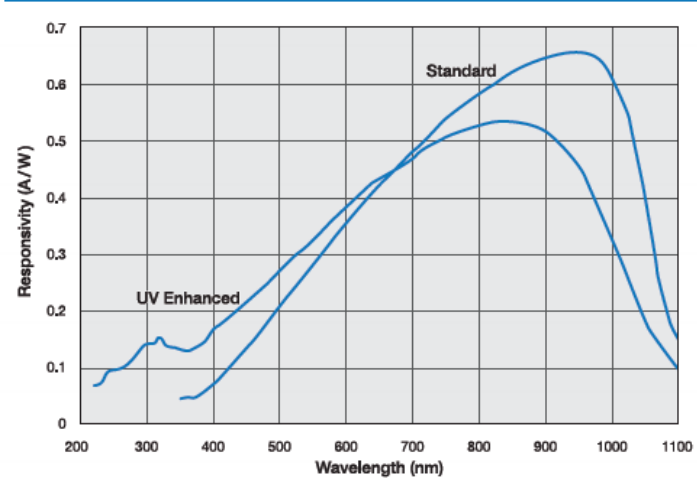


PC + Lab-VIEW **DAQ ($f_s = 10 \text{ MHz}$, sampling frequency)**
 Real time analysis; signal averaging on N samples $f_s^* = f_s/N$

■ Typical Gain vs. Frequency $R_f = 10 \text{ Kohm}$



■ Typical Spectral Response



Fields of Application

- **Combustion dynamics analysis and instability detection**

- **250 kW** Liquid Oil/Air Rapid Premixed burner in Savona Combustion Laboratory.
- **300 kW** H₂/O₂ MICOS burner in ENEA Casaccia Research Center in Rome.
- **500 kW** CH₄/Air Centro Caldaie ANSALDO burner in Gioia del Colle (Bari).
- **3000 kW** CH₄/Air Centro Caldaie ANSALDO burner in Gioia del Colle (Bari).
- **5000 kW** coal/water slurry ITEA flameless oxy-combustion burner in Gioia del Colle (Ba).

The first four burners can experience **thermo-acoustic instabilities**.

These are driven by coupling between heat release fluctuations and pressure oscillations. Acoustics of the system is the feedback mechanism to induce self-excited growing amplitude oscillations of pressure.

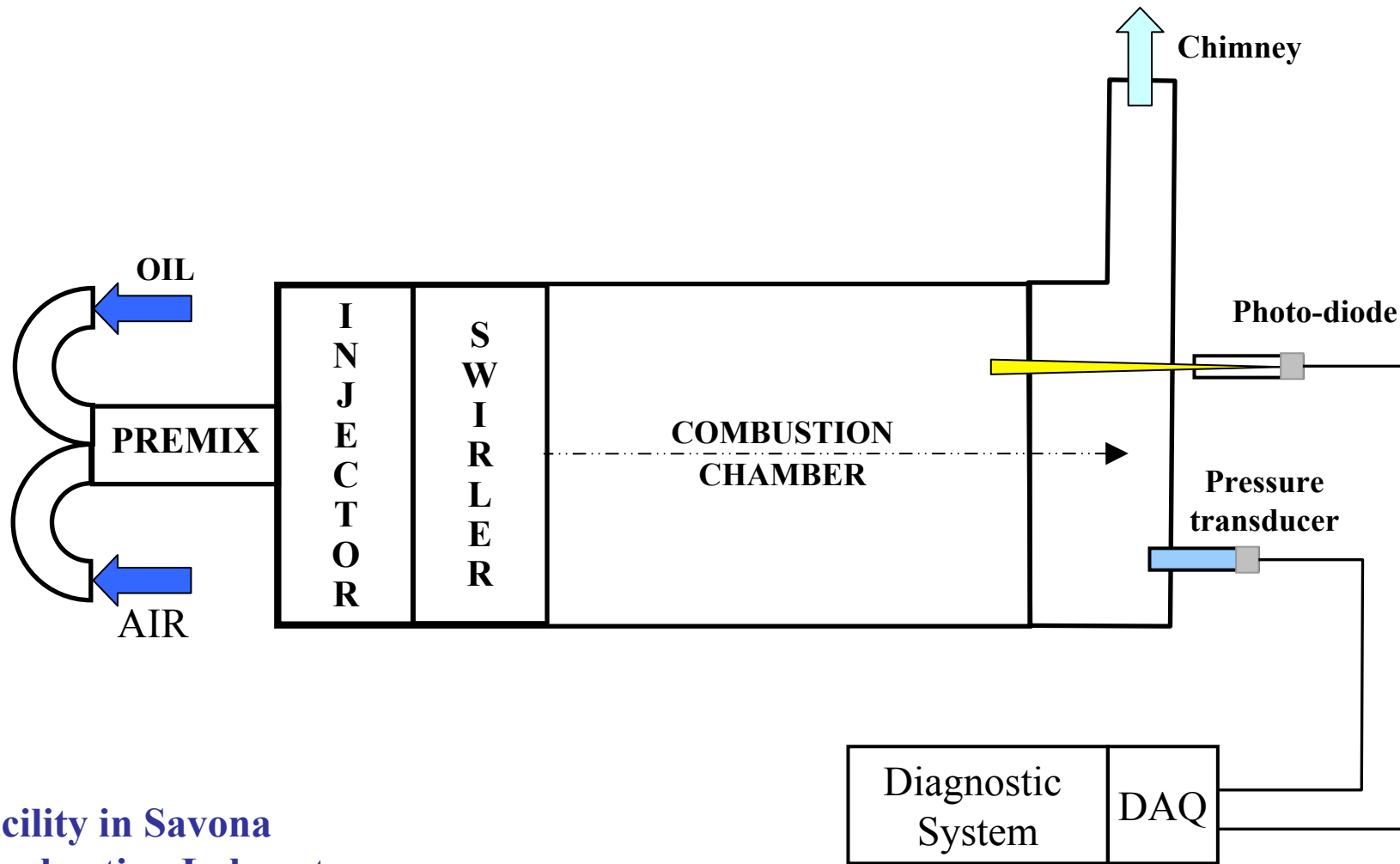
When heat release and pressure oscillation are in phase, **thermal energy** is directly “**converted**” into acoustic energy.

- **Control systems**

- **Anemometry**

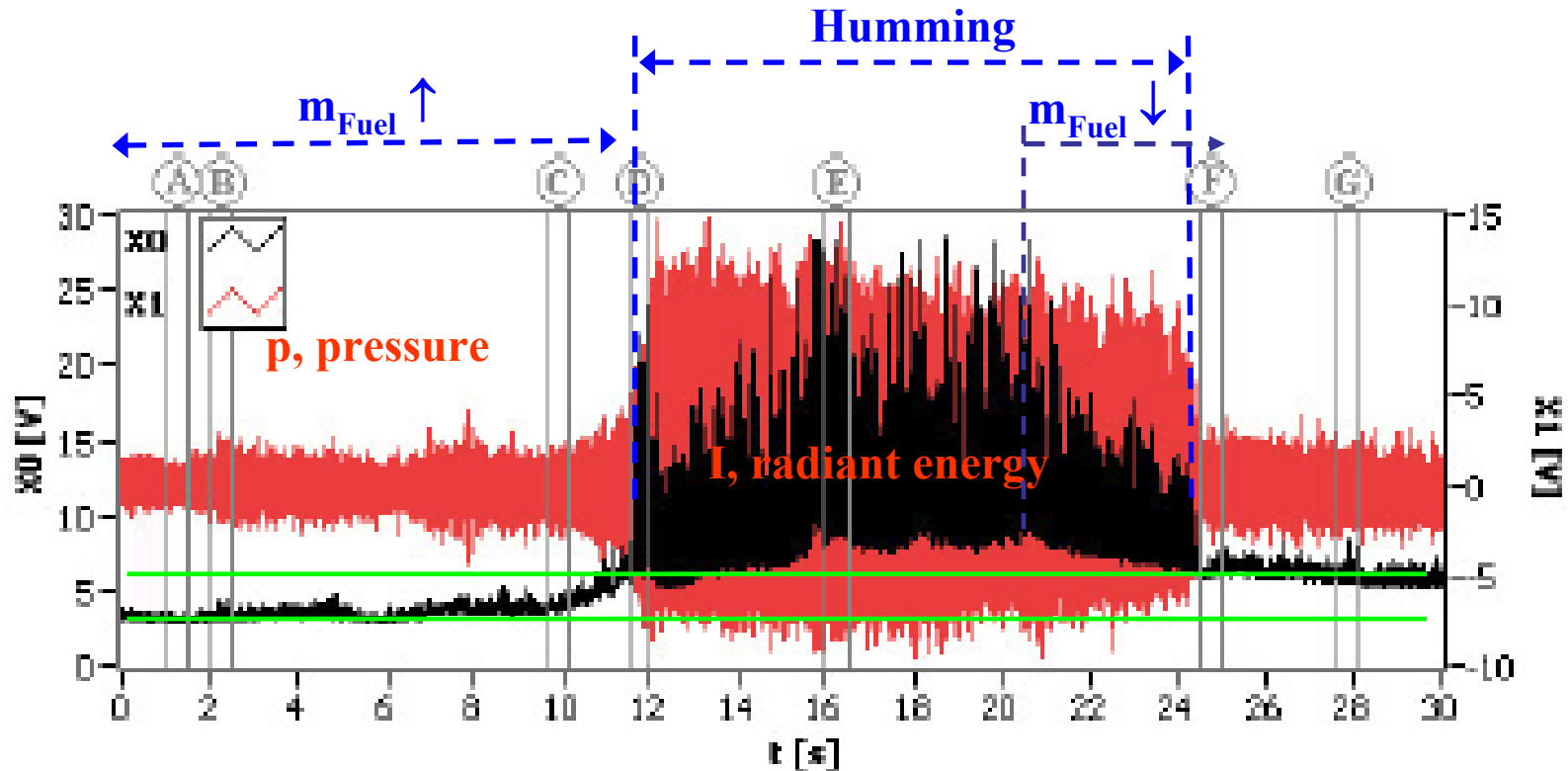
- **Measure of the sound speed (and estimation of temperature, work in progress)**

BURNER A: 250 kW Premixed Liquid Oil / Air Burner



Facility in Savona
Combustion Laboratory

BURNER A: 250 kW Premixed Liquid Oil / Air Burner



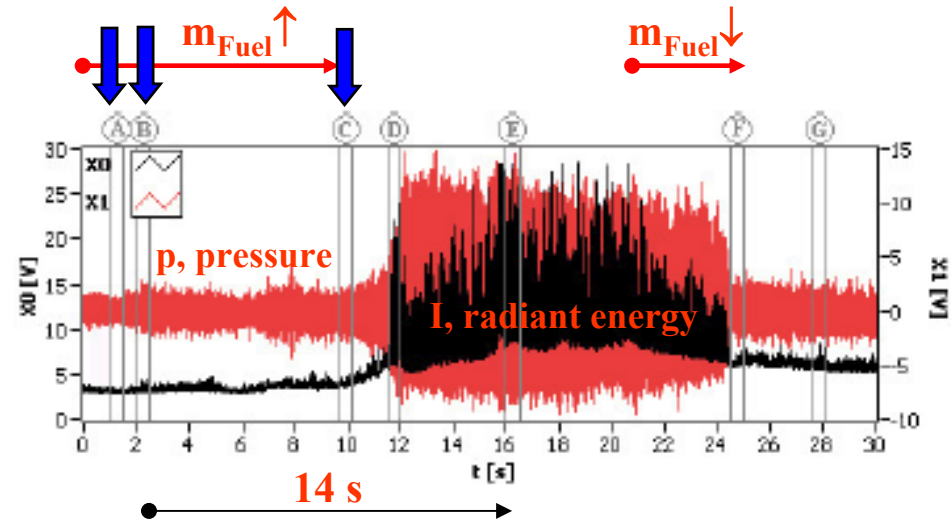
- 30 s observation
- 7 time windows of 0.5 s
- **transition to humming** by **increasing m_{Fuel}** from 0.168 up to 0.232 g/s in 10 s
- pressure – radiant energy cross-correlation, auto-correlation, frequency analysis

A, Stable Mode: no cross- and auto- correlations; small amplitude peak frequencies:

f_I @ 15, 39, 52, 66 Hz
 f_p @ 17, 54, 74, **80** Hz

B, Towards Instability: cross- and auto- correlations \uparrow ; dominant f @ **80** Hz.

- Increasing m_{Fuel} forces radiant energy to **intermittently synchronize** with pressure.
- These events have **short life-time**, but appear early, **14 s prior** fully establishment of instability in E.



Increasing m_{Fuel} more energy is released, $T \uparrow$, and **precursor** events become **more frequent**.

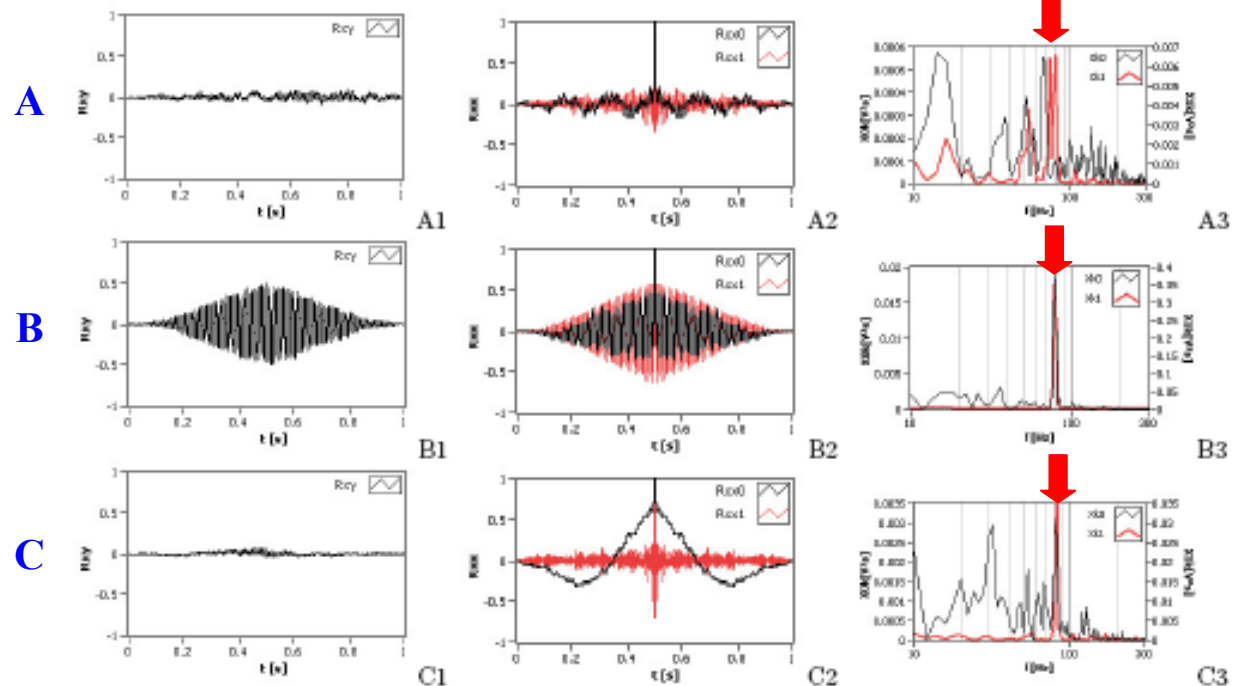
C, Towards Instability: f @ **80** Hz tends to be “**steady**”, i.e., also present when p - I **cross-correlation** is **negligible**.

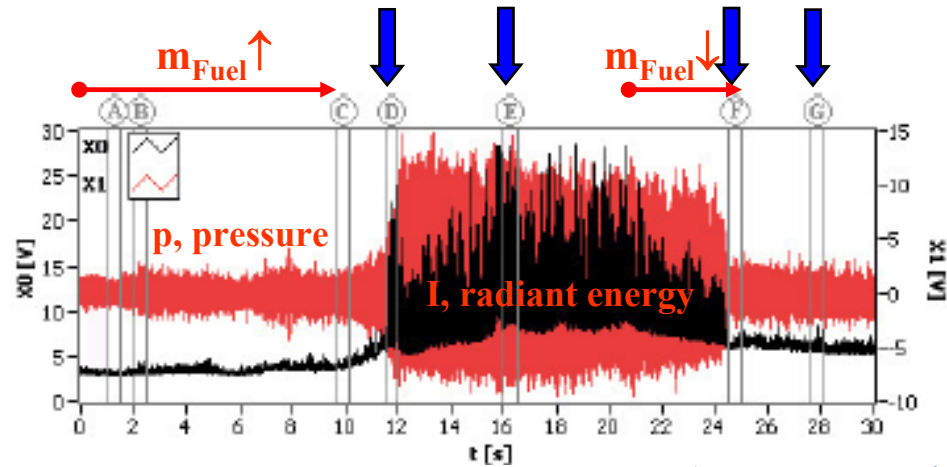
Radiant energy is still auto-correlated, evidencing instability. The “no burst” mode is due to not removing the local average \rightarrow **drift**.

Cross-correlation

Auto-correlation

Spectra

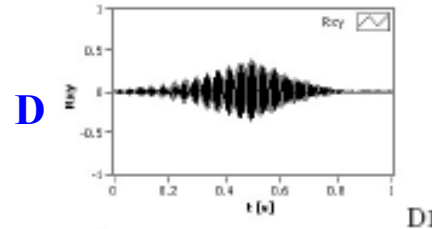




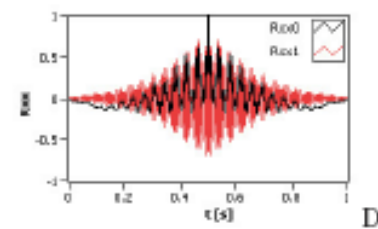
D, Humming Onset:

- Cross- and auto- **correlations** \uparrow .
- $T \uparrow$
- **frequency** \uparrow : $f @ 112, 136$ Hz.

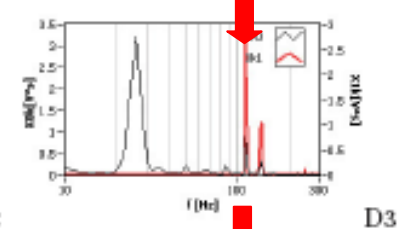
Cross-correlation



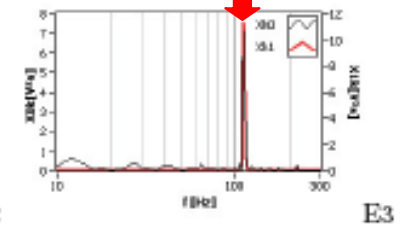
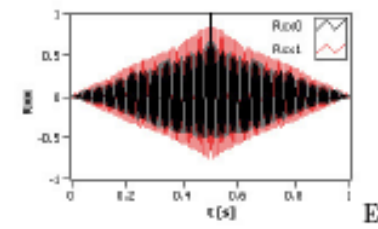
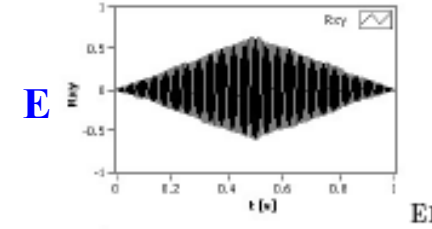
Auto-correlation



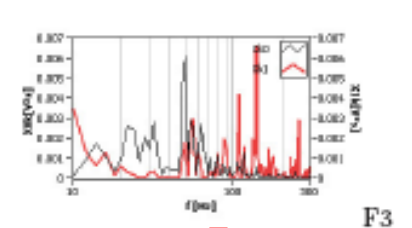
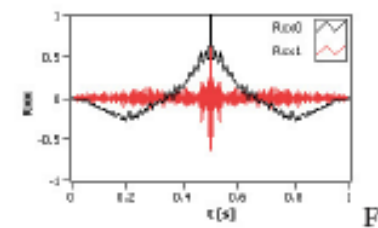
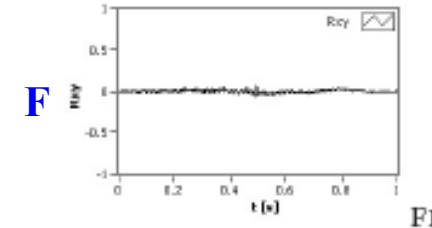
Spectra



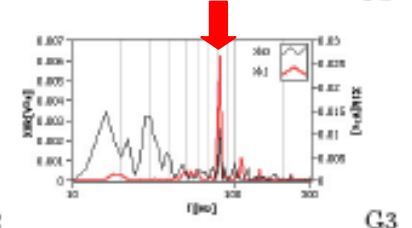
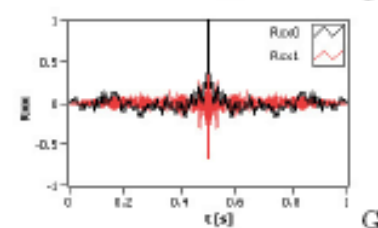
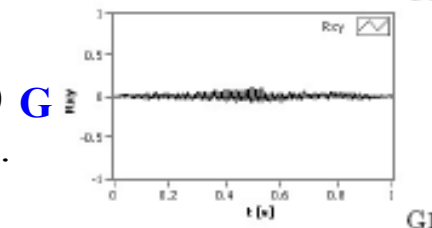
E, Inside the Humming: one frequency selected @ 112 Hz.



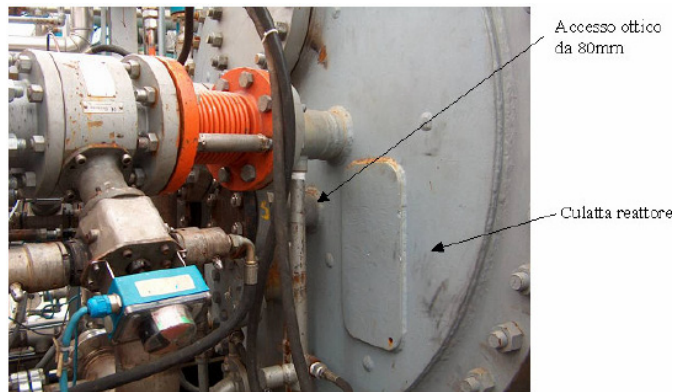
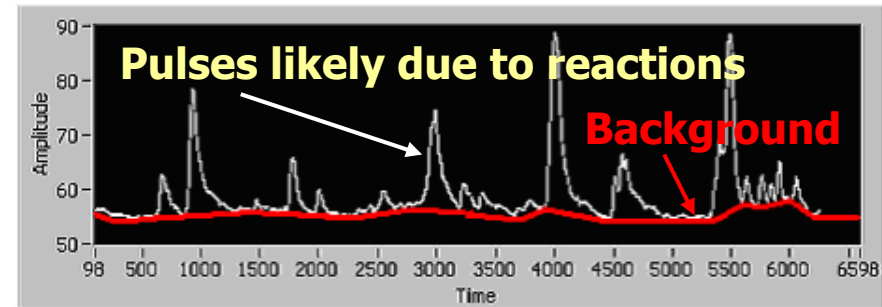
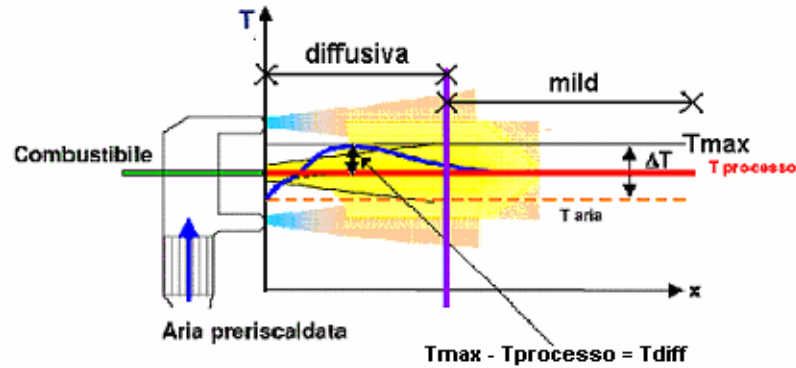
F, Humming Exit: many frequencies appear again, as at “humming” onset.



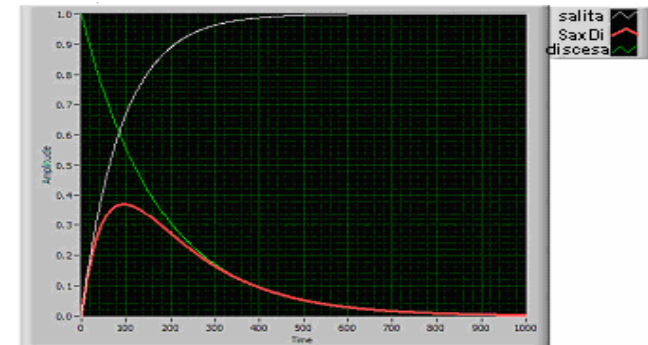
G, Towards the Stable Mode: the system slowly (T stays high, inertia) turns back to its stable configuration.



BURNER E: Flameless Oxy-Combustion of Coal/Water Slurry (Isotherm PWR-ITEA)



**Work in progress:
Looking for process indicators**



$$p_t = r_0 (1 - e^{-kt})$$

p = products concentration

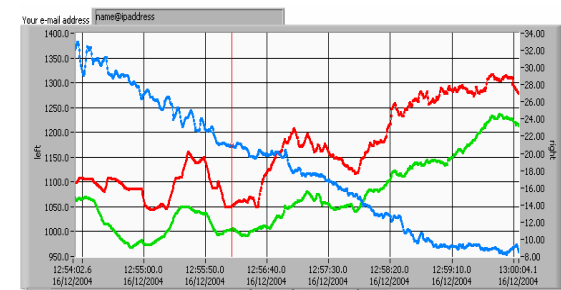
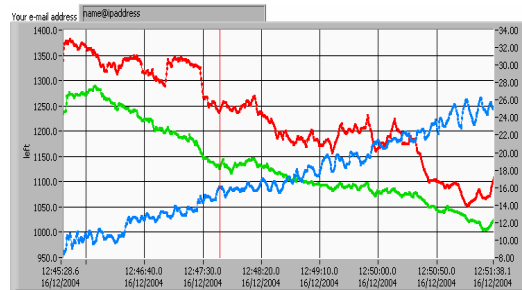
r_0 = initial concentration

k = reaction rate

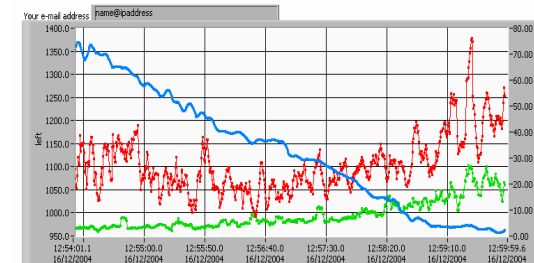
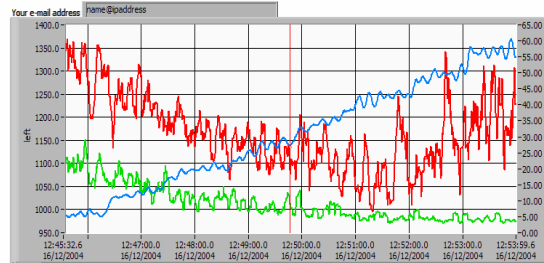
BURNER E: Flameless Oxy-Combustion of Coal/Water Slurry (Isotherm PWR-ITEA)

A **pyrometer** shows **T↓** (initial T = 1800 °C) when the cold (200 °C) **O₂↑**, in agreement with the **ODC background**. The system becomes **less reactive**:

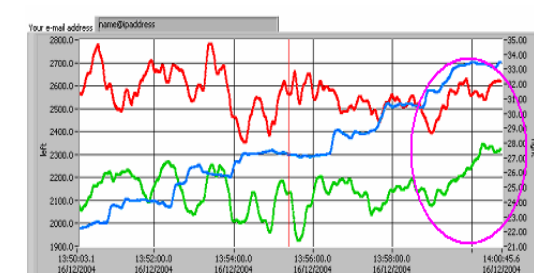
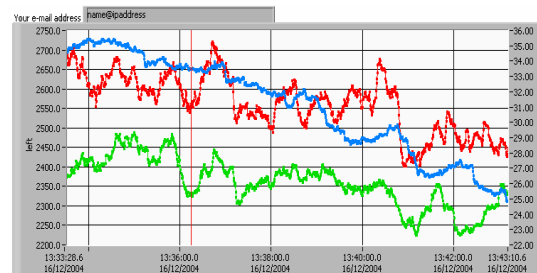
- **rise and decrease times ↓**
- **average pulse amplitude ↓**



Changes of **rise (green)** and **decrease (red)** times versus **O₂ mass flow rate (blue)**.



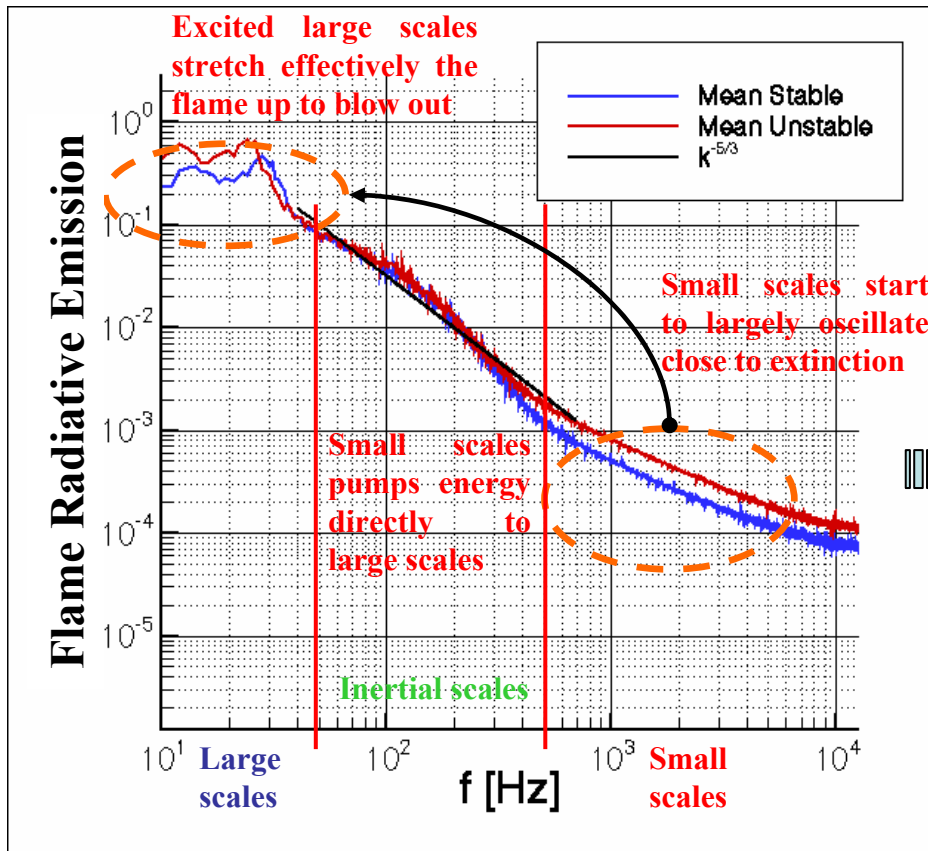
Changes of number of **validated impulses (red)** and of their **average value (green)** versus **O₂ mass flow rate (blue)**.



Changes of **rise (green)** and **decrease (red)** times versus **hot exhaust gases mass flow rate (blue)**.

Low sensitivity to hot exhaust gases flow rate

Towards Instability Analysis



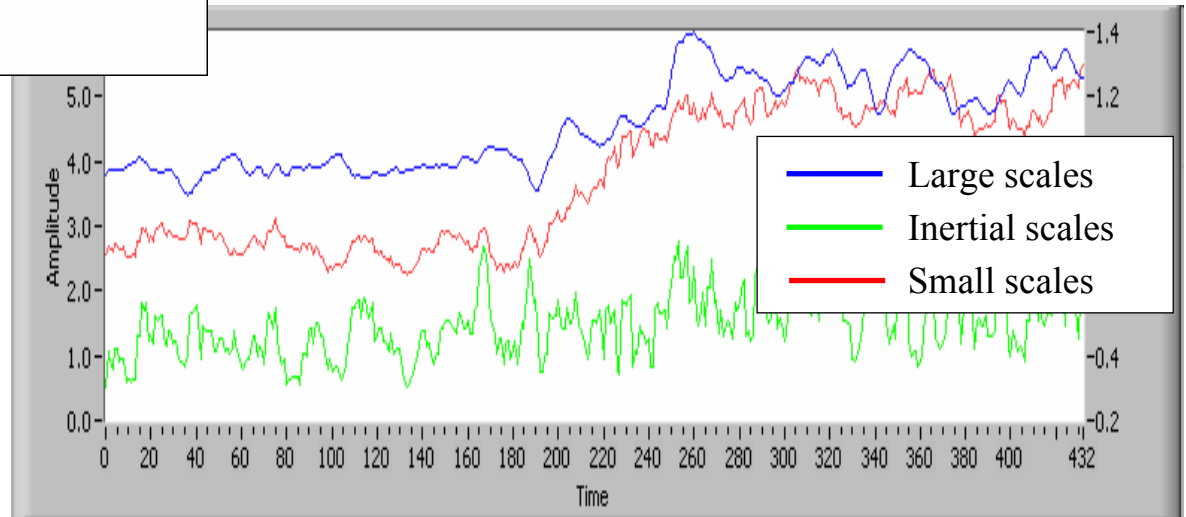
← Spectra **averaged** by using **60** spectra, each sampled in **1 s**, when a flame is **stable** and when is **close to extinction**.

Non local (in wave numbers and not in space) scale interaction!

Control

Dynamics of the three ranges when the flame is **close to extinction**.

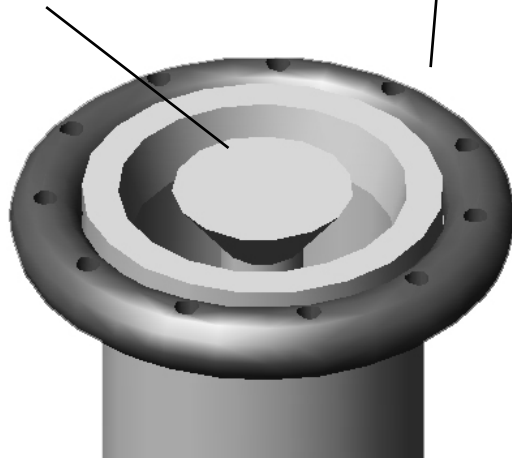
When the flame is unstable, small scales fluctuations cause large scale fluctuations (opposite when the flame is stable).



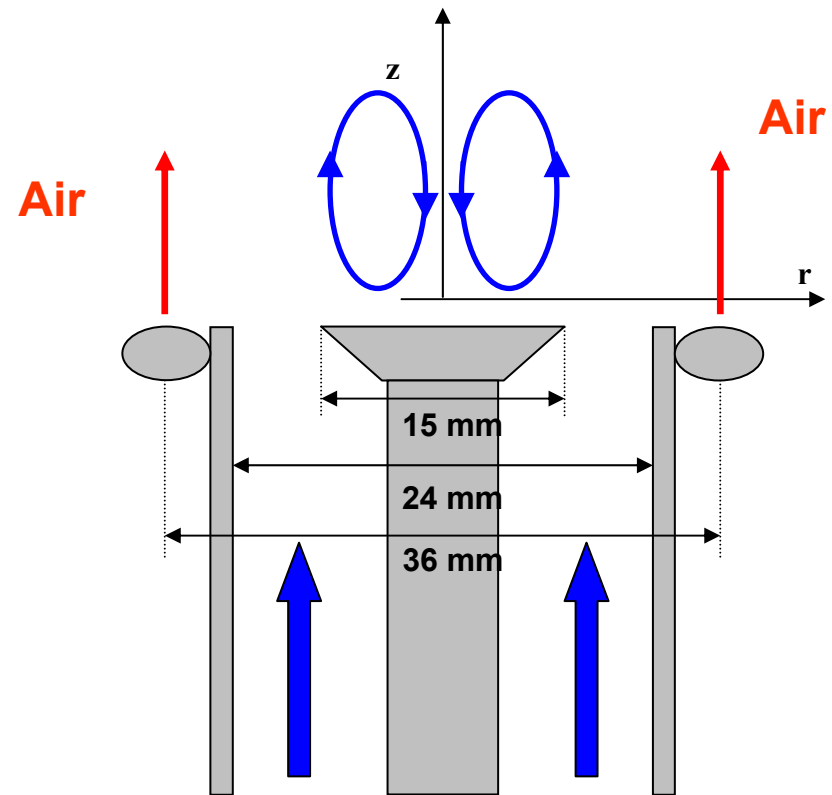
An Example of Active Control Strategy

Surrounding control air jets
($d = 2$ mm)

Bluff-body



5 on/off valves array ($2^N = 32$ air mass flow rate values), $f_{ctrl} = 10$ Hz



Air + Methane (CH₄)

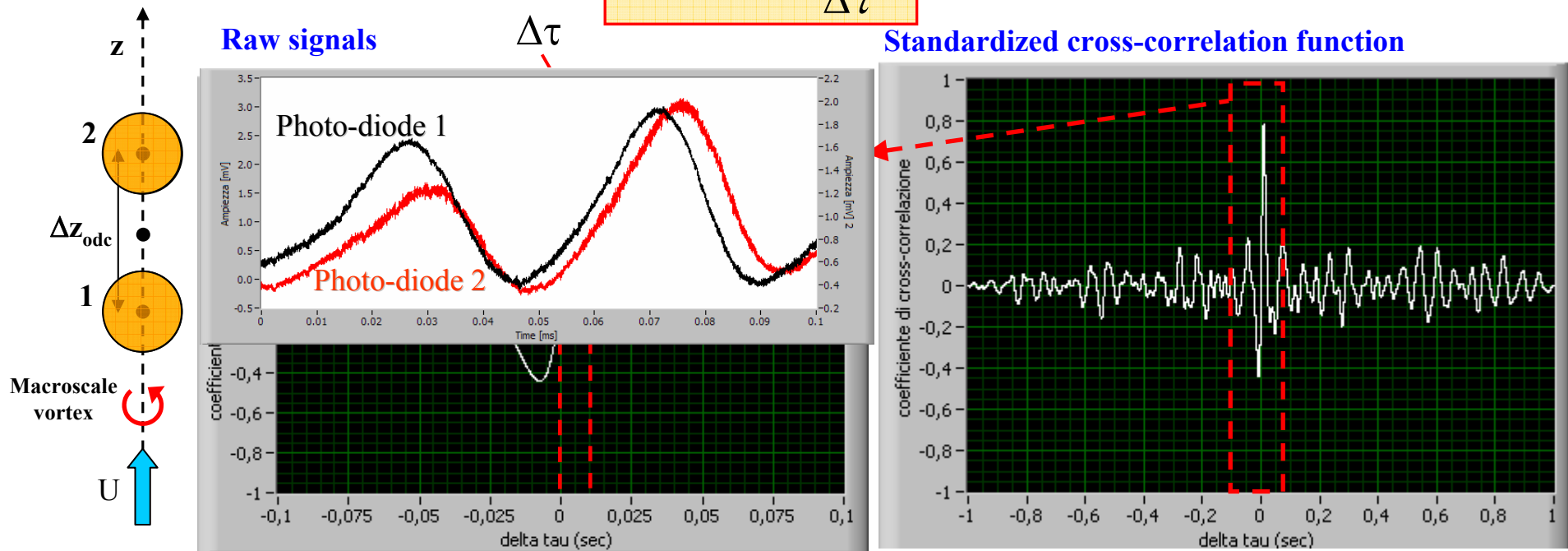
Active control strategy based on the activation of surrounding air jets **derived from** numerical **LES** simulation.

[Giacomazzi E. and Bruno C., ISABE 2001]

ODC (Optical Diagnostics of Combustion) Anemometry methodology

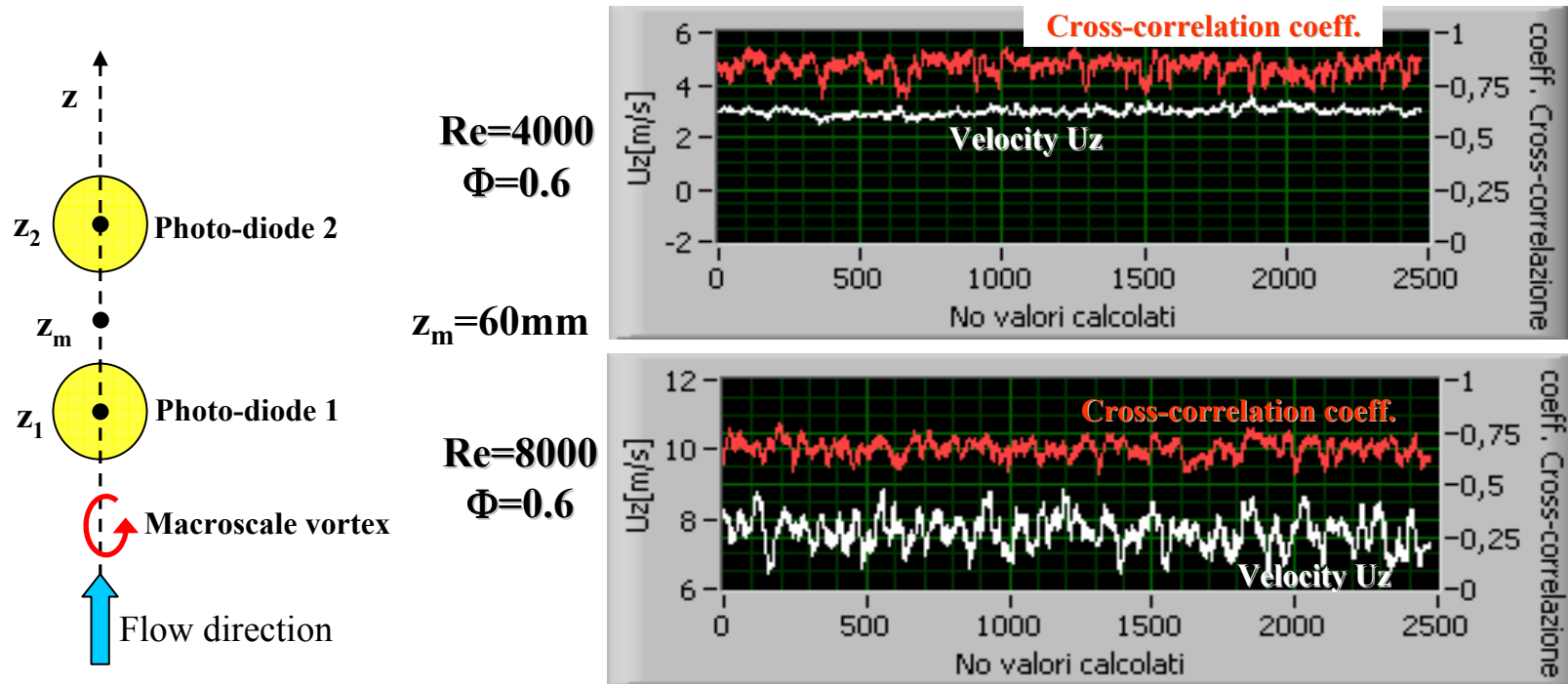
- If **two photodiodes** look at two different spatial locations, and if **the same macro-scale** is revealed by the two photo-diodes **the cross-correlation between their signals is high** and the motion of that scale captured.
- Due to transport (convection), **the same structure** is found at two different locations but **temporarily shifted** ($\Delta\tau$). This delay time is associated to the velocity component along the direction of the two photodiodes.
- To define the **time shift** between the two signals acquired at the same time, the **standardized cross-correlation function** is used and shows a peak at the time shift between the two signals.
- The axial velocity component can then be defined as the ratio between the **photodiodes distance** (Δz_{ODC}) and the **time shift** ($\Delta\tau$).

$$U_z(\Delta\tau) = \frac{\Delta z_{ODC}}{\Delta\tau}$$



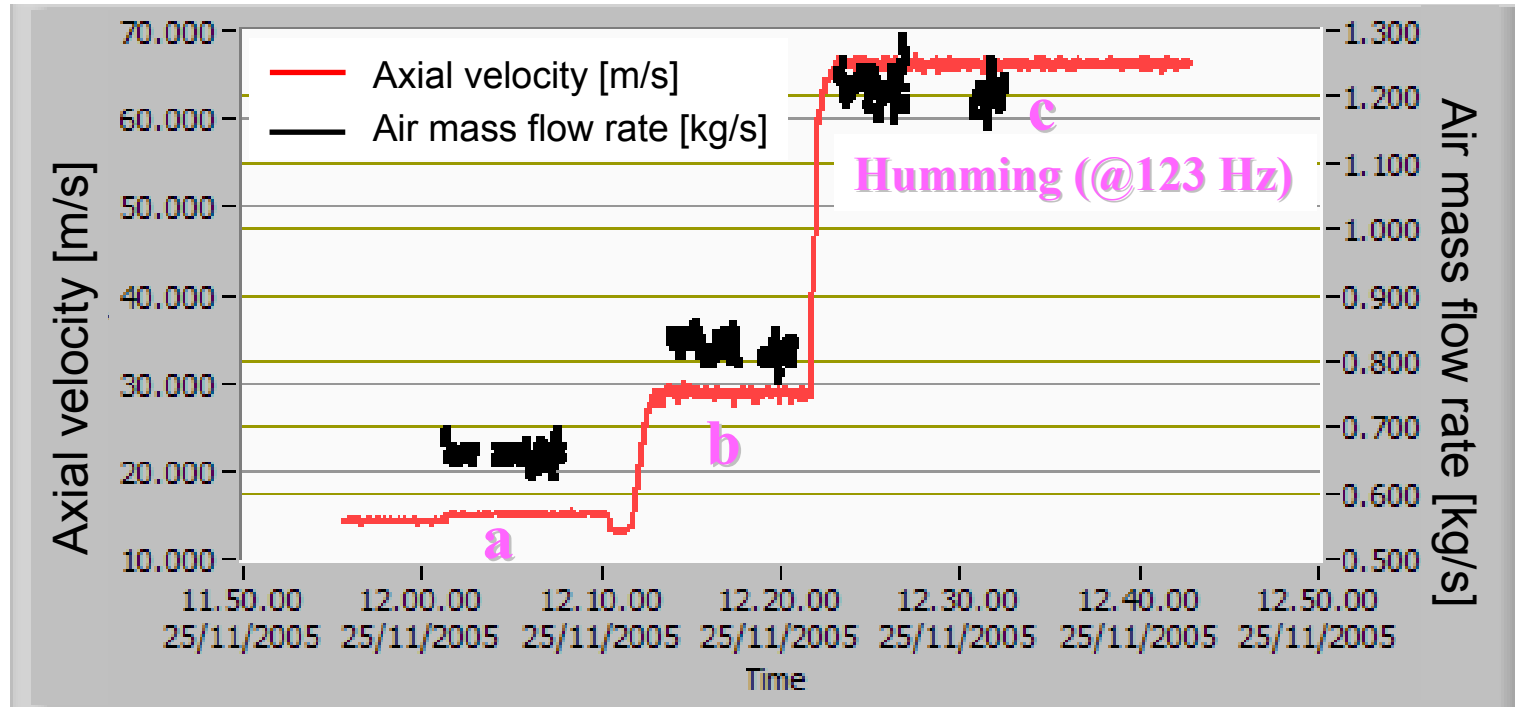
ODC (Optical Diagnostics of Combustion) Anemometry methodology

The measured axial velocity is associated to the middle point (z_m) between the centers of the two areas monitored by photo-diodes.



- The **cross-correlation coefficient** indicates how much the macroscale eddy structure revealed by the photo-diode 1 lives (no formation and dissipation, but only transport).
- If the cross-correlation gives a **weak response (<0.5)** the coherence of the structure revealed by the first photo-diode is not maintained up to the second photo-diode and it is not possible to determine the velocity component.

Comparison between ODC velocity and mass flow rate for TG3000 (CCA)



	W_{air} [kg/s]	Velocity[m/s]
a	$\cong 0.56$	$\cong 22$
b	$\cong 0.75$	$\cong 35$
c (Humming)	$\cong 1.25$	$\cong 65$

In the industrial burner the ODC Anemometry is able to follow the changing of mass flow rate in real-time and it provides the expected values.

Conclusions

- Experiments proved that **radiant energy** can be used to extract information related to both **chemical kinetics** and **turbulence dynamics**.
 - Relation with **chemistry** is also clear theoretically and **proved** numerically (LES).
 - Relation with **turbulence** explained here (Exp. In Fluids) needs further numerical **work** (LES or DNS) to draw definite conclusions.

Optical Diagnostics of Combustion

- high **frequency response** > 10 kHz
- **real time** analysis
- **self-sufficient** to detect instabilities and LBO

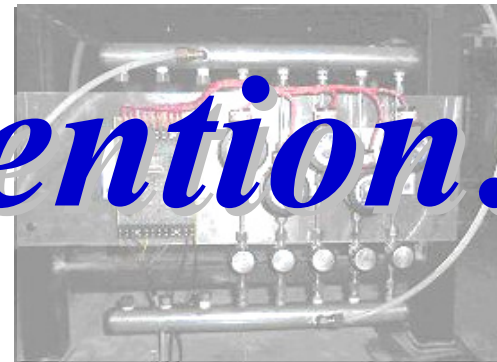
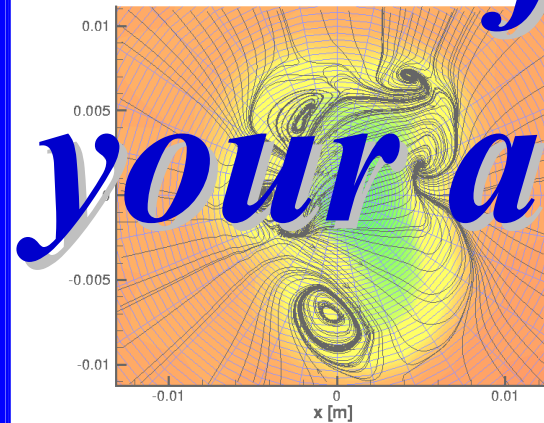
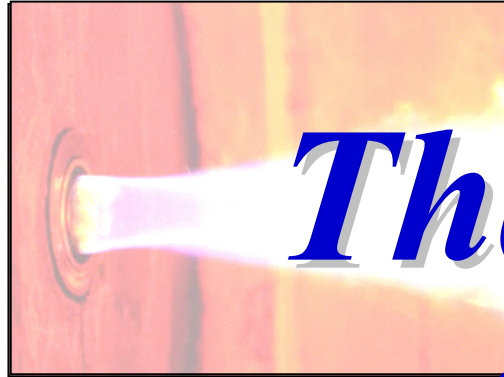
- **low cost**

- **non-intrusivity**
- **no** need of **seeding**
- use of **optical fibers** (harsh environments)

- chemical and turbulent **information**

These features make ODC suitable to detect the **stable or unstable state** of a flame and to be used as sensor for **active control** of combustion in **gas-turbines** (small size and low weight make it also suitable for **aerospace applications**).

The End



*Thanks
for
your attention!*