Combustion assistée par plasma :
Du challenge de la mesure de température en combustion turbulente à un diagnostic pertinent pour les décharges nanosecondes

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GDR EMILI – 25 octobre 2023 - Nancy

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REMERCIEMENTS

Une illustration puisant dans de nombreuses collaborations

G. Cléon, A. Lo, P. Vervisch, H. Ajrouche, F. Guichard, B. Lecordier, L. Lacour, D. Honoré, P. Tardiveau, A. Brisset

EXFIDIS, FAMAC, PASTEC

BIOENGINE project, co-financed by the European Union with the European regional development fund (ERDF) and by the Normandy Regional Council

INTRODUCTION

Illustrer l'intérêt du croisement des disciplines

Une opportunité : la combustion assistée par plasma

Un diagnostic d'une discipline à l'autre

→ **La Diffusion Raman Spontanée**

COMBUSTION ET TRANSITION ENERGETIQUE

Les enjeux : une combustion neutre en carbone, efficace, propre et sûr

⚠ Émission $CO_{2,}$, émission Nox, stabilité des flammes, allumage

Combustion encore 84% de la production d'énergie : la transition est une phase clé

Combustion neutre en carbone = combustion « défossilisée »,
orientée vers de nouveaux vecteurs énergétiques issues des EnR, capturer le CO_2

Focus : sur les mobilités lourdes, le transport aérien, les industries fortes émittrices en CO_2

COMBUSTION ASSISTÉE PAR PLASMA

Flame stabilization

- Steady phenomenon
- Specificity: low energy addition
  - Few % of flame power

Ignition

- Single event
- Enlarge the flammability domain
  - highly diluted reactants,
  - high-pressure conditions,
  - re-ignition under various thermodynamic conditions

- **combined production of**
  - Reactive species, radicals
  - Heat with non-equilibrium effect

affect combustion chemical kinetics

CARACTÉRISER LA COMBUSTION TURBULENTE

What do we want to characterize?

- High temperature reactive flows
- Chemical reaction
  - Burning velocity…
- Mass transfer, mixing
- Heat transfer

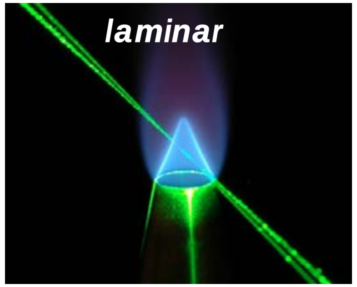
What do we want to measure?

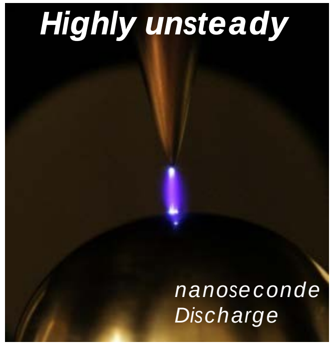
- Local composition
- Temperature
- Aerodynamics

- gradients

- Simultaneously
  - Joined pdf
  - Conditioned data

- Temporal monitoring





What difficulties?

- Gas
- High temperature
- Luminous medium
- Reactive flows:
  - Numerous species
- Small tiime scale:
  - Time resolution < 1µs
- Sharp gradients:
  - Spatial resolution ~100µm
- 3D phenomenon
- Numerous interactions

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COMBUSTION TURBULENTE ET MESURE DE TEMPÉRATURE ?

Flamme : milieu hostile mais fragile

Flamme turbulente : milieu hétérogène, instationnaire (même si stationnaire en moyenne souvent)

milieu hétérogène : fort gradient, résolution spatiale ~100µm, résolution temporelle <1µs

mesure locale -> ~~Absorption~~

mesure instantanée (< 1µs) -> ~~LIF~~ où beaucoup d'hypothèses sur incertitude en fonction de T, sur l'influence du quenching

ATTRAIT DE LA DIFFUSION RAMAN SPONTANÉE

Diffusion de la lumière

- Quelque soit la longueur d'onde du laser
  mais plus efficace avec les courtes longueurs d'onde

Toutes les espèces présentes dans le volume de mesure diffusent la lumière : mesures multi-espèces

Un rayonnement très faible limitant ses champs d'application depuis sa découverte

section efficace caractéristique 10^{-30} cm^2/sr

à comparer à l'absorption/LIF : 10^{-18} cm^2/sr

DRS : UN CHALLENGE EN COMBUSTION TURBULENTE

in flames

- Gas
- Low density
- High temperature
- Lower density
- Reacting flow
- Numerous species
- Parasitic flame emission
- LIF interferences

In turbulent flames

+

- Short time scales
- Time resolution <1µs
- Sharp gradients
- Spatial resolution ~ 100µm
- Linewise measurements

→

Diffusion Raman Scattering

Energetic pulsed laser
w/o optical breakdown
Window damage
Nonlinear phenomena

1D: imaging spectrograph

High throughput of the collection system

High efficiency of the detector

Fast gating

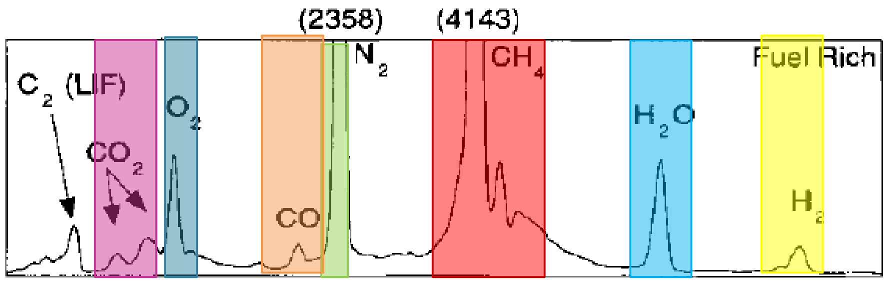
MESURE DE T PAR DIFFUSION RAMAN SPONTANÉE

Dès 1972, proposition de mesurer T par ajustement de spectre

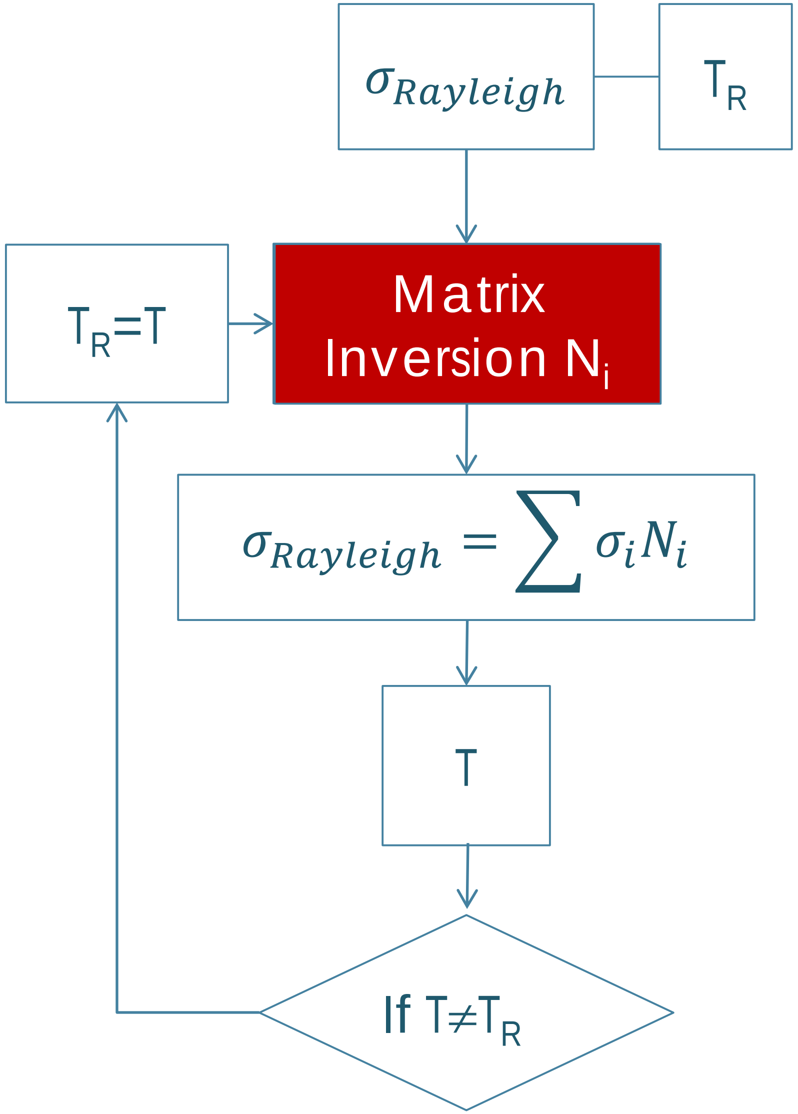
M. Lapp, et al, Science, 175 (1972) 1112

- Mais trop peu de signal pour les flammes turbulentes :
  - temps exposition court,
  - faible volumen de mesure

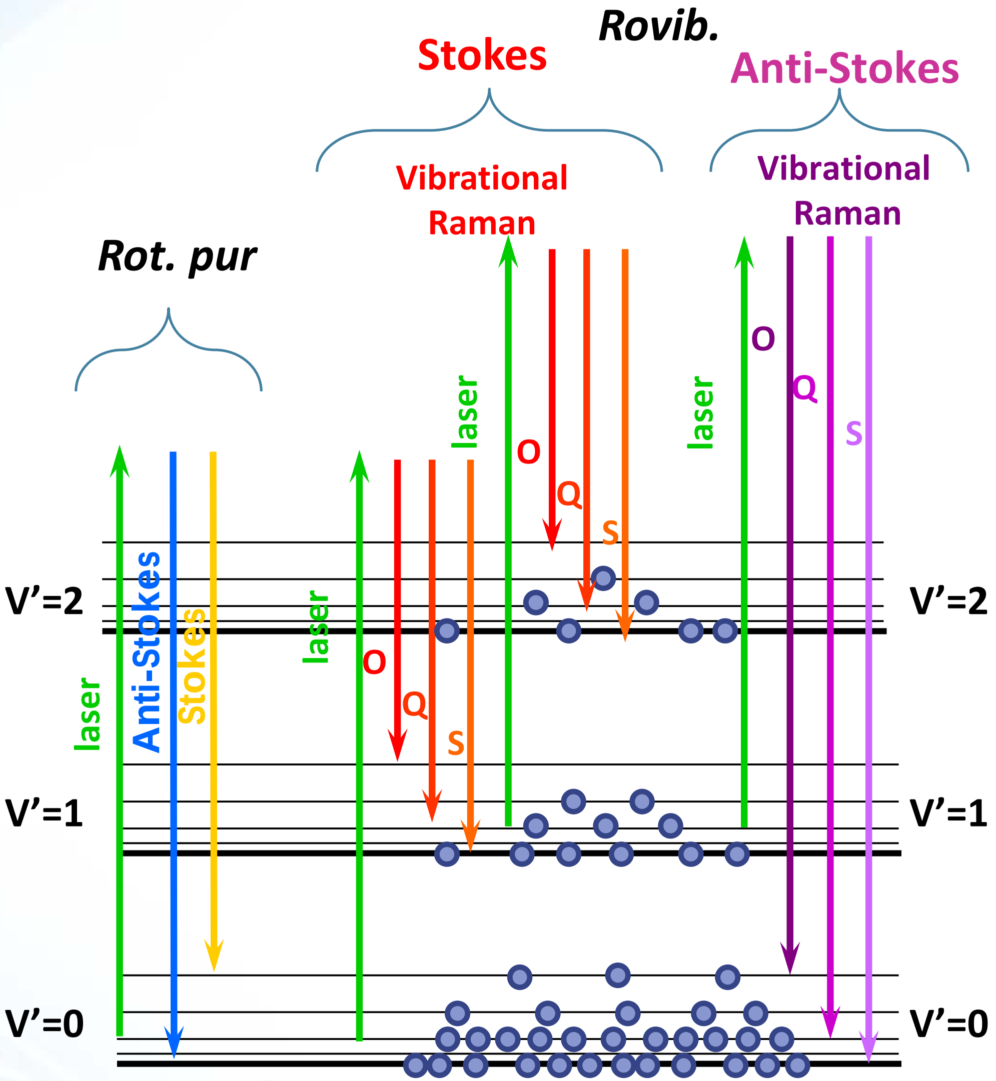
- En 1988, une proposition sans ajustement de spectres : Rayleigh-Raman

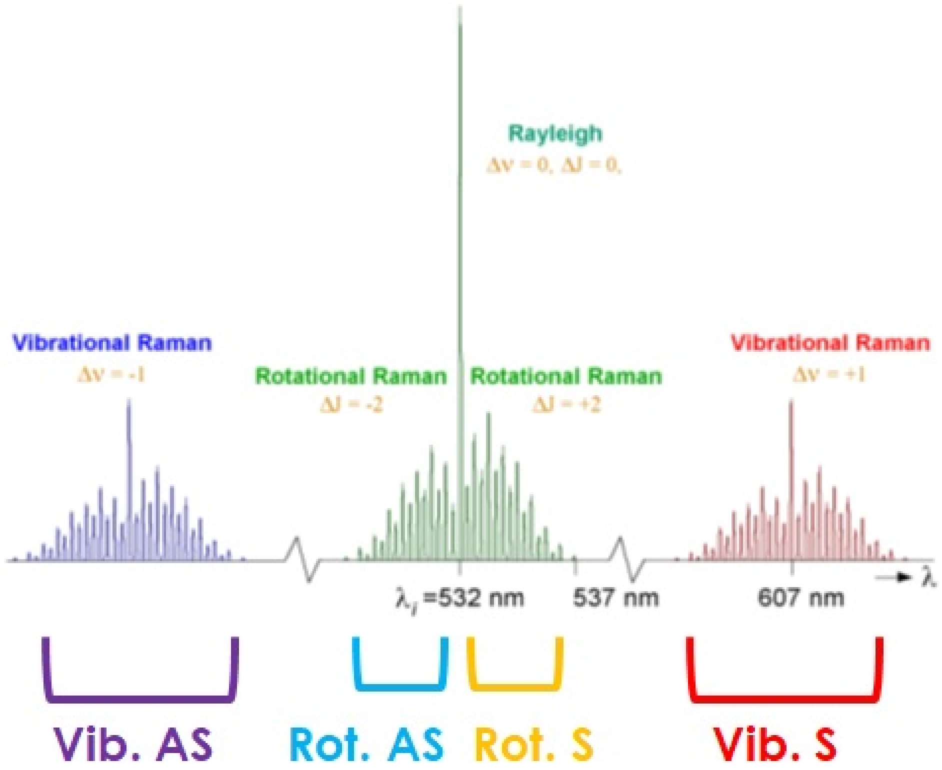


Dibble 1988, Barlow 1989



PRINCIPE DE LA DIFFUSION RAMAN : BREF RAPPEL





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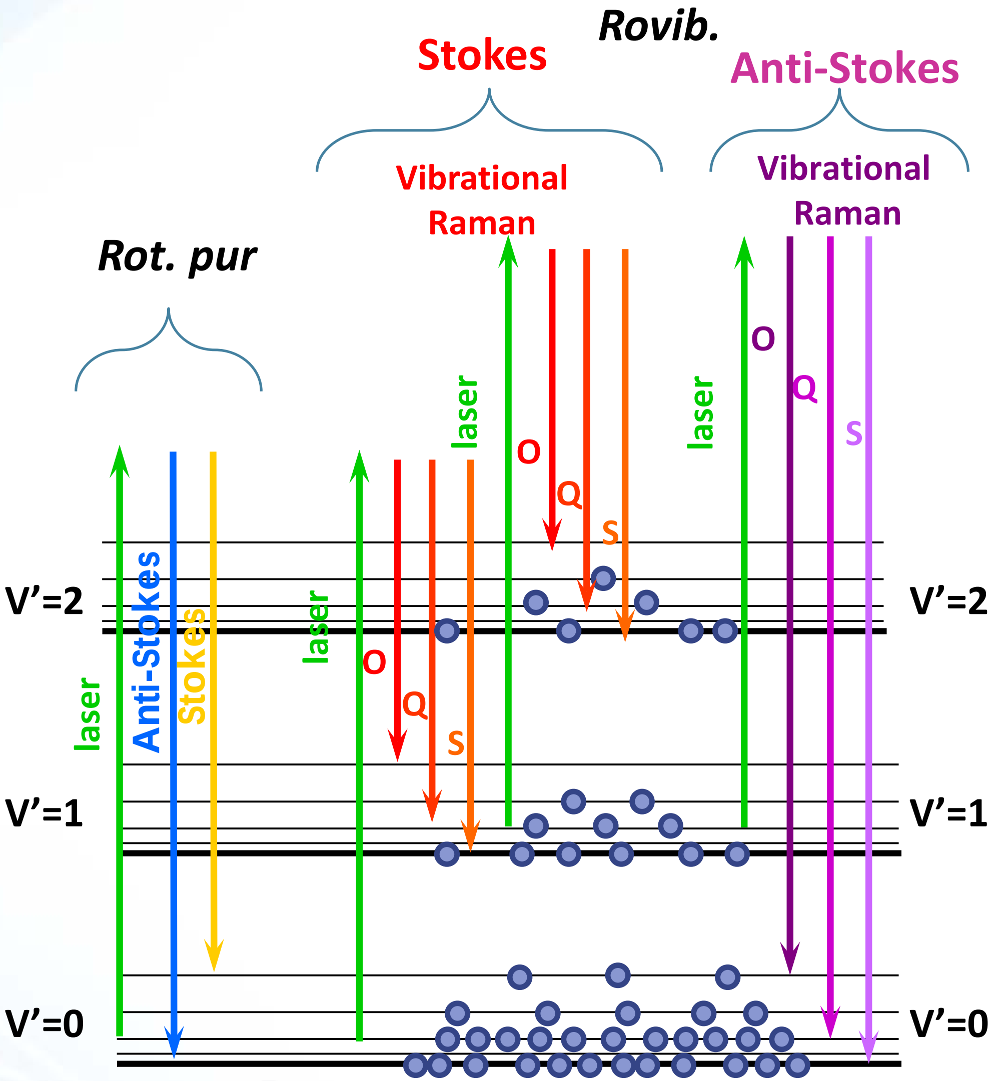
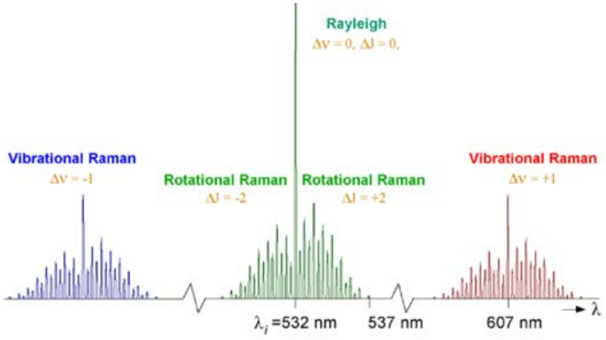
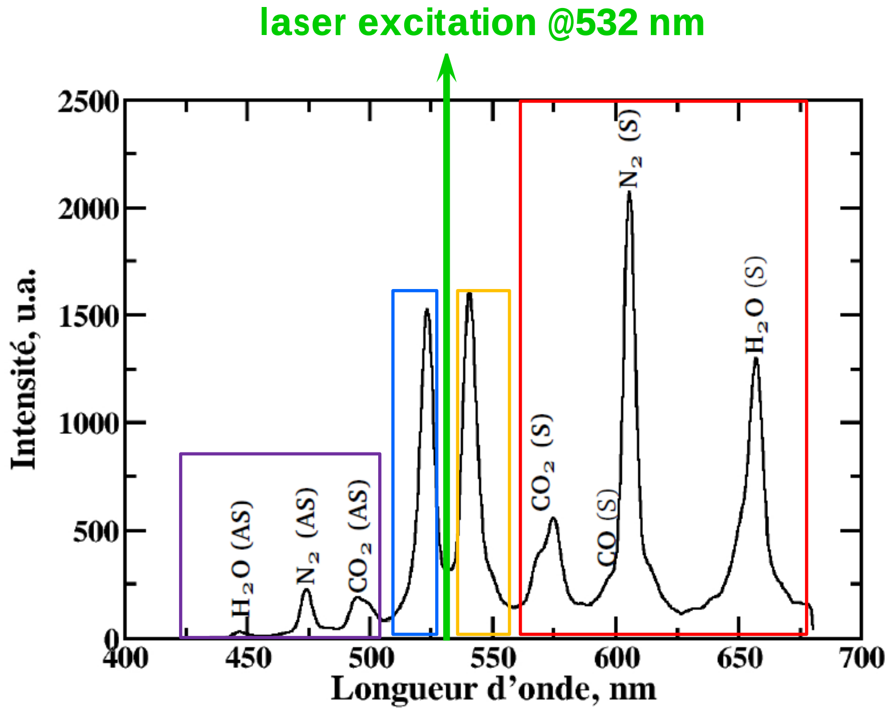
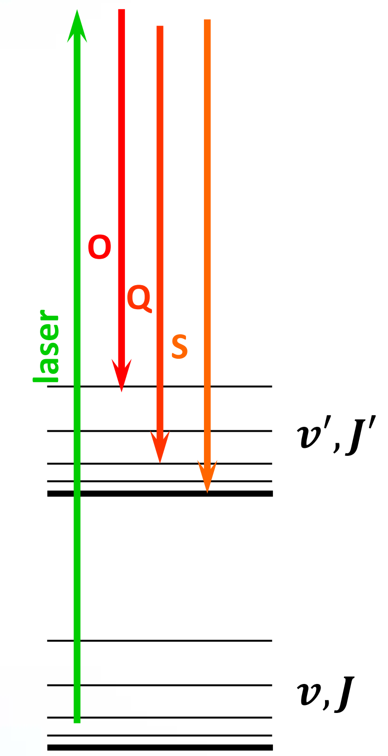






AJUSTEMENT SPECTRAL



- **Transition moment from (v,J) to (v',J')**

$$\vec{P} = \varepsilon_0 < v, J|\vec{p}|v', J' > = \varepsilon_0 < v, J|\boldsymbol{\alpha}|v', J' > \vec{E}$$

- **Cross section**

$$\left(\frac{\partial\sigma}{\partial\Omega}\right)_{v,J\to v',J'} = \pi^2\left(\boldsymbol{\omega}_0 - \Delta\boldsymbol{\omega}_{v,J\to v',J'}\right)^4 \langle v, J|\boldsymbol{\alpha}|v', J'\rangle^2$$

- $[\alpha] = [\alpha_0] + \left(\frac{\partial[\alpha]}{\partial Q}\right)_{\mathbf{0}} Q$

$$I^{\Omega}_{v,J\to v',J'} = \Lambda V \left(\frac{\partial\sigma}{\partial\Omega}\right)_{v,J\to v',J'} N_{v,J} I_0$$

Collection system efficiency (Λ)

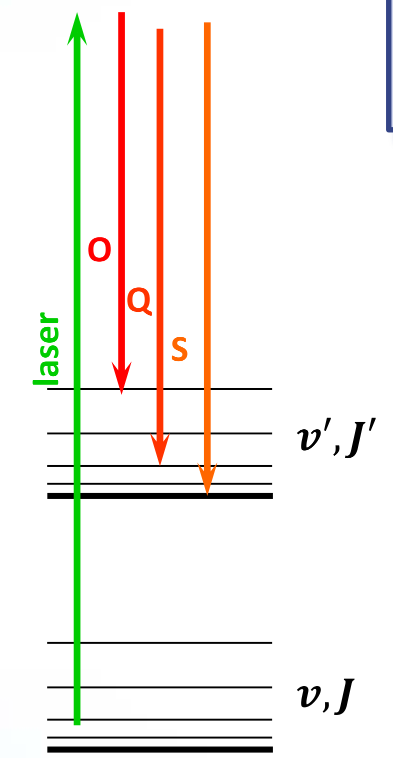
Probe volume (V)

Cross section (molecules, laser choice)

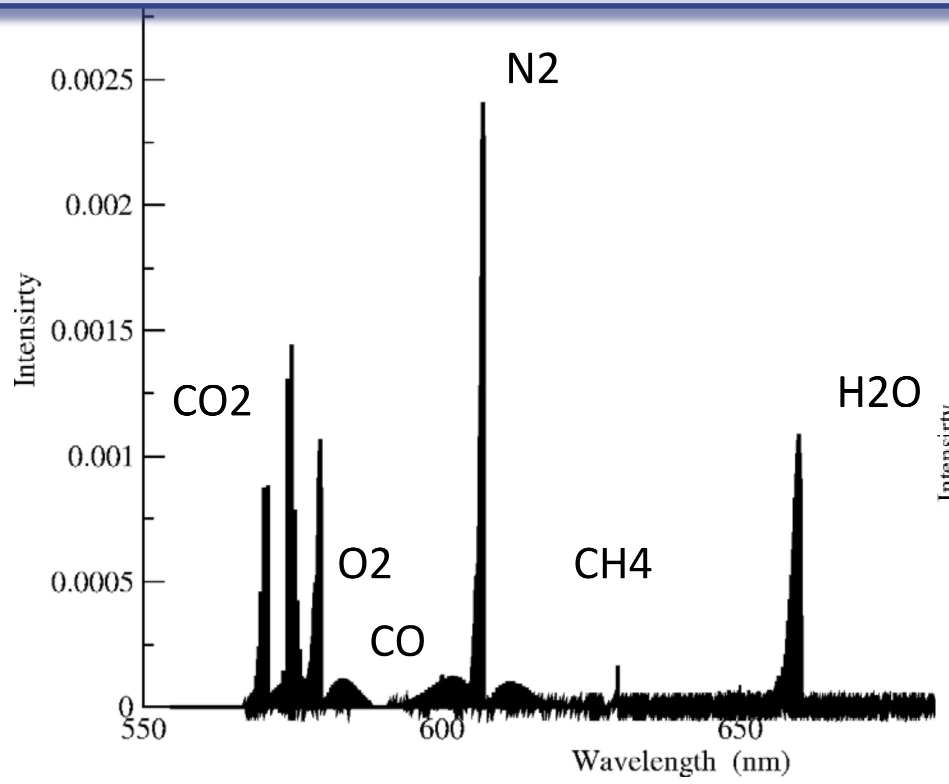
Density number ($N_{v,J}$)

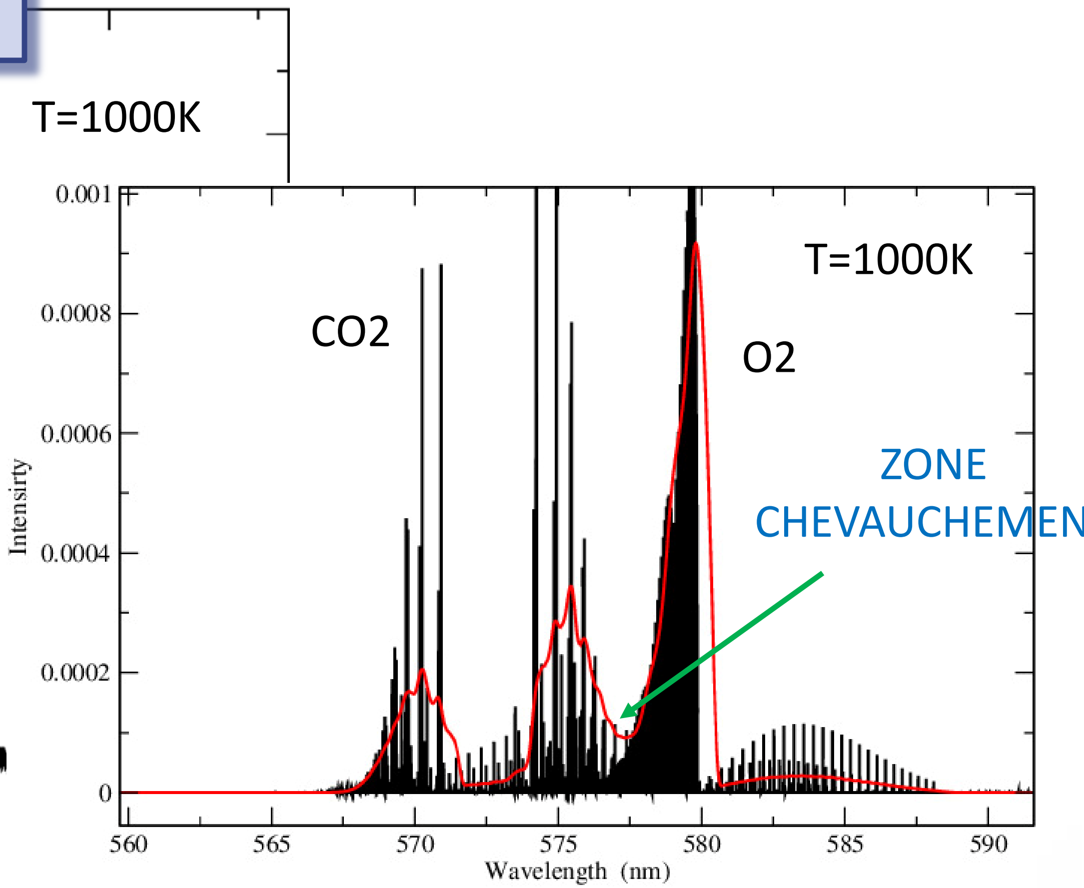
Laser irradiance (I_0)

AJUSTEMENT SPECTRAL



$$I^{\Omega}_{v,J\rightarrow v',J'} = \Lambda V \left(\frac{\partial\sigma}{\partial\Omega}\right)_{v,J\rightarrow v',J'} N_{v,J} I_0$$





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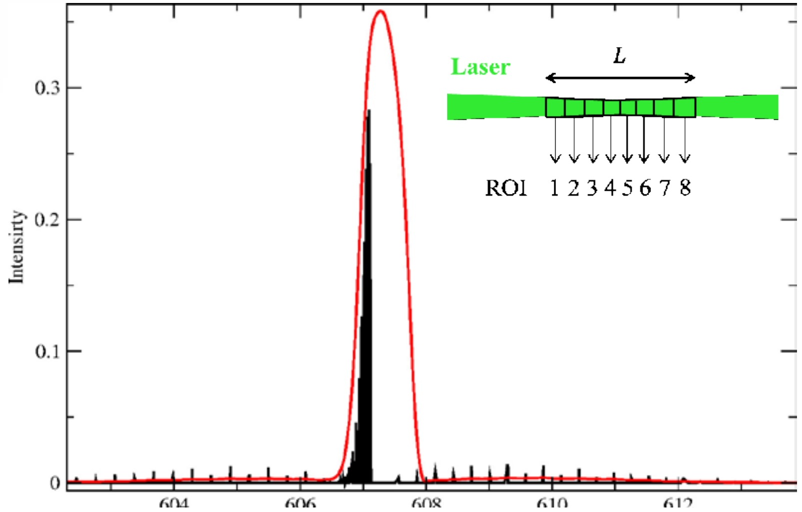
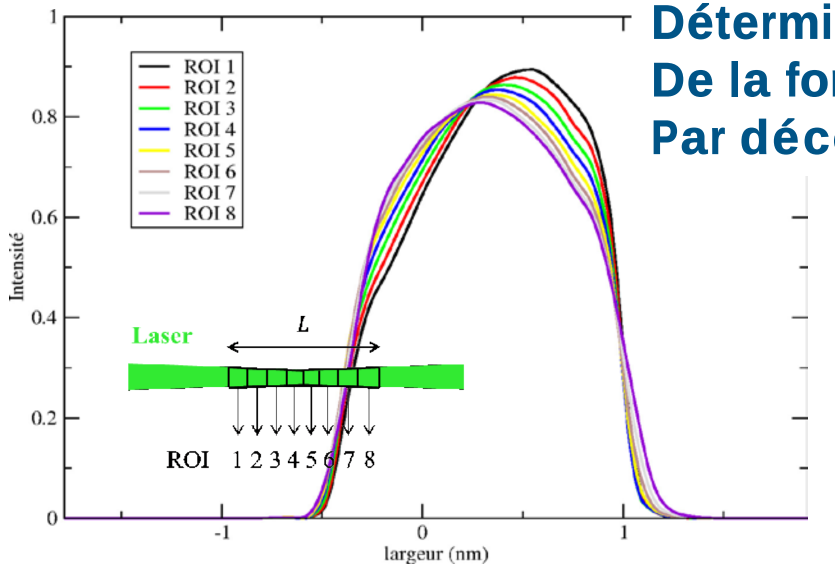
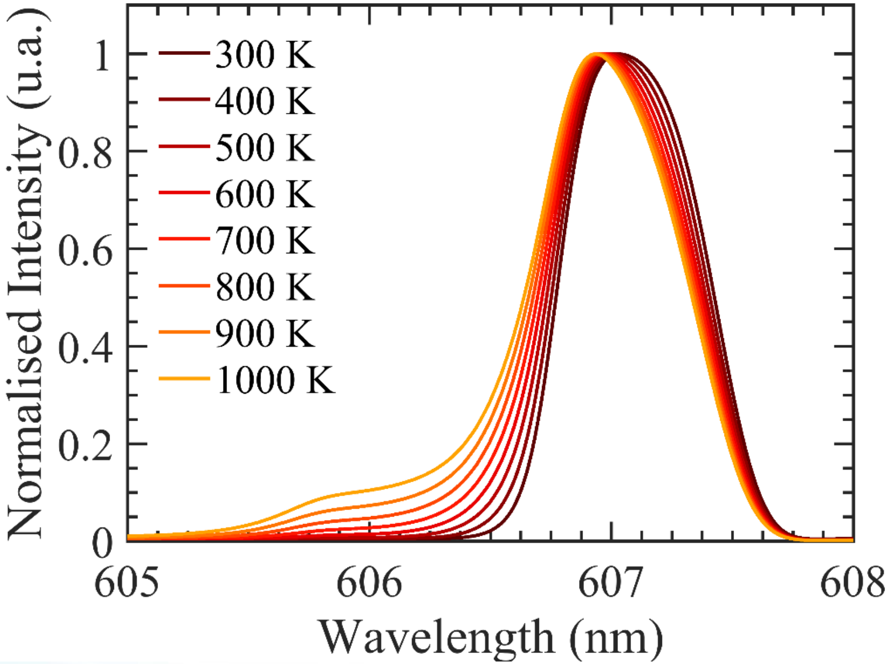
TEMPÉRATURE MALGRÉ UNE FAIBLE RÉSOLUTION SPECTRALE

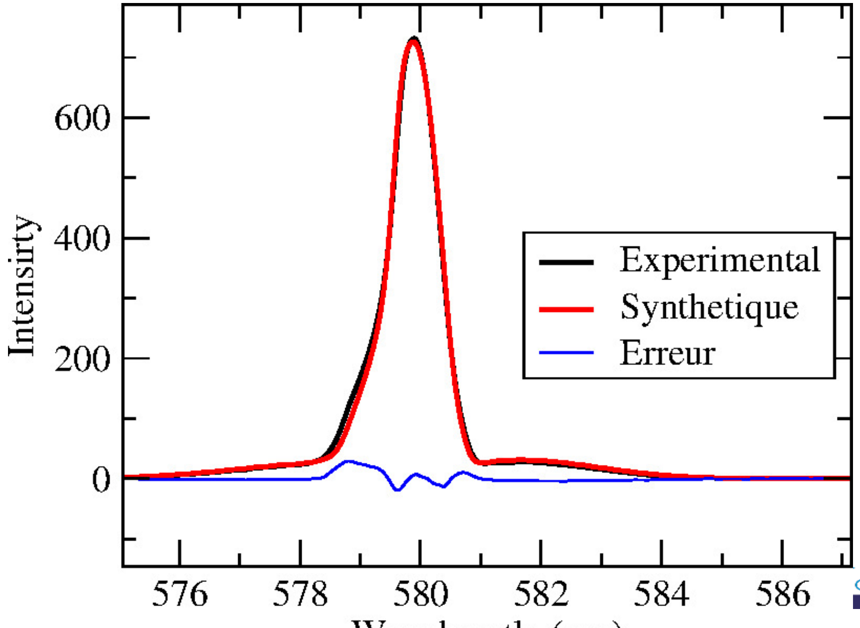
Spectre synthétique (N2 à 300K)





Détermination locale
De la fonction d'appareil
Par déconvolution

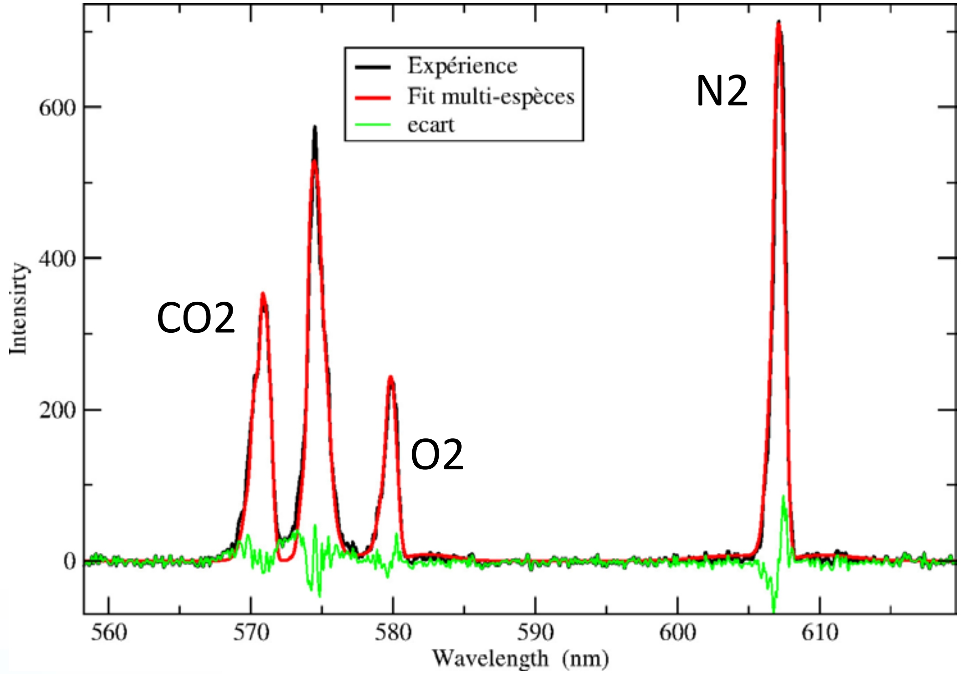




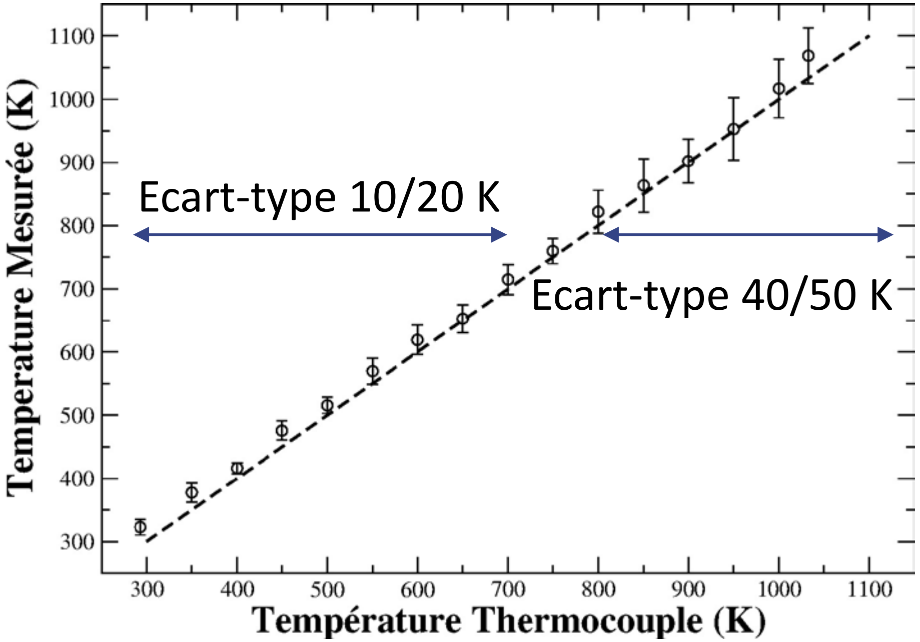
MESURE A BASSE TEMPÉRATURE

Spectre O2/N2/CO2

Validation sur Jet d'Air (70%)/CO2 (30%) chauffé de 300 à 1033K

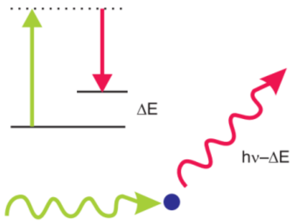


Nouvelle approche pour la T°
(Minimisation N2/O2/CO2)

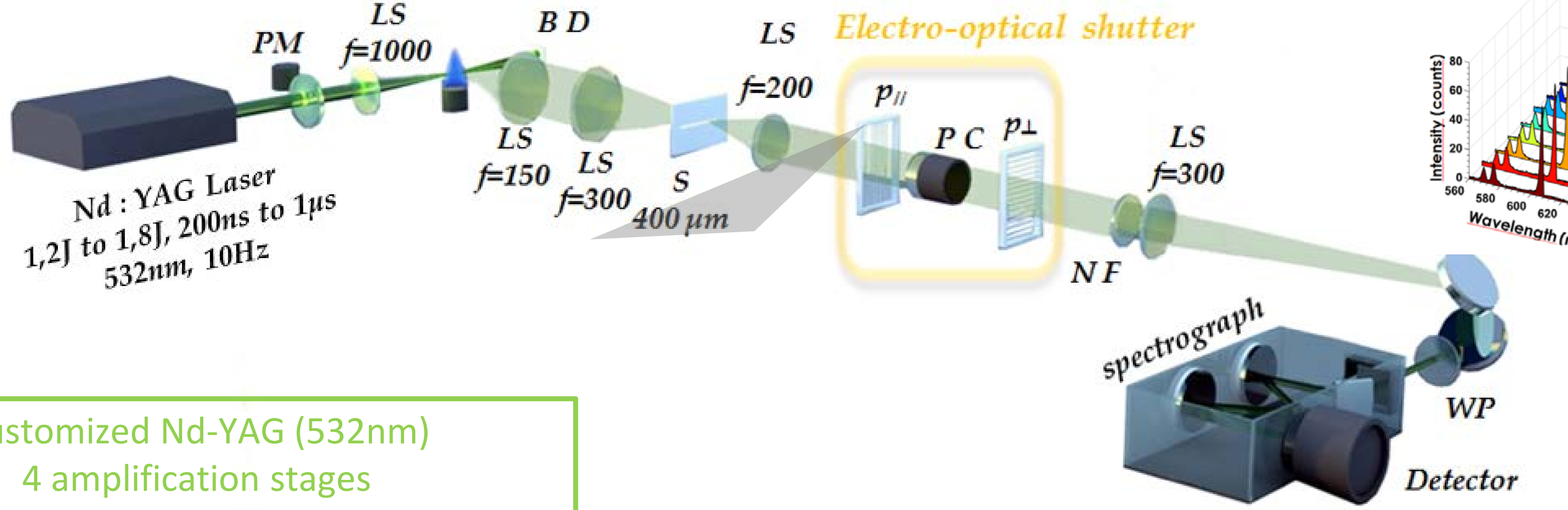


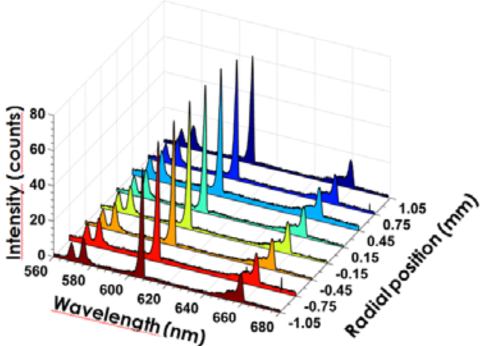
DISPOSITIF EXPÉRIMENTAL

Need high energy pulse, sensitive detection and fast gating

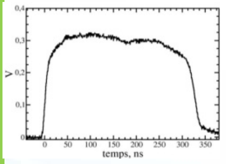


Pockels cell +
2 crossed polarizers
1µs gate width





Customized Nd-YAG (532nm)
4 amplification stages
2 doubling crystals
1,8J for 1µs at 10 Hz



Achromat lenses of large aperture
Efficient imaging spectrograph
Ultra-sensitive BI-CCD

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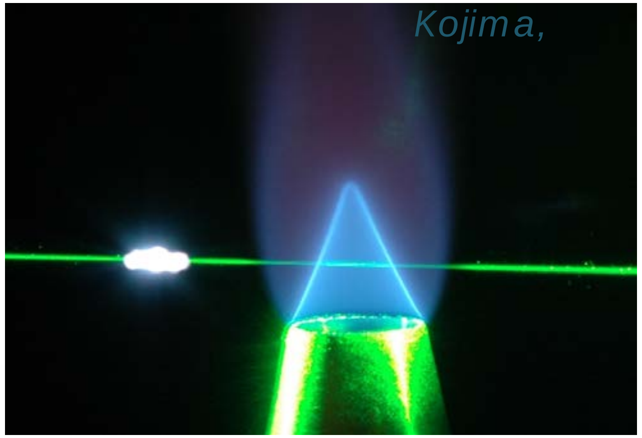
LE CHOIX DU LASER

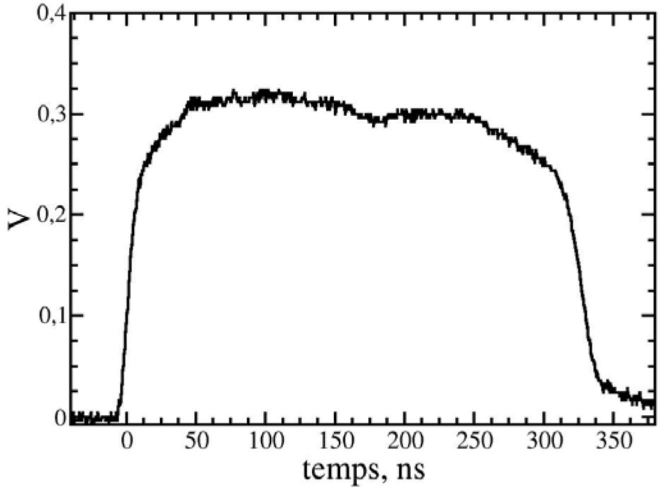
- **Minimum energy required for single-shot measurement :1 Joule (Meier, 2002)**
  - **Window damage**
  - **Non-linear effects**
    - ***Optical breakdown, stimulated Raman scattering***
  - **Laser pulse stretching**
    - ***Maximal irradiance: 35 GW/cm² (Cléon, 2007)***

Dye laser , 2µs, 1J x 2 (mirror) *Dibble et al.(1990)*

Pulse stretcher, 400 ns, 1.6J *Magnotti et al (2014)*

Long pulse laser, 300 ns-1µs, 1.8J *Guichard et al. (2018),*





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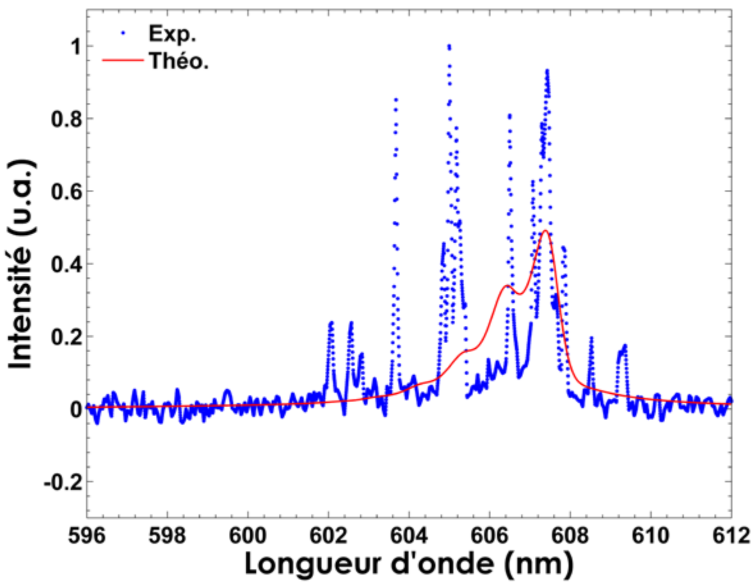
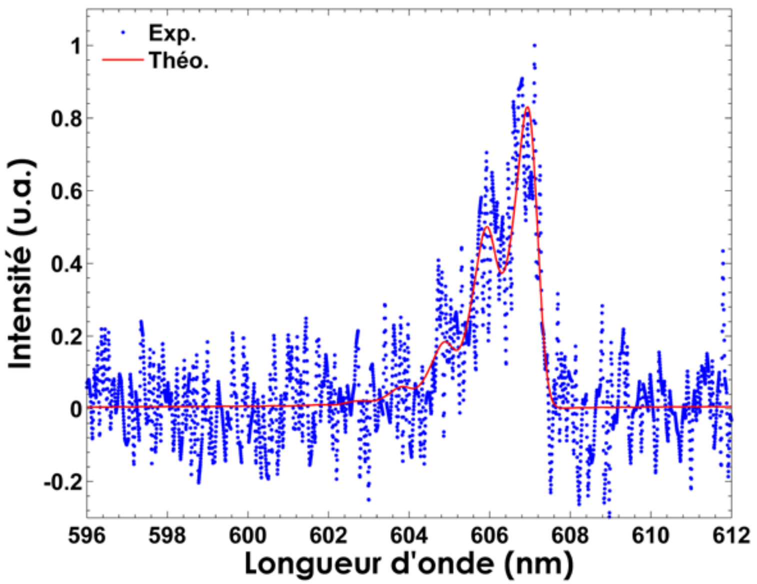
LE CHOIX DU DETECTEUR

- **ICCD camera**
  - Fast gating(~1ns)
  - High shot noise

- **Back-illuminated CCD camera**
  - Very high quantum efficiency (QE>80%)
  - Low noise
  - Very high detectability
  - But full-frame architecture





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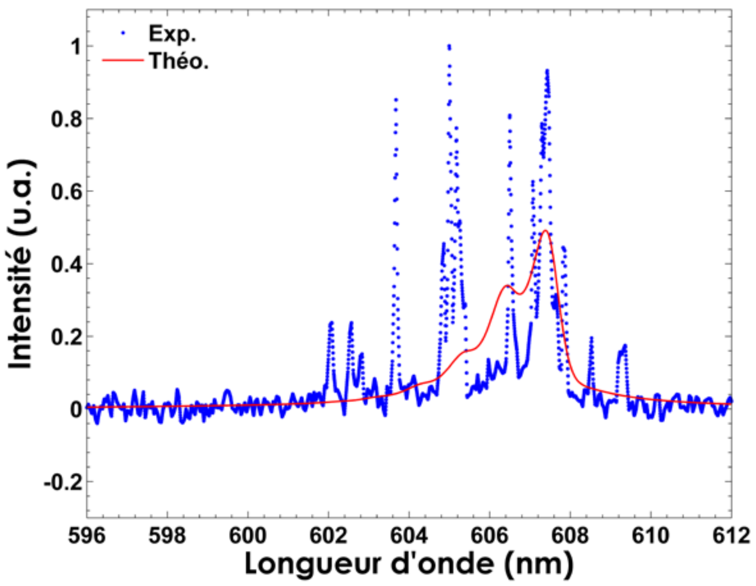
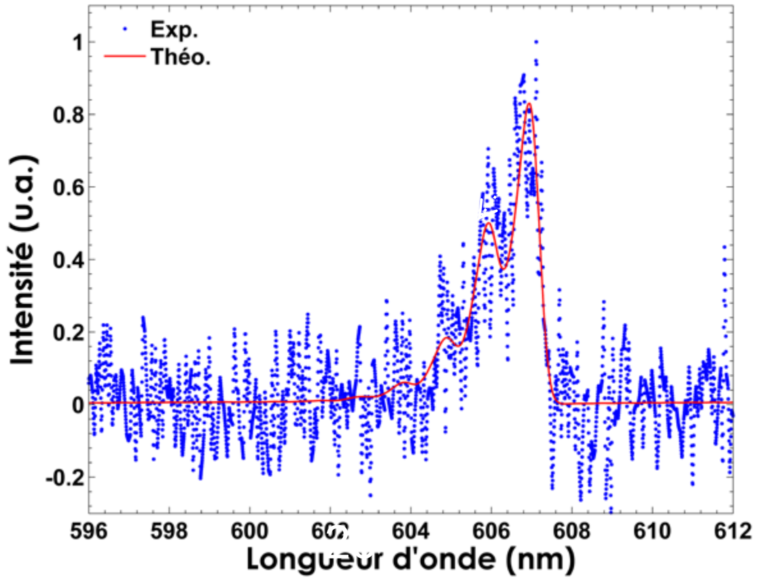
Instantaneous measurement in flames: detector choice

- ICCD camera
  - Fast gating(~1ns)
  - High shot noise

- Back-illuminated CCD camera
  - Very high quantum efficiency (QE>80%)
  - Low noise
  - Very high detectability
  - But full-frame architecture

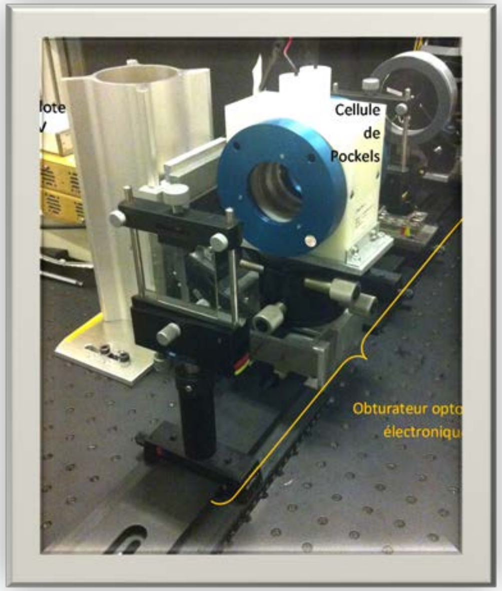
➡ Impose fast shutter

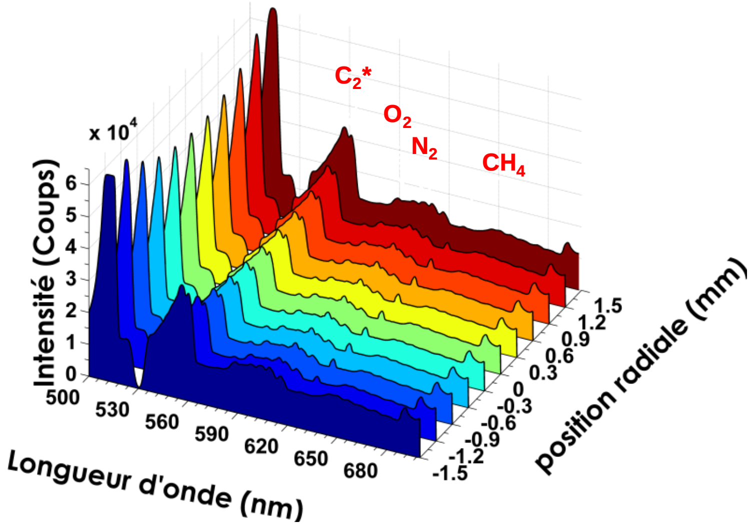


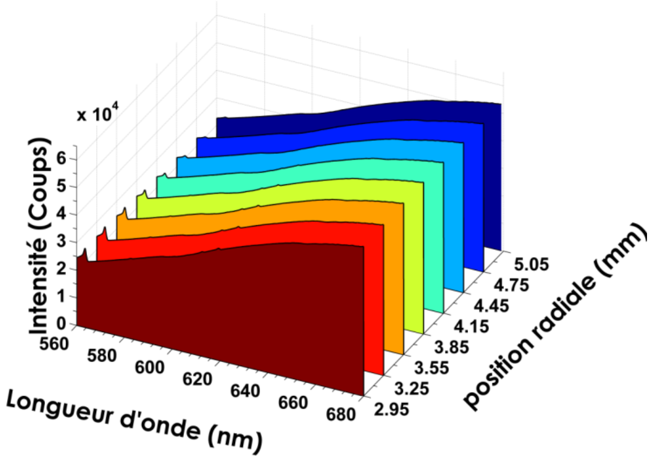


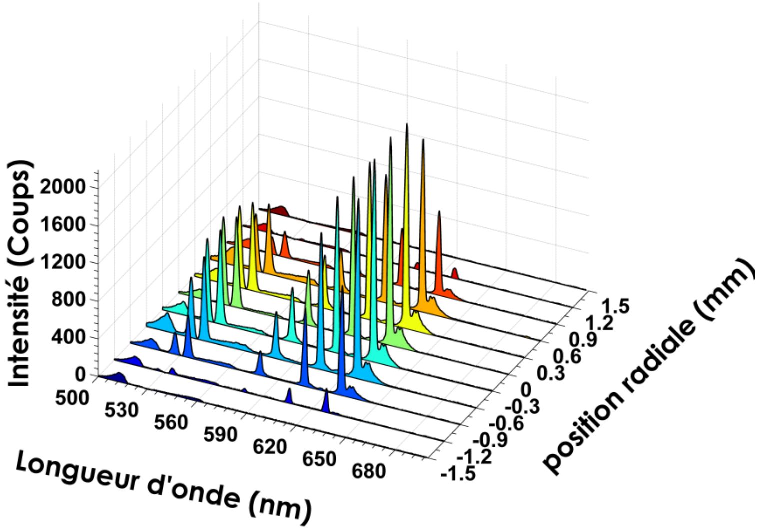
Obturation pour les caméras rétro-éclairées

- **Obturateur opto-électronique**
  - **Cellule de Pockels entre deux polariseurs croisées**





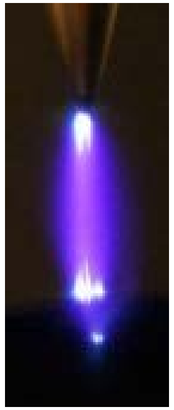


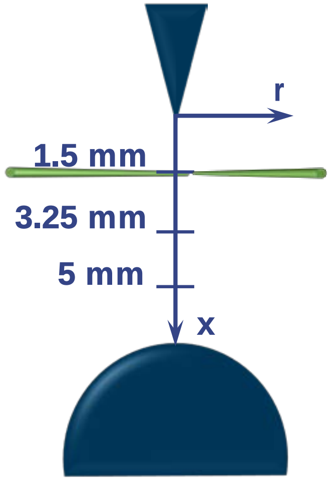


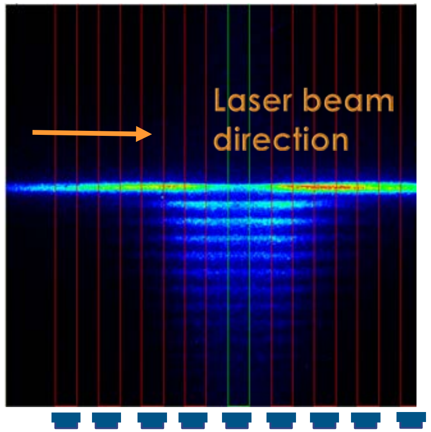
Ajrouche et al, 2015

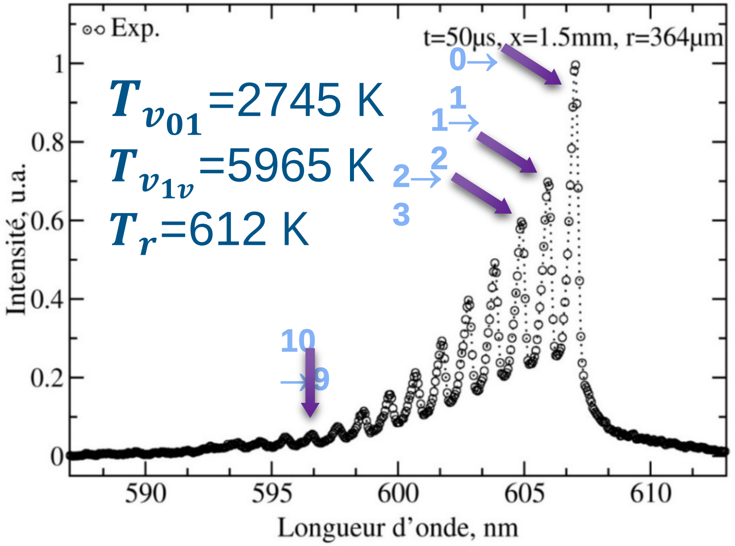
Décharge nanoseconde

INTEREST FOR INVESTIGATION OF AIR DISCHARGE









Lo et al. Appl. Phys B(2012)

The interest of SRS is to provide :

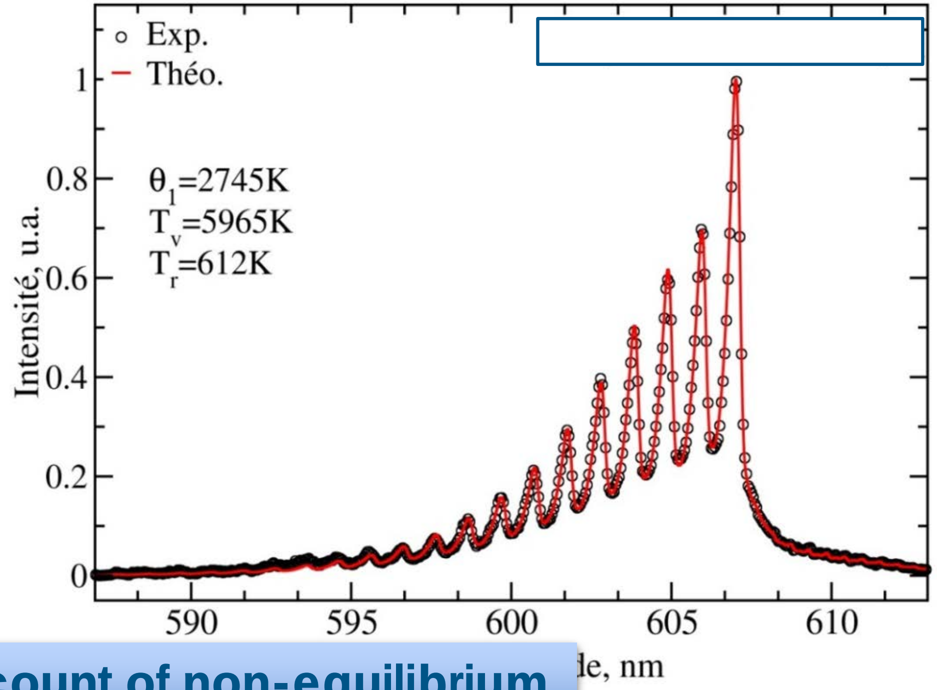
Linewise measurements : 1D profiles without scanning

Good spatial resolution : <200 µm along r

To probe many vibrational levels simultaneously

Measurement of the vib. population up to v=16

INTEREST FOR INVESTIGATION OF AIR DISCHARGE



Lo et al.
Appl. Phys B(2012)

Taking into account of non-equilibrium

- **3 temperatures to describe the energetic state of $N_2(X)$**
- **T_{rot} : rotational temperature = T**
  - Available from our experimental procedure despite the moderate spectral resolution
- **$T_{v_{01}}$ relative to population of v=0 and v=1**
  - Measurement of the vib. population up to v=16
- **$T_{v_{1v}}$ Boltzmann distribution for v≥1**

Two vibrational temperatures resulting for competition between V-T, V-V exchanges and e^- energy distribution function

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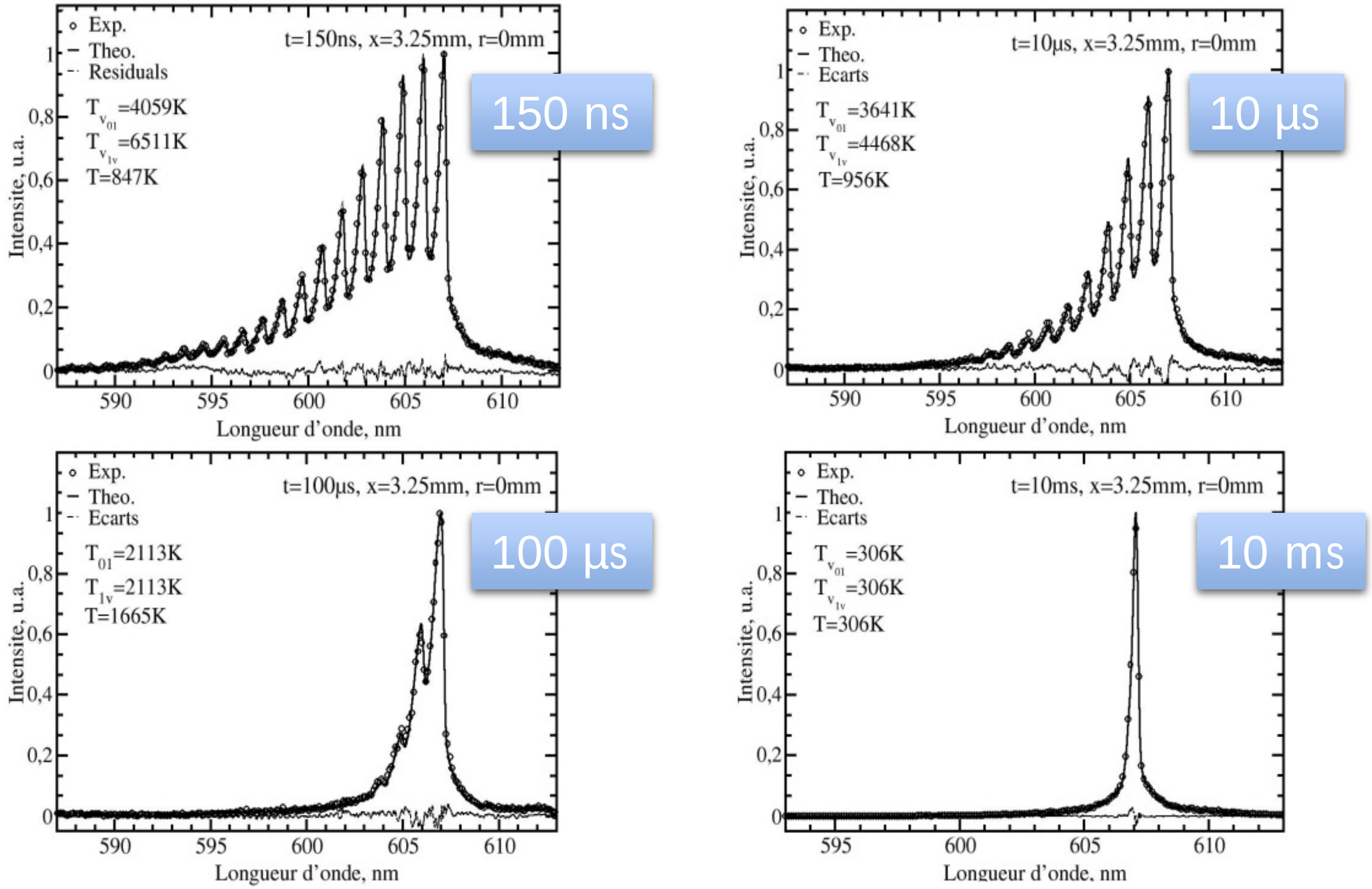
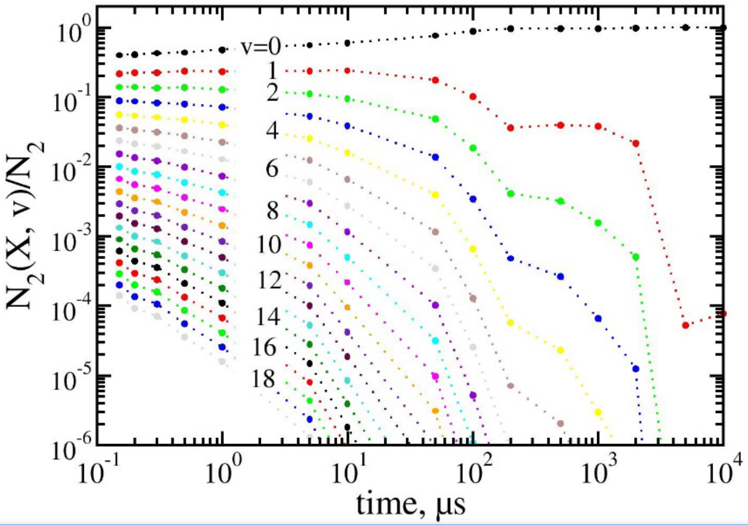
N_2 RAMAN SPECTRA

Examples of $N_2(X)$ spectra for ns-discharge in air
Averaged over 2000 shots



LO et al, J. Phys. D: Appl. Phys., 47 (2014) 115201

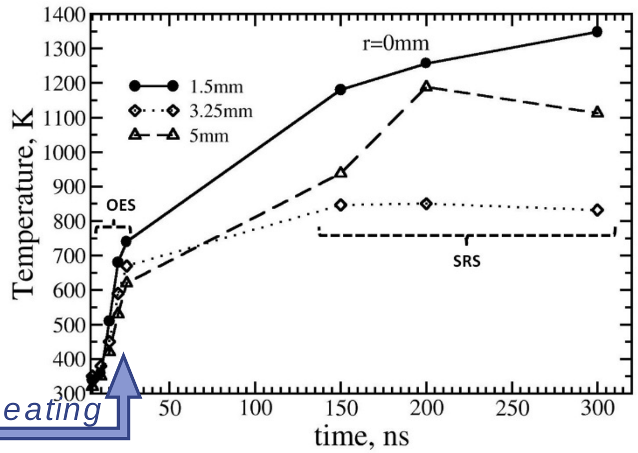


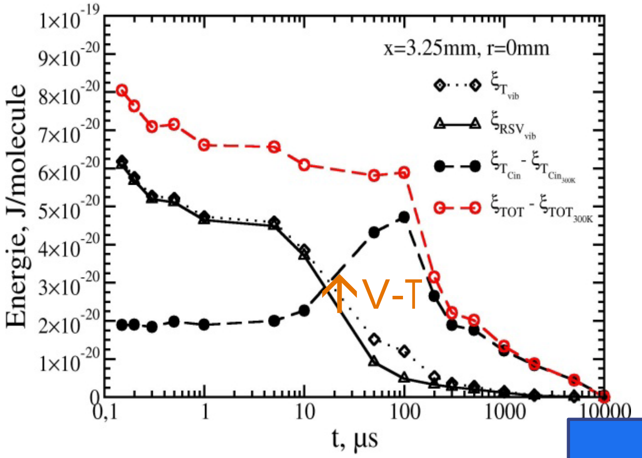
Lo et al.
J. Phys. D (2014)

Spectrum modeling providing complete VDF described by 3 temperatures

QUANTITATIVE CHARACTERIZATION OF ENERGY DEPOSITION

- **SRS combined with emission spectroscopy**
  - **very fast heating and time relaxation of the energy deposition**
    Most of energy transfer to gas





- **Quantification of energy on each mode of storage**
  - **For N_2**
    - *150ns : 75% of energy in vibration*
    - *150ns -10µs: no transfer*
    - *10µs-100µs: V-T transfer*
    - *After 200 µs : relaxation*

20 mJ deposited

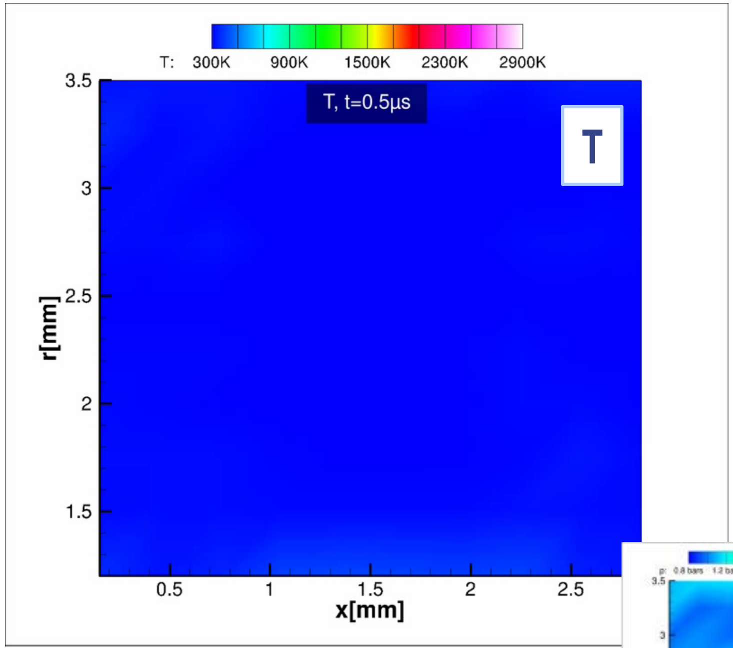
Energy	N_2	O_2	Total
E^i_{Tot}(150 ns)	12.50 mJ @ 62.5%	5.00 mJ @ 25%	17.50 mJ @ 87.5%
$E^i_{T_{\mathrm{vib}}}$(150 ns)	9.50 mJ @ 47.5%	0.27 mJ @ 1.4%	9.77 mJ @ 48.9%
$E^i_{T_{\mathrm{Cin}}}$(150 ns)	3.00 mJ @ 15%	0.73 mJ @ 3.7%	3.73 mJ @ 18.7%
$E^{\mathrm{dis}}_{\mathrm{Tot}}$(150 ns)	—	4.00 mJ @ 20%	4.00 mJ @ 20%

LO et al, J. Phys. D: Appl. Phys., 47 (2014) 115202

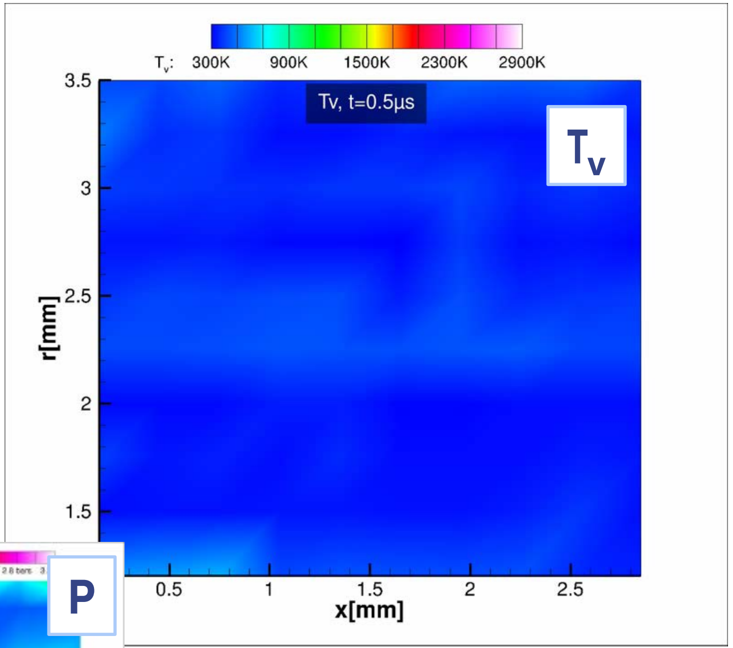
ANALYSE SPATIO-TEMPORELLE : EXEMPLE NS SPARK

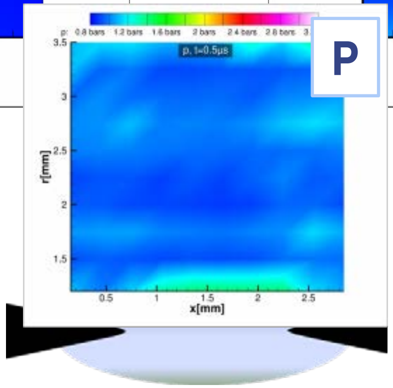
T and T_v in the surrounding of the spark reconstruction par les profils 1D phasés

Space and time evolution of T



Space and time evolution of T_v





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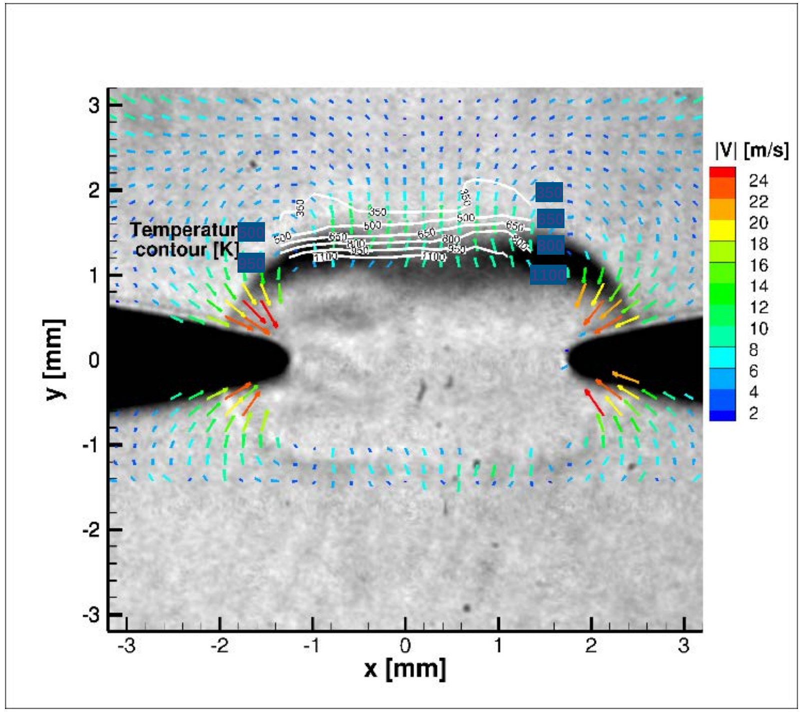
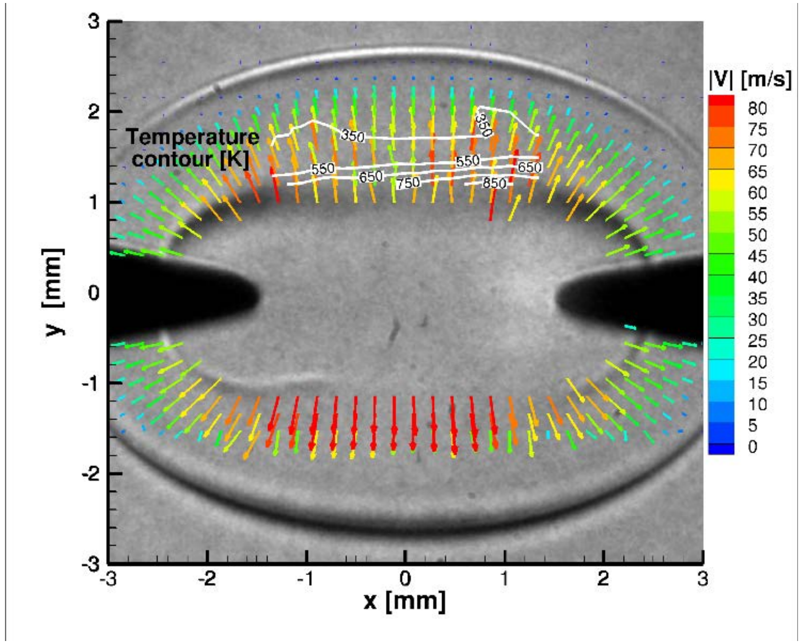
HYDRODYNAMIC EFFECTS

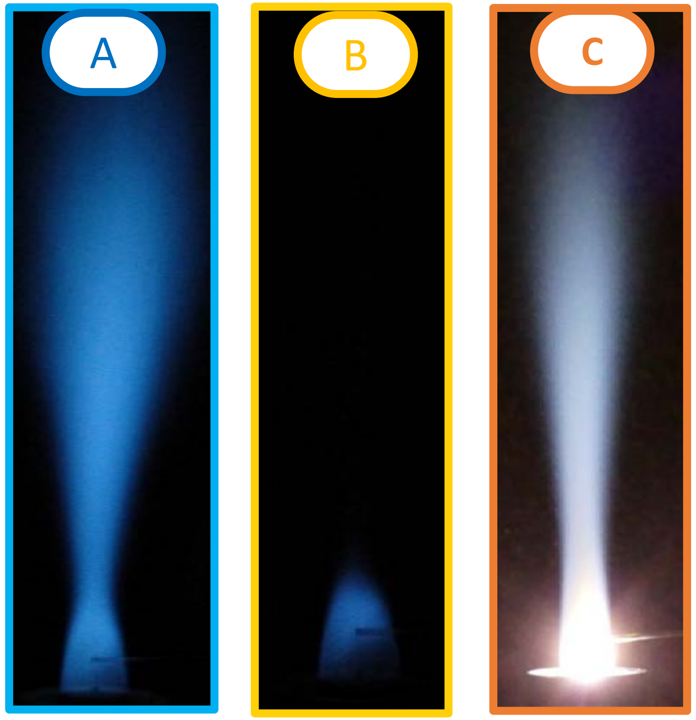
SRS combined with other diagnostics





EM2C's Schlieren images

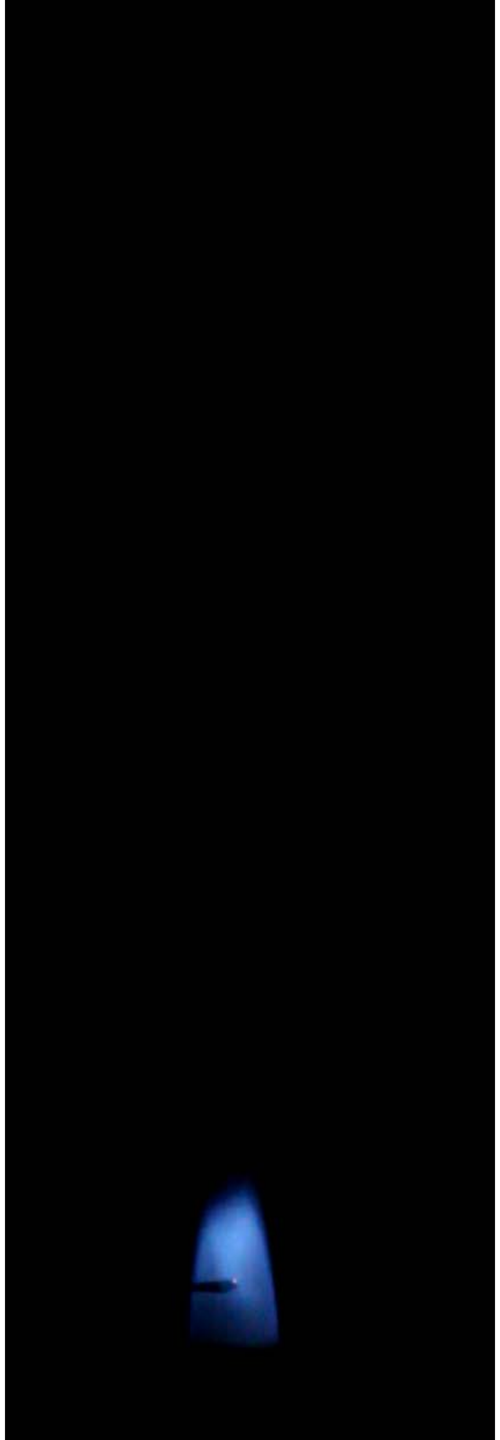
Combustion Assistée par plasma

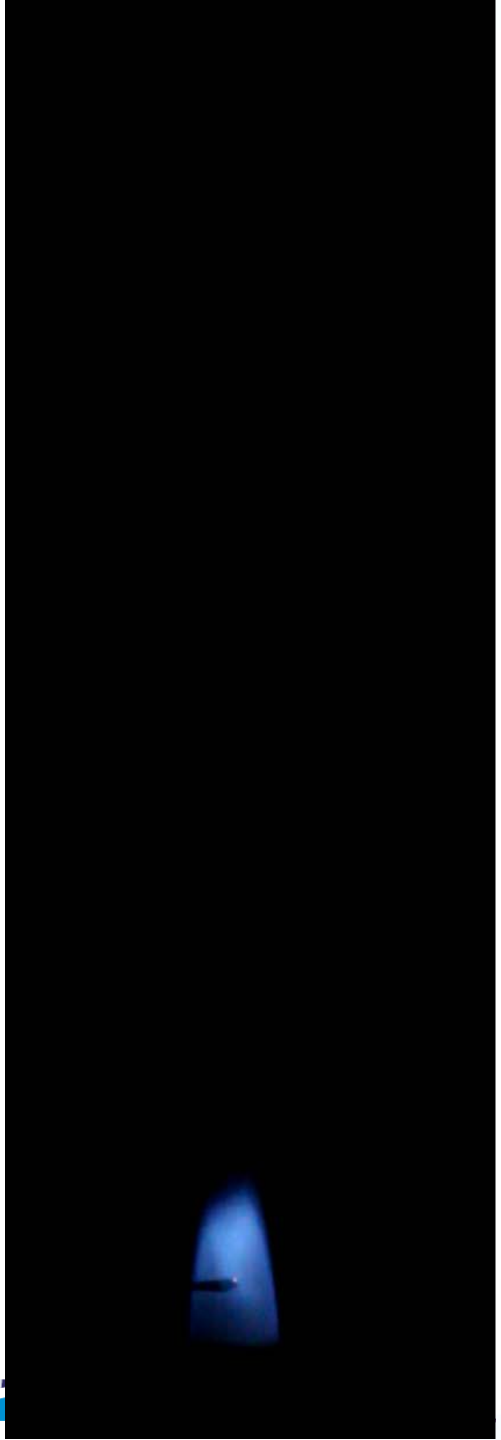


stable flame

RZ flame

RZ flame +NRP





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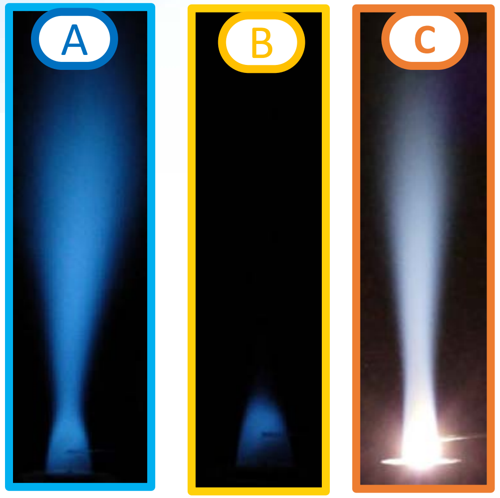
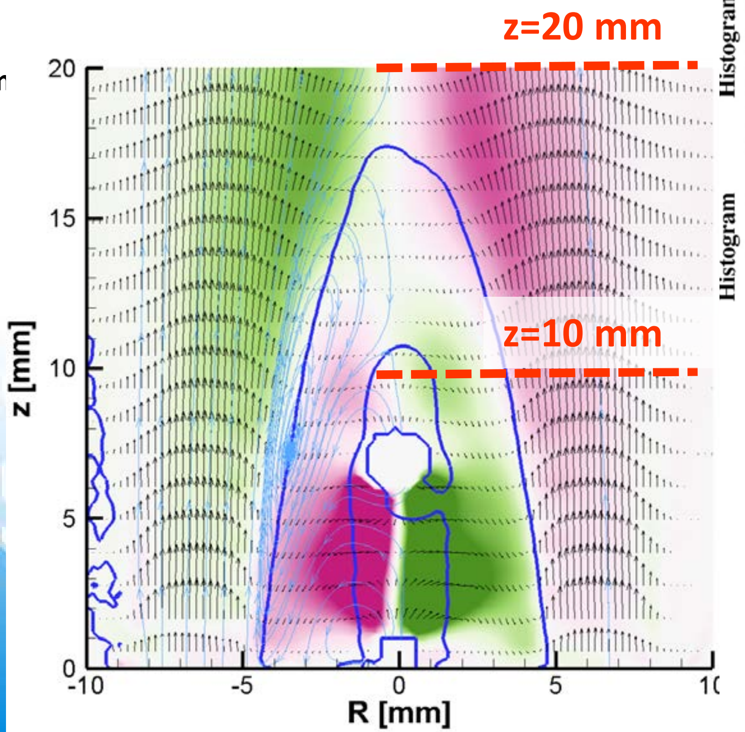
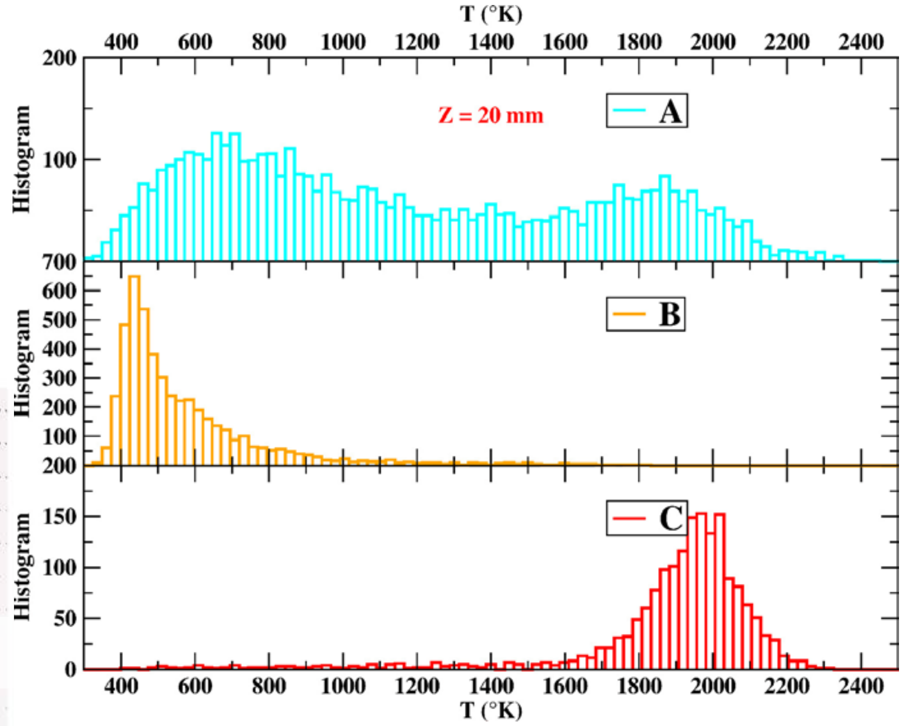
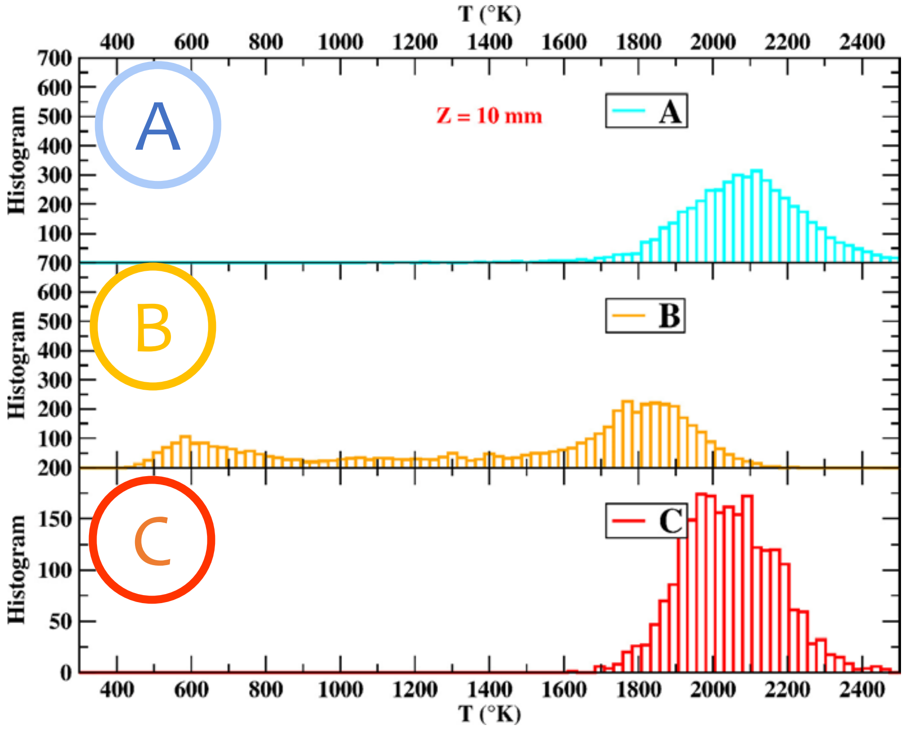
EFFECT OF THE DISCHARGE B → C







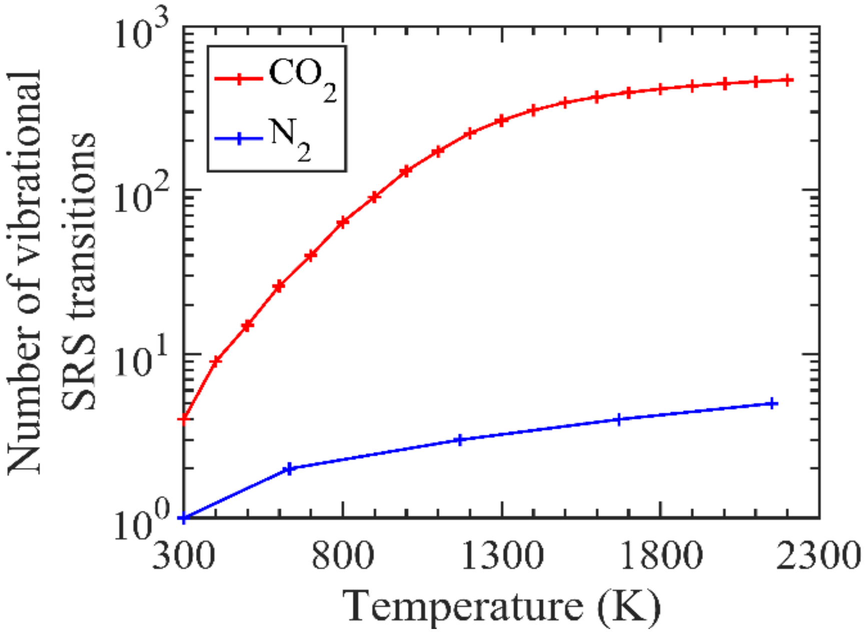


EXCITATION VIBRATIONNELLE DU CO2

difficulties?

- Number of transitions
- Confidence of spectroscopic data
- Fermi resonance at high temperature

ν_1 ν_2 ν_3



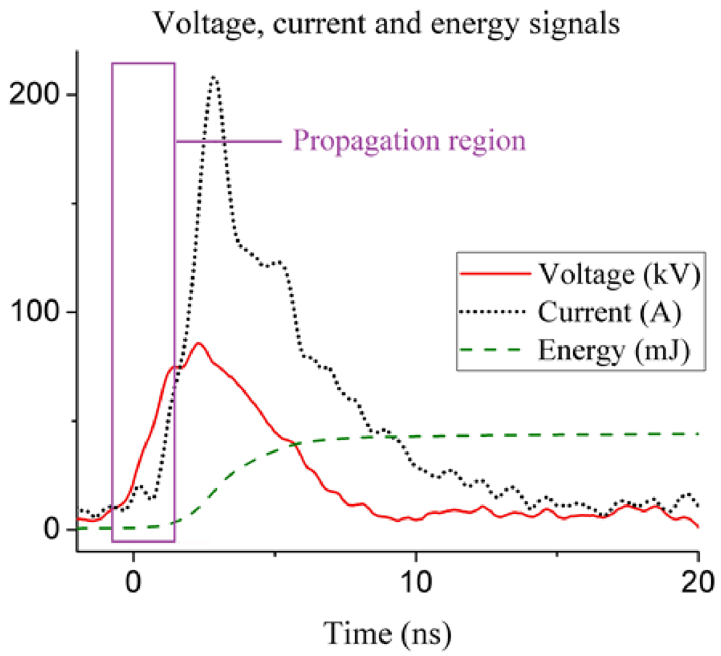
Hot temperature vibrational data base

- R. Lemus, et al(2014) J. Chem. Phys, 141
- 892 pure vibrational SRS transitions between 1100 and 1500 cm^{-1}, involving energy levels up to 15 000 cm^{-1}

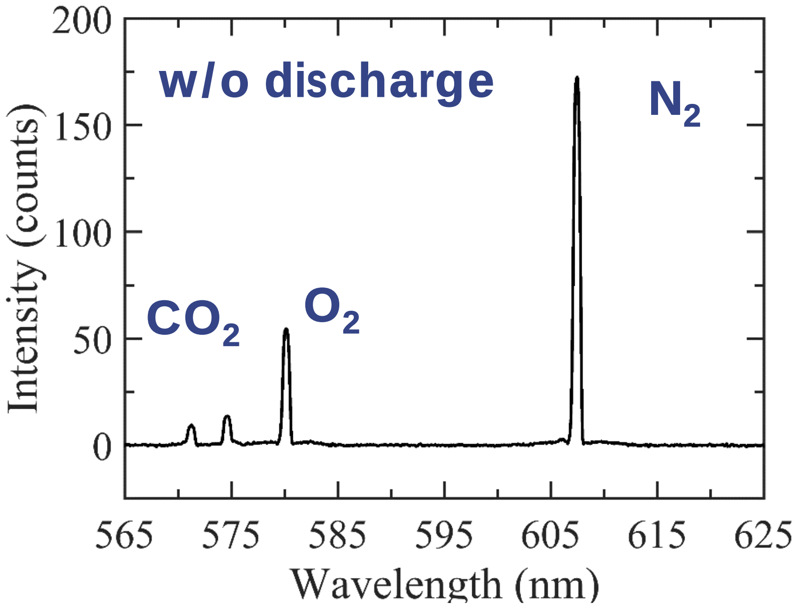
VIBRATIONAL CO_2 SRS FOR NS-DISCHARGE ANALYSIS

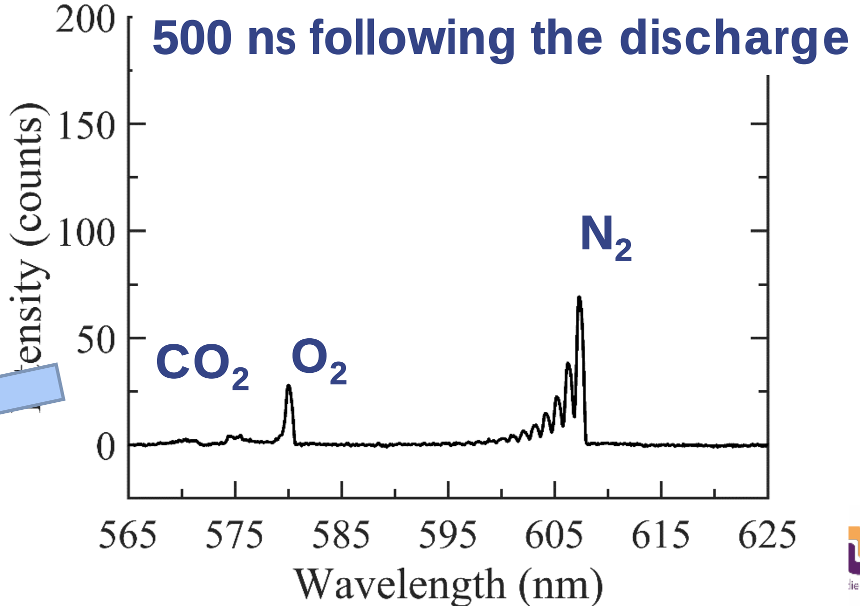
Air doped with 4% of CO_2

- Pin to plane discharge
- HV=85kV
- gap=18mm
- Total pulse duration: 10ns (FWHM=6ns)



Brisset, Tardiveau, GRC 2018





N_2
T_r= 671 K
T_{v01}= 2583 K
T_{v1v}= 4037 K

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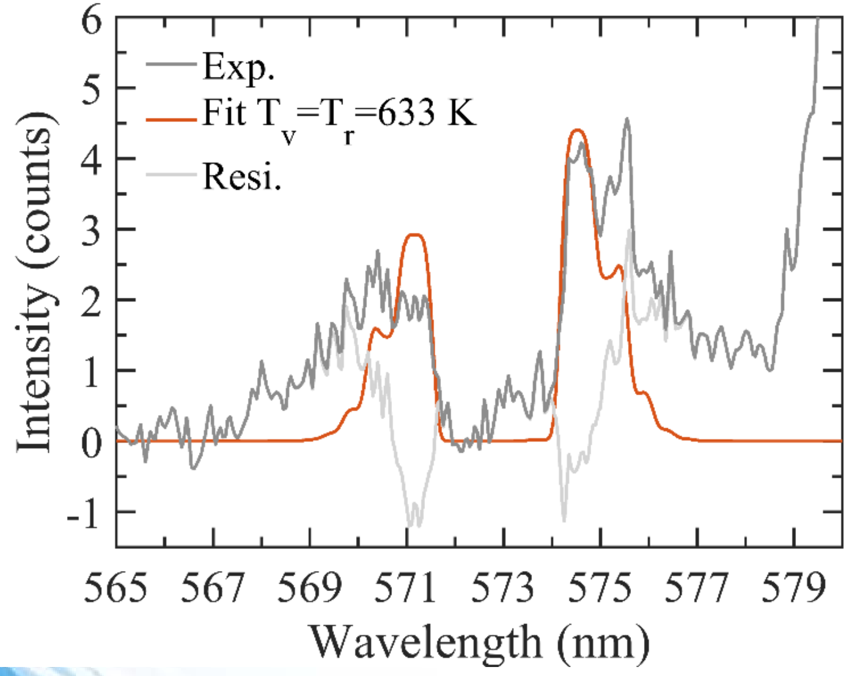
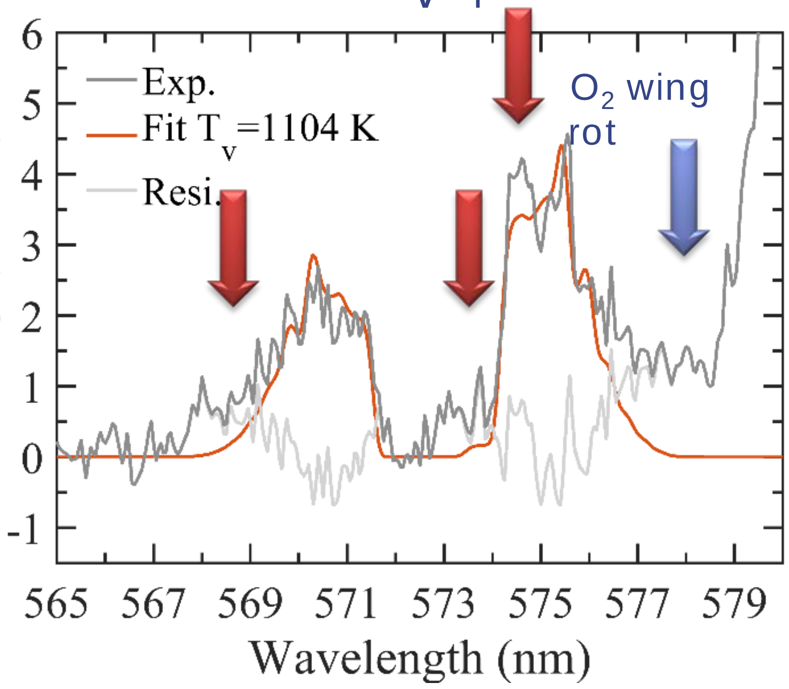
HORS ÉQUILIBRE DU SPRECTRE DE CO_2

$$f(E(1,2,1) \propto \exp(-\frac{hc.E(1,2,0)}{kT_{12}}) * \exp(-\frac{hc.E(0,0,1)}{kT_3})$$

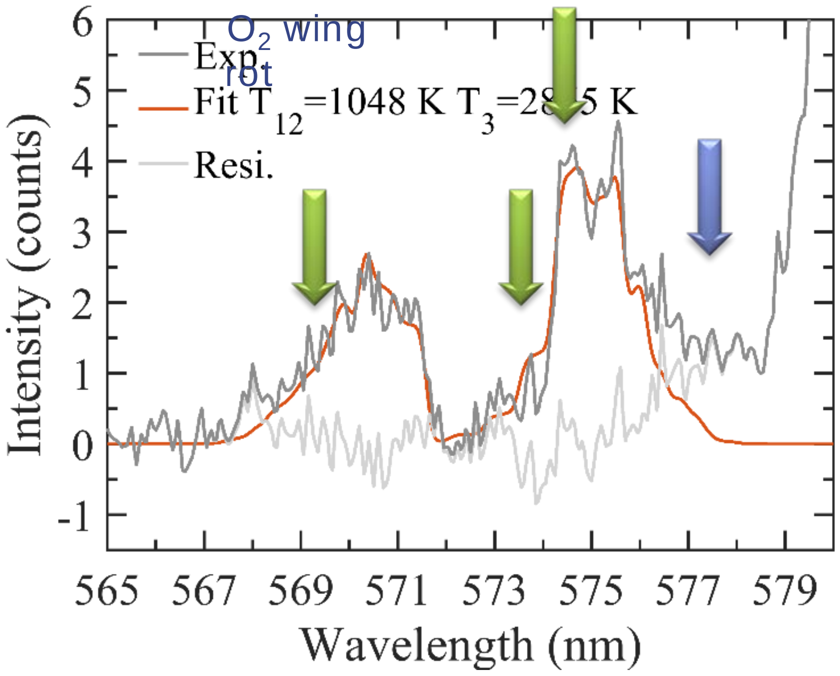
Simulation
$T_v=T_r$



Simulation
$T_v \neq T_r$

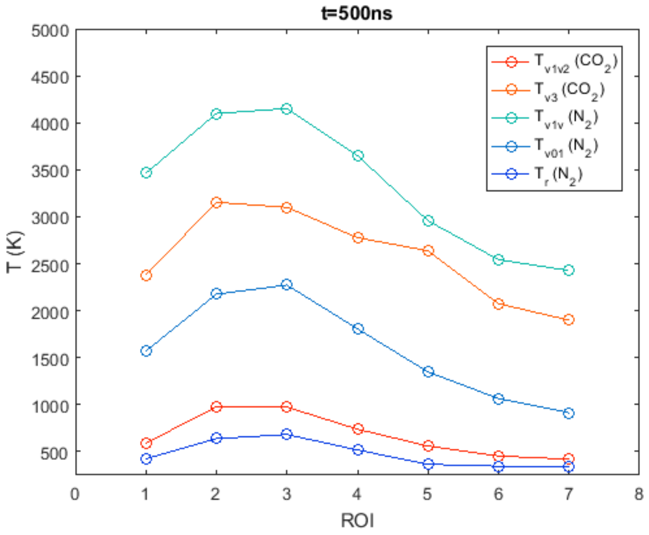


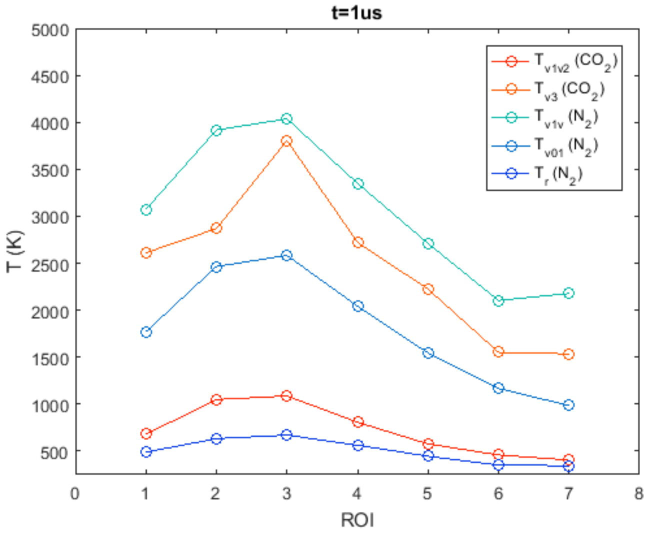
Simulation
$T_v \neq Tr$, $T_{12} \neq T_3$



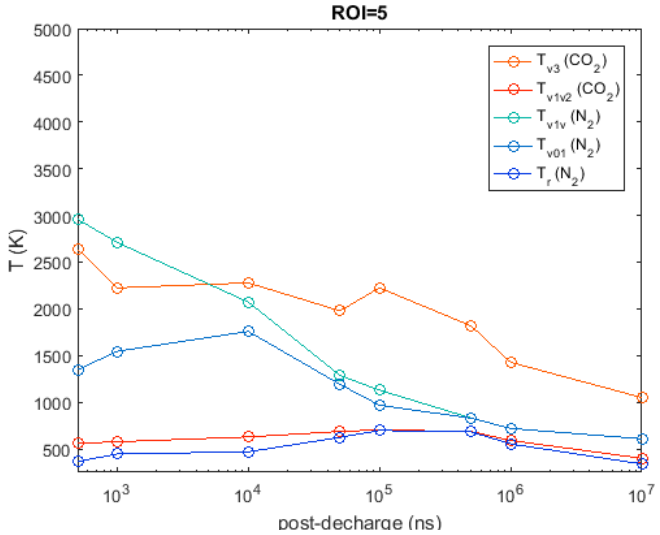
ANALYSE SPATIO-TEMPORELLE

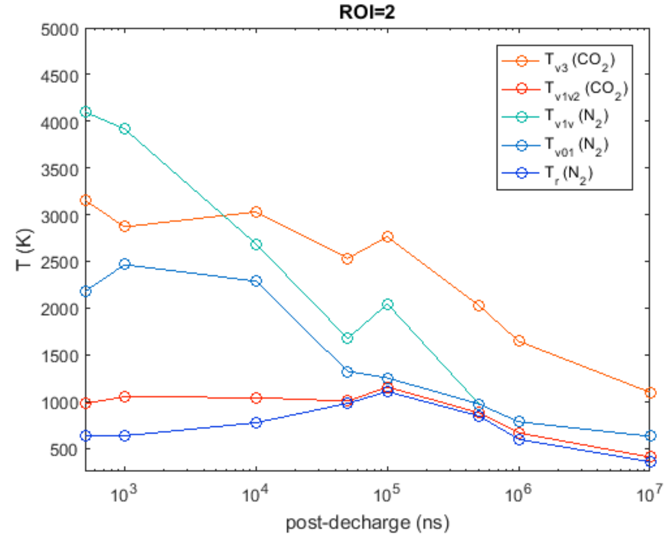
Radial profiles





Axial time evolution





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CONCLUSION

CONCLUSION

Diffusion Raman spontanée :

un diagnostic à revisiter

En combustion, en plasma, les 2 à la fois

pour les plasmas hors équilibre : mesure simultanée T et températures vibrationnelles

mesure à Pa ou plus

mesure 1D : information spatio-temporelle

moyenne de phase possible

Intérêt pour les enjeux de la transition énergétique

Combustion turbulente : nouveaux combustibles « défossilisés » en combustion aérobie, en oxycombustion diluée au CO2 , hydrogène

Combustion assistée par plasma

Valorisation du CO_2 : catalyse, catalyse assistée par plasma

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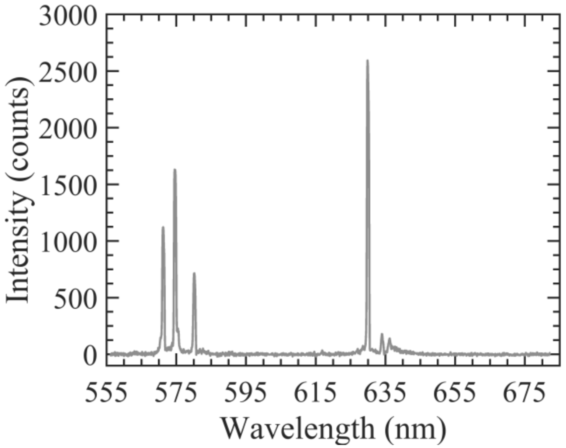
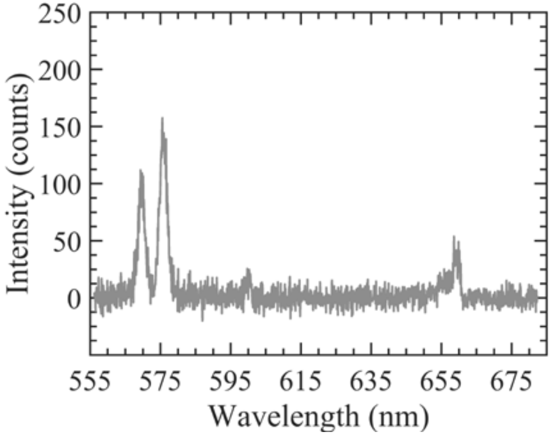
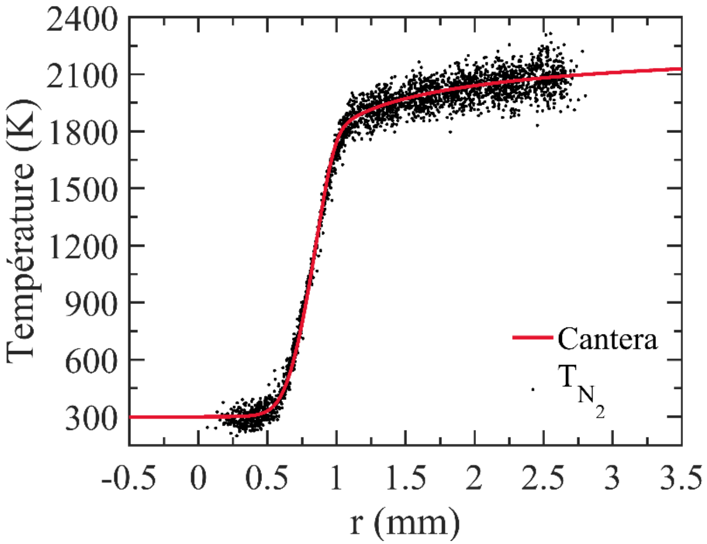
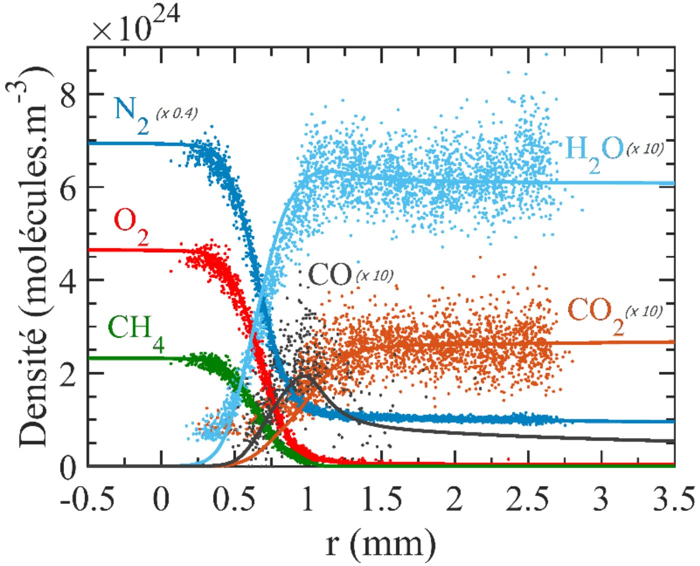
SIMULTANEOUS T AND MULTISPECIES CONCENTRATION









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