Plasma-assisted combustion: applications and fundamental mechanisms

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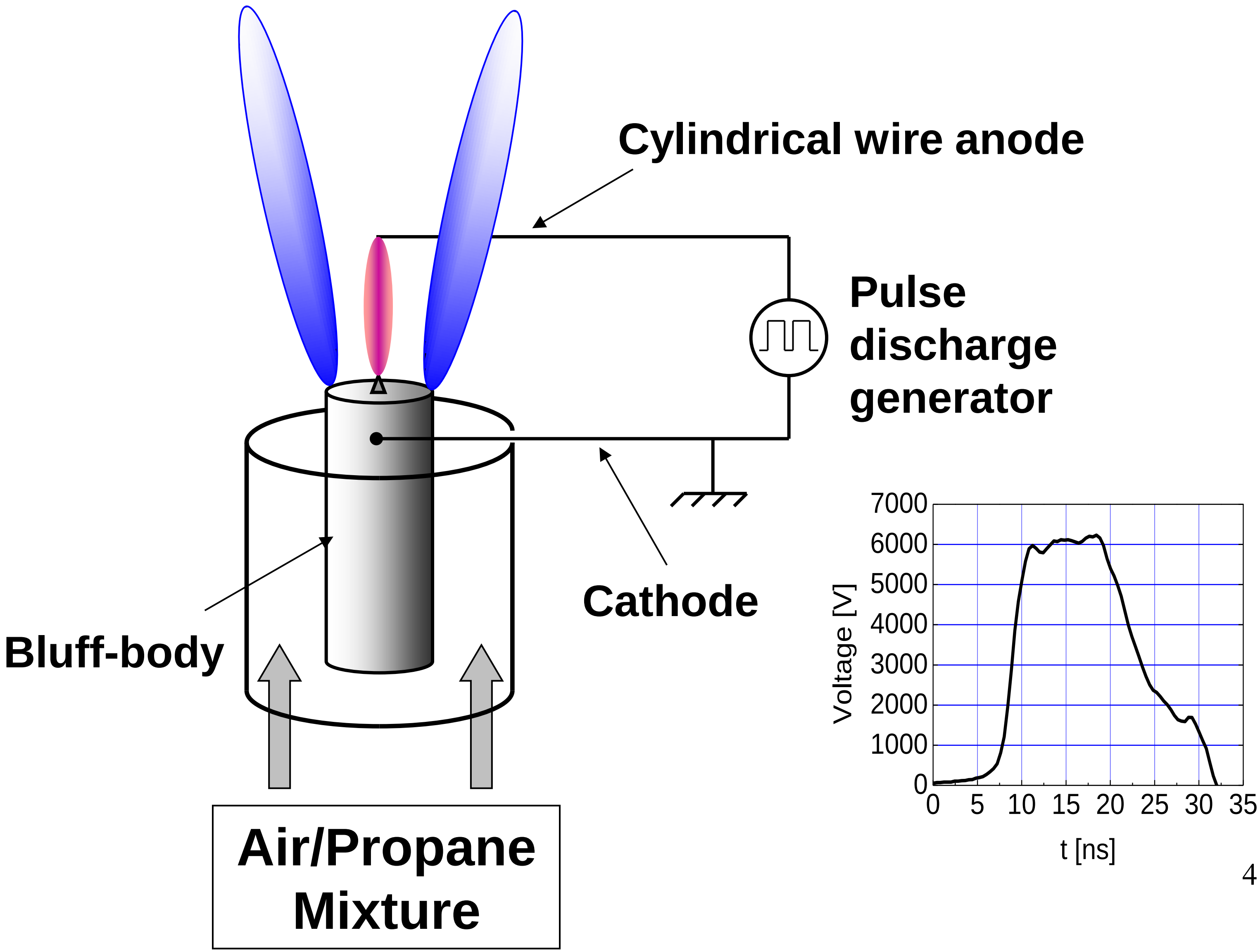
Outline

- Demonstrations of plasma assisted combustion:
  - Lean flame stabilization
  - Control of thermo-acoustic instabilities
- Fundamental mechanisms:
  - Chemical and thermal effects of NRP discharges
  - Measurements of NO emissions
- Conclusions

Stabilization of Lean Premixed Flames using NRP discharges

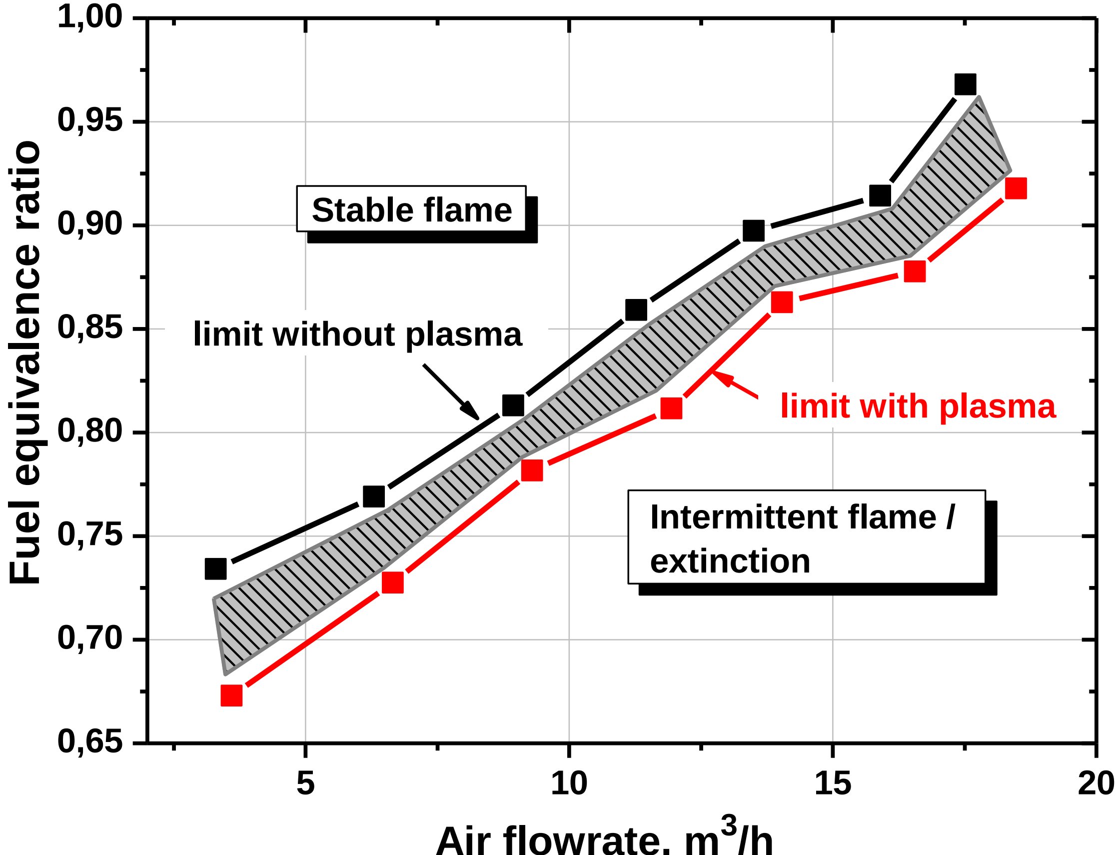
Mini-PAC burner:
25-kW Lean Premixed Propane-Air Burner



Mini-PAC burner

Stability regimes of mini-PAC burner

NRP: 2.3 mJ/pulse, PRF=30 kHz, Plasma power: 70 W



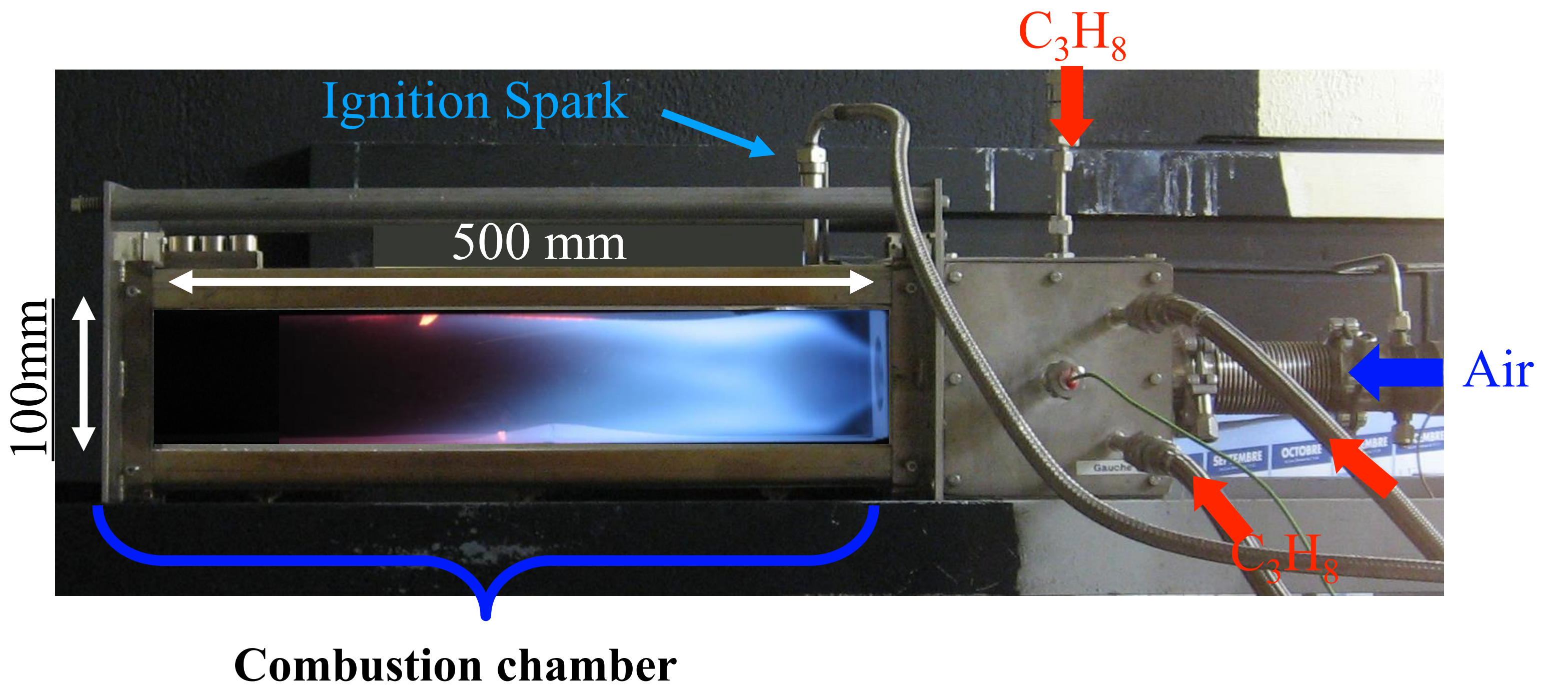
Pilla, et al 2006

- NRP discharge lowers the lean extinction limit by about 10% and consumes less than 1% of the flame power

Stabilization of
Larger Scale Combustors

52-kW two-stage swirled gas turbine injector

Propane/air at 1 bar



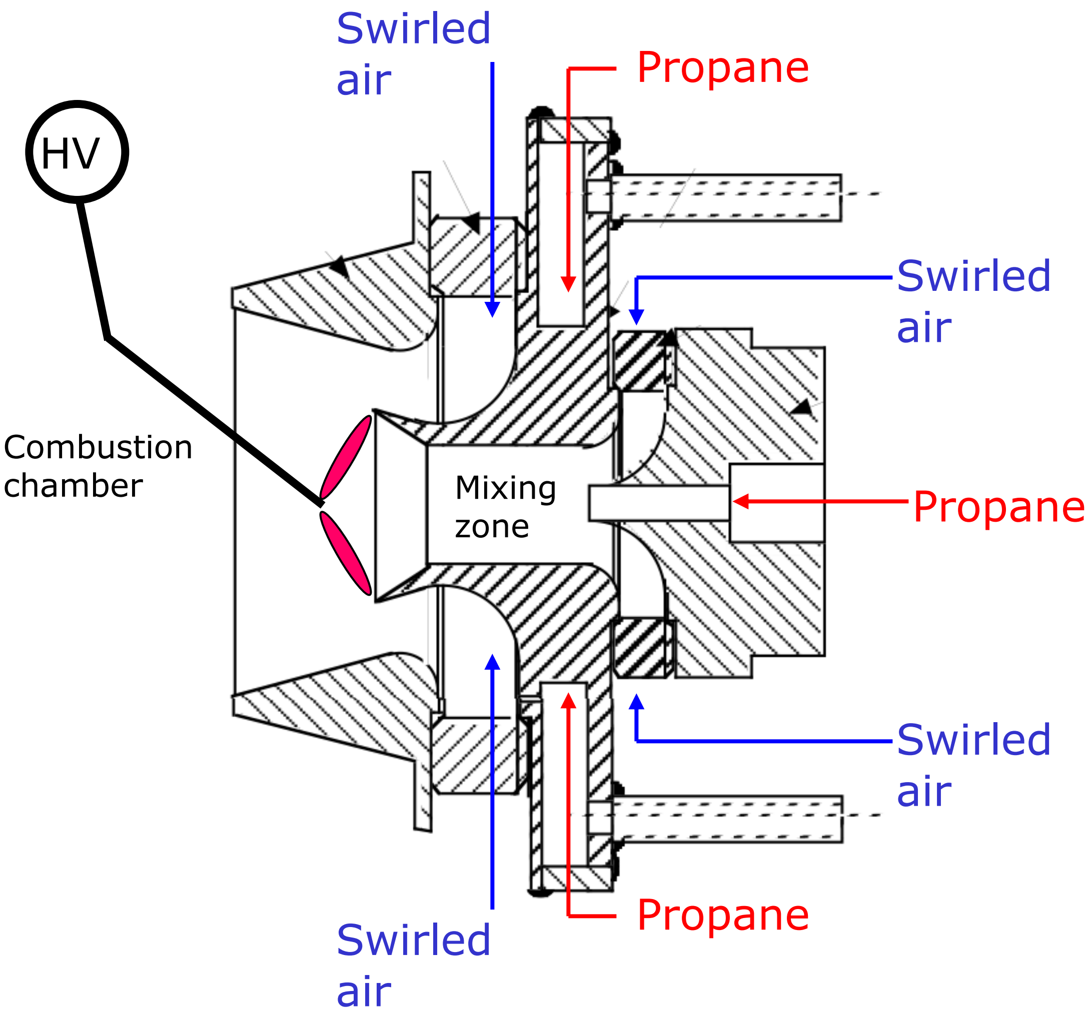
Air: 105 m³/h
Propane: 2.1 m³/h
Max power: 52 kW
Exit velocity: 40 m/s

S. Barbosa, G. Pilla, D. Lacoste P. Scouflaire, S. Ducruix, C.O. Laux, D. Veynante, European Combustion Meeting, Vienna, 2009

Two-stage swirled gas turbine injector

Premixed propane/air, 52 kW, 1 atm

S. Barbosa, G. Pilla, D. Lacoste P. Scouflaire, S. Ducruix, C.O. Laux, D. Veynante, European Combustion Meeting, Vienna, 2009



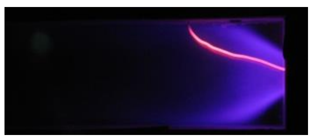
Lower extinction limit of the two-stage burner

Constant air flow rate: 105 m³/h

Without plasma

2.1 m³/h
Φ=0.47

1.95 m³/h
Φ=0.44



1.8 m³/h
Φ=0.4

Extinction
Φ= 0.4

Gain 70%

Extinction
with plasma
Φ=0.11

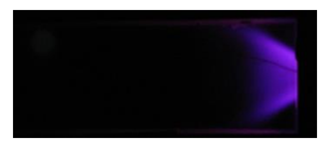
With plasma, 30 kHz

2.1 m³/h
Φ=0.47

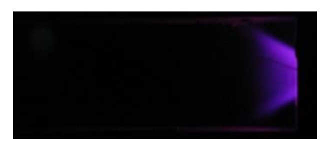
1.95 m³/h
Φ=0.44

1.8 m³/h
Φ=0.4

1.65 m³/h
Φ=0.37



1.35 m³/h
Φ=0.3

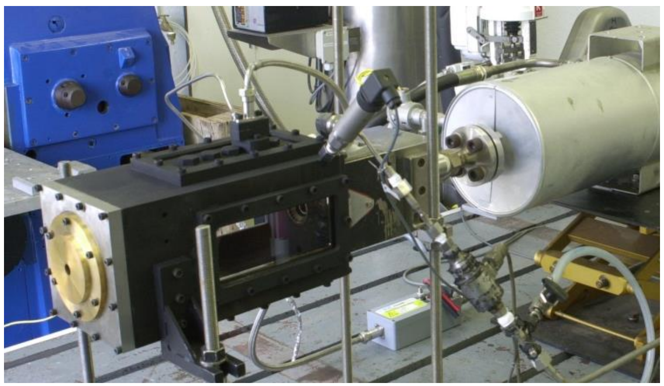


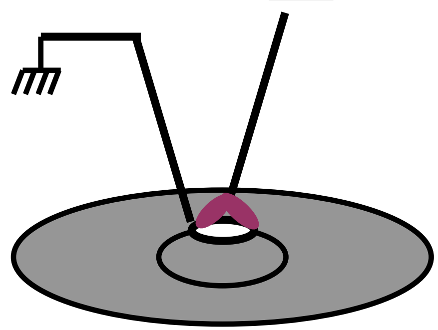
1.2 m³/h
Φ=0.27

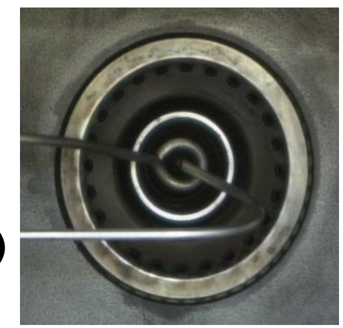
1.05 m³/h
Φ=0.23

200 kW Turbulent Aerodynamic Injector (ONERA/MERCATO)

Kerosene/air at 3 bar







G. Heid, G. Pilla, R. Lecourt D.A. Lacoste, ISABE 2009

Without plasma

Extinction: Φ = 0.44

With plasma, 100 kHz

Extinction: Φ = 0.21

- 52% reduction of the Lean Extinction Limit
- Power consumed by NRP discharge: < 1% of flame power

Dynamic control of thermo-acoustic instabilities

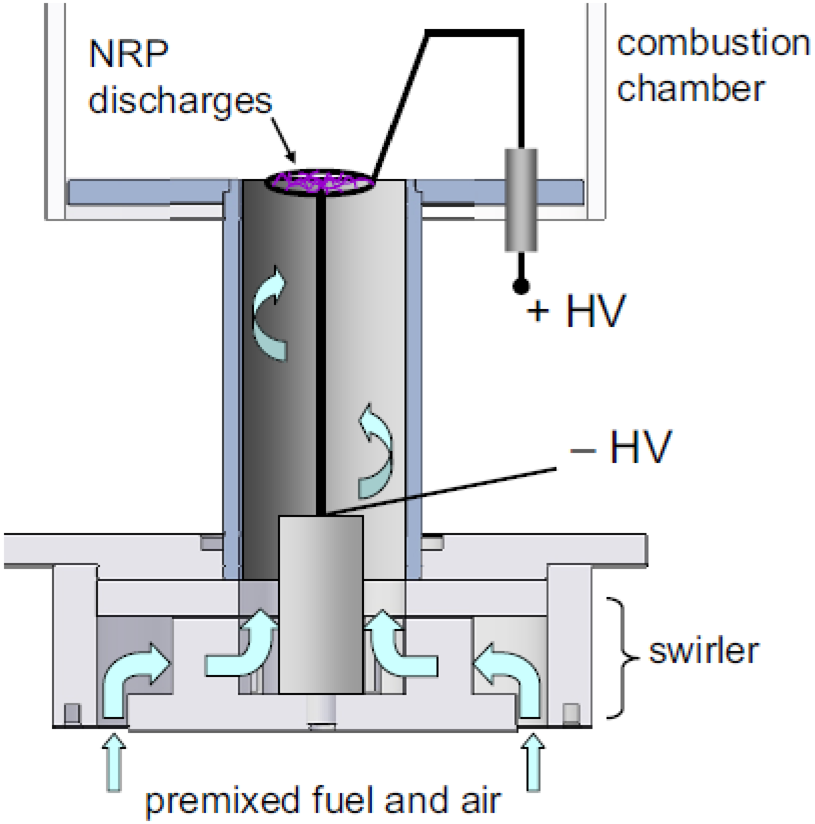
Closed loop control of a turbulent swirled flame

Pulse duration 10 ns

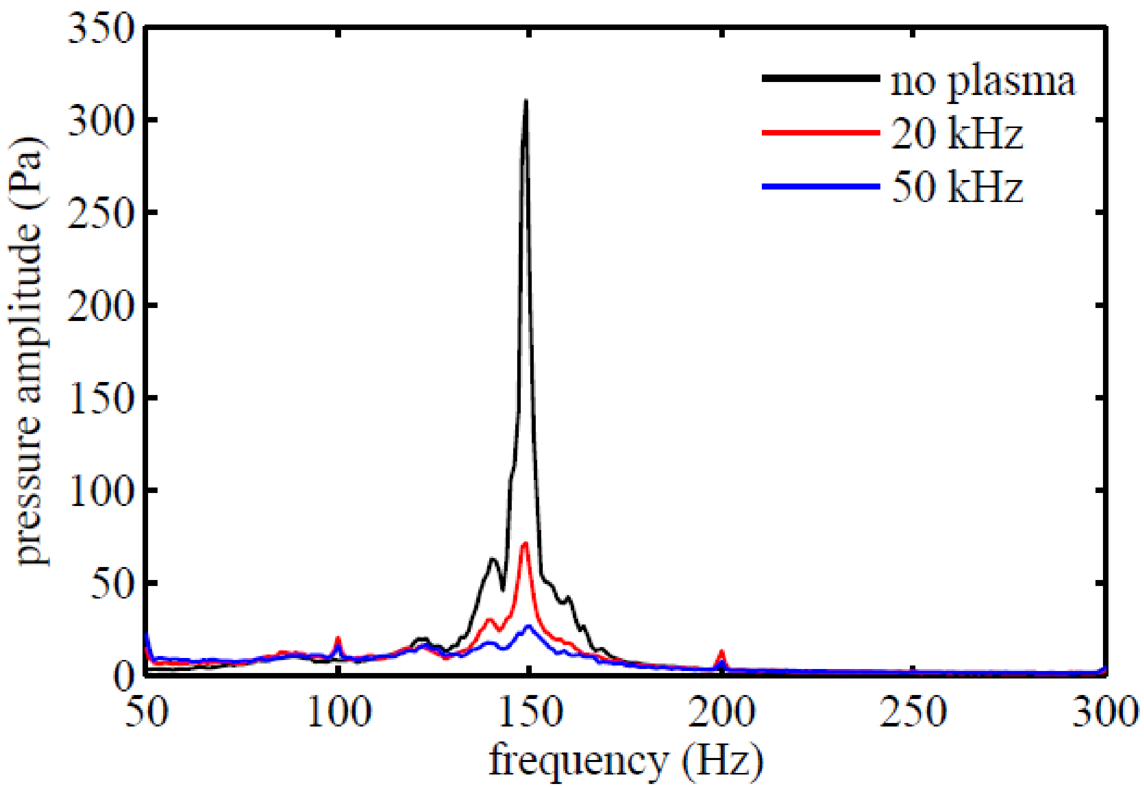
Pulse amplitude 12 kV

Pulse repetition frequency 10–50 kHz

$P_{\mathrm{NRP}} / Q_{\mathrm{th}} < 1\%$



Closed loop control of a turbulent swirled flame



$$\phi = 0.66,\ Q_{\mathrm{th}} = 43\,\mathrm{kW}$$

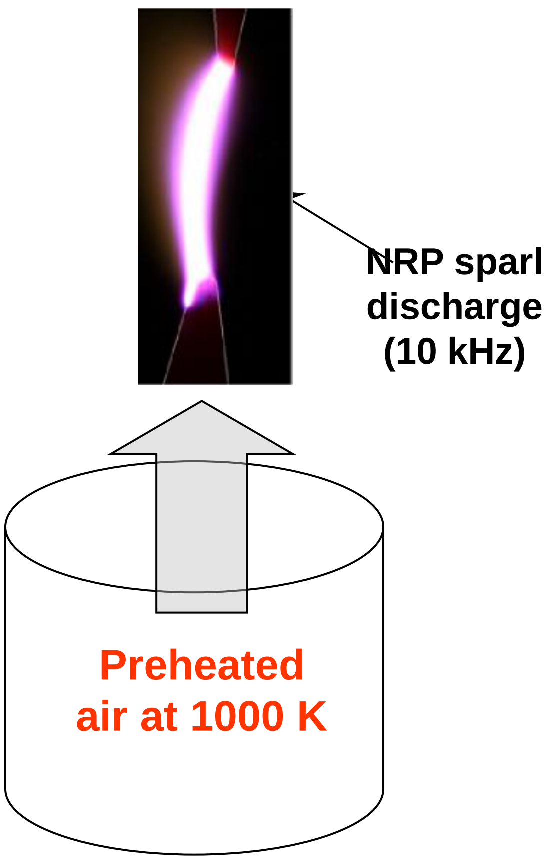
Lacoste, Moeck, Durox, Laux, Schuller, J. Eng. Gas Turb. Power, 135, Oct. 2013

FUNDAMENTAL MECHANISMS

Chemical and thermal effects of NRP discharges

![CENTRALE PARIS logo] ![CNRS logo]

Experimental approach



Study NRP discharge in air at 1000 K, 1 atm:

- 10-ns pulse
- 5.7 kV
- Gap: 4.5 mm
- 10 kHz
- 0.67±0.02 mJ/pulse

Investigation of two-step mechanism for oxygen dissociation

$$N_2 + e \rightarrow N_2^* + e \quad (N_2^* = N_2\ A, B, C)$$

Thresholds: 6.2, 7.4, 11.0 eV

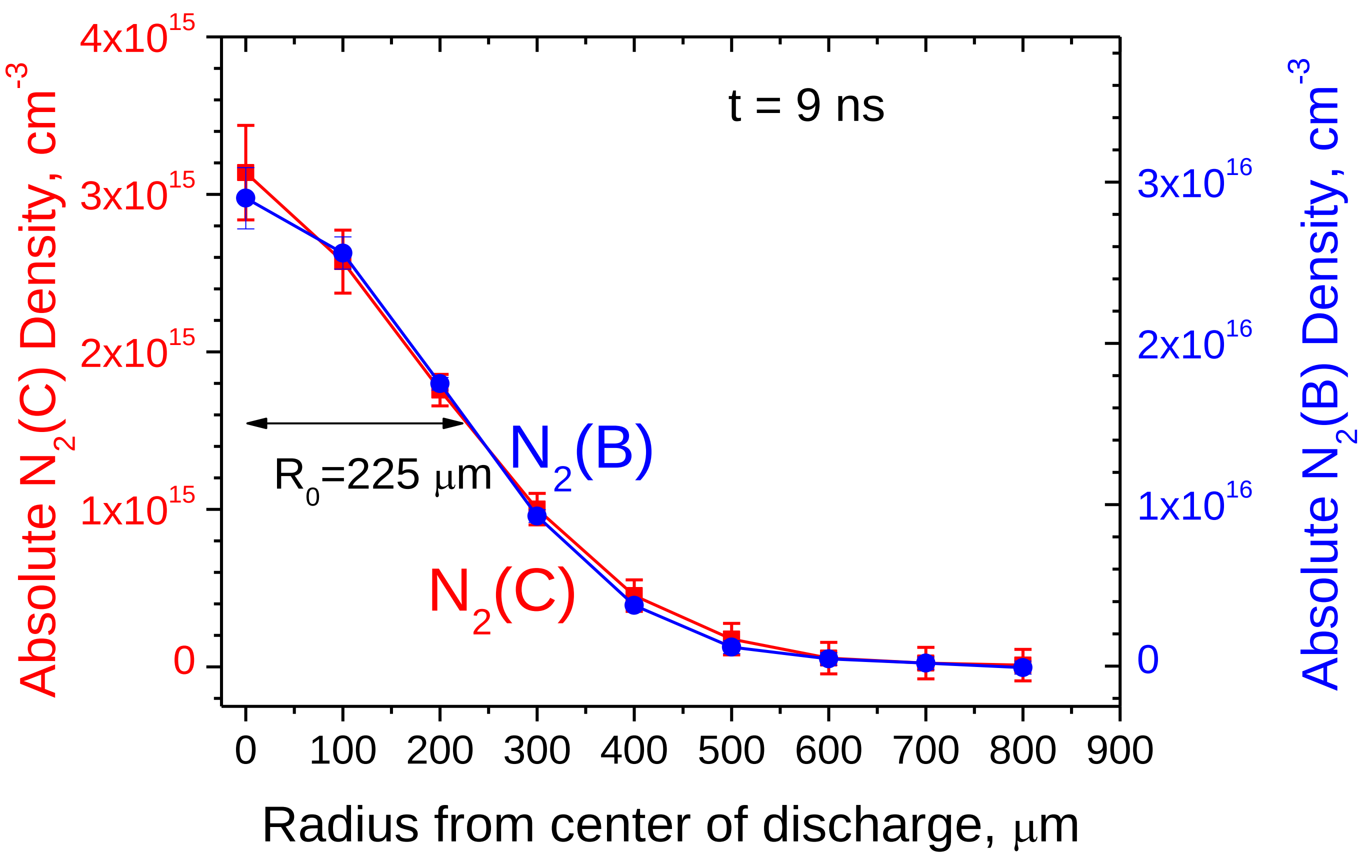
$$N_2^* + O_2 \rightarrow N_2 + O + O + \Delta T$$

ΔT = 1.0, 2.2, 5.9 eV

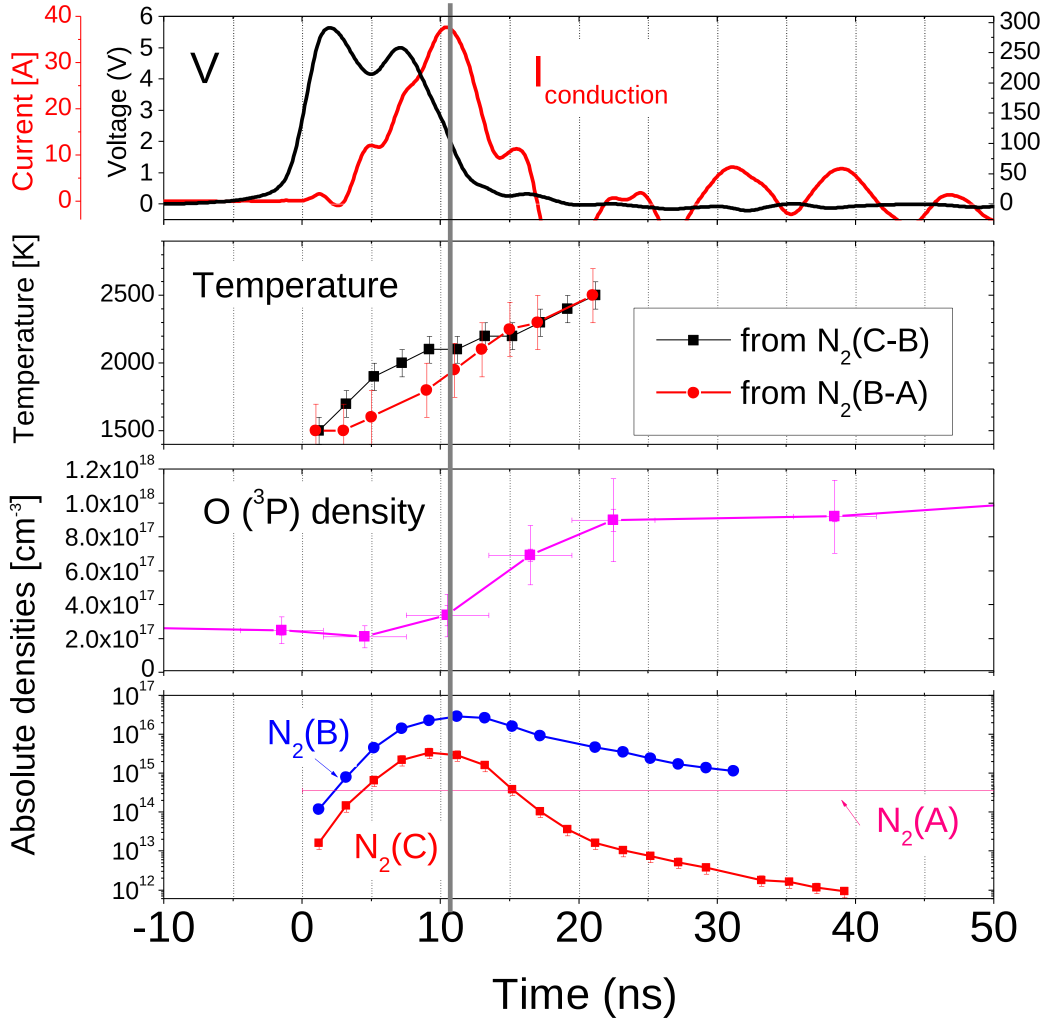
Measured quantities:

- Electrodynamics: U, I, Energy
- Discharge radius
- O atoms: TALIF
- N_2 A: CRDS
- N_2 B and N_2 C: OES
- Electrons: Stark broadening
- Temperature: OES (T_{rot} N_2 C and T_{rot} N_2B)

Discharge radius



Synchronized measurements of V, I, temperature, densities



Electric energy: 670±20 μJ/pulse

Ultrafast heating: 900 K in 20 ns

$\eta_{heating}$ =21±5%

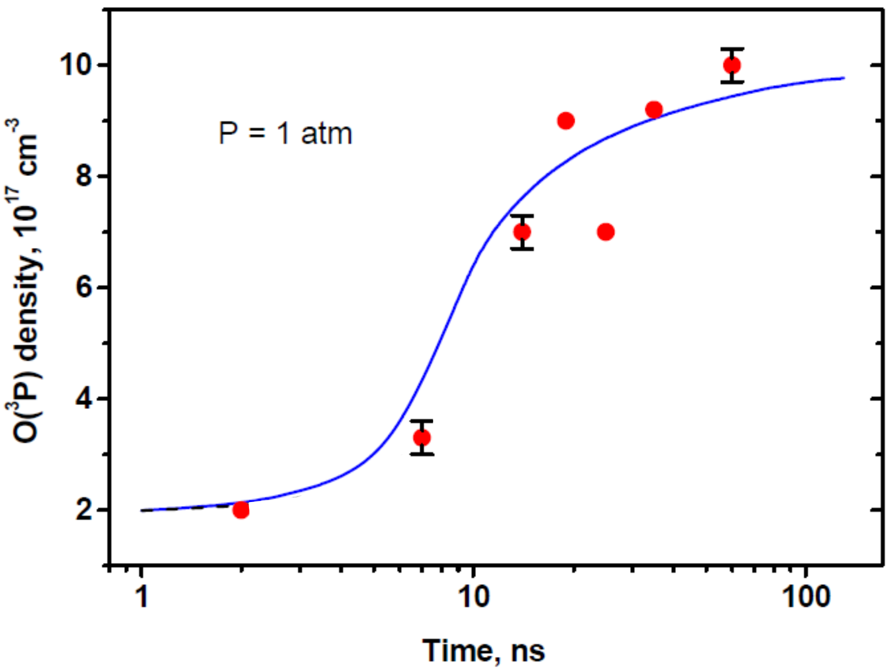
50% dissociation of O_2

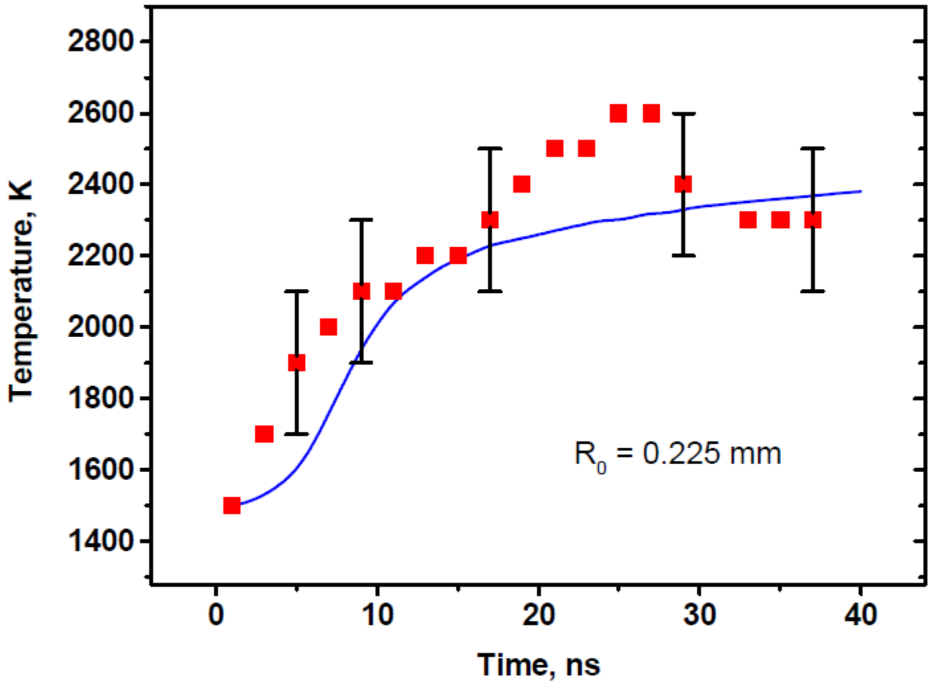
$\eta_{diss.}$ = 35±5%

Rusterholtz et al., J. Phys D., 2013, in press

Measured and predicted temporal profiles of O and Temperature

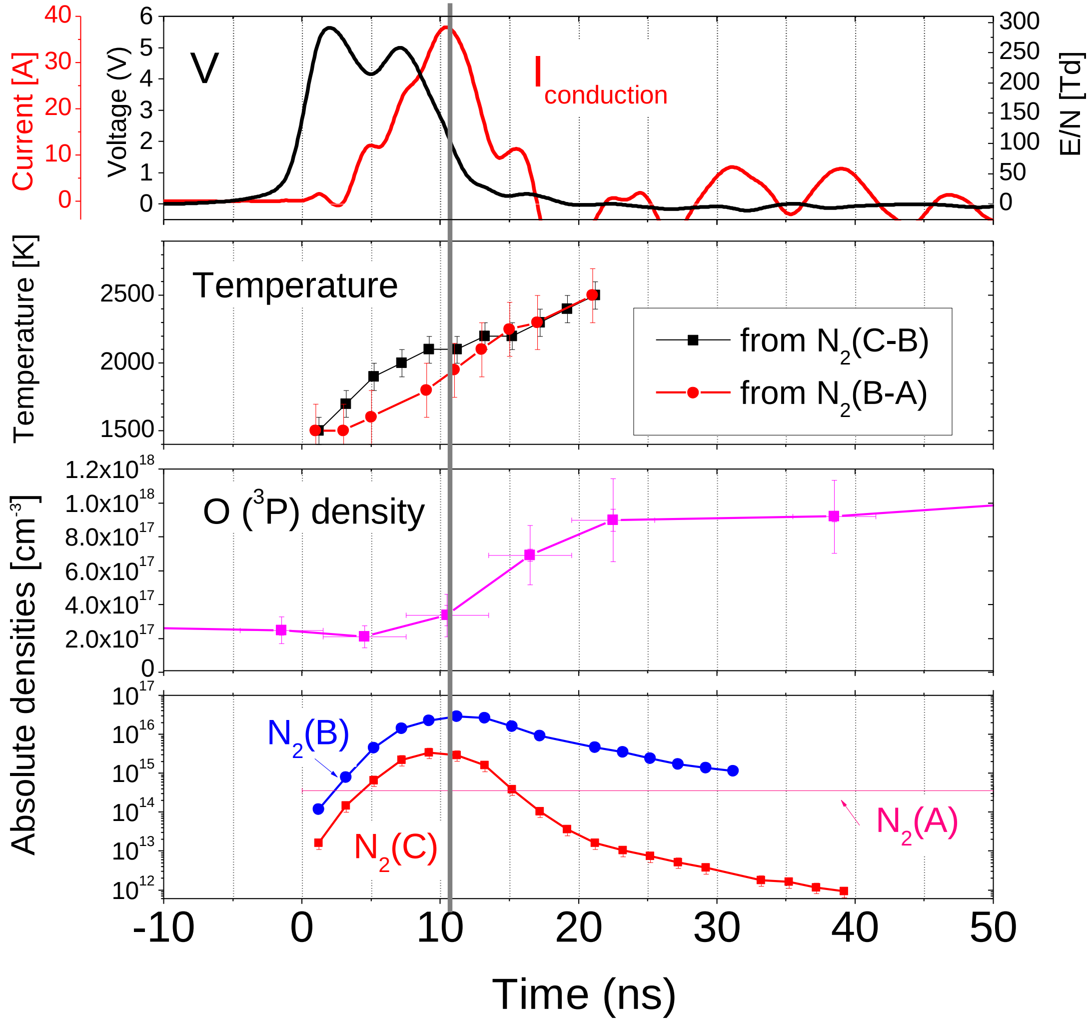
Measurements: present work Simulations: N. Popov, AIAA 2013-1052, Jan. 2013





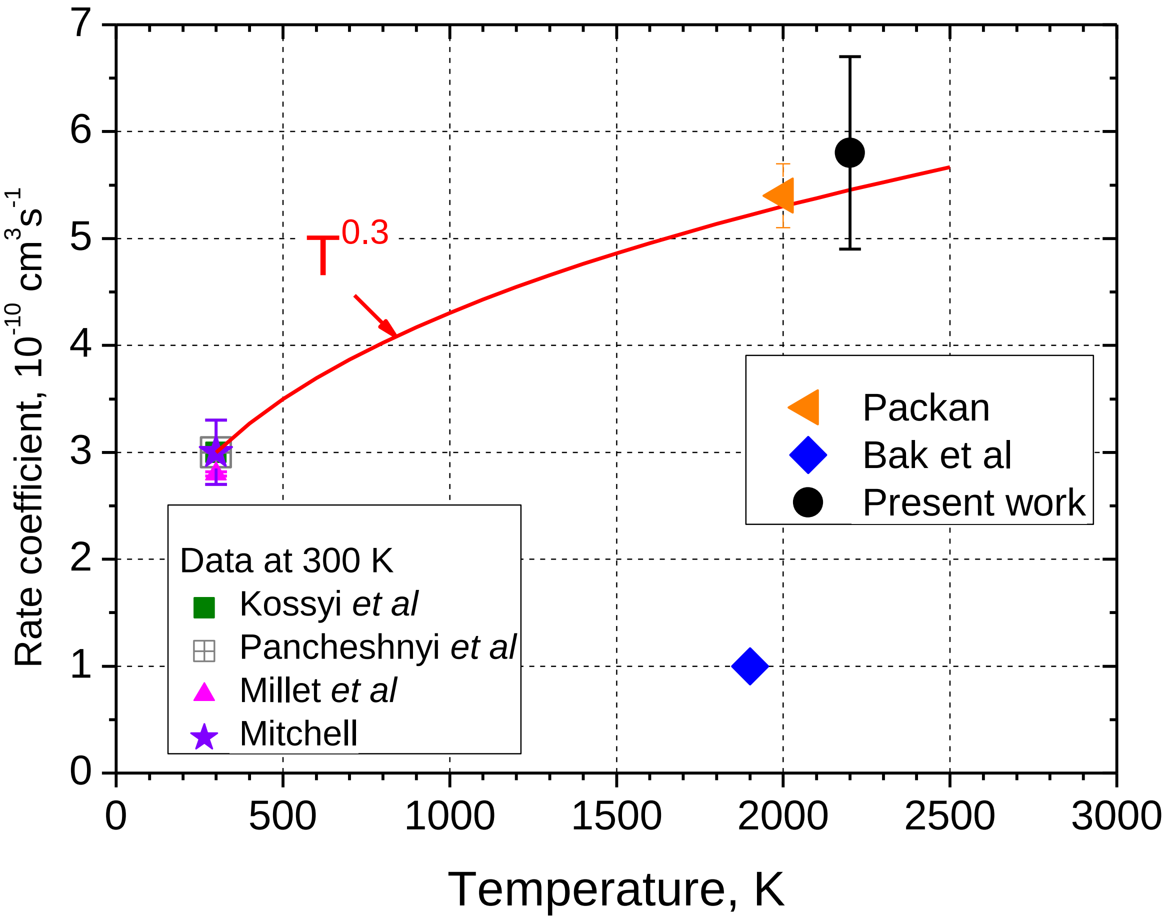
- Confirmation of the two-step mechanism of ultrafast heating and oxygen dissociation
- Full reference test case for numerical simulations

Synchronized measurements of V, I, temperature, densities



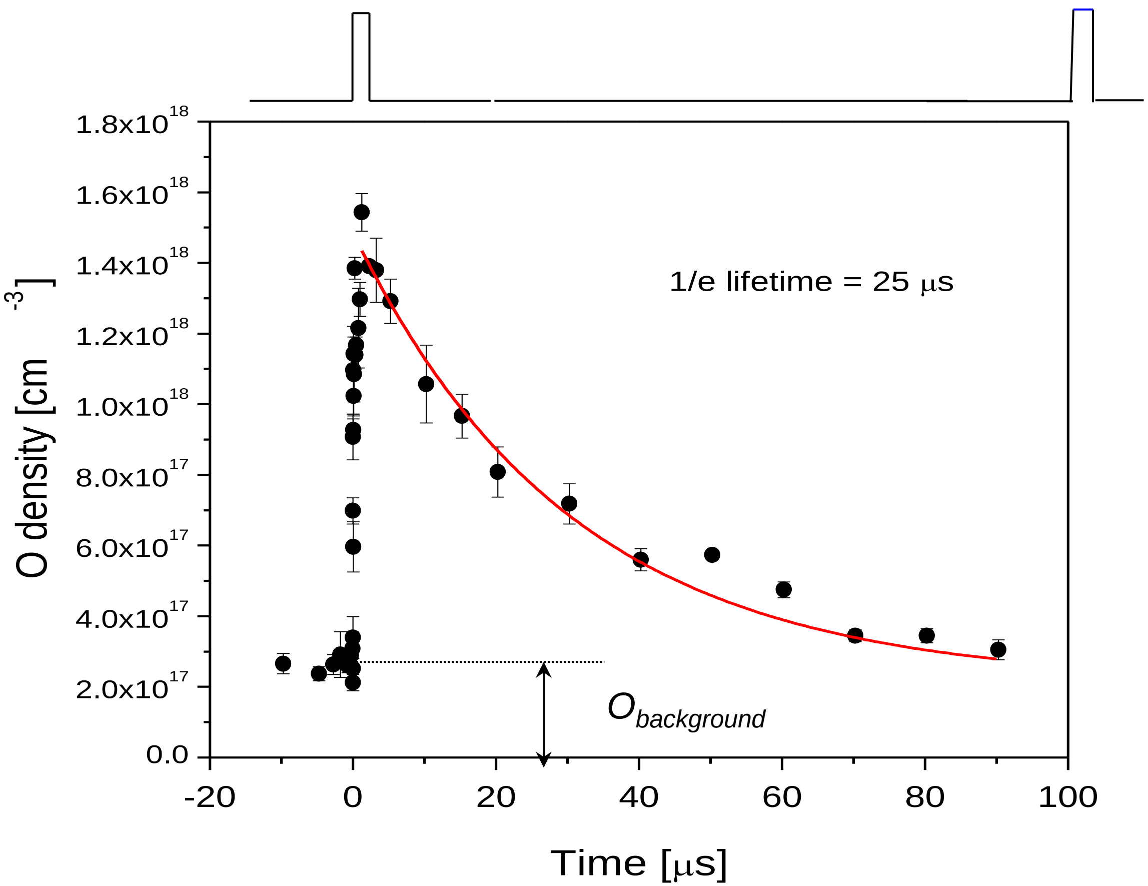
Rusterholtz et al., J. Phys D., 2013, in press

Quenching rates of N_2 C by O_2 at high temperature



- Recommended rate: $3x10^{-10}(T/300)^{0.3}$
- Same value obtained at 2000 K by Packan (NRP glow with no O atoms) and present work (NRP spark with 50% O_2, 50% O)

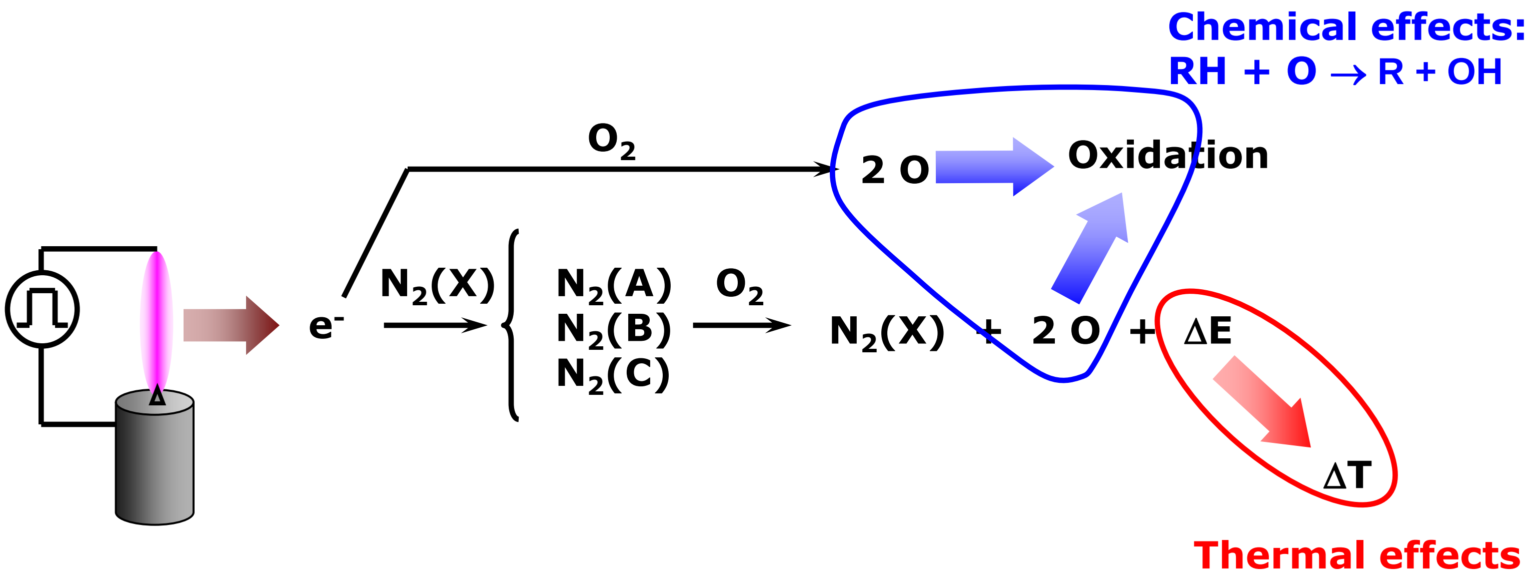
TALIF measurements of O density during one pulse cycle (100 μs)



Stancu, Kaddouri, Lacoste, Laux, J. Phys. D., 2010.

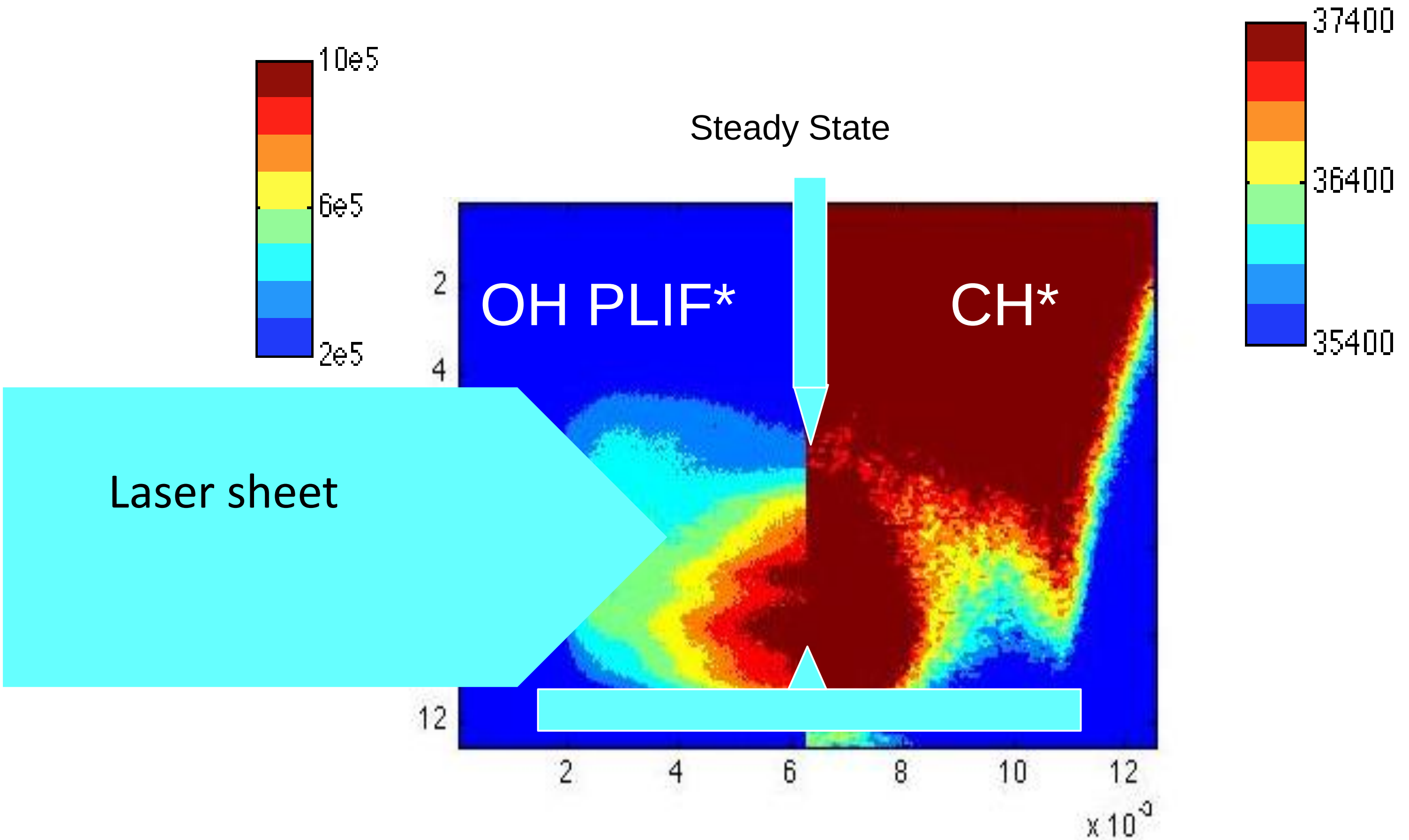
- O lifetime in air: 25 μs
- Even shorter in presence of fue (Uddi, Jiang, Mintusov, Adamovich, Lempert, Proc. Combust. Inst. 2009)

Processes involved in flame stabilization by NRP discharges



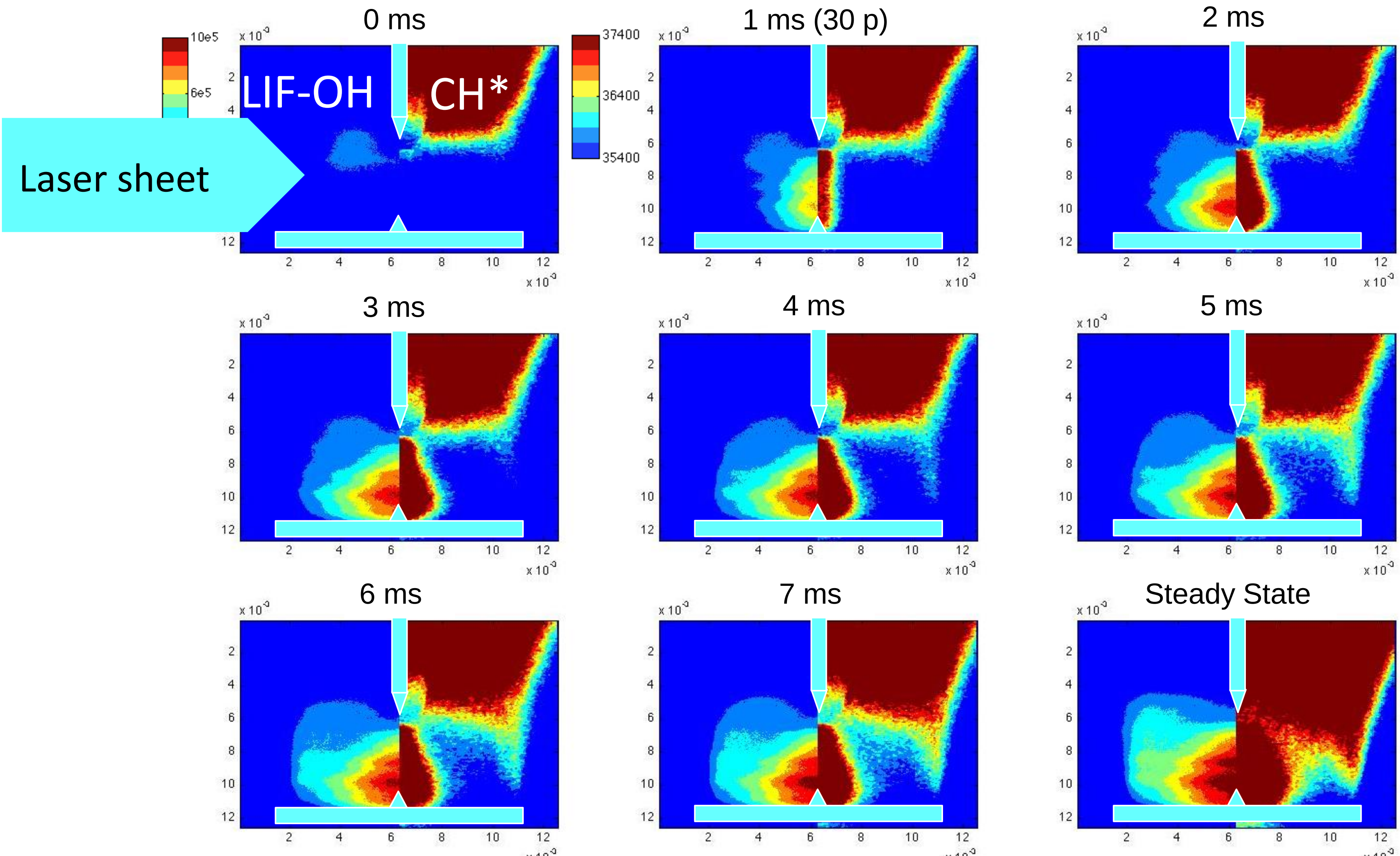
CH* emission and OH PLIF

Propane/air ϕ = 0.8, 1 bar, Flame power: 1.2 kW, Discharge power 12 W, PRF 30 kHz



Dynamic response of flame to discharge

Propane/air ϕ = 0.8, 1 bar, Flame power: 1.2 kW, Discharge power 12 W, PRF 30 kHz

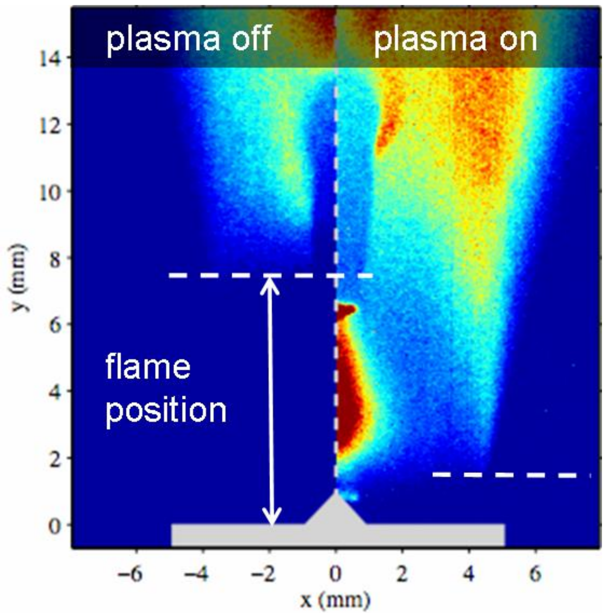


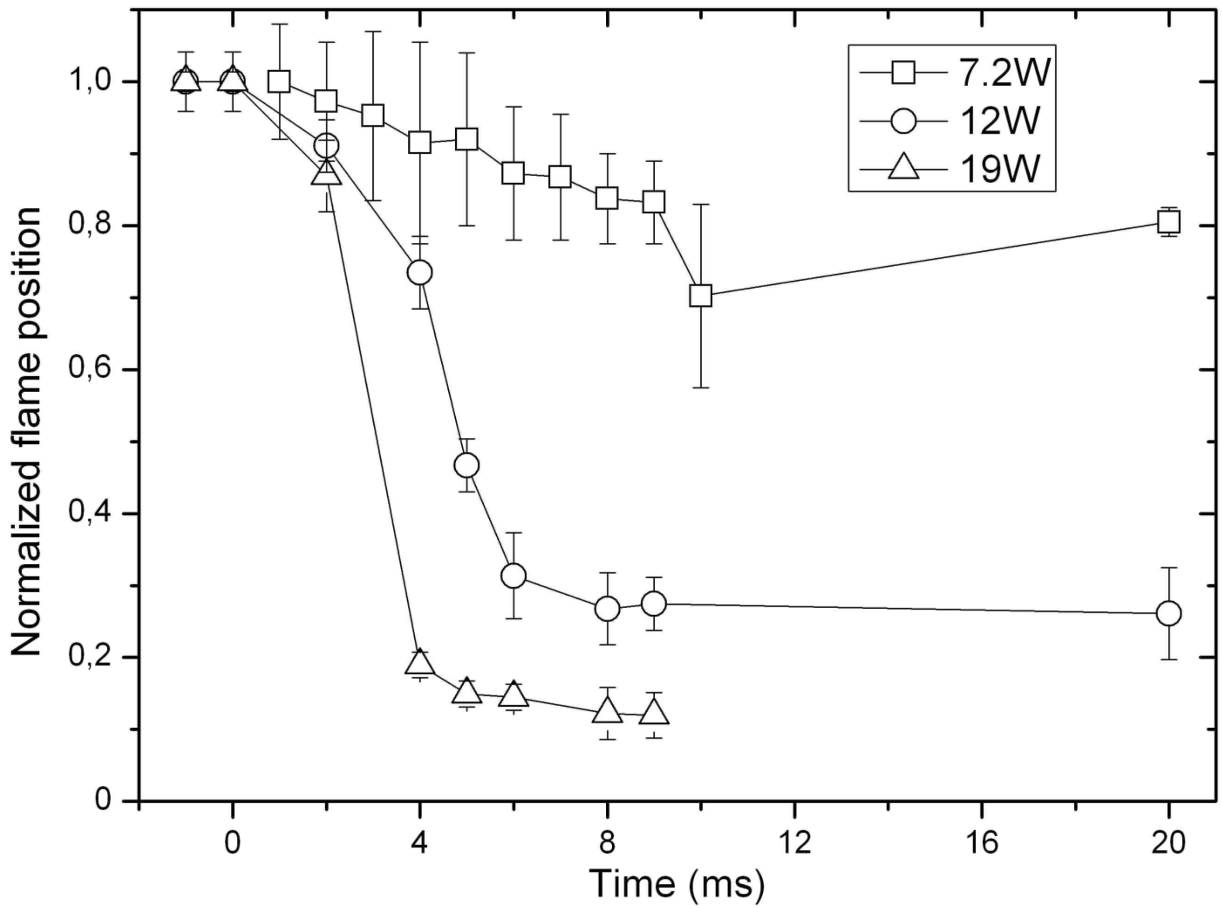
- Stabilization when OH reaches incoming fresh gases

Relative importance of Thermal and Chemical Effects

Temporal evolution of flame front vs discharge power

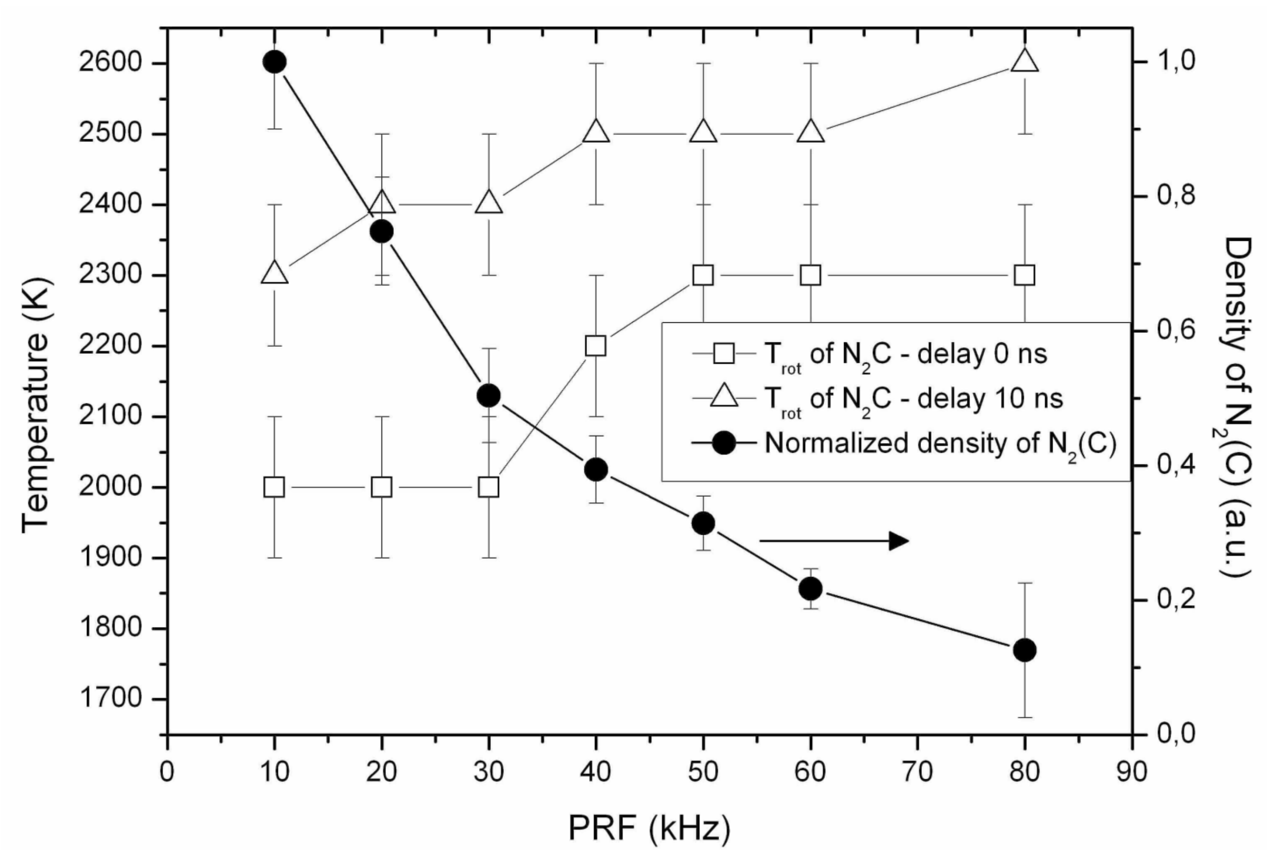
Propane/air ϕ = 0.8, 1 bar, Flame power: 1.2 kW





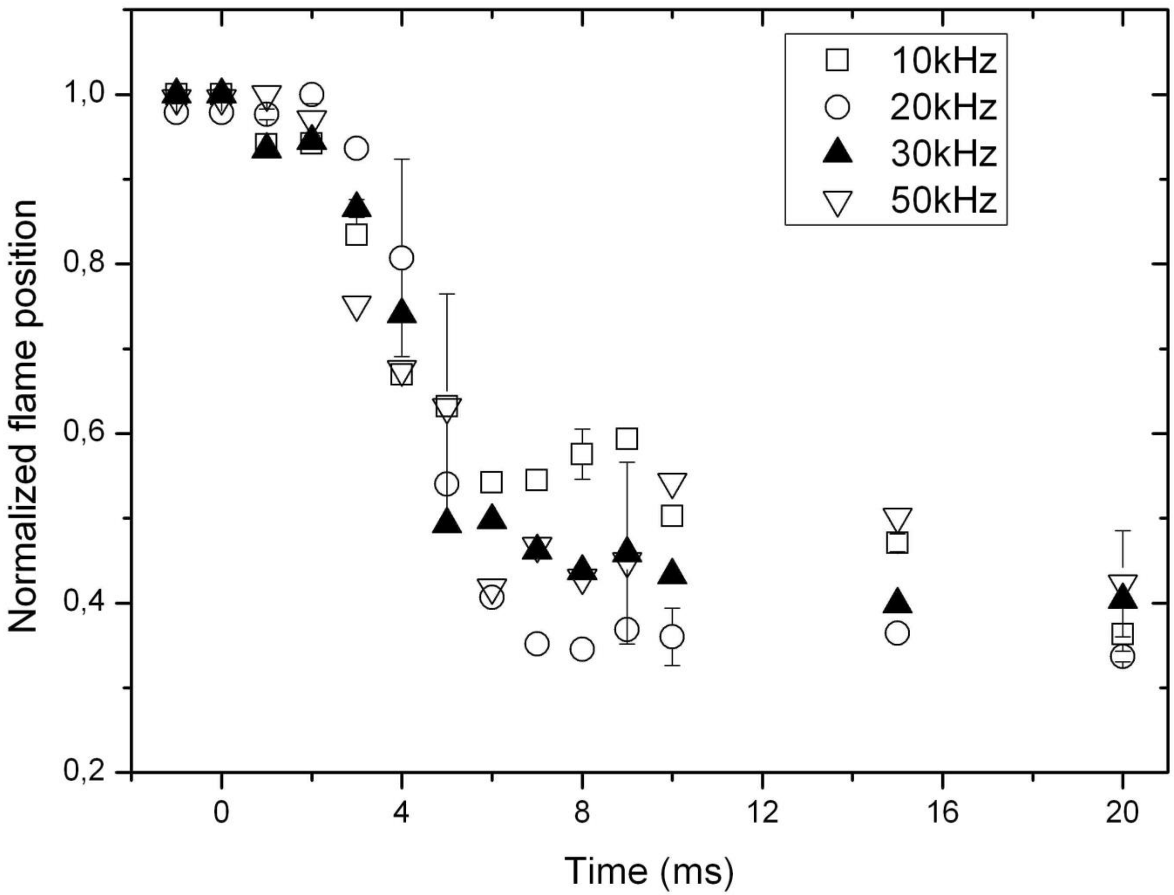
Lacoste, Xu, Moeck, Laux
Proc. Comb. Institute, 2013

Effect of pulse frequency on heating and O production at fixed discharge power = 12 W



- Heating increases with PRF
- O density decreases with PRF

Effect of pulse frequency on flame front evolution at fixed discharge power = 12 W



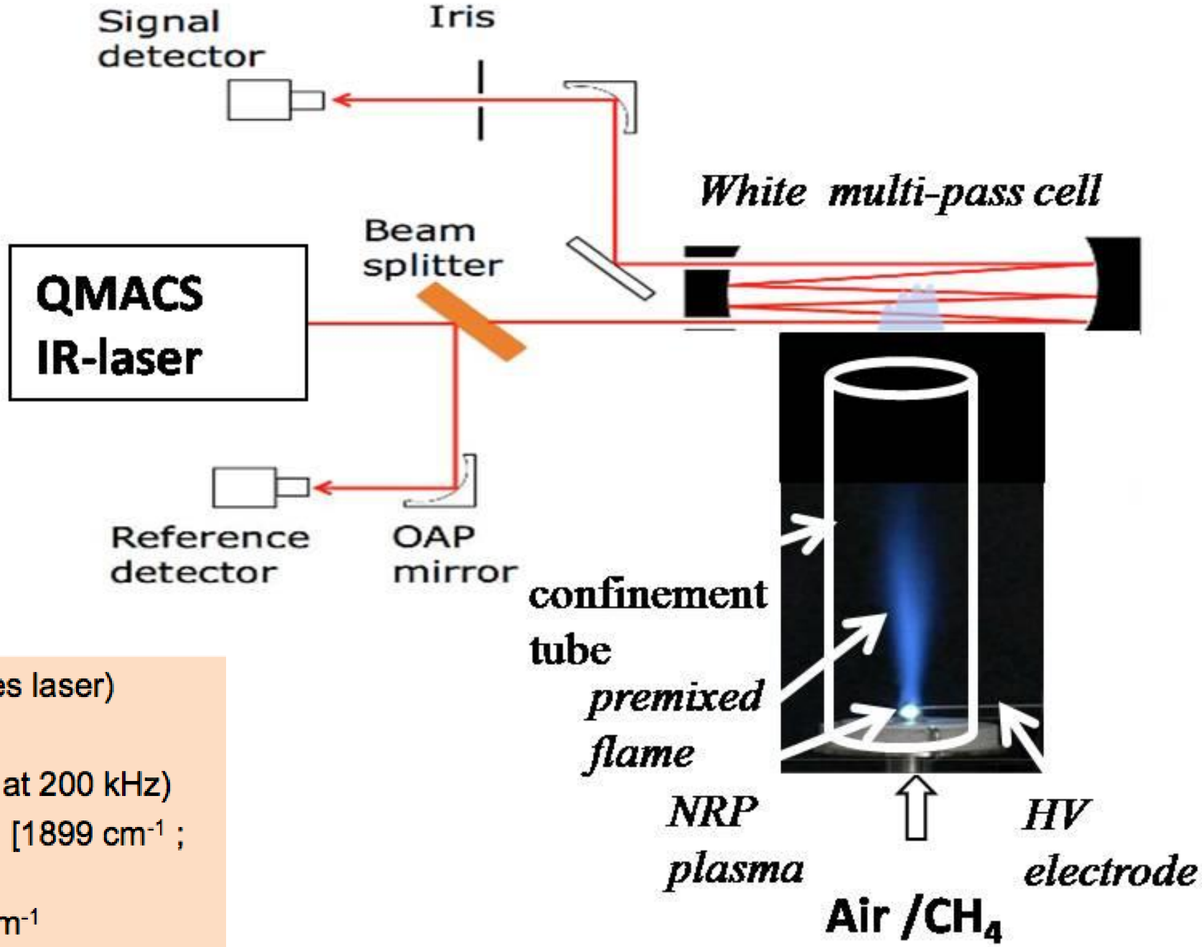
Thermal vs chemical effects

Pulse frequency	**10 kHz**	**80 kHz**
Average discharge power	12 W	12 W
Energy per pulse	1.2 mJ	0.15 mJ
Normalized O density at end of pulse	1	0.1
Temperature at end of pulse	2300 K	2600 K
Time to reattach flame	5 ms	5 ms

- Stabilization does not depend on whether the energy goes into heat or dissociation. It only depends on the TOTAL discharge power

NO measurements

Setup for NO measurements

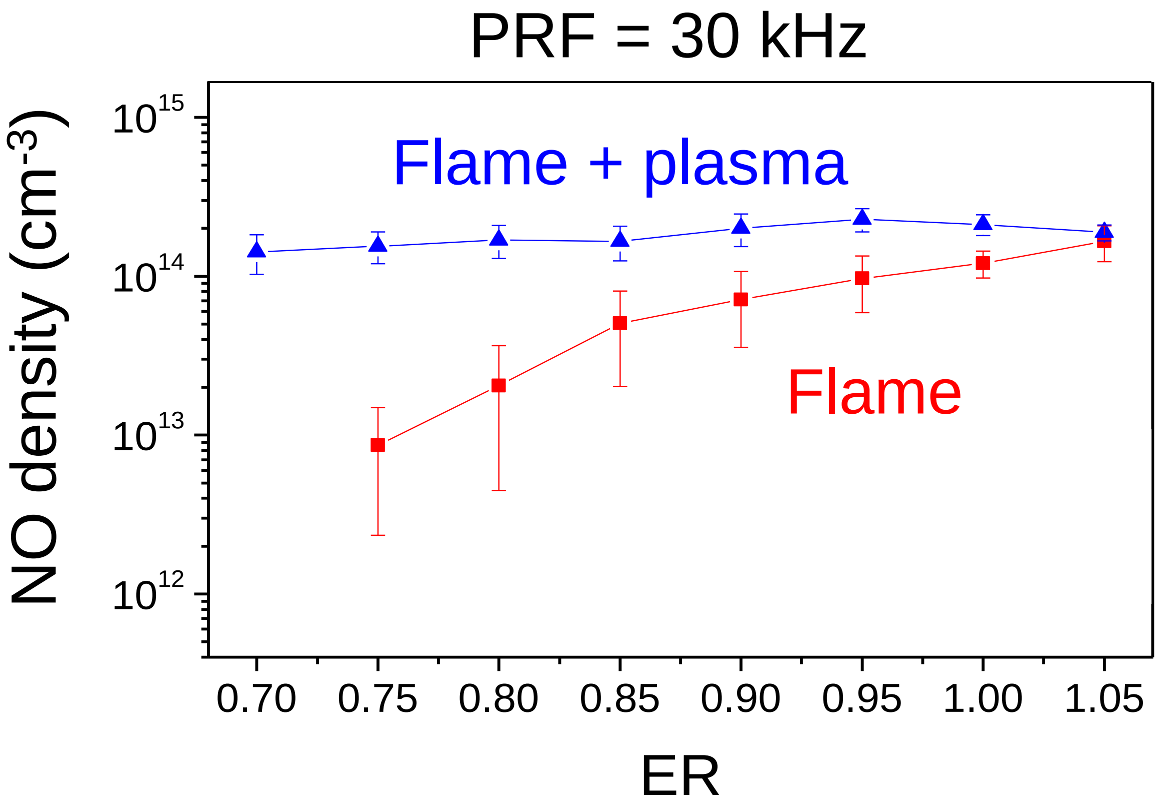


- Sb1770 DN model (Alpes laser)
- 2mW maximum power
- Interpulse (10 ns pulse, at 200 kHz)
- Spectral range: 10 cm^{-1}, [1899 cm^{-1} ; 1909 cm^{-1}]
- Spectral width: 0.006 cm^{-1}

$$(X_{1/2}, v = 0) \rightarrow (X_{1/2}, v = 1) \text{ R6.5 at } 1900.076 \text{ cm}^{-1}$$

Stancu, Simeni, Laux, ICPIG 2013

NO measurements in a premixed methane/air flame (mini-PAC)



Stancu, Simeni, Laux, ICPIG 2013

Conclusions

- NRP discharges can efficiently stabilize lean flames, with < 1% of flame power:
  - Mini-Pac: propane/air at 1 bar, 25 kW
  - Two-stage injector: propane/air at 1 bar, 52 kW
  - Aerodynamic injector: kerosene/air at 3 bar, 200 kW
  - Dynamic control of combustion instabilities

- Fundamental processes:
  - Complete reference test case for 2 D simulations of NRP discharge in pin-pin geometry
  - High temperature quenching rates for N_2 C and N_2 B
  - Chemical and thermal effects (ultrafast heating and O_2 dissociation) inducing production of OH. Appear to have equivalent impact on flame stailization

- Need to investigate
  - How to reduce NOx emissions
  - Higher pressure applications