Kinetic mechanism and sub-ns measurements of nanosecond thermal sparks in air

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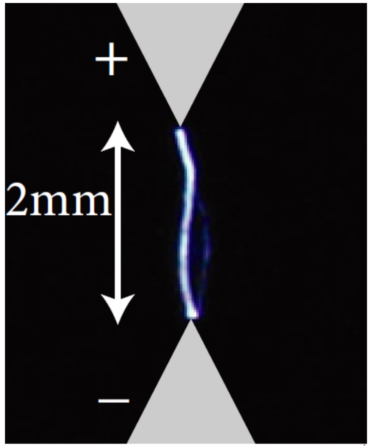
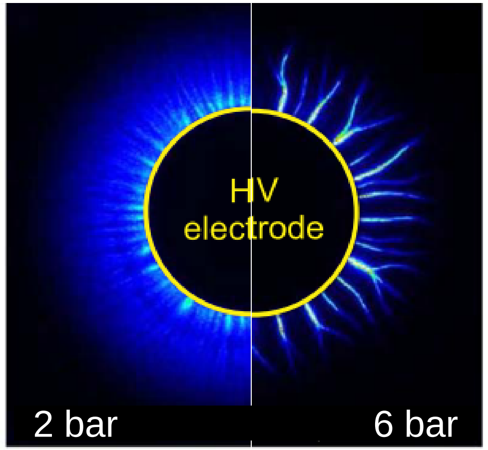
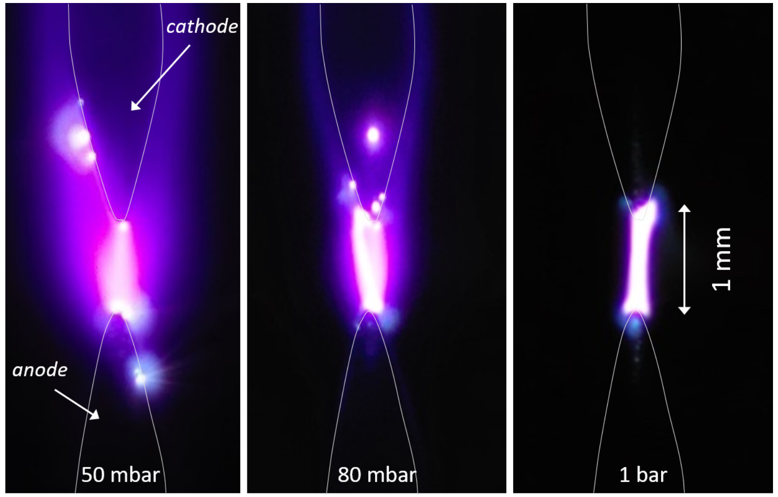
1 – Fully-ionized nanosecond discharges(?)







Nanosecond discharges can produce highly ionized plasmas [1-10]

- Full ionization: $n_e \sim 10^{19}$ cm^{-3}
- Thermal equilibrium: $T_e = T_{gas}$ = 30,000 K – 70,000 K

} thermal spark

Rising interest in the community:

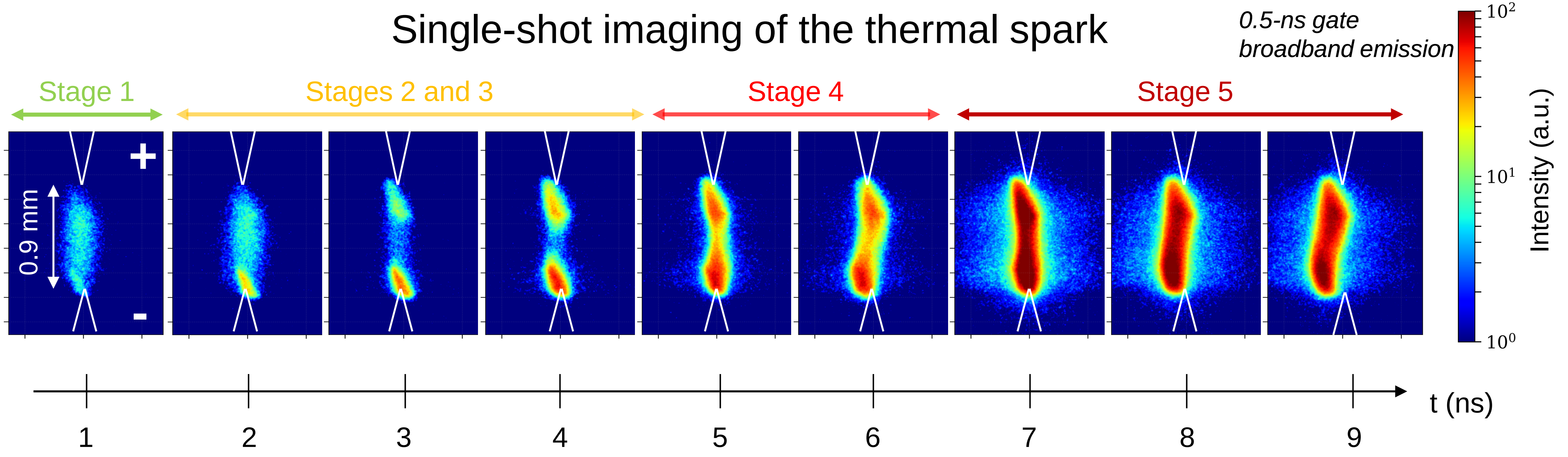
- ➢ Is it possible to get full ionization in ~10 ns?
- ➢ Same thermal spark in Refs. [1-10]?
- ➢ Mechanism of formation?

Beginning of Ph.D. → [6]

[1] van der Horst *et al.*, (2012) *J. Phys. D. Appl. Phys.*
[2] Shao *et al.* (2012) *J. Phys. D. Appl. Phys.*
[3] Sainct et al., (2013) *AIAA Scitech Forum*
[4] Stepanyan et al., (2014) *Plasma Sources Sci. Technol.*
[5] Houpt & Leonov, (2016) *J. Thermophys. Heat. Trans.*
[6] Lo *et al.*, **(2017)** *Plasma Sources Sci. Technol.*
[7] Orrière *et al.*, **(2019)** *J. Phys. D. Appl. Phys.*
[8] Shcherbanev *et al.*, **(2019)** *Plasma Sources Sci. Technol.*
[9] Parkevich *et al.*, **(2019)** *Plasma Sources Sci. Technol.*
[10] Minesi *et al.*, **(2020)** *Plasma Sources Sci. Technol.*

2 - Thermal spark formation

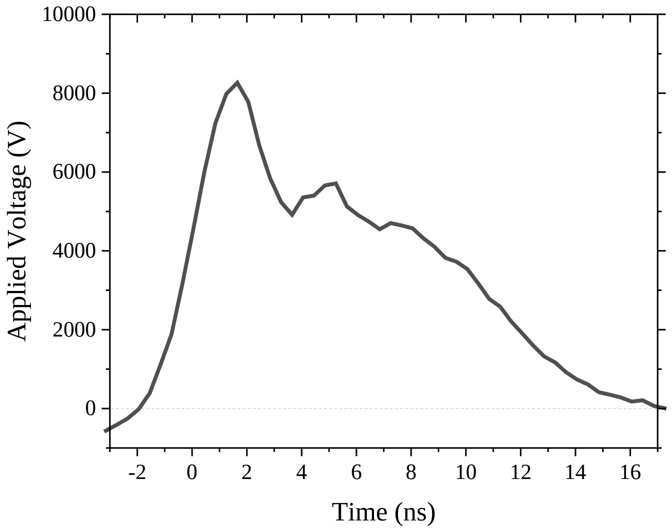
Single-shot imaging of the thermal spark



Formation of a thermal spark in 5 stages:

1. Partially ionized plasma
2. Formation, in <0.5 ns, of a filament at the cathode
3. Formation, in <0.5 ns, of a filament at the anode
4. Filament propagation (10^4-10^5 m/s)
5. Fully ionized plasma

✓ Applicable to the results of other groups [8,11]



[8] Shcherbanev *et al.*, (2019) *Plasma Sources Sci. Technol.*
[10] Minesi *et al.* (2020) *Plasma Sources Sci. Technol.*
[11] Orriere (2019) *Ph.D. thesis*

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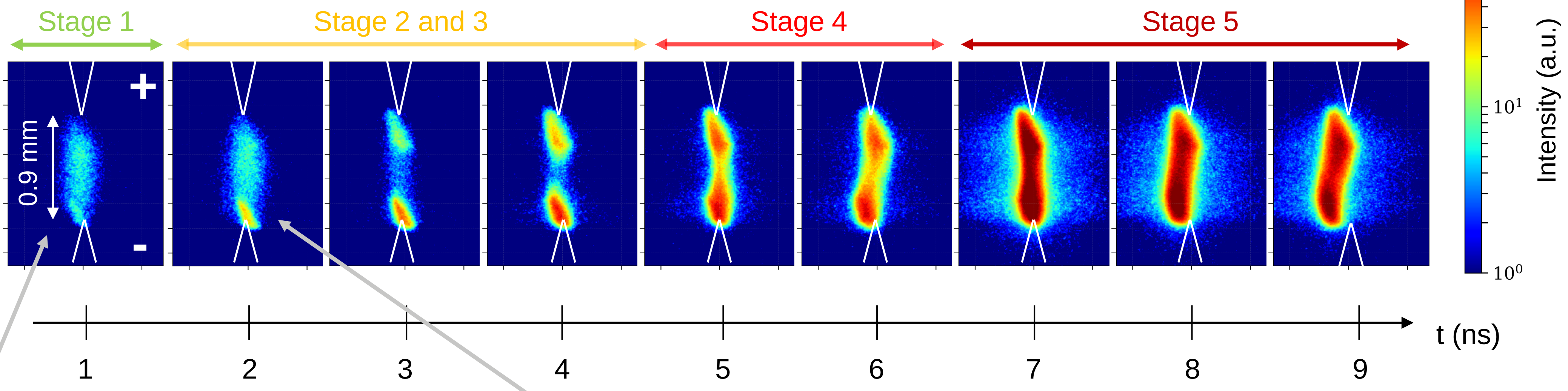
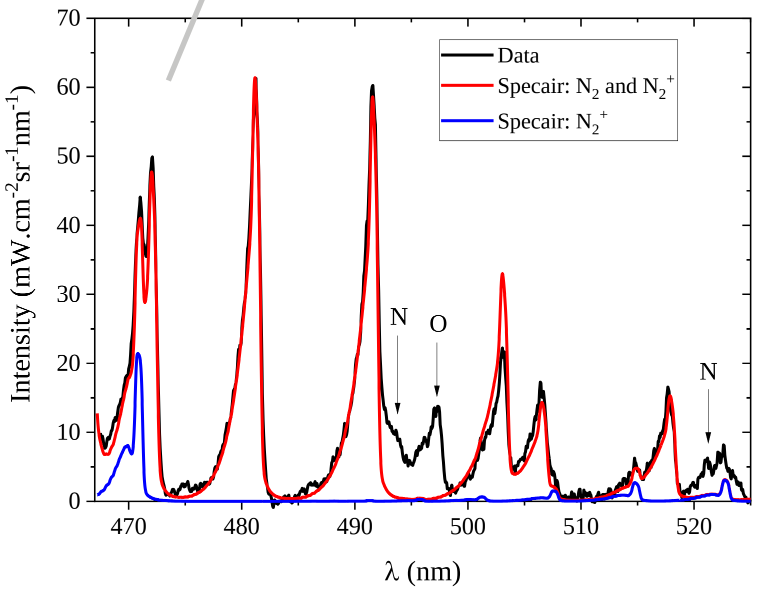
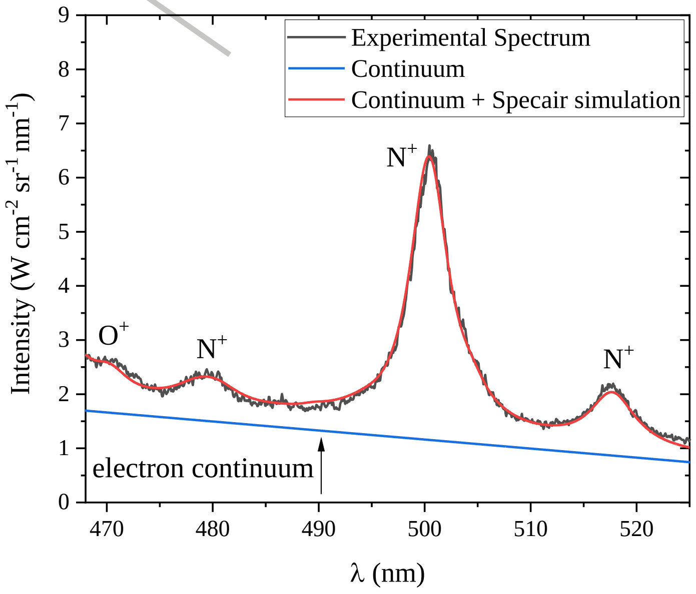






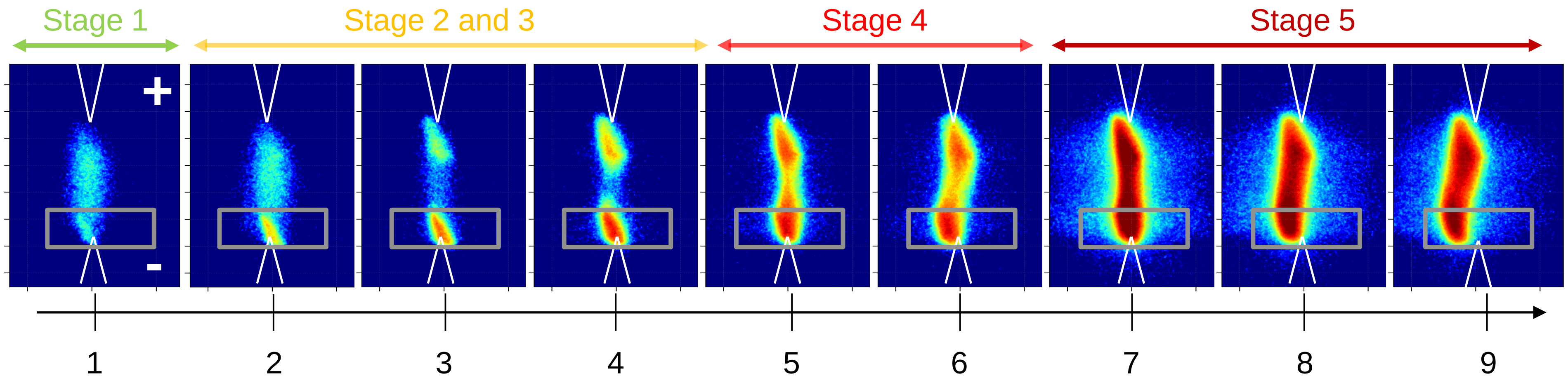
Focus on the filament formation:

- Abruptly generated in < 0.5 ns
- Spectrum:
  1. N_2 second positive system
  2. N^+ and O^+ lines

From partially to fully ionized in 0.5 ns(!)

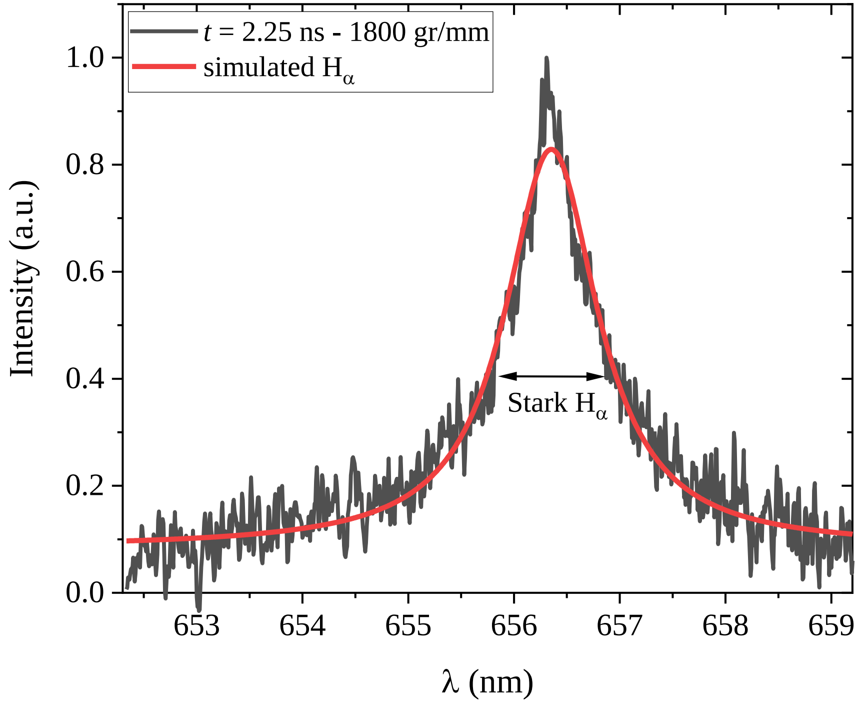
➢ Focus of investigations

2 - Filament formation – electron number density

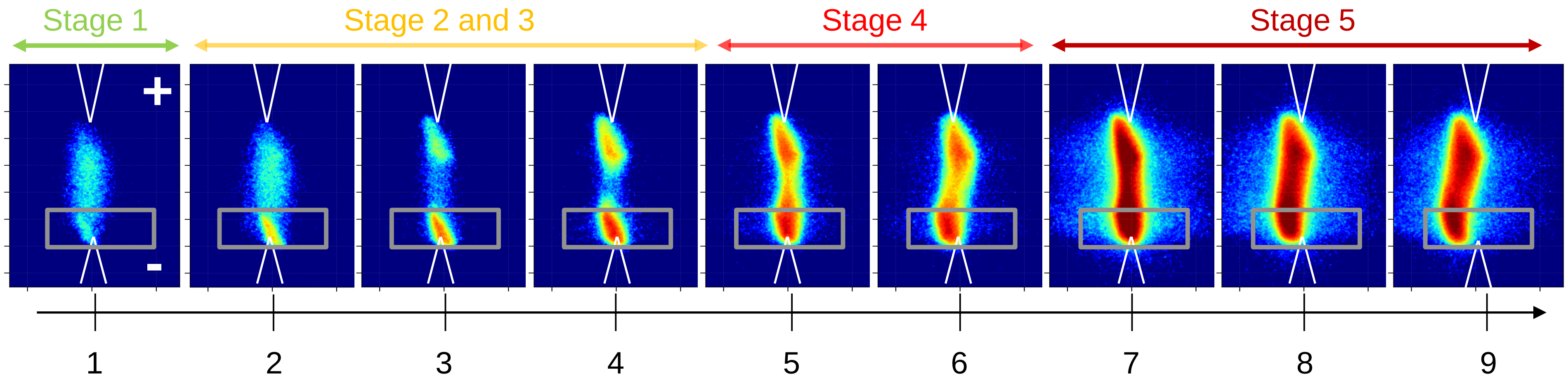


Objective: measure n_e with spatial and temporal resolution

- H_α Stark broadening [1,2]

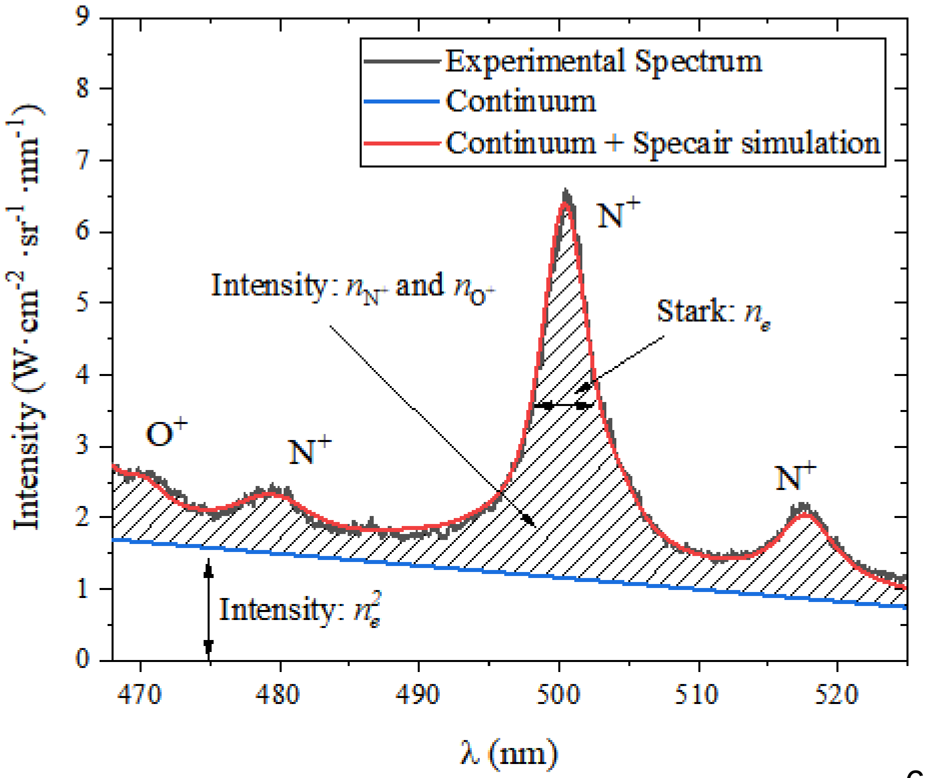


[1] Minesi *et al.*, (2020) *Plasma Sources Sci. Technol.*
[2] Gigosos *et al.*, (2003) *Spectroc. Acta B*
[3] Specair
[4] Bastiaans *et al.*, (1985) *Spectroc. Acta B*



<u>Objective:</u> measure n_e with spatial and temporal resolution

- H_α Stark broadening [1,2]
- N^+ and O^+ OES [1,3]
  - Stark broadening
  - Electronic temperature: 30,000 – 50,000 K
- Calibrated OES of ionic lines [3]
- Electron continuum [4]



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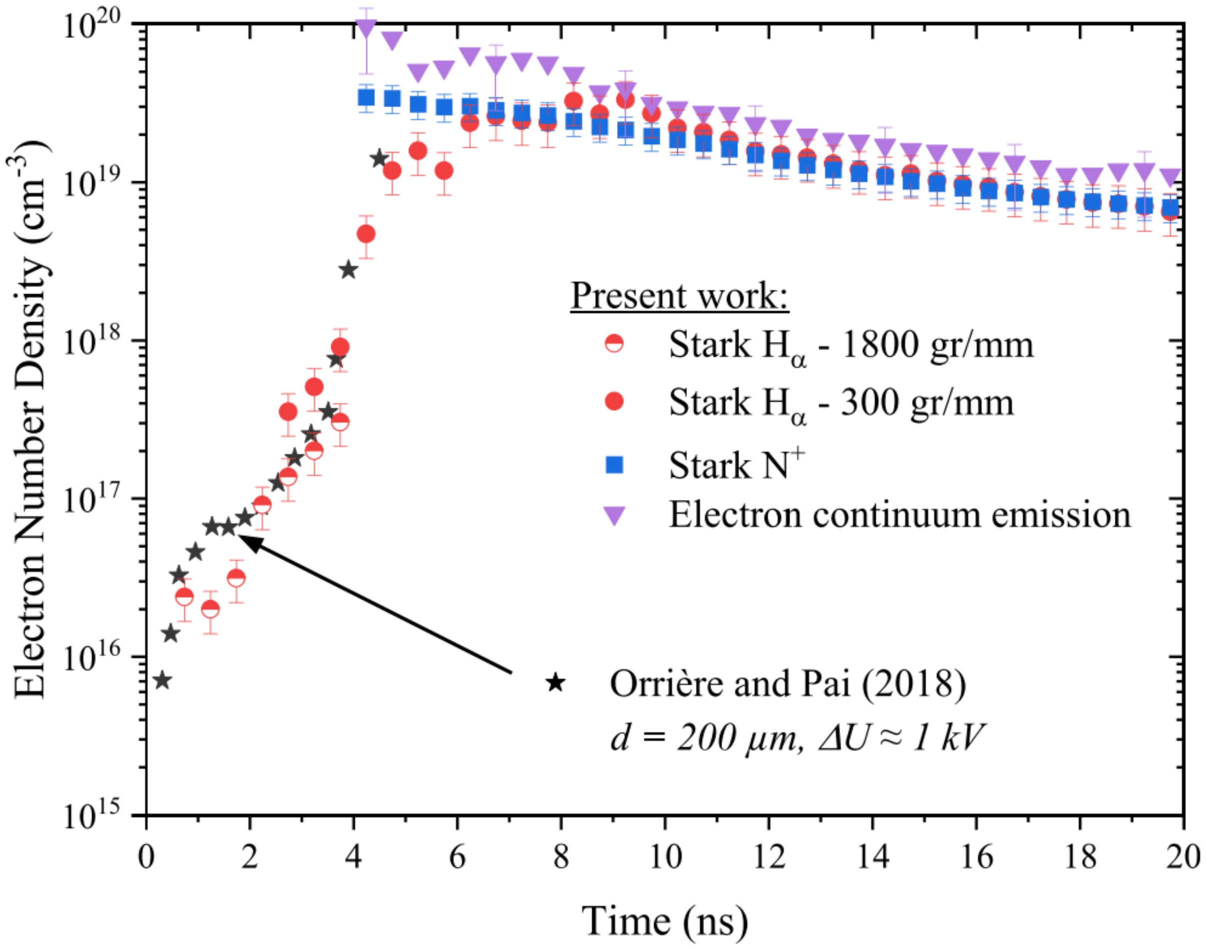
2 – Summary of the electron number density measurements

Ambiant air / 1.2-mm gap



Three techniques demonstrate:

- 3-orders of magnitude increase in 0.5 ns
- Full ionization: $n_e = 4{\cdot}10^{19}\ \text{cm}^{-3}$
- Slow decay after the pulse

Temperature by OES: 30,000 – 50,000 K

Achievements:

- ☑ Characterized experimentally
- ☐ Explanation

ZDPlasKin: *0-D kinetic + gas energy equation*[1]
BOLSIG+: *Electron Energy Distribution Function*[2]

ZDPlasKin

$$\frac{dN_i}{dt} = \sum_{reac,i} \alpha_i R_i$$

$$\frac{N_{gas}}{\gamma - 1}\frac{dT_{gas}}{dt} = \sum_{reac,i} \varepsilon_i \cdot R_i + P_{elas} n_e$$

BOLSIG+

$$\frac{\partial f_e}{\partial t} + v \cdot \nabla f - \frac{e}{m}\boldsymbol{E} \cdot \boldsymbol{\nabla}_v f = C[f]$$

Baseline mechanism

- Laux *et al.* (1999) *37 reactions*
  - N_2 , O_2 , NO, N_2^+, O_2^+, NO^+, N, O, e-
- Popov (2016) *13 reaction*
  - $N_2^* + O_2 \rightarrow N_2 + O + O$
  - $N_2^* + O \rightarrow$ products

[1] Pancheshnyi *et al., (ver. 2.0a, Sep 2017),* ZDPlasKin, (University of Toulouse, LAPLACE, CNRS-UPS-INP)
[2] Hagelaar *et al.*, (2005, 2015) *Plasma Sources Sci. Technol.*

2 – Model and reaction set for thermal spark chemistry

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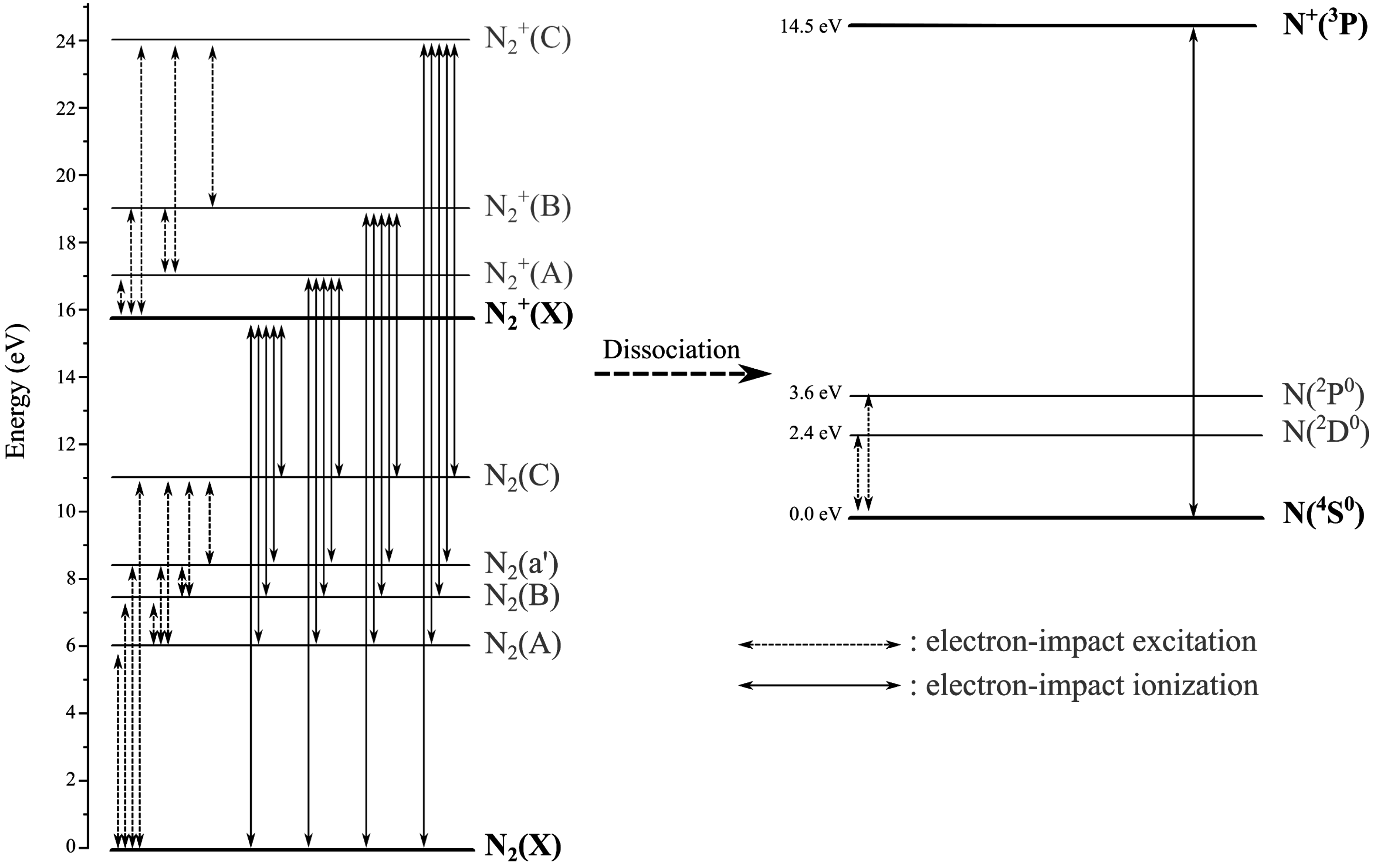

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- Bacri *et al.* (1982) [3] *20 reactions*
  - N_2(A, B, a', C) +e →N_2^+(X, A, B, C)+2e

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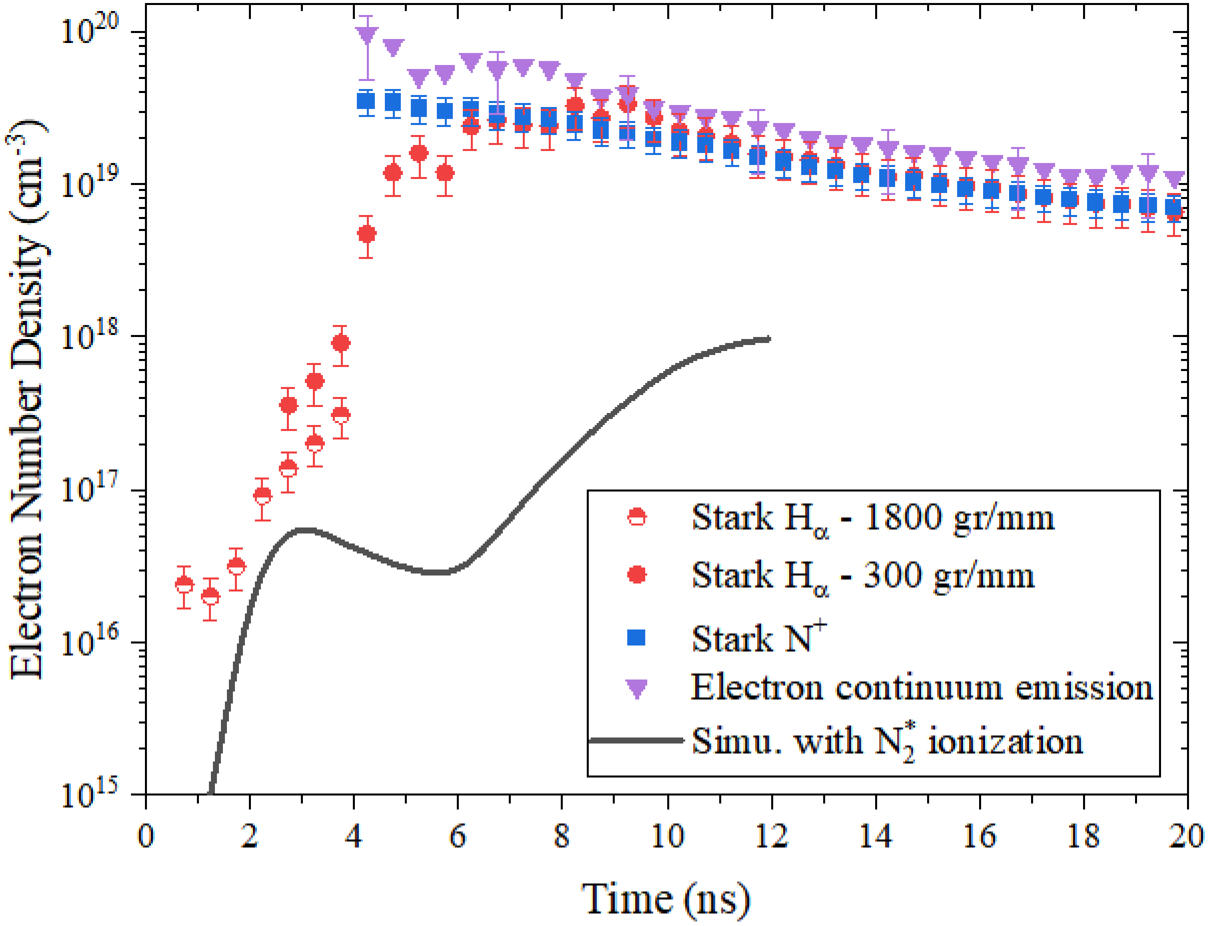
[2] Hagelaar *et al.*, (2005, 2015) *Plasma Sources Sci. Technol.*
[3] Shcherbanev *et al.*, (2019) *Plasma Sources Sci. Technol.*

2 – Comparison experiments and simulations



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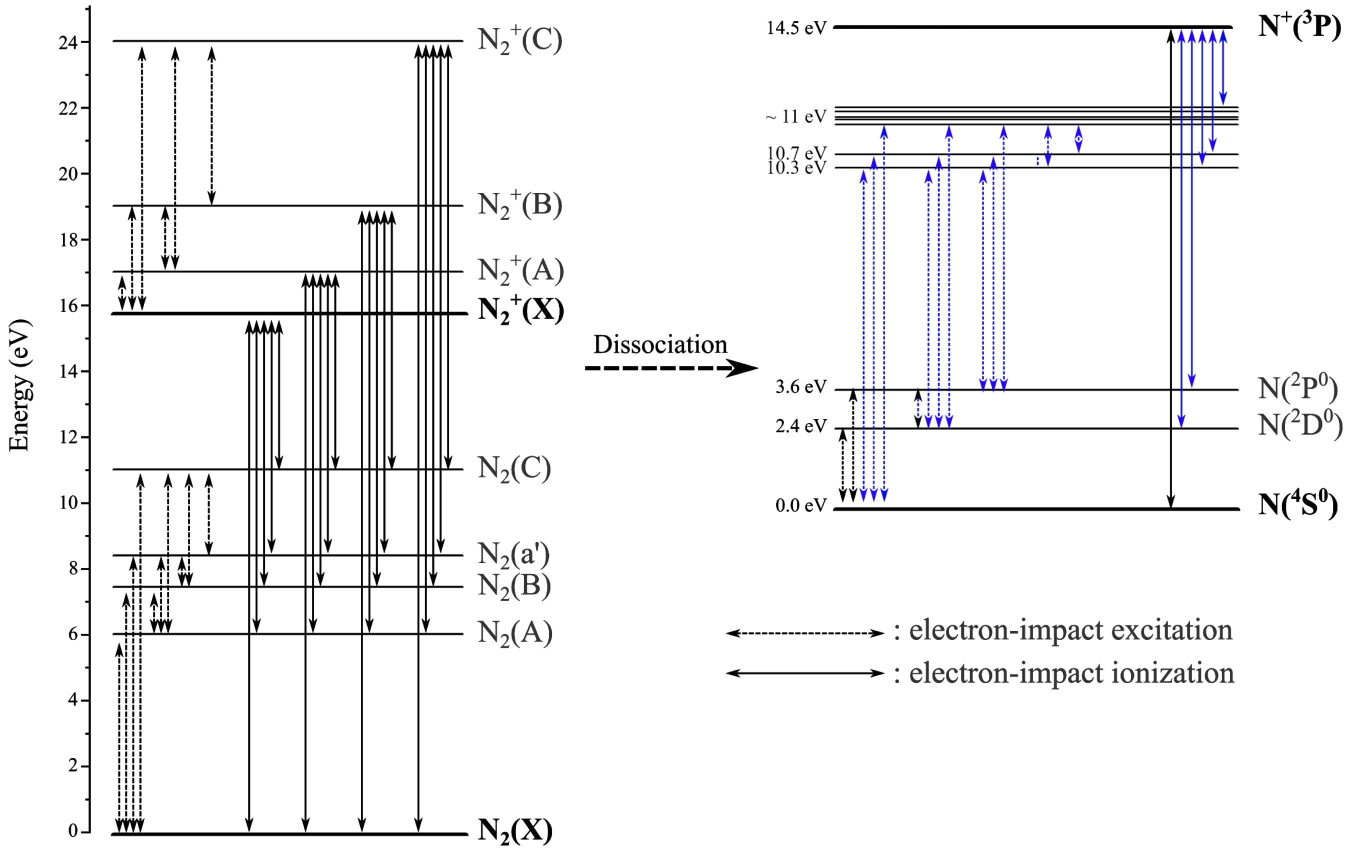

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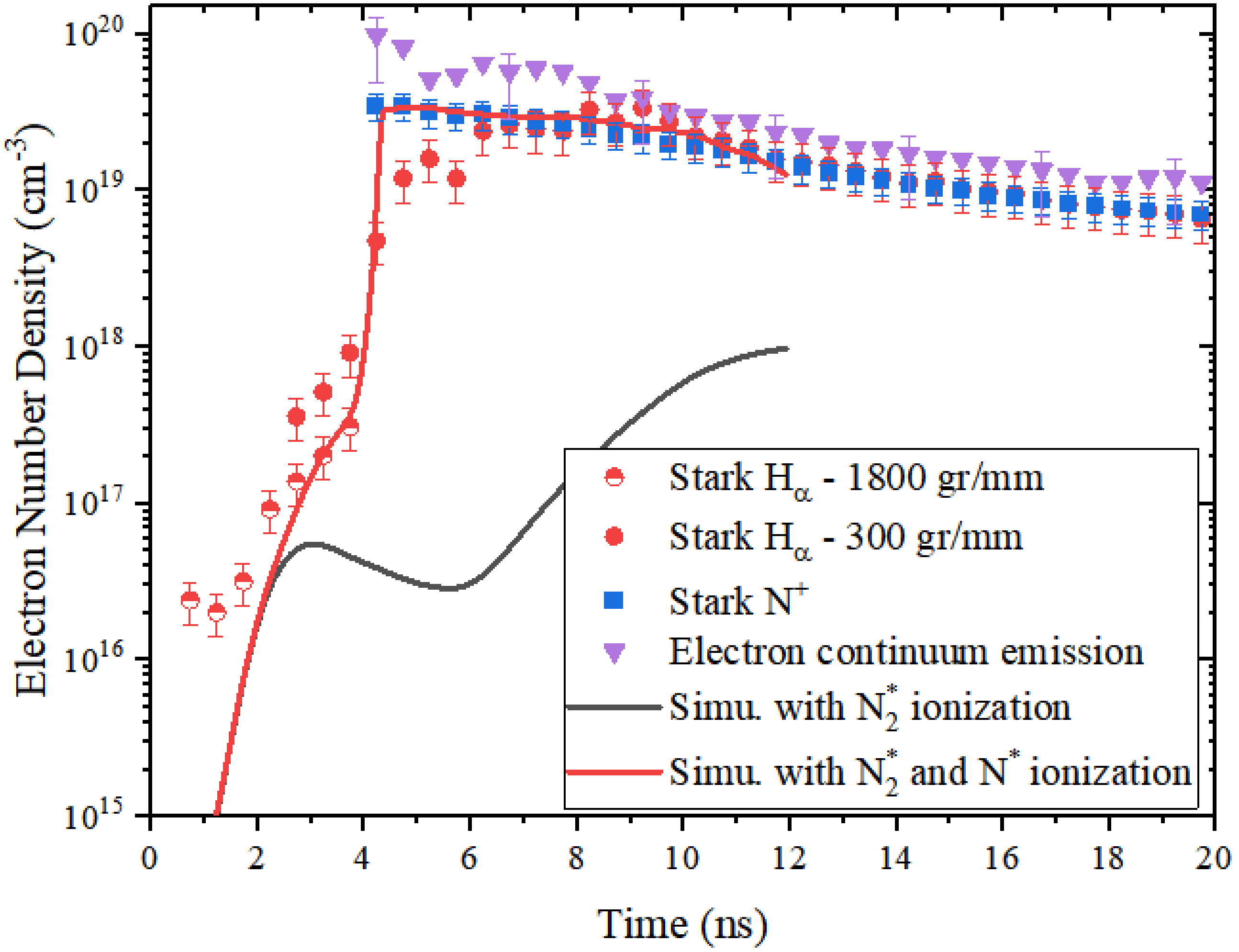
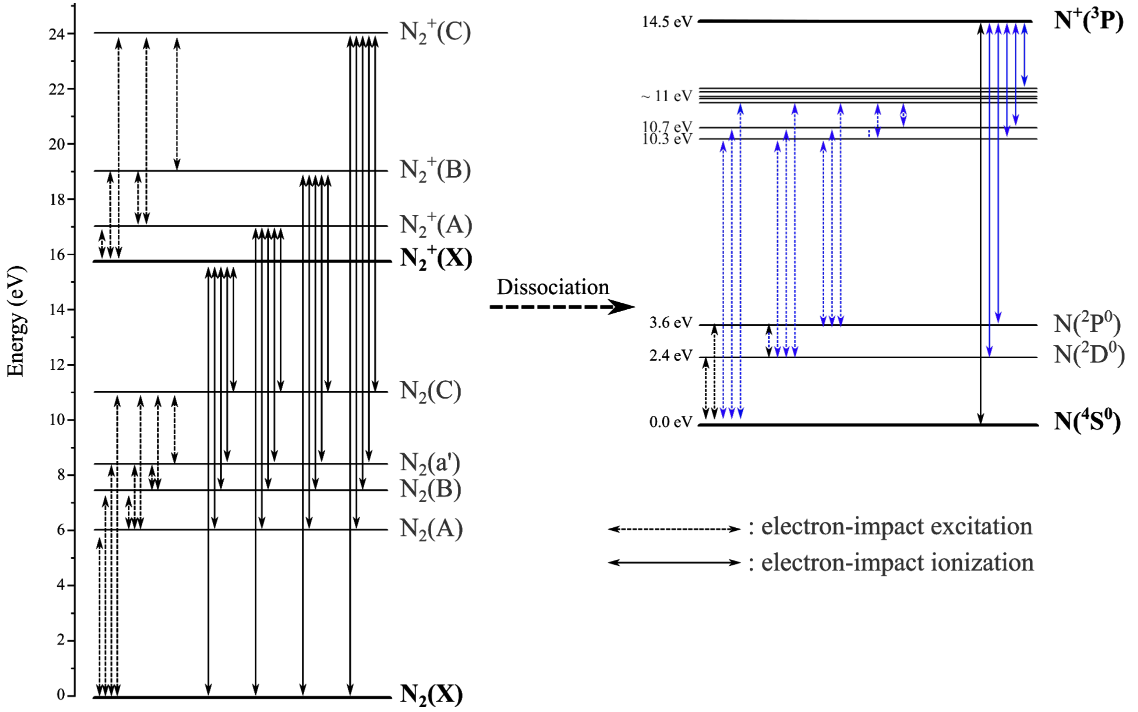
Additional reactions *30 reactions*

- Wang *et al.* (2014) & Ciccarino *et al.* (2019
  - ➢ N(^{4}S, ^{2}D, ^{2}P, …) + e → N^+ + 2e
- Tayal *et al.* (2016)
  - ➢ O(^{3}P, ^{1}D, ^{1}S) + e → O^+ + 2e

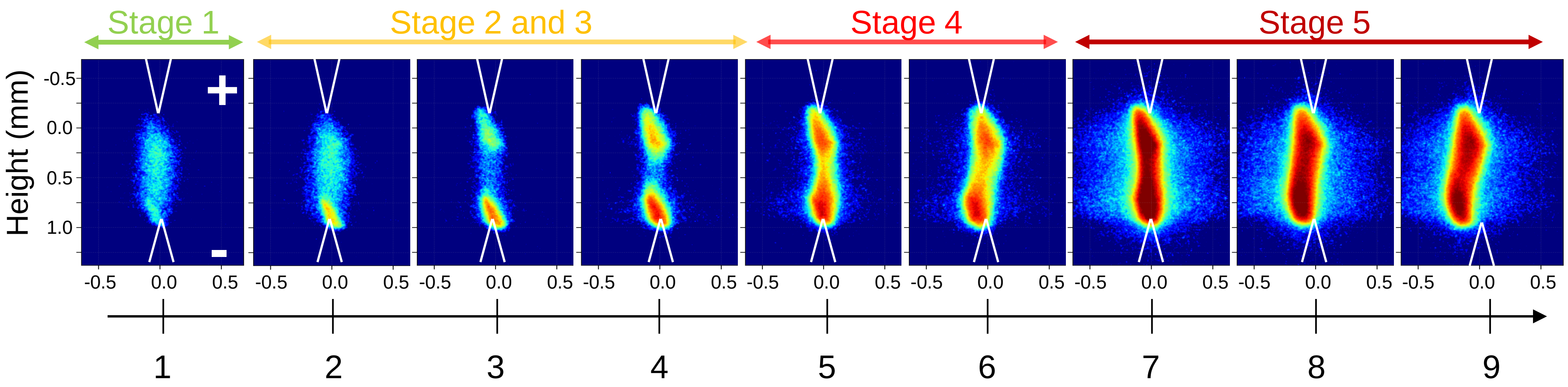
[1] Pancheshnyi *et al., (ver. 2.0a, Sep 2017),* ZDPlasKin, (University of Toulouse, LAPLACE, CNRS-UPS-INP)
[2] Hagelaar *et al.* (2005, 2015), *Plasma Sources Sci. Technol.*
[3] Shcherbanev *et al.*, (2019) *Plasma Sources Sci. Technol.*
[4] Minesi *et al.*, (2023) *Plasma Sources Sci. Technol.*

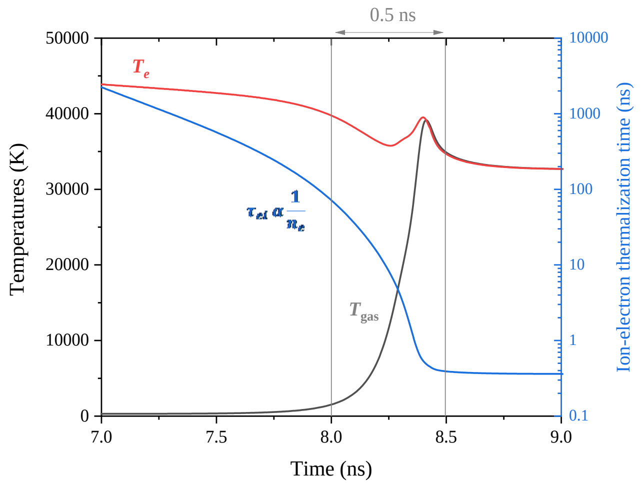


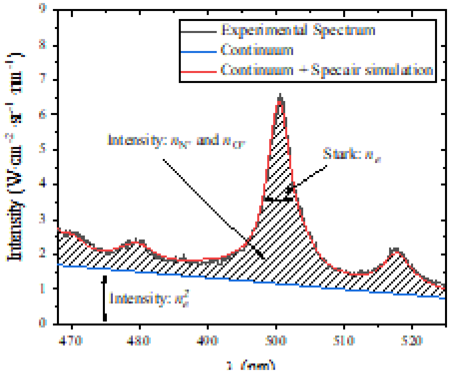


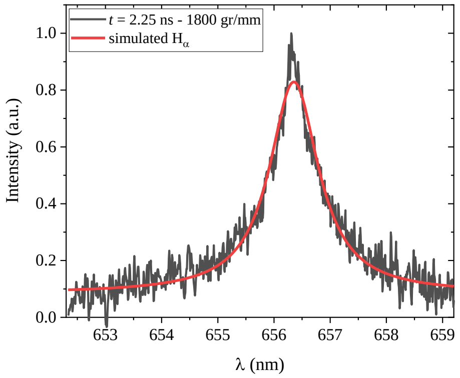
- ☑ Characterized experimentally
- ☑ Explanation

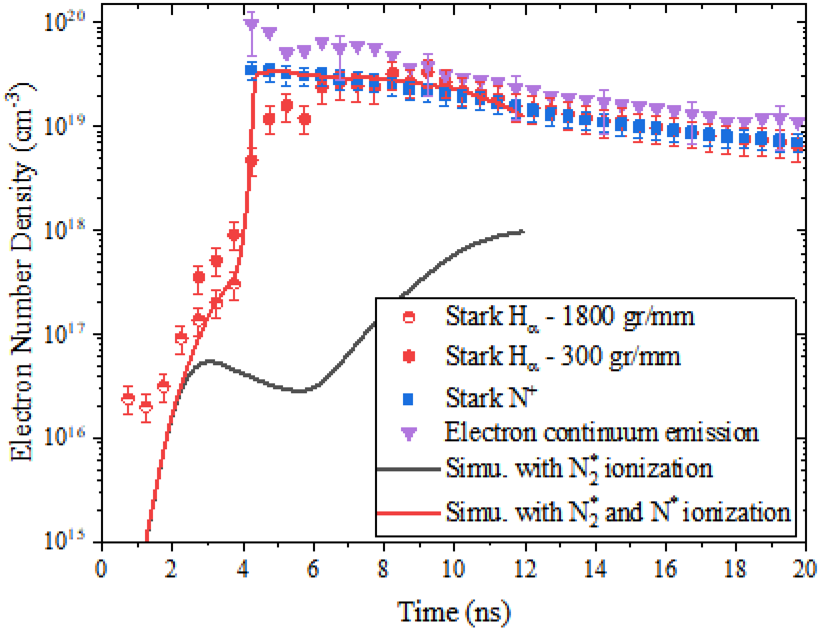
2 – Summary of our findings











<u>We understood:</u>

- Formation of a thermal spark in 5 stages
- Isentropic expansion responsible for n_e decay
- Increase of n_e due to ionization by electron-impact of N*
- Increase of T_{gas} due to electron-ion collisions

2 – What's next?

<u>Thesis:</u> EM2C, CentraleSupélec, Université Paris-Saclay

- New regime of ns discharge: thermal spark
- Plasma-assisted combustion of CH_4 flames

<u>Post-doc:</u> University of California, Los Angeles (UCLA)

- Tunable Diode Laser Absorption Spectroscopy (TDLAS)
- Shock tube

<u>Context:</u>

- Shift toward carbon-neutral fuels: H_2, **NH_3**, alcohols …

<u>New scientific questions:</u>

- Impact of NRP discharges on NH_3 flames
  - ❑ Stabilization
  - ❑ Pollutant
- Thermal *vs* non-thermal discharges in flame
  - ➢ ANR "Thermonia" submitted this year