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Electric field and electron properties of a diffuse nanosecond pulsed discharge in air at atmospheric pressure

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► **To cite this version:**

Alexandra Brisset, Pierre Tardiveau, T. Guenin, Ana Sobota. Electric field and electron properties of a diffuse nanosecond pulsed discharge in air at atmospheric pressure. 35th ICPIG, Jul 2023, Egmond aan Zee (Pays Bas), France. hal-04917354

HAL Id: hal-04917354

<https://hal.science/hal-04917354v1>

Submitted on 3 Feb 2025

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Context: Atmospheric pressure plasmas (APPs) create large amounts of reactive species. The nature and amount of these species is highly dependent on the space-time electric field distribution (E) of the discharge. E is difficult to tune because it is rapidly screened by the discharge space charge (ps time scale). **Because of the E screening, a gas particle is usually only subjected to high fields during the very rapid passage of the E field peak during propagation (~10 - 100ps).**

In search for the generation of high energy chemistry, it was suggested some years ago to apply extremely fast and intense voltage rise rates. It was recently demonstrated in [1] that **high electric fields (~800 Td) could be maintained shortly with this technique**, and this surprisingly induced other remarkable properties of the discharge : *i)* high stability *ii)* large volume (cm³ !) *iii)* high reactivity (~10 times superior to moderate voltage rise rates) *iv)* remains close to ambient temperature (tunable).

Outcomes of this work:

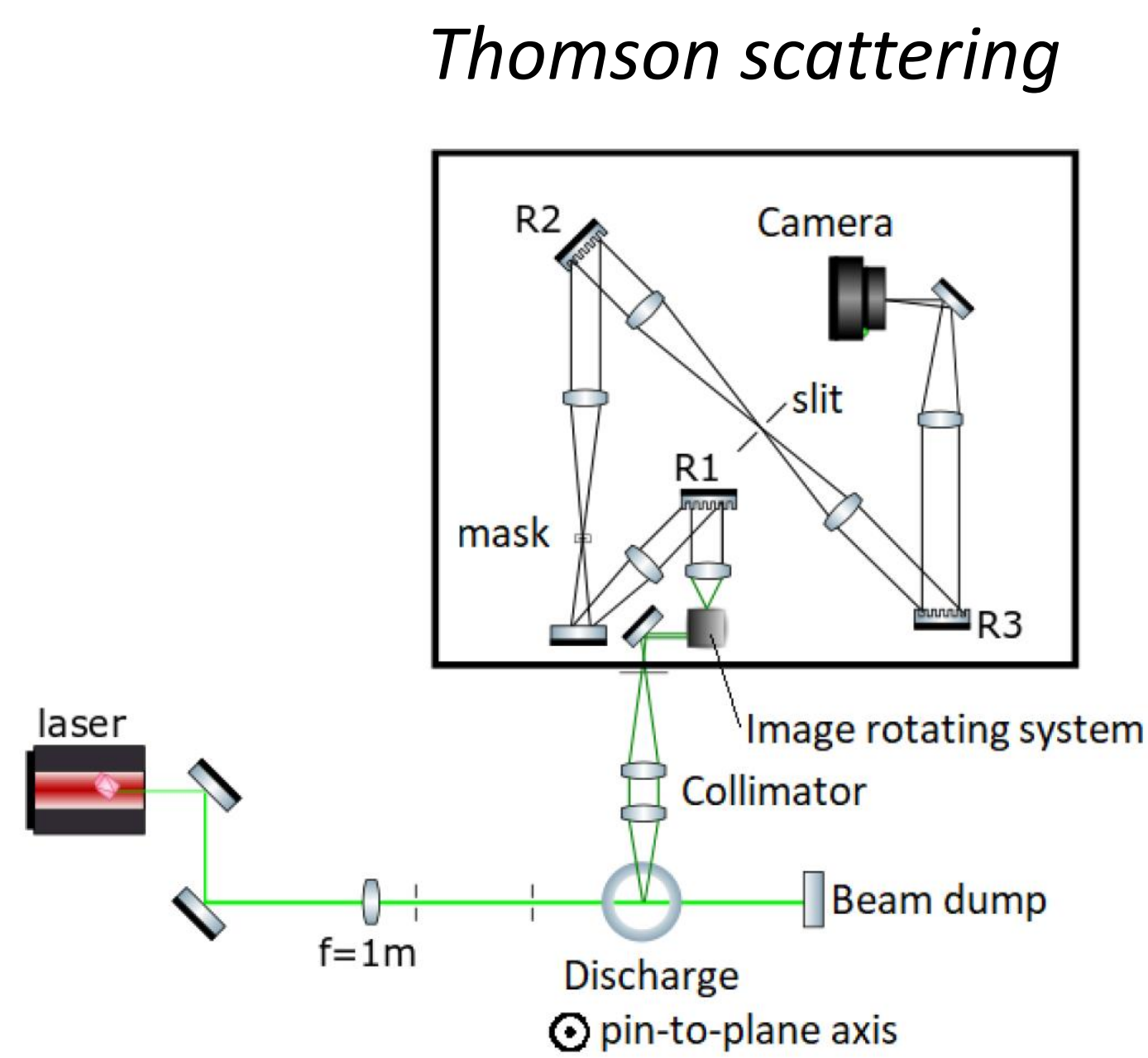
- Specificities of the electron distribution function at high overvoltage: splitting in 2 regions,
- Ground for the control of the filamentation process,
- Ground for the explanation of a ns-electric field rise (~700 Td) in the vicinity of the anode

Methods:

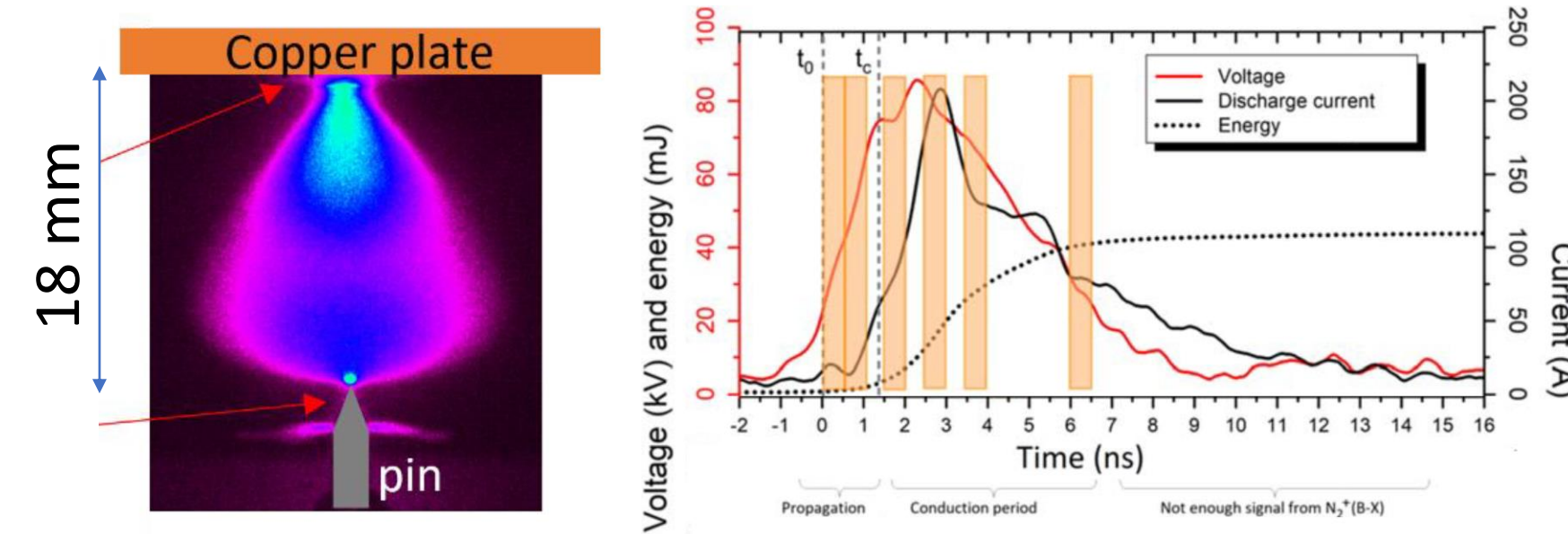
Incoherent Thomson Scattering, Optical Emission Spectroscopy, Stark broadening analysis.

Experimental setup:

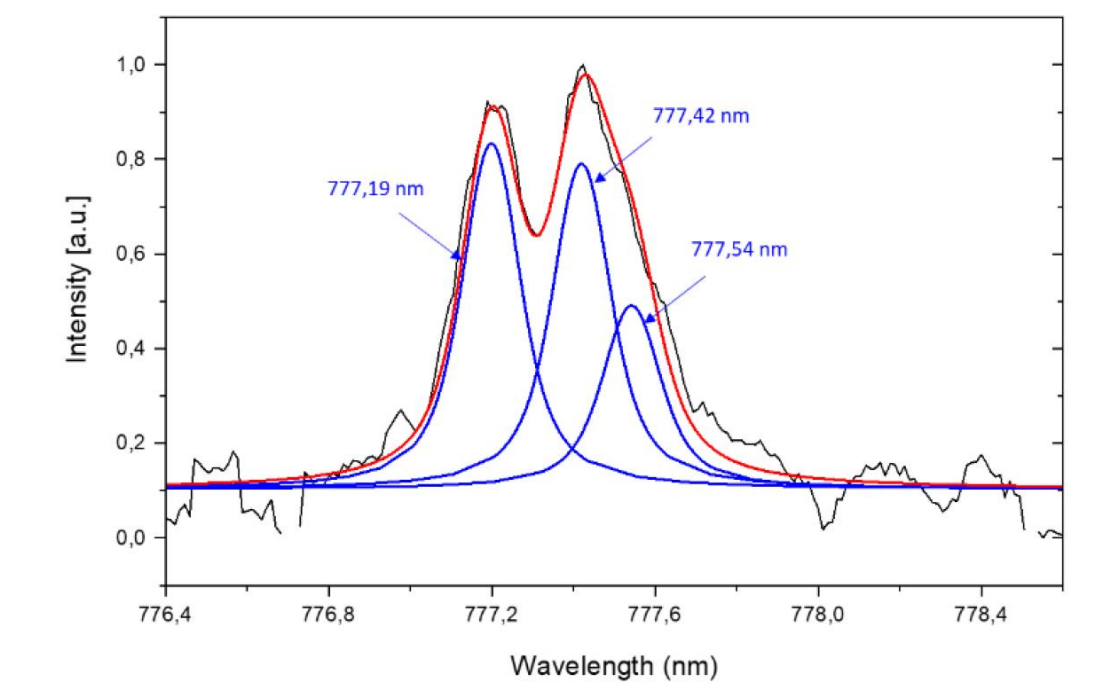
- pin-plane geometry, 18mm gap
- ~100 μm pin radius
- Voltage peak 85 kV, rise time 2 ns
- Repetition frequency 5 Hz
- P = 1 atm, 1 L.min⁻¹, flow of synthetic air
- 200 ps Ekspla laser, 532 nm, 70 mJ
- Triple grating spectrometer



Diffuse Fast Ionization Wave



Stark broadening of O*

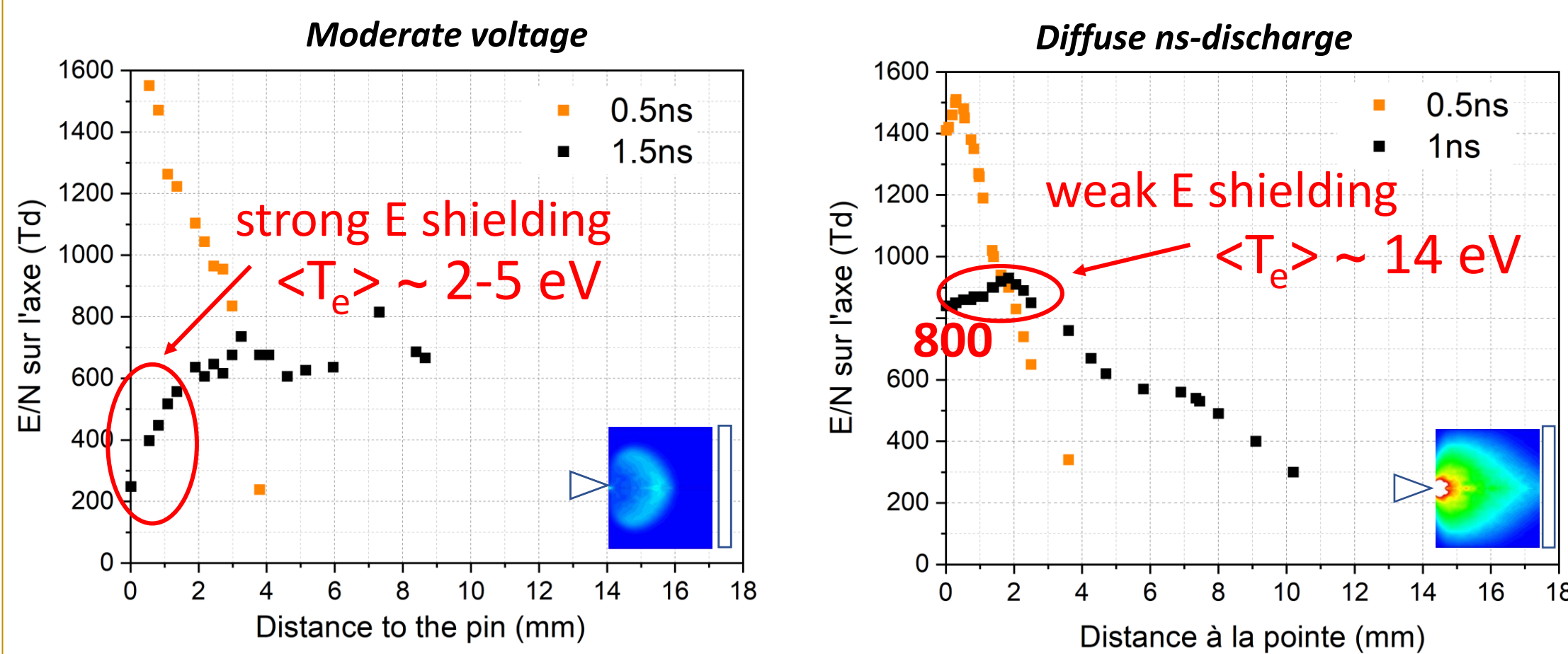


Oxygen lines deconvolution at r = 30 μm, over Δz = 300μm from the pin. Time integration is 3 ns from 5 ns after the start of the discharge.

Effect of high overvoltages: maintaining high electric fields, enhancing ionization and dissociation, filamentation ?

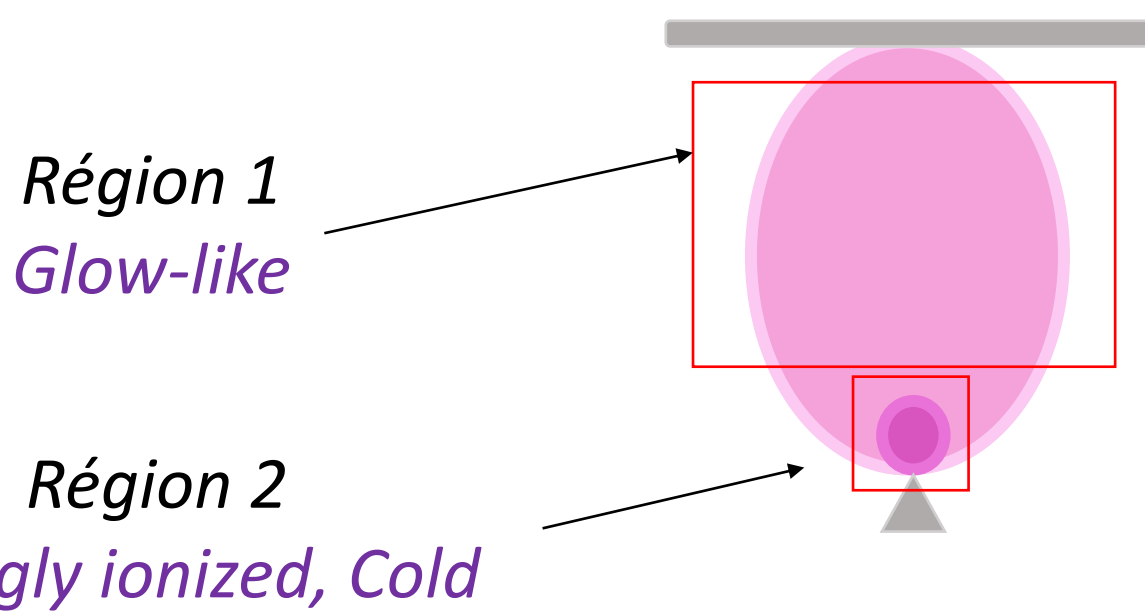
There are fundamental differences in E/N distributions at moderate and at high overvoltage

Reduced electric field E/N



In the diffuse ns-discharge :

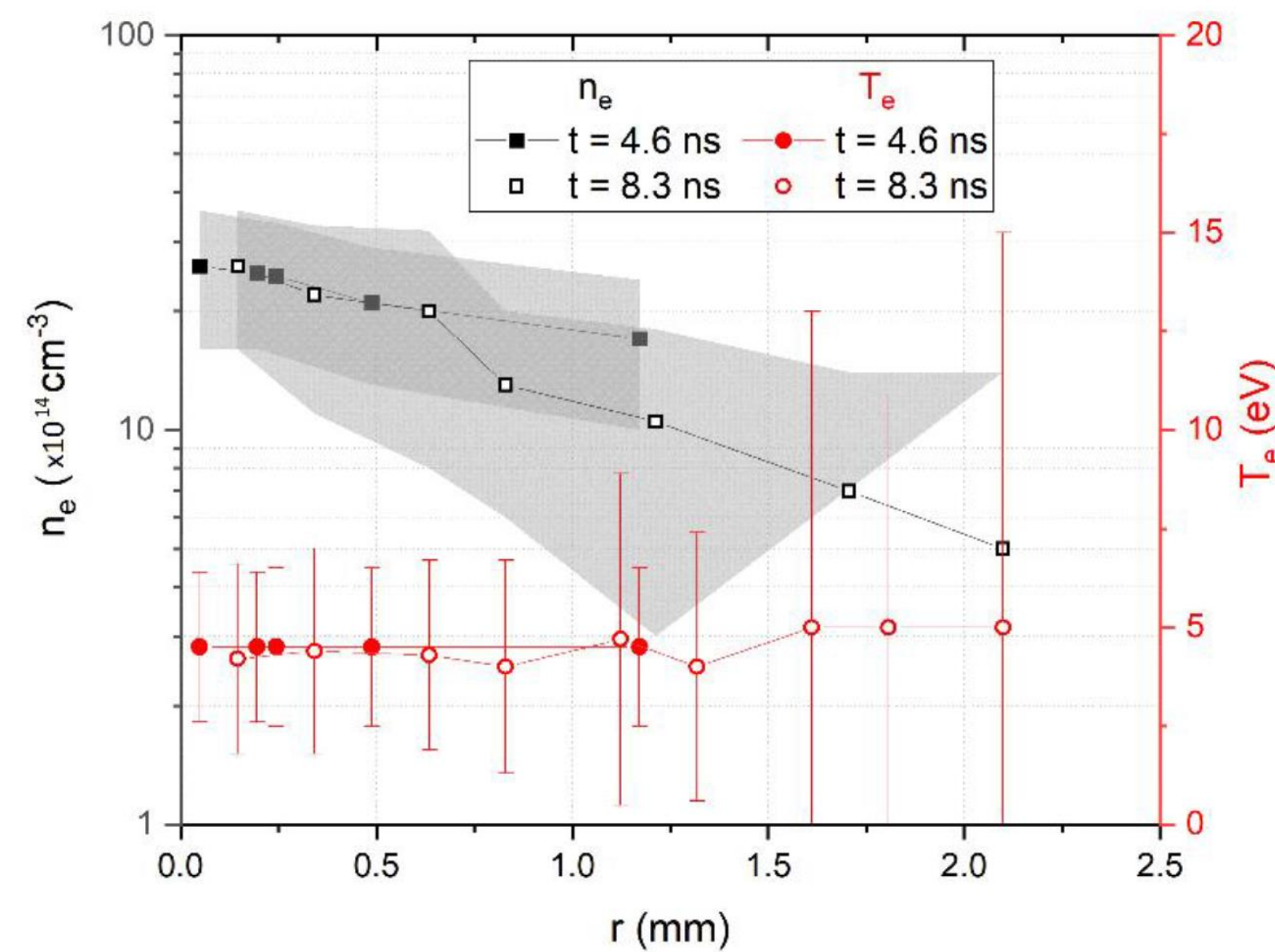
- At 500 ps : E/N maximum (~1000 Td) is not located at the discharge emission front.
- At 1 ns : high E/N fields (~800 Td) are maintained from the pin to the position of the field maximum
- At 2-3 ns : E/N homogenizes along the gap (~200 Td)
- At 4-6 ns : E/N rises again strongly (~700 Td) in the vicinity of the pin and decreases in the gap



Discharge develops as a highly reactive glow-like discharge and splits after ~ 6 ns in the vicinity of the pin into a high E/N, strongly ionized, region

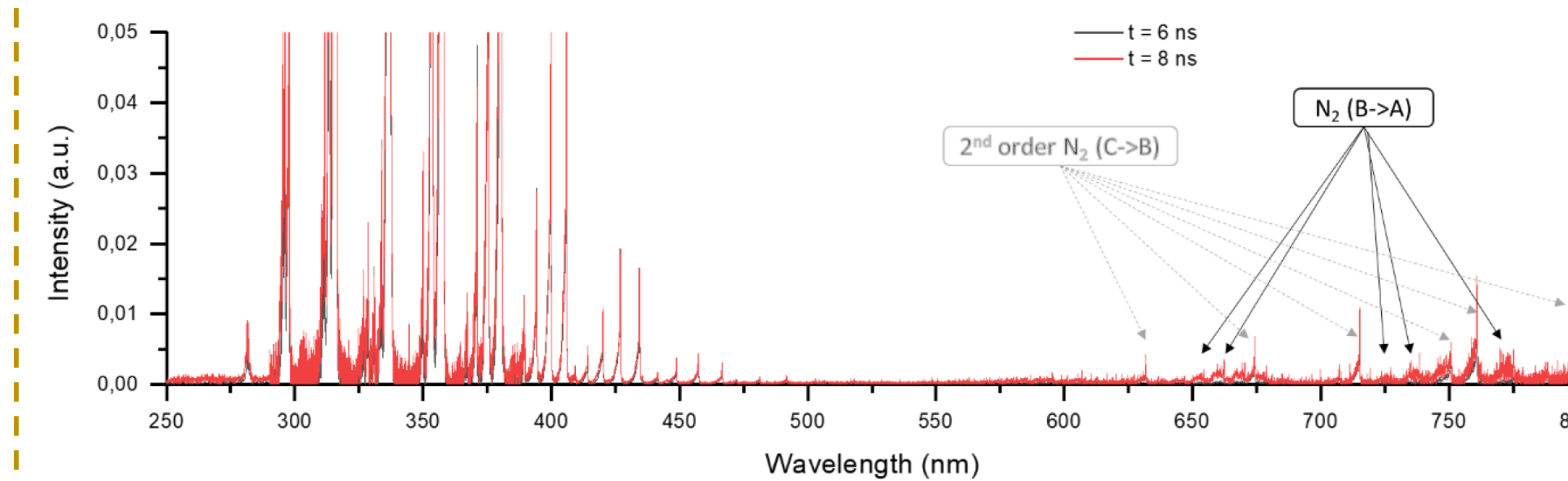
Region 1 (main gap) is a highly reactive homogeneous glow like discharge

Radial electron density



- n_e ~ 10¹⁵ cm⁻³ in the majority of the gap
- High T_e maintained in the gap (~3 eV)
- T_e and n_e are homogeneous radially over several mm

gap region: Typical spectrum of cold APPs

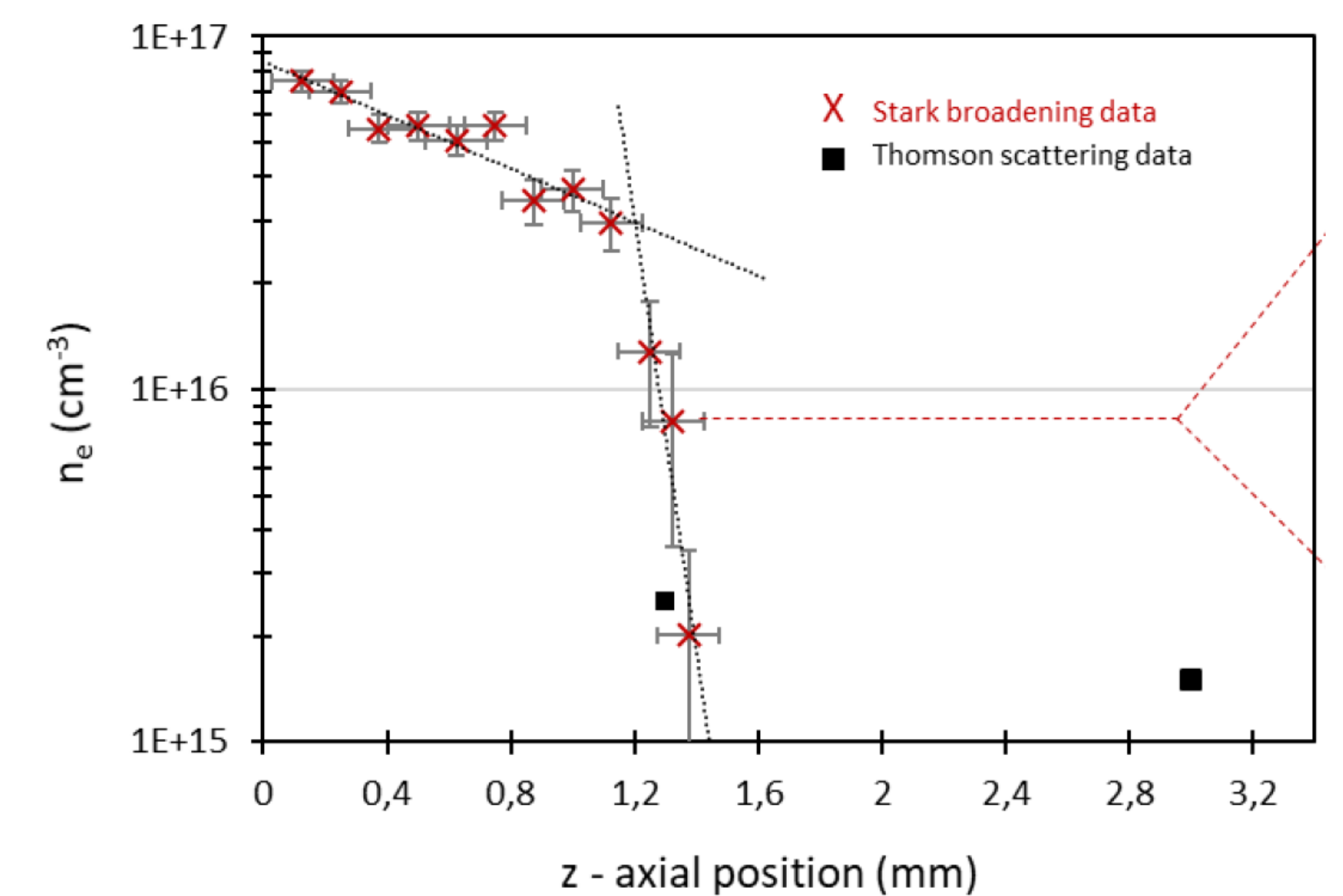


Remarkable properties :

- High reactivity (n_e ~ 10¹⁵cm⁻³, n_{(N2(C))} ~ 5x10¹⁵cm⁻³)
- Large volume (cm⁻³ !)

Region 2 (pin vicinity) is a peculiar strongly ionized non-thermal region

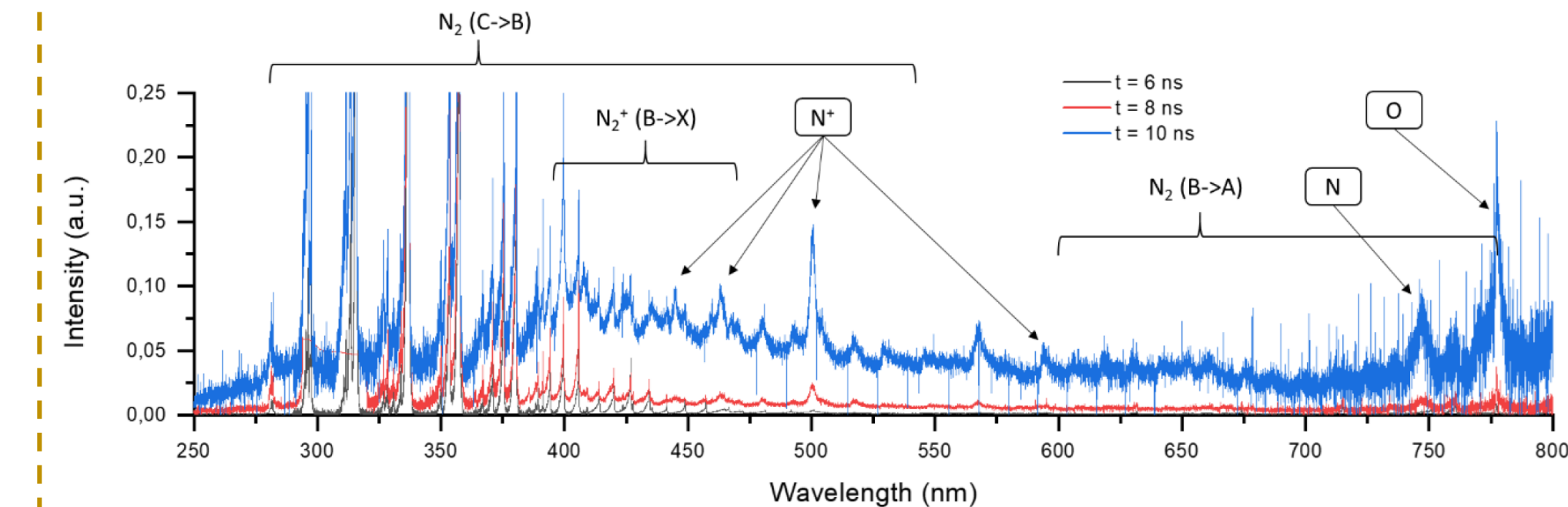
Axial electron density



At 8ns :

- n_e ~ 5x10¹⁶ cm⁻³ on the first 1 mm
- Drop down to 10¹⁵ cm⁻³ in 500 μm
- Coherent with TS, continuum emission and E/N field rise

pin region: additional O*, N*, N , continuum**



Filamentation ?

- Localized strong ionisation ~10¹⁷ cm⁻³
- Low temperature (<1000K) ?

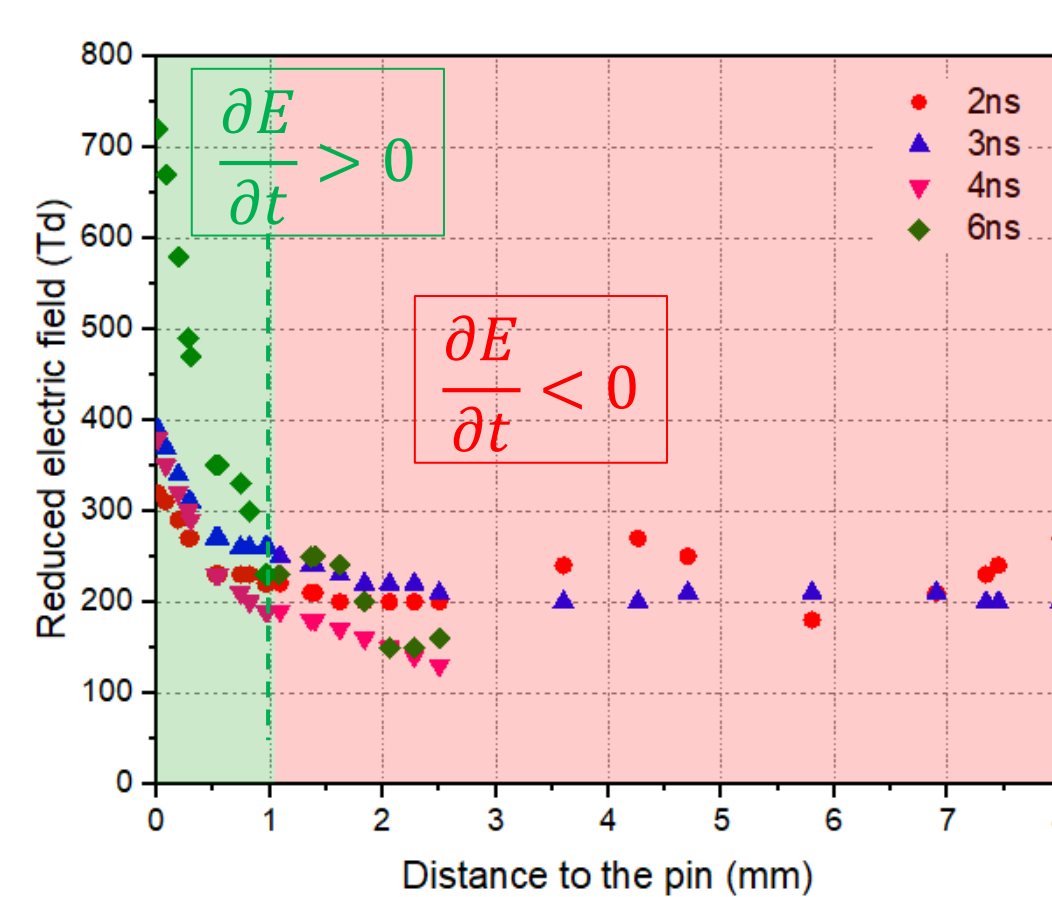
Kinetics induced ns-electric field rise:

After breakdown and return stroke: $I = e \times n_e \times \mu_e \times E \times S$

Hypothesis, based on high E/N fields in the vicinity of the pin:

$$\frac{1}{E(x,t)} \frac{\partial E(x,t)}{\partial t} = -\frac{1}{\tau} - \underbrace{v_i(x,t)}_{\text{ionization freq.}} + \underbrace{k_{rD} \cdot n_{N_2^+}(x,t)}_{\text{dissociative recombination}} + \underbrace{k_r \cdot n_e^2(x,t)}_{\text{3-body dissociative recombination}}$$

current decrease, ionization freq., dissociative recombination, 3-body dissociative recombination



In the pin region, E/N is high (≥200 Td):

- Weak attachment processes
 - Strong recombination processes
- ⇒ Local ns-E field rise ?

Conclusion:

- most of the volume of the discharge (region 1) is quite representative of a quasi-steady state glow discharge
- once propagation is completed (~2 ns) region 1 has rather homogeneous properties (n_e ~ 10¹⁵ cm⁻³ and T_e ~ 3 eV).
- ≥ 6 ns, a sub-millimetric region (region 2) develops, characterized by :
 - strong ionization (higher than 1%)
 - n_e ≥ 10¹⁷ cm⁻³
 - continuum of emission (from UV to near-IR)
 - ns-E field rise
- In region 2, the radiative recombination of N₂⁺ could help to explain the continuum and a sharp electric field rise (~700 Td)

Perspectives:

- Kinetic model describing ns-E field rise
- Better understanding and control of filamentation

References:

[1] Brisset et al. Plasma Sources Sci. Technol. 28 (2019) 055016

Acknowledgments:

ANR-13-BS09- 0014 research program
Éole grant from the French-Dutch network.