Combustion Assisted by Nanosecond Repetitively Pulsed Plasmas

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Contents

Motivation

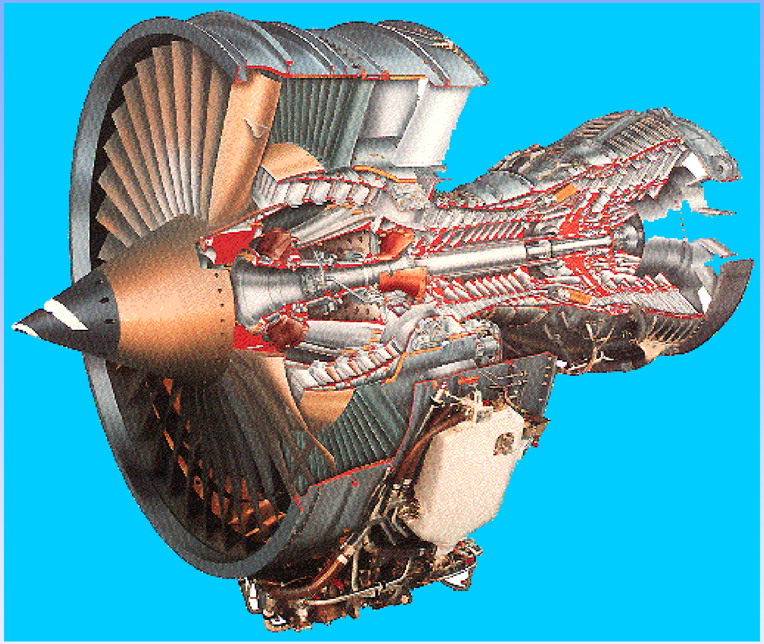
- Internal combustion engines
- Industrial burners (domestic heating, …)
- Gas turbine engines
  - Subsonic aircraft
  - Energy production
- SCRAMJETS (super-stato-réacteurs)

Internal combustion engines

Objectives:

- **Burn lean or diluted fuel/air mixtures to reduce pollutant emissions**
- **Reduce ignition delay**

Gas turbine/aircraft engines



- **Objective: burn lean fuel/air mixtures to reduce pollutant emissions**

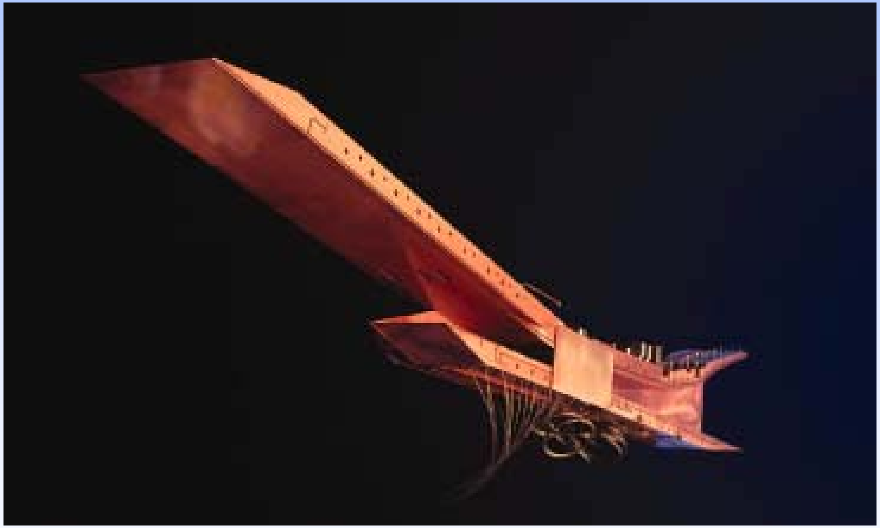
Scramjet engines for hypersonic aircraft

Hyper-X (NASA)

- Mach 7-10
- Hydrogen-fueled

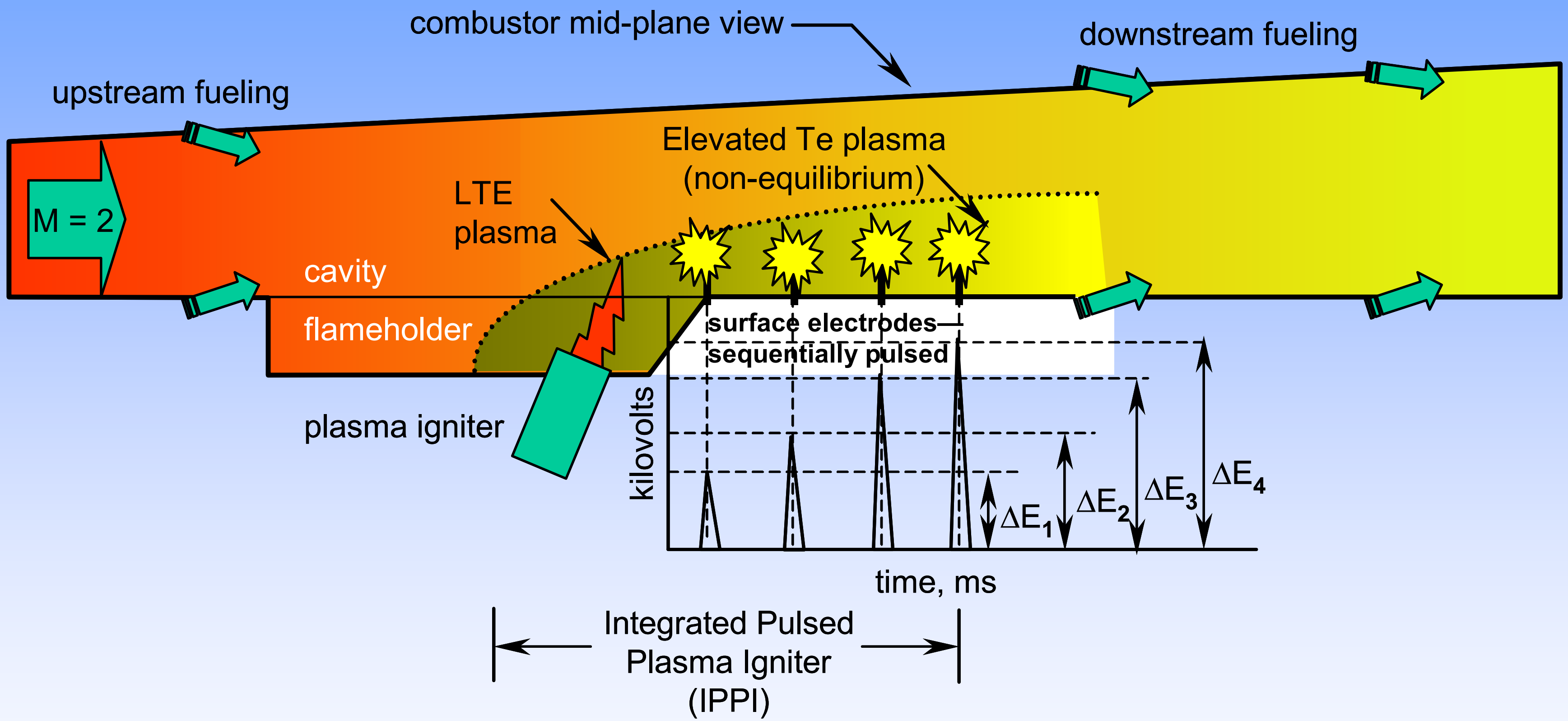
HyTech (AFOSR)

- Mach 4-8
- Hydrocarbon-fueled



- **Objective: ignite chamber**

Scramjet engines for hypersonic aircraft



Discharges for PAC

Sparks (arcs)

Glow discharges (DC or pulsed)

Filamentary discharges (DC or pulsed)

Laser discharges (DC or pulsed)

- **Article Review:** **S. M. Starikovskaia, "Plasma assisted ignition and combustion",** J. Phys. D: Appl. Phys. **39** (2006) R265–R299

Nanosecond discharges

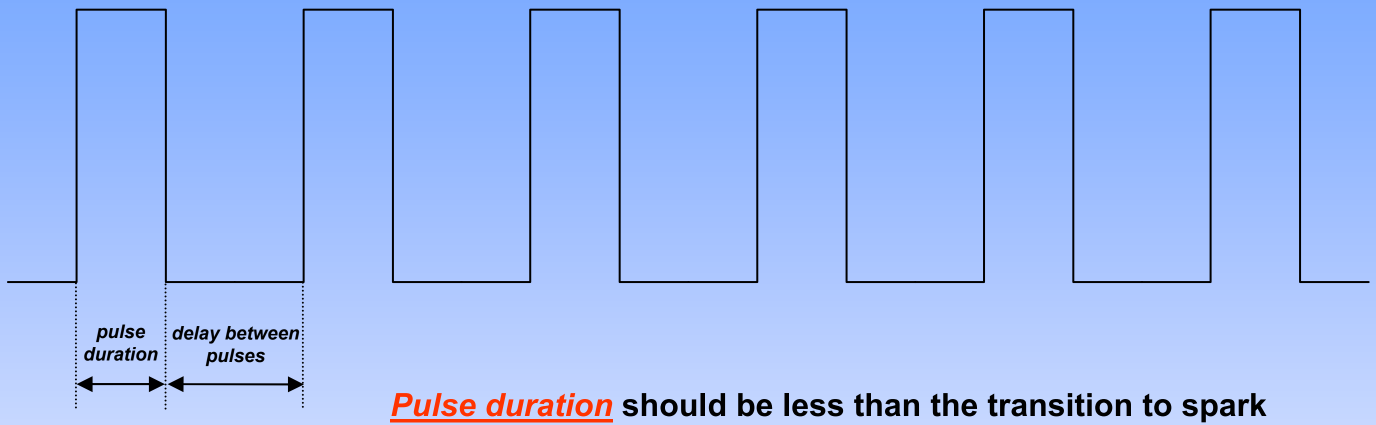
$K=V/V_{breakdown}$

- Single pulses (widely used for pas 15 years)
  - Townsend: $K < 1$
  - Streamer/filament: $K \geq 1$
  - Fast Ionization Wave: $K>>1$

- Repetitive nanosecond pulses (proposed and demonstrated at Stanford University 1999-2002)
  - Glow: $K < 1$
  - Streamer/filament: $K \geq 1$
  - (FIW: $K>>1$)

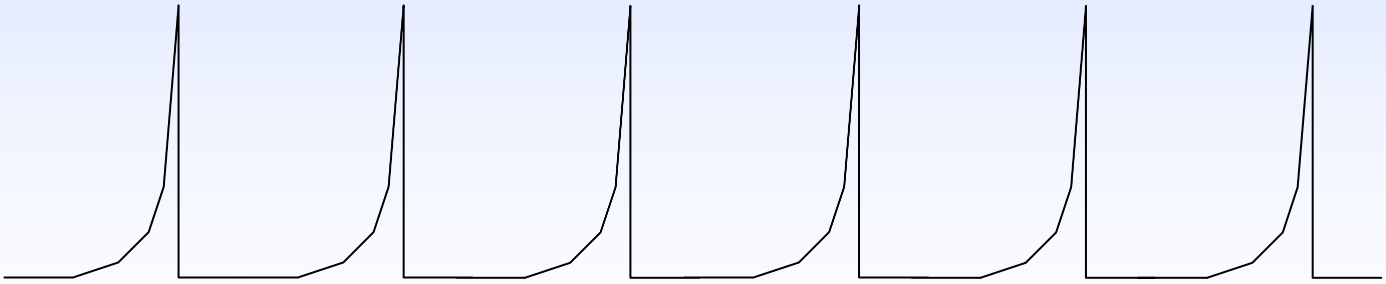
Repetitively pulsed discharges

VOLTAGE



Pulse duration **should be less than the transition to spark**
Delay between pulses **should match the relevant recombination time**

CURRENT

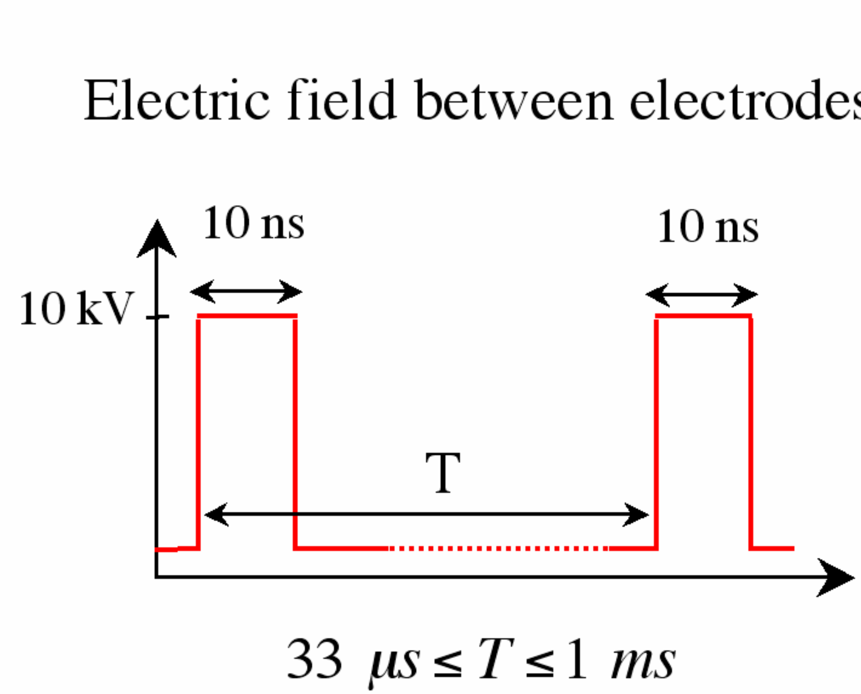


Energy deposition per pulse is very small (3 mJ for 5 kV / 10 ns pulses).

Typical repetitive nanosecond discharge system

Characteristics

- Up to 10 kV amplitude
- 10 ns long
- Fast rise time ~ 2 - 3 ns
- Repetition rate: 1 - 30 kHz



$33\ \mu s \leq T \leq 1\ ms$

Two discharge regimes:

- Low voltage: diffuse glow discharge
- High voltage: filamentary discharge

Two applications

Flame ignition in ICE (Internal Combustion Engines)

Propose an alternative to conventional spark plug systems, which have several limitations:

- Inability to ignite lean or diluted mixtures
- Localized ignition
- Cathode erosion

Flame stabilization in LPP (Lean Premixed Prevaporized) reactors

Lean flames burn at lower temperatures, thus emit fewer pollutants (NOx, soot), but are unstable

Ignition of Propane-Air Mixtures by a Sequence of Nanosecond Pulses

S. Pancheshnyi, D.A. Lacoste, A. Bourdon, C.O. Laux

Conventional vs. Repetitive Nanosecond Ignition Systems

SPARK PLUG SYSTEM

1. Siemens HOM 7700 732 263 pulse voltage generator (12V, 5A):
    - Amplitude: 25 kV
    - Duration: 1.5-2.0 ms
    - Peak pulse power: 20 W
    - Pulse energy: 60 mJ
2. BOSCH ZR6SPP332 spark plug

REPETITIVE NANOSECOND DISCHARGE SYSTEM

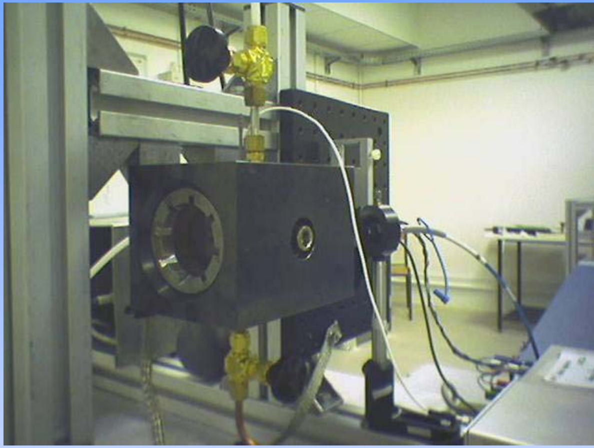
1. FPG 10-30MS pulse generator:
    - Amplitude: 5 kV
    - Duration: 10 ns (fixed)
    - Repetition rate: 1-30 kHz
    - Peak pulse power: 500 kW
    - Max pulse energy: 3 mJ
2. Point-to-plane geometry with 1.5-mm interelectrode distance.
    - BOSCH Y6DC spark plug
    - Grounded disk 10 mm in diameter

Ignition and breakdown

- Ignition requires breakdown of the combustible mixture
- Breakdown occurs when the voltage becomes larger than a certain value (the breakdown voltage): 3-4 kV/mm/bar.
- If one keeps applying voltage after breakdown, we get a spark
  ⇒ gas heating, high energy consumption, erosion
- For car engine ignition, breakdown requires very high voltages (45-60 kV at 15 bars)
  ⇒ technological issues, EM interferences,…
- Alternate approach: use train of pulses below the breakdown voltage

Experimental setup

60-cm^3 steel chamber with 2 quartz windows



Pressure range: 0.4 – 2.5 bar.

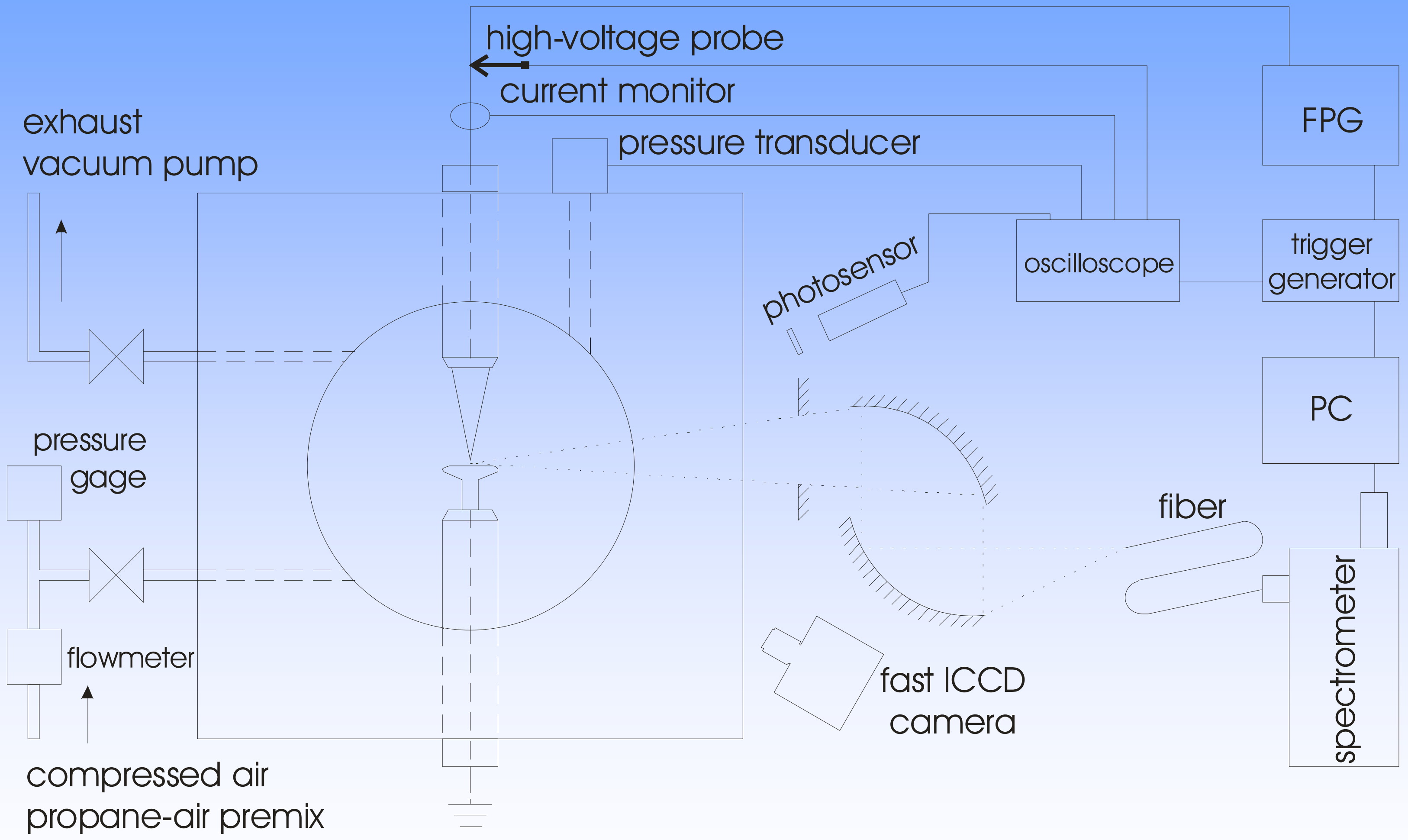
Mixtures used:

- Dry air
- Propane-air
  - Stoichiometric
  - Lean ($\phi = 0.7$)
  - Stoichiometric mixture with 30% N_2 dilution

Measurements:

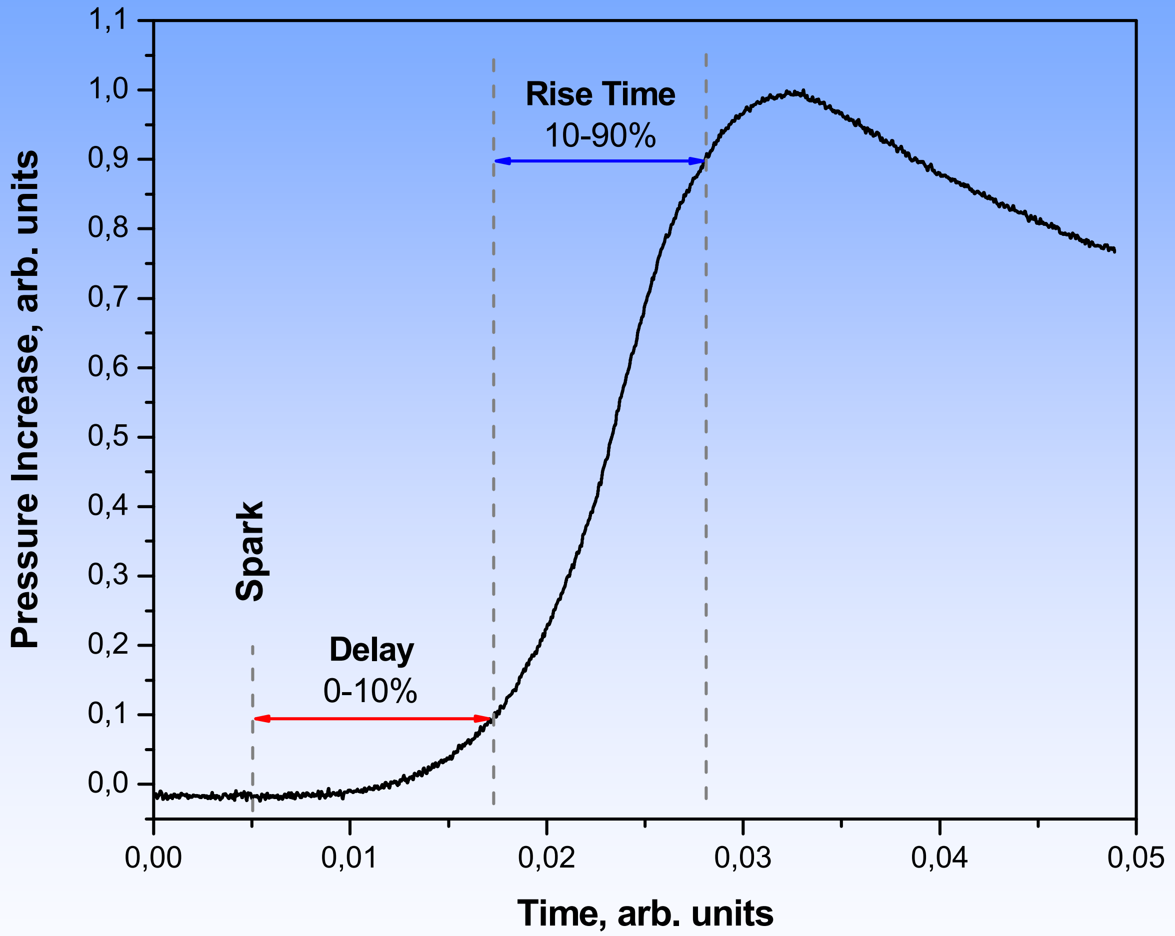
- Voltage (LeCroy high-voltage probe), current (Pearson monitor)
- Pressure trace (AVL quartz pressure transducer)
- OH emission (Hamamatsu photosensor module with UV filter)
- Spectral emission (Acton spectrometer + ICCD camera)
- Ultrafast imaging (Photron intensified camera)

Electrical and Optical Diagnostics



Propane-air mixture ignition by trains of 5 kV/10 ns pulses in pressure range 0.5-2.5 bar

Definitions : Ignition delay and combustion rise time



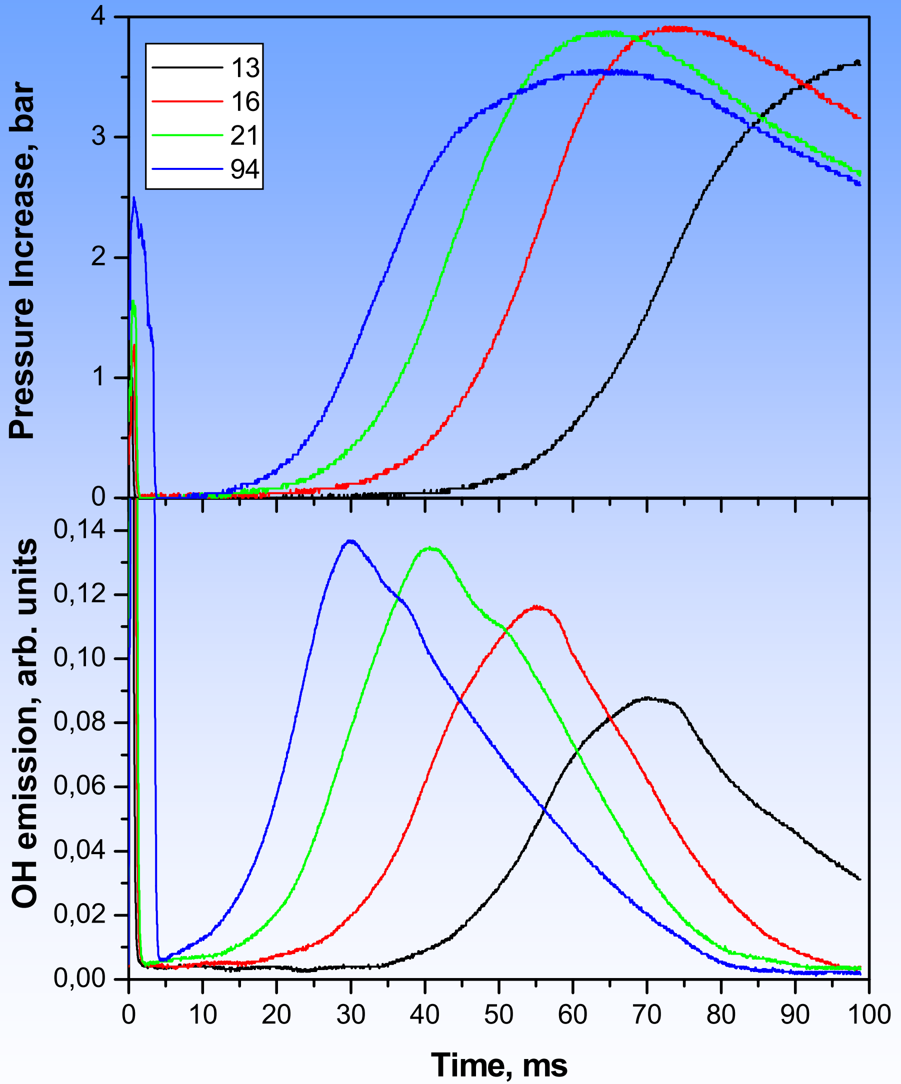
<u>Ignition delay time:</u>

Time from spark to a 10% pressure increase

<u>Pressure rise time:</u>

Time for the pressure to increase from 10% to 90% of the maximum value

Ignition by repetitive nanosecond discharge



Stoichiometric propane-air mixture diluted by 30% N_2

Ignition source	Energy, mJ (# of pulses)	Delay Time, ms	Rise Time, ms
Ordinary spark	30 (1)	no ignition	
Nano-second repetitive discharge	22 (13)	56	31
	27 (16)	39	25
	36 (21)	29	25
	160 (94)	22	25

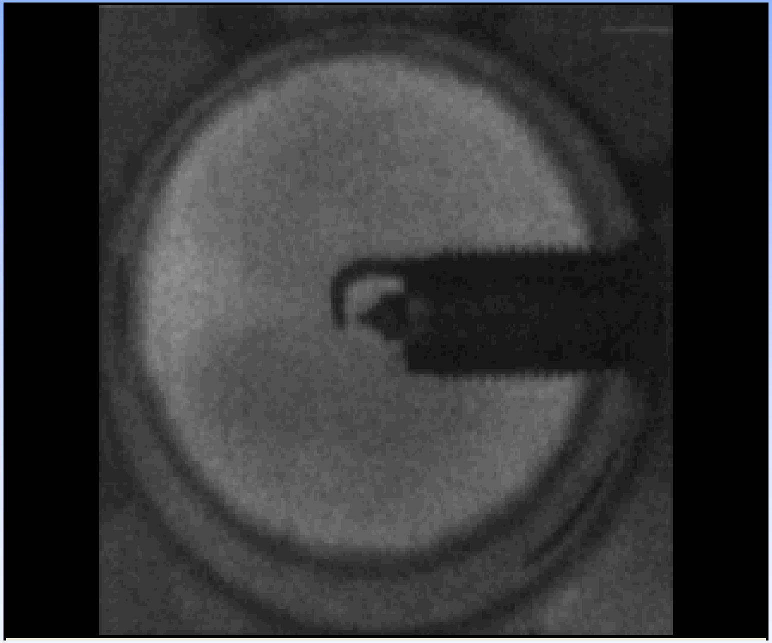
1-bar propane-air mixture, 1.5 mm gap, train of pulses: 5 kV, 10 ns, 30 kHz

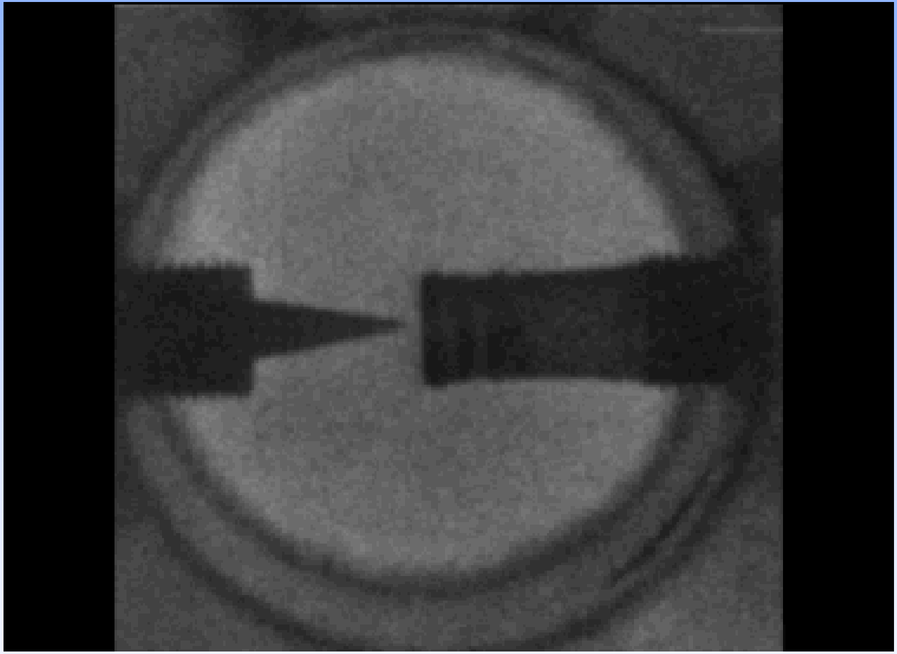
Ultrafast imaging of the ignition of a lean C_3H_8-air mixture: $\phi = 0.7$, 2 bar

Conventional ignition system

(Ignition requires several sparks)

Nanosecond discharge



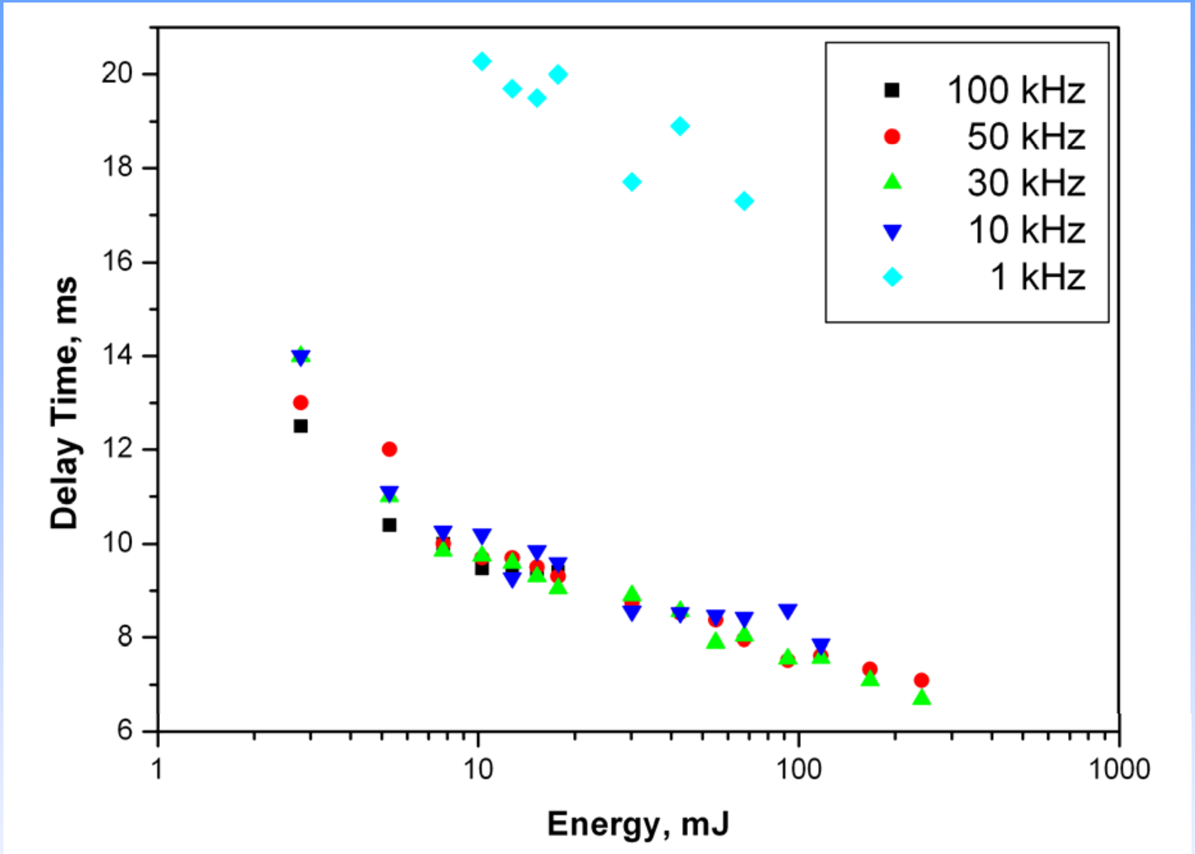


Framerate: 30 kHz

Exposure time: 33 μs

Total time: 35 ms

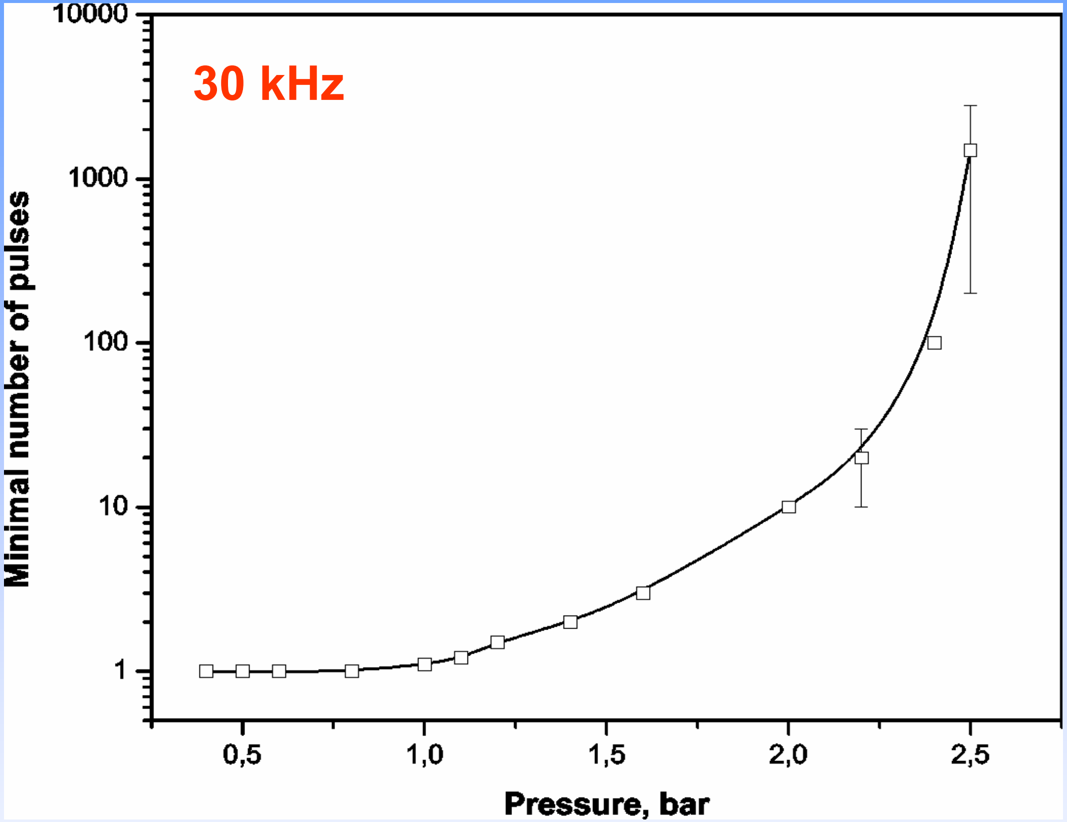
Influence of the repetition rate



- Ignition delay decreases abruptly between 1 and 10 kHz (at 1 bar)
- Ignition delay decreases with number of pulses applied

1-bar propane-air mixture ϕ =1, 1.5 mm gap, train of pulses: 5 kV, 10 ns

Minimal number of pulses for ignition

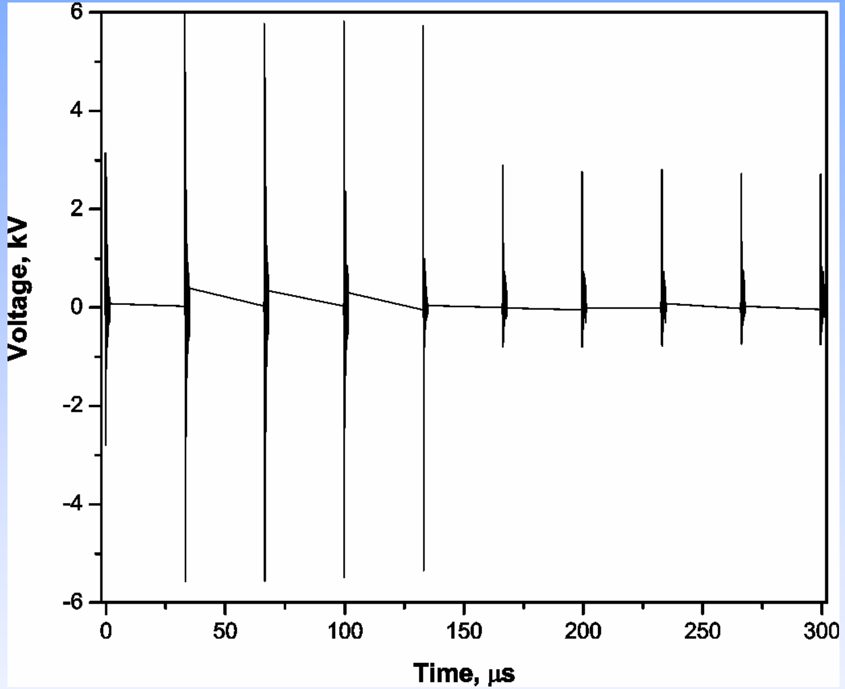


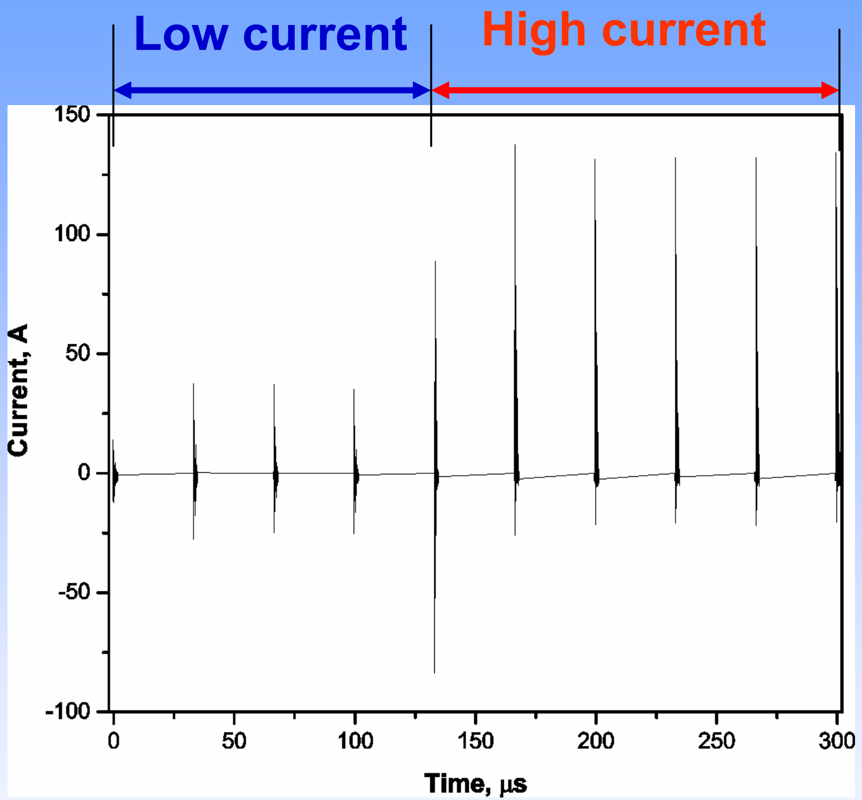
- Maximum operating pressure: 2.5 bar (for 5-kV pulses at d = 1.5 mm)
- To operate at higher pressure, need more than 5 kV or shorter gap

1-bar propane-air mixture ϕ =1, 1.5 mm gap, train of pulses: 5 kV, 10 ns

1-bar air plasma produced by a train of 10 pulses of 5 kV/10 ns at 30 kHz

Discharge in air at 1 bar

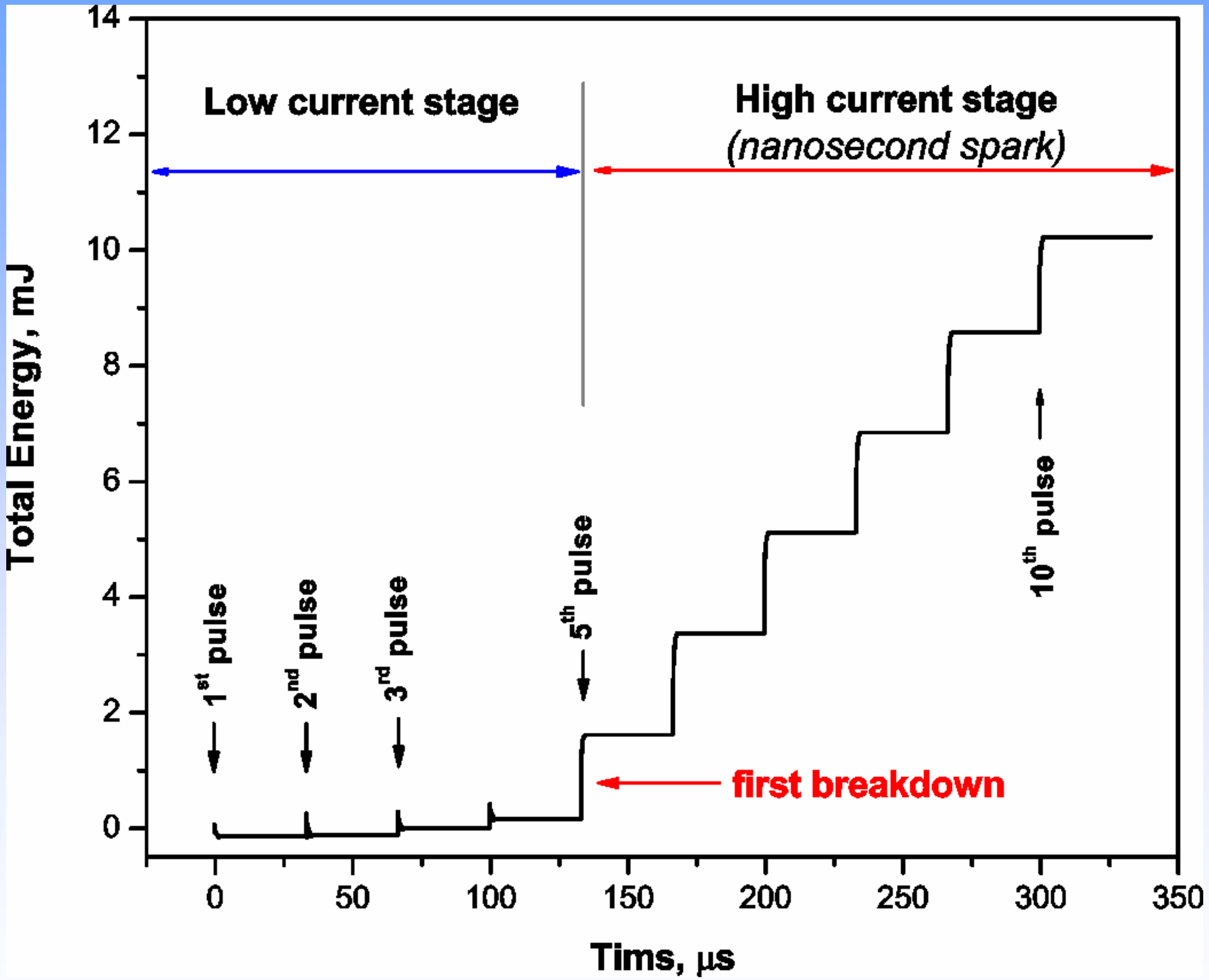




Ignition occurs only if there is at least one high-current pulse in the train

1 bar, air, 1.5 mm gap, 10-pulse train: 5 kV, 10 ns, 30 kHz

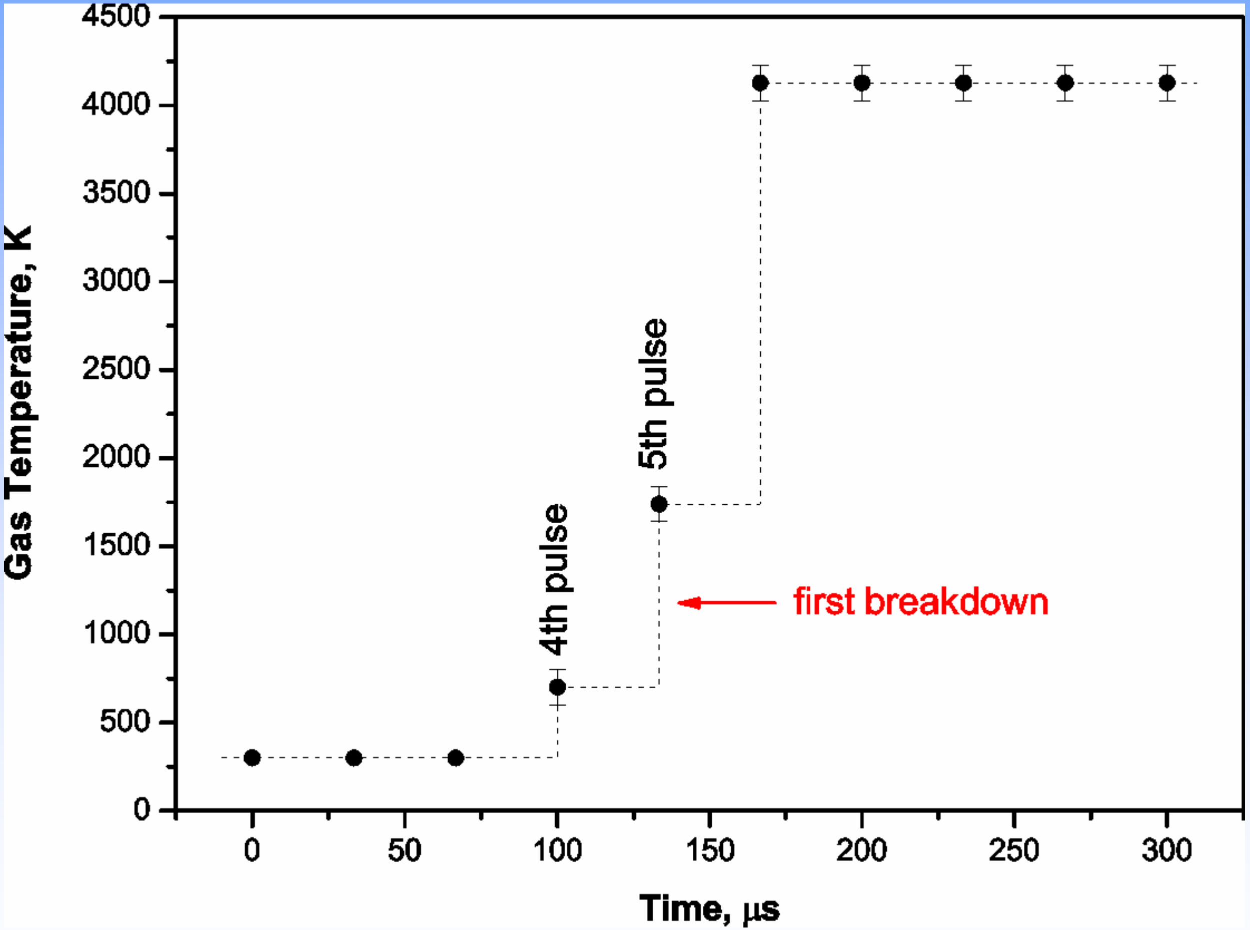
Energy deposited



1 bar, air, 1.5 mm gap, 10-pulse train: 5 kV, 10 ns, 30 kHz

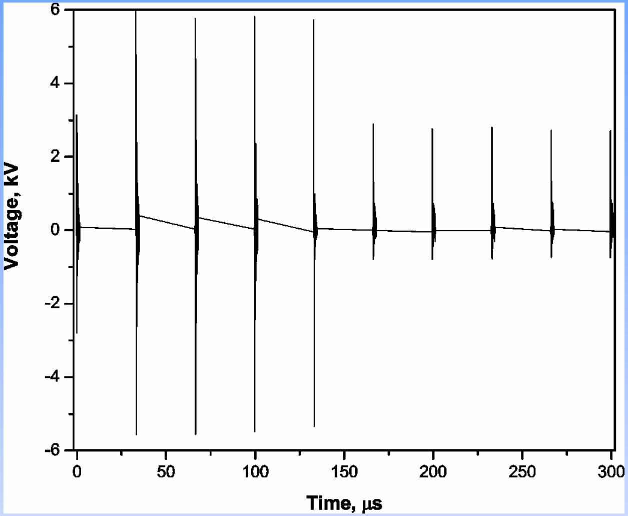
Temperature measurements

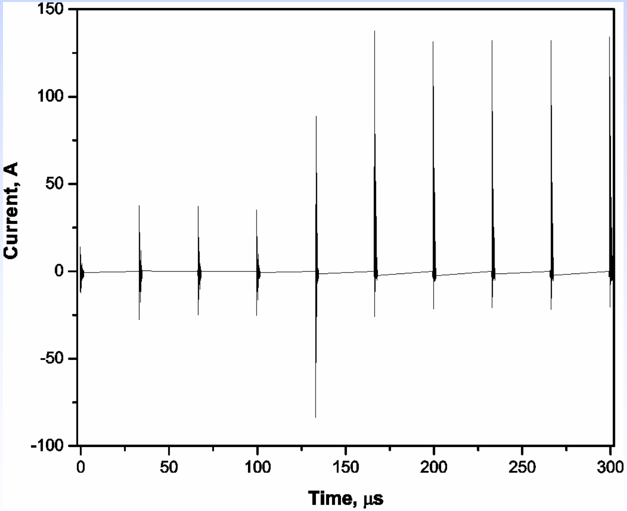
(from fit of N_2 C-B rotational lines)

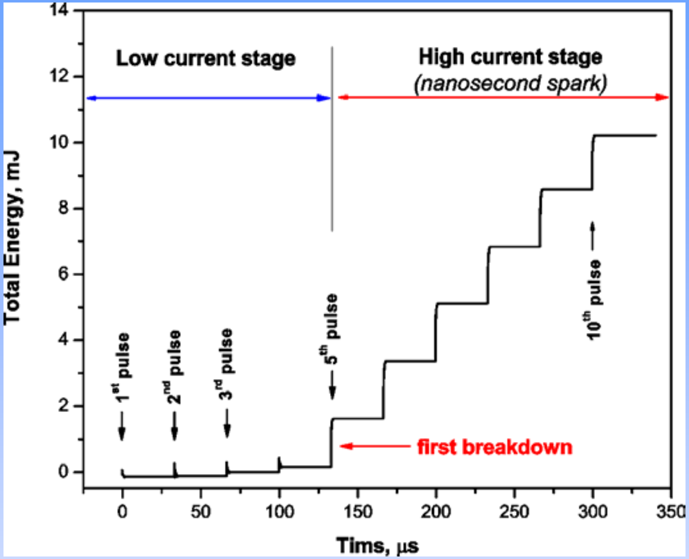


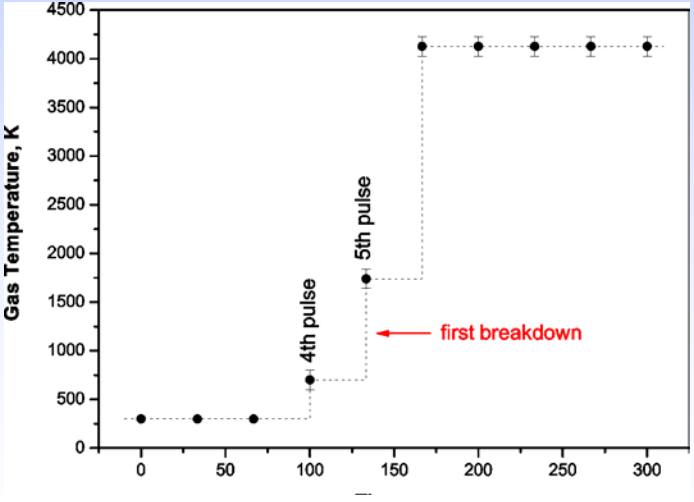
1 bar, air, 1.5 mm gap, 10-pulse train: 5 kV, 10 ns, 30 kHz

Summary









1 bar, air, 1.

First four pulses create favorable conditions for breakdown

Observations

- A train of repetitive nanosecond pulses **below the breakdown voltage** can efficiently ignite lean/diluted propane-air up to some pressure limit (here 2.5 bars with 5 kV pulses across 1.5-mm gap).

- Pressure limit can be increased with higher voltage, shorter gap, or pre-ionization

- The power consumption is 6-20 times lower than spark plug (typically 3-10 mJ required vs. 60 mJ for spark plug)

- Increasing the number of pulses and/or repetition rate reduces the ignition delay time

- Initial pulses create heat, which favors ignition.
  Question: which active species (radicals, ions, excited molecules or atoms) are formed, how, and in what quantities ?

What we think is going on

- Initial pulses produce radicals via reactions such as:
  - $N_2 + e \rightarrow N_2^* + e$
  - $N_2^* + O_2 \rightarrow N_2 + O + O$ (« hot » O atoms)
- Hot O atoms transfer energy to gas
- $\Rightarrow T \uparrow \Rightarrow N \downarrow \Rightarrow E/N \uparrow$
- Eventually E/N becomes sufficient to produce breakdown

Stabilization of a Lean Premixed Air-Propane Turbulent Flame using a Nanosecond Repetitively Pulsed Plasma

G. Pilla, D. Galley, D. Lacoste, F. Lacas,
D. Veynante and C. Laux

Programme INCA "INitiative en Combustion Avancée"
SNECMA, CNRS (EM2C, CORIA), ONERA

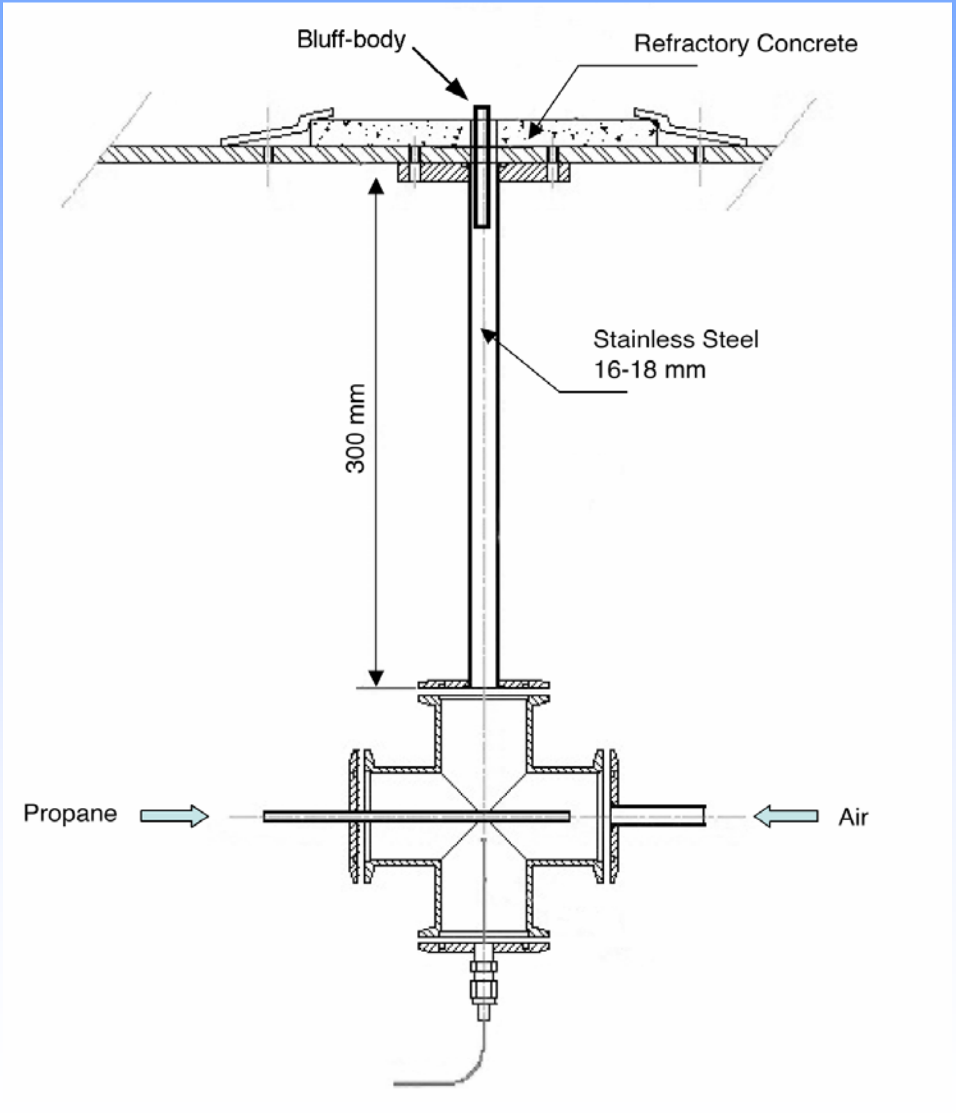
Flame stabilization strategy

- A single nanosecond high voltage pulse is sufficient to **ignite**, but not to **stabilize** a flame

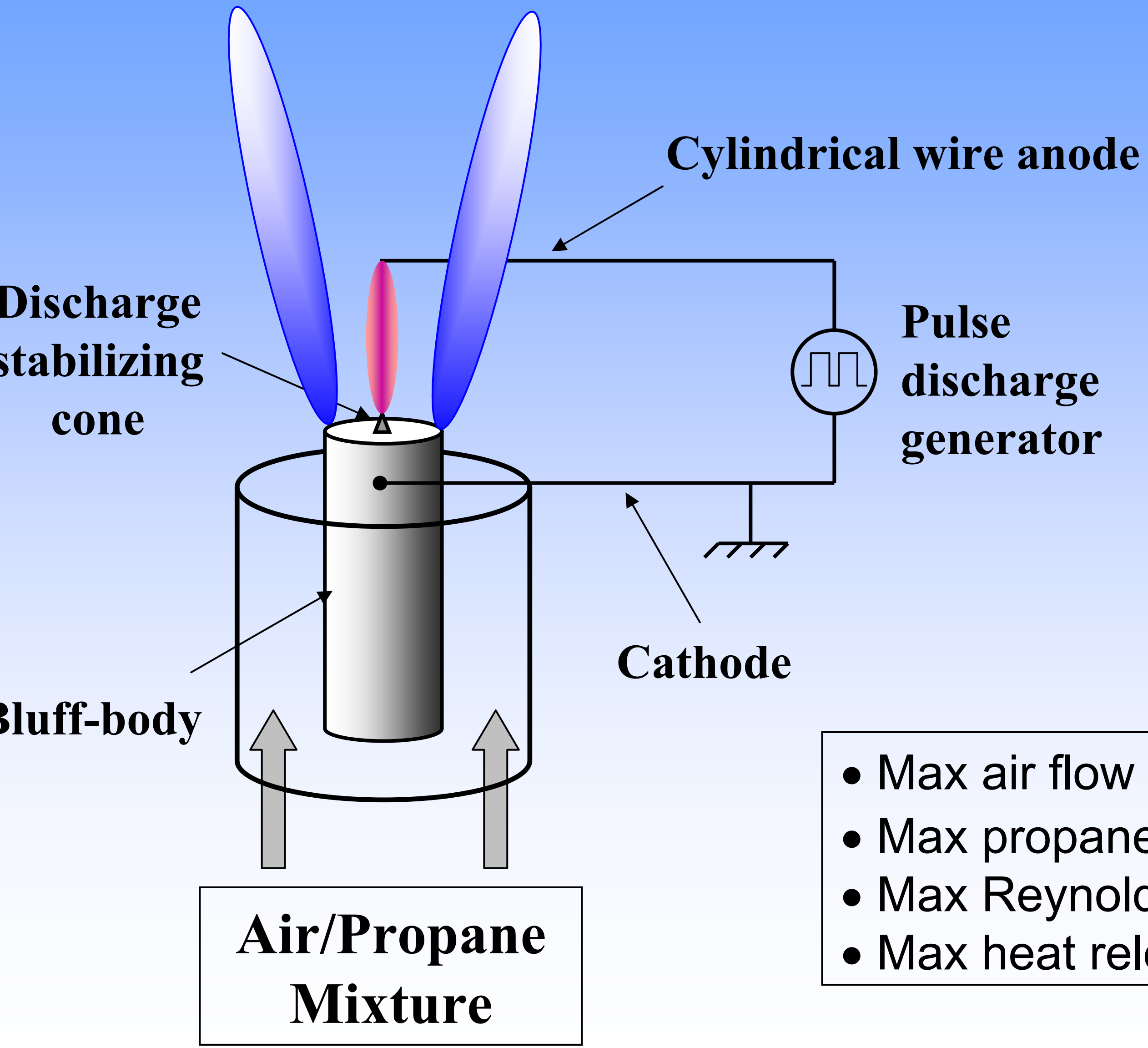
- Flame ***stabilization*** requires to excite the gas continuously over extended time (and with reasonable power)

⇨ interest of NRPP

Lean Premixed Burner

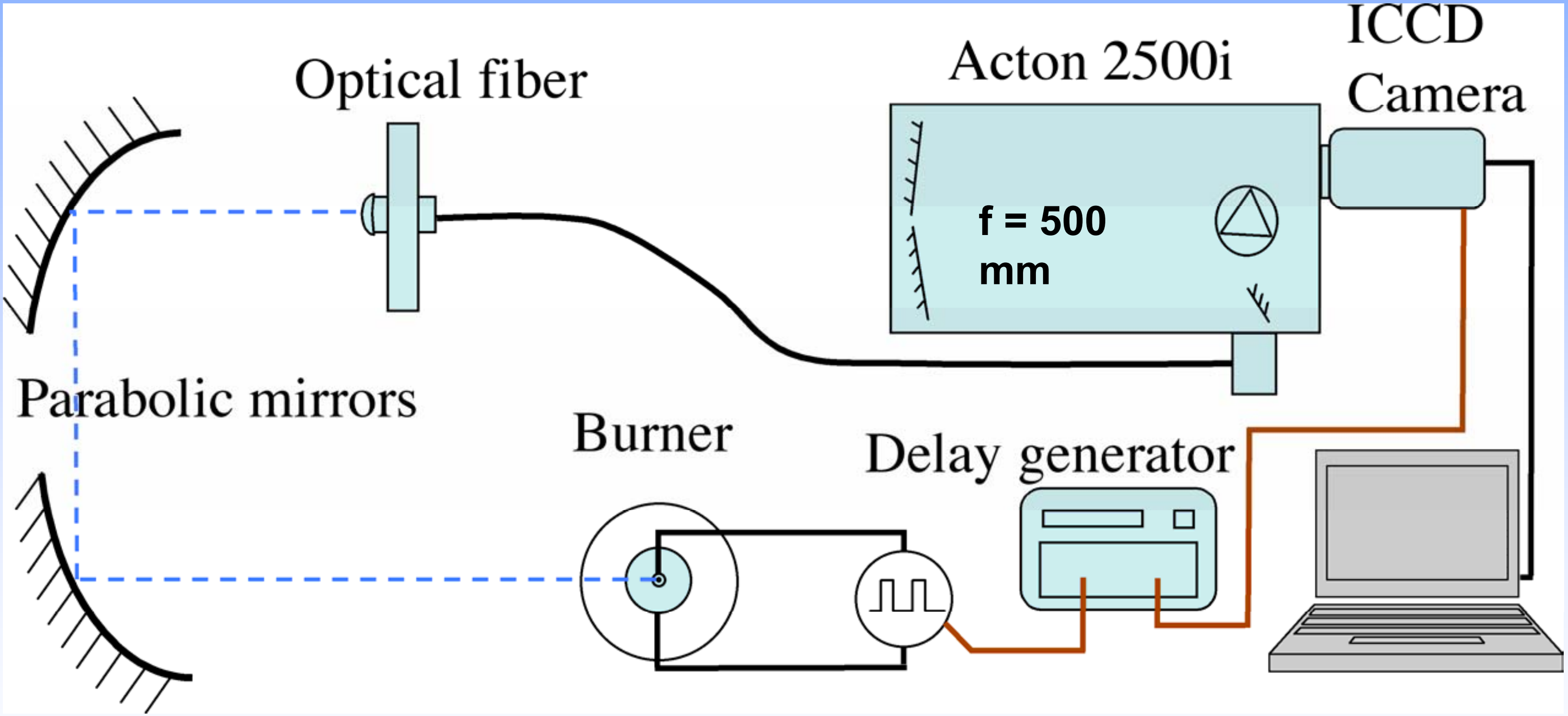


Lean Premixed Burner

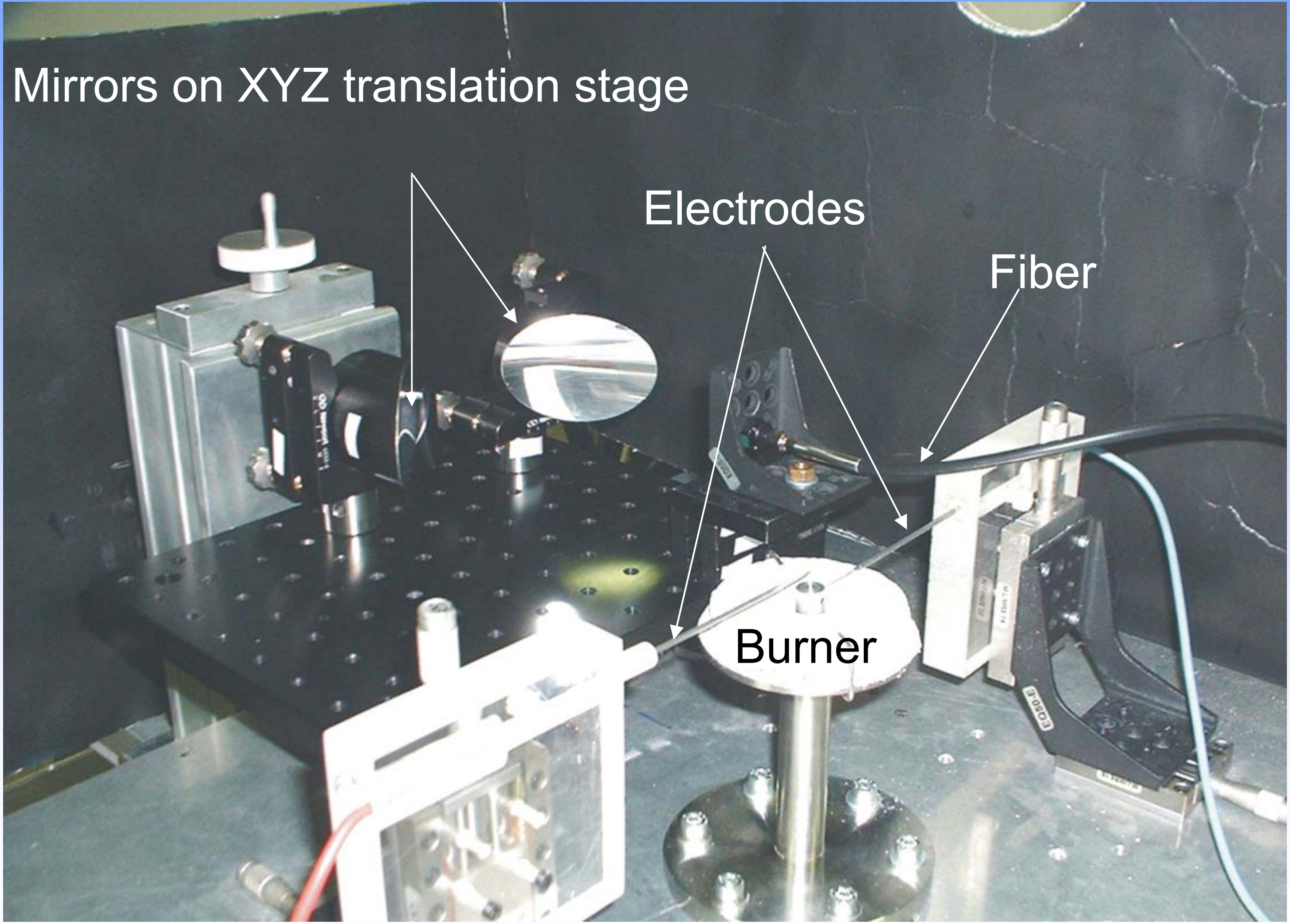


- Max air flow rate: 25 m^3/h
- Max propane flow rate: 1 m^3/h
- Max Reynolds number: 30,000
- Max heat release: 25 kW

Optical diagnostics setup



Experimental setup



Mirrors on XYZ translation stage

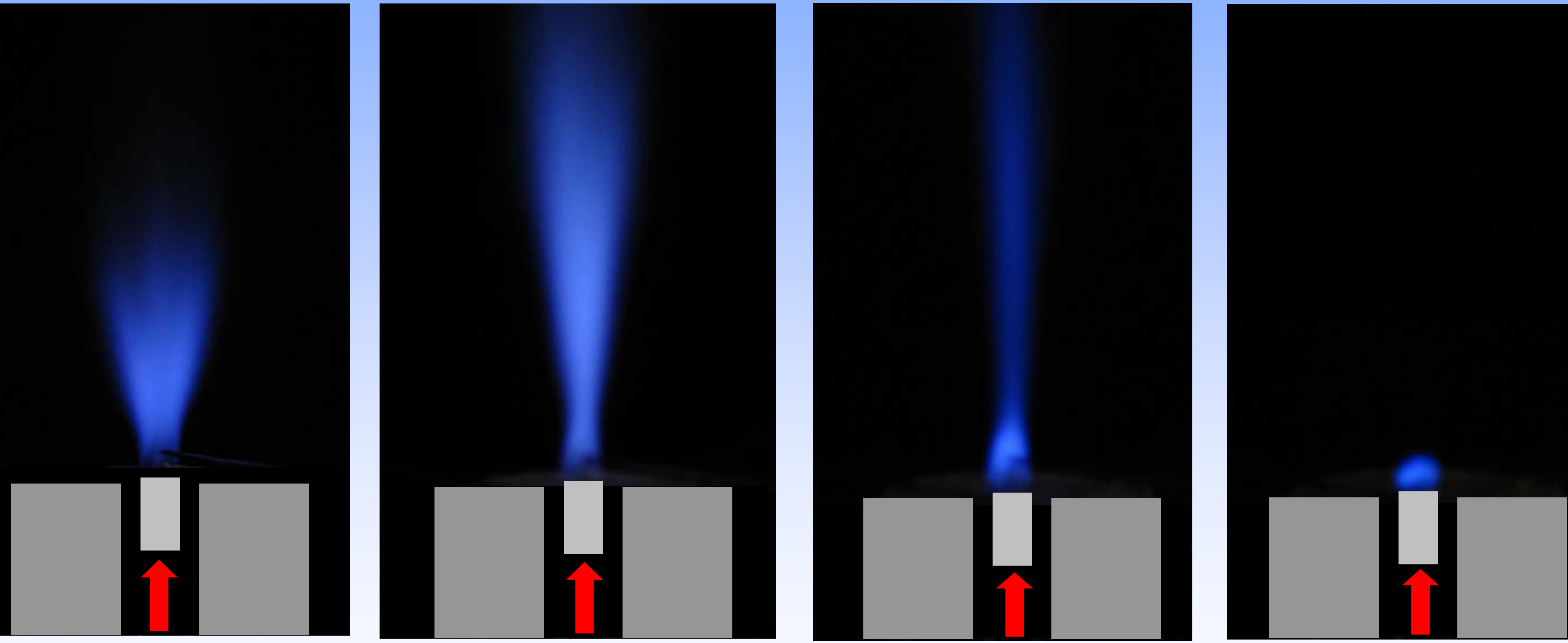
Electrodes

Fiber

Burner

Three flame regimes

Increasing air flow rate or decreasing Φ



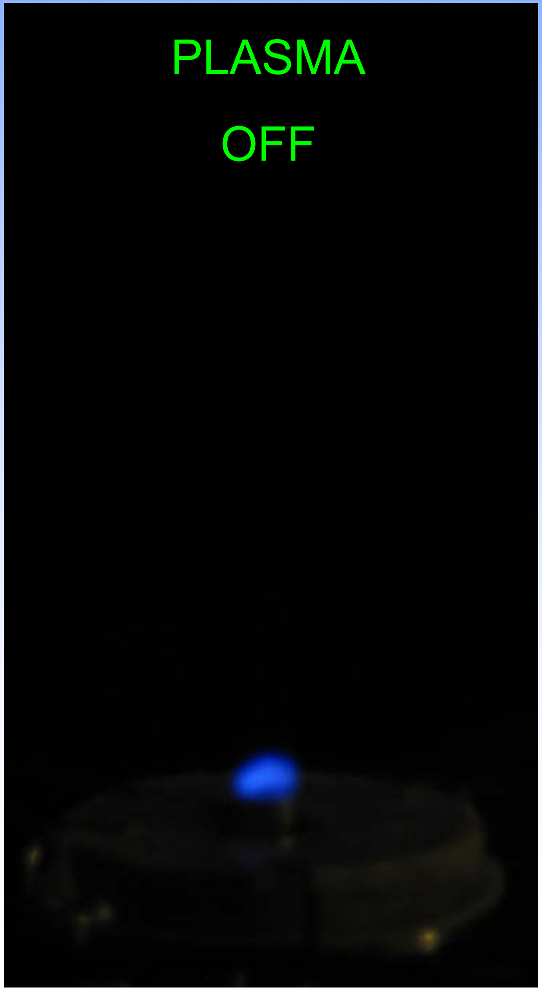
-shaped flame

Intermittent flame

Pilot flam
(confined t
recirculation zone

Flame stabilization by plasma

$\Phi = 0.8$, Air flow rate = 15 m^3/h

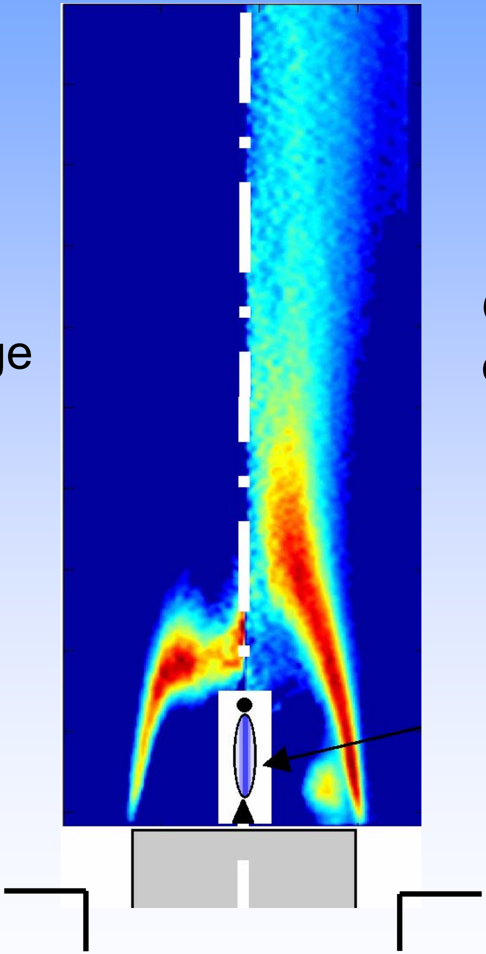

PLASMA

OFF


PLASMA

ON

OH spontaneous emission



H* emission
ithout discharge

OH* emission with discharge (P=75 W)

Mask to block the emission of the plasma (discharge behind)

Parameters:

Air: 14.7 m^3/h

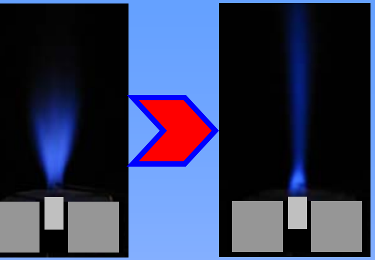
Propane: 0.5 m^3/h

P_{flame}=12.5 kW

P_{plasma}=75 W (streamer mode)

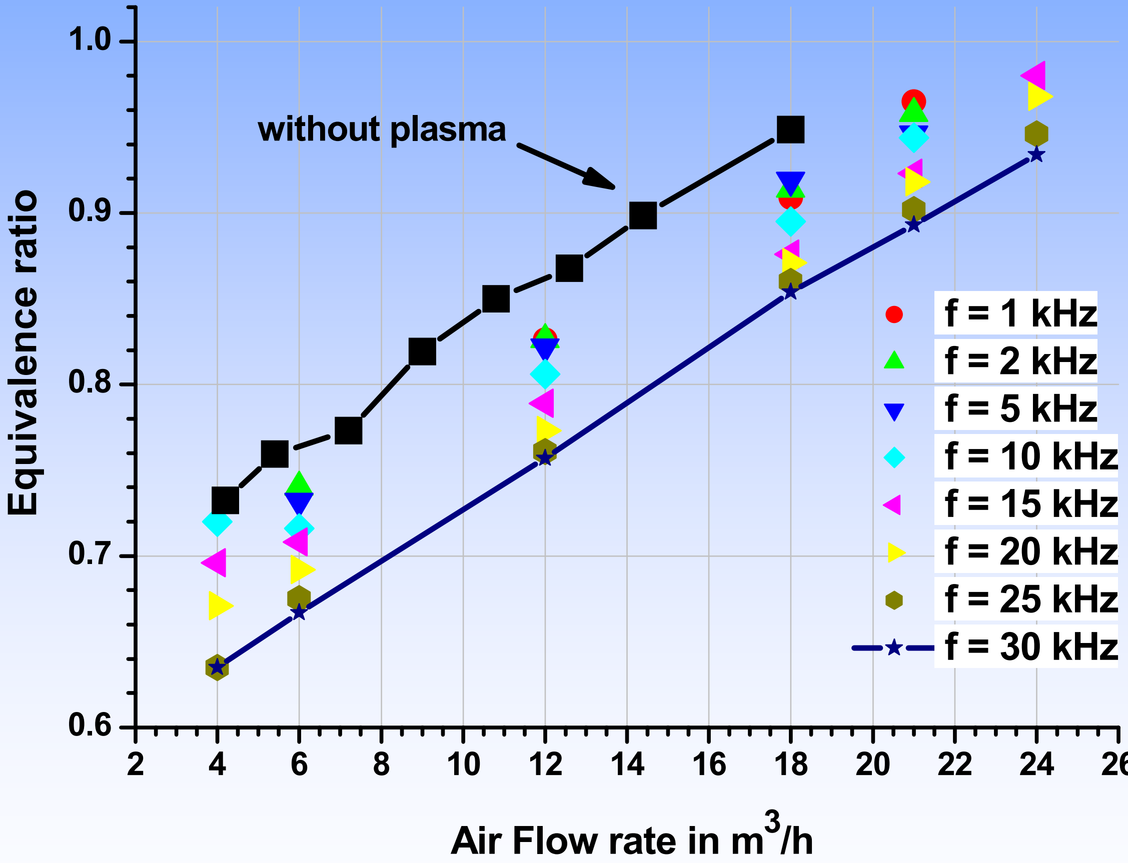
- With the plasma, the pilot flame becomes a V-shaped flame

Influence of repetition rate on burner regimes

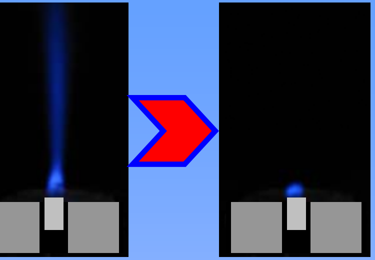


Flame regimes

V-shaped flame to intermittent flame

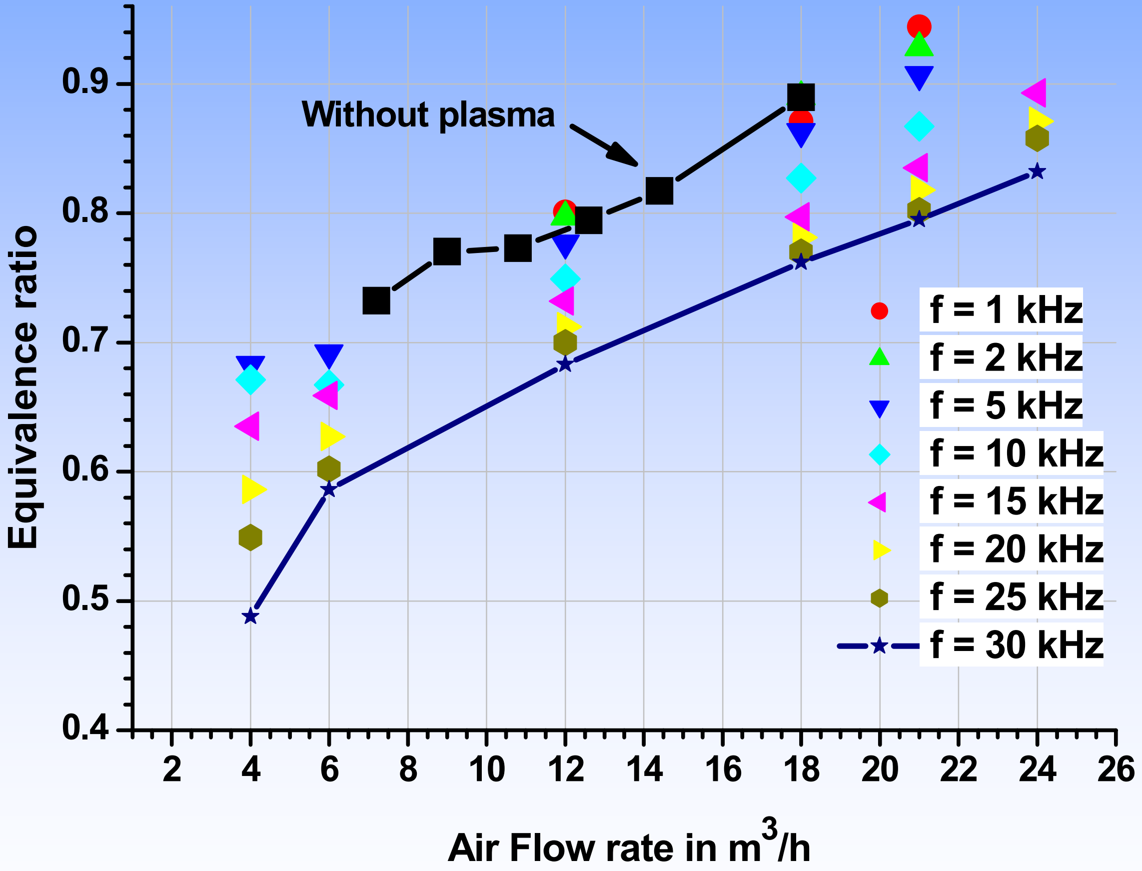


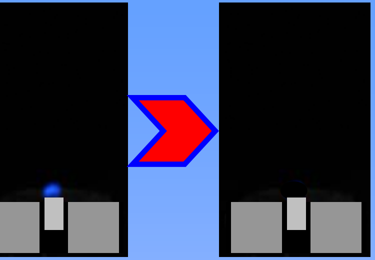
- **Extension of the domain of stability of the flame**



Flame regimes

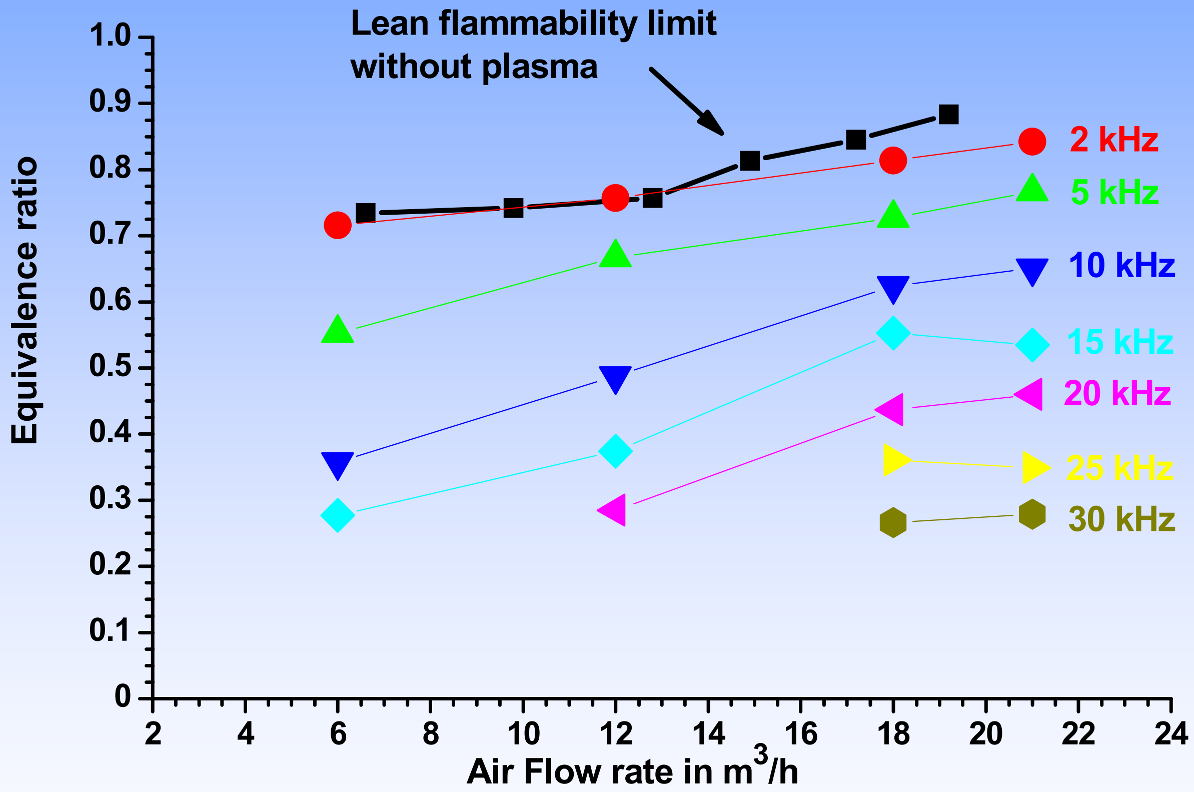
Intermittent flame to pilot flame



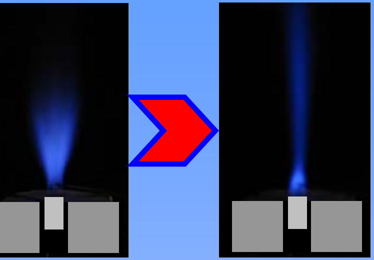


Flame regimes

Pilot flame to extinction

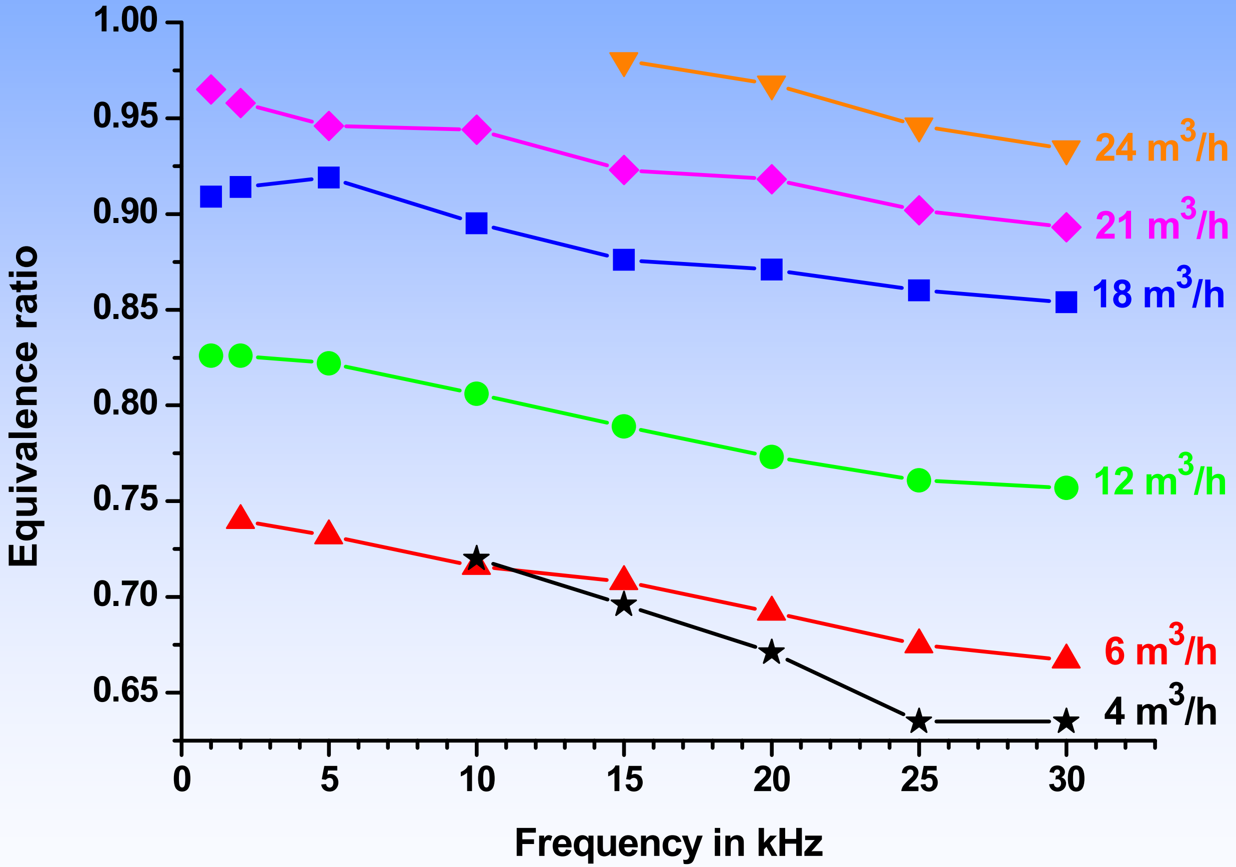


- **The domain of existence of the pilot flame is considerably extended by the plasma for f > 5 kHz.**



Flame regimes

Transition from the V-shaped flame to the intermittent flame

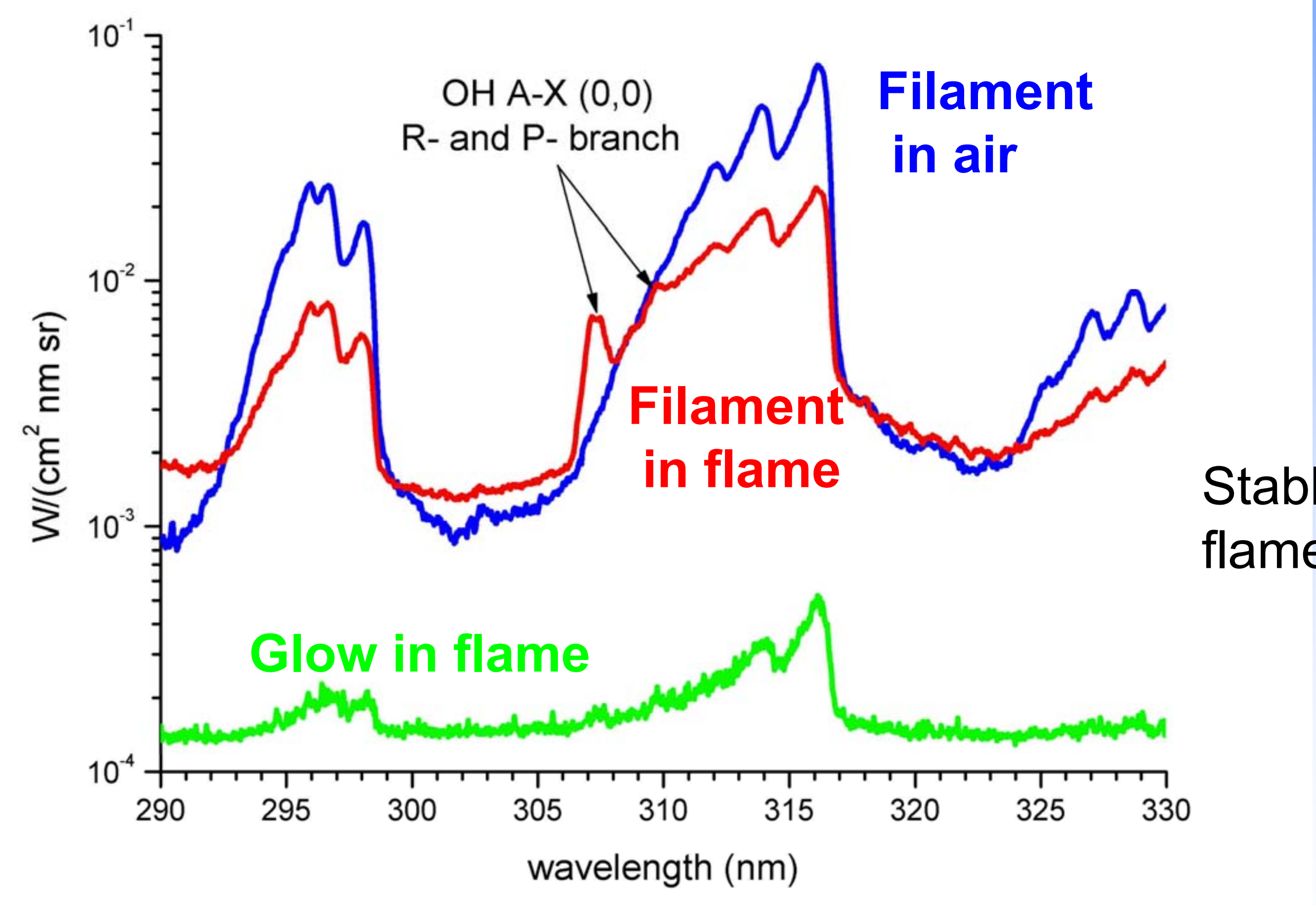


- **The critical equivalence ratio decreases about linearly with the frequency (by about 10% from 0 to 30 kHz) -> residence time**

Optical diagnostics

Time-resolved spectroscopy

Spectra integrated over the 100 ns following the pulse

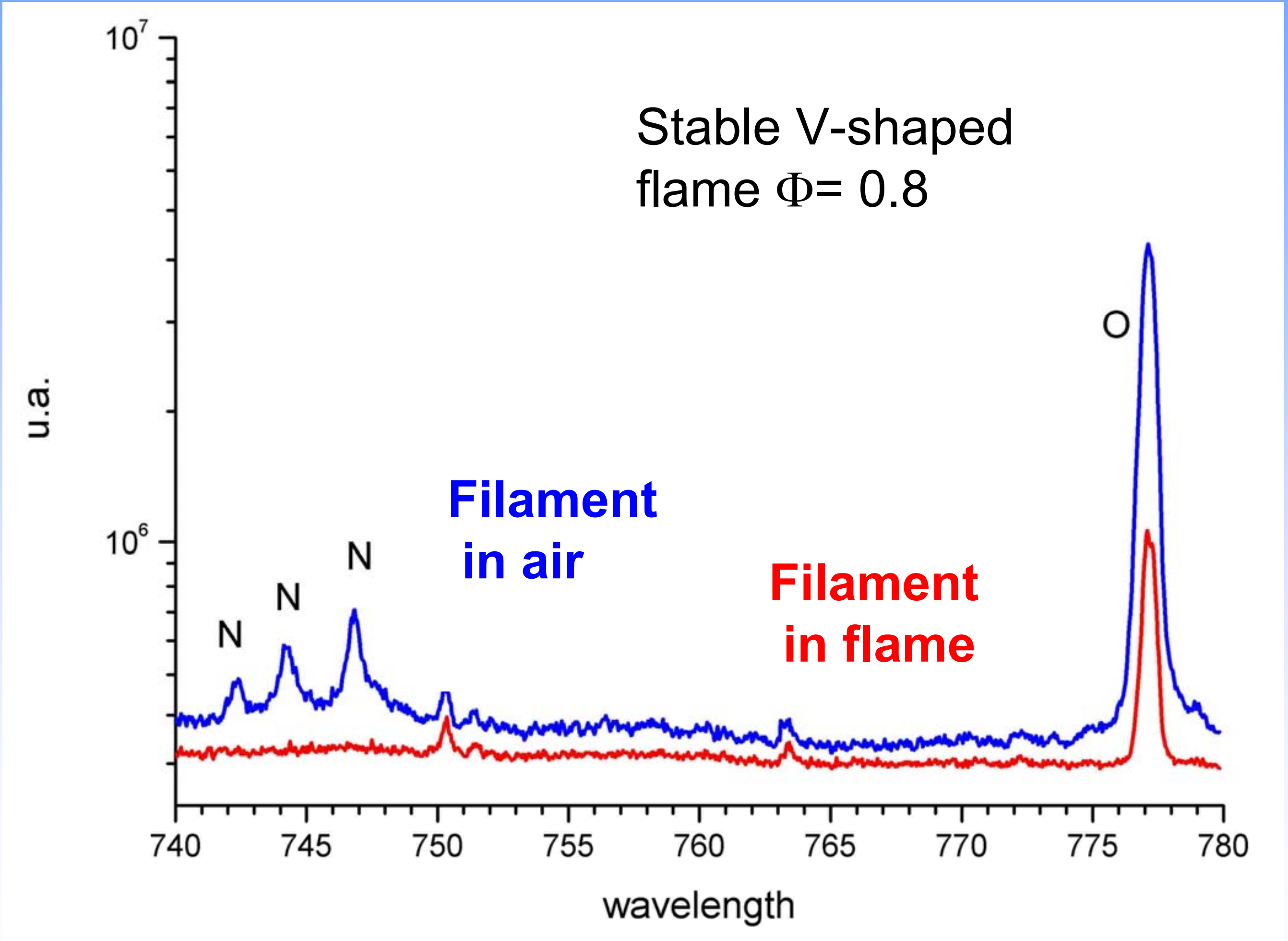


Stable V-shaped flame Φ= 0.8

- Filamentary discharge in flame produces OH radicals

Time-resolved spectroscopy

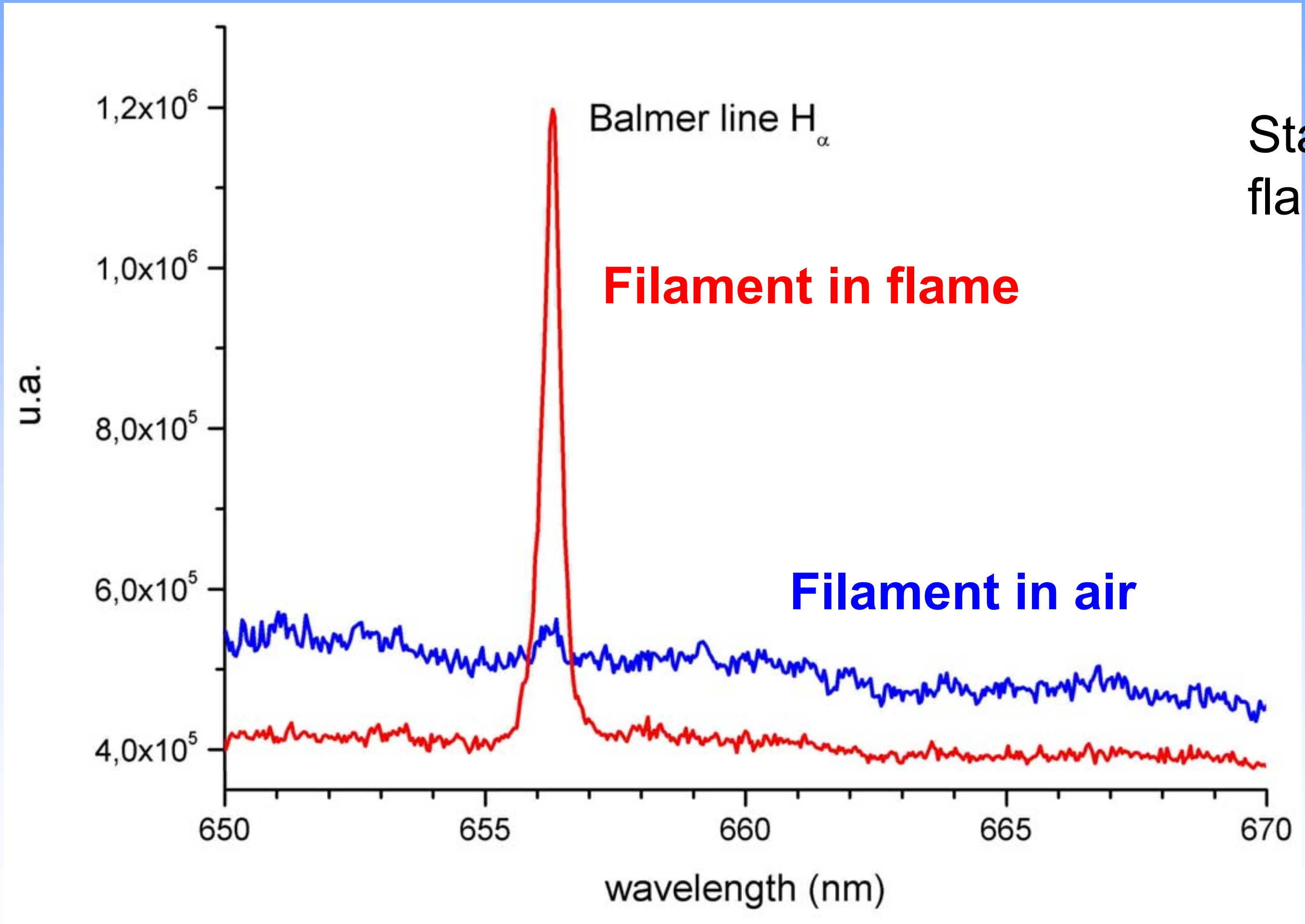
Spectra integrated over the 100 ns following the pulse



- Filamentary discharge produces O atoms in flame, but less than in pure air. No N atoms produced in flame.

Time-resolved spectroscopy

Spectra integrated over the 100 ns following the pulse

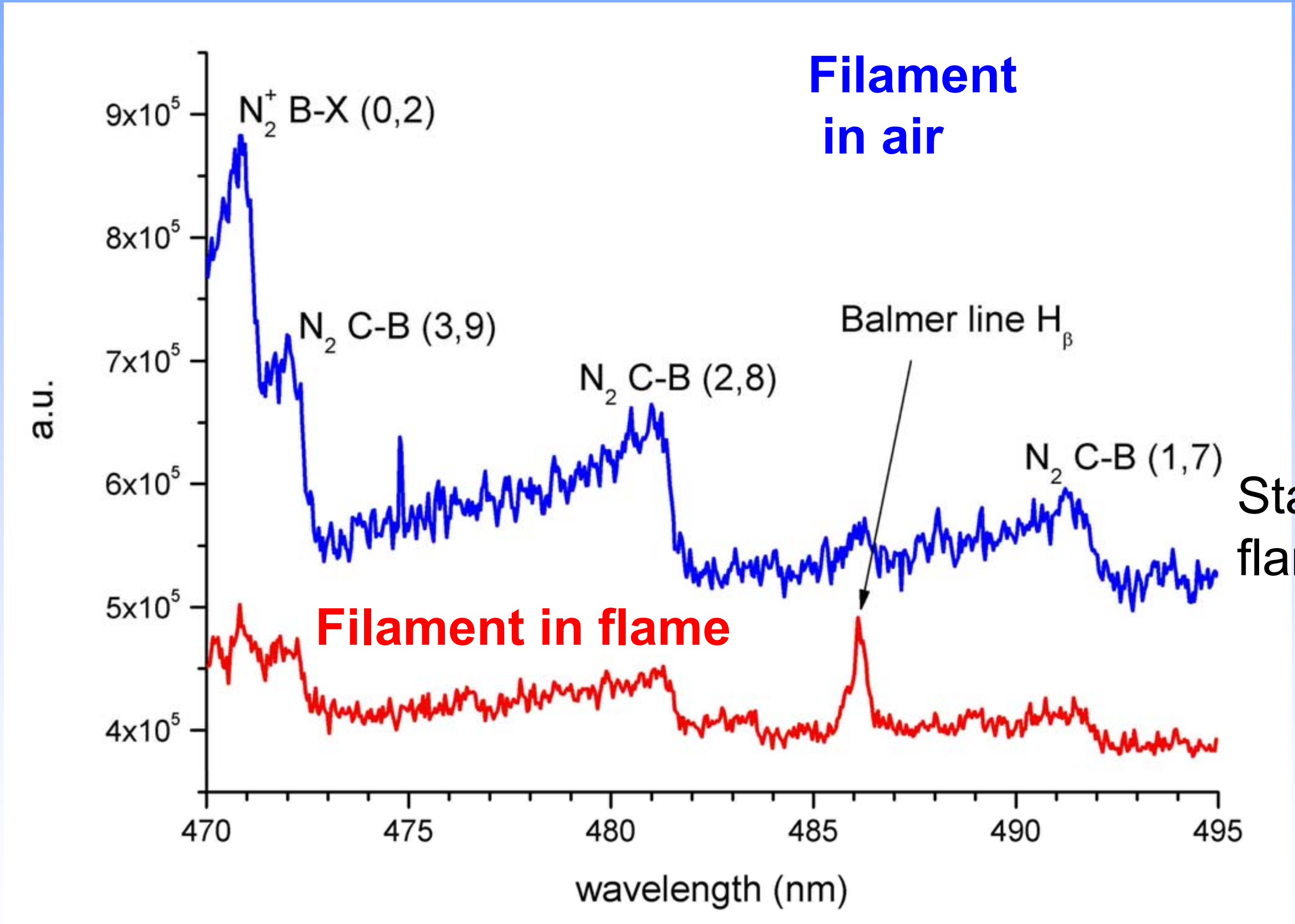


Stable V-shaped flame Φ= 0.8

- Filamentary discharge produces H atoms (H_α Balmer line)

Time-resolved spectroscopy

Spectra integrated over the 100 ns following the pulse

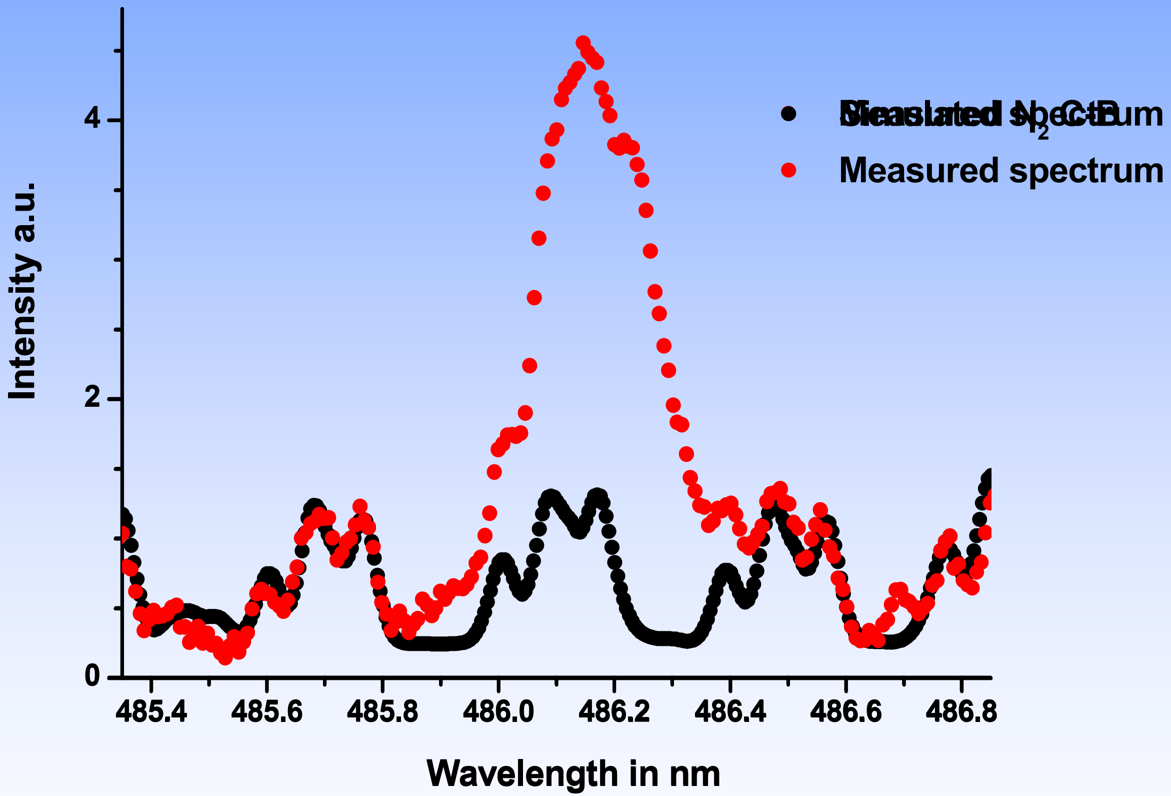


Stable V-shaped flame Φ= 0.8

- Filamentary discharge in flame produces H atoms (Hβ Balmer line)

Electron number density measurements

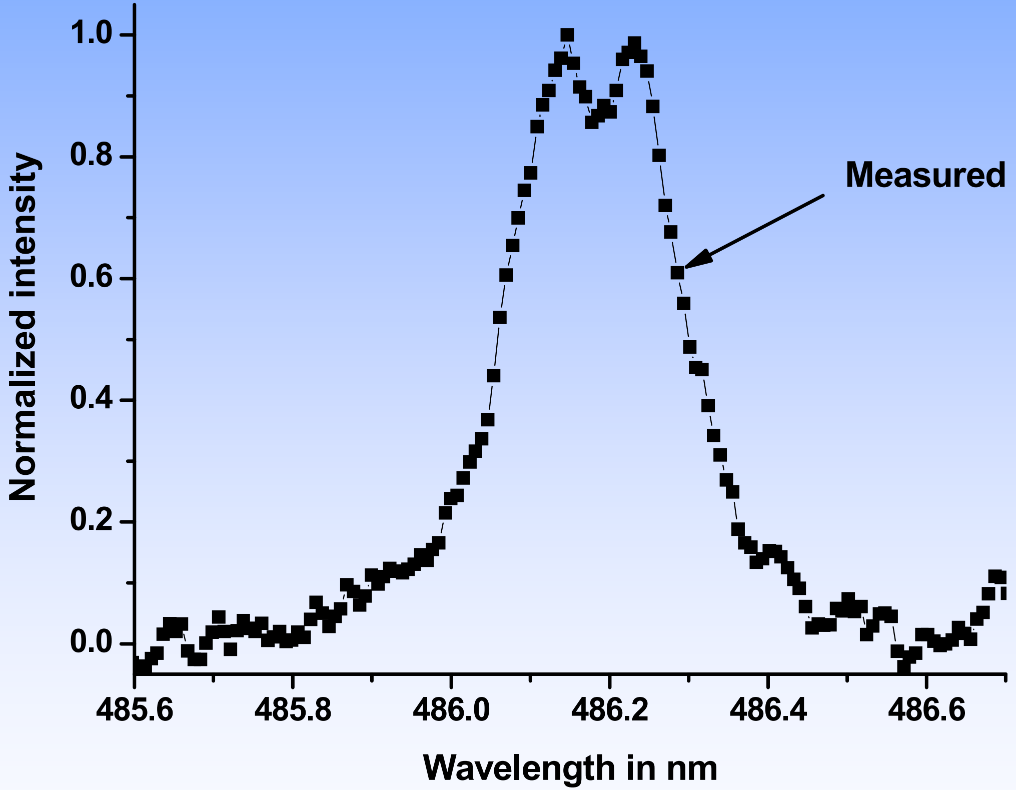
Repetition rate of the discharge : 30 kHz, propane/air flame at Φ=0.8



- **Subtraction of a simulated spectrum of N_2 C-B**

Electron number density measurements

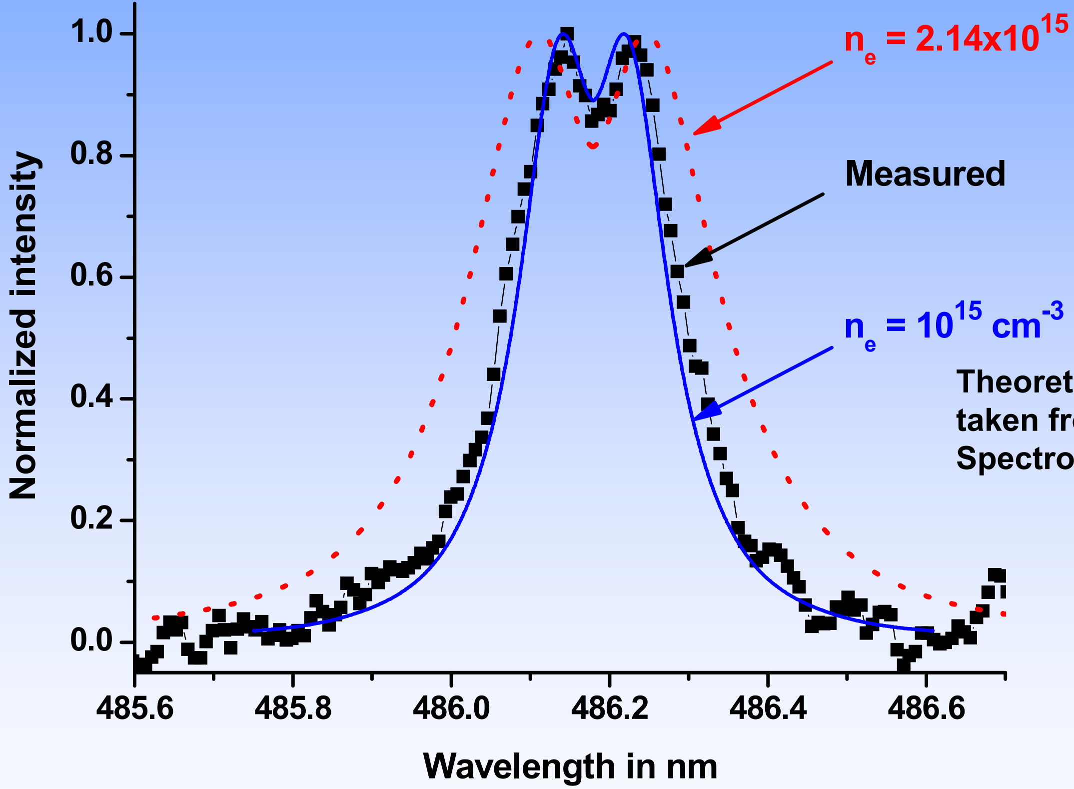
Repetition rate of the discharge: 30 kHz, propane/air flame at $\Phi=0.8$



- **Isolated spectrum of H_β**

Electron number density measurements

Repetition rate of the discharge : 30kHz, propane/air flame at Φ=0.8



$n_e = 2.14x10^{15}$

Measured

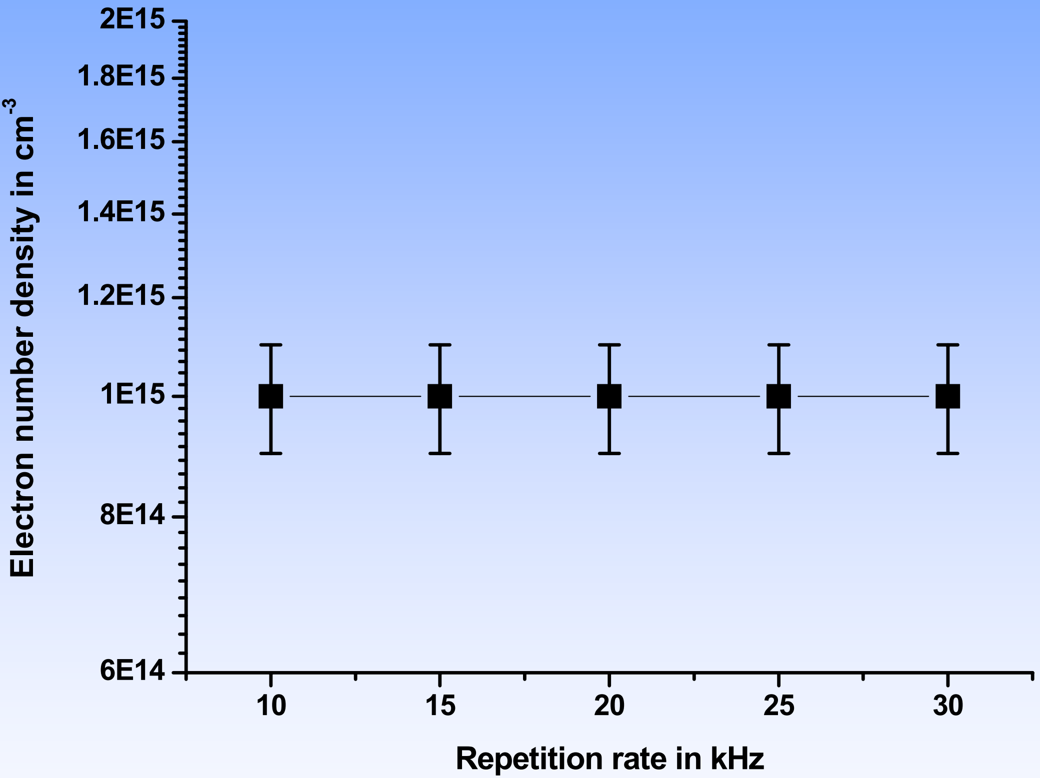
$n_e = 10^{15}\ cm^{-3}$

Theoretical Stark broadened profil
taken from: Gigosos et al.,
Spectrochim. Acta B, 58 (2003) 148

- **$n_e = 10^{15}\ cm^{-3}$ (± 10%)**

Electron number density measurements

propane/air flame at Φ=0.8

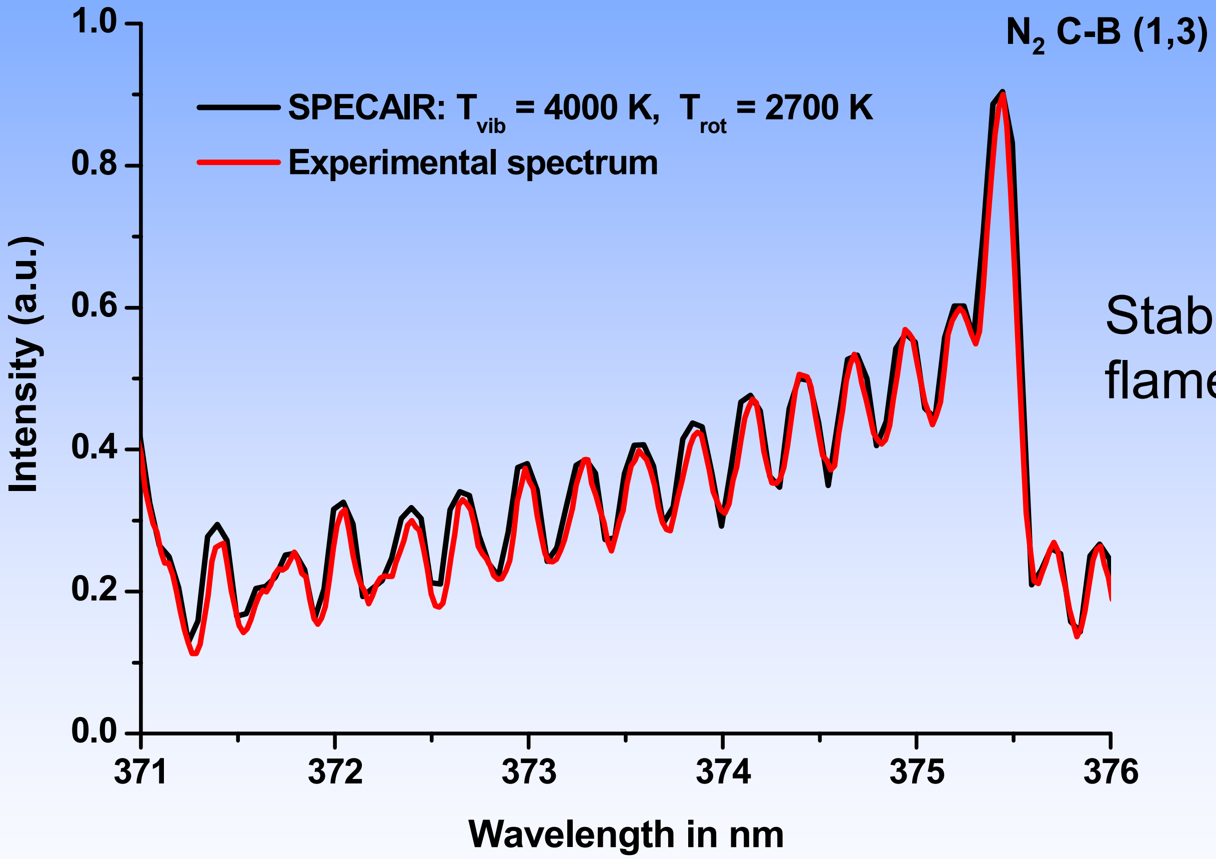


Electron number density constant for frequencies between 10 and 30 kHz

$n_e = 10^{15}$ cm^{-3} (± 10%)

Temperature measurements

Repetition rate of the discharge : 30 kHz

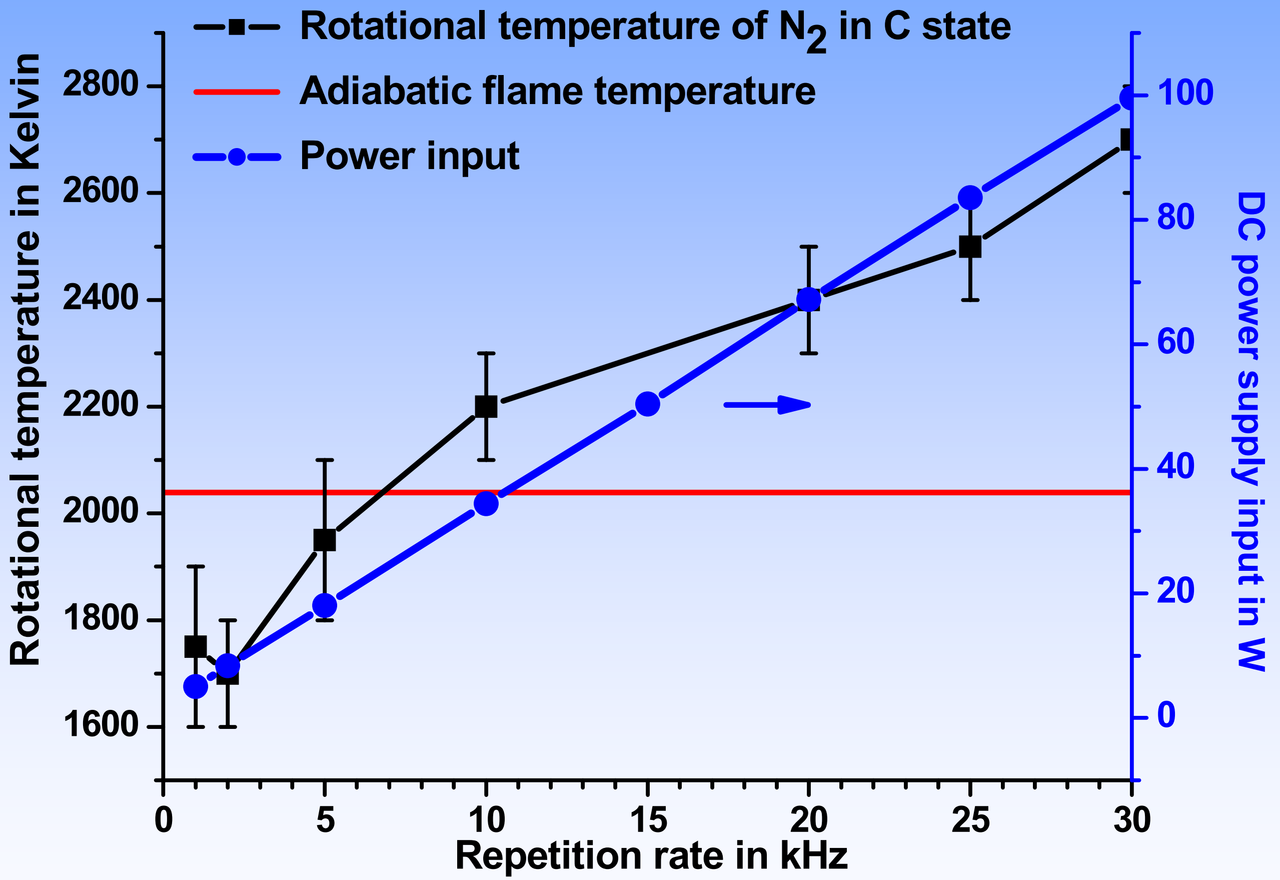


Stable V-shape
flame Φ = 0.8

- **Filamentary regime at 30 kHz in flame: T_{rot}= 2700 K, T_{vib}= 4000 K.** (Adiabatic Flame temperature: 2034 K, propane-air at Φ=0.8)

Temperature measurements

Frequencies from 1 to 30 kHz, propane/air flame at Φ=0.8



- **temperature increases as the frequency increases**
- **power injected in the discharge increases in similar way**

What we know

- Power required for stabilization is low: 75 W for 25 kW turbulent flame

- Filamentary discharge is much more efficient than glow discharge

- Significant effect of the repetition rate : extension of the domain of stability proportional to the frequency

- Filamentary discharge produces :
  - Heat (about 700 K)
  - Radicals: O, H, OH
  - Electronically excited species (N_2*, OH*,O*,…)
  - Electrons, and therefore ions: $[e] \cong [NO+] \cong 10^{15}$ cm^{-3}

What we think is important

- Three key characteristic times
  - T, period between pulses: 33 μs – 1 ms
  - τ, residence time in plasma region: ~1 ms
  - t_{SL} time of flame propagation : 2.5 ms
- Location of discharge: must be in hot region (E/N higher) and/or recirculation region (τ higher).
- Need to understand mechanism of radical and ion formation + their effect on time of flame propagation

Conclusions

- Repetitive nanosecond discharges are very efficient in reducing ignition delay time and improving the stability of lean/diluted premixed flames

- The power requirements are lower than with conventional spark plug techniques

- There is a clear need for detailed quantitative diagnostics of the species produced by the pulses

- Numerical simulations are in progress with 2-temperature chemistry and flame/plasma/flow coupling