

Numerical simulations of plasma assisted combustion

Yacine Bechane, Stéphane Q.E. Wang, Victorien Blanchard,
Nicolas Menesi, Boris Kruljevic, Jean-Baptiste Perrin-Terrin,
Nicolas Vaysse, Daniel Durox, Nasser Darabiha, Corine Lacour
Christophe O. Laux, Benoît Fiorina

EM2C – CNRS-UPR288, CentraleSupélec, Université Paris-Saclay
CORIA – CNRS-UMR6614, INSA Rouen, Normandie Univ.



Decarbonizing combustion

Development of new combustion systems based on low-carbon and carbon-free fuels

Hydrogen H_2

- Prevent CO_2 emissions
- Prevent *Soots* emissions
- Don't prevent NO_x emissions

Ammonia NH_3

- Prevent CO_2 emissions
- Prevent *Soots* emissions
- Don't prevent NO_x emissions

Sustainable aviation fuels (SAF)

- Reduce CO_2 emissions
- Reduce *Soots* emissions
- Don't prevent NO_x emissions



Fig: Hydrogen fueled aircraft engine

How Sustainable Aviation Fuel works

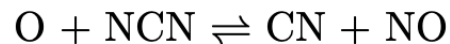
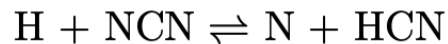
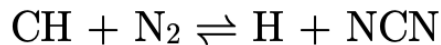


Nitrogen Dioxides (NO_x) emissions

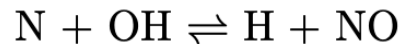
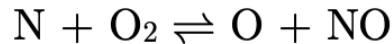
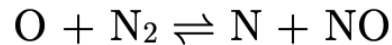
Nitrogen Dioxides (NO_x)

- Form at high temperature ($T > 1800 \text{ K}$)
- Global warming potential 300 times higher than CO_2

Prompt NO



Thermal NO



Limit NO_x emissions by maintaining a low flame temperature inside combustion chambers

Reduce flame temperature by operating at lean combustion regimes

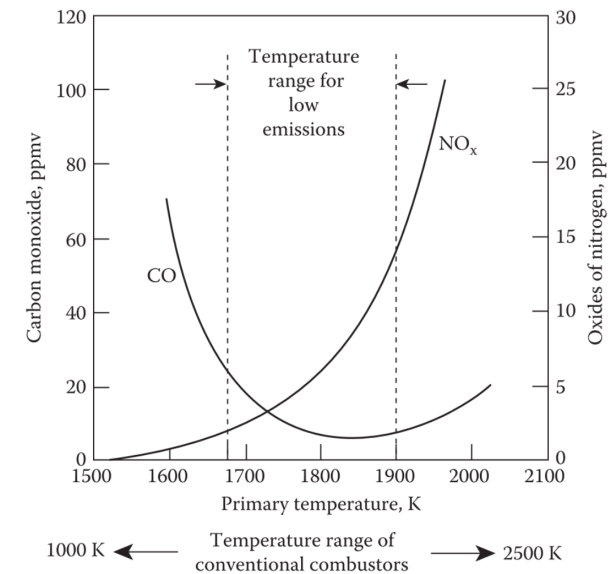


Fig: Influence of temperature on CO and Nox emissions [1]

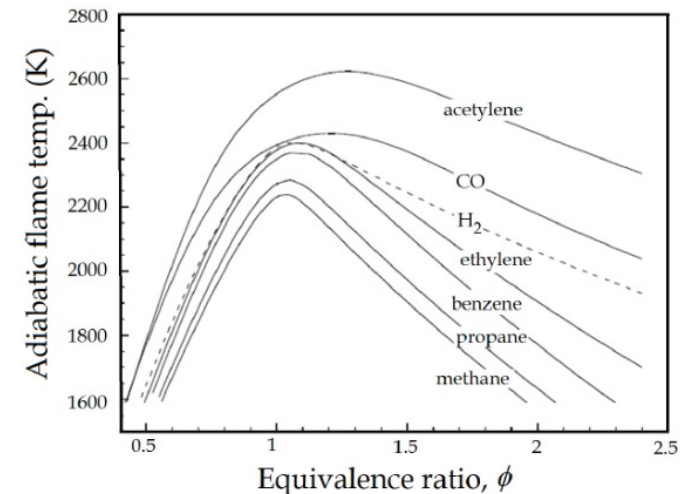


Fig: Adiabatic flame temperature as function of the equivalence ratio [2]

[1] Lefebvre & Ballal (2010)

[2] Law (2006)

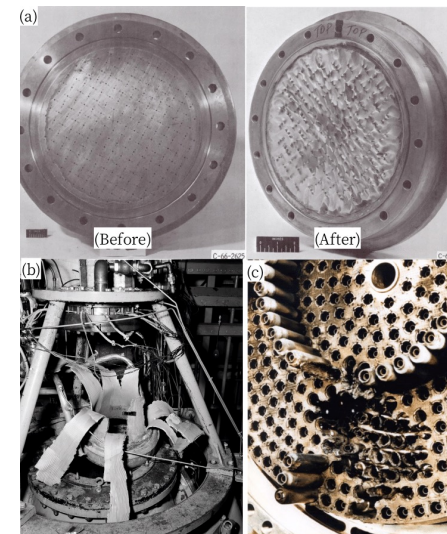
Lean combustion regimes

Drawbacks of lean combustion regimes:

- Ignition failures
- Incomplete combustion
- Flames instabilities (oscillation, blowout)



Fig: Damaged combustor [1].



Development of passive and active methods to enhance and control lean combustion

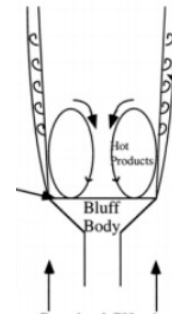
[1] T. LIEUWEN and V. Y. (Eds). Combustion Instabilities in Gas Turbine engines. Operationnal Experience, Fundamental mechanisms, and Modelling, volume 210. American Institute of Aeronautics and Astronautics, 2005.

Passive flame stabilization techniques

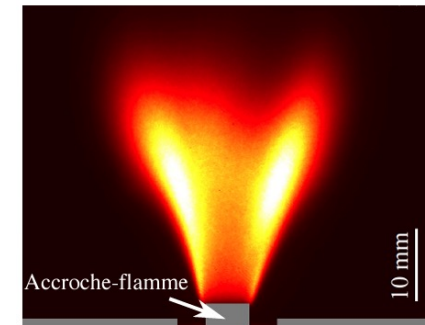
Passive control methods are based on geometrical modification of combustion chambers.

Bluff body

- Create a low velocity recirculation zone
- Enhance flame anchoring.



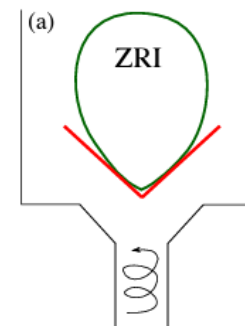
Flame stabilization by a bluff-body



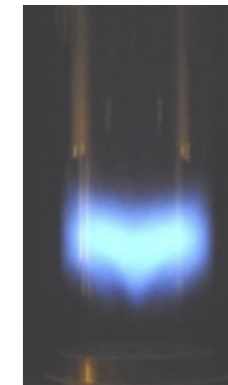
Flame stabilized on a bluff-body [1].

Swirler

- Create a low velocity zone
- Improve the mixing of reactants and recirculating products.



Flame stabilization by a swirler [2]



Swirled flame stabilized above the injector [3].

Trapped vortex combustor

Limits of passive methods:

- Flexibility
- Efficiency at very lean regimes

[1] T. Guiberti, Analysis of the topology of premixed swirl stabilized confined flames. Thesis (2015)

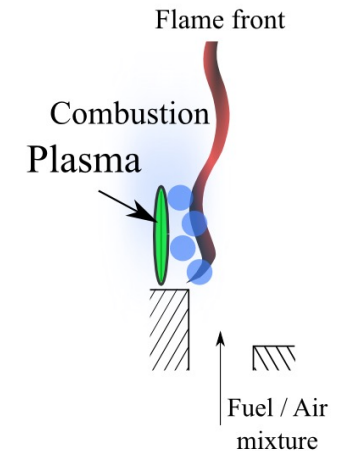
[2] P. Jourdain, Analyse des mécanismes de stabilisation d'oxy-flammes prémélangées swirlées. Thesis (2017)

[3] Durox et al (2013). Flame dynamics of a variable swirl number system and instability control. Combustion and Flame 160 (9), 1729–1742.

Active flame stabilization techniques

Plasma-assisted combustion

- Apply electrical discharges to generate a plasma
- Plasma initiates and enhances combustion through thermal, chemical and hydrodynamic effects



A variety of electric discharges

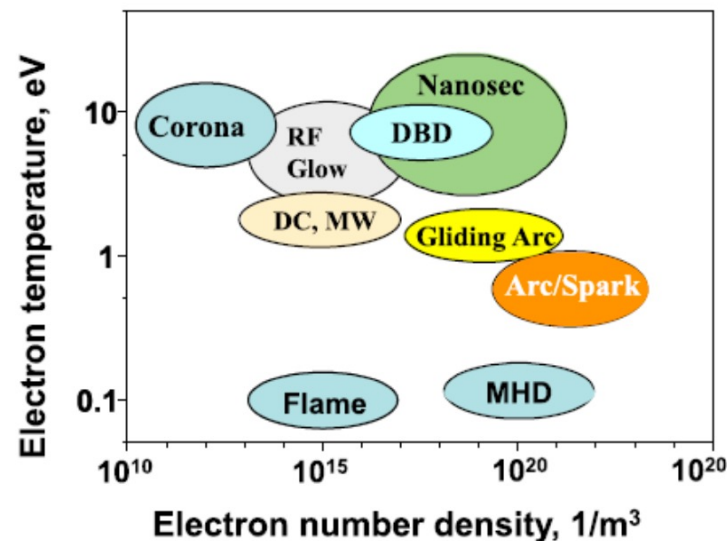


Fig : Schematic of electron temperature and number density for different discharges [1]

[1] Ju, Y. and W. Sun. Plasma assisted combustion: Dynamics and chemistry. Progress in Energy and Combustion Science 48, 21–83. (2015)

Flame ignition by plasma discharges

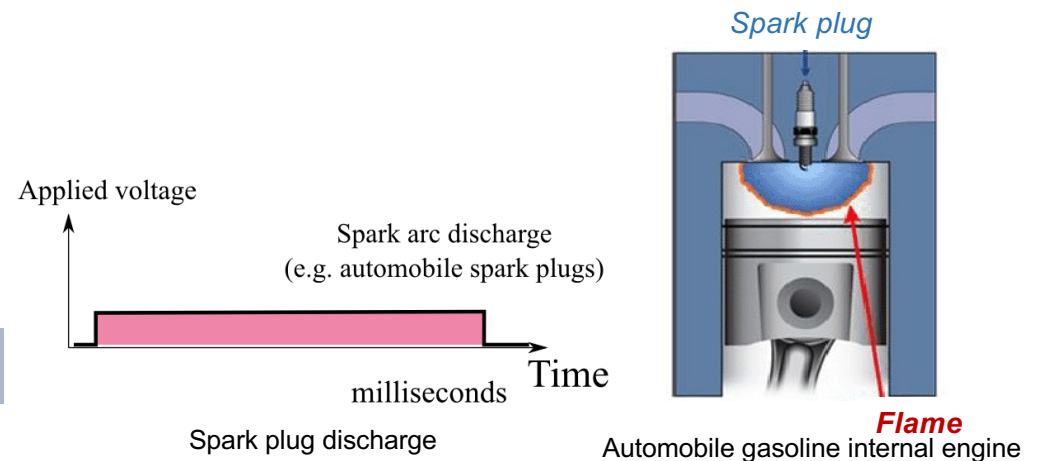
- Spark arc electric discharges

Ignite internal and aircraft combustion engine

Initiate combustion via thermal effect

High temperatures
(10 000 to 50 000 K)

High energy consumption



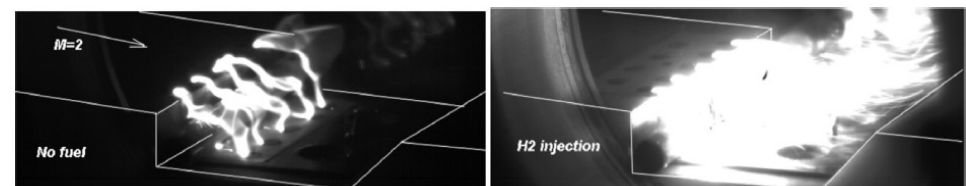
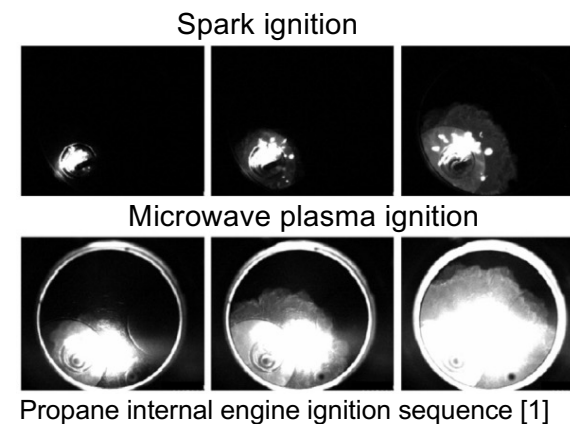
- Microwave discharges

- Ignition of lean internal combustion engine

- Gliding arc discharges

- Ignition of supersonic reactive flows

- Reduce the ignition delay time
- Extend the ignition limit
- Consume less energy

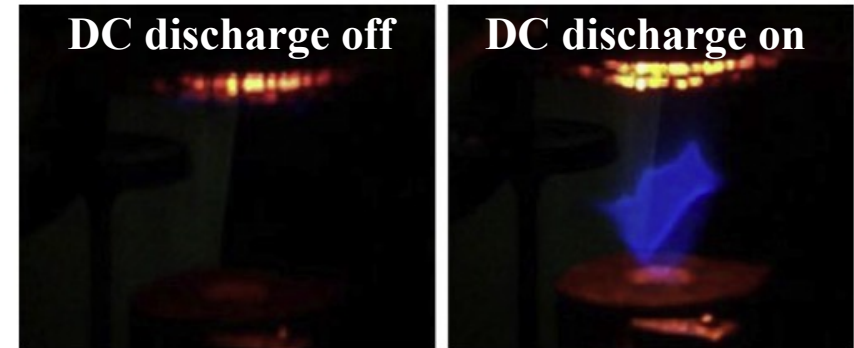


[1] Ikeda Y, Nishiyama A, Kaneko M. In: 47th AIAA-2009-223.

[2] Leonov et al (2006) Plasma-assisted ignition and flameholding in high-speed flow. In: 44th AIAA-2006-563.

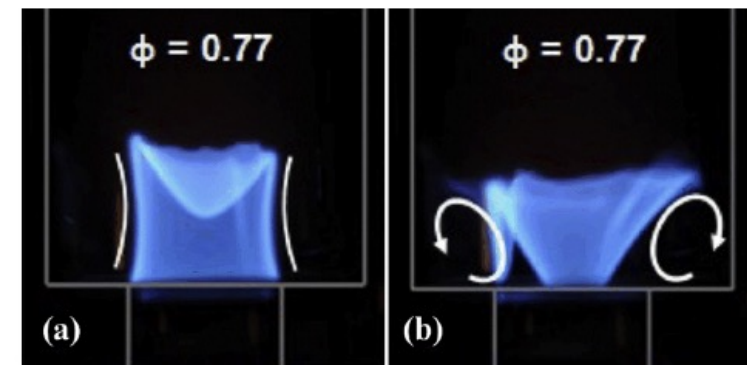
Flame stabilization by plasma discharges

- Direct-current (DC) discharges
 - Flame stabilization via chemical effects



Lean propane-air flame. (left) DC discharge off, (right) DC discharge on. [1]

- Dielectric-barrier discharge (DBD)
 - Flame stabilization via hydrodynamic effects



Direct photographs of CH₄/air flames (a) without and (b) with DBD discharge [2]

- Improve flame stability
- Extend lean Blow-Off limit (LBO)

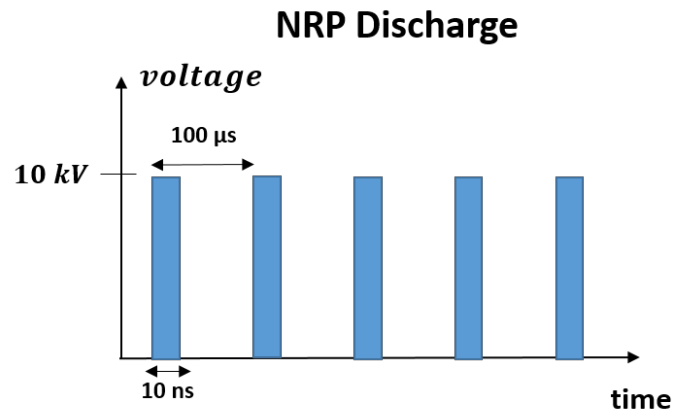
[1] Ganguly BN. Hydrocarbon combustion enhancement by applied electric field and plasma kinetics. Plasma Phys Control Fusion (2007) ;49:B239.

[2] Versailles P, Chishty WA, Vo HD. Application of dielectric barrier discharge to improve the flashback limit of a lean premixed dump combustor. J Eng GasTurbines Power (2012)

NRP discharges

Nanosecond Repetitively-Pulsed (NRP) discharges

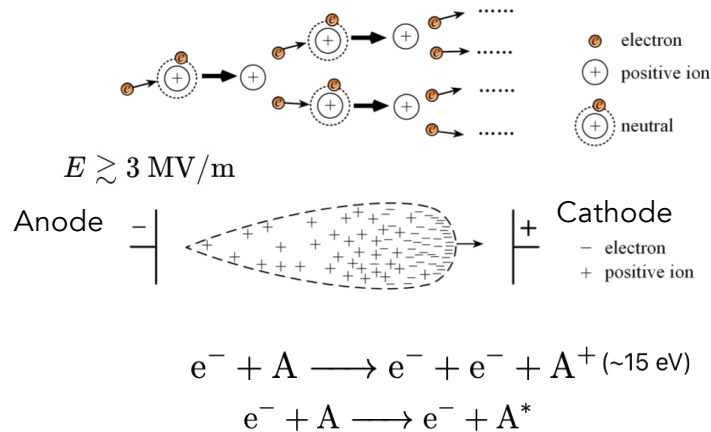
- High voltage pulses of few nanoseconds
- Pulse applied repetitively at high frequencies



Schematic representation of NRP discharges voltage

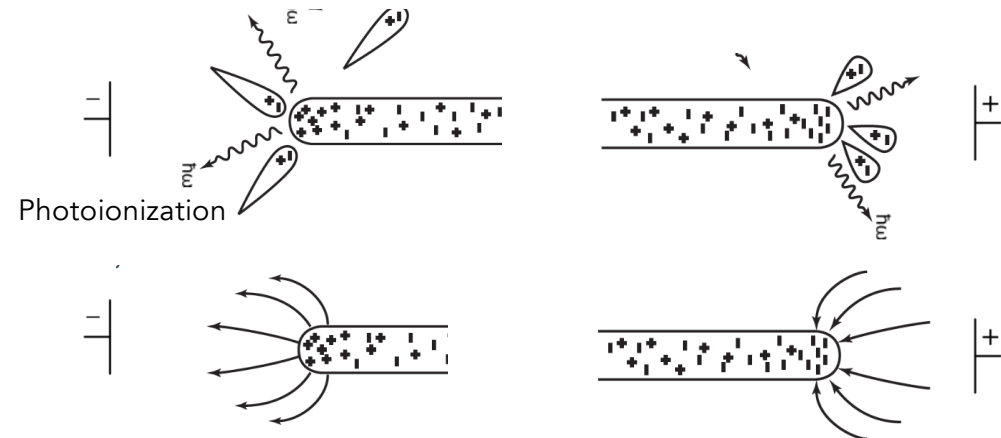
Electric arc formation

I. Electron avalanche



- Electrodes induced electric field

II. Streamers



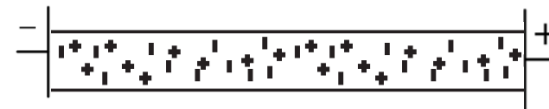
- Space charge induced electric field
- Charges velocity (10^5 - 10^6 m/s)
- Low electric current – Low conductivity - Low gas temperature

III. Breakdown



- Multiple streamers merge
- An electrical path between the anode and cathode is created
- Increase of electric current, conductivity and temperature

IV. arc



- High electric current – High conductivity - High gas temperature
- Fully ionized gas

The emergence of NRP discharges

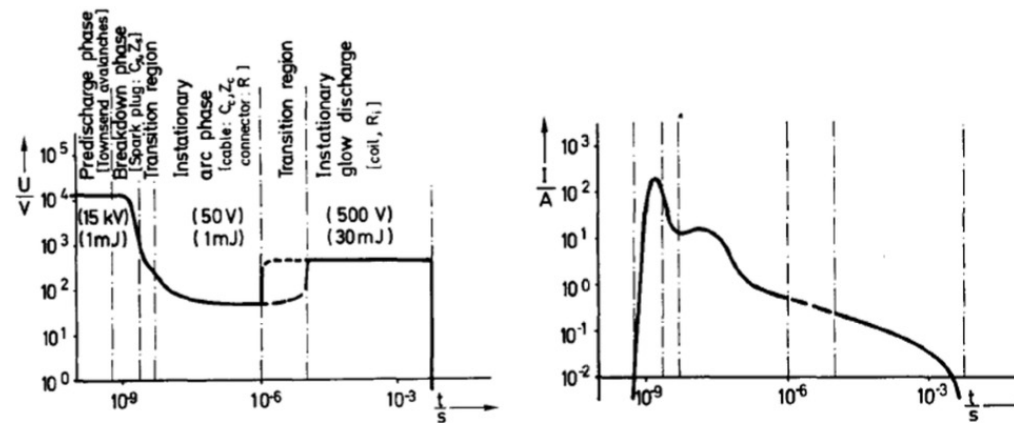


Fig: (a) Diagram of voltage, (b) current during ignition, indicating steps of ignition [1]

Pre-breakdown phase

$t \approx 1e-9s$

- Streamers propagation
- Non-equilibrium plasma ($T_e(10000K), T_h(1000K)$)
- Partially ionized molecules
- Strong molecular excitation

1% discharge energy

Breakdown phase

$t \approx 1e-8s$

- Bridged gap
- Transition to equilibrium plasma ($T_e = T_h = 60000K$)
- Fully dissociated and ionized molecules (endothermic process)
- Strong shock wave

2% discharge energy

Arc phase

$t \approx 1e-6s$

- electric current
- ionized gas cools down
- Ions – electrons recombination
- Joule effect
- Gases radiation

3% discharge energy

Glow phase

$t \approx 1e-3s$

- Heating of the hot burnt gases
- Gases radiation

94% discharge energy

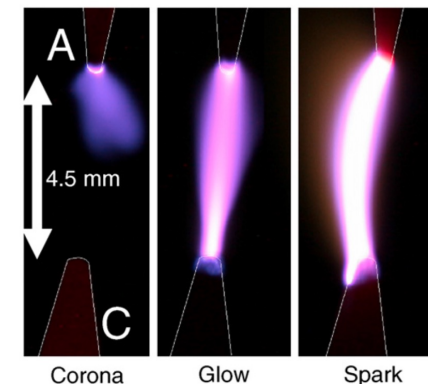
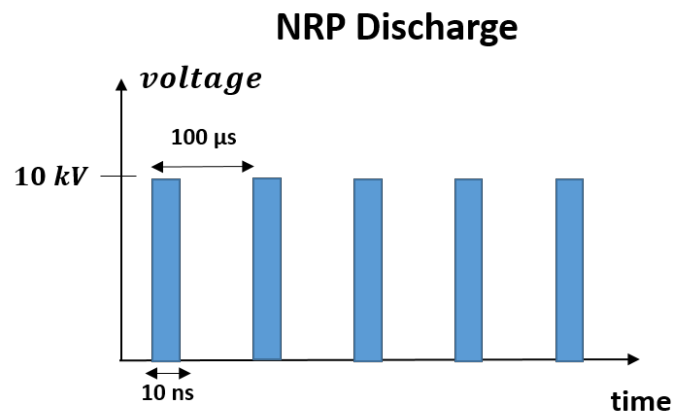
Energy efficiencies of spark ignition is around 10% to 30%

[1] Maly and Vogel (1979)

NRP discharges

Nanosecond Repetitively-Pulsed (NRP) discharges

- High voltage pulses of few nanoseconds
- Pulse applied repetitively at high frequencies



Digital camera images of NRP discharges corona, glow and spark regimes in air
1 atm air at 1000K and PRF of 10 kHz. 5kV, 5,5 kV and 6 kV

Corona regime

- small pulse energy $\leq 1 \mu\text{J}$
- light emission

Glow regime

- pulse energy $\leq 100\mu\text{J}$
- small gas heating
- active species production

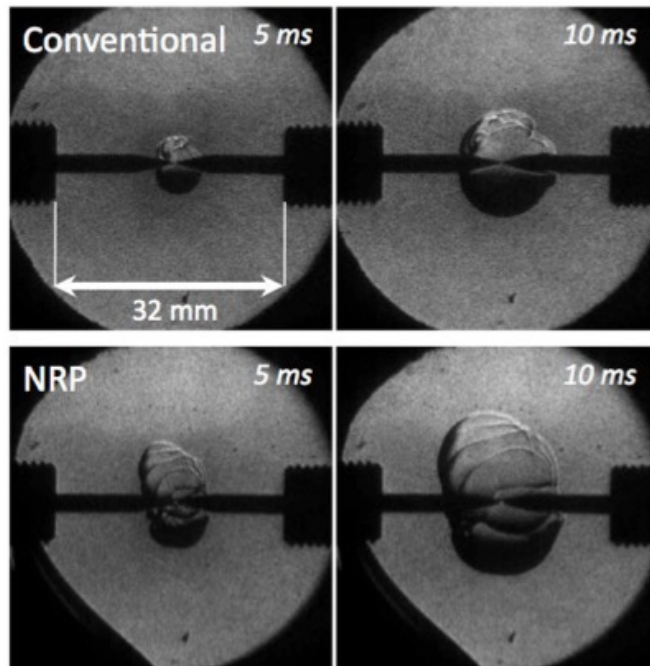
Spark regime

- pulse energy $\approx m\text{J}$
- moderate gas heating
- important active species production

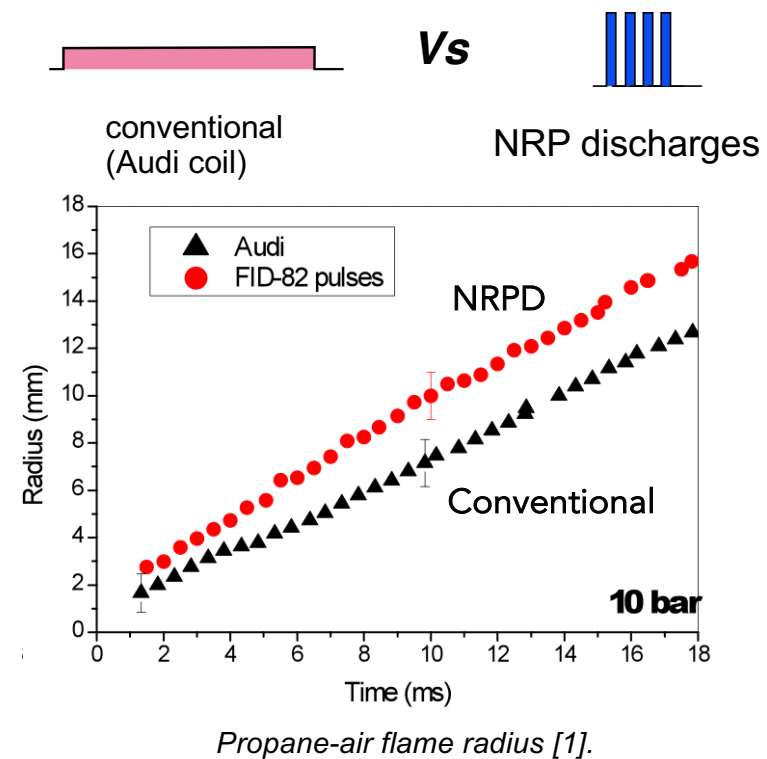
Flame ignition by NRP discharges

Plasma-assisted ignition of lean propane-air mixtures

Two different Ignition system



Same deposited energy



Ignition kernel propagates about 18% faster when mixture is ignited by NRP discharges

[1] Xu, Lacoste, Laux. Plasma Chemistry and Plasma Processing Vol.36 (1) (2016)

Flame stabilization by NRP discharges

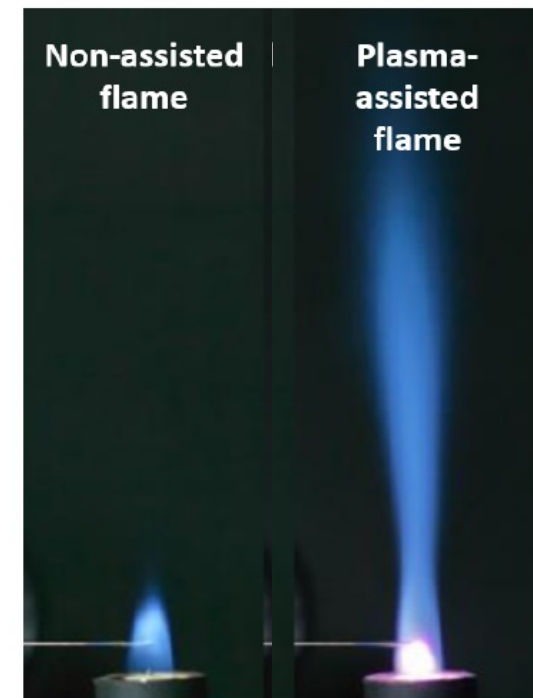
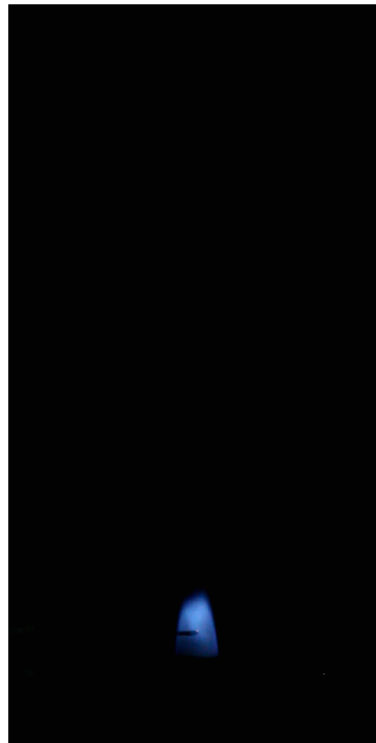
Plasma-assisted methane-air flame stabilization

Premixed CH₄-air flame

- $\phi = 0.8$

Discharge:

- duration: 10 ns
- voltage: 6.8 kV
- energy: 2.0 mJ
- frequency: 20 kHz
- gap: 5 mm
- $\frac{P_{elec}}{P_{flame}} = 0.3 \%$

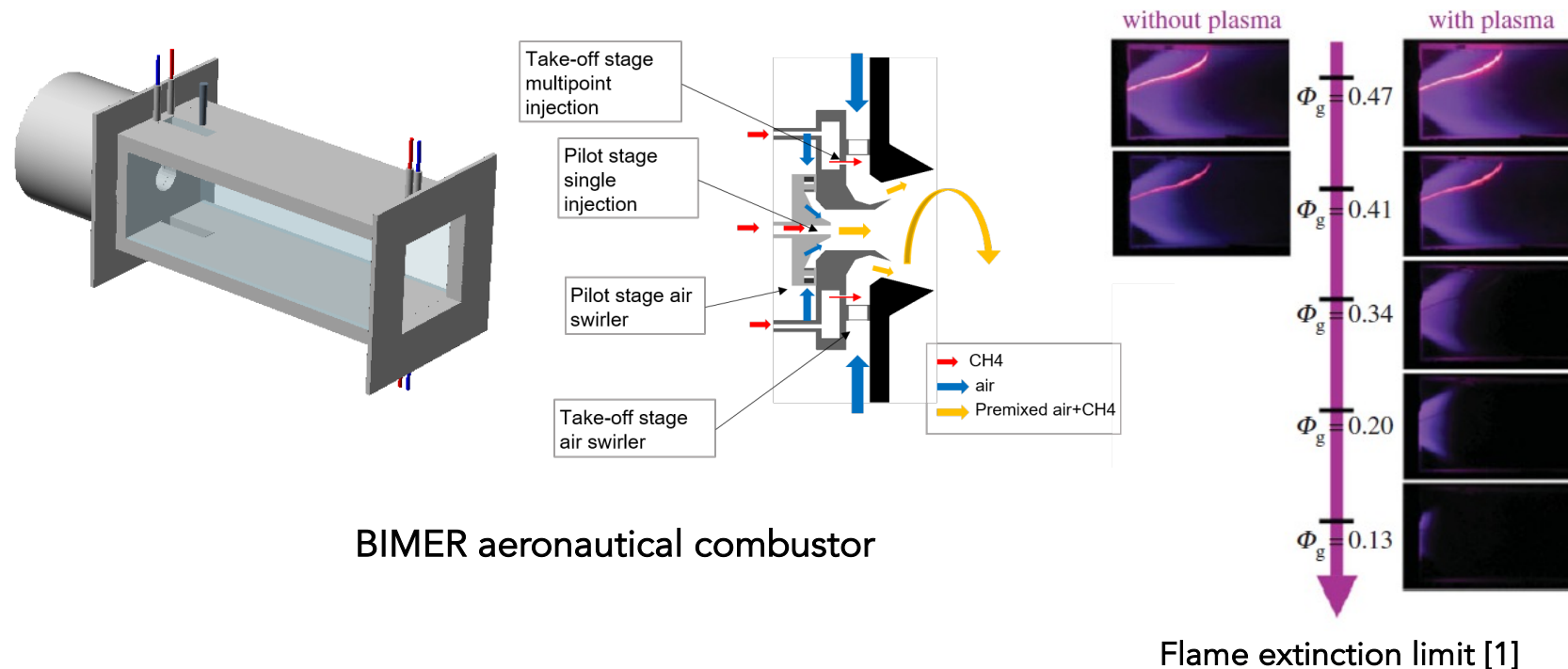


Photographs of the lean flame ($\phi = 0.8$) without (left) and with (right) NRP discharges applied at 20 kHz.

[1] G. Pilla, D. Galley, D A. Lacoste, F. Lacas, D. Veynante and C O. Laux IEEE TRANSACTIONS ON PLASMA SCIENCE 2006

Flame stabilization by NRP discharges

Plasma-assisted extension of Lean Blow Off (LBO) limit



An important increase of flame stability domain was obtained with NRP discharge

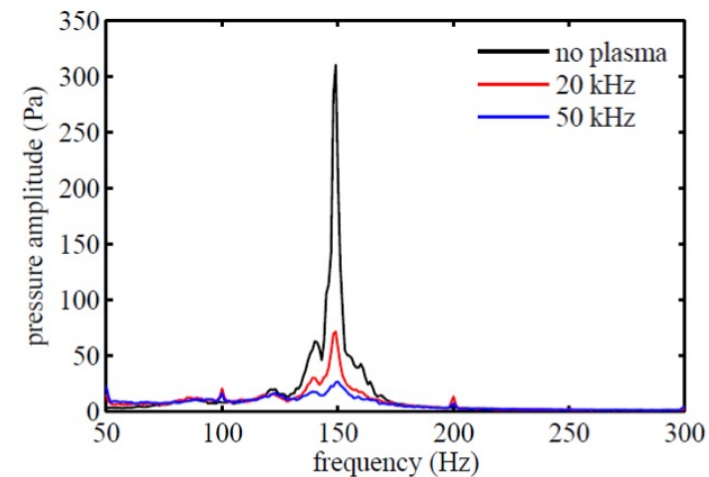
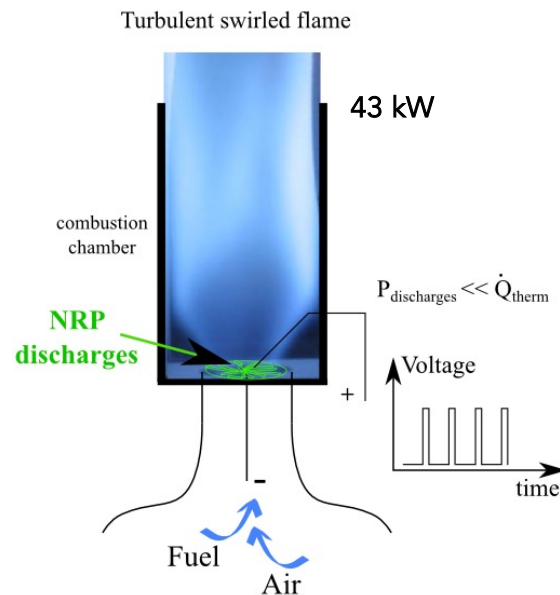
[1] S. Barbosa, G. Pilla, D. Lacoste, P. Scoufflaire, S. Ducruix, C. Laux & D. Veynante Philosophical transactions A, 2015

Flame stabilization by NRP discharges

Plasma-assisted dynamic control of thermo-acoustic instabilities

NRP discharges

- Pulse duration 10 ns
- Pulse repetition frequency 10 - 50 kHz



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

Important decrease of thermo-acoustic instabilities with NRP discharges

[1] Lacoste, Moeck, Durox, Laux, Schuller. Effect of Nanosecond Repetively Pulsed Discharges on the Dynamics of a Swirl-Stabilized Lean Premixed Flame. J. Eng. Gas Turbines Power (2013)

Experiments of Plasma assisted combustion

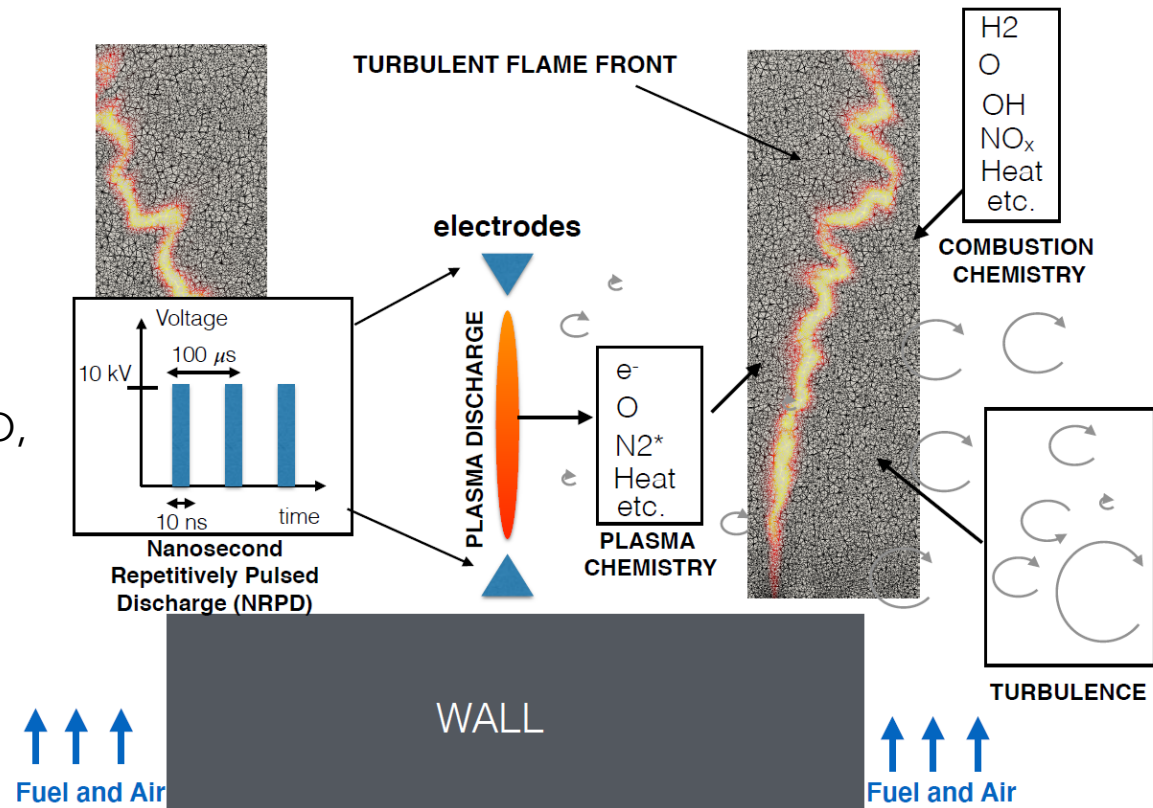
Low NRP discharge power < 1%

Experiment	MiniPac Pilla 2008	Multi-point Barbosa 2015	Mercato Heid 2008	EM2C/TU Berlin Moeck 2015	FGC/NASA 2016
Type of burner	Bluff-body	Swirled	DEM21 mechanical injector	Swirled	7-LDI
Gas mixture	Methane/air Propane/air	Propane/air	Kerosene (L) Air (150°C)	Natural gas/air $\phi = 0.66$	Methane/air (0.6)
Pressure	1 bar	1 bar	3 bar	1 bar	1 bar
Thermal power (Q_{th})	11 kW	52 kW	50 kW	43 kW	20 kW
Plasma power (P_{plasma})	70 W	350 W	Max 500 W	315 W @50 kHz	< 200 W
P_{plasma}/Q_{th}	0.6%	0.7%	1.5%	0.7%	<1%
Pulser frequency	30 kHz	30 kHz	30 kHz	10-50 kHz	?
Result	LBO reduced by ~10%	LBO: 0.47→0.11 (global)	LBO: 0.44→0.21	Elimination of thermoacoustic instabilities	Elimination of thermoacoustic instabilities

NRP discharges effects on combustion

NRP discharges effects

- **Thermal effect** : moderate increase of the temperature (1000 to 3000 K)
- **Chemical effects** : production of highly reactive chemical species (O, OH,...)



Plasma-flame interaction mechanisms ?

Plasma assisted combustion

- Through what mechanisms do the thermal and chemical effects of NRP discharges affect combustion?
- What set of parameters ensures optimal efficiency of NRP discharges? (electrode position, pulse repetition frequency, pulse energy)
- What tool can researchers or engineers specializing in combustion use to evaluate the performance of NRP discharges in practical combustion systems?

Numerical simulations required to design plasma-assisted reactive systems

Outline

- I. General context
- II. Numerical modeling of plasma-assisted combustion
- III. Numerical simulations of flames ignition by NRP discharges
- IV. Numerical simulations of flame stabilization by NRP discharges
- V. New modelling

Numerical modeling of plasma-assisted combustion

Governing equation

Plasma discharge



Drift-Diffusion equations

$$\begin{aligned}\partial_t n_e + \vec{\nabla} \cdot (n_e \vec{v}_e - D_e \vec{\nabla} n_e) &= S_e + S_{ph} \\ \partial_t n_n + \vec{\nabla} \cdot (n_n \vec{v}_n - D_n \vec{\nabla} n_n) &= S_n \\ \partial_t n_p + \vec{\nabla} \cdot (n_p \vec{v}_p - D_p \vec{\nabla} n_p) &= S_p + S_{ph} \\ \nabla^2 V &= -\frac{q_e}{\epsilon_0} (n_p - n_n - n_e) \\ \vec{E} &= -\vec{\nabla} V \\ \vec{v}_i &= \mu_i \vec{E}\end{aligned}$$

Combustion



Navier-Stokes equations

$$\begin{aligned}\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_i)}{\partial x_i} &= 0 \\ \frac{\partial(\rho u_j)}{\partial t} + \frac{\partial(\rho u_i u_j)}{\partial x_i} &= -\frac{\partial p}{\partial x_j} + \frac{\partial \tau_{ij}}{\partial x_i} \\ \frac{\partial(\rho e)}{\partial t} + \frac{\partial(\rho u_i e)}{\partial x_i} &= -\frac{\partial q_i}{\partial x_i} + \frac{\partial(\sigma_{ij} u_i)}{\partial x_i} \\ \frac{\partial(\rho Y_k)}{\partial t} + \frac{\partial(\rho u_i Y_k)}{\partial x_i} &= -\frac{\partial(\rho V_{k,i} Y_k)}{\partial x_i} + W_k \dot{\omega}_k^c\end{aligned}$$

Plasma/combustion chemistry

Governing equation

Plasma chemistry

(3.10)	$e + O_2 \rightarrow e + O_2(^1\Delta_g)$	σ	[50]
(3.11)	$e + O_2 \rightarrow e + O_2(^1\Sigma_g^+)$	σ	[50]
(3.12)	$e + O_2 \rightarrow e + O_2(4.5 \text{ eV})$	σ	[50]
(3.13)	$e + He \rightarrow e + He(2s^1S)$	σ	[51]
electron impact dissociative excitation			
(3.14)	$e + O_2$		
(3.15)	$e + O_2$		
(3.16)	$e + O_2$		
(3.17)	$e + CH_4$		
(3.18)	$e + CH_4$		
(3.19)	$e + CH_4$		
(3.20)	$e + CH_4$		
electron ionization			
(3.21)	$e + O_2$		
(3.22)	$e + He$		
(3.23)	$e + CH_4$		
(3.24)	$e + CH_4$		
quenching			
(3.25)	$O_2(^1\Delta_g)$		
(3.26)	$O_2(^1\Delta_g)$		
(3.27)	$O_2(^1\Sigma_g^+)$		
(3.28)	$O_2(4.5 \text{ eV})$		
(3.29)	$O_2(^1\Delta_g)$		
(3.30)	$O_2(^1\Sigma_g^+)$		
(3.31)	$O_2(4.5 \text{ eV})$		
(3.32)	$O_2(4.5 \text{ eV})$		
(3.33)	$O_2(^1\Delta_g)$		
(3.34)	$O_2(^1\Delta_g)$		
(3.35)	$O_2(^1\Delta_g)$		
(3.36)	$O_2(^1\Delta_g)$		
(3.37)	$O_2(^1\Delta_g)$		
(3.38)	$O_2(^1\Delta_g)$		
(3.39)	$O_2(^1\Sigma_g^+)$		
(3.40)	$O_2(^1\Sigma_g^+)$		
(3.41)	$O_2(^1\Sigma_g^+)$		
(3.42)	$O_2(^1\Sigma_g^+)$		
(3.43)	$O_2(4.5 \text{ eV})$		
(3.44)	$O_2(4.5 \text{ eV})$		
(3.45)	$O(^1D) + CH_4 \rightarrow CH_3 + OH$	1.13×10^{-10}	[60]
(3.46)	$O(^1D) + CH_4 \rightarrow CH_3OH + H$	3.00×10^{-11}	[60]
(3.47)	$O(^1D) + CH_4 \rightarrow CH_3O + H_2$	7.50×10^{-12}	[60]
(3.48)	$O(^1D) + He \rightarrow O + He$	1.00×10^{-13}	[49]
(3.49)	$O(^1D) + O \rightarrow O + O$	8.00×10^{-12}	[48]
(3.50)	$O(^1D) + O_2 \rightarrow O + O_2$	$6.40 \times 10^{-12} \exp(67/T)$	[48]
(3.51)	$O(^1D) +$		
(3.52)	$O(^1D) +$		
(3.53)	$O(^1D) +$		
(3.54)	$O(^1D) +$		
(3.55)	$O(^1S) +$		
(3.56)	$O(^1S) +$		
(3.57)	$O(^1S) +$		
(3.58)	$O(^1S) +$		
(3.59)	$O(^1S) +$		
(3.60)	$O(^1S) +$		
(3.61)	$O(^1S) +$		
(3.62)	$O(^1S) +$		
quenching			
(3.63)	$He(2s^1S)$		
(3.64)	$He(2s^1S)$		
(3.65)	$He(2s^1S)$		
(3.66)	$He(2s^1S)$		
(3.67)	$He(2s^1S)$		
(3.68)	$He(2s^1S)$		
(3.69)	$He(2s^1S)$		
(3.70)	$He(2s^1S)$		
(3.71)	$He(2s^1S)$		
(3.72)	$He(2s^1S)$		
(3.73)	$He(2s^1S)$		
electron-ionization			
(3.74)	$e + O_2^+$		
(3.75)	$e + O_2^+$		
(3.76)	$e + O_2^+$		
(3.77)	$e + O_2^+$		
(3.78)	$e + O^+$		
(3.79)	$e + O^+$		
(3.80)	$e + He^+$		
(3.81)	$e + e + He^+ \rightarrow He(2s^1S) + e$	$5.12 \times 10^{-10} T_e^{-4.5}$	[49]
(3.82)	$e + CH_4^+ \rightarrow CH_3 + H + H$	$1.70 \times 10^{-7} (300/T_e)^{0.5}$	[63]
(3.83)	$e + CH_4^+ \rightarrow CH_3 + H$	$1.70 \times 10^{-7} (300/T_e)^{0.5}$	[63]
(3.84)	$e + CH_3^+ \rightarrow CH_3 + H$	$3.50 \times 10^{-9} (300/T_e)^{0.5}$	[63]
(3.85)	$e + CH_2^+ \rightarrow CH + H$	$2.50 \times 10^{-7} (300/T_e)^{0.5}$	[63]
charge exchange			
(3.86)	$O^+ + O_2 \rightarrow O_2^+ + O$	$2.00 \times 10^{-11} (300/T_e)^{0.5}$	[48]
(3.87)	$O^+ + O_3 \rightarrow O_3^+ + O_2$	1.00×10^{-10}	[48]
(3.88)	$He^+ + O_2 \rightarrow O^+ + O + He$	$1.07 \times 10^{-9} (7/300)^{0.5}$	[49]
(3.89)	$He^+ + O_3 \rightarrow O^+ + O_2 + He$	$1.07 \times 10^{-9} (7/300)^{0.5}$	[49]
(3.90)	$He^+ + O_2 \rightarrow O_2^+ + He$	$3.30 \times 10^{-11} (7/300)^{0.5}$	[49]
(3.91)	$He^+ + O_2(^1\Sigma_g^+) \rightarrow O^+ + O + He$	$1.07 \times 10^{-9} (7/300)^{0.5}$	[49]
(3.92)	$He^+ + O_2(^1\Sigma_g^+) \rightarrow O_2^+ + He$	$3.30 \times 10^{-11} (7/300)^{0.5}$	[49]
(3.93)	$He^+ + O \rightarrow O^+ + He$	$5.00 \times 10^{-11} (7/300)^{0.5}$	[49]
(3.94)	$He^+ + O(^1D) \rightarrow O^+ + He$	$5.00 \times 10^{-11} (7/300)^{0.5}$	[49]
(3.95)	$He^+ + O(^1S) \rightarrow O^+ + He$	$5.00 \times 10^{-11} (7/300)^{0.5}$	[49]
(3.96)	$CH_4^+ + O_2 \rightarrow CH_4 + O_2^+$	5.00×10^{-10}	[4]
optical transitions and pre-dissociation			
(3.97)	$O_2(^1\Delta_g) \rightarrow O_2$	2.60×10^{-4}	[48]
(3.98)	$O_2(^1\Sigma_g^+) \rightarrow O_2(^1\Delta_g)$	1.50×10^{-3}	[48]
(3.99)	$O_2(^1\Sigma_g^+) \rightarrow O_2$	8.50×10^{-2}	[48]
(3.100)	$O_2(4.5 \text{ eV}) \rightarrow O_2$	1.10×10^1	[48]
O_3 reactions			
(3.101)	$O_3 + O_2 \rightarrow O_3 + O + O_2$	$2.51 \times 10^{-10} \exp(-11600/T)$	[48]
(3.102)	$O_3 + O \rightarrow O_2 + O + O$	$4.15 \times 10^{-10} \exp(-11430/T)$	[48]
(3.103)	$O_3 + O \rightarrow O_2 + O_2(^1\Delta_g)$	$1.00 \times 10^{-11} \exp(-2300/T)$	[48]
(3.104)	$O + O_2 + O_2 \rightarrow O_3 + O_2$	$7.60 \times 10^{-34} (300/T)^{1.9}$	[48]
(3.105)	$O + O_2 + O \rightarrow O_3 + O$	$3.90 \times 10^{-23} (300/T)^{1.9}$	[48]
(3.106)	$O + O_2 + He \rightarrow O_3 + He$	$3.40 \times 10^{-34} (300/T)^{1.2}$	[49]

Combustion chemistry

REACTIONS
20+M=>O2+M 1.200E+17 -1.000 .00
H2/ 2.40/ H2O/15.40/ CH4/ 2.00/ CO/ 1.75/ CO2/ 3.60/ C2H6/ 3.00/ AR/ .83/
O+H+M=>OH+M 5.000E+17 -1.000 .00
H2/2.00/ H2O/6.00/ CH4/2.00/ CO/1.50/ CO2/2.00/ C2H6/3.00/ AR/ .70/
O+H2=>H+OH 3.870E+04 2.700 6260.00
OH2O2=>OH+OH2 3.800E+13 .000 .00
O+H2O2=>OH+H2O 3.800E+13 .000 .00
O+CH=>H+CO H2/2.00/ H2O/6.00/ CH4/2.00/ CO/1.50/ CO2/2.00/ C2H6/3.00/ AR/ .70/
O+CH2=>H+HCO H+CH2(S)=>CH+H2 H+CH2C(=O)=>CH2S+H2 1.150E+08 1.900 7530.00
O+CH2=>H+HCO H+CH3(=M)=>CH4(=M) H+HCCO=>CH2(S)+CO 1.000E+14 .000 .00
O+CH2(S)=>H2 LOW / 2.620 H+CH2CO=>HCCO+H2 5.000E+13 .000 8000.00
O+CH2(S)=>H2 TROE/ .7830 H+CH2CO=>CH3+CO 1.130E+13 .000 3428.00
O+CH3=>H+H2 H2/2.00/ H2O/6.00/ H+CHCOH=>H+CH2CO 1.000E+13 .000 .00
O+CH4=>OH+CH2 H+HCO(=M)=>CH2O(=M) H2+CO(=M)=>CH2O(=M) 4.300E+07 1.500 79600.00
O+CH4(=M)=>CO LOW / 2.470 LOW / 5.070E+27 -3.420 84350.00
LOW / 6.020 TROE/ .7824 TROE/ .8320 197.00 1540.00 1030.00 /
H2/2.00/ O2/6.00/ H2/2.00/ H2O/6.00/ CH4/2.00/ CO/1.50/ CO2/2.00/ C2H6/3.00/ AR/ .70/
H+HCO=>H2+CO OH+H2O=>H2O H2+CO(=M)=>H2O2(=M) 2.160E+08 1.510 3430.00
H+CH2O(=M)=>CH2OH(=M) 2OH(=M)=>H2O2(=M) 7.400E+13 -370 .00
O+HCO=>H+CO2 LOW / 1.270 LOW / 2.300E+18 -9.900 -1700.00/
O+CH2O=>OH+H2 TROE/ .7187 TROE/ .7346 94.00 1756.00 5182.00 /
O+CH2OH=>OH+H2O H2/2.00/ H2O/6.00/ CH4/2.00/ CO/1.50/ CO2/2.00/ C2H6/3.00/ AR/ .70/
O+CH2OH=>OH+H2O H+CH2O(=M)=>CH3O H+CO=>O+H2O 3.570E+04 2.400 -2110.00
O+CH3O=>OH+H2 H+CH2O(=M)=>CH3O OH+H2O2=>O2+H2O 1.450E+13 .000 -500.00
O+CH3OH=>OH+H2 TROE/ .7590 DUPLICATE
O+CH3OH=>OH+H2O OH+H2O2=>H2O2+H2O 2.000E+12 .000 427.00
O+C2H=>CH+CO H2/2.00/ H2O/6.00/ H+CH2CO=>HCO+H2 DUPLICATE
O+C2H2=>H+H2C H+CH2OH(=M)=>CH3O OH+H2O2=>H2O2+H2O 1.700E+18 .000 29410.00
O+C2H2=>H+H2C LOW / 4.363 DUPLICATE
O+C2H2=>H+H2C TROE/ .6000 OH+CO=>H+CO 5.000E+13 .000 .00
O+C2H3=>H+HCH H2/2.00/ H2O/6.00/ OH+CH=>H+HCO 5.000E+13 .000 .00
O+C2H4=>CH3+H H+CH2OH=>H2+CH2O OH+CH2=>CH2(S)+H2O 2.000E+13 .000 .00
O+C2H5=>CH3+H H+CH2OH=>OH+CH3 H+CH2CO=>H+H2O 1.130E+07 2.000 3000.00
O+C2H6=>OH+H2 H+CH2OH=>CH2(S)+H OH+CH2(S)=>H+CH2O 3.000E+13 .000 .00
O+HCCO=>H+H2C H+CH3O(=M)=>CH3OH OH+CH3(=M)=>CH3OH(=M) 2.790E+18 -1.430 1330.00
O+CH2CO=>OH+H2 LOW / 4.663 LOW / 4.000E+36 -5.920 3140.00/
O+CH2CO=>OH+H2 TROE/ .700 TROE/ .4120 195.00 5900.00 6394.00 /
O+CH2CO=>CH2+H2 H2/2.00/ H2O/6.00/ CH4/2.00/ CO/1.50/ CO2/2.00/ C2H6/3.00/
O2+CO=>O+CO2 OH+CH3=>CH2+H2O 5.600E+07 1.600 5420.00
O2+CH2O=>H2O2 H+CH3O=>H2+CH2O H+CH2CO=>CH2(S)+H2O 6.440E+17 -1.340 1417.00
H+O2+H=>HO2+H H+CH3O=>OH+CH3 OH+CH4=>CH2(S)+H2O 1.000E+08 1.600 3120.00
O2/ .00/ H2O/ H+CH3O=>CH2(S)+H2 OH+CO=>H+CO2 4.760E+07 1.228 700.00
H+2O2=>H2O+O2 H+CH3OH=>CH2OH+H2 OH+HCO=>H2O+CO 5.000E+13 .000 .00
O+H2O2=>H2O+O2 H+CH3OH=>CH3O+H2 OH+CH2CO=>H2O+H2O 3.430E+09 1.180 -447.00
H+O2+H2O=>H2O H+C2H(=M)=>C2H2(=M) OH+CH2OH=>H2O+CH2O 5.000E+12 .000 .00
H+O2+H2O=>H2O LOW / 3.750 OH+CH2CO=>H2O+CH2O 5.000E+12 .000 .00
H+O2+O=>OH2 TROE/ .6464 OH+CH3OH=>H2OH+H2O 1.440E+06 2.000 -840.00
H+O2+O=>OH2 H2/2.00/ H2O/6.00/ OH+CH2CO=>CH2O+H2O 6.300E+06 2.000 1500.00
H+M=>C+H2M OH+C2H2(=M)=>C2H3 OH+C2H2=>H+HCO 2.000E+13 .000 .00
H2/ .00/ H2O/ OH+C2H2(=M)=>CH3 OH+C2H2(=M)=>H+CH2CO 2.180E+04 4.500 -1000.00
2H+H2=>2H2 TROE/ .7507 OH+C2H2(=M)=>H+HCOH 5.040E+05 2.300 13500.00
2H+H2O=>H2+H2 H2/2.00/ H2O/6.00/ OH+C2H2(=M)=>C2H2+H2O 3.370E+07 2.000 14000.00
2H+CO2=>H2+CO H+C2H3(=M)=>C2H4 OH+C2H2(=M)=>CH3+CO 4.830E+04 4.000 -2000.00
H+OH+M=>H2O+M LOW / 1.400 OH+C2H3(=M)=>H2O+C2H2 5.000E+12 .000 .00
H2/ .73/ H2O/ OH+C2H4(=M)=>C2H5 OH+C2H4(=M)=>C2H3+H2O 3.600E+06 2.000 2500.00
H+OH2=>OH+H2 H2/2.00/ H2O/6.00/ OH+C2H5=>C2H5+H2O 3.540E+06 2.120 870.00
H+OH2=>OH+H2 H+C2H5(=M)=>C2H3 OH+C2H5(=M)=>H2O+H2O 7.500E+12 .000 2000.00
H+OH2=>OH+H2 H+C2H4(=M)=>C2H5 2HCO2=>O2+H2O2 1.300E+11 .000 -1630.00
H+OH2=>OH+H2 LOW / 0.600 DUPLICATE
H+OH2O2=>OH+H2 TROE/ .9753 2HCO2=>O2+H2O2 4.200E+14 .000 12000.00
H+OH2O2=>OH+H2 H2/2.00/ H2O/6.00/ DUPLICATE
H+CH2H4=>C2H3+H2 OH+C2H2=>O+OH+CH2O 2.000E+13 .000 .00
H+C2H5(=M)=>C2H6 OH+C2H3=>O2+CH4O 1.000E+12 .000 .00
H2/2.00/ H2O/6.00/ OH+C2H6=>H+HCOH 3.780E+13 .000 .00
H2/2.00/ H2O/6.00/ OH+C2H6=>CH2+H2O H2O+CO=>OH+CO2 1.500E+14 .000 23600.00
H2/2.00/ H2O/6.00/ OH+C2H6=>HCO+H2O2 H2O+C2H2O=>HCO+H2O2 5.600E+06 2.000 12000.00
C+O2=>O+CO 5.800E+13 .000 576.00
C+CH2=>H+C2H 5.000E+13 .000 .00
C+CH3=>H+C2H2 5.000E+13 .000 .00

Simulation of NRP discharge in air

2-D simulation of a single NRP discharge pulse in air

- Air initial conditions
 - $T_0 = 1000$ K
 - $P_0 = 1$ atm
- NRP discharge parameters
 - Pulse voltage 5 kV
 - Pulse duration 10 ns

During the voltage pulse

- Solving Drift-Diffusion streamers equations.

Simulation results

- Increase of electron density due to air ionization
- Establishment of a conductive current
- Formation of a hot cylinder in the discharge zone

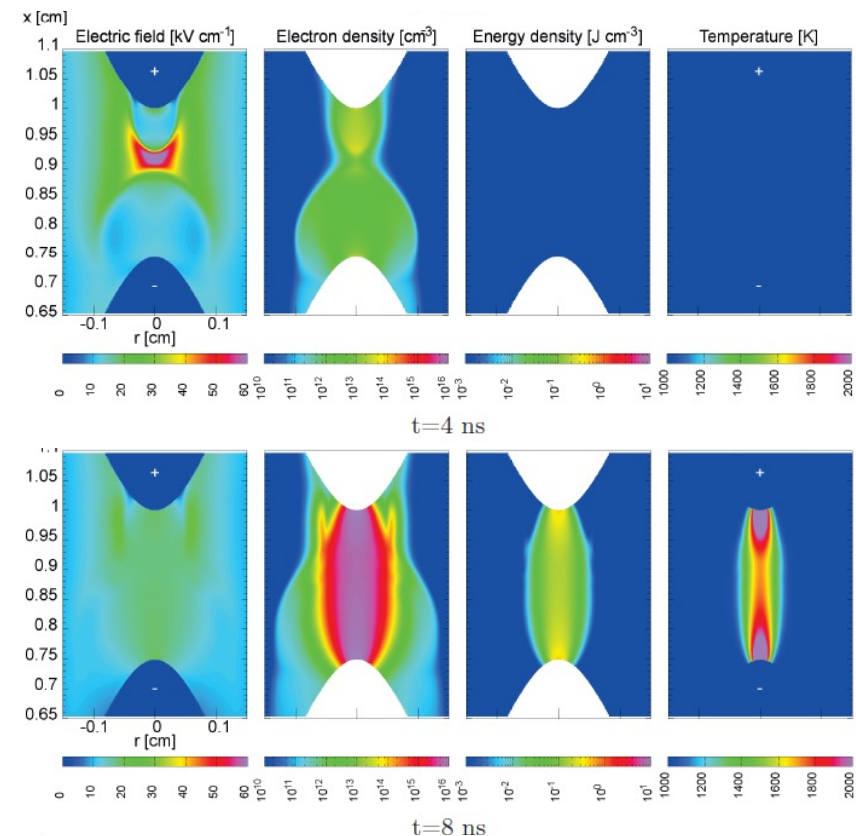


Fig : Cross-sectional views of the magnitude of the electric field, electron density, discharge energy density and neutral gas temperature [1]

[1] Tholin, F. and A. Bourdon (2013). Simulation of the hydrodynamic expansion following a nanosecond pulsed spark discharge in air at atmospheric pressure. Journal of Physics D: Applied Physics 46, 365205.

Simulation of H_2 -air flame ignition by NRP discharge

2-D simulation of a lean H_2 -air mixture by a single NRP discharge pulse

- H_2 -air initial conditions
 - $T_0 = 1000$ K
 - $P_0 = 1$ atm
 - $\phi = 0.3$
- NRP discharge parameters
 - Pulse voltage 5 kV
 - Pulse duration 10 ns

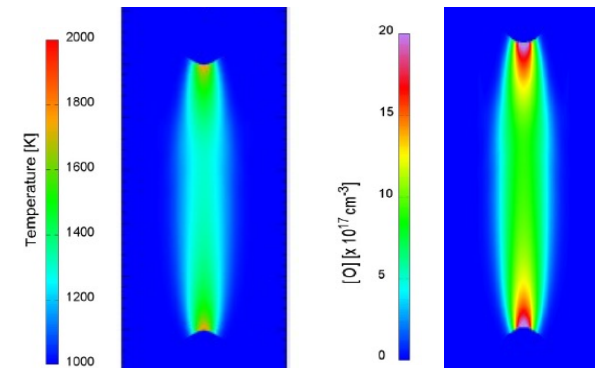


Fig : 2D distribution of gas temperature and the density of atomic oxygen at $t = 20$ ns [1].

Charged species

- Solving Drift-Diffusion equations
- Using an air plasma chemical mechanism

Neutral species

- Solving Navier-Stokes equations.
- Using H_2 -air combustion chemical mechanism

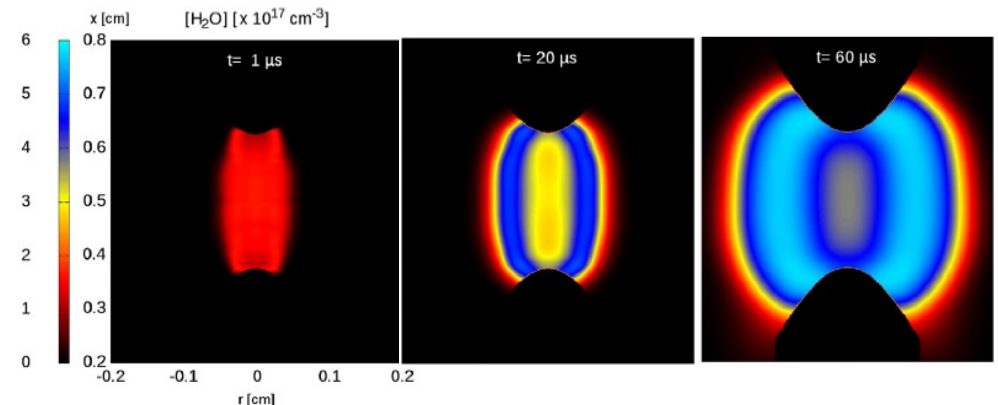


Fig : 2D distribution of the H_2O density for the ignition of a lean H_2 -air mixture by a single NRP discharge pulse [1].

[1] Tholin, F., D. Lacoste, and A. Bourdon (2014). Influence of fast-heating processes and o atom production by a nanosecond spark discharge on the ignition of a lean h_2 /air premixed flame. Combustion and Flame 161 (5), 1235–1246.

Numerical simulations of plasma assisted combustion

2-D simulation of a lean CH_4 -air mixture by a series of NRP discharge pulses

- CH_4 -air initial conditions
 - $T_0 = 300 \text{ K}$
 - $P_0 = 1 \text{ atm}$
 - $\phi = 0.8$
- NRP discharge parameters
 - Pulse voltage 5 kV
 - Pulse duration 10 ns
 - Pulse frequency 50 kHz

Charged species

- Solving Drift-Diffusion equations
- Using an air plasma chemical mechanism

Neutral species

- Solving Navier-Stokes equations.
- Using CH_4 -air combustion chemical mechanism

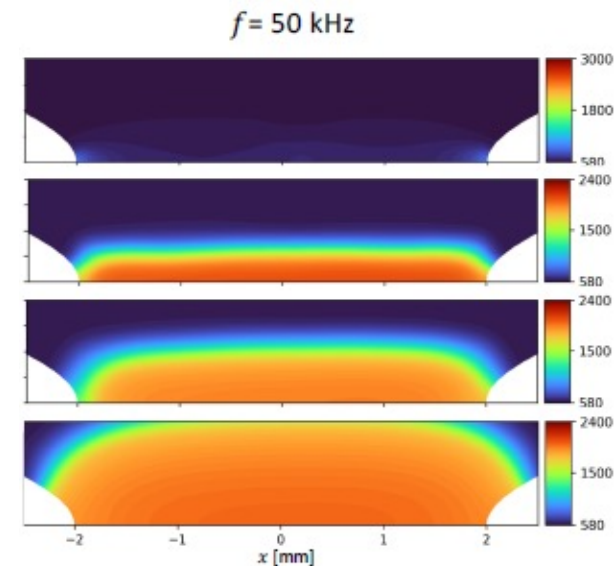


Fig : 2D distribution of temperature for the ignition of a lean CH_4 -air mixture by a single NRP discharge pulse [1].

[1] Barleon, N., L. Cheng, B. Cuenota, O. Vermorel, and A. Bourdon (2022). Investigation of the impact of nrp discharge frequency on the ignition of a lean methane-air mixture using fully coupled plasma-combustion numerical simulations. Proceedings of the Combustion Institute.

Plasma assisted combustion simulations

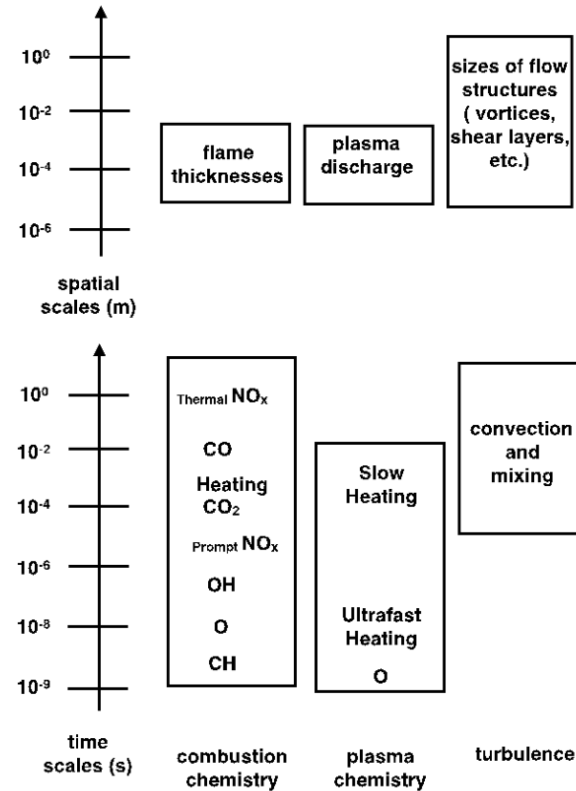
Capture NRP discharges effects using semi empirical plasma source terms

Plasma/combustion chemistry

Combustion



Navier-Stokes equations



Reduced computational cost for 3-D turbulent combustion

Phenomenological model of plasma-assisted combustion

NRP discharges physics

During the pulse



1. Creation of a high electric field
2. Increase of electrons kinetic energy
3. Collision of the electrons with heavy particles
4. Electrons impacts lead to :
 - species excitation
 - species ionization
 - species dissociation

$f(E/N)$
Reduced electric field

Spark NRP discharges (100 - 300 Td)

About 90 % of the discharge energy is transferred into **electronic and vibrational excitation of N₂ molecules**

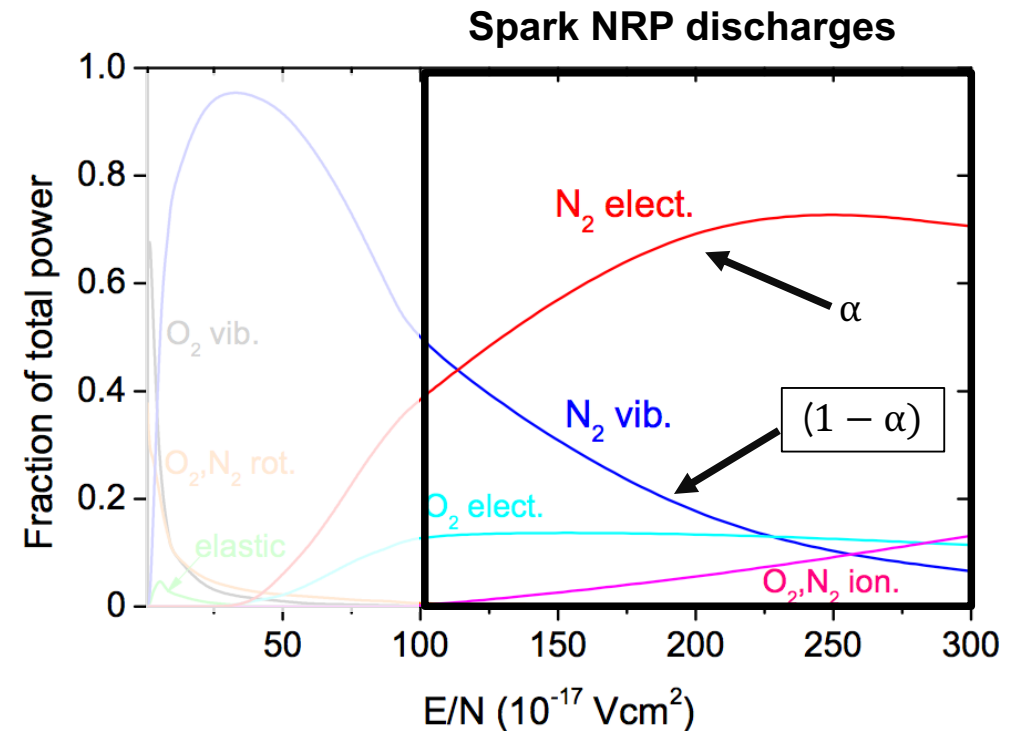


Fig: Fractional of power transferred by electrons to heavy particles as a function of E/N [1].

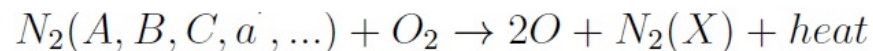
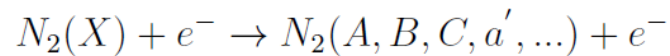
[1] N. L. Aleksandrov "Electron distribution function in 4:1 N₂-O₂ mixture" Teplofiz. Vys. Temp, vol, 19, No. 1, pp 22-27, 1981.

NRP discharges physics

Ultrafast phenomena (50 nanoseconds) :

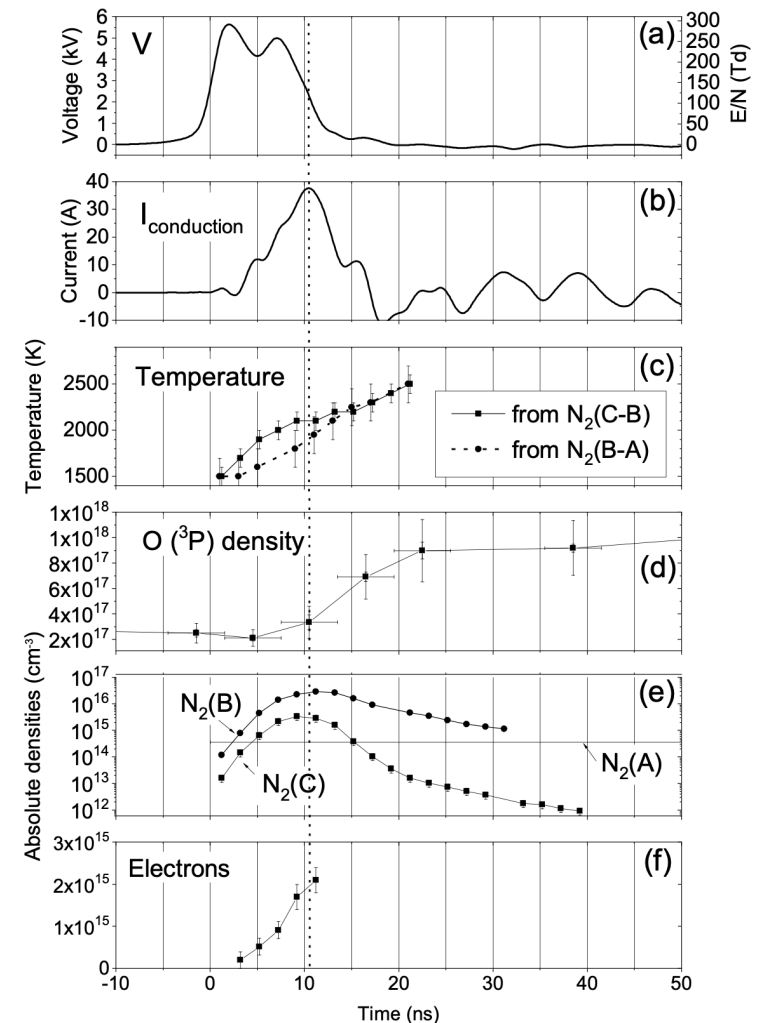
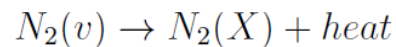
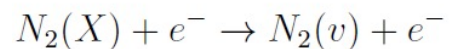
Relaxation of electronic states of N₂

- Ultrafast increase of O atoms concentration
- Ultrafast increase gas temperature



Slow phenomena (micro - milliseconds) :

Relaxation of vibrational states of N₂

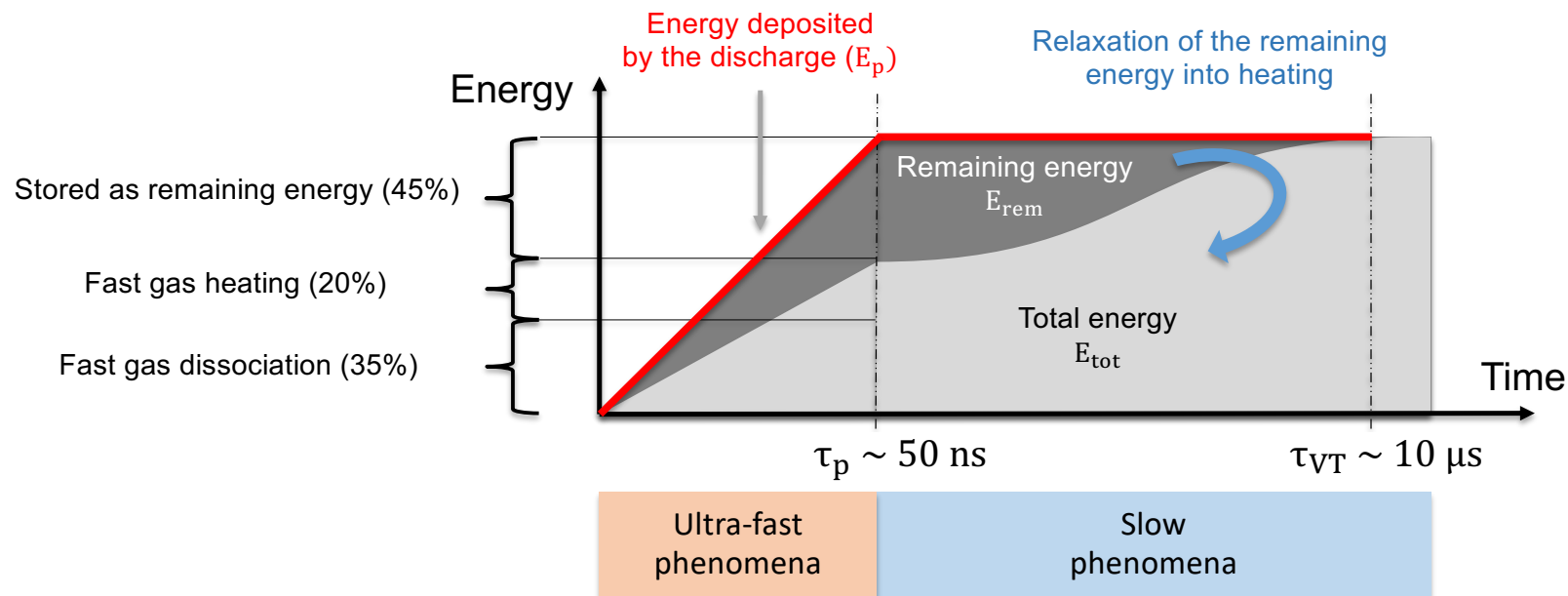
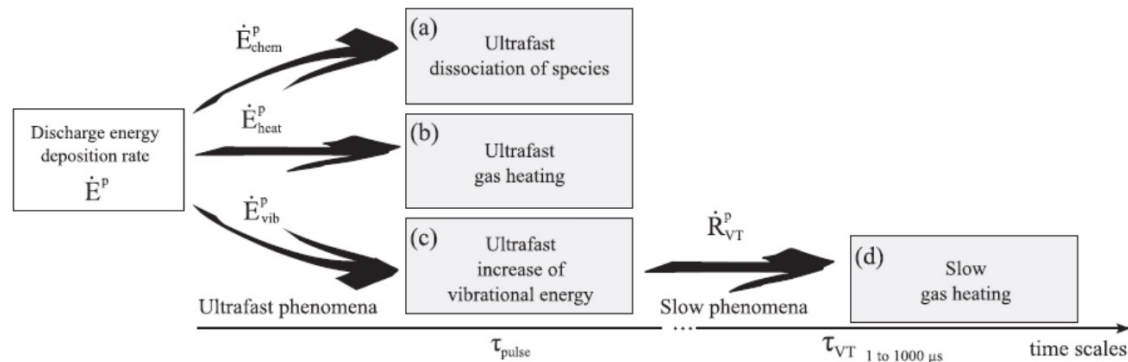


[1] N. Popov, Investigation of the mechanism for rapid heating of nitrogen and air in gas discharges., Plasma Physics Reports 27 (10), 886-896. (p. 25, 39, 49) (2001) (2001).

[2] N. Popov, Fast gas heating in a nitrogen oxygen discharge plasma: I. kinetic mechanism. Journal of Physics D: Applied Physics 44 (28) (2011).

[3] D. L. Rusterholtz Ultrafast heating and oxygen dissociation in atmospheric pressure air by nanosecond repetitively pulsed discharges., Journal of Physics D: Applied Physics 46, 464010.

NRP discharges Model



[1] M. Castela, B. Fiorina, A. Coussement, O. Gicquel, N. Darabiha, C.O.Laux, Modelling the impact of non-equilibrium discharges on reactive mixtures for simulations of plasma-assisted ignition in turbulent flows, Combustion and Flame 166 133-147 (2016).

NRP discharges Model

The impact of the plasma is captured by additional source terms

Model equations [1] (Navier-Stokes equations)

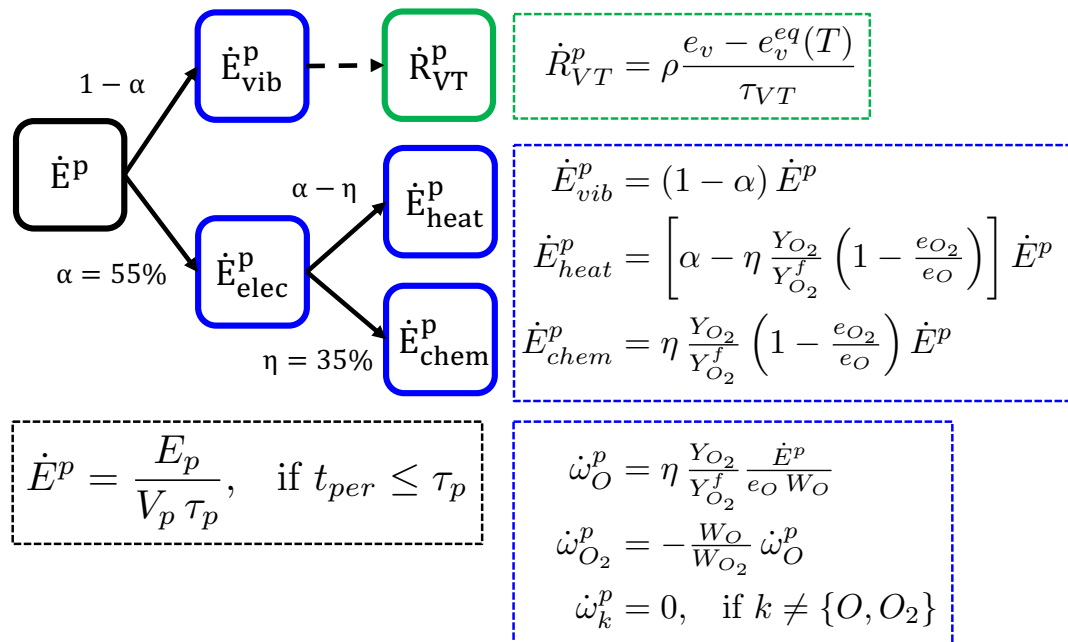
$$\begin{aligned}
 \frac{\partial(\rho u_j)}{\partial t} + \frac{\partial(\rho u_i u_j)}{\partial x_i} &= -\frac{\partial p}{\partial x_j} + \frac{\partial \tau_{ij}}{\partial x_i} \\
 \frac{\partial(\rho e)}{\partial t} + \frac{\partial(\rho u_i e)}{\partial x_i} &= -\frac{\partial q_i}{\partial x_i} + \frac{\partial(\sigma_{ij} u_i)}{\partial x_i} + \boxed{\dot{E}_{chem}^p} + \boxed{\dot{E}_{heat}^p} + \boxed{\dot{R}_{VT}^p} \\
 \frac{\partial(\rho Y_k)}{\partial t} + \frac{\partial(\rho u_i Y_k)}{\partial x_i} &= -\frac{\partial(\rho V_{k,i} Y_k)}{\partial x_i} + W_k \dot{\omega}_k^c + \boxed{W_k \dot{\omega}_k^p} \\
 \boxed{\frac{\partial(\rho e_{vib})}{\partial t} + \frac{\partial(\rho u_i e_{vib})}{\partial x_i}} &= \frac{\partial}{\partial x_i} \left(\rho D \frac{\partial e_{vib}}{\partial x_i} \right) + \boxed{\dot{E}_{vib}^p} - \boxed{\dot{R}_{VT}^p}
 \end{aligned}$$

Slow vibrational energy relaxation into heat

[1] M. Castela, B. Fiorina, A. Coussement, O. Gicquel, N. Darabiha, C.O.Laux, Modelling the impact of non-equilibrium discharges on reactive mixtures for simulations of plasma-assisted ignition in turbulent flows, Combustion and Flame 166 133-147 (2016).

NRP discharges Model

NRP discharges source terms

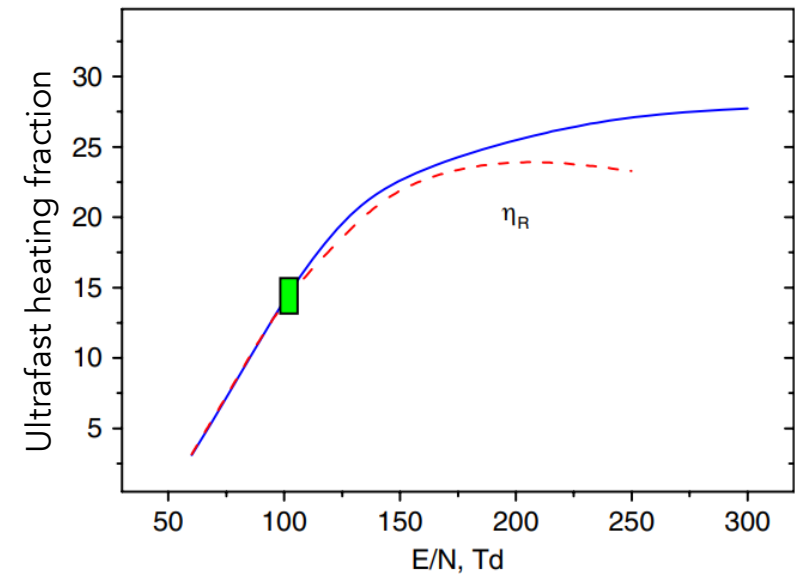
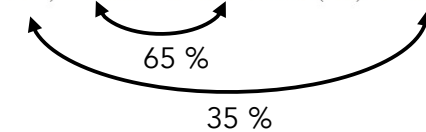
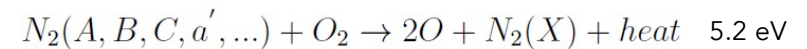
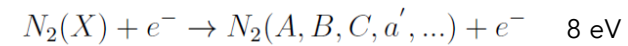


Heat = 20%

$\alpha = 55\%$

$\eta = 35\%$

$(1 - \alpha) = 45\%$



Fast gas heating in a nitrogen–oxygen discharge plasma [1,2]

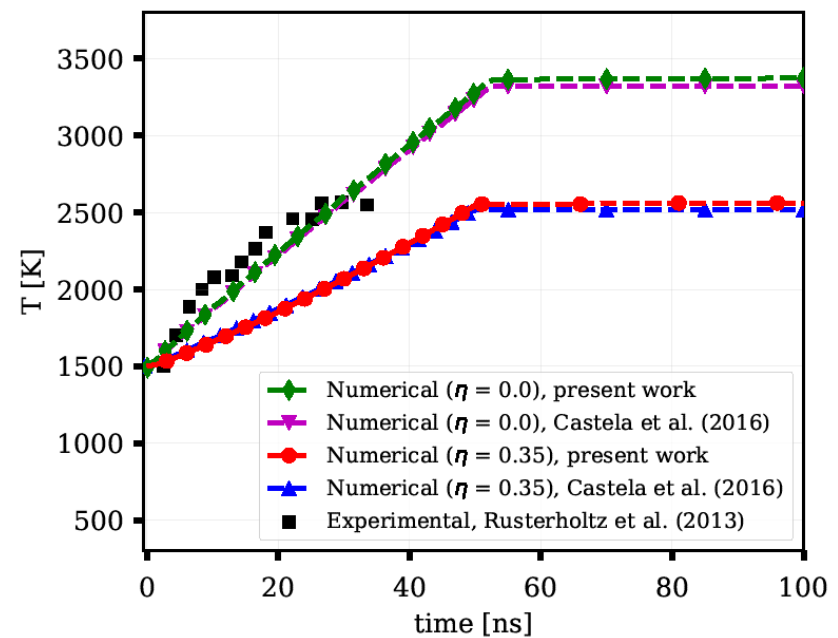
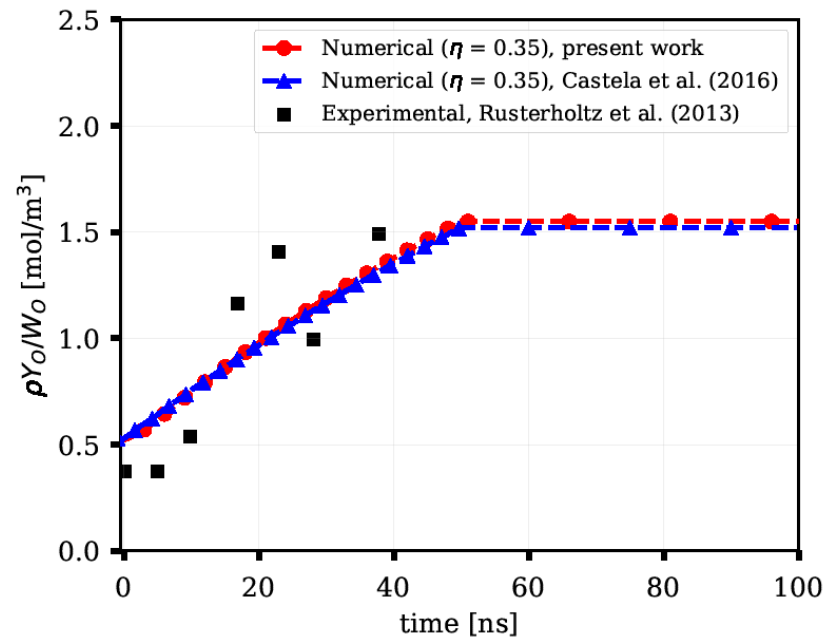
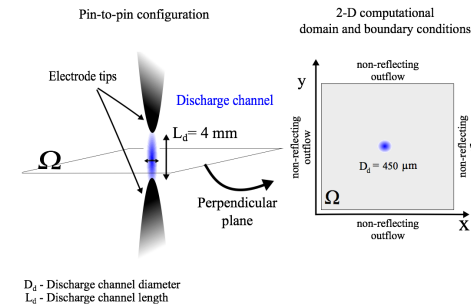
[1] N. Popov, Journal of Physics D: Applied Physics 44 (28) (2011).

[2] D. L. Rusterholtz Ultrafast heating and oxygen dissociation in atmospheric pressure air by nanosecond repetitively pulsed discharges., Journal of Physics D: Applied Physics 46, 464010.

[3] M. Castela, B. Fiorina, A. Coussement, O. Gicquel, N. Darabiha, C.O.Laux., Combustion and Flame 166 133-147 (2016).

NRP discharge in the air

Single nanosecond pulse in air



The model is able to capture the ultrafast increase of O atoms and temperature.

Numerical simulations of flame ignition by NRP discharges

Methane-air mixture ignition by NRP discharges

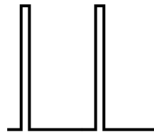
I. Only thermal effects are considered :

- Mixture ignites after **4 discharges**
- Gas temperature rises up to **3600 K** $\gg T_{ad}$



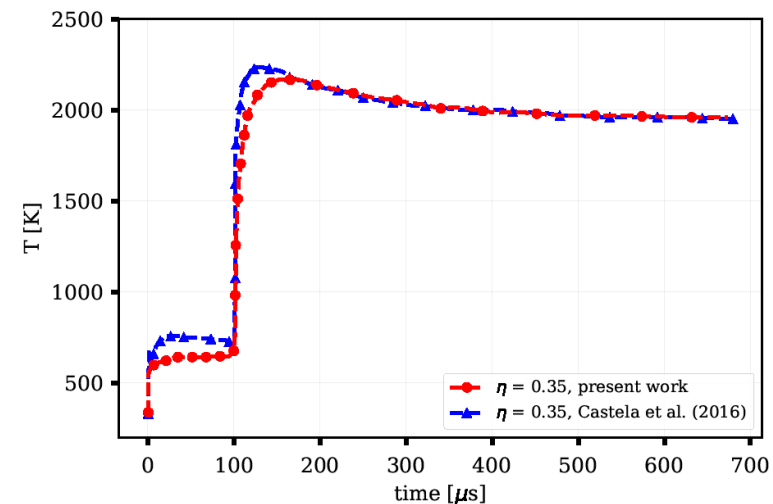
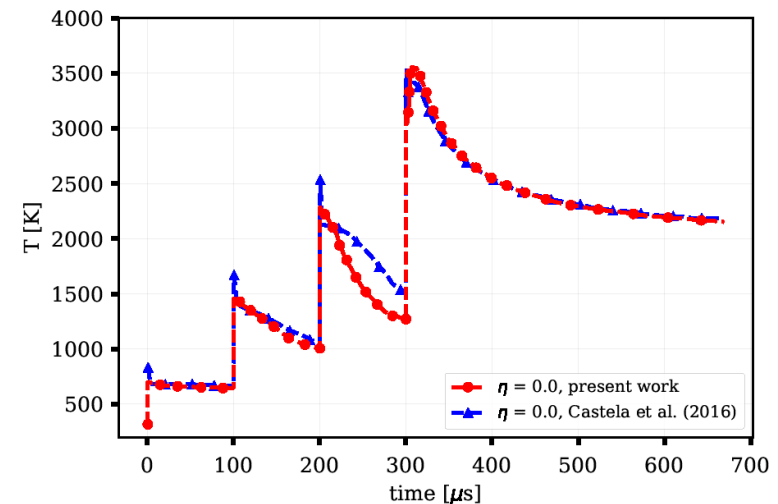
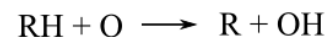
II. Both thermal and chemical effects are considered :

- Mixture ignites after **2 discharges**
- Gas temperature rises up to **2400 K**



Enhances chain-branching reactions
even at low gas temperatures

Oxidation of molecules



Hydrodynamic effects of NRP discharges

Experimental and numerical investigations of methane-air mixture ignition by a single NRP discharge pulse

Methane-air mixture :

- Equivalence ratio = 0.8
- $T_{INT} = 300$ K
- $P = 1$ bar

NRP discharges

- 1 pulse
- Energy per pulse = 0.8 mJ

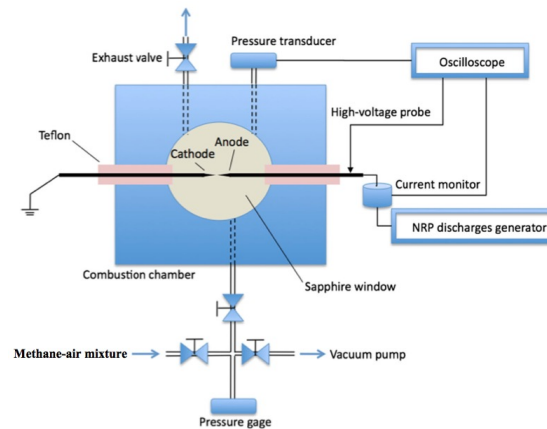


Fig :Schematic representation of the experimental setup

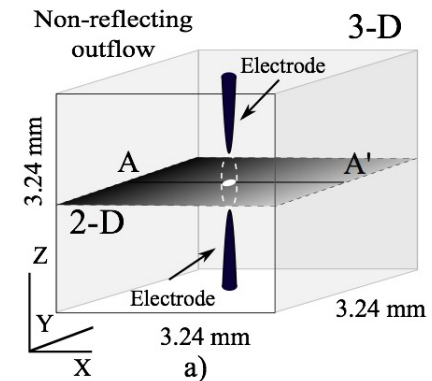


Fig :Schematic representation of the 3-D computational domain

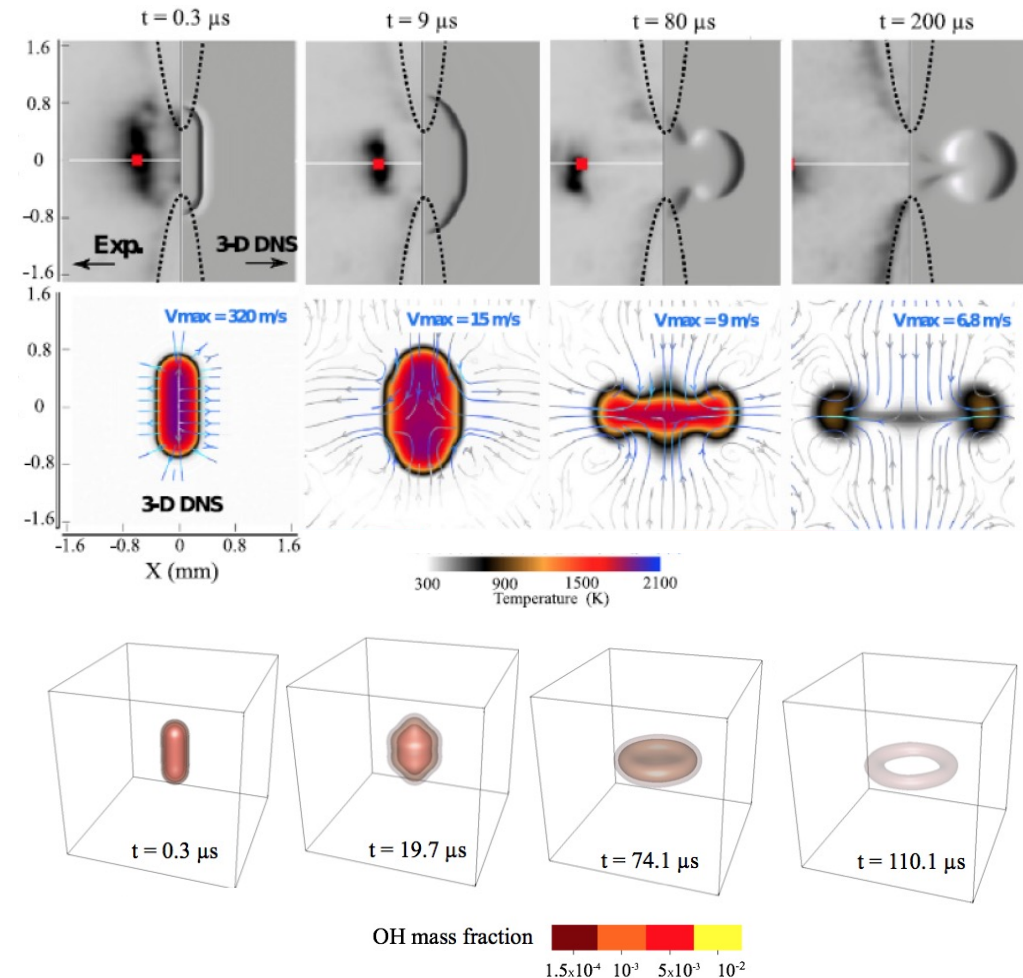
[1] M. Castela, S. Stepanyan, B. Fiorina, A. Coussement, O. Gicquel, N. Darabiha and C.O. Laux. A 3-D DNS and experimental study of the effect of the recirculating flow pattern inside a reactive kernel produced by nanosecond plasma discharges in a methane-air mixture. Proc. Combust. Inst. Vol 36 (2) (2017).

Hydrodynamic effects of NRP discharges

3-D simulation of methane-air mixture ignition by a single NRP discharge pulse [1]

The hydrodynamic effects of NRP discharges induce :

- The entrainment of fresh gases toward the center of the ignition kernel
- The Collapse and evolution of the kernel from a cylindrical shape to a toroidal shape
- The extinction of the kernel



Vorticity equation

$$\frac{D\vec{\omega}}{Dt} = (\vec{\omega} \cdot \vec{\nabla})\vec{u} - \vec{\omega}(\vec{\nabla} \cdot \vec{u}) + \frac{1}{\rho^2}[\vec{\nabla}\rho \times \vec{\nabla}p] + \nu \nabla^2 \vec{\omega}$$

Baroclinic instabilities

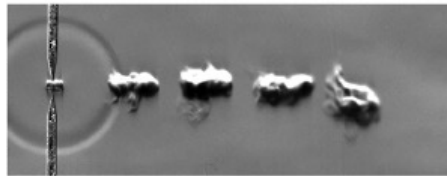
[1] M. Castela, S. Stepanyan, B. Fiorina, A. Coussemont, O. Gicquel, N. Darabiha and C.O. Laux. A 3-D DNS and experimental study of the effect of the recirculating flow pattern inside a reactive kernel produced by nanosecond plasma discharges in a methane-air mixture. Proc. Combust. Inst. Vol 36 (2) (2017).

Flow tunnel configuration

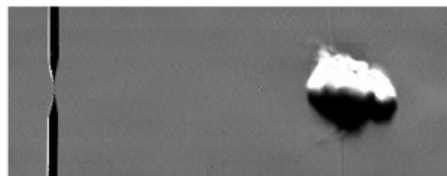
Flow tunnel : methane-air premixed burner [1].

Depending on the flow inlet velocity and pulse repetition frequency, three pulses interaction regimes can be obtained:

- Decoupled regime (zero ignition probability)



- Fully coupled regime (high ignition probability)



- Partially coupled regime (ignition limit)

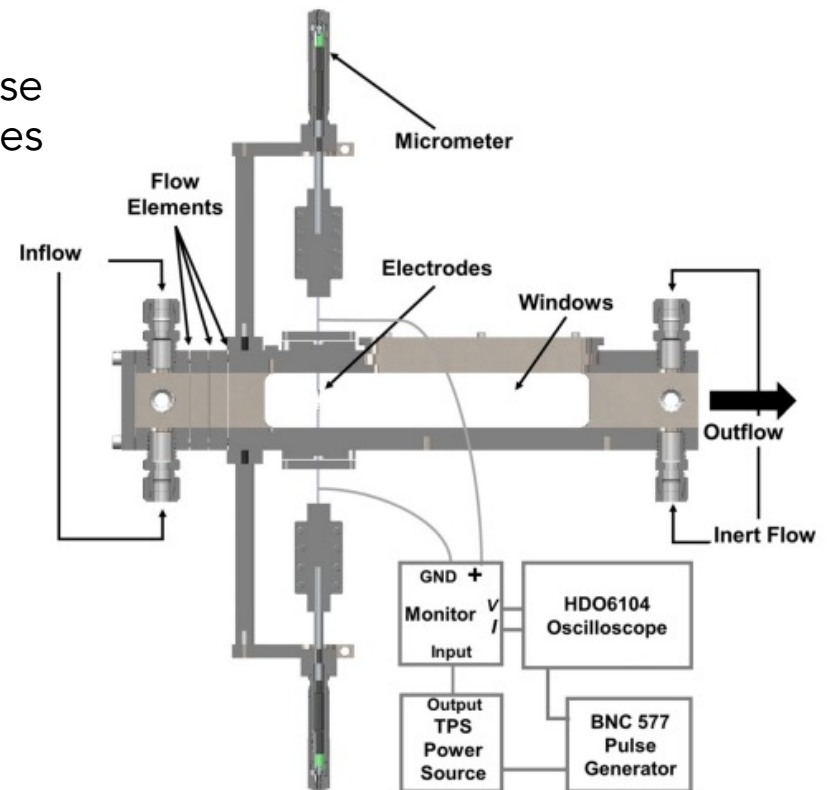
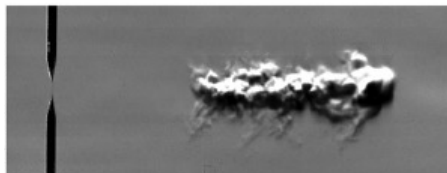


Fig :Schematic representation of the experimental setup

[1] J. K. Lefkowitz , T. Ombrello . An exploration of inter-pulse coupling in nanosecond pulsed high frequency discharge ignition. Combustion and Flame 180 (2017) 136–147

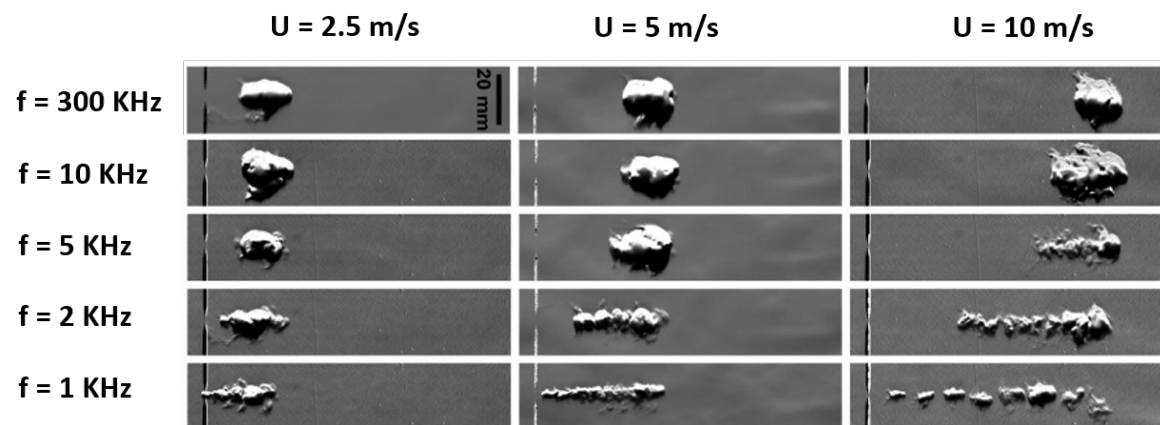
LES of flow tunnel ignition by NRP discharges

Simulations objectives

- Validation of the phenomenological plasma-assisted combustion model against experimental data

Two parametric studies

- Influence of the **flow inlet velocity** on pulses interaction regimes and mixture ignition
- Influence of the **pulse repetition frequency** on pulses interaction regimes and mixture ignition



[1] J. K. Lefkowitz , T. Ombrello . An exploration of inter-pulse coupling in nanosecond pulsed high frequency discharge ignition. Combustion and Flame 180 (2017) 136–147

LES of flow tunnel ignition by NRP discharges

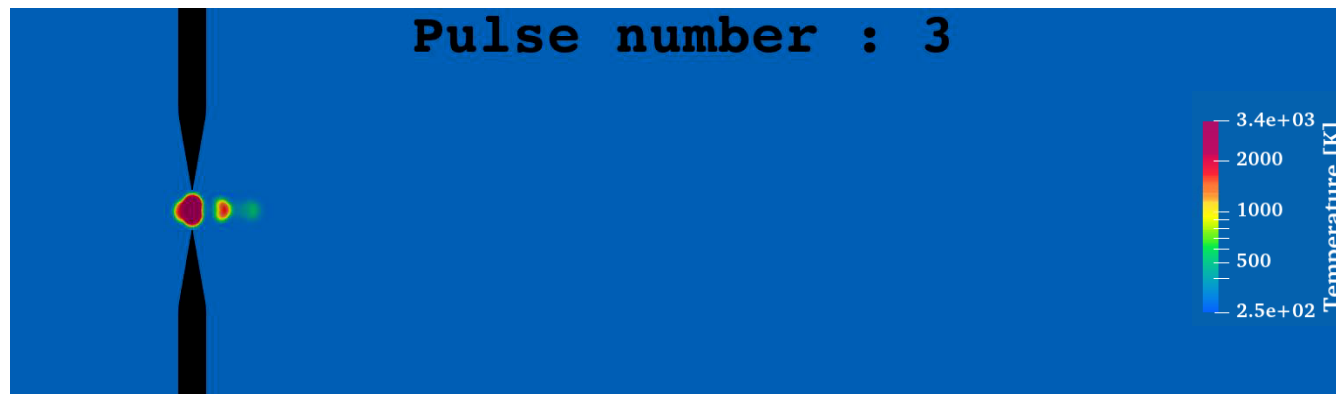
Influence of flow velocity

Operating conditions :

- $\phi = 0.6$
- $U_{inlet} = 2.5 \text{ m.s}^{-1}$
- $PRF = 5 \text{ KHz}$
- $E_{pulse} = 2.9 \text{ mJ}$
- Series of 10 pulses



	Pulses interaction regime	Mixture ignition (simulation)
$U_{inlet} = 2.5 \text{ m.s}^{-1}$	Fully coupled	yes
$U_{inlet} = 5 \text{ m.s}^{-1}$		
$U_{inlet} = 10 \text{ m.s}^{-1}$		



Temperature [k]

[1] Y. Bechane , B. Fiorina. A numerical investigation of plasma-assisted ignition by a burst of nanosecond repetitively pulsed discharges. Combustion and Flame, Volume 259 (2024)

LES of flow tunnel ignition by NRP discharges

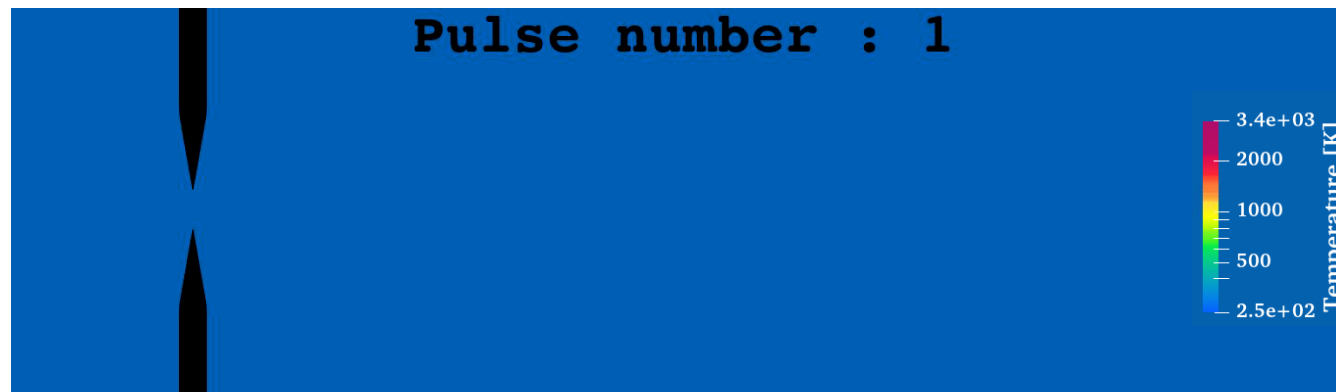
Influence of flow velocity

Operating conditions :

- $\phi = 0.6$
- $U_{inlet} = 5 \text{ m.s}^{-1}$
- $PRF = 5 \text{ KHz}$
- $E_{pulse} = 2.9 \text{ mJ}$
- Series of 10 pulses



	Pulses interaction regime	Mixture ignition (simulation)
$U_{inlet} = 2.5 \text{ m.s}^{-1}$	Fully coupled	yes
$U_{inlet} = 5 \text{ m.s}^{-1}$	Fully coupled	yes
$U_{inlet} = 10 \text{ m.s}^{-1}$		



Temperature [k]

[1] Y. Bechane , B. Fiorina. A numerical investigation of plasma-assisted ignition by a burst of nanosecond repetitively pulsed discharges. Combustion and Flame, Volume 259 (2024)

LES of flow tunnel ignition by NRP discharges

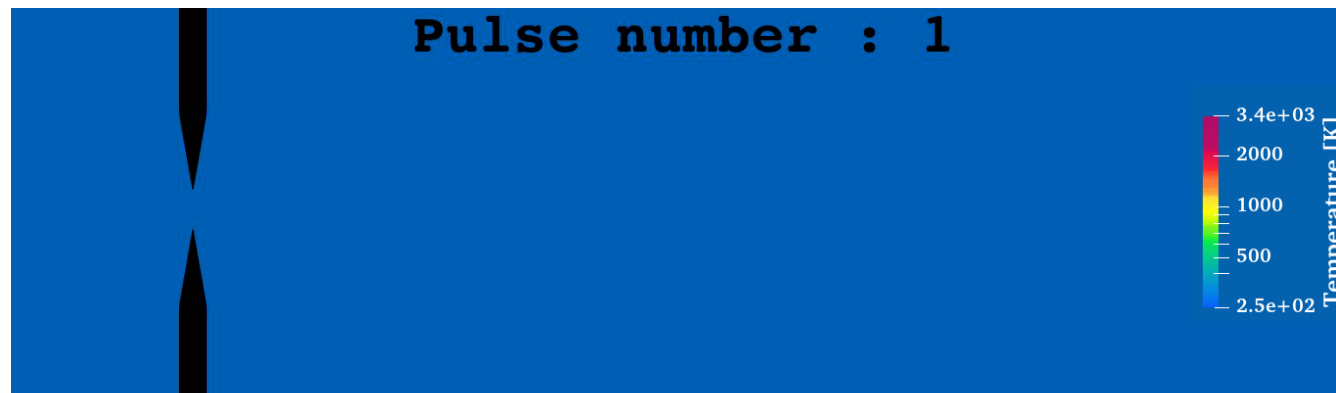
Influence of flow velocity

Operating conditions :

- $\phi = 0.6$
- $U_{inlet} = 10 \text{ m.s}^{-1}$
- $PRF = 5 \text{ KHz}$
- $E_{pulse} = 2.9 \text{ mJ}$
- Series of 10 pulses



	Pulses interaction regime	Mixture ignition (simulation)
$U_{inlet} = 2.5 \text{ m.s}^{-1}$	Fully coupled	yes
$U_{inlet} = 5 \text{ m.s}^{-1}$	Fully coupled	yes
$U_{inlet} = 10 \text{ m.s}^{-1}$	Partially coupled	no



Temperature [k]

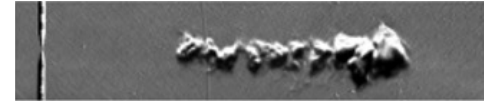
[1] Y. Bechane , B. Fiorina. A numerical investigation of plasma-assisted ignition by a burst of nanosecond repetitively pulsed discharges. Combustion and Flame, Volume 259 (2024)

LES of flow tunnel ignition by NRP discharges

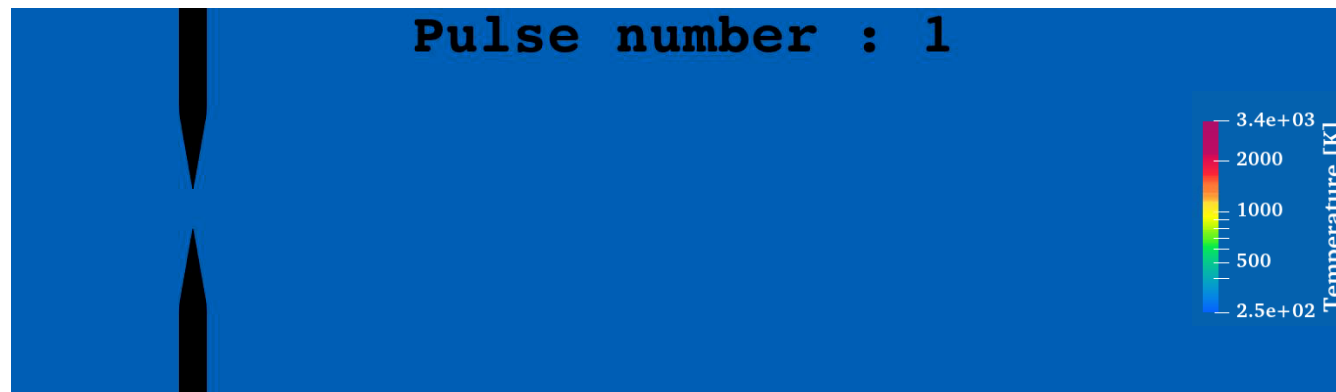
Influence of pulse repetition frequency (PRF)

Operating conditions :

- $\phi = 0.6$
- $U_{inlet} = 10 \text{ m.s}^{-1}$
- $PRF = 2 \text{ KHz}$
- $E_{pulse} = 2.9 \text{ mJ}$
- *Series of 10 pulses*



	Pulses interaction regime	Mixture ignition (simulation)
PRF = 2 KHz	Decoupled	no
PRF = 5 KHz	Partially coupled	no
PRF = 10 KHz		
PRF = 50 KHz		



Temperature [k]

[1] Y. Bechane , B. Fiorina. A numerical investigation of plasma-assisted ignition by a burst of nanosecond repetitively pulsed discharges. Combustion and Flame, Volume 259 (2024)

LES of flow tunnel ignition by NRP discharges

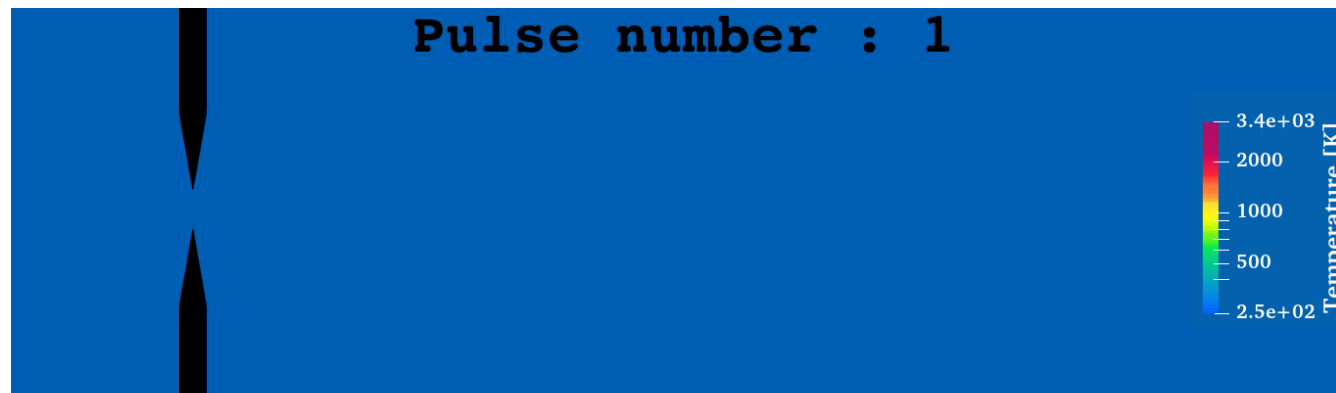
Influence of pulse repetition frequency (PRF)

Operating conditions :

- $\phi = 0.6$
- $U_{inlet} = 10 \text{ m.s}^{-1}$
- $PRF = 10 \text{ KHz}$
- $E_{pulse} = 2.9 \text{ mJ}$
- *Series of 10 pulses*



	Pulses interaction regime	Mixture ignition (simulation)
PRF = 2 KHz	Decoupled	no
PRF = 5 KHz	Partially coupled	no
PRF = 10 KHz	Fully coupled	yes
PRF = 50 KHz		



Temperature [k]

[1] Y. Bechane , B. Fiorina. A numerical investigation of plasma-assisted ignition by a burst of nanosecond repetitively pulsed discharges. Combustion and Flame, Volume 259 (2024)

LES of flow tunnel ignition by NRP discharges

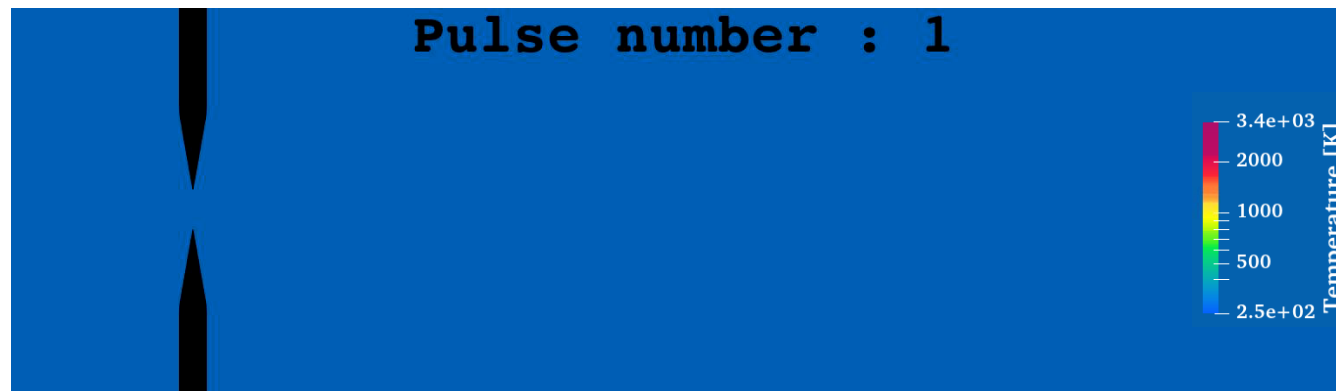
Influence of pulse repetition frequency (PRF)

Operating conditions :

- $\phi = 0.6$
- $U_{inlet} = 10 \text{ m.s}^{-1}$
- $PRF = 50 \text{ KHz}$
- $E_{pulse} = 2.9 \text{ mJ}$
- *Series of 10 pulses*



	Pulses interaction regime	Mixture ignition (simulation)
PRF = 2 KHz	Decoupled	no
PRF = 5 KHz	Partially coupled	no
PRF = 10 KHz	Fully coupled	yes
PRF = 50 KHz	Fully coupled	yes



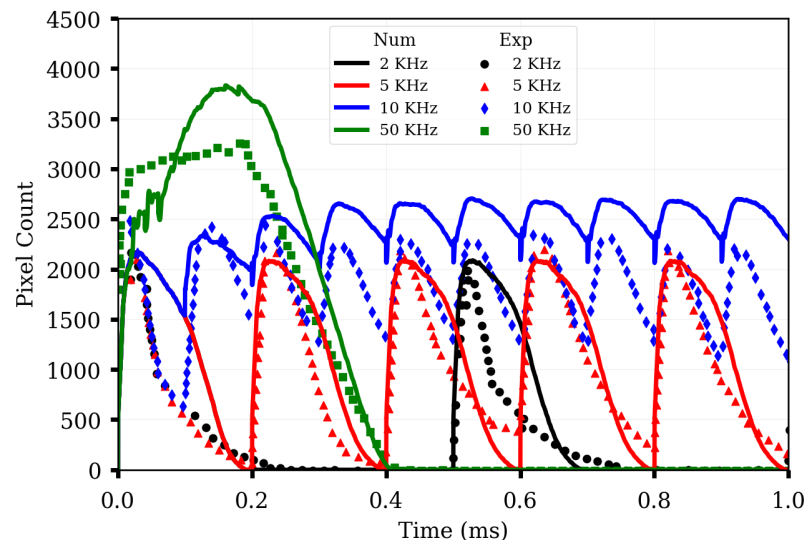
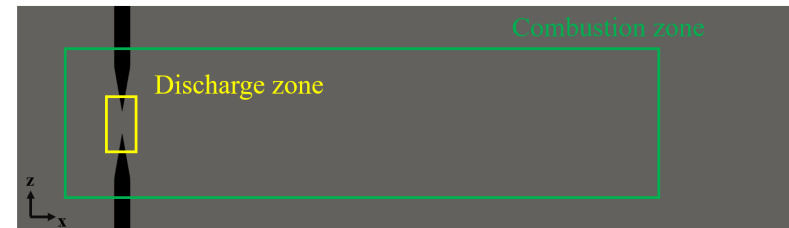
Temperature [k]

[1] Y. Bechane , B. Fiorina. A numerical investigation of plasma-assisted ignition by a burst of nanosecond repetitively pulsed discharges. Combustion and Flame, Volume 259 (2024)

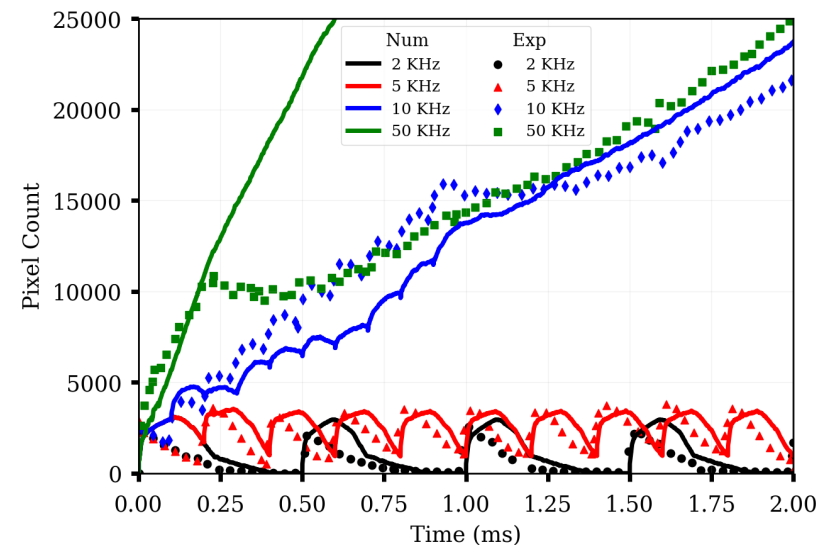
Comparison with the experiment

Number of pixels with detectable OH :

- OH-PLIF measurements
- Numerical simulations



Number of pixels in region of interest with detectable OH (Concentration [1], PLIF signal [2]) for various pulses frequency conditions.



Number of pixels in region of interest with detectable OH (Concentration [1], PLIF signal [2]) for various pulses frequency conditions.

- [1] Y. Bechane , B. Fiorina. A numerical investigation of plasma-assisted ignition by a burst of nanosecond repetitively pulsed discharges. Combustion and Flame, Volume 259 (2024)
- [2] J. K. Lefkowitz , S. D. Hammack , C. Carter, T. Ombrello . Elevated OH production from NPHFD and its effect on ignition. Proceedings of the Combustion Institute 000 (2020) 1–8

Pulses interaction regimes

Dimensionless Analysis

Pulses interaction regimes control parameters

1. Gases residence time in the discharge zone

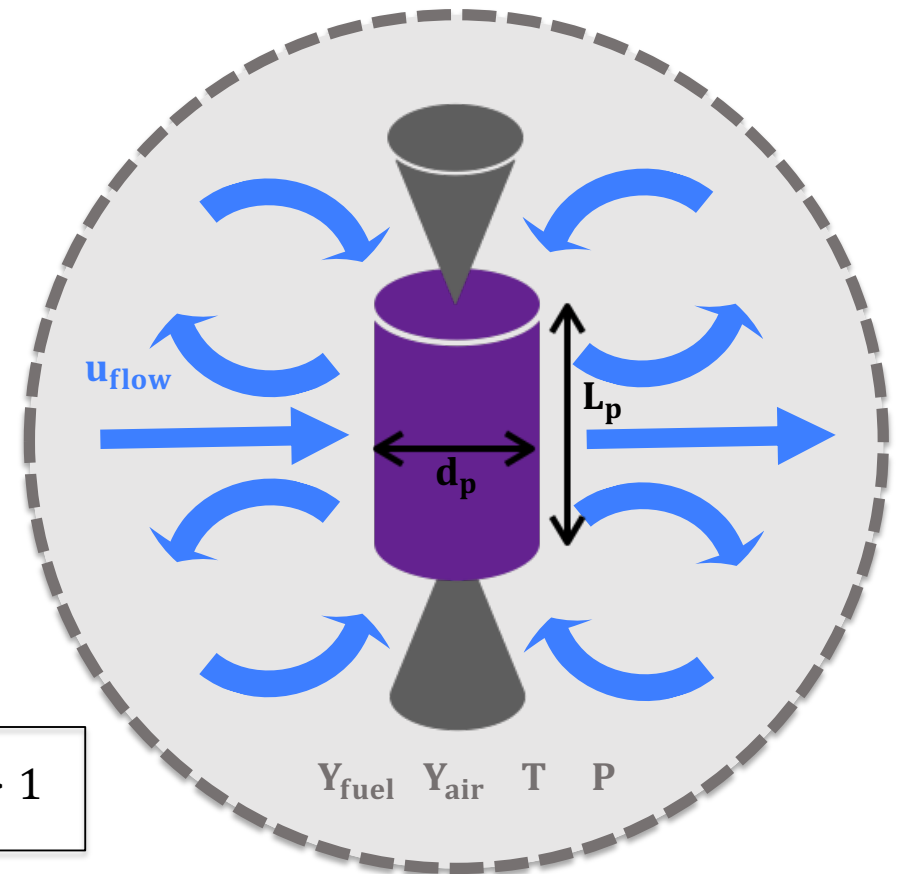
$$\tau_{\text{res}} \approx \frac{d_p}{u_{\text{flow}}}$$

2. Inter-pulse time

$$\tau_{\text{ip}} = \frac{1}{f_p}$$

Pulse Interaction Regime [1]: $\text{PIR} = \frac{\tau_{\text{res}}}{\tau_{\text{ip}}}$

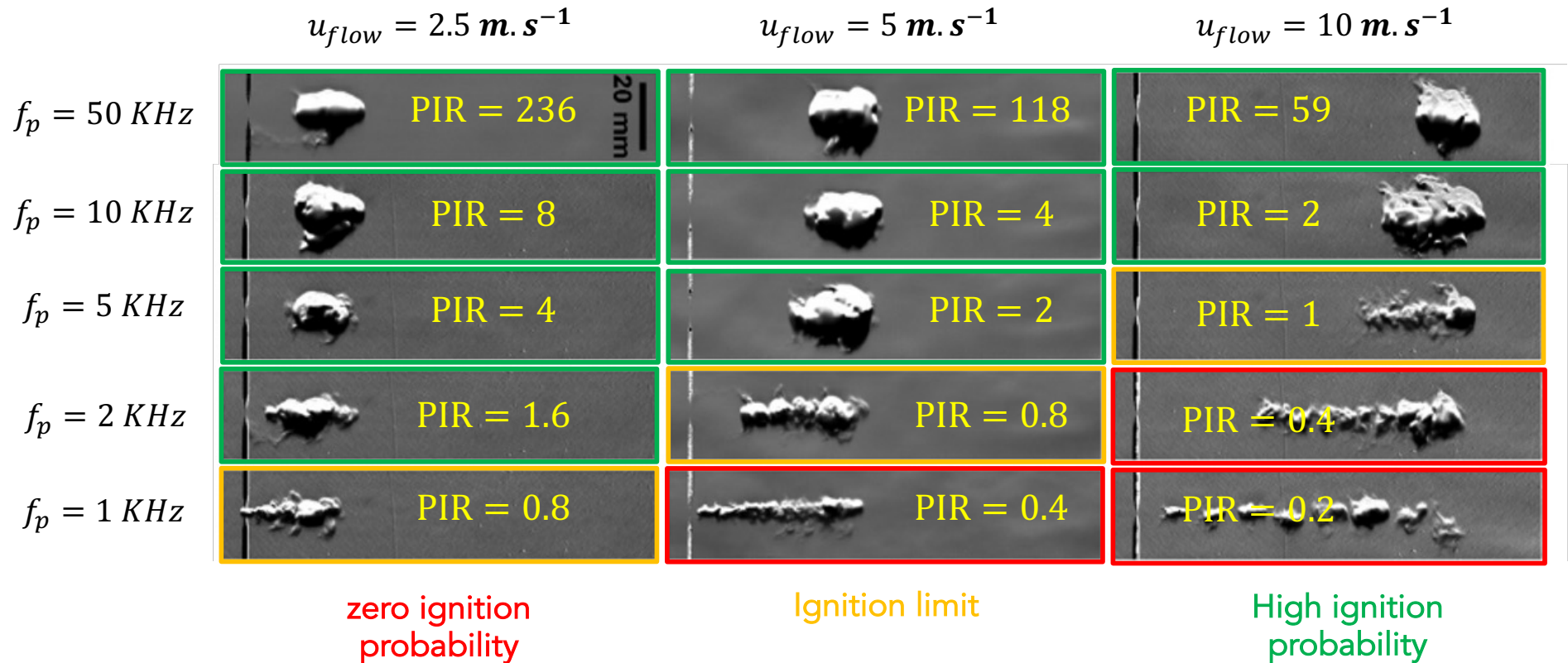
Cumulative effect requires : $\tau_{\text{res}} > \tau_{\text{ip}} \Rightarrow \text{PIR} > 1$



[1] Y. Bechane , B. Fiorina. A numerical investigation of plasma-assisted ignition by a burst of nanosecond repetitively pulsed discharges. Combustion and Flame, Volume 259 (2024)

Pulses interaction regimes

Dimensionless Analysis



Dimensionless approach is limited:

- Does not give the number of pulses required
- Estimation of residence time not straightforward (recirculating flow pattern between electrodes has not been considered)

Low-order modeling of Ignition by NRPDs

Perfectly-Stirred Reactor (PSR) modeling [1]

Flow dynamics Detailed finite-rate chemistry (combustion) Ultra-fast plasma phenomena

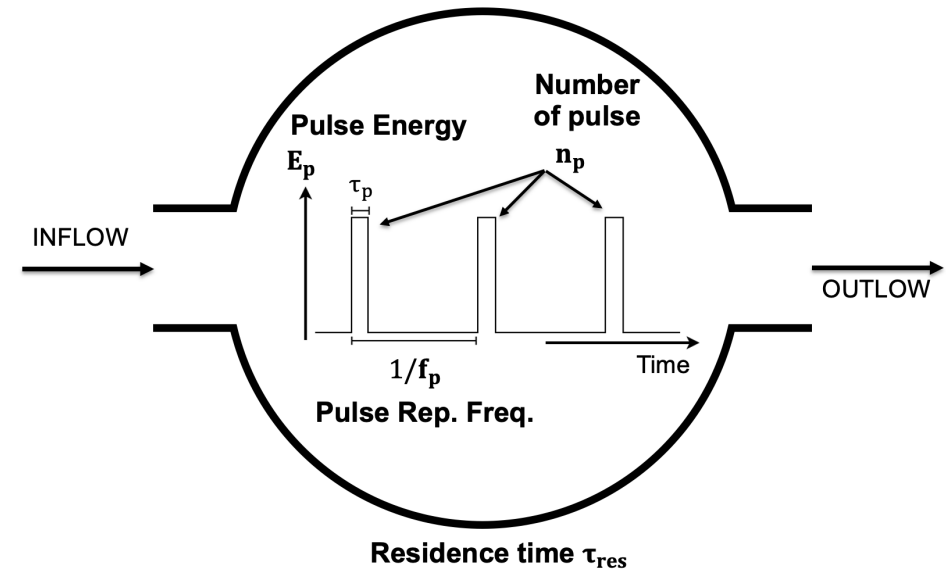
$$\frac{dY_k}{dt} = \frac{1}{\tau_{res}} (Y_k^{in} - Y_k) + \frac{W_k \dot{\omega}_k^c}{\rho} + \frac{W_k \dot{\omega}_k^p}{\rho}$$

$$\frac{dh}{dt} = \frac{1}{\tau_{res}} \left(\sum_{k=1}^{N_{sp}} Y_k^{in} h_k^{in} - \sum_{k=1}^{N_{sp}} Y_k h_k \right) + \frac{\dot{E}_{chem}^p}{\rho} + \frac{\dot{E}_{heat}^p}{\rho} + \frac{\dot{R}_{VT}^p}{\rho}$$

$$\frac{de_v}{dt} = \frac{1}{\tau_{res}} (e_v^{in} - e_v) + \frac{\dot{E}_{vib}^p}{\rho} - \frac{\dot{R}_{VT}^p}{\rho}$$

$$P = \rho RT \sum_{k=1}^{N_{sp}} \frac{Y_k}{W_k}$$

Slow plasma phenomena

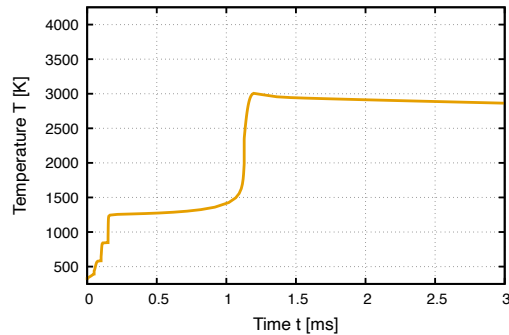


Considered fixed:
 Equivalence ratio ϕ
 Temperature T
 Pressure P
 Plasma geometry d_p and L_p
 Pulse duration τ_p

[1] S.Q.E. Wang, Y. Bechane, N. Darabiha, B. Fiorina. Efficiency analysis of ignition by Nanosecond Repetitively Pulsed discharges using a low-order model. *Appl. Energy Combust. Sci.* 15, 2023.

Low-order modeling of Ignition by NRPDs

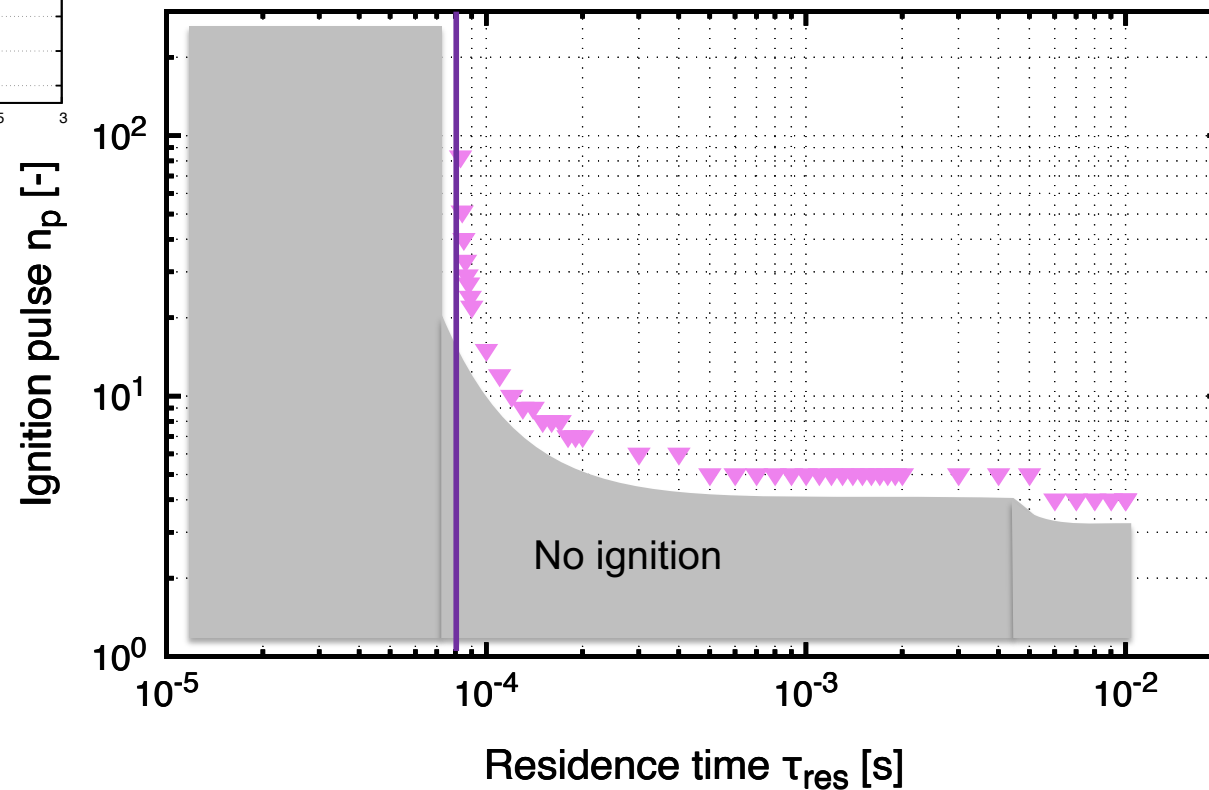
Effect: Residence Time



at $\tau_{\text{res}} = 10$ ms
Minimum number of pulse = 4

$E_p = 3.5$ mJ
 $f_p = 20$ kHz
 $n_p = 1$ to ∞
 $\tau_{\text{res}} = 0.01$ to 10 ms

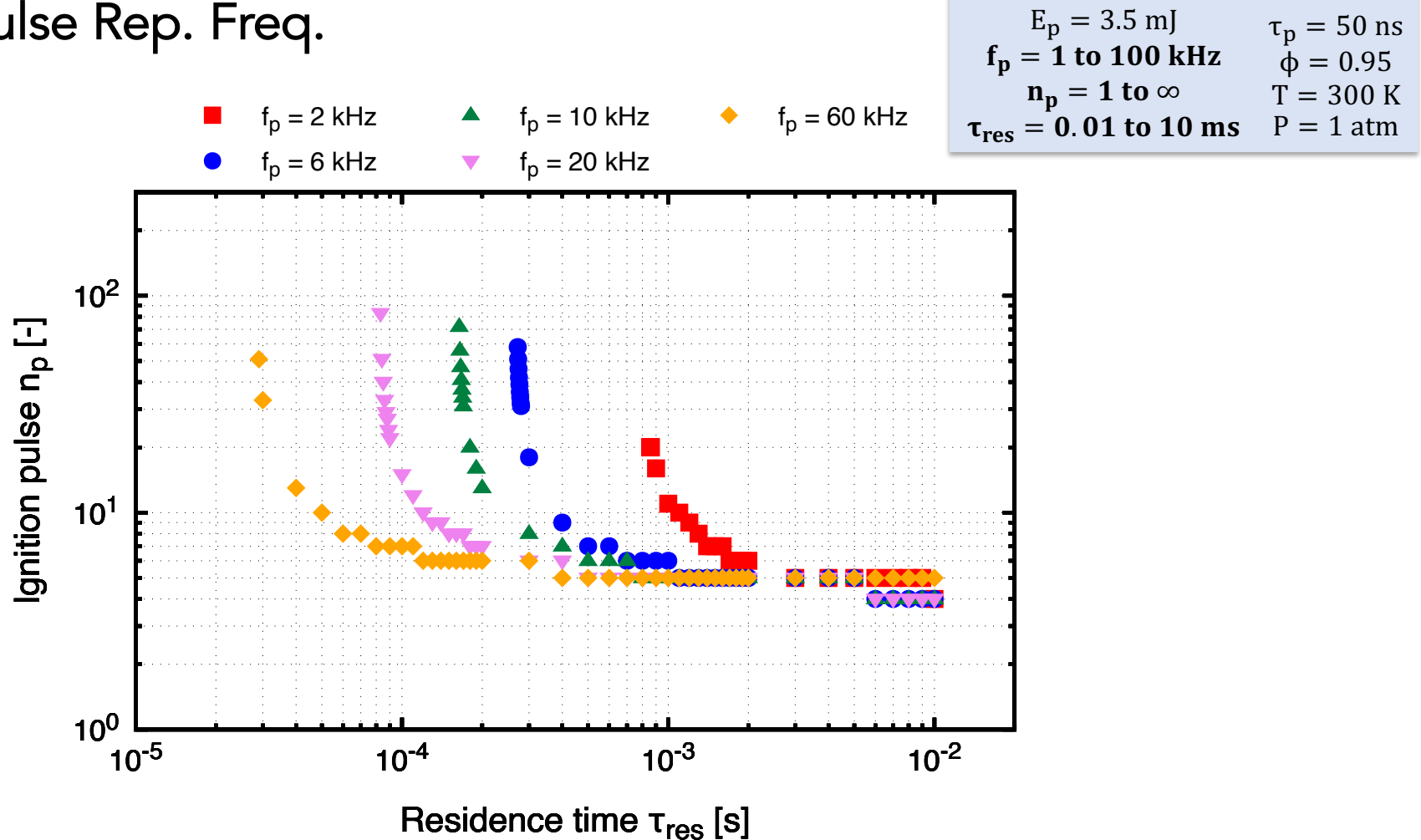
$\tau_p = 50$ ns
 $\phi = 0.95$
 $T = 300$ K
 $P = 1$ atm



For a given E_p and $f_p \rightarrow$ the number of pulse n_p increases when τ_{res} decreases.

Low-order modeling of Ignition by NRPDs

Effect: Pulse Rep. Freq.



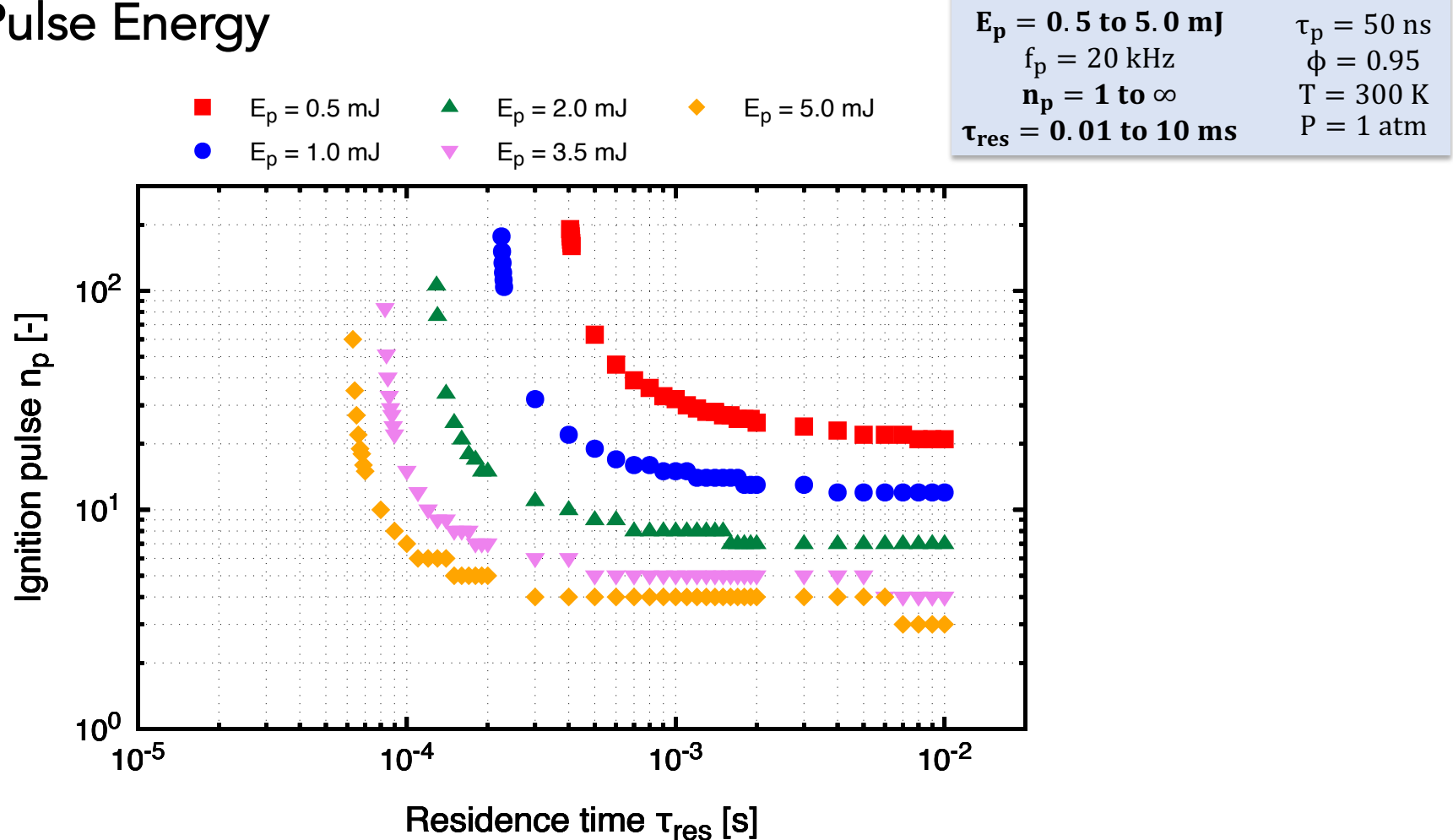
Increasing Pulse Rep. Freq.:

- Extend the ignition domain
- Decrease the number of pulse to ignite

→ To be energy-efficient: Increase f_p

Low-order modeling of Ignition by NRPDs

Effect: Pulse Energy



Increasing Pulse Energy:

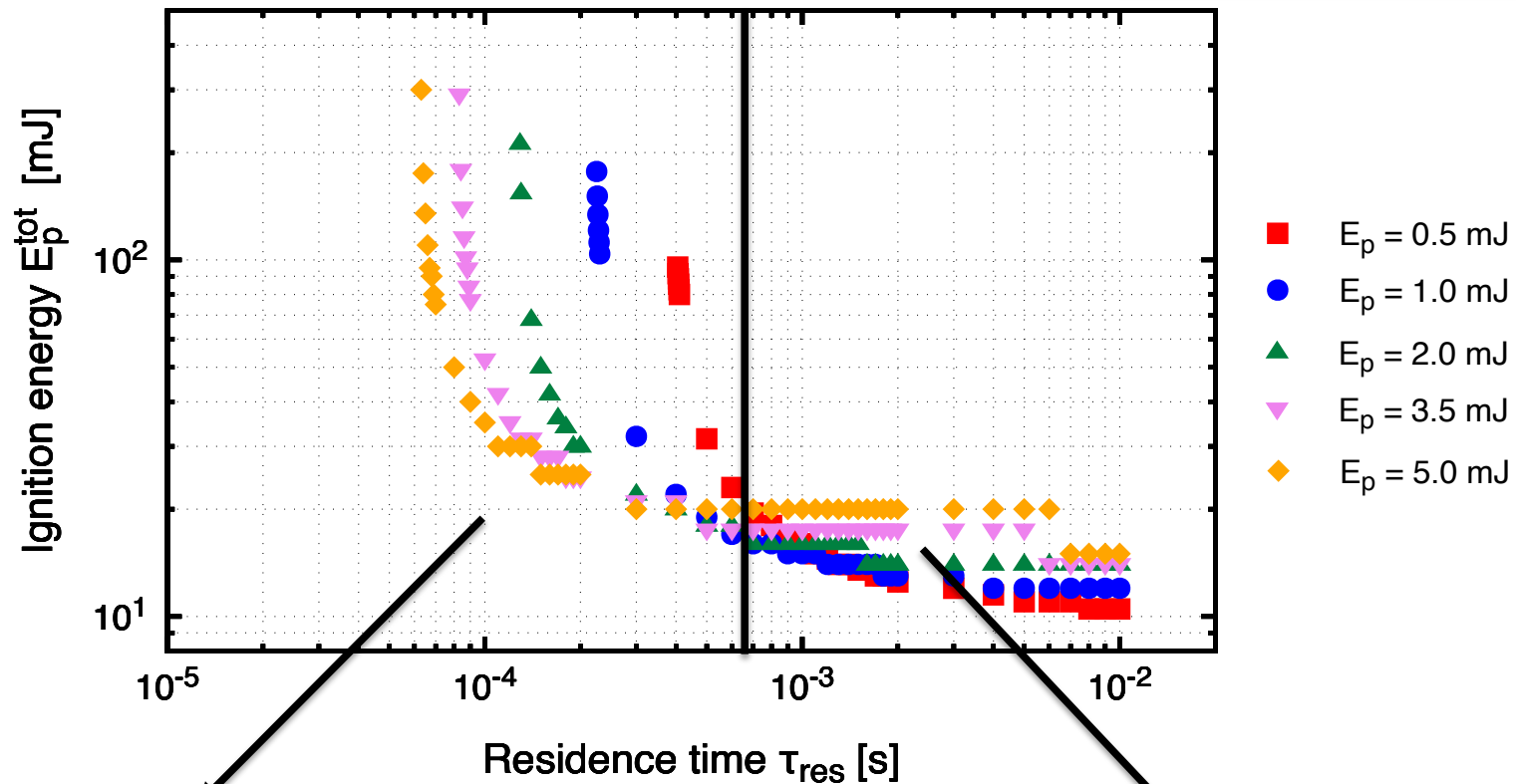
- Extend the ignition domain
- Decrease the number of pulse to ignite

→ To be energy-efficient:
Increase / Decrease n_p ?
Increase / Decrease E_p ?

Low-order modeling of Ignition by NRPDs

Total Ignition Energy defined as: $E_p^{\text{tot}} = n_p E_p$

$E_p = 0.5 \text{ to } 5.0 \text{ mJ}$ $\tau_p = 50 \text{ ns}$
 $f_p = 20 \text{ kHz}$ $\phi = 0.95$
 $n_p = 1 \text{ to } \infty$ $T = 300 \text{ K}$
 $\tau_{\text{res}} = 0.01 \text{ to } 10 \text{ ms}$ $P = 1 \text{ atm}$



For **short** τ_{res} ,
more energy-efficient:
high E_p (and low n_p)

For **long** τ_{res} ,
more energy-efficient:
low E_p (and high n_p)

Low-order modeling of Ignition by NRPDs

$\tau < \tau_{critical}$ No ignition

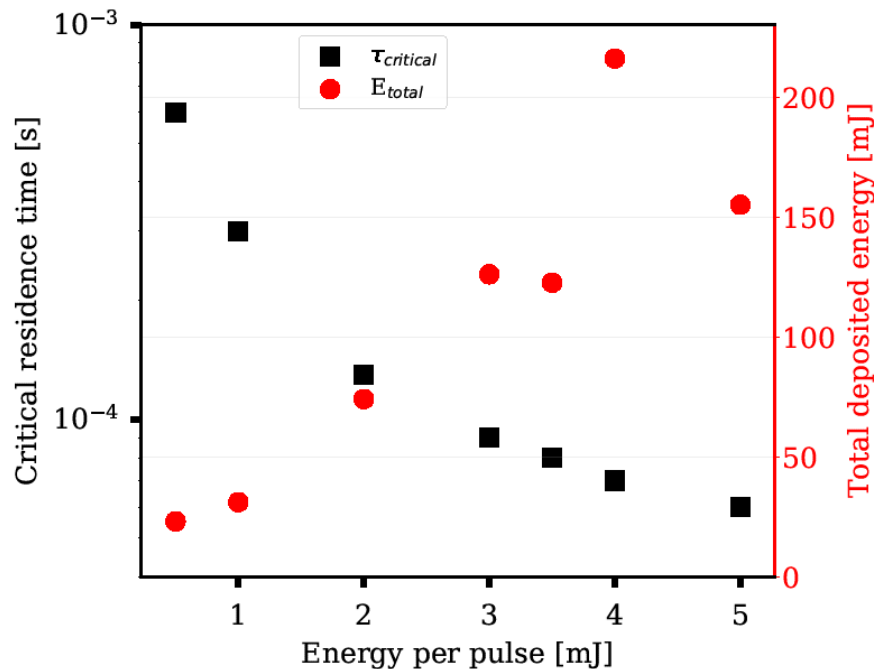
$\tau \geq \tau_{critical}$ Ignition

$$E_p^{tot} = n_p E_p$$

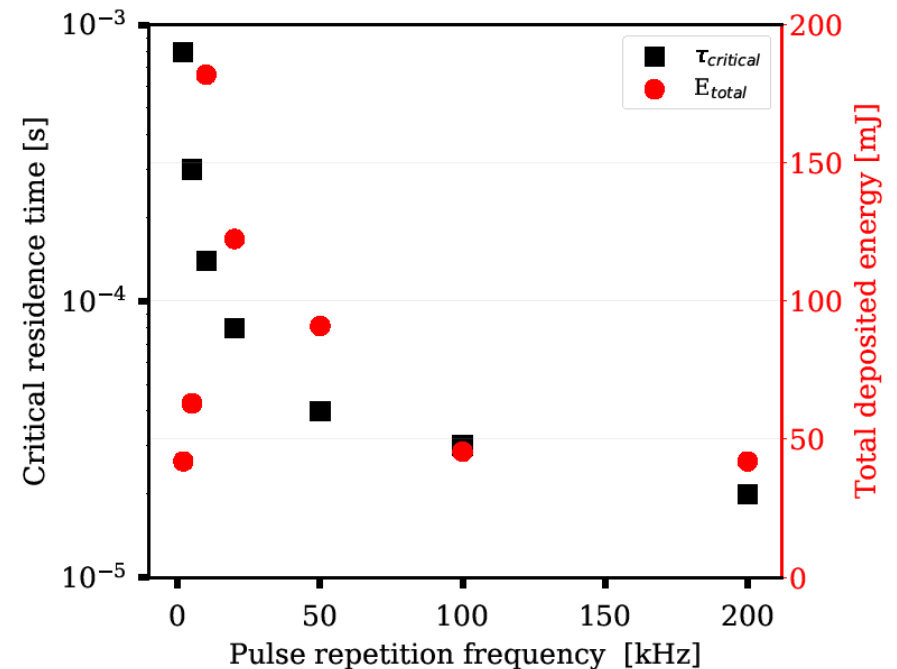
$E_{pulse} = 5 \text{ mJ}$ and $PRF = 20 \text{ kHz} \Rightarrow \tau_{critical} = 6 \cdot 10^{-5} \text{ s}$ and $E_p^{tot} = 155 \text{ mJ}$

$E_{pulse} = 3.5 \text{ mJ}$ and $PRF = 50 \text{ kHz} \Rightarrow \tau_{critical} = 4 \cdot 10^{-5} \text{ s}$ and $E_p^{tot} = 91 \text{ mJ}$

$E_{pulse} = 3.5 \text{ mJ}$ and $PRF = 200 \text{ kHz} \Rightarrow \tau_{critical} = 2 \cdot 10^{-5} \text{ s}$ and $E_p^{tot} = 42 \text{ mJ}$



Critical residence time $\tau_{critical}$ (black square) and total deposited energy at this residence time E_{total} (red circle) for different values of pulse energy E_{pulse} with a constant pulse repetition frequency $PRF = 20 \text{ kHz}$.



Critical residence time $\tau_{critical}$ (black square) and total deposited energy at this residence time E_{total} (red circle) for different values of pulse repetition frequency PRF with a constant pulse repetition frequency $E_{pulse} = 3.5 \text{ mJ}$.

LES of the flow tunnel

Conclusions

- The LES phenomenological plasma-assisted combustion model predicts well pulses interaction regime and flames ignition.
- To ensure efficient ignition by NRP discharge the pulses should be applied :
 - In low velocity region (high gases residence time)
 - At high pulse repetition frequencies

Numerical simulations of flame Stabilization by NRP discharges

Mini-PAC Burner

Choice of an operating point close to lean blow-out where **NRP discharge effects** are the most relevant

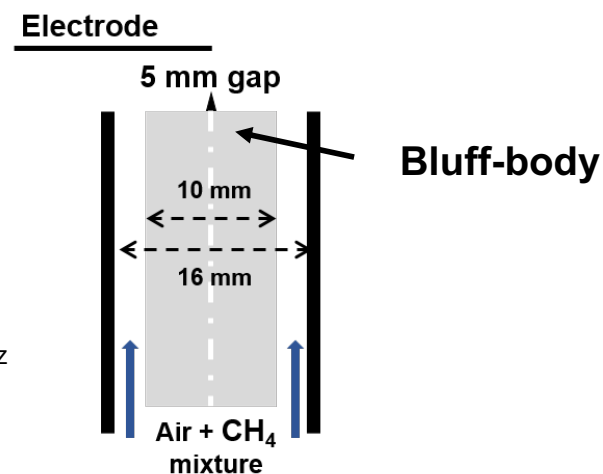
Premixed CH₄-air flame

- $\phi = 0.8$

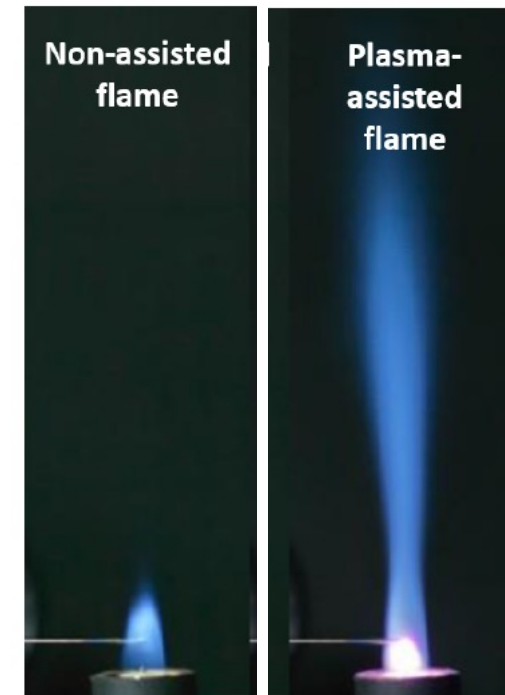
**Pulse
discharge
generator**

Discharge:

- duration: 10 ns
- energy: 2.0 mJ
- frequency: 20 kHz
- gap: 5 mm
- $\frac{P_{elec}}{P_{flame}} = 0.3 \%$



Mini-Pac burner_[1]



Photographs of the lean flame ($\phi = 0.8$) without (left) and with (right) NRP discharges applied at 20 kHz [2].

[1] Y. Bechane, B. Fiorina. Numerical investigations of turbulent premixed flame ignition by a series of Nanosecond Repetitively Pulsed discharges. Proceedings of the Combustion Institute

[2] V.P. Blanchard, N. Q. Minesi, S. Stepanyan, G.D. Stancu, C. O. Laux Dynamics of a lean flame stabilized by nanosecond discharges AIAA Scitech 2021 Forum

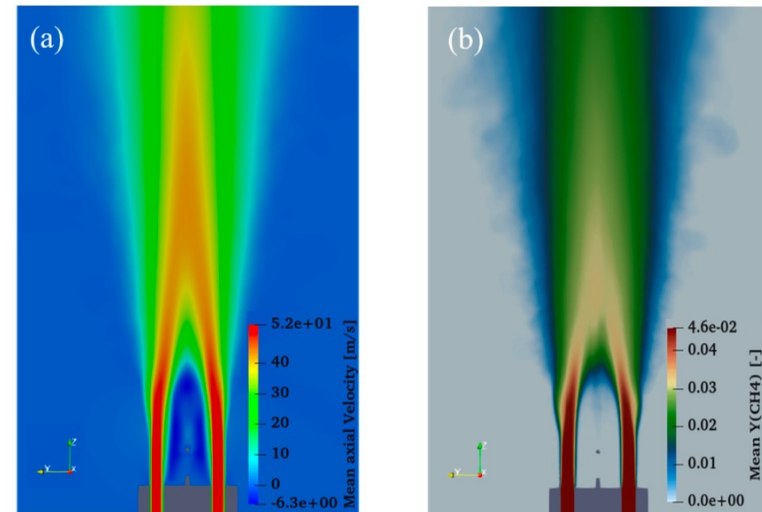
LES of the Mini-PAC burner

Premixed CH₄-air flame

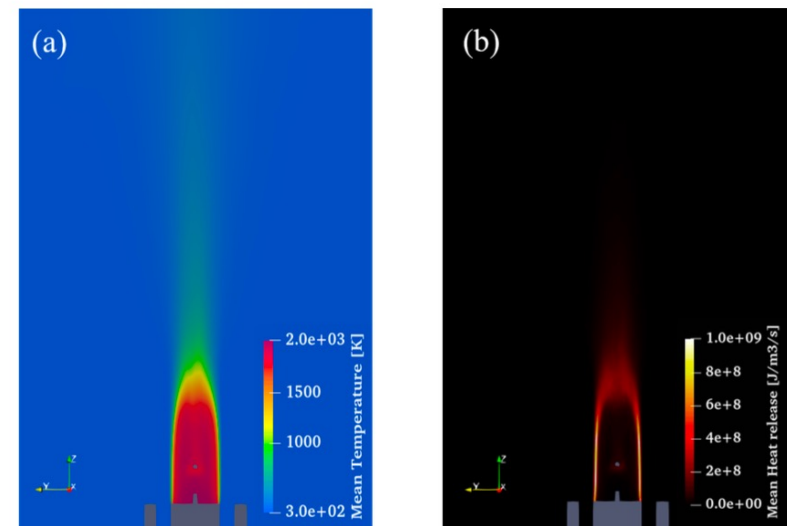
- $\phi = 0.8$

Without NRP discharge

- Weak flame
- Flame confined in the bluff-body recirculation zone



(a) Mean axial velocity. (b) Mean methane (CH₄) mass fraction



(a) Mean temperature. (b) Mean heat release

LES of the Mini-PAC burner

Premixed CH₄-air flame

- $\phi = 0.8$

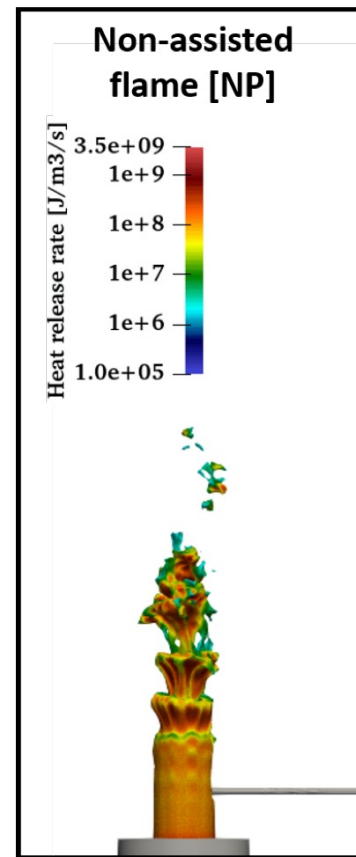
Without NRP discharge

- Weak flame
- Flame confined in the bluff-body recirculation zone

With NRP discharge

- Developed flame
- Flame propagates outside the bluff-body recirculation zone

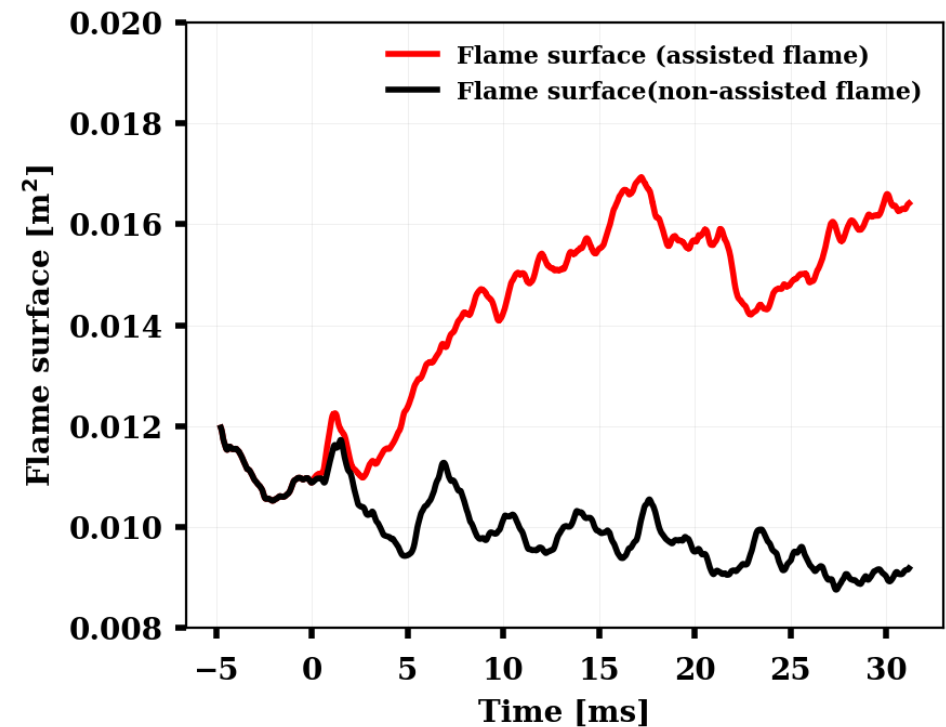
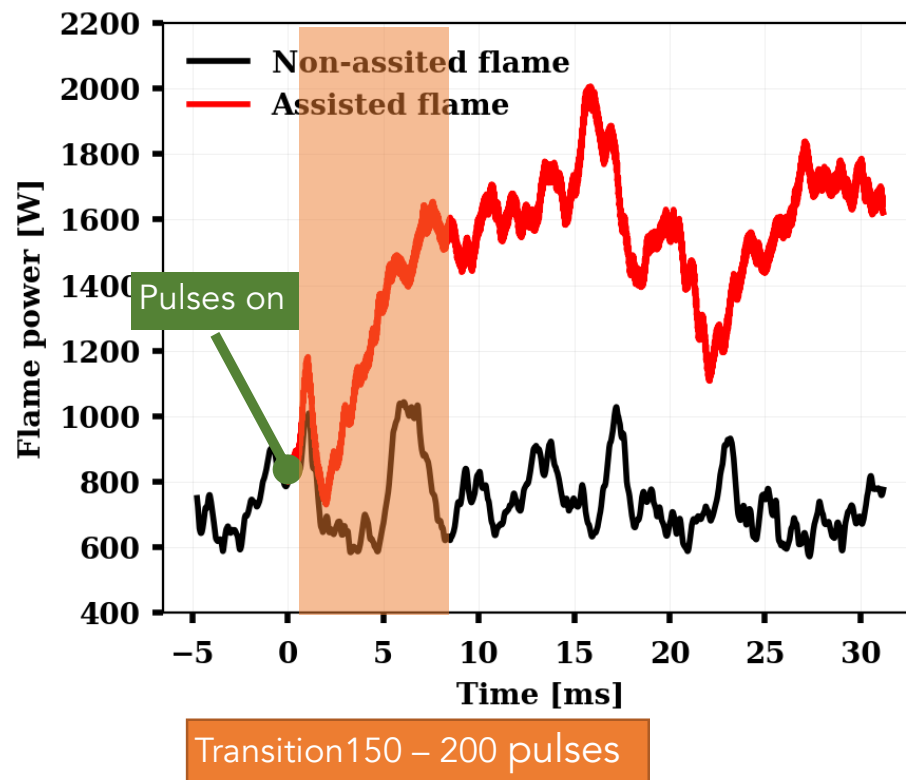
In agreement with the experiment



Flame surface colored by the heat release (left) without NRP discharge (right) with NRP discharge

LES of the Mini-PAC burner

Influence of NRP discharges on the flame power and surface



Flame power: $P = \int_V (\Xi/F) \bar{\omega}_H dV$

Flame surface: $\mathcal{A} = \int_V \Xi |\nabla c| dV$

LES of the Mini-PAC burner

Influence of NRP discharges on the flame power and surface

$\langle P_{NP} \rangle$: Total time average flame power without plasma

$\langle P_P \rangle$: Total time average flame power with plasma

Gain in power : $\eta_P = \langle P_P \rangle / \langle P_{NP} \rangle$

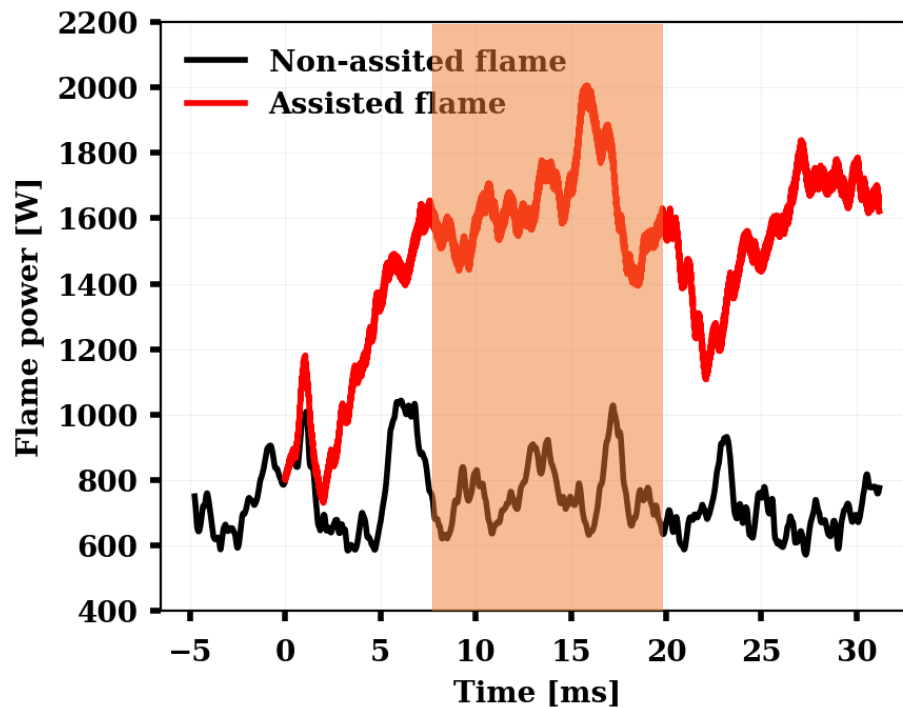
$\langle \mathcal{A}_{NP} \rangle$: Total time average flame surface without plasma

$\langle \mathcal{A}_P \rangle$: Total time average flame surface with plasma

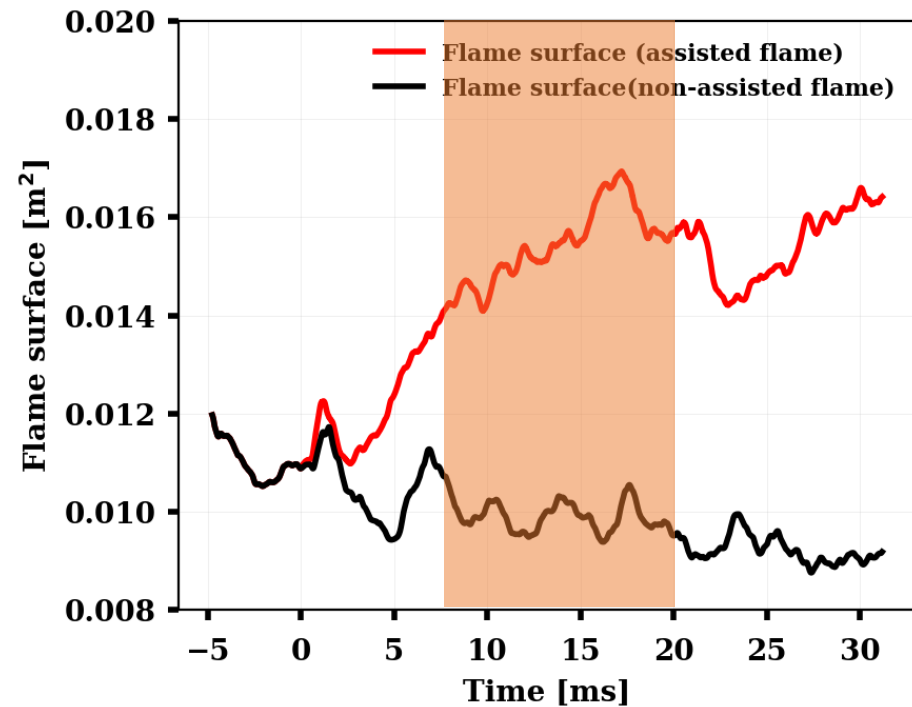
Gain in flame surface : $\eta_{\mathcal{A}} = \langle \mathcal{A}_P \rangle / \langle \mathcal{A}_{NP} \rangle$

LES of the Mini-PAC burner

Influence of NRP discharges on the flame power and surface



$$\eta_P = \langle P_P \rangle / \langle P_{NP} \rangle = 2.13$$



$$\eta_A = \langle \mathcal{A}_P \rangle / \langle \mathcal{A}_{NP} \rangle = 1.54$$

70% of the gain in flame power is explained by an increase in flame surface

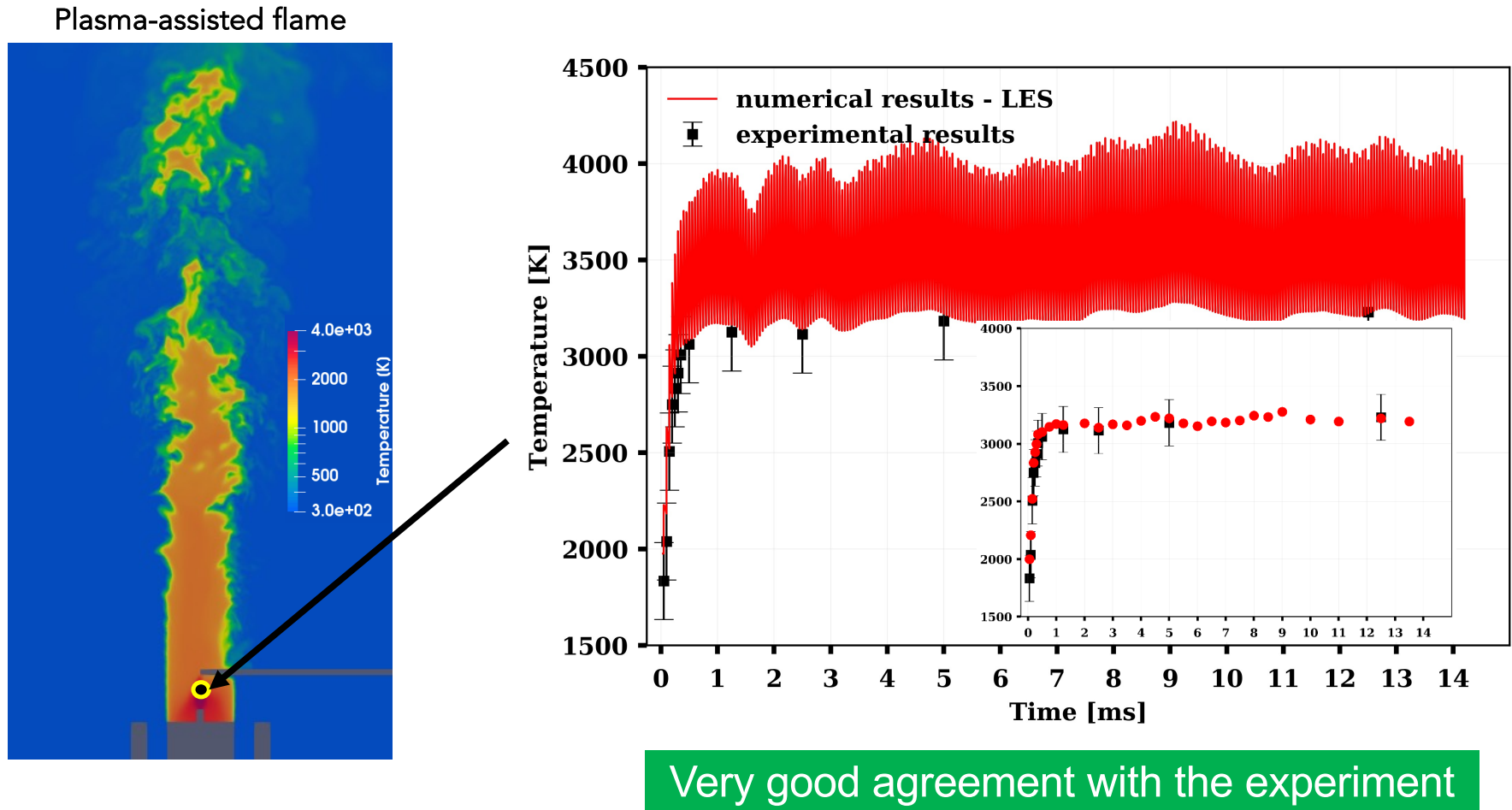
Mechanisms of flame stabilization

Question

- By what mechanisms does NRP discharge improve the combustion ?
- Where do the remaining 30% of flame power increase come from ?

Simulation - experiment comparison : Temperature

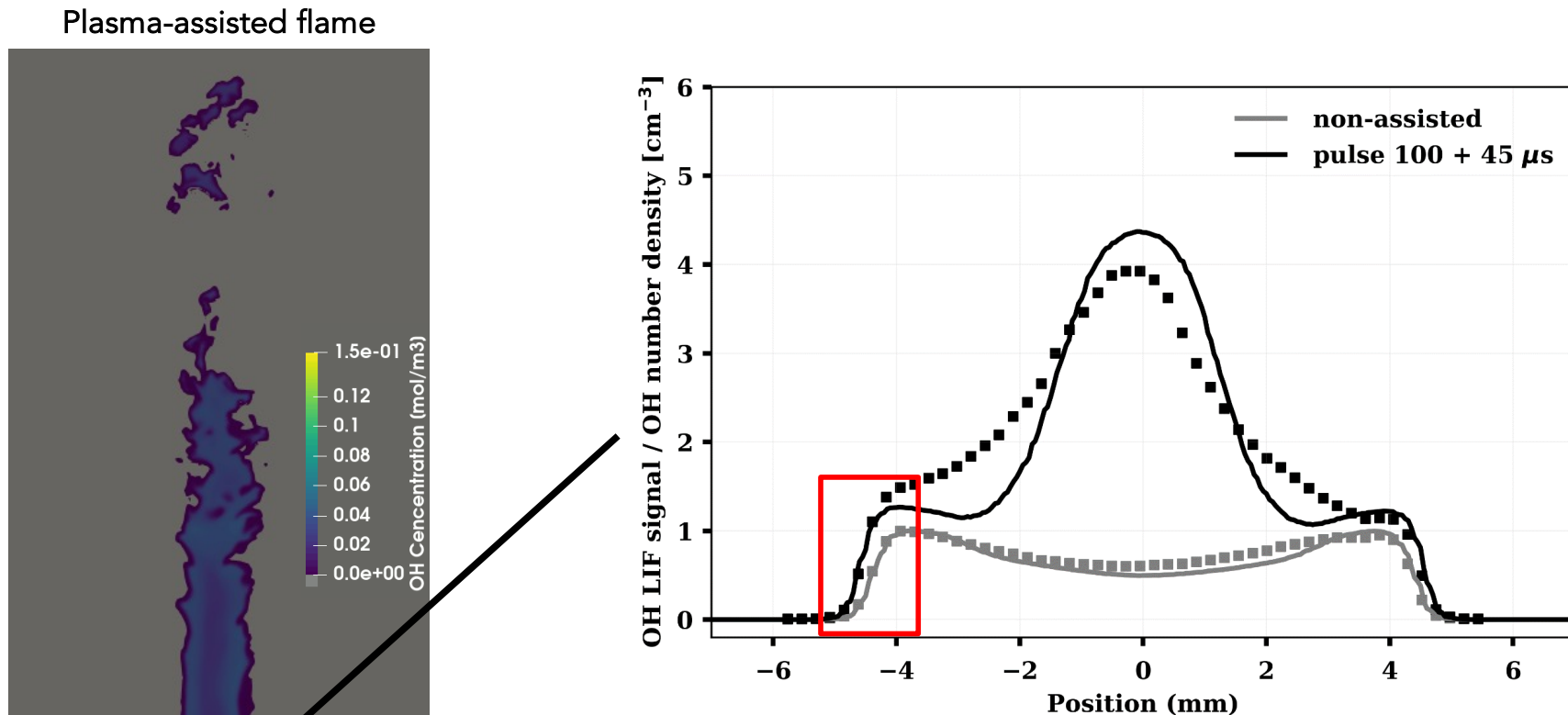
Gas temperature measured by Optical Emission Spectroscopy (OES) at the center of the discharge [1]



[1] V.P. Blanchard, N. Q. Minesi, S. Stepanyan, G.D. Stancu, C. O. Laux Dynamics of a lean flame stabilized by nanosecond discharges AIAA Scitech 2021 Forum

Simulation - experiment comparison : OH density

OH density measured by Laser Induced Fluorescence (LIF) [1]



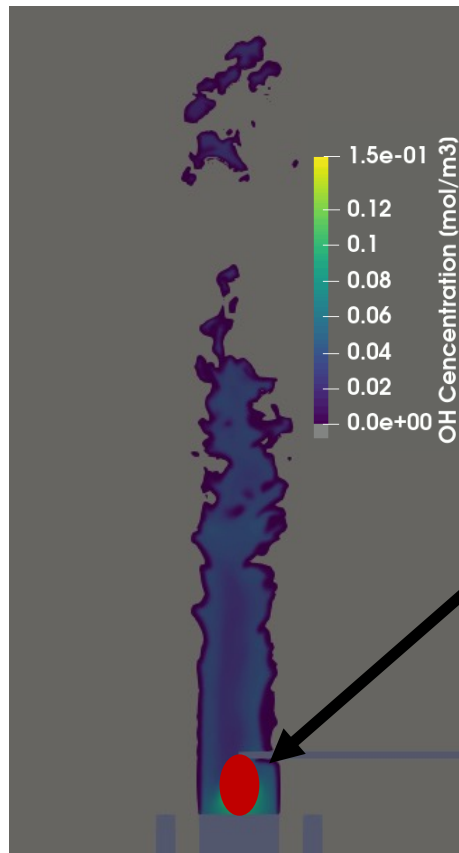
Very good agreement with the experiment

[1] N.Minesi. Thermal spark formation and plasma-assisted combustion by nanosecond repetitive discharges. Thesis (2020) Université Paris-Saclay

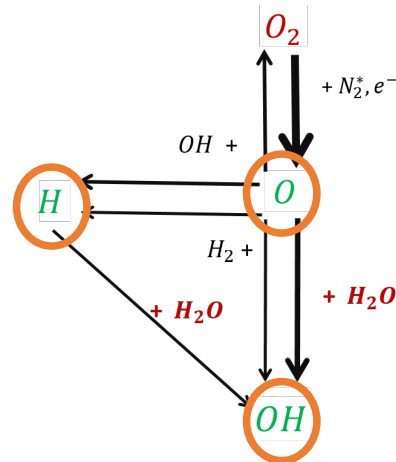
Stabilization mechanism

Chemical analysis in the discharge zone

Plasma-assisted flame

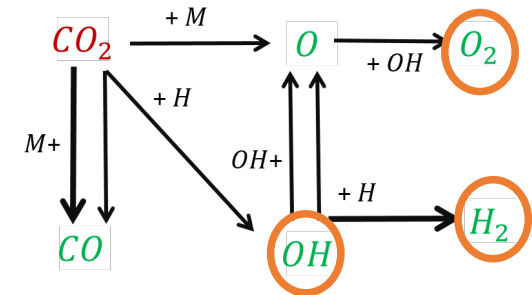


Chemical pathways during the pulse



Oxidation of H_2O by O
Production of O , OH and H

Chemical pathways after the pulse

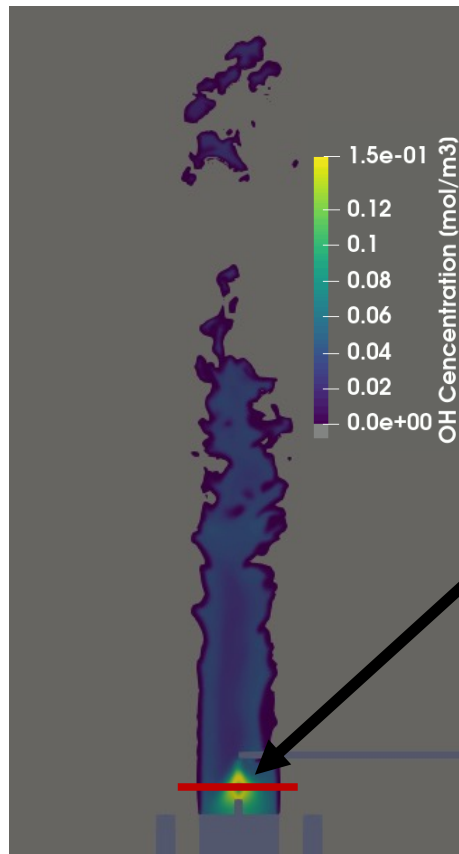


Thermo-dissociation of CO_2
Production of H_2 , CO and O_2

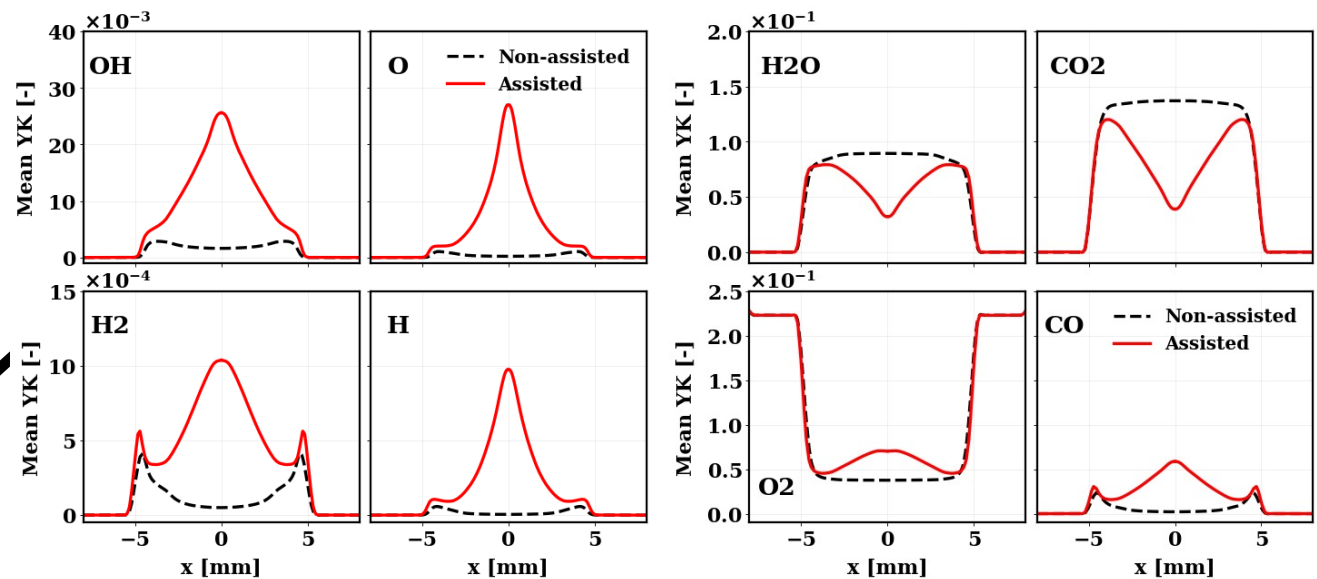
Stabilization mechanism

Convection in the recirculation zone

Plasma-assisted flame



Chemical species 1-D profiles

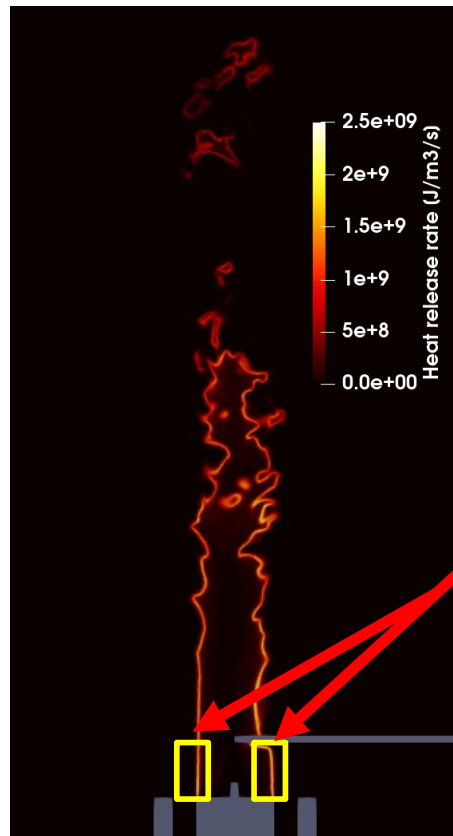


Convection of the produce species from the discharge zone toward the flame front

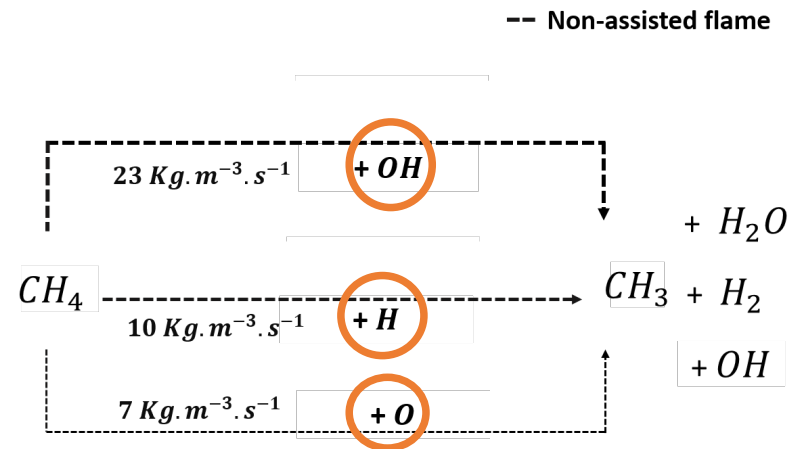
Stabilization mechanism

Chemical analysis at the flame front

Plasma-assisted flame



CH_4 consumption at the flame front

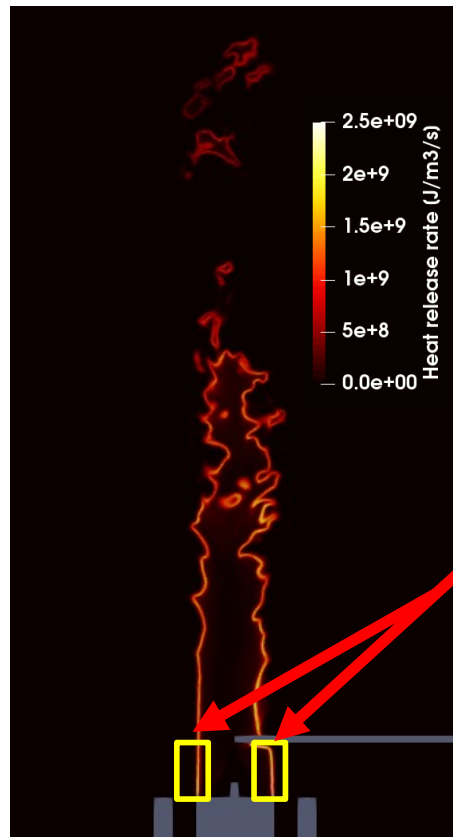


The chemical pathways of CH_4 consumption are enhance by the NRP discharges produced species

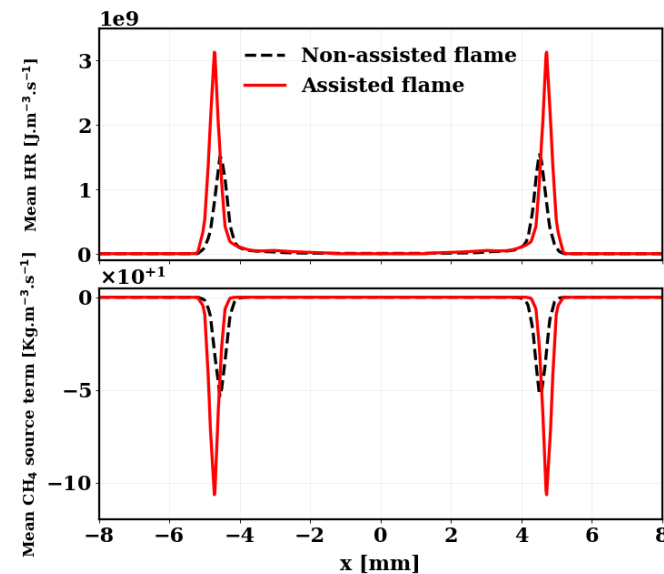
Stabilization mechanism

Chemical analysis at the flame front

Plasma-assisted flame



Heat release and CH_4 species 1-D profiles



The increase CH_4 consumption leads to an increase of the heat release and the flame speed

Stabilization mechanism

It increases the heat release
(30% of gain in flame power)

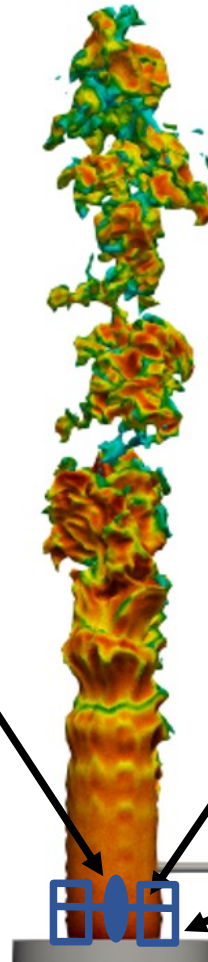
It increases the flame speed. The
total flame surface is increased
(70% of gain in flame power)

In the discharge zone, the NRPD
produces O atom and heat

- O reacts with H_2O to form OH, O, H.
- CO_2 dissociates to form OH, H_2 and O_2

OH, O and H are convected to
the flame front thanks to the
bluff-body recirculation zone

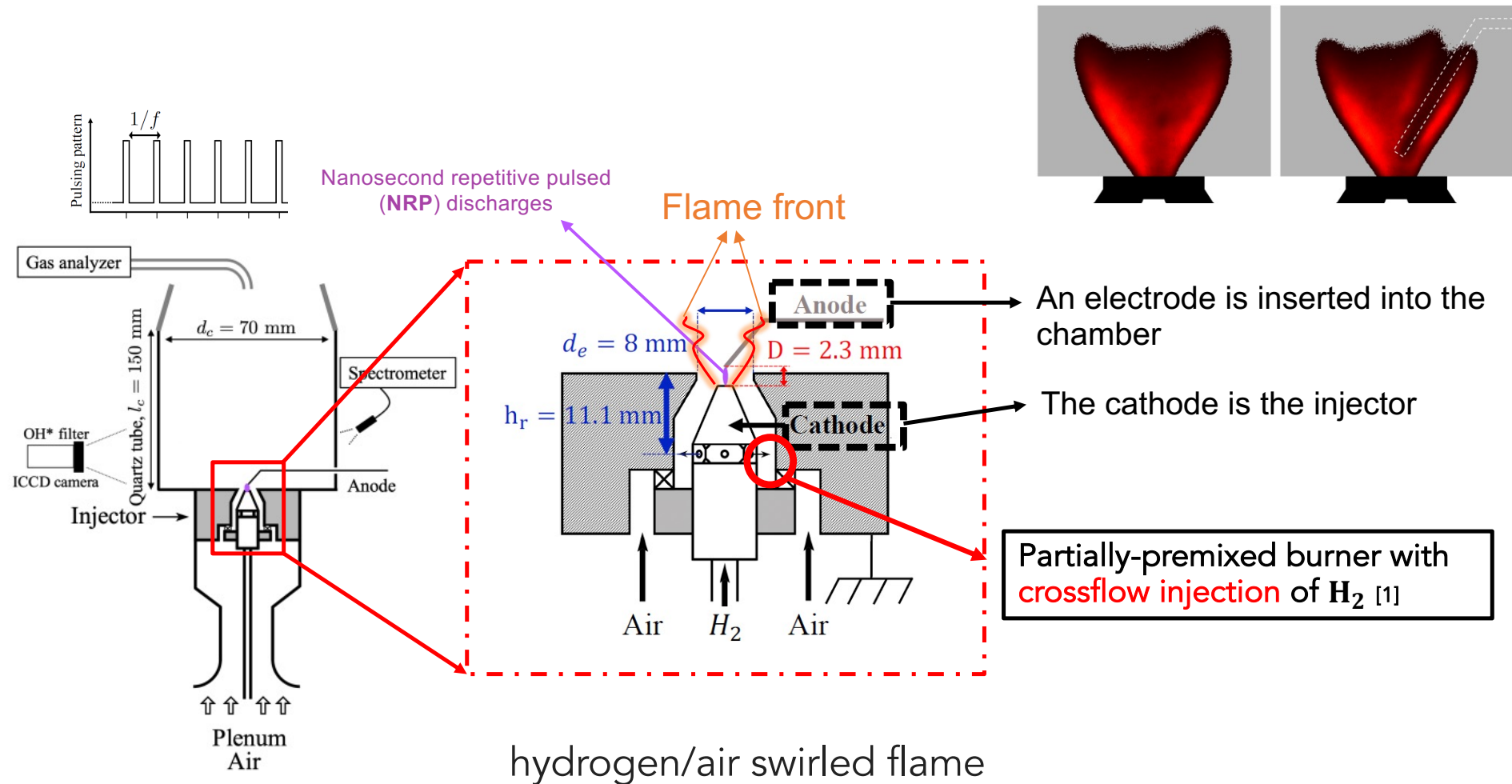
In the flame front, OH,
O and H enhance the
consumption of CH_4



Numerical simulation of flame lean blowout limit extension by NRP discharges

SICCA-H2 combustion chamber

Extend the Lean Blow-Off (LBO) limit

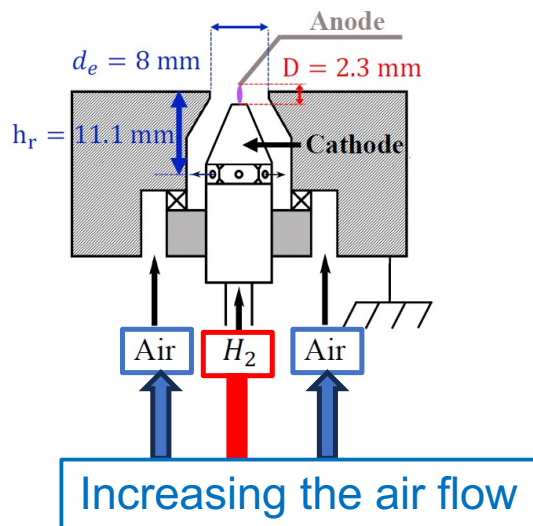


[1] J.B. Perrin-Terrin, N. Vaysse, D. Durox, R. Vicquelin, S. Candel, C. Laux, A. Renaud, *Proceedings of the Combustion Institute* 40 (1-4) (2024) 105546.

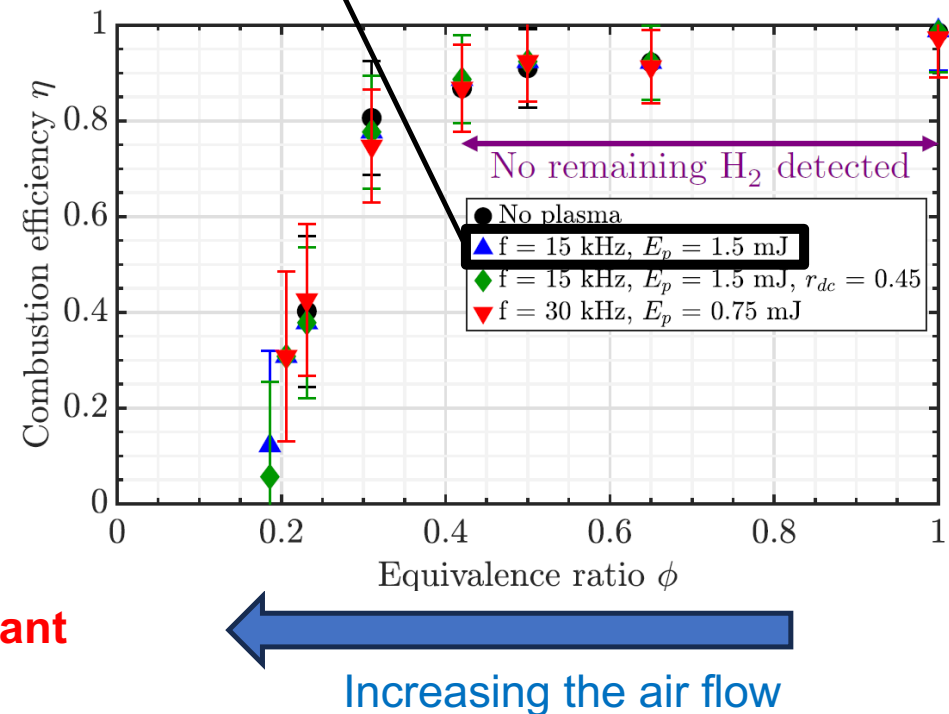
SICCA-H2 combustion chamber

Extend the Lean Blow-Off (LBO) limit

These parameters are simulated: 15 kHz, $E_p = 1.5$ mJ



The hydrogen mass flow is held constant



[1] J.B. Perrin-Terrin, N. Vaysse, D. Durox, R. Vicquelin, S. Candel, C. Laux, A. Renaud, *Proceedings of the Combustion Institute* 40 (1-4) (2024) 105546.

LES SICCA-H2 LBO simulations

Numerical set-up

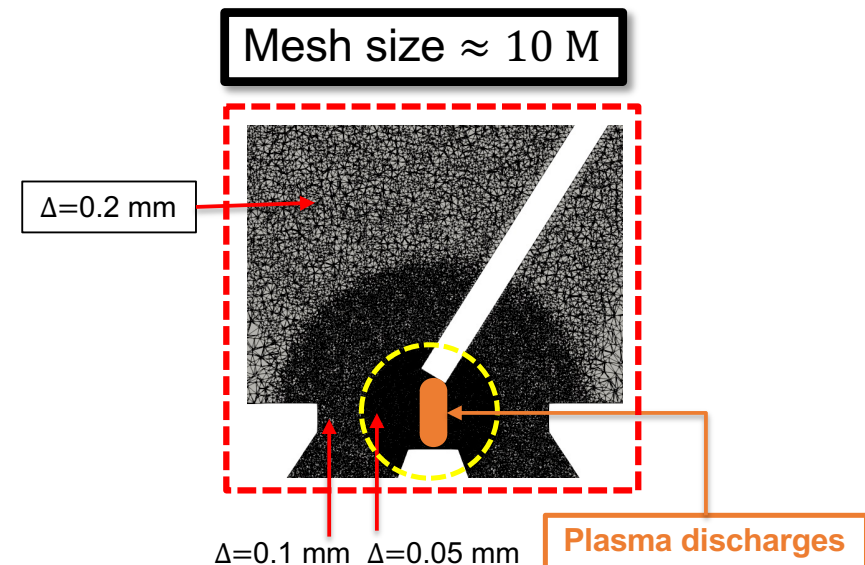
- **VDS** : Variable Density Solver
- **Time discretisation**: TFV4A 4-step, 4th order
- **Space discretisation** :
- **Space discretisation** : **Central 4th order** scheme
- **Turbulence model** : Dynamic Smagorinsky
- **Kinetic scheme** :
 - SanDiego mechanism (9 species, 21 reactions)
 - TFLES combustion model
 - Charlette model

Discharge parameters

- Pulse repetition frequency : $f_p = 15$ KHz.
- Pulse energy : $E_p = 1.5$ mJ.

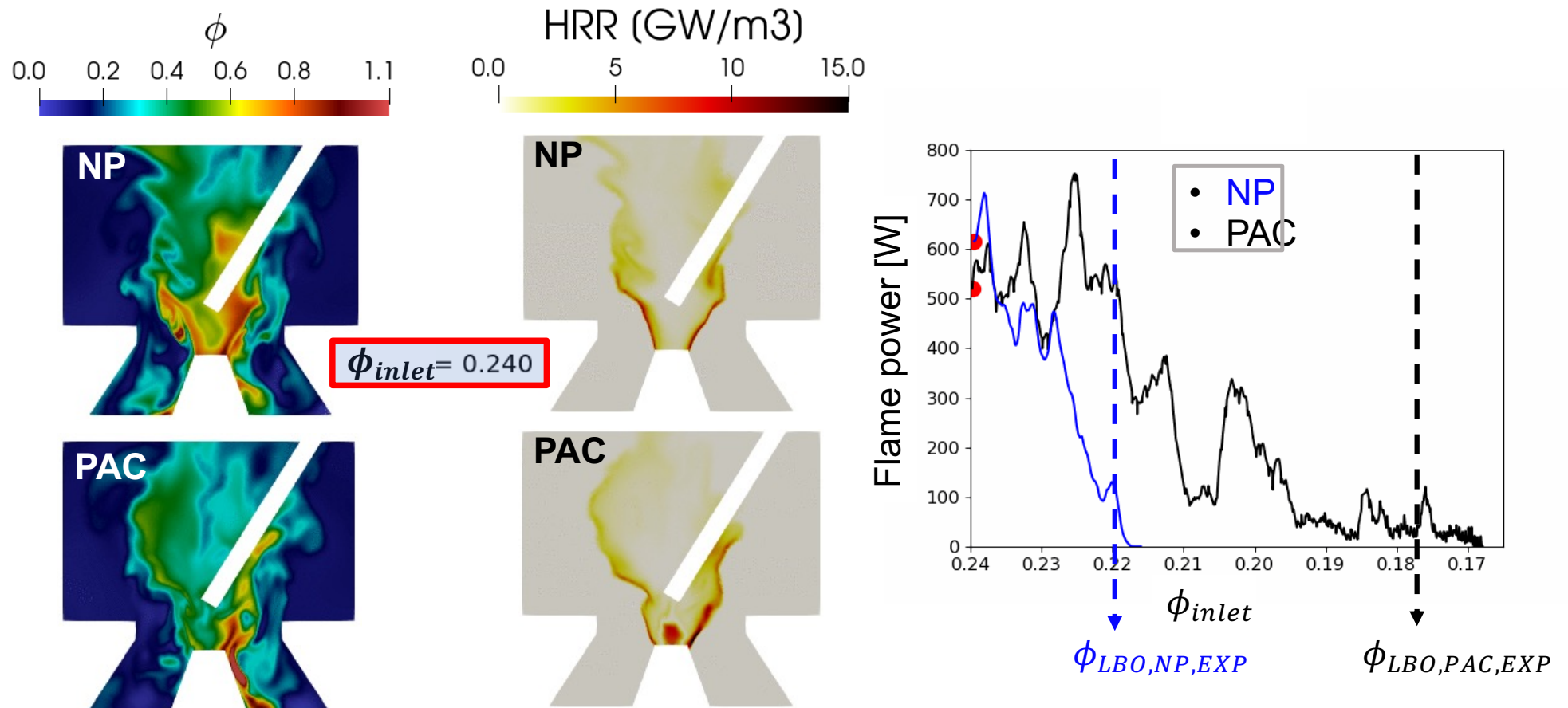
Operating conditions

- Simulations start from $\phi_{inlet} = 0.240$. (NP, PAC)
- The same increase in air flow is imposed on the NP and PAC cases ($6.70 \cdot 10^3$ (NL/min)/s)



LES SICCA-H2 LBO simulations

Extend the Lean Blow-Off (LBO) limit [1]

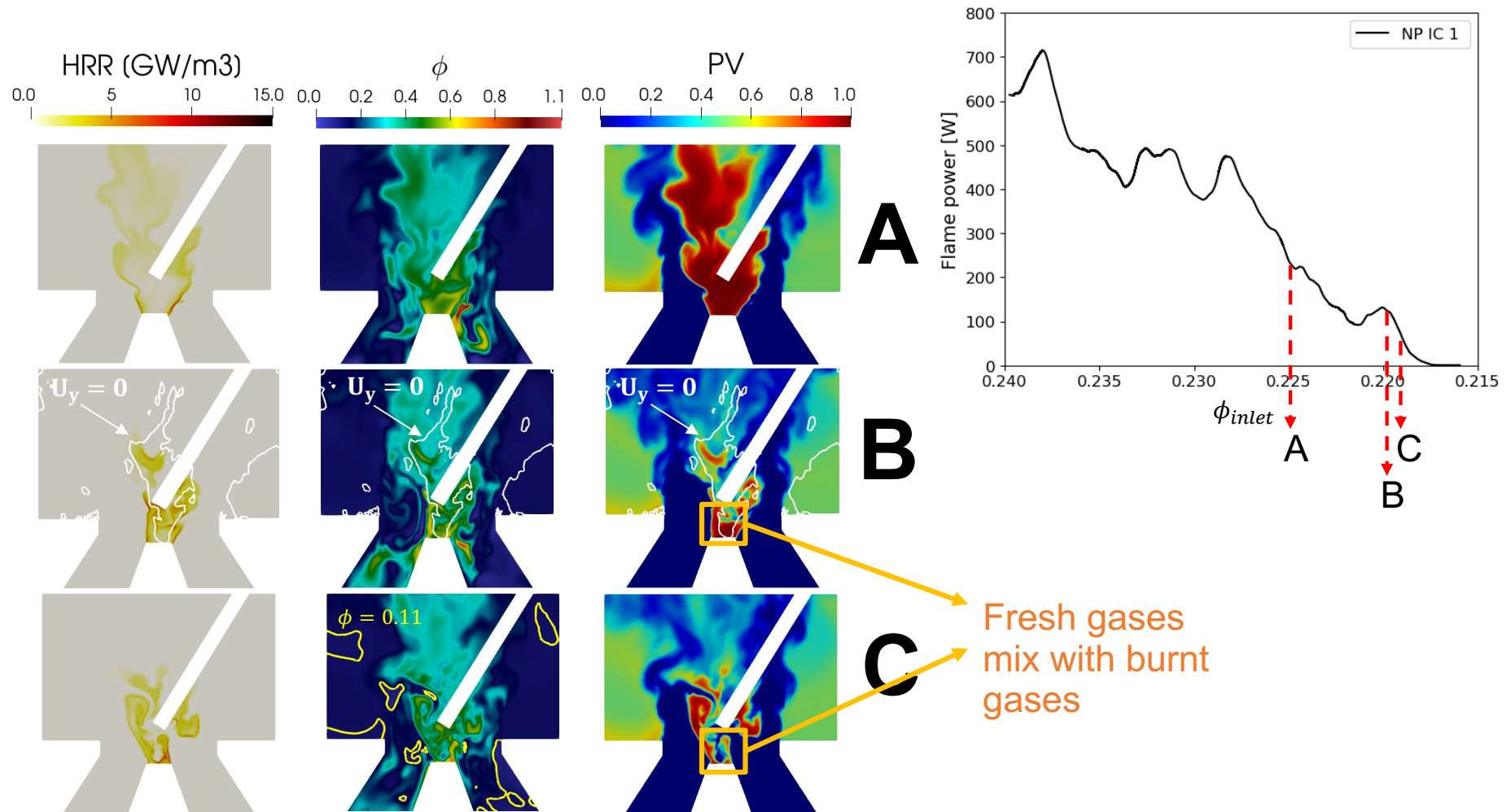


Very good agreement with the experiment

[1] B. Kruljevic et al Numerical study on the impact of Nanosecond Repetitively Pulsed discharges on the lean blowout limit for a hydrogen/air swirled flame. Combustion and Flame 277 (2025)

LES SICCA-H2 LBO simulations

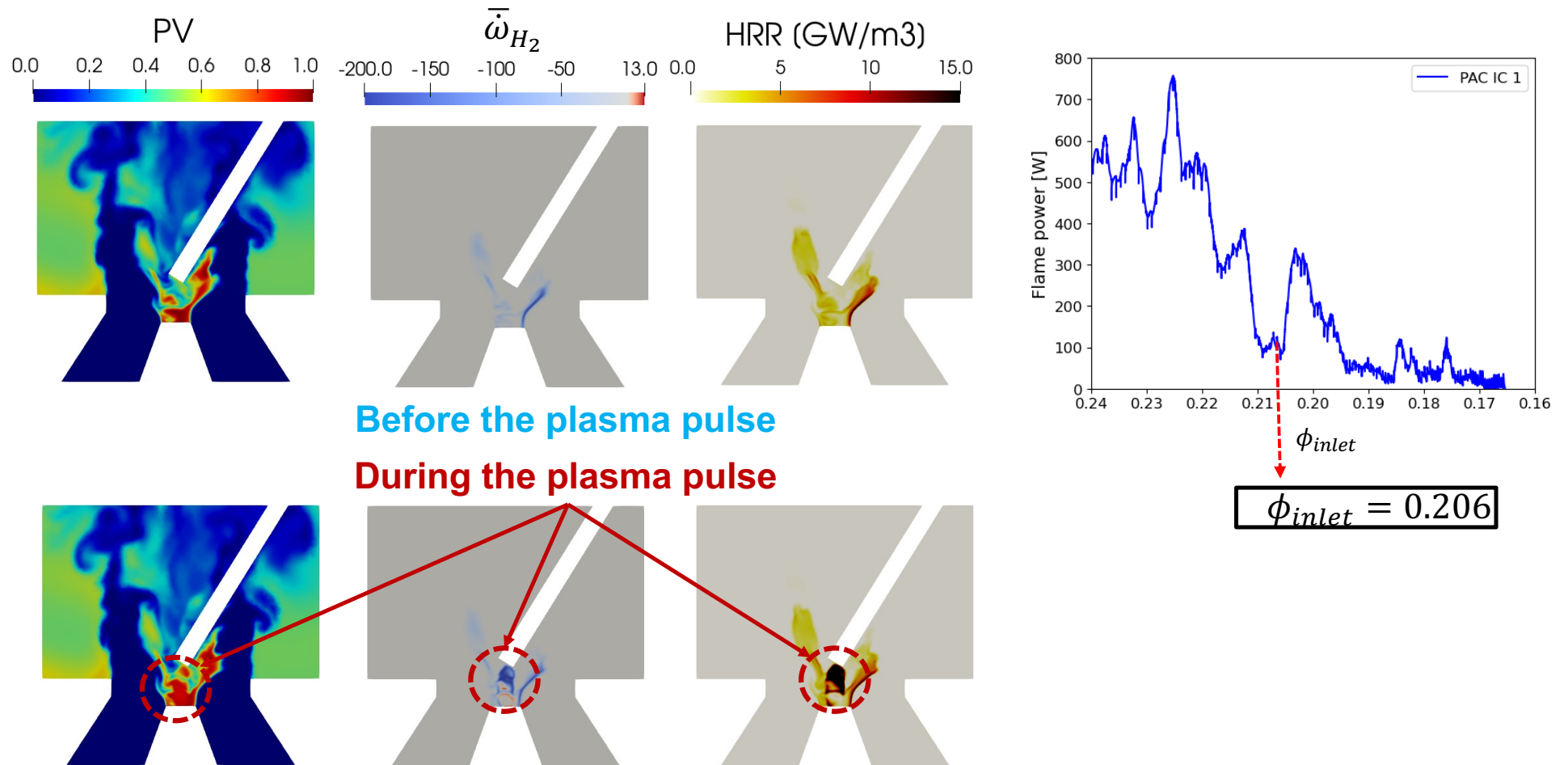
Lean Blow-Off (LBO) mechanism -NP



[1] B. Kruljevic et al Numerical study on the impact of Nanosecond Repetitively Pulsed discharges on the lean blowout limit for a hydrogen/air swirled flame. Combustion and Flame 277 (2025)

LES SICCA-H2 LBO simulations

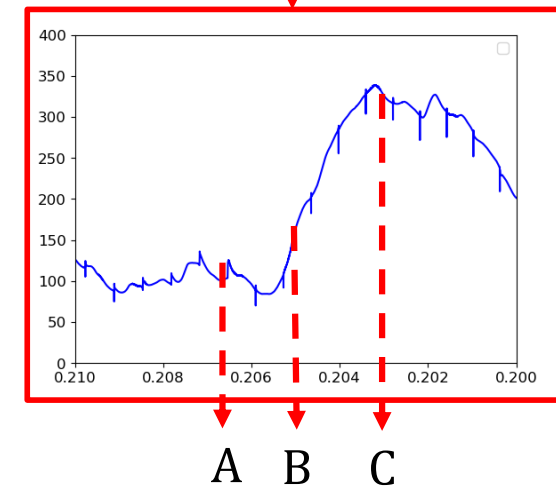
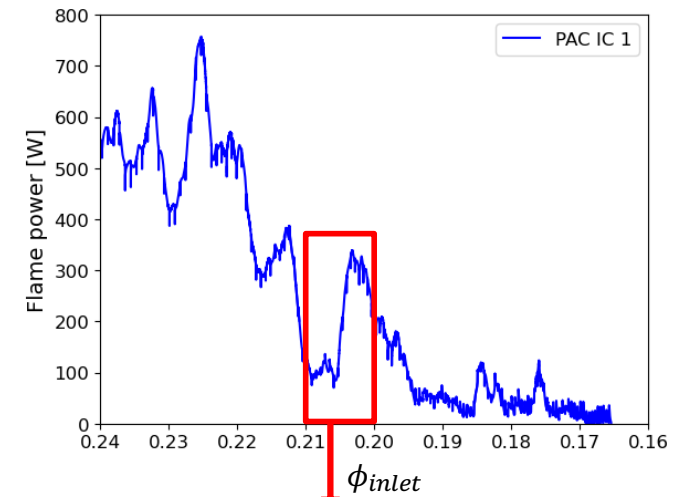
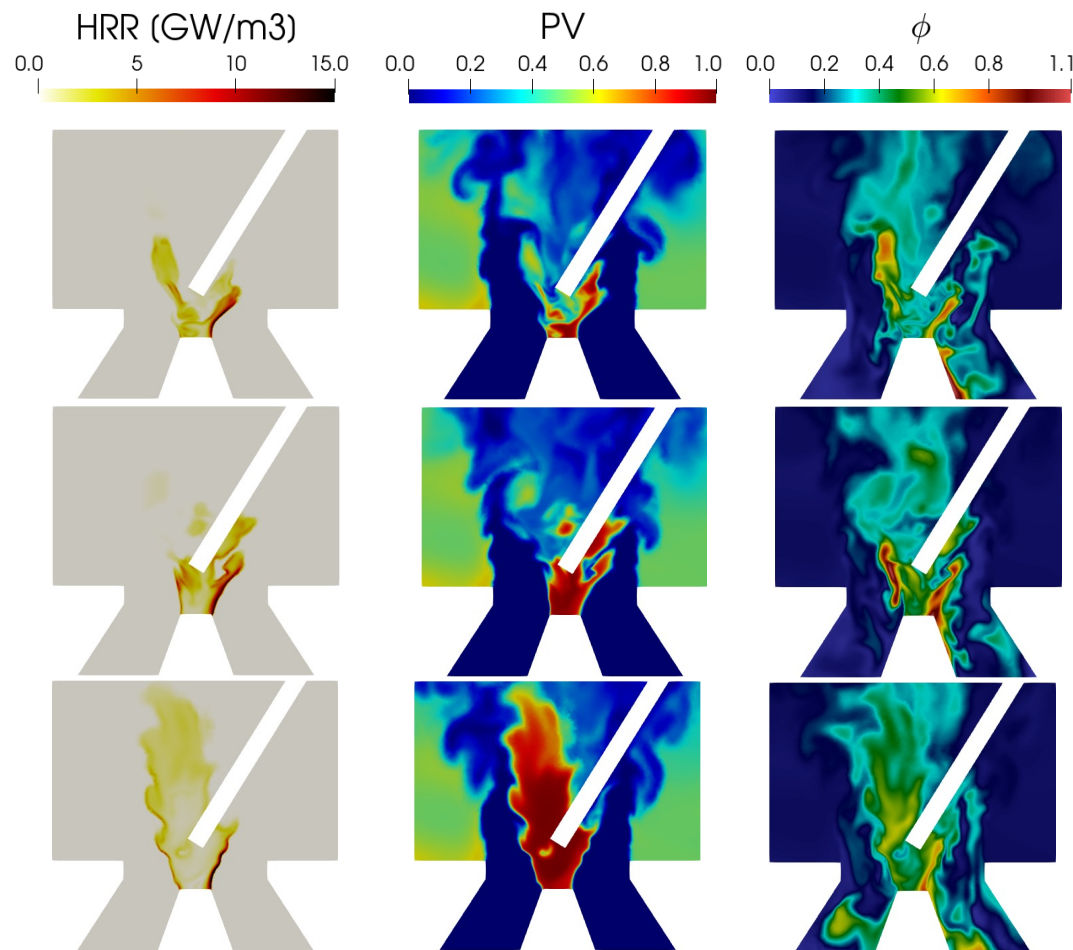
Lean Blow-Off (LBO) extension mechanism - PAC



[1] B. Kruljevic et al Numerical study on the impact of Nanosecond Repetitively Pulsed discharges on the lean blowout limit for a hydrogen/air swirled flame. Combustion and Flame 277 (2025)

LES SICCA-H2 LBO simulations

Lean Blow-Off (LBO) extension mechanism - PAC

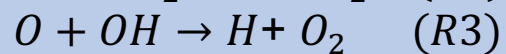
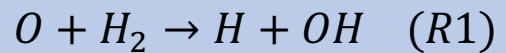


[1] B. Kruljevic et al Numerical study on the impact of Nanosecond Repetitively Pulsed discharges on the lean blowout limit for a hydrogen/air swirled flame. Combustion and Flame 277 (2025)

LES SICCA-H2 LBO simulations

Chemical analysis

Plasma in fresh gases



Plasma in products

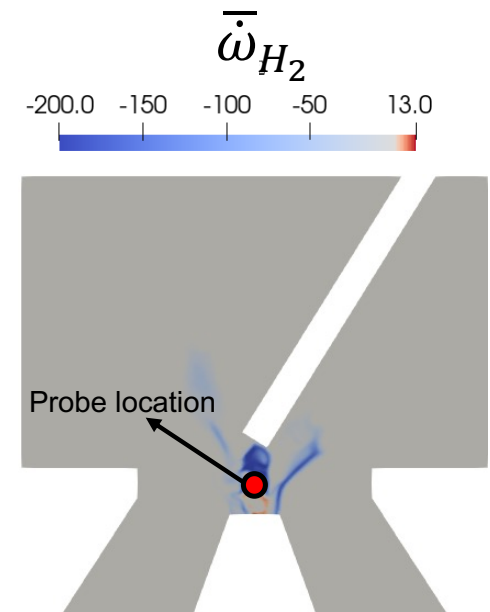
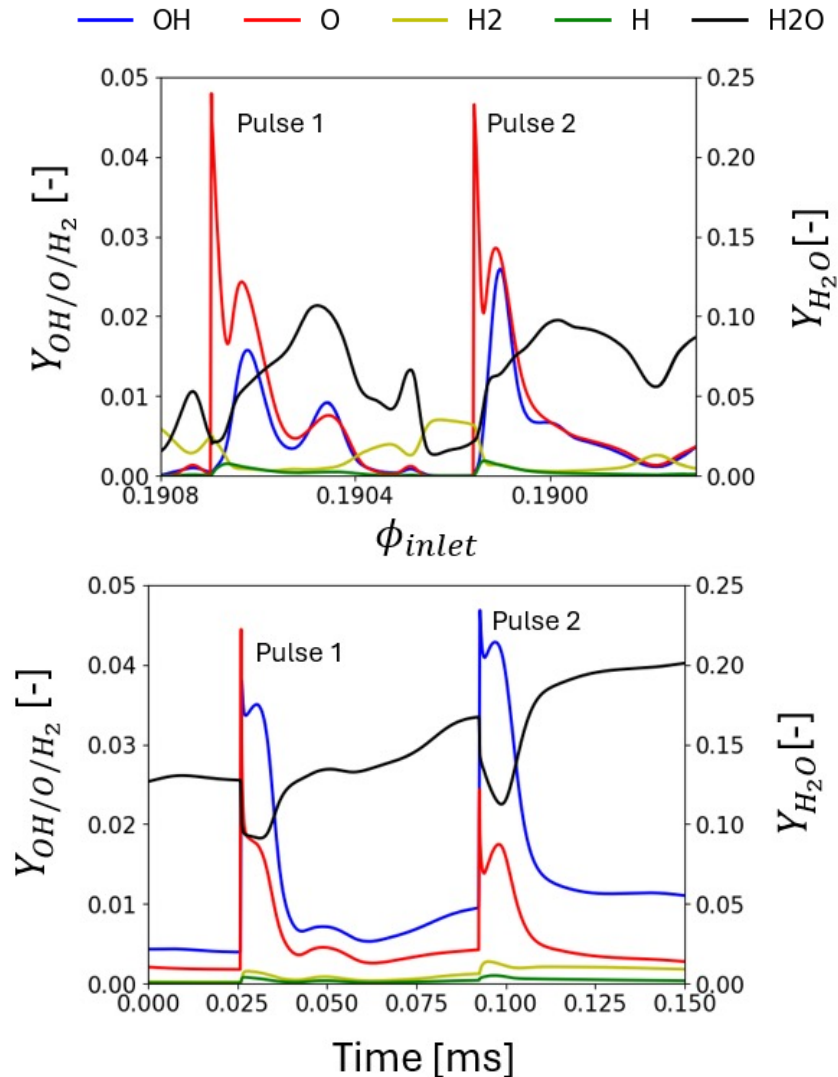
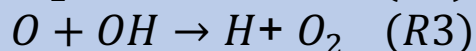
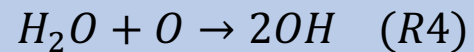


Fig : Top: The mass fractions of O, H, OH, H₂ and H₂O during two pulses, in the case when fresh gases enter the discharge zone. Bottom: The mass fractions of O, H, OH, H₂ and H₂O during two pulses at stable conditions for $\phi_G = 0.231$.

LES SICCA-H2 LBO simulations

Good agreement between the LES/PAC and experiments for the LBO limit

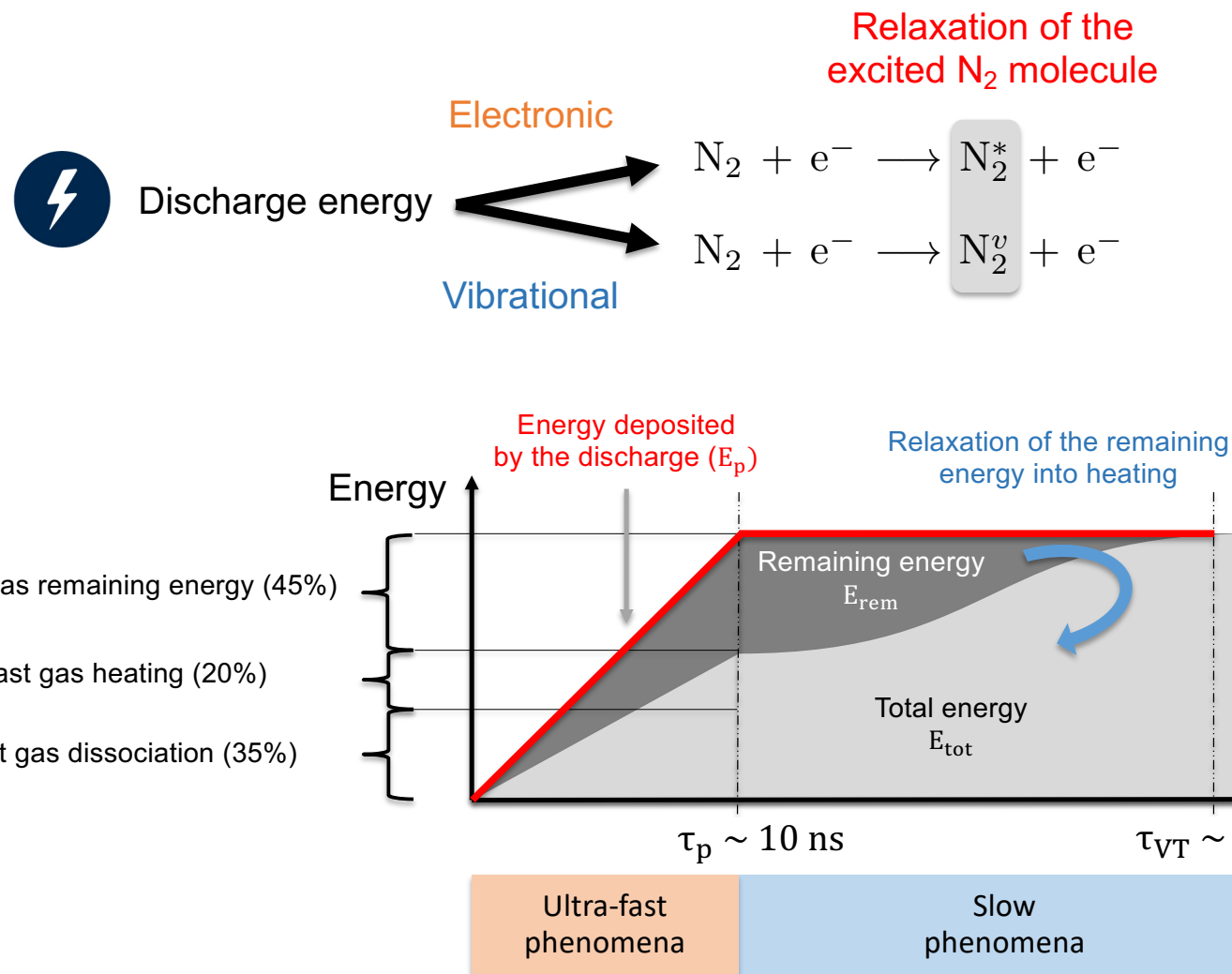
- The LBO is well predicted for both the PAC and unassisted cases
- The good agreement is true also for different initial conditions

The NRP discharges are producing radicals and heat inside of the recirculation region → stabilizing the flame

- Hydrogen is consumed when the fresh gases enter the recirculation zone
- Water is consumed when the plasma acts on the burnt gases

New modelling

Phenomenology of NRP discharges

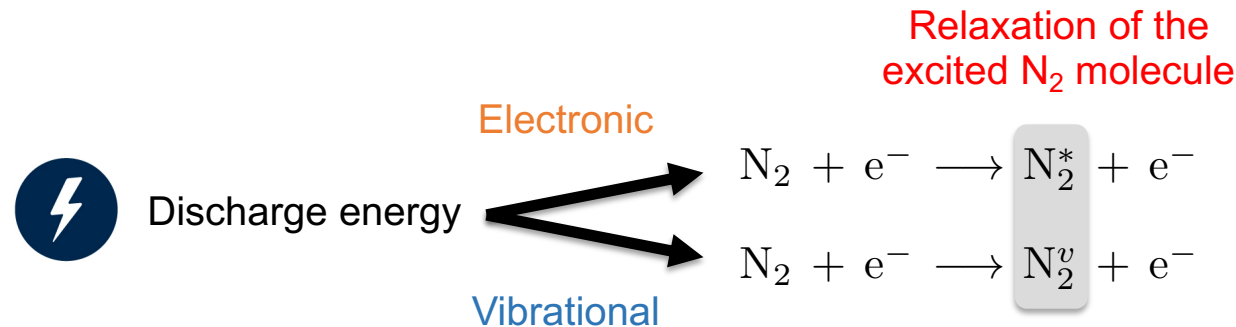


[1] D.L. Rusterholtz et al., *J. Phys. D: Appl. Phys.* 46, 2013.

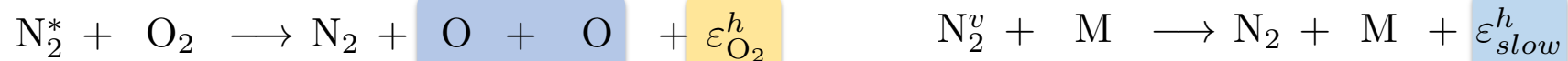
[2] N.A. Popov, *51st AIAA Aerospace Sciences Meeting*, Grapevine, Texas, USA, 2013.

[3] M. Castela et al., *Combust. Flame* 166, 2016.

Phenomenology of NRP discharges

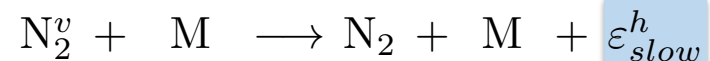
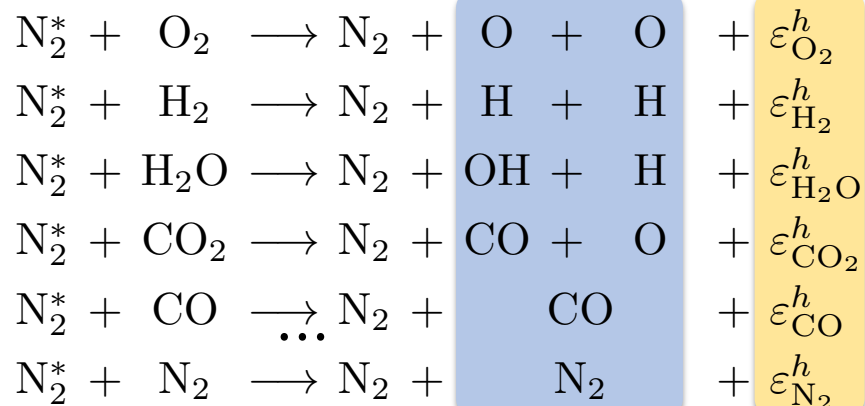


In pure air



➔ **Model of:** Castela et al., *Combust. Flame* 166, 2016.

In burnt gases

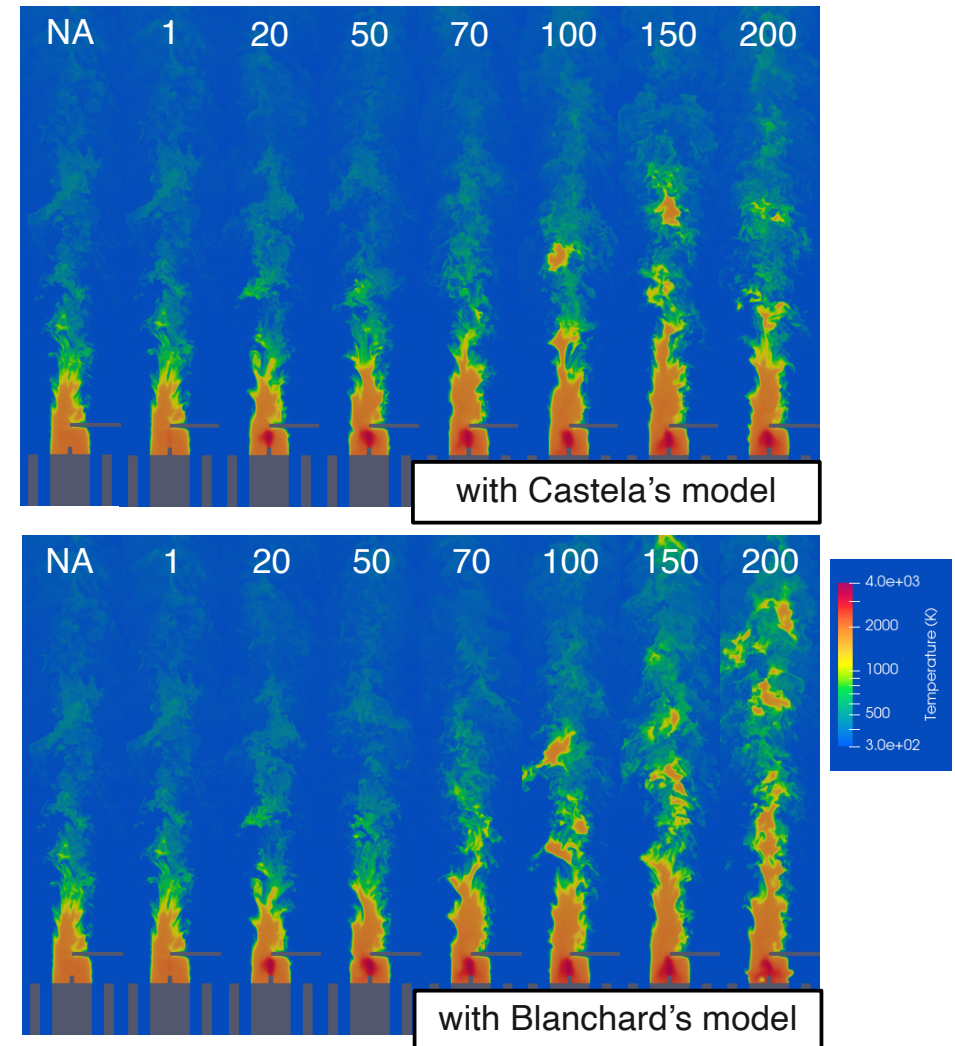
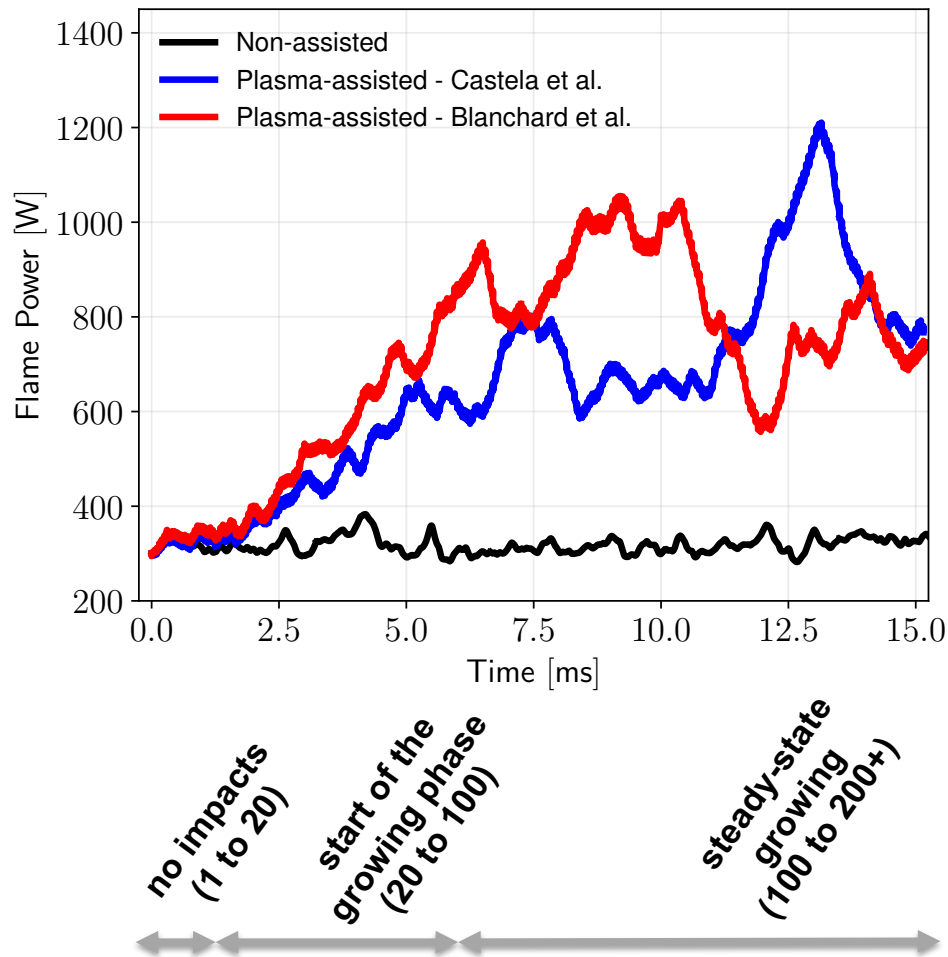


➔ **Model the dissociation of other species!**

Model of: Blanchard (Ph.D. thesis, Univ. Paris-Saclay, France, 2023)

LES of the Mini-PAC burner

Evolution: Flame power

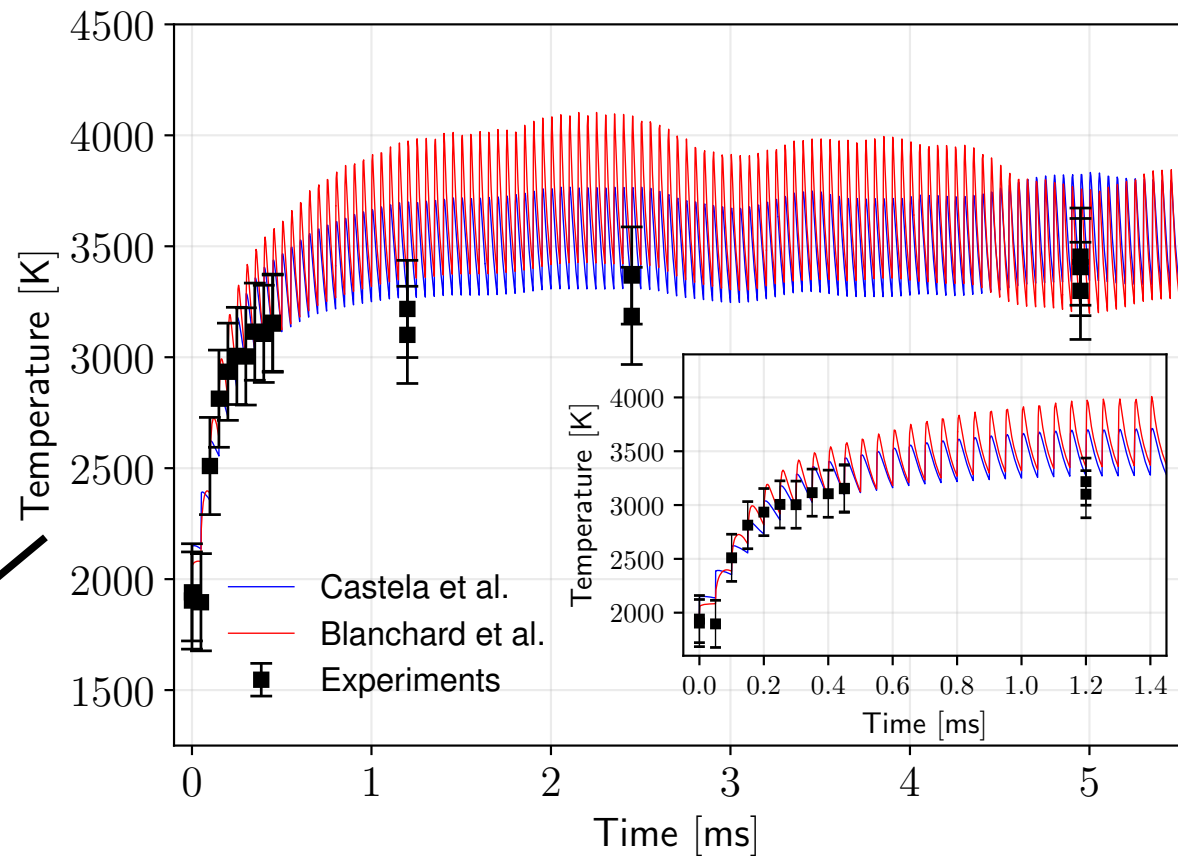
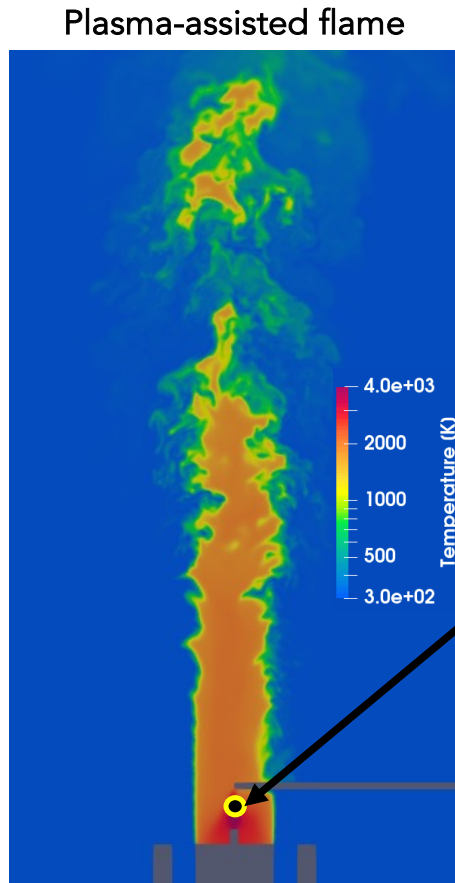


➔ Overall: similar results for Mini-PAC

[1] S.Q.E. Wang, Y. Bechane, V. P. Blanchard, C. Lacour, C. O. Laux and B. Fiorina. Impact of N2* quenching process modeling on large-eddy simulation of plasma-assisted combustion. CST-MCS (2025)

LES of the Mini-PAC burner

Evolution: Gas temperature

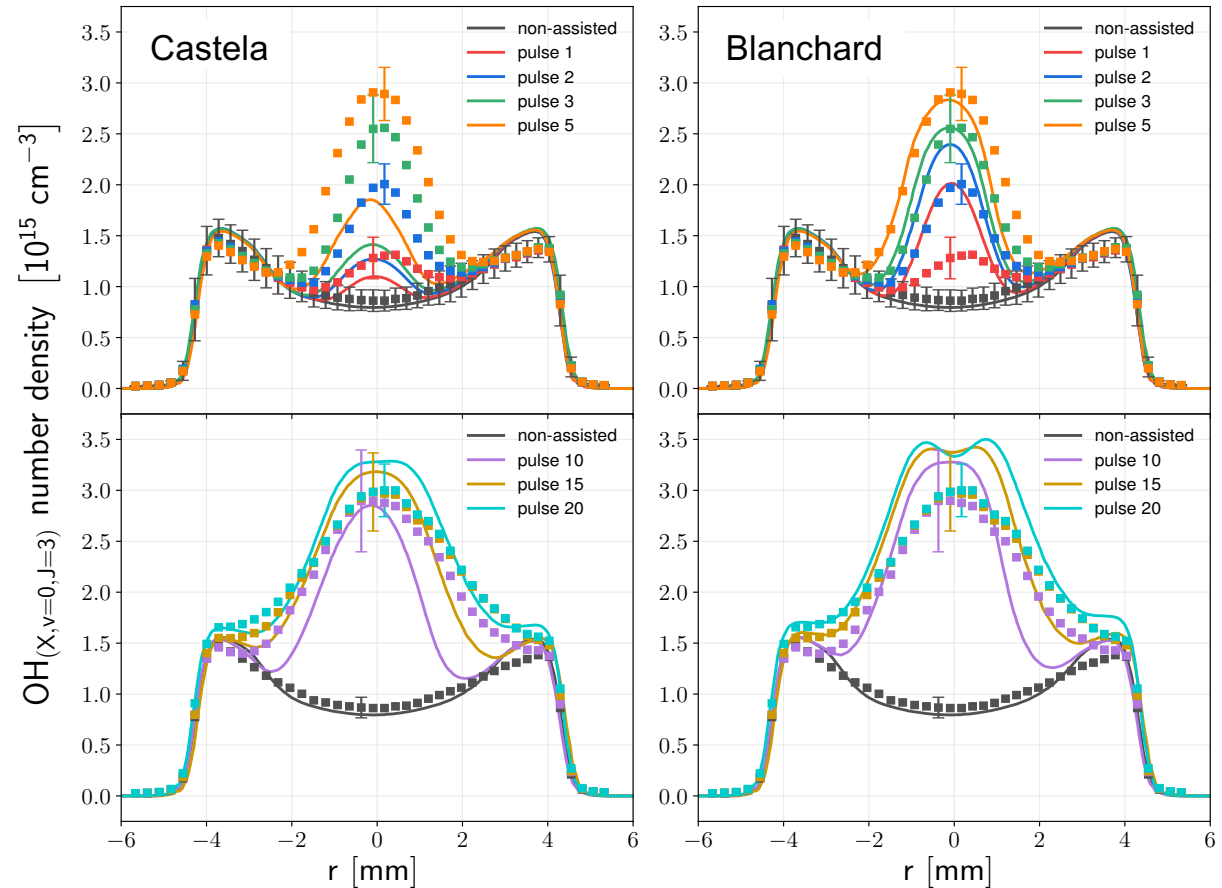
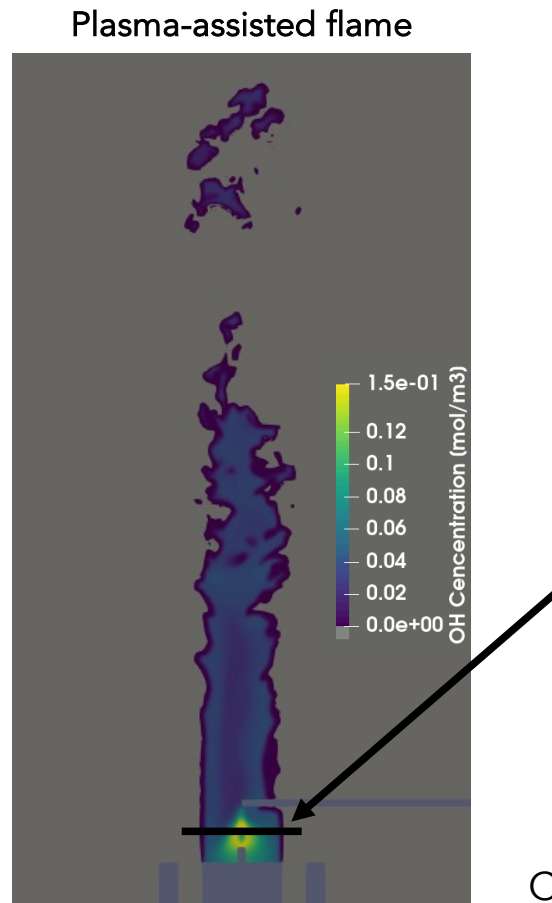


➔ Overall: similar results for Mini-PAC

[1] S.Q.E. Wang, Y. Bechane, V. P. Blanchard, C. Lacour, C. O. Laux and B. Fiorina. Impact of N2* quenching process modeling on large-eddy simulation of plasma-assisted combustion. CST-MCS (2025)

LES of the Mini-PAC burner

Evolution: OH number density



Comparison Castela's/Blanchard's model:

- ☐ Similar results at steady-state pulsing and growing regimes.
- ☐ Slight better performance of Blanchard's during transient phase.

[1] S.Q.E. Wang, Y. Bechane, V. P. Blanchard, C. Lacour, C. O. Laux and B. Fiorina. Impact of N₂* quenching process modeling on large-eddy simulation of plasma-assisted combustion. CST-MCS (2025)

Perspectives

Question

- What about Nox production?