



COMBUSTION OF LIQUID AMMONIA, ASSISTED BY PLASMA
DISCHARGES, AS A NOVEL AND CLEAN ENERGY CONVERSION
METHOD

Deliverable D3.1

Report on plasma-NH₃ energy efficiency studies

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Executive Summary

The present report, entitled “**D3.1- Plasma-NH₃ energy efficiency studies**,” is the first deliverable of WP3 - “Plasma dynamics and plasma systems development” and relates to T3.1 – “Plasma NH₃ energy efficiency studies”.

The main goal of D3.1: T3.1 was to provide an experimental study of efficiency of ammonia dissociation by nanosecond plasmas. Nanosecond discharge in long dielectric tubes at moderate pressures (tens of mbar) in the form of a fast ionization wave (FIW), which best fulfil the criteria for measurements of energy efficiency in terms of the G-factor (eV per particle), was developed and used to obtain results with a high experimental accuracy (within 5-15%).

During the experimental preparation stage, the two CAIPIRINH₃A partners jointly, CERTH and CNRS, developed a 2D-axisymmetric numerical model of the discharge in the form of a fast ionization wave. A scientific publication has been published in Plasma Sources Science and Technology (PSST) in 2025. This paper presents a detailed axisymmetric numerical analysis of a nanosecond discharge propagating in a long tube in pure nitrogen. A fluid (continuum) description of the plasma is the core of the physical model used in the computational software COPAIER — a multi-species and multi-temperature plasma fluid solver allowing for self-consistent description of the plasma spatial and temporal evolution. The model is validated against CNRS experimental data on discharge speed of propagation, energy delivered to plasma, electric fields and radial distribution of electron density and optical emission intensity as a function of pressure and high-voltage pulse polarity.

Analysis of advantages and challenges of plasma-assisted combustion resulted in participation in a tutorial review published in 2026 in two parts in Plasma Sources Science and Technology (PSST). The review is aimed to guide readers from fundamental combustion and plasma physics to the mechanisms and practical applications relevant to the most modern energy and propulsion systems. Work on these papers provided a comprehensive overview of the state of the art in plasma-assisted combustion up to 2026, establishing a broader scientific framework for the development of plasma-assisted combustion of ammonia within the project.

Nanosecond discharge tube (nDT) setup was developed specifically to study plasma efficiency at different parameters of the discharge. A set of experimental tests in CNRS LPP laboratory confirmed a proper response of the discharge to changing of external parameters and a possibility to control, during the experiments, the range of the electric fields and specific energy delivered to plasma (SED). The nDT setup has been adapted to experimental study of NH₃ plasma.

The discharge setup and the high-voltage generator were moved to LU, and a few experimental sessions were organized at the Division of Combustion Physics of Lund University. For the first time, we obtained a complete set of advanced data on plasma parameters – synchronized within 0.2 ns current, electric field, and specific delivered energy in moderate pressure (tens of mbar) spatially uniform diffuse plasma of ammonia at 10-15 kV 20 ns 10-20 Hz discharge.

Experimental measurements of optical emission spectra have been performed, revealing presence of molecular bands and atomic lines of excited species, namely electronically excited NH, NH₂ and H in UV and visible ranges of spectra. A series of experiments showed that H-TALIF measurements in an NH₃ environment are challenging even at moderate pressures due to the very strong absorption of 205 nm radiation associated with an electronic-vibrational transition of the ammonia molecule. Additional experiments were therefore conducted to investigate the feasibility of three-photon excitation at longer wavelengths outside the NH₃ absorption range, and recommendations were developed regarding the feasibility of absolute calibration of such measurements. The experimental concept was subsequently modified towards the determination of the G-value for the formation of electronically excited NH(A). These studies were performed using absolute optical emission spectroscopy at 335 nm. The G-values obtained are presented in this report.

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1 Introduction

1.1 Scope

To gain deeper insights in kinetics of plasma-assisted combustion, it is necessary to understand plasma action on fuel, oxidizer and their mixtures. While this is done, during the last decades, for most traditional fossil fuels, it is only now that this field has matured enough for alternative and greener fuels. In particular, it is a case for plasma-assisted ammonia combustion.

The importance of ammonia combustion research is underlined by a recent, 26-31 of July 2026, International Symposium on Combustion in Kyoto. Mini-Symposium on Future Fuels for Energy Conversion, with CAIPIRINH₃A member Prof. Agustín Valera-Medina as moderator, including, for example, talks of Dr. Toshiro Fujimori (IHI Corporation; Japan) "Ammonia Power Generation Technology Development and Challenges in Combustion Technology" and of Prof. Christine Rousselle (University of Orléans; France) "Hydrogen and Ammonia Challenges for Application in Internal Combustion Engines". The Mini-Symposium claimed: "As global energy demands grow alongside the need to reduce carbon emissions, future fuels such as hydrogen, ammonia, synthetic fuels (including sustainable aviation fuels, SAF), and metal fuels are increasingly viewed as critical solutions for hard-to-electrify sectors, including transportation, power generation and industrial heating."

Ammonia (NH₃) is considered a potential carbon-free energy carrier due to the absence of CO₂, energy density comparable to fossil fuels, and the availability of established technologies for its storage and transport. As for other fuels, plasma-assisted combustion can provide significant benefits for ammonia by enhancing ignition, stabilizing the flame, and extending the operating range^{1,2,3,4,5}. However, advanced laser-based diagnostic techniques have only recently begun to be applied to the study of plasma-assisted ammonia combustion, and experimental data on kinetics in this area remain limited, especially for plasma action on ammonia and ammonia-contained gas mixtures^{6,7}.

To quantify the action of plasma on NH₃-containing mixture, G-value of H-atoms and N-atoms production should be measured experimentally, allowing a conclusion on efficiency of NH₃ dissociation by plasma of pulsed nanosecond discharge. Although the technique of direct measuring of efficiency of N₂ dissociation has been recently developed in LPP group^{8,9}, this technique has never been used for study of NH₃ kinetics. Together with the LUND team, a protocol was developed for the experimental determination of the G-factor of NH₃ dissociation in a nanosecond pulsed discharge under high reduced electric fields. The G-factor represents the energy cost of a specific plasma-chemical process (in this case, ammonia dissociation), expressed in particles per 100 eV of

¹ J. Choe, W. Sun, T. Ombrello, C. Carter, Plasma assisted ammonia combustion: Simultaneous NO_x reduction and flame enhancement, *Combustion and Flame* 228 (2021) 430-432. DOI: 10.1016/j.combustflame.2021.02.016

² M. Shahsavari, A.A. Konnov, X.-S. Bai, A. Valera-Medina, T. Li, M. Jangi, Synergistic effects of nanosecond plasma discharge and hydrogen on ammonia combustion, *Fuel* 348 (2023) 128475. DOI: <https://doi.org/10.1016/j.fuel.2023.128475>

³ K. Deng, A. He, S. Ye, W. Lin, W. Kang, Q. Lin, J. Zhu, Z. Liang, Addressing NO_x formation mechanisms of NH₃/H₂ dual-fuel flame under DBD plasma-assisted combustion resolved by intermediate radicals analysis, *International Journal of Hydrogen Energy* 96 (2024) 938-951. DOI: <https://doi.org/10.1016/j.ijhydene.2024.11.346>

⁴ A.M. Radwan, M.C. Paul, Plasma assisted NH₃ combustion and NO_x reduction technologies: principles, challenges and prospective, *Int. J. Hydrogen. Energy* 52 (2024) 819-833. DOI: <https://doi.org/10.1016/j.ijhydene.2023.10.087>

⁵ Z. Wang, B. Aravind, S. Mashruk, A. Valera-Medina, Numerical investigation on the combustion characteristics of premixed NH₃-air flames using gliding arc plasma, *Journal of the Energy Institute* 123 (2025) 102314. DOI: <https://doi.org/10.1016/j.joei.2025.102314>

⁶ H. Tang, S. Gubbi, W. Sun, Investigation of flame structure in plasma-assisted ammonia swirling flames using NH planar laser-induced fluorescence, *Combustion and Flame* 274 (2025) 114006. DOI: <https://doi.org/10.1016/j.combustflame.2025.114006>

⁷ K. Deng, A. He, S. Ye, W. Lin, W. Kang, Q. Lin, J. Zhu, Z. Liang, Addressing NO_x formation mechanisms of NH₃/H₂ dual-fuel flame under DBD plasma-assisted combustion resolved by intermediate radicals analysis, *International Journal of Hydrogen Energy* 96 (2024) 938-951. DOI: <https://doi.org/10.1016/j.ijhydene.2024.11.346>

⁸ T.L.Chng, N.D.Lepikhin, I.S.Orel, N.A.Popov, S.M.Starikovskaia, TALIF measurements of atomic nitrogen in the afterglow of a nanosecond capillary discharge, *Plasma Sources Sci. Technol.* 29 (2020) 035017 (14pp), <https://doi.org/10.1088/1361-6595/ab6f9c>

⁹ I. Orel, Y. Haouchat, T.L. Chng, N.A. Popov, S.M. Starikovskaia, Nanosecond discharges as a tool for measuring energy efficiency (G-values) at high reduced electric fields based on nitrogen dissociation, *Plasma Sources Science and Technology* 34 (2025) 115014 <https://doi.org/10.1088/1361-6595/ae163a>

deposited energy. It is expected that under high reduced fields (hundreds of Td), nanosecond discharges will achieve high energy efficiency of dissociation

Within this deliverable (D3.1) of CAIPIRINH₃A, a novel approach for measuring the energy efficiency of ammonia dissociation in plasma is developed. This work is performed in collaboration with Lund University (LU) taking into account a possibility to work with ammonia in LU. Discharge tube developed at CNRS, devices for electrical measurements, high-voltage cables are delivered from Paris to Lund for joint experiments. The results of the experiments are reported below.

1.2 Relation to other tasks and deliverables

This deliverable reports on the results of **T3.1 (CNRS, LU, UoB)** on a) experimentally obtained dataset on G-factor of NH₃ dissociation in plasma for a wide interval of electric fields and specific delivered energies; b) data for validation of kinetic mechanism suggested in **T2.1 (LU, UoB) “NH₃ combustion kinetics and modelling (M1-M18)”** and plasma simulations of **T3.2 (ONERA, CETH, UoB), “Self-consistent modelling of plasma induced effects in air-NH₃ mixtures” (M7-M24)**; d) expert conclusion about the optimal discharge configuration for plasma systems as a part of combustion installation planned to be developed in **T2.4 (CARDIFF, CAP), “Combustor design, optimization and preliminary testing (M18-M36)”**. These data will guide the development of optimal plasma systems in **T3.3 (CNRS, CETH, CARDIFF), “Plasma systems development and characterization (M13-M36)”**.

T3.1 experimentally investigates the energy efficiency of NH₃ dissociation as a function of plasma parameters. Nanosecond discharges in long dielectric tubes at moderate pressures (tens of mbar) developed in the form of a fast ionization wave (FIW) best fulfil the criteria for measurements of energy efficiency in terms of the G-factor (eV per particle) and was used to obtain results with a high experimental accuracy (within 5-15%). This is allowed by advanced measurements of electric fields and specific energy deposition leveraging unique diagnostics and methods available in CNRS.

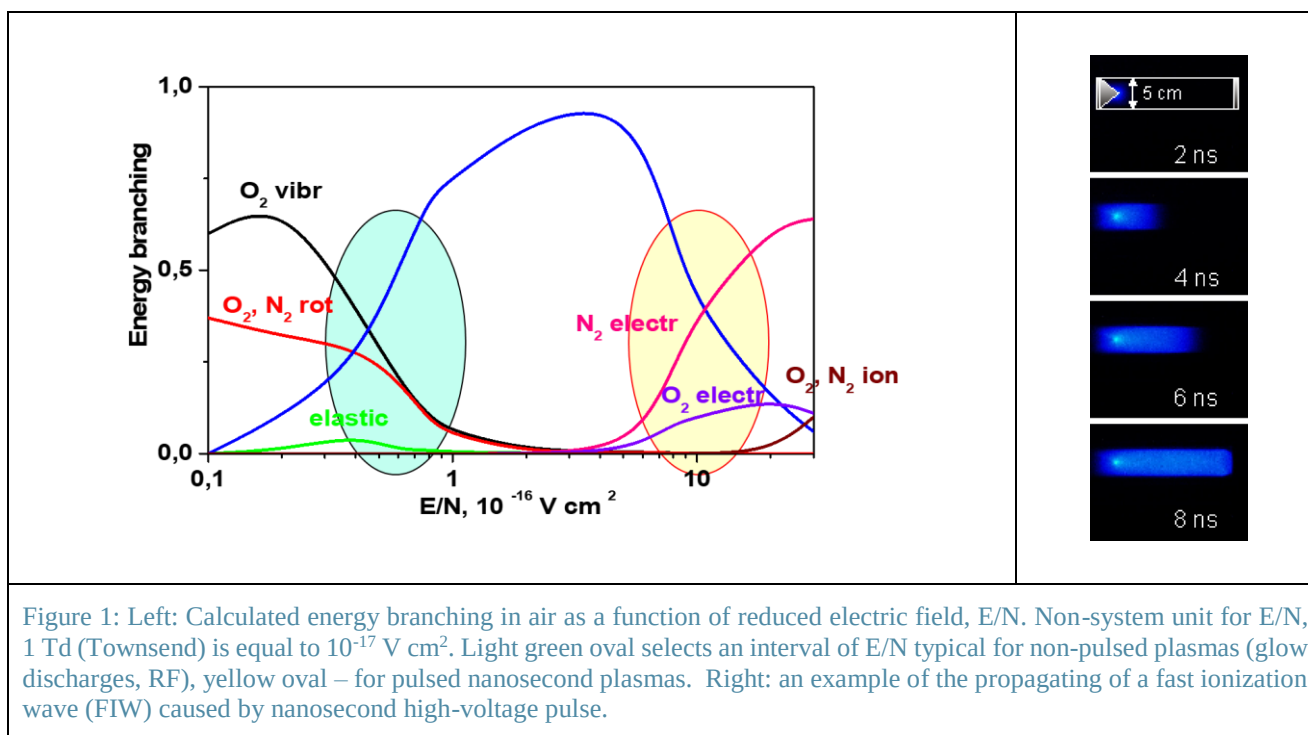
The experimental data set obtained within **D3.1** is a very important crossroad between the theoretical description of the efficiency of plasma action on ammonia and plasma-assisted ammonia combustion, - and building a discharge setup which will be working in the most efficient way for technical application in a plasma-assisted ammonia burner. The results aid the comprehension of plasma in NH₃ dynamics and dissociation efficiency which will drive the development of dedicated plasma sources (**T3.3**) and also be used to validate plasma models (**T3.2**) and plasma chemistry mechanisms **developed in T2.1** for similar regimes.

2 Report on plasma-NH₃ energy efficiency studies

2.1 Methodology

Pulsed nanosecond plasma at moderate pressures is known to be used for validation of chemical kinetics at high reduced electric fields, E/N , where E is the electric field and N is the gas density.

Figure 1 (left) shows calculated energy branching (or part of energy spent for excitation of a particular internal degree of freedom in plasma by collisions with electrons) as a function of E/N . Two regions are selected in the figure: tens of Townsends ($1 \text{ Td} = 10^{-17} \text{ V cm}^2$) and hundreds of Td. In the first one, marked with a light green oval, the energy goes mainly to excitation of vibrational levels of molecular nitrogen (blue curve), while in the second one marked with a yellow oval, the energy goes mainly to electronically excited levels of the molecules (rose curve for N₂ and violet curve for O₂) and finally, a significant part of this energy goes to dissociation.



In pulsed nanosecond discharges, it is possible to obtain a diffuse plasma at high E/N in a controllable and repetitive way. When a high-voltage pulse of 10 kV or higher is applied to the high-voltage electrode of a discharge tube filled with a gas mixture at 1-100 mbar, a fast ionization wave (FIW), starts from the high-voltage electrode of a positive or negative polarity, and propagates along the discharge gap with a velocity of the order of cm/ns. This propagation, taken by ICCD imaging, is clearly seen in Figure 1 (right) for 5 cm diameter and 20 cm length tube in air. For a few tens of nanoseconds, a plasma with well-established parameters allows kinetic study of processes with electrons, being further supported by kinetic modelling. This peculiarity of development of nanosecond pulsed discharges was suggested, within CAIPIRINH₃A Project, as a basis to study ammonia dissociation at high electric fields.

2.1.1 Chemical kinetic and 2D model validation

Before starting the experiments in NH₃, we analysed the possibility of describing a pulsed nanosecond discharge in the form of a fast ionization wave numerically in 2D approximation. This was made in collaboration with CERTH and resulted in a joint paper published in 2025¹⁰. This paper presents a detailed axisymmetric numerical analysis of a nanosecond discharge propagating in a long tube in pure nitrogen. A fluid (continuum) description of the plasma is the core of the physical model used in the computational software COPAIER^{11,12} – a multi-species and multi-temperature plasma fluid solver allowing for self-consistent description of the plasma spatial and temporal evolution (the main author of the paper, Konstantinos Kourtzanidis, is a co-developer of the solver, originally developed at CAIPIRINH₃A partner ONERA).

The modeling is conducted using a self-consistent plasma fluid solver under the local mean energy approximation, including photoionization. The discharge develops at moderate pressures, 1–10 Torr, in the form of a fast ionization wave (FIW). Simulations are performed for both negative and positive polarities of the voltage pulse applied to the high-voltage electrode. The computational results are validated against available

¹⁰ K. Kourtzanidis, S.M. Starikovskaia, Spatiotemporal dynamics of nanosecond pulsed discharge in the form of a fast ionization wave: self-consistent two-dimensional modeling and comparison with experiments under negative and positive polarity, J. Phys. D: Appl. Phys. 58 (2025) 195202 <https://doi.org/10.1088/1361-6463/adcace>

¹¹ K. Kourtzanidis, G. Dufour and F. Rogier F, Self-consistent modeling of a surface ac dielectric barrier discharge actuator: in-depth analysis of positive and negative phases, J. Appl. Phys. 54 (2020) 045203

¹² G. Dufour and F. Rogier, Numerical modeling of dielectric barrier discharge based plasma actuators for flow control: the copaiер/cedre example (2015) Aerospace Lab, https://aerospacelab.onera.fr/sites/default/files/2024-01/AL10-05_0.pdf

experimental data, including FIW velocity within the studied pressure range, electron density, longitudinal electric field, and the radial distribution of emission of excited species on a nanosecond timescale. The proposed modeling approach successfully reproduces key features of FIW development in nitrogen at moderate pressures and can be used as a valuable tool for optimizing nanosecond discharge experiments.

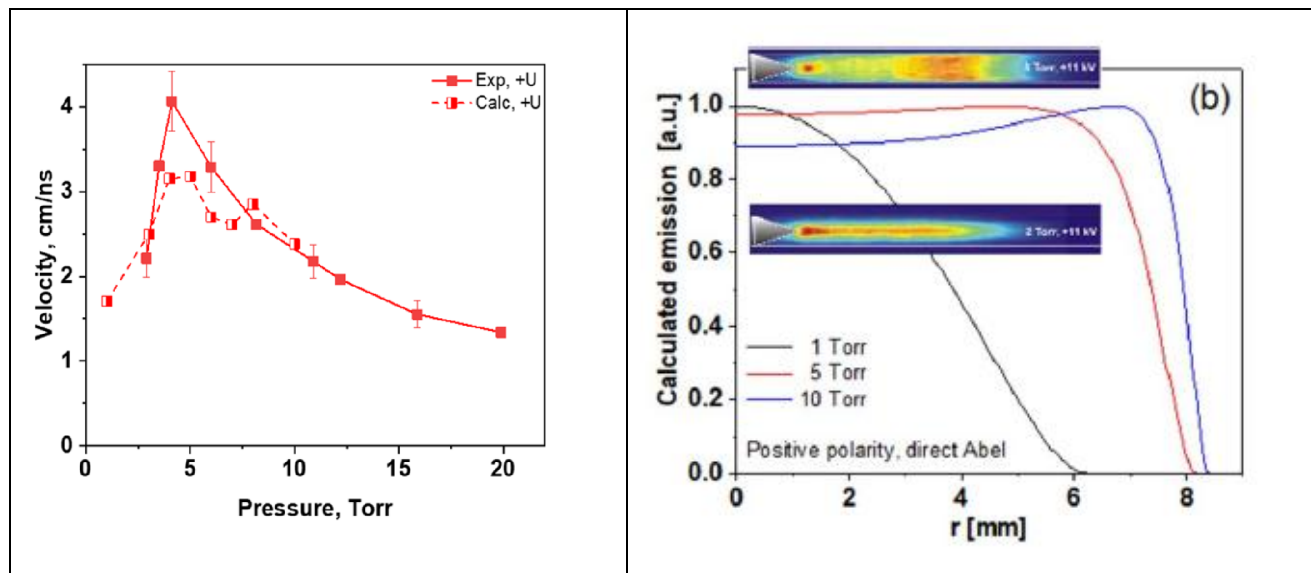


Figure 2: Validation of 2D model on example of positive polarity FIW in nitrogen. Left: experimental (filled symbols) and calculated (half-filled symbols) velocities of the fast ionization wave as a function of pressure. Right: calculated direct Abel inversion of calculated N₂(C) density profiles. Experimental ICCD images for 8 and 2 Torr are presented in the same figure.

The analysis of advantages and challenges of plasma-assisted combustion within the CAIPIRINH₃A project resulted in the participation in a tutorial review^{13,14} published in 2026 in two parts in Plasma Sources Science and Technology (PSST). The review is explicitly structured to guide readers from fundamental combustion and plasma physics to the mechanisms and practical applications relevant to modern energy and propulsion systems.

Part 1: Fundamentals of Combustion and Plasma establishes the scientific baseline needed to understand PAC. It begins with a review of classical combustion theory, including chemical kinetics, flame structure, ignition, stability, and pollutant formation. The text then introduces plasma physics at a level tailored for combustion researchers, explaining key plasma types (thermal vs. non-thermal), discharge methods, and energy coupling mechanisms. A central theme is how non-equilibrium plasmas can selectively excite electrons, generate radicals, and promote chemical reactions without significantly increasing gas temperature. By bridging combustion chemistry and plasma physics, Part 1 clarifies why plasmas are uniquely effective for ignition enhancement, flame stabilization, and kinetic control, especially under lean, low-temperature, or high-speed flow conditions.

Part 2: Mechanisms and Applications builds directly on this foundation, focusing on how plasma interacts with reacting flows and how these interactions are exploited in practice. It details the dominant PAC mechanisms, such as enhanced radical production, accelerated chain-branching reactions, vibrational excitation, and improved mixing effects. The document emphasizes the multi-scale nature of PAC, spanning nanosecond electron dynamics to macroscopic flame behaviour. It then surveys experimental diagnostics, modeling approaches, and numerical challenges associated with plasma–combustion coupling. The latter sections expand into applications, including gas turbines, scramjets, internal combustion engines, and low-emission burners, highlighting both demonstrated benefits and current limitations such as efficiency, durability, and scalability.

¹³ S.M. Starikovskaia, V. Lafaurie, J.-B. Perrin-Terrin, and C.O. Laux, Foundations of plasma-assisted combustion. Part 1. Fundamentals of combustion and plasma (Topical review), Plasma Sources Science and Technology, 35 (2026) 023001, <https://doi.org/10.1088/1361-6595/ae3a17>

¹⁴ C.O. Laux, J.-B. Perrin-Terrin, V. Lafaurie, and S.M. Starikovskaia, Foundations of plasma-assisted combustion. Part 2. Mechanisms and applications (Topical review), Plasma Sources Science and Technology, 35 (2026) 023002, <https://doi.org/10.1088/1361-6595/ae0f0f>

Taken together, the two parts offer a structured, end-to-end treatment of plasma-assisted combustion—from first principles through mechanisms to engineering implementation.

Finally, UoB together with LU developed a non-equilibrium NH₃ plasma-combustion model, integrating thermal and plasma kinetic effects. A Cantera-based C++ 0D plasma solver, CanPlasKin, was implemented by UoB as a unified reactor model where neutral combustion chemistry, plasma species kinetics, electron density evolution, and the gas-phase energy equation are solved simultaneously within a single ODE system (see for details the Deliverable D2.1 CAIPIRINH₃A Report, “Detailed kinetic modeling of plasma-NH₃ combustion and experimental validation”). The development of a new reduced plasma-chemical kinetic mechanism that will be used for CFD-based simulations within CAIPIRINH₃A is underway, and this will serve as the central kinetic framework for all subsequent modelling activities in T2.2 and T3.2, ensuring methodological consistency. The role of the experimental part of T3.1 is to provide a set of data for validation, of NH₃ kinetics in the fast ionization wave, and the energy cost of NH₃ dissociation in high electric fields.

Below we provide a detailed description of the nanosecond tube discharge (nTD) setup, experimental methods and approaches as well as experimental results. We note that, because of technical and administrative complexities while preparing work with ammonia, it was decided, by invitation from LU, to perform the NH₃ experiments in Lund. An important additional benefit of the joint work with Lund University is having direct access to a powerful park of laser systems for laser diagnostics at their facilities. As a result of these internal negotiations, the discharge setup and high-voltage generator, after adjustment of FIW on non-combustible gases, were moved to LU and mounted in the LU laboratory. The first nanosecond FIW discharge in ammonia have been obtained.

2.1.2 Nanosecond tube discharge (nTD) setup

Figure 3 (left) displays a cross-sectional schematic of the experimental apparatus. The discharge is produced in a cylindrical quartz tube with an internal diameter of 20 mm or 10 mm and wall thickness of 2 mm. This quartz tube is sandwiched (along its length) between a pair of hollow, truncated conical brass electrodes, giving an interelectrode gap distance of 30-80 mm. A 5-mm-diameter hole is bored through each electrode to enable a regular supply of air to the discharge tube. A cylindrical, copper waveguide with an internal diameter of 66 mm partially encapsulates the quartz tube and serves as a grounded screen to facilitate more stable discharge initiation and development. A typical photo of discharge in air is provided by Figure 3 (right), illustrating a diffuse (non-contracting) character of obtained plasma.

Gas or gas mixture enters and exits the discharge tube via two glass side arms (see figure 1(a)), located upstream and downstream respectively of the quartz tube, at a flow rate of 10-30 sccm using a Brooks Instruments 5850TR mass flow controller. The present flow rate was chosen to ensure discharge stability since higher flow rates were found to be detrimental in this respect. The working (static) pressure within the discharge tube is maintained at 20 mbar. The average readings of two pressure sensors located approximately at equidistant locations upstream and downstream of the tube are taken. These measurements are acquired using a pair of CMR 362 capacitive pressure sensors (from Pfeiffer Vacuum SAS).

Nanosecond duration, HV pulses are produced by an FDS 3-1NM1 (FID GmbH) high-voltage generator (HVG). Positive polarity, 10-12 kV amplitude, HV waveforms with a rise time of 2 ns and a full width at half maximum (FWHM) of 20 ns are supplied by this HVG at a repetition rate of 10 Hz. These pulses are delivered to the HV electrode via a 25 m long, 50 Ω impedance, RG213 coaxial cable. A similar, 100-m-long coaxial cable is connected separately to the low voltage (LV) electrode, but with its other end short-circuited.

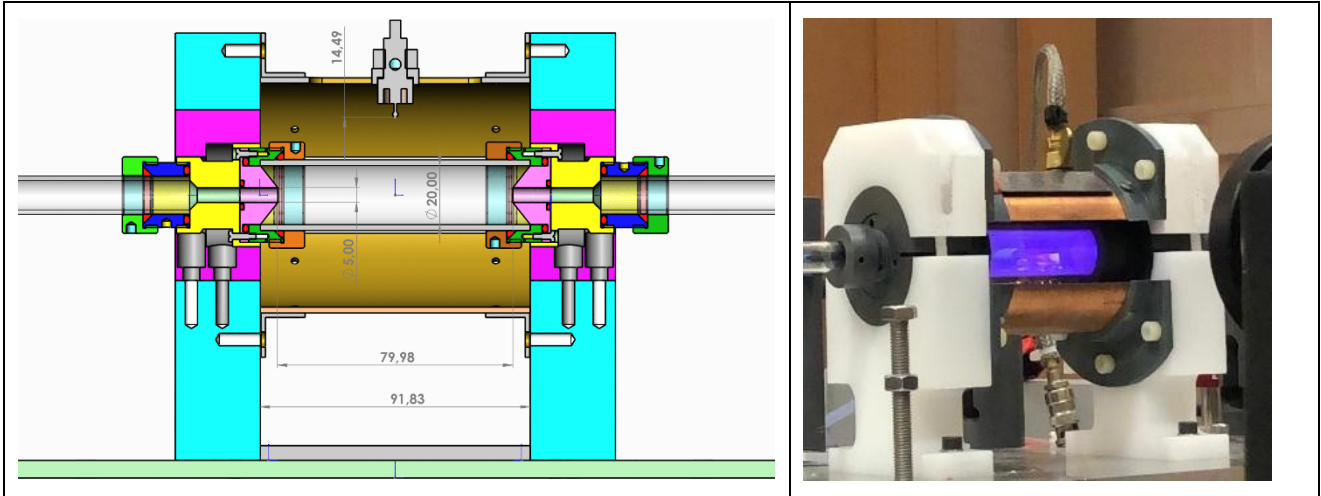


Figure 3: Sectional schematic of the nanosecond tube discharge (nTD), with the measurement region (left). Image of the nTD with a discharge initiated in air at pressure 20 mbar (right).

These HV waveforms are monitored using two custom-made, calibrated back current shunts (BCS), embedded within each of the coaxial cables connected to the HV and LV electrodes. These HV traces are subsequently post-processed and used to compute the specific energy deposition (SED) within the discharge. Longitudinal electric field was measured by a custom-made calibrated capacitive probe, the probe can be seen in figure 3 (left), embedded in the grounded screen near the centre of the tube.

2.1.3 Back current shunts

The current and voltage in the high voltage cable are measured by two custom-made calibrated back current shunts installed 12.5 m before and after the discharge tube (BCS1 and BCS2) in the coaxial cable connecting the high-voltage generator and the discharge tube; and in the cable serving as the end load of the tube. The back current shunt consists of a set of low-inductive parallel resistors (KOA Speer CF1/2C2R2J) soldered into the cable shield break. When the high voltage pulse propagates in the cable, the current flowing in the shielding of the cable is equal to the current in the central wire of the cable I , but they have opposite directions. The voltage drop on the BCS made of an equivalent resistor with the impedance R each in this case can be written as:

$$U_{BCS} = \frac{IR}{n}. \quad (1)$$

The signal from BCSs is registered by an oscilloscope (OSC). Since typical values of U_{BCS} can reach tens of volts, the attenuators are used on the input channels of the OSC to avoid its over-range. If the attenuator reduces the signal in K_{att} times, the detected value of the voltage drop on the BCS registered by oscilloscope is equal to

$$U_{osc} = \frac{U_{BCS}}{K_{att}} = \frac{IR}{nK_{att}}. \quad (2)$$

From the last equation it follows that the value of the current in the central wire of the high voltage cable can be calculated as

$$I = U_{osc} \frac{n}{R} K_{att}. \quad (3)$$

The voltage between the central wire and the shielding of the cable can be calculated using the Ohm's law for the long transmission lines: $U = IZ$, where $Z = 50 \text{ Ohm}$ is the wave resistance of the used high voltage cable. The back current shunts are installed 12.5 m before and after the discharge tube to avoid the superposition of signals propagating in the cable. For example, the pulse incident on the discharge cell and the pulse reflected from the discharge cell due to the impedance mismatching. Indeed, the coefficient of reflection of the high voltage pulse propagating in the cable with impedance Z from the load with impedance R can be written as

$$K_U = \frac{R - Z}{R + Z} \quad (4)$$

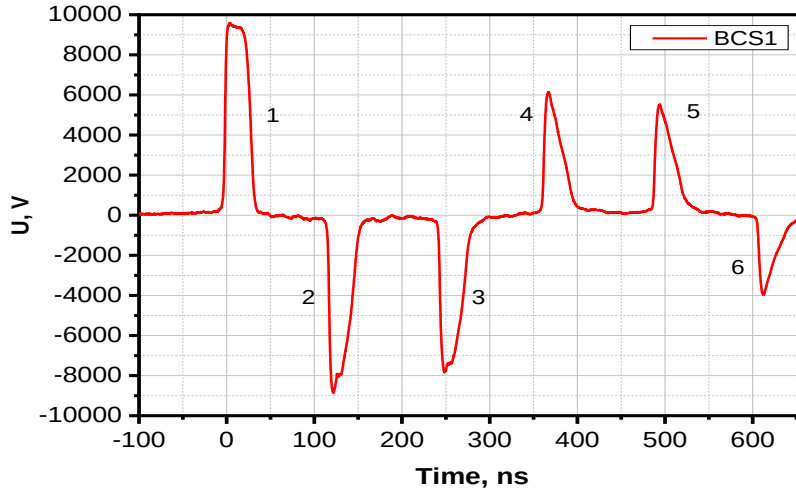


Figure 4: Typical waveform from the back current shunt (up) and the construction of the back current shunt (down). Low-inductive resistors are soldered in parallel to the opening in the shield of a coaxial cable [6].

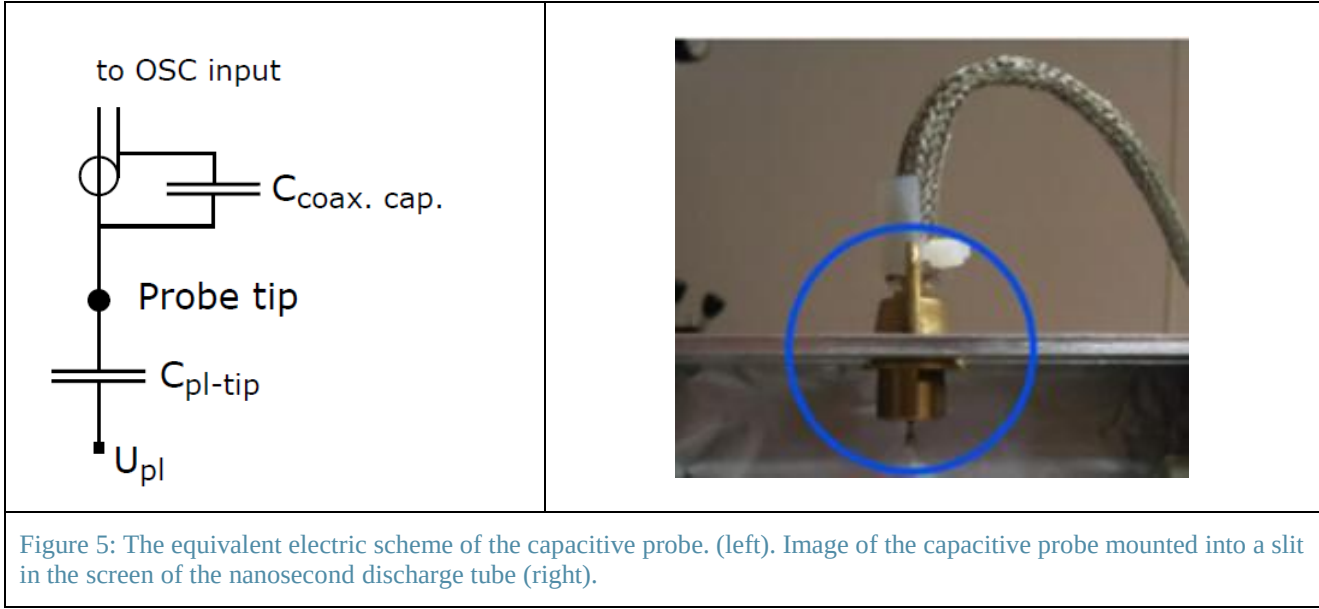
There are two limit cases. At infinite load $R = \infty$, $K_U = 1$ and high voltage pulse reflects from the load completely with the same polarity. If the load is characterized by zero load (short circuit) $R = 0$, $K_U = -1$ and high voltage pulse reflects from the load completely with the opposite polarity. The impedance of the discharge cell is finite and high $R \geq Z$, thus, the voltage pulse reflects partially with the same polarity. To separate the two pulses, the distance between BCS and the point of reflection should be longer than half of the part of the cable "occupied" by the signal. The voltage pulse with full width τ occupies the part of the cable with the length $V\tau$, where $V = c/\sqrt{\epsilon} = 0.2$ m/ns is the velocity of the electromagnetic wave propagations in the cable with the vacuum light speed c and the dielectric permittivity $\epsilon = 2.25$ of the insulator in the cable (polyethylene). For pulse with $\tau = 60$ ns, the corresponding length is 12 m, thus the incident and reflected pulses are separated with a "factor of safety" 2.

Figure 4 (up) shows an example of the signal from the back current shunt (BCS) and the image of the shunt itself (down) consisting of a set of resistors connected in parallel. The voltage on the BCS is measured by the 50-Ohm input of an oscilloscope (600 MHz – 1 GHz bandwidth). An example presented in the figure, shows a set of the pulses: pulse 1 is the incident pulse traveling from the high-voltage generator to the discharge cell; pulse 2 is a reflected from the nDT cell pulse. Pairs of pulses "3-4" and "5-6" correspond to similar sets of "incident-reflected" pulses produced due to the reflection of the reflected pulse (2 or 4) from the input of the high-voltage generator (with an input load $Z=0$ Ohm for the case in the figure).

2.1.4 Capacitive probe and synchronization of data with data of the BCS

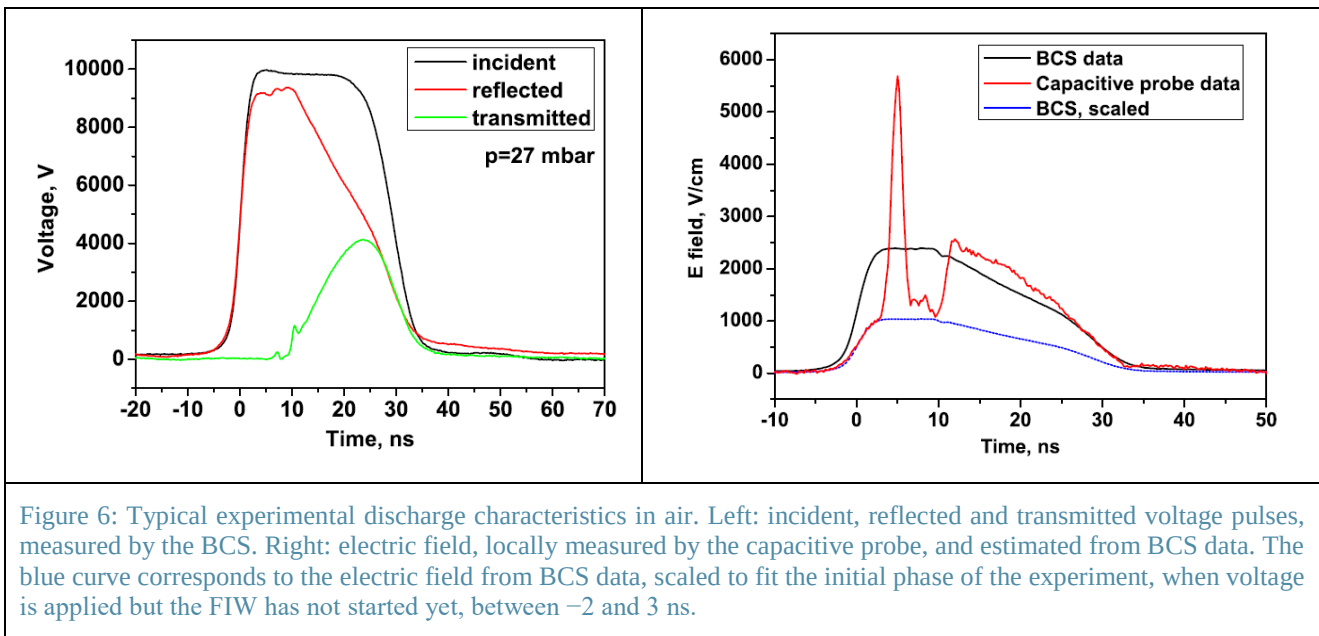
The capacitive probe (CP) is the capacitive divider, installed near the discharge tube surface. The equivalent electric scheme is presented in Figure 5, left. U_{pl} is the electric potential in the plasma, the capacitor C_{pl-tip} denotes the electric capacitance between the probe tip and the plasma, $C_{coax.cap.}$ is the coaxial capacitor: the lead is

connected to the probe tip and the central wire of the coaxial cable going to the input channel of the oscilloscope, the cylindrical body is connected to the shielding of the cable. The photo of the probe is given by Figure 5, right.



The probe tip is connected to the central wire of the coaxial signal cable going to the input channel of the oscilloscope (OSC) through the lead of the coaxial capacitor with the capacitance $C_{\text{coax.cap.}}$. The cylindrical body of the capacitor is connected to the shielding of the signal cable with impedance $Z = 50 \text{ Ohm}$. When the electric potential in the plasma changes, the electric current flows through the coaxial cable to charge the capacitance between the probe tip and the plasma. Therefore, the potential of the probe tip $U_{\text{probe}}(t)$ is measured by the oscilloscope, and, thus, the potential in the plasma at any time instant $U_{\text{pl}}(t)$ can be reconstructed.

It is important to note that capacitive probe measures longitudinal component of the electric field. In the front of the ionization wave, first 2-3 ns, the electric field is directed radially, toward the grounded screen. In the front, the reduced electric fields are very high, thousands of Td, but the electron density is still low – and so the deposited energy is negligible comparing to the energy in plasma after closing the discharge gap. After closing the gap, the field is mainly directed along the discharge tube axis. As a consequence, the capacitive probe fits perfectly well for the measurements of the field during the active discharge phase, when the deposited energy is high. An additional important advantage of the capacitive probe is that the data can be synchronized with the data from the back current shunt with the accuracy determined by acquisition of the oscilloscope, 0.2 ns in our case.



As example, the incident, reflected and transmitted voltage pulses obtained from the BCS are shown in Figure 6 (left). The incident and reflected waveforms were measured using a BCS on the HV side, whereas the transmitted waveform was measured using a BCS on the LV side. The incident and reflected waveforms in the figure have been adjusted to correlate in time, taking into account the length of the cables and the speed of the discharge propagation. The voltage on the HV electrode is a sum of the incident and reflected voltages. The reduced electric field E/N , locally measured by the capacitive probe and estimated on the basis of the difference between the high voltage (HV) and low voltage (LV) electrode potentials obtained from the BCS measurements, is shown in Figure 6(right). An additional curve in the figure represents a scaled version of the field measured by BCSs. This scaled version represents the initial phase of the discharge when the FIW has not started yet. Once the FIW starts, the high and narrow peak in E/N of about 750 Td at $t = 5$ ns corresponds to the passing of the FIW near the capacitive detector. Finally, the time interval between 13 and 33 ns corresponds to the energy deposition phase having a high current with a still high (around 200 Td), spatially uniform electric field. The local field then roughly follows the global, unscaled field, because of the conductive nature of the plasma channel connecting the two electrodes. This technique was now applied to the discharge in ammonia.

2.1.5 Adaptation of the nanosecond discharge tube for ammonia experiments

The nanosecond discharge tube (nDT) is initially developed for non-corrosive gases. To adapt the discharge setup for ammonia, all brass components in the electrode connections were replaced with stainless-steel components. All dielectric materials in direct contact with ammonia were replaced with PEEK. All vacuum seals were replaced with ammonia-resistant seals.

The discharge tube was tested for vacuum tightness and high-voltage operation at the CNRS LPP laboratory (Figure 7, left). A procedure for the assembly and disassembly of the discharge tube, including the replacement of individual components, was established (Figure 7, right)

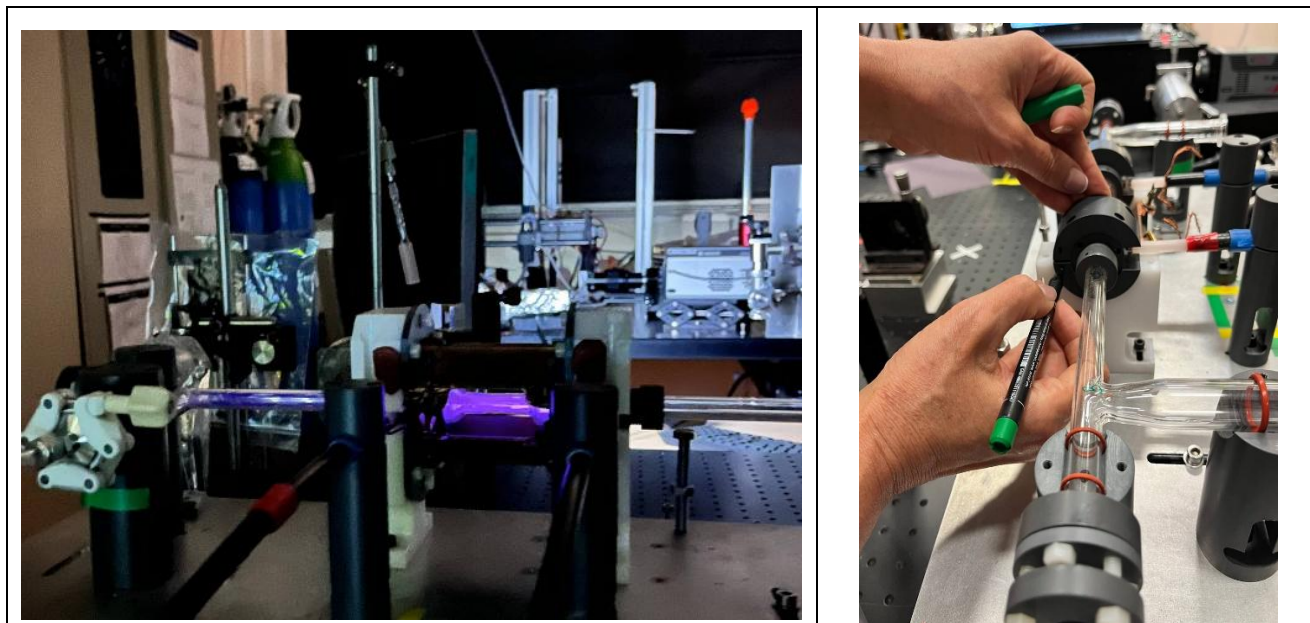


Figure 7: Testing of discharge with new spare parts (stainless steel electrodes and PEEK isolators) at LPP CNRS, Paris (left); assembling the nanosecond discharge tube with new spare parts and preparing of packaging for mission in Lund University (right).

2.2 Results

2.2.1 Discharge in air: tailoring of the discharge geometry and electrical data

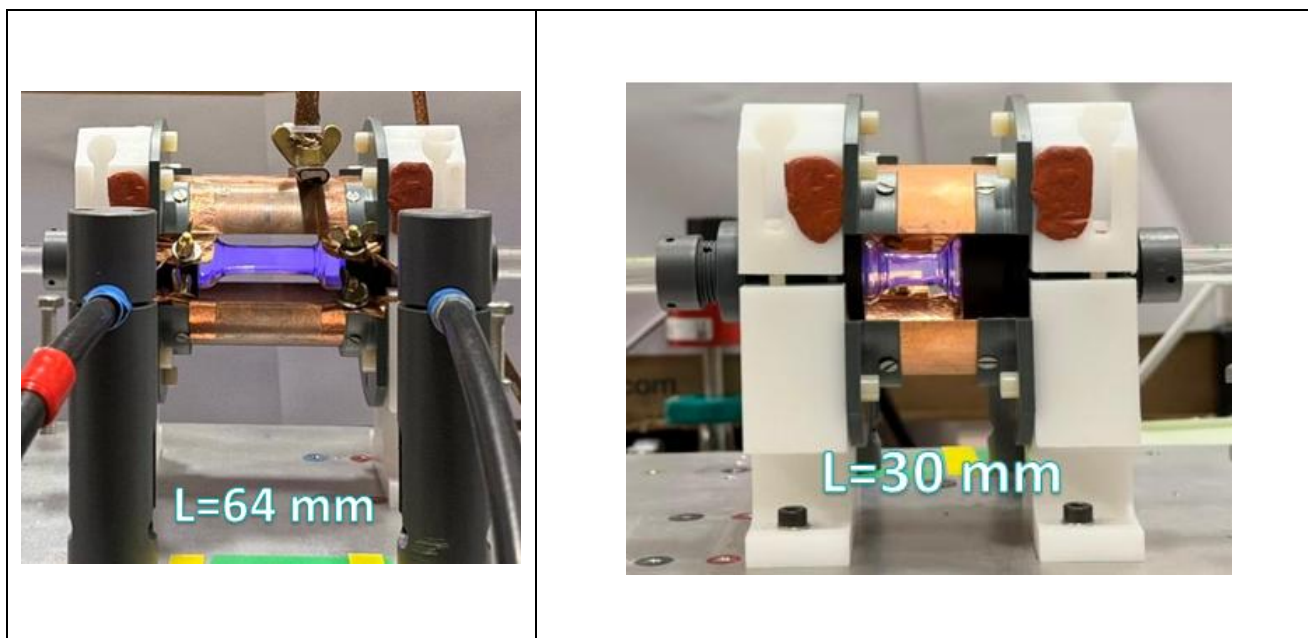


Figure 8: Photos of the nanosecond discharge in air for two different inter-electrode distances: 64 mm (left) and 30 mm (right). Different inter-electrode distances provide different electric field.

The modified design of the discharge tube allows the plasma parameters to be varied. To control the electric field, a set of four tubes with different lengths is provided, corresponding to different interelectrode distances ranging from 30 mm to 80 mm. To vary the electron density and energy deposition, two tube diameters are available in the measurement region: 20 mm and 10 mm.

Figure 8 shows photographs of the discharge in air for an interelectrode distance of 64 mm (left) and 30 mm (right). It can be clearly seen that the discharge remains diffuse (non-contracted) in both cases.

An important parameter of plasma is specific delivered energy (SED). This parameter is measured in electron-volts per particle (per molecule) and provides an idea about chemical reactivity of obtained plasmas. Specific delivered energy 0.001-0.001 eV/molecule corresponds to a weak excitation. In this case ionization degree, $n_e/N \ll 1$, a part of excited species is low, and reactivity is driven by processes of electron impact with main components of the gas mixture. These components play essential role in chemistry and/or spectroscopy, being, for example, main quenching partners in collisions with electronically excited species.

Higher specific deposited energies, about 1 eV/molecule at high E/N provide strongly non-equilibrium plasmas with a high density of electronically excited species. Peculiarity of this plasma is that, although optical spectra of the low SED discharges (0.001-0.01 eV/molecule) and middle SED discharges (1 eV/molecule) are almost identical and show molecular bands of excited levels of molecules, plasma chemistry is very different: in the case of middle SED, electronically excited species actively participate not only in collisions with neutral species, but also in secondary collisions with electrons, providing additional ionization and dissociation, as well as in collisions with atoms and radicals: this is an analogue of a “non-diluted” chemistry under conditions of a gas discharge. High SED. 5 eV/particle and higher, correspond to filamentation (contraction) of the discharge and fast passage to a local thermal equilibrium (LTE), optical spectra of plasma being substantially changed with a dominating cw (continuum wavelength) spectrum and strong atomic lines emission.

Figure 9 shows results of preliminary tests in air. Specific delivered energy as a function of gas pressure is shown on the left. It is clearly seen that for different distances between the electrodes (from 30 to 64 mm), a typical SEDs is found to be in the range from 0.001 to 0.01 eV/molecule, providing an ideal for kinetic study case of “strongly diluted” chemistry. Synchronised waveforms of reduced electric field, current and delivered energy for the first incident pulse for 64 mm interelectrode distance is shown on the right. For comparison, the electric field for 34 mm interelectrode distance is shown in the same figure.

In this sense, a nanosecond fast ionization wave (FIW) at 20 mbar closes the inter-electrode gap at very high fields (kTd). This fast ionization wave provides the initial electron density and makes the diffuse discharge possible. While the gap is closed, the active current of about 100 A flows through the gap during the discharge pulse. This is the main time interval when the energy is deposited to a gas. We observe that the FIW starts at the middle of the pulse, at 10 ns (see Figure 9), and the closing of the gap takes place at 12 ns. As far as the delay of the start of the discharge decreases with pressure, we can expect starting the discharge earlier at atmospheric pressure. The experiment at 20 mbar proves that we are able to tailor the reduced electric field as a function of the distance between the electrodes within a wide range, from hundreds to thousands of Td. Within the scheduled installation for plasma-assisted ammonia combustion at atmospheric pressure (T2.4), necessary high fields will be kept by decreasing the distance between the electrodes: thousands of Td at 20 mbar before closing the gap correspond to hundreds of Td at atmospheric pressure and ambient temperature conditions when: (a) gas density increases by a factor of 50; (b) interelectrode gap decreases from a few cm to a few mm, by a factor of 10. As a result, the reduced electric field will decrease by a factor of 5 – the fields being optimal for energy delivered to dissociation. Another important issue for building a plasma system as a part of combustion installation planned to develop in T2.4, is to increase a specific energy delivered (SED) to the discharge, or energy per particle (typically provided in eV per particle). In the case of a fundamental study of kinetics, we will keep SED=0.01 eV/molecule to make plasma as uniform in space as possible and to guarantee an access to kinetic information. In the actual combustion system, the SED should be 1-2 orders of magnitude higher, 0.1-1 eV/molecule. This will be achieved by decreasing the discharge volume: indeed, a typical diameter of atmospheric pressure streamer is sub-mm, so the diameter of a plasma under study will be decreased from 1 cm to 1 mm, by a factor of 10. When the same current should pass the plasma channel, the energy density will be increased by a factor of 100. We consider, for the moment, two possible configurations of plasma systems for combustion installation: or pin-to-pin with a few mm distance, or surface dielectric barrier discharge (SDBD) with a plasma divided on a few tens of microchannels providing multiple points of plasma pre-treatment for ammonia. Both systems will be developed, tested and compared in the near future.

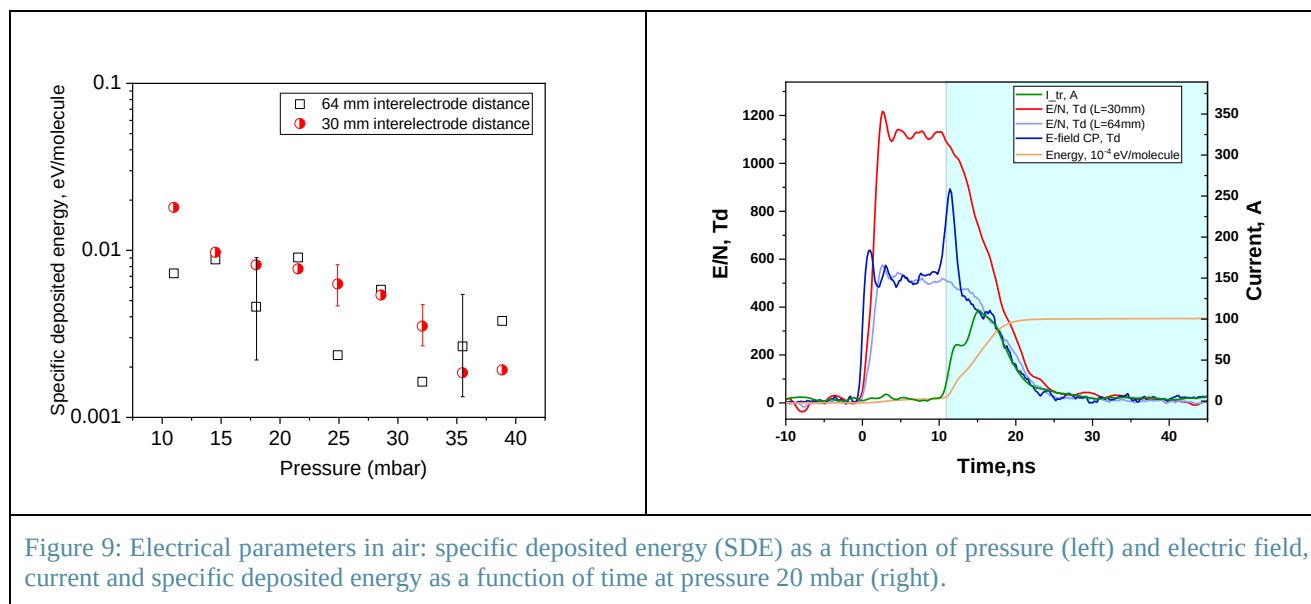
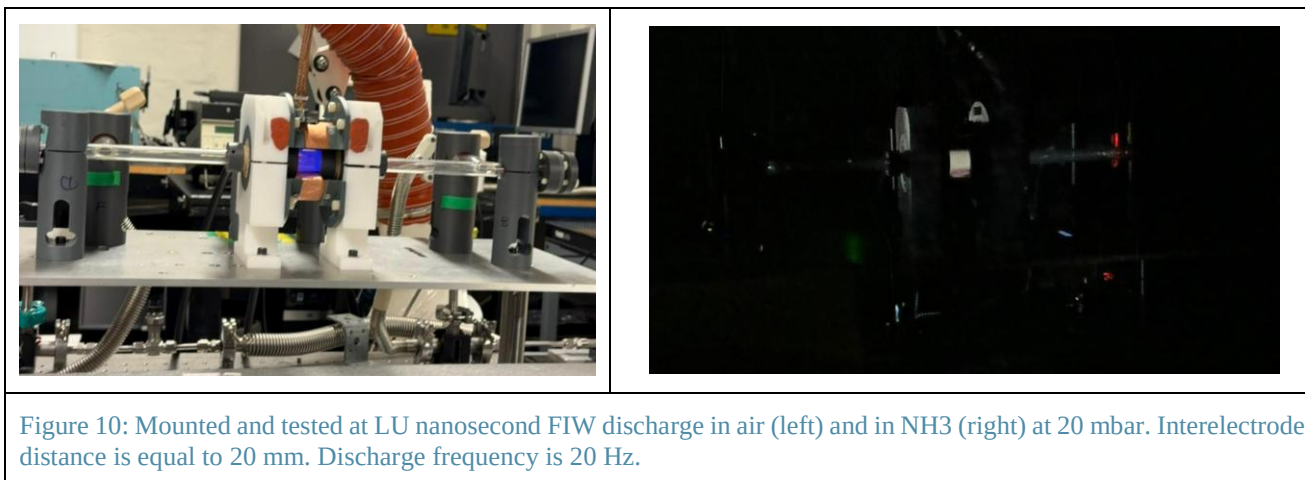


Figure 9: Electrical parameters in air: specific deposited energy (SDE) as a function of pressure (left) and electric field, current and specific deposited energy as a function of time at pressure 20 mbar (right).

2.2.2 Discharge in ammonia: tests of stability

After moving the discharge tube to Lund, we (i) tested the discharge system for the absence of leaks; and (ii) tested how stable is the fast ionization wave in ammonia. Figure 10 shows a photo of the discharge in air at Lund facilities during the tests, and a photo of the discharge in ammonia (right). It is well seen that the colour of the discharge changes from blue (provided by the second positive system of molecular nitrogen in air, $N_2(C^3\Pi_u) \rightarrow N_2(B^3\Pi_g)$) to a white colour typically provided by different molecular bands at different wavelengths.



2.2.3 Electrical data for discharge in 20 mbar of NH₃

NH₃ plasma is different from air plasma: it is more stable with a smaller scattering of plasma ignition delay time, which can be within a few nanoseconds in air but close to zero in ammonia.

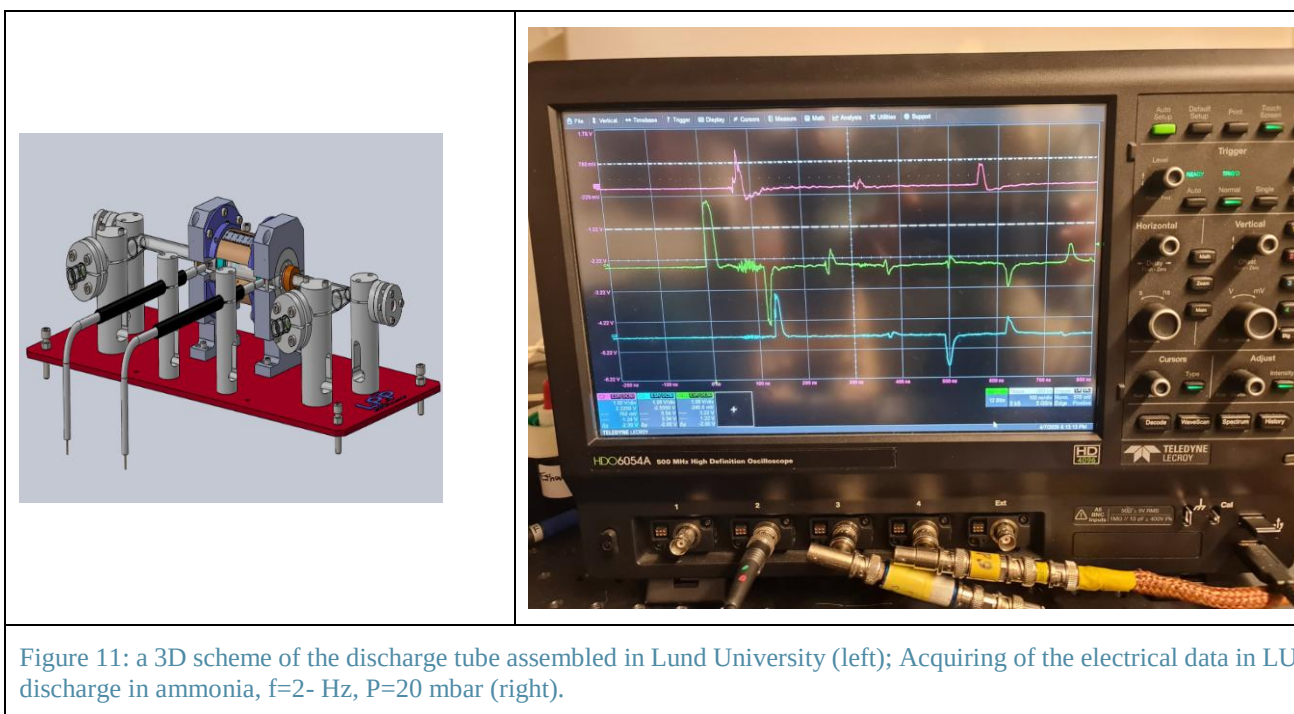


Figure 11 shows a 3D scheme of the discharge tube assembled now in Lund University. Two black tubes represent high-voltage cables from the side of the high voltage and low voltage electrode. The back current shunt, embedded in these cables, provide a green waveform for the HV side and blue waveform for the LV side (Figure 11 on the right). The capacitive detector is seen in the left figure in the slit of the copper screen around the tube. The waveform obtained from the capacitive probe is represented as a magenta curve on the oscilloscope.

2.2.4 ICCD imaging for discharge in 20 mbar of NH₃

ICCD imaging is necessary to understand the distribution of plasma over the radius of the discharge tube. In the case when: (i) the emission is due to a direct excitation of a corresponding molecular band by electron impact, and (ii) the normalized emission distribution stays non-changed first few nanoseconds of the discharge, this distribution can be related to the radial distribution of the electron density. As such, an Abel-inverted distribution of radial emission taken by ICCD can be used as initial data or as validation of the electron density distribution for 2D modeling. Analysis of Figure 12 leads to the conclusion that the obtained plasma is diffused with a possible

minimum in the center and higher electron density in the near-wall region. Special attention should be given to this fact at further data analysis.

ICCD images presented in the figure, will be used for more detailed analysis of plasma parameters. Indeed, if we can prove, by means of numerical modeling, that the excitation of the main electronic levels participating in the formation of ICCD image, is directly linked to the reaction with electron impact, then the ICCD images, after reverse Abel transformation¹⁵, can be used to analyse a radial distribution of electron density in obtained plasmas.

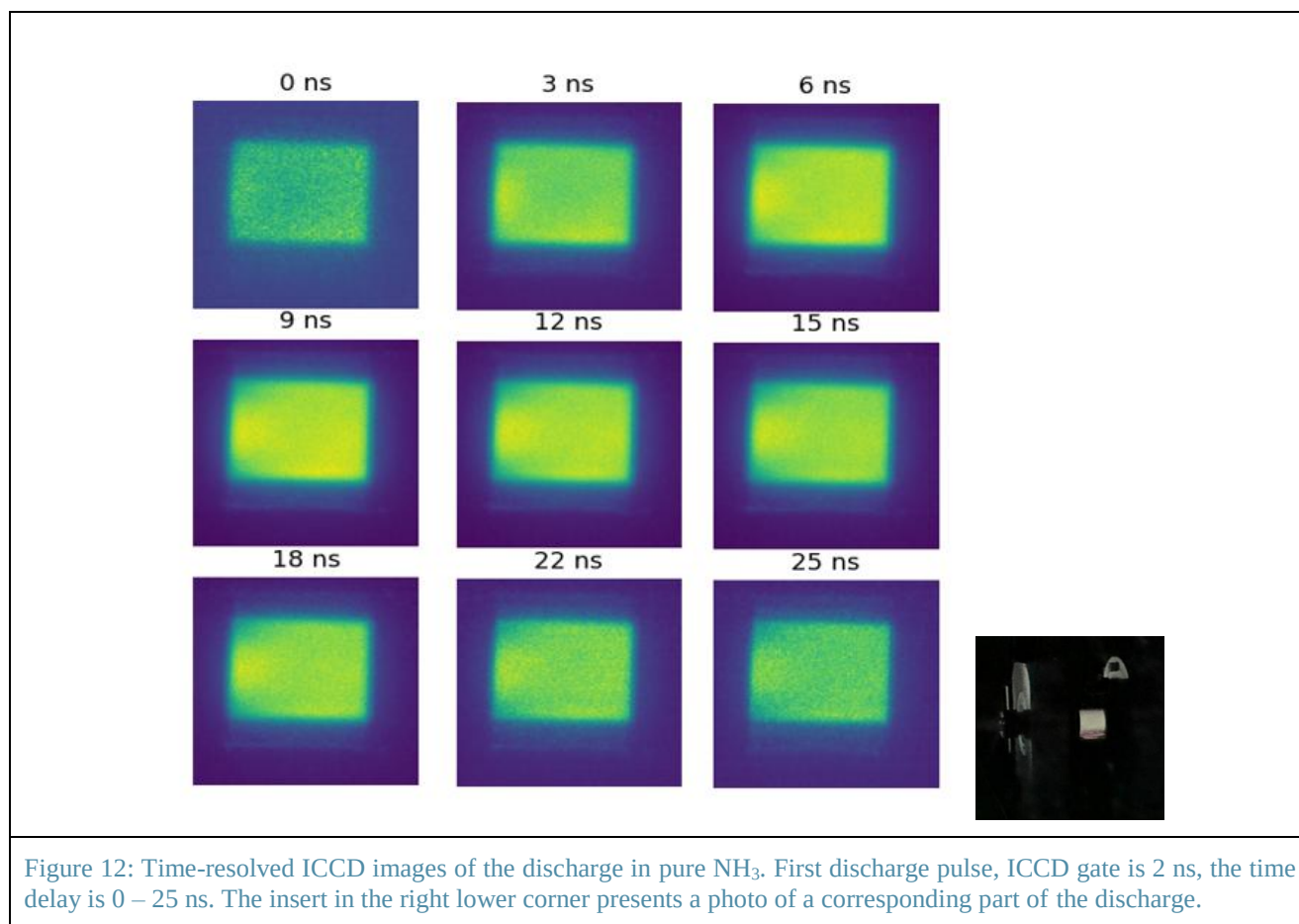


Figure 12: Time-resolved ICCD images of the discharge in pure NH₃. First discharge pulse, ICCD gate is 2 ns, the time delay is 0 – 25 ns. The insert in the right lower corner presents a photo of a corresponding part of the discharge.

2.2.5 Optical emission spectra (OES) for discharge in 20 mbar of NH₃

Optical emission spectra were taken time-resolved (3 ns ICCD gate) and integrated over 50 ns ICCD gate.

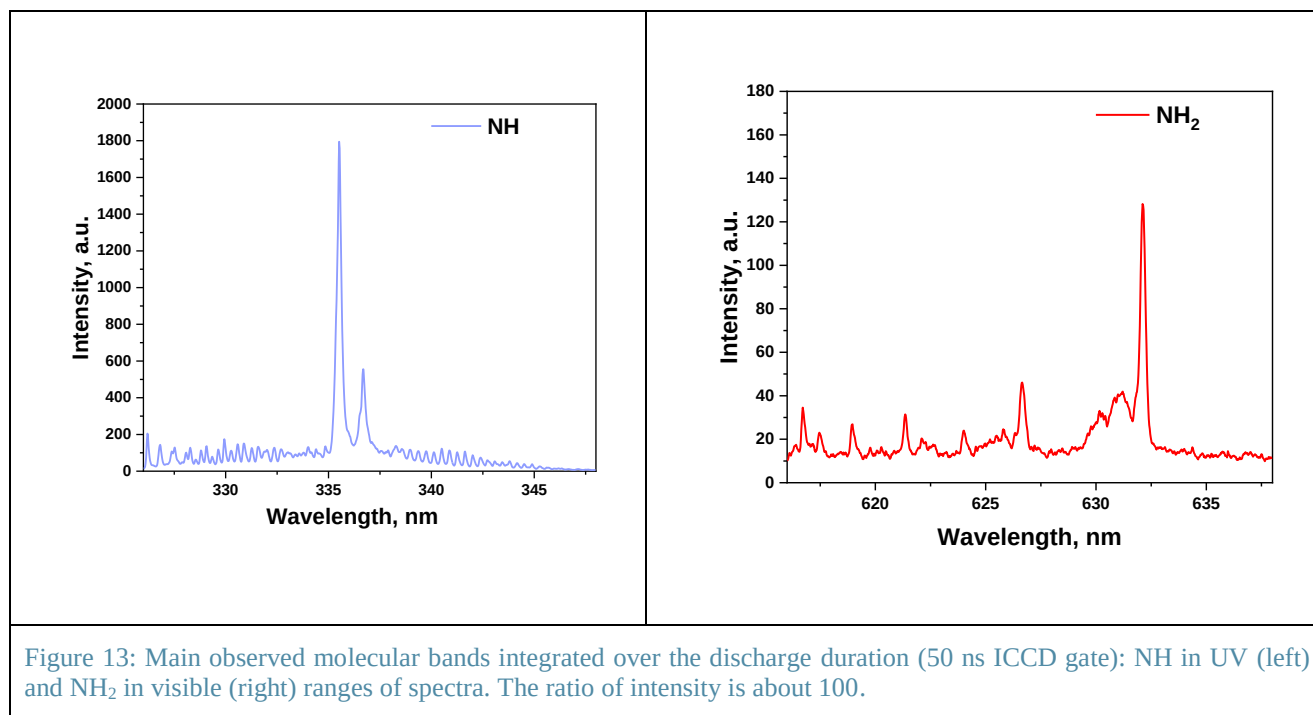
We note that the identification of spectra was done based on the recent paper from the LU group¹⁶. The paper is devoted to the effects of atmospheric-pressure nanosecond pulsed discharge on ammonia/air flames using optical emission spectroscopy (OES). Spatially-resolved OES of NH₃/air flames with and without discharges in the 200–800 nm range presented in LU paper allowed us to identify the molecular bands in NH₃ fast ionization wave.

The most bright band observed in the UV range of spectra, this is NH (A-X) transition. Figure 13 (left) reproduces a part of this transition. A possibility of seeing a parasitic or partly produced in the discharge molecular nitrogen corresponding to N₂(C-B) transition at 337 nm will be analyzed during data treatment, first two weeks of September. Numerical modeling of NH and N₂ together will allow splitting these two bands. A peak at 335 nm (1800 a.u.) corresponds to the peak of NH (A-X) transition. Emission in the visible part of the spectrum is much weaker but much broader (see Figure 13 (right)). Numerous non-intense bands of NH₂ should be differentiated

¹⁵ J. L. Muelle, S. Siltanen (Eds.) Linear and Nonlinear Inverse Problems with Practical Applications. (Computational Science & Engineering), 2012, Society for Industrial and Applied Mathematics. <https://doi.org/10.1137/1.9781611972344>

¹⁶ J. Sun, Yu. Bao, J. Ravelid, S. Nilsson, A.A. Konnov, A. Ehn, Application of emission spectroscopy in plasma-assisted NH₃/air combustion using nanosecond pulsed discharge, Combustion and Flame, 263 (2024), 113400, <https://doi.org/10.1016/j.combustflame.2024.113400>

from the second order of the UV emission, additional analysis will be performed within September 2026. H α atomic line is presented in the spectrum. An additional set of experiments was done to get absolute calibration of OES data.



2.2.6 Quantitative data for FIW plasma in NH₃; electrical data

Figure 14 shows the experimental setup used to measure the electrical parameters of plasma produced in NH₃. The discharge tube described above is sandwiched between two coaxial cables; back current shunts are placed so that incident and reflected (BCS1) waveforms of voltage/current in the cable can be measured separately; BCS2 measured the transmitted current. Capacitive probe, CP, moving in the slit of a metal screen of the discharge tube, serves to measure the longitudinal electric field.

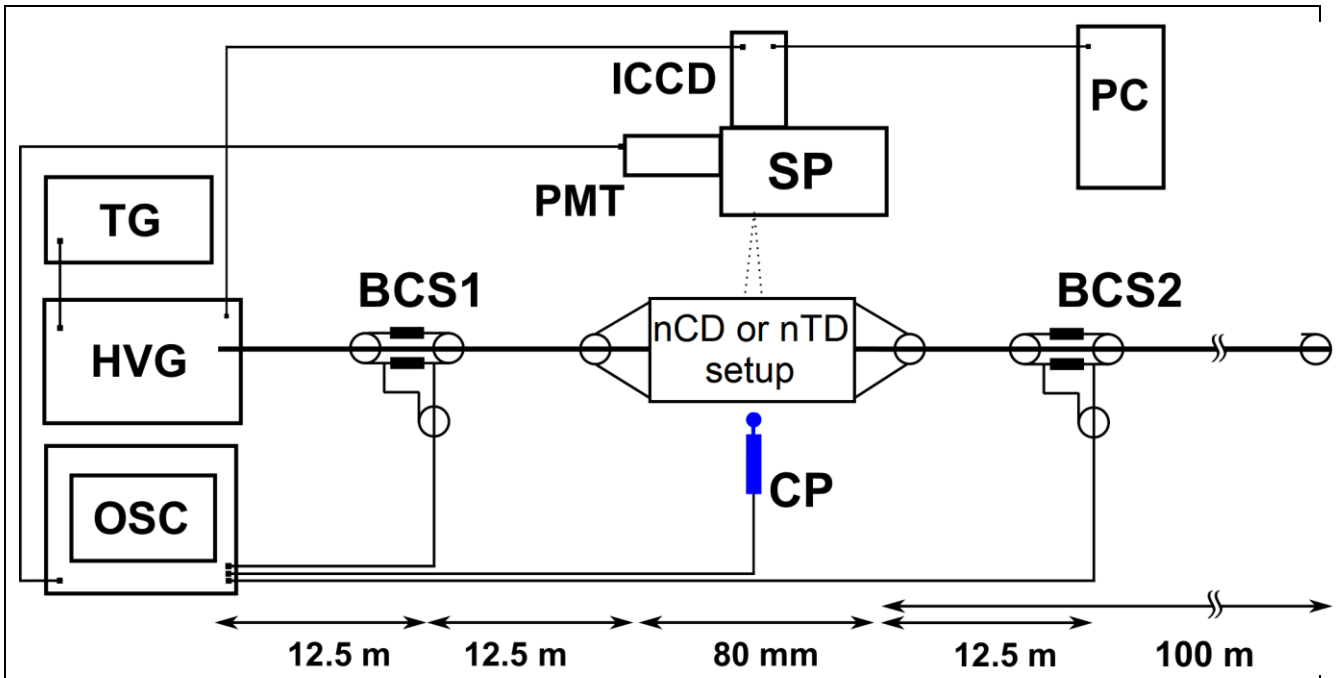


Figure 14: A general scheme of the experimental setup with the basic experimental equipment. TG is triggering generator, HVG is high voltage generator, OSC is oscilloscope, BCS is back current shunt, CP is capacitive probe, PMT is photomultiplier tube, ICCD is intensified charge-coupled device (camera), SP is spectrometer, PC is personal computer.

A typical signal from the BCS1 recalculated to the voltage in the cable (attenuation coefficient $K=8100$) is shown in Figure 15 (left). It is clearly seen that already a second pulse is significantly attenuated by the generator, so that there is only one main pulse. A zoom to the first incident pulse (Figure 15 (right)) provides characteristics of the pulse: positive polarity, voltage amplitude of +16.1 kV, FWHM of 19.4 ns, rise time 0.1-0.9 of 1.25 ns. Gas flow was kept constant and equal to 50-100 sccm. The repetitive frequency in these experiments was 20 Hz.

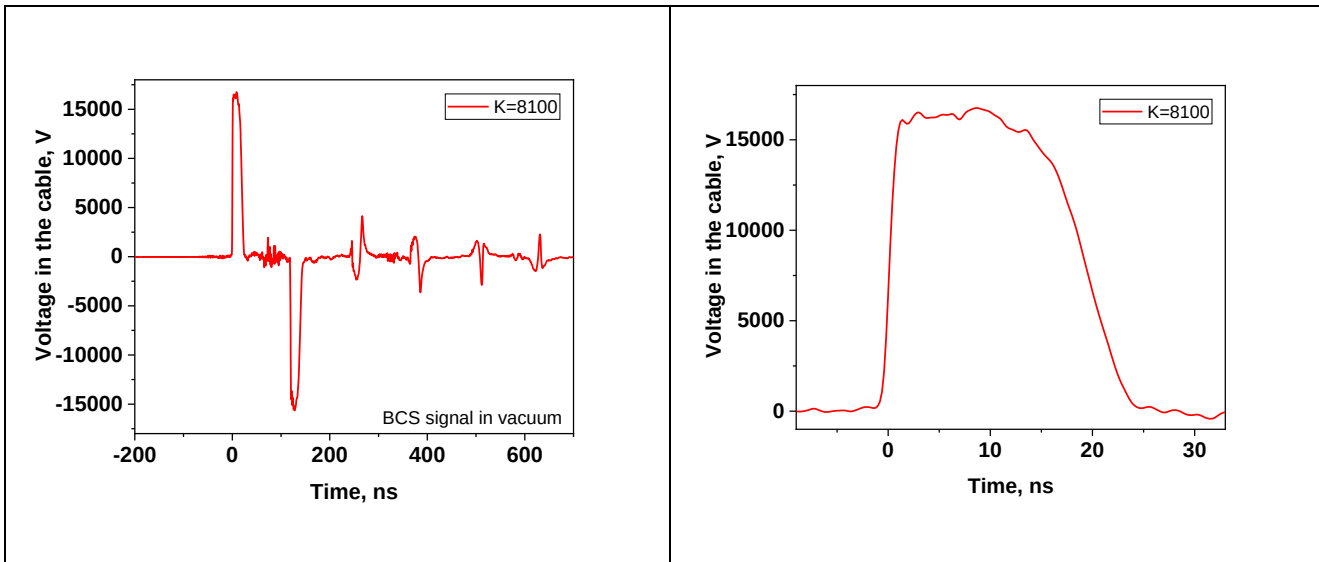


Figure 15: Total signal from the back current shunt BCS1 installed between the high voltage generator and nanosecond discharge tube, nDT, in vacuum (left) and zoomed incident pulse traveling from the generator to the nDT. Coefficient $K=8100$ includes a division coefficient of the BCS itself and a coefficient due to 2 attenuators and used for data treatment.

Figures 16 and 17 present the results of data treatment using a home-made MATLAB code. It is seen from accumulated statistics (Figure 16 (left)) that even if there is a noticeable part of low current events (about 20-25%), the majority of events correspond to a discharge current within 80-100 A. Breakdown happens at the second half of the pulse, around 15 ns (Figure 16 (right)), and active current starts flowing through the discharge

gap. Current was obtained via two methods, through the difference between the incident and reflected waveforms, and the data from the BCS2 for transmitted current being in a good agreement.

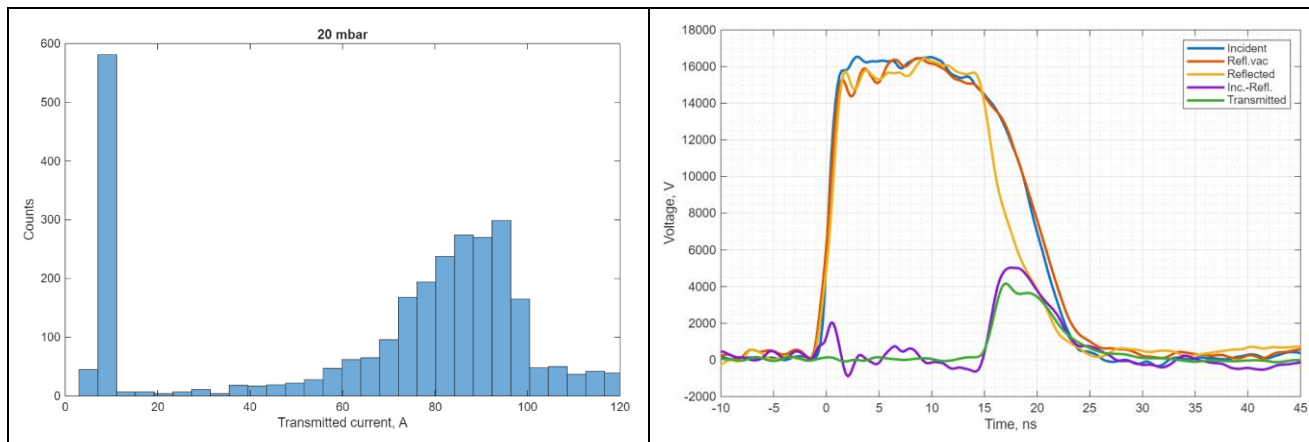


Figure 16: Statistics accumulated over a few hundred discharge events (left) and data from the back current shunts (right) – should be divided by the impedance of the cable, $Z=50$ Ohm to recalculate to current.

Synchronized electric field obtained through a capacitive probe (CP), current through the discharge gap and energy deposited in the discharge, are presented in the Figure 17 (left). The same data for energy but recalculated for a given number of ammonia densities at ambient temperature and 20 mbar pressure (specific delivered energy, or SED) are presented in Figure 17 (right). The obtained value was measured at $(8-9) \times 10^{-3}$ eV/molecule. The difference between the measurements by the back current shunts and the capacitive probe is due to systematic difference between the current measured by the two techniques. The reasons of this discrepancy will be clarified during the data treatment in the first half of September 2026. This value corresponds to a maximum statistical distribution of current (see Figure 16 (left)); the maximum value obtained in NH₃ in this discharge setup is of 3×10^{-2} eV/molecule.

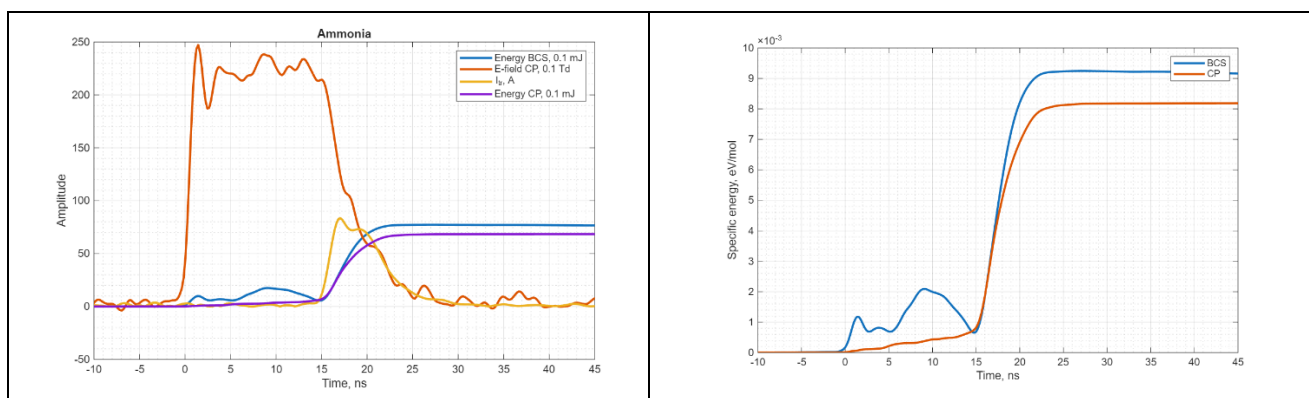


Figure 17: Synchronized electric field, current and delivered energy (left) and delivered energy obtained by two different techniques (right). The details are discussed in the text.

Obtained set of quantitative data on electrical parameters of the discharge presented in this section – namely synchronized in time electrical current, electric field and specific delivered energy, will be used, together with the time-resolved data on distribution of plasma emission in NH₃ over the cross-section of the discharge tube (see the data on ICCD emission and OES data above) as data for validation of kinetic mechanism suggested in T2.1 and plasma simulations of T3.2.

2.2.7 Quantitative data for FIW plasma in NH₃: absolute calibration and the density of excited NH(A)

In plasma science, calibration of TALIF using noble gases is a standard technique for obtaining absolute densities of O, H, and N atoms. This approach was proposed about 20 years ago by Niemi et al.¹⁷ and has been widely used by the community. The principle of the calibration is to introduce a noble gas into the discharge cell, using a two-photon excitation wavelength similar to that of the atom under investigation. The fluorescence signal from the noble gas is then compared with the fluorescence signal from the atom under study. The main advantage of this calibration method is that the geometrical factor is excluded from the analysis, while the density of the noble gas can be measured relatively easily.

A scheme of two-photon excitation of krypton, hydrogen, and nitrogen is given by Figure 18 (right). During our work we considered as a main challenge achieving the absolute calibration on Krypton: according to 2025 publication of Stakikovskiy and Dogariu¹⁸ from Princeton/TAMU, there might be a factor of 20 or higher in the calibration of 2001 by Niemi et al. The authors of the paper published in 2025 used a femtosecond laser while the authors of the paper published in 2001 used a nanosecond laser system. Taking these into account, we started theoretical work on comparison of femtosecond and nanosecond TALIF. From this work we have obtained results that will be presented in a scientific paper which will be sent to PSST during Autumn 2026. The conclusion is that mathematics based on the ratio of two-photon cross-sections, is equally valid for femtosecond and nanosecond systems in quadratic regime of fluorescence as a function of laser intensity.

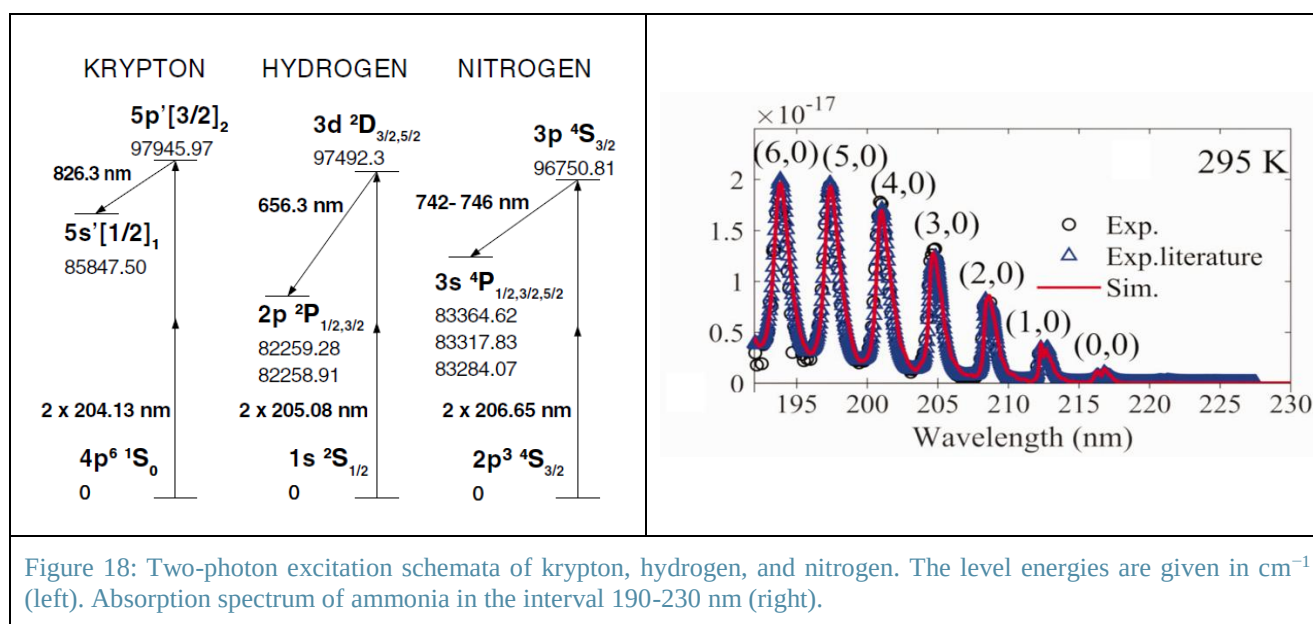


Figure 18: Two-photon excitation schemata of krypton, hydrogen, and nitrogen. The level energies are given in cm⁻¹ (left). Absorption spectrum of ammonia in the interval 190-230 nm (right).

Another serious challenge encountered was that the absorption in UV in NH₃ is strong enough: even at 20 mbar, the absorption at 205.08 nm is too strong to get a H-TALIF. Figure 18 (right) provides recent data¹⁹ showing a high local maximum of absorption near 205 nm. This maximum prevents doing H-TALIF at 205.8 nm. To address this we have considered the following workarounds: (i) try N-TALIF at 206.65 nm; (ii) try H-TALIF but in perpendicular direction taking into account possible partial absorption; (iii) try 3-photon H-TALIF at higher wavelength implementing an additional procedure for calibration.

Instead, we decided to get an absolute value of excited NH(A³Π(v'=0)). Optical emission spectrum of A³Π(v'=0)→X³Σ⁻(v''=0), obtained at 335-336 nm, was used for absolute calibration. Two lamps, one Deuterium

¹⁷ K. Niemi, V. Schulz-von der Gathen and H. F. Dobe, Absolute calibration of atomic density measurements by laser-induced fluorescence spectroscopy with two-photon excitation, J. Phys. D: Appl. Phys. 34 (2001) 2330-2335 <https://doi.org/10.1088/0022-3727/34/15/312>

¹⁸ A. Stakikovskiy and A. Dogariu, Calibration of hydrogen atoms measurement using femtosecond two-photon laser-induced fluorescence, Optics Express, 33 (2025), 26286-26305 <https://doi.org/10.1364/OE.562851>

¹⁹ W. Weng, S. Li, M. Aldén, Z. Li, Ultraviolet absorption cross-sections of ammonia at elevated temperatures for nonintrusive quantitative detection in combustion environments, Applied Spectroscopy 75 (2021) 1168-1177 <https://doi.org/10.1177/0003702821990445>

(Cathodeon) with non-absolute spectrum in Lund, and one laser breakdown lamp with absolute calibration (ISTEQ) at CNRS LPP laboratory in Paris were used to get the absolute value via calibration.

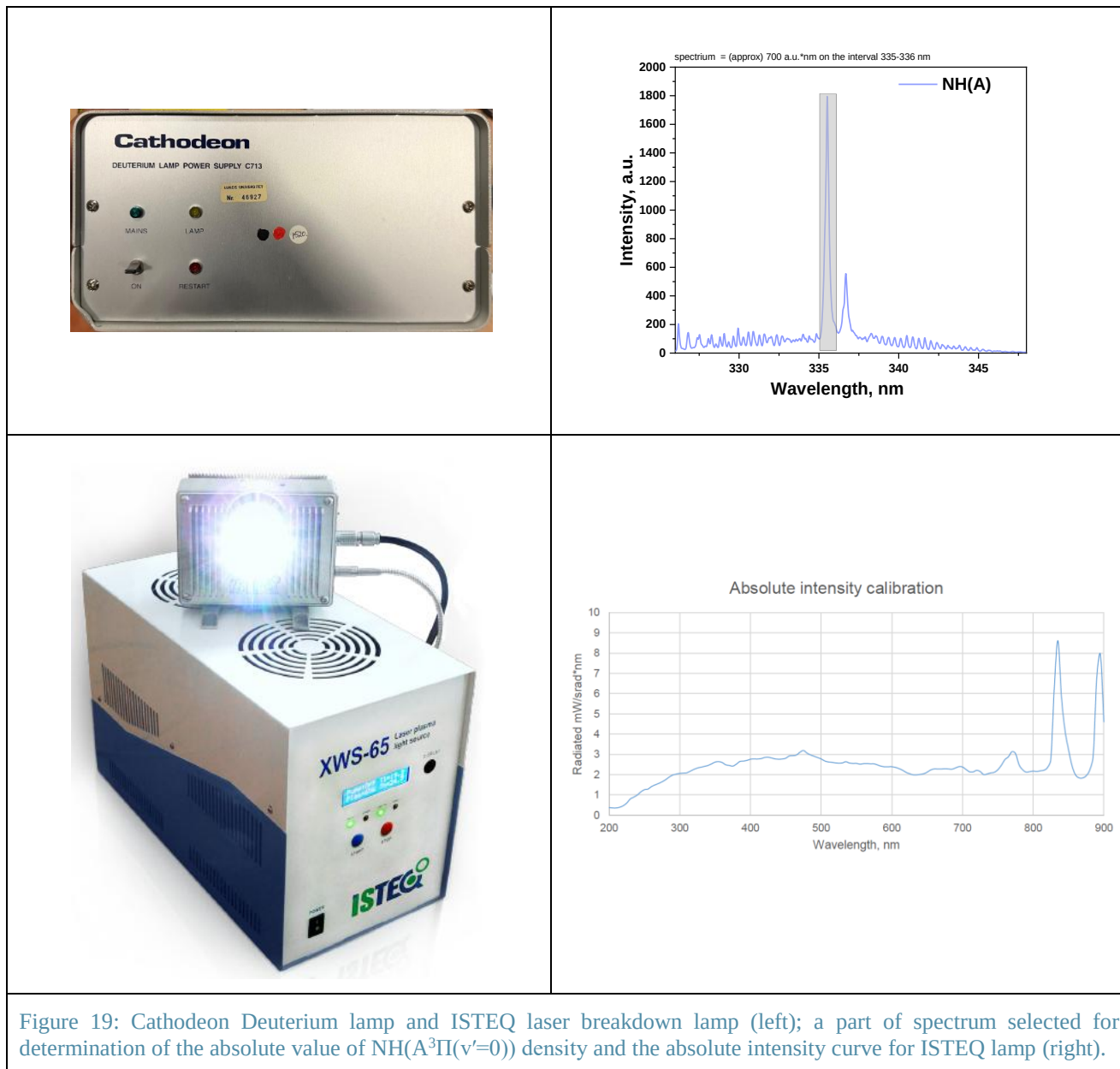


Figure 19: Cathodeon Deuterium lamp and ISTEQ laser breakdown lamp (left); a part of spectrum selected for determination of the absolute value of $\text{NH}(\text{A}^3\Pi(v'=0))$ density and the absolute intensity curve for ISTEQ lamp (right).

Every time a lamp was used for the calibration, an iris 5 mm in diameter was fixed at the point corresponding to the axis of the lamp. A tube cut in 2 along the axis was placed after the iris mimicking the passing of the light through the discharge tube and assuring the same geometry as in plasma experiment. The spectra were collected with the help of Acton spectrometer and PIMax4 Princeton Instruments ICCD camera. Plasma optical emission was compared to Cathodeon deuterium non-calibrated lamp. Cathodeon lamp was then sent from Lund to Paris to ensure continuity of measurements and to compare the emission to the emission of ISTEQ laser breakdown lamp with known absolute values of emission intensity. Below we present the first results on absolute calibration in the interval 335-336 nm, first for the experiment in Lund (Plasma vs Deuterium Cathodeon lamp):

<u>Lund NH plasma</u>		<u>Lund NH deuterium lamp</u>	
I_mean, a.u.	1140.209	I_mean, a.u.	1391.120
accumulations	400	Accumulations	400
Gate	3ns	Gate	3ms
Gain	90	Gain	90
Slit	100um	Slit	100um

And second, for the experiment in Paris (Deuterium Cathodeon lamp vs laser breakdown ISTEQ lamp):

<u>EP NH deuterium lamp</u>		<u>EP NH absolute laser breakdown lamp</u>	
I_mean, a.u.	15072.156	I_mean, a.u.	23603,.70
accumulations	400	Accumulations	400
gate	3ms	Gate	20us
gain	90	Gain	90
slit	100um	Slit	100um

These data, being treated, allow deducing the density of exciting states and further, G-factor of NH(A) production. We also will extract the decay of NH(A) in time, providing these new data for the team doing kinetic numerical modeling. This will be done during the data treatment in September 2026.

To link the absolute intensity of the light I [mW/(srad x nm)] of the ISTEQ lamp, see Figure 19 (right) and the density of the particles ([NH(A)]) emitting light in plasma, the following expression should be used (see detailed description of the absolute calibration procedure in ²⁰, page 46):

$$\varepsilon_{\lambda} = \frac{1}{4\pi} \frac{hc}{\lambda} A_{e'v'J'-e''v''J''} n_{e'v'J'} \phi(\lambda) \quad (5)$$

Here ε_{λ} is the spectral emitivity of the light source; $A_{e'v'J'-e''v''J''}$ is the Einstein coefficient of spontaneous emission corresponding to the transition from state (e', v', J') to (e'', v'', J'') , reduced in our case to A_{00} , the transition between zero vibrational levels of the upper and the lower state; $\phi(\lambda)$ is the normalized line profile, $n_{e'v'J'}$ is the

²⁰ A. Salmon, Diagnostics and kinetics of reactive oxygen and nitrogen species in atmospheric pressure non-equilibrium pulsed discharges for bio-decontamination (2017) PhD Thesis, University Paris-Saclay

density of the upper state of the emitting transition ($[NH(A)]$ in our case), h the Planck constant, c the speed of light, and λ the photon wavelength. In the first approximation, we will consider $\phi(\lambda)=1$. In practice, the intensity collected from plasma along the diameter is the line-of sight integration of the emissivity:

$$I_{abs}(\lambda) = \int_0^L \epsilon_{\lambda}(r) dx \quad (6)$$

In the last equation, L is the emission column length, and I_{abs} the emission intensity in absolute units, $mW/(cm^2 \cdot sr \cdot nm)$.

Comparing known absolute intensity of emission from the calibrated lamp to the emission intensity of plasma, one can deduce the density of emitting particles, $[NH(A)]$.

The experiments at LPP CNRS and in Lund were performed in slightly different geometries which was dictated by the space available for the experiment and by the relative intensities of the lamps. For example, the intensity of ISTEQ lamp is very high comparing to the Cathodeon lamp – and this was a reason why the experiment in Paris was performed without light collecting by a lens – while in Lund, 5 cm diameter lens was used to collect the radiation of plasma/LU Cathodeon lamp.

In LPP CNRS, the geometry for 2 lamps was identical, and the only correction needed for comparison, is a gate duration factor (see the Tables above): EP_NH_absolute_laser breakdown lamp provided 23603 a.u. during 20 μs – while Lund NH_deuterium_lamp at EP provided 15072 a.u./150 = 100.5 a.u. (to correct for the same gate of the ICCD, 3 ms to 20 μs). As far as EP_NH_absolute_laser breakdown lamp provides 2.43 $mW/(sr \cdot nm)$, the Lund NH_deuterium_lamp at EP provides $2.43 \times (100.5)/23603 = 0.01 mW/(sr \cdot nm)$.

Having this ratio between the absolute intensities of the EP_NH_absolute_laser breakdown lamp and Lund NH_deuterium_lamp at EP, will also take into account the geometry of the experiment in Lund. In Lund, we had to use a lens to collect radiation. Collection of the radiation from plasma was naturally restricted by the diameter of the lens, 5 cm, and the lens was situated 30 cm apart from the discharge tube axis. Collection of radiation from the lamp was limited by 5 mm diameter diaphragm installed at the axis of the discharge tube; the lamp was placed 50 cm apart from the diaphragm. These last geometrical factors should be taken into account: the light is collected to the lens and projected to the ICCD matrix from different space angles: comparing the factors for the space angle d^2/R^2 , where d is the diameter of the lens or diaphragm, and R is the distance from plasma to lens or from the lamp to the diaphragm, we conclude that the ratio of the space angles for collection of radiation from plasma and from the Deuterium lamp is equal to 280.

Further, comparing the emission from plasma (1140 a.u. during 3 ns) and Deuterium lamp (1391 a.u./ 10^6 being corrected to the duration of the ICCD gate, 3 ms for the lamp), and taking into account a space factor 280 deduced above, we conclude that the intensity of plasma radiation is $(1140 \times 10^6/1391)/280 = 2.93 \times 10^3$ times stronger than the emission from the Deuterium lamp.

Taking into account the Einstein coefficient of spontaneous emission for the considered transition²¹ $A_{00}=2.5 \times 10^6 s^{-1}$, and that the energy of transition (335 nm) is equal to 3.7 eV, the emission column length is $L=1cm$, we consider that for $[NH(A)]$ in the discharge, it will obtain a value of $[NH(A)]=2.4 \times 10^{11} cm^{-3}$.

The calculation of the G-factor demands knowing the specific deposited energy (SED). The energy deposited in discharge in this experiment, SED, is about 7 mJ (see Figure 17 (left)). The volume of plasma is defined by the diameter of the discharge tube, 1 cm, and the interelectrode distance, 3 cm. At these parameters, the volume is equal to $V=2.35 cm^3$. Specific deposited energy is equal to $SED=3 \times 10^{-3} J/cm^3$ or, recalculation to eV per unit volume, $SED=1.76 \times 10^{16} eV/cm^3$. Calculation of G-factor (or G-value) provides the following result:

²¹ N. Lamoureux, L. Gasnot, P. Desgroux. Quantitative NH measurements by using laser-based diagnostics in low-pressure flames. Proceedings of the Combustion Institute, Elsevier, 2019, Proceedings of the Combustion Institute, 37 (2), pp.1313-1320 <https://doi.org/10.1016/j.proci.2018.09.007>

$G = \text{SED}/[\text{NH(A)}] = 1.76 \times 10^{16} \text{ eV/cm}^3 / 2.4 \times 10^{11} \text{ cm}^{-3} = 7.3 \times 10^4 \text{ eV/NH(A)}$. If to discuss a validity of the obtained data, from one side, the values of NH(A) density seem to be reasonable: compare to linear densities of nitrogen active species in atmospheric pressure streamer²² (Figure 20 (left)) obtained by Pancheshnyi et al. G-values (or energy cost) can be quite high: Figure 20 (right) presents the energy cost (G-value) of electron-impact dissociation of nitrogen molecules as a function of the reduced electric field E/N , calculated by N.A. Popov²³ with (1) cross-sections of Cosby (1993) and (2) with the cross-sections of Phelps (1985) for excitation of highly energetic states of N₂ of energy above 13 eV. The symbols show the experimental data of Matsumoto et al (2010) at 900 Td (diamond) and of Gherardi et al (2008) at 130 Td (circle). Figure is taken from [18]. It is clearly seen that, for E/N in the interval 50-100 Td, the G-values are as high as 10^4 - 10^3 eV/atom. Even if the values sound reasonable, we believe that additional analysis is required to validate the obtained results. This analysis is planned to be done within Autumn 2026, together with teams working for numerical modeling.

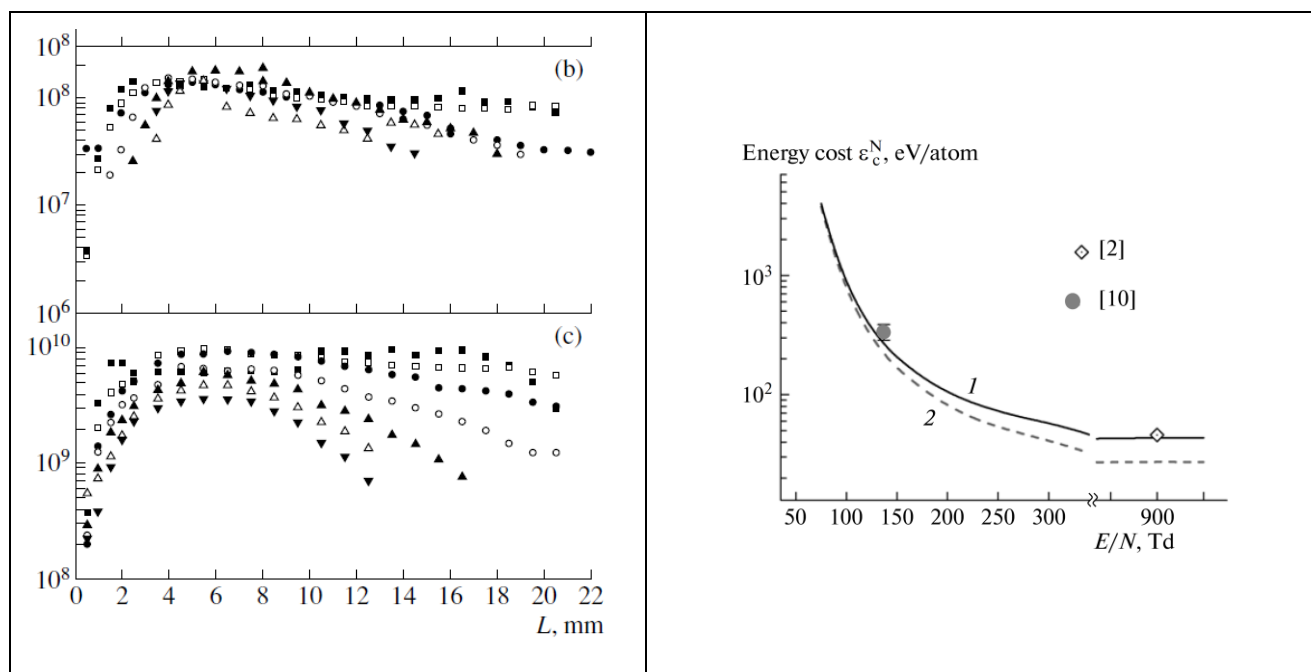


Figure 20: Peak densities of (b) $\text{N}_2^+(\text{B}^2_+ \text{u}, v=0)$, and (c) $\text{NO}(\text{A}^2_+ \text{u}, v=0)$ in the streamer head vs. the distance from the high-voltage electrode for different interelectrode distances (density decrease with interelectrode distance): 20, 24, 28, 34, 42, 54, and 92 mm (left) measured by Pancheshnyi et al. (see text). Energy cost of electron-impact dissociation of nitrogen molecules as a function of the reduced electric field E/N , calculated by N.A. Popov (see text) with (1) cross-sections of Cosby (1993) and (2) with the cross-sections of Phelps (1985) for excitation of highly energetic states of N₂ of energy above 13 eV (right).

The data on absolute value of NH(A) density presented in this section, together with the G-value for NH(A) production in nanosecond FIW discharge, will be used as a dataset providing the efficiency of NH₃ dissociation in plasma. These, to our knowledge, are the first available data on G-value for NH(A) production in ammonia plasma at high electric fields. These results, together with the experimental data on plasma parameters in ammonia described above, will be now used for validation of kinetic mechanism suggested in T2.1 and plasma simulations of T3.2. The results of simulations, together with experimental data on the optimal discharge configuration described above, will be used to build, in the near future, the plasma system(s) for a combustion installation. Our expert conclusion at this stage is that two systems will be tested and compared: a pin-to-pin discharge with a few mm gap and a multi-point surface dielectric barrier (SDBD) discharge at atmospheric pressure. The electric fields will be between similar to those in kinetic experiments of this deliverable, while the specific energy delivered to plasma (SED) will be 1-2 orders of magnitude higher.

²² S. V. Pancheshnyi, S. V. Sobakin, S. M. Starikovskaya, A. Yu. Starikovskii, Discharge Dynamics and the Production of Active Particles in a Cathode-Directed Streamer, 2000, Plasma Physics Reports, Vol. 26, No. 12, pp. 1054–1065

²³ N.A. Popov, Dissociation of Nitrogen in a Pulse Periodic Dielectric Barrier Discharge at Atmospheric Pressure, 2013, Phys. Reports 39, 420

2.3 Conclusions

Under CAIPIRINH₃A WP3 “Plasma dynamics and plasma systems development” – T3.1 “Plasma NH₃ energy efficiency studies” the report on plasma-NH₃ energy efficiency studies (D3.1) is prepared as a result of collaborative work of CAIPIRINH₃A partners at CNRS, LU, UoB. The aim of the WP3 was to provide an experimental study of efficiency of ammonia dissociation by nanosecond plasmas.

To study the complex dynamics of nanosecond pulsed discharge (NPD) in quiescent and controlled NH₃ environments and leveraging advanced plasma diagnostics, CNRS developed an experimental procedure for determining the energy efficiency of NH₃ dissociation under high electric fields.

A numerical code is developed by CERTH to reproduce the measured values and to predict a behaviour of the FIW discharge for a wide range of pressures and voltages. The code is validated on experimentally obtained data on discharge in molecular nitrogen - the results have been published in PSST in 2025. UoB together with LU developed a non-equilibrium NH₃ plasma-combustion model (under T2.1), integrating thermal and plasma kinetic effects. A Cantera-based C++ 0D plasma solver, CanPlasKin (see D2.1), was implemented by UoB as a unified reactor model where neutral combustion chemistry, plasma species kinetics, electron density evolution, and the gas-phase energy equation are solved simultaneously within a single ODE system.

Analysis of advantages and challenges of plasma-assisted combustion resulted in participation in a tutorial review published in 2026 in two parts in Plasma Sources Science and Technology (PSST). The review is aimed to guide readers from fundamental combustion and plasma physics to the mechanisms and practical applications relevant to the most modern energy and propulsion systems. Work on these papers provided a comprehensive overview of the state of the art in plasma-assisted combustion up to 2026, establishing a broader scientific framework for the development of plasma-assisted combustion of ammonia within the project.

During T3.1, we encountered challenges with nanosecond discharge in ammonia because of the late hiring and experimental restrictions at CNRS. This situation has been approved by the EC already - which resulted to the extension of the D3.1 submission. This extension allowed us plan and deliver an unique experimental campaign at Lund.

The experiments on the nanosecond diffuse moderate pressure discharge in NH₃ were performed during a few experimental sessions at the Division of Combustion Physics of Lund University. The discharge setup – nanosecond discharge tube (nDT) - was modified by CNRS and LU for NH₃ study replacing all corrosive parts for non-corrosive, and a set of tests have been performed in LPP CNRS in air, showing a capacity of experimental control of plasma parameters by changing a geometry of the nanosecond discharge tube (nDT). While moderate pressure conditions allow developing a wide range of diagnostics, the obtained data are valuable for high pressure conditions because the majority of the electron impact processes are 2-body reactions.

The nanosecond pulsed discharge (NPD) in the form of the fast ionization wave (FIW) developing in a long discharge tube in NH₃ and providing a diffuse moderate pressure plasma, tens of mbars, has been obtained by the first time by CNRS and LU teams. It was shown that a nanosecond fast ionization wave (FIW) at 20 mbar closes the inter-electrode gap at very high fields (kTd). This fast ionization wave provides the initial electron density and makes the diffuse discharge possible. While the gap is closed, the active current of about 100 A flows through the gap during the discharge pulse. This is the main time interval when the energy is deposited to a gas. We observe that the FIW starts at the middle of the pulse, at 10 ns (see Figure 9), and the closing of the gap takes place at 12 ns. As far as the delay of the start of the discharge decreases with pressure, we can expect starting the discharge earlier at atmospheric pressure. The experiment at 20 mbar proves that we are able to tailor the reduced electric field as a function of the distance between the electrodes within a wide range, from hundreds to thousands of Td.

In the future installation for plasma-assisted combustion of ammonia at atmospheric pressure (T2.4), necessary high fields will be kept by decrease of the distance between the electrodes: thousands of Td at 20 mbar before closing the gap correspond to hundreds of Td at atmospheric pressure and ambient temperature conditions when (a) gas density increases by a factor of 50; (b) interelectrode gap decreases from a few cm to a few mm, by a factor of 10. As a result, the reduced electric field will decrease by a factor of 5 – the fields being optimal for energy delivered to dissociation.

Another important issue for building a plasma system as a part of combustion installation planned to develop in T2.4, is to increase a specific energy delivered (SED) to the discharge, or energy per particle (typically provided

in eV per particle): if for fundamental study of kinetics, we keep SED=0.01 eV/molecule to make plasma as uniform in space as possible and to guarantee an access to kinetic information, in real combustion system the SED should be 1-2 orders of magnitude higher, 0.1-1 eV/molecule. This will be achieved by decreasing the discharge volume: indeed, a typical diameter of atmospheric pressure streamer is sub-mm, so the diameter of a plasma under study will be decreased from 1 cm to 1 mm, by a factor of 10. When the same current should pass the plasma channel, the energy density will be increased by a factor of 100. We consider, for the moment, two possible configurations of plasma systems for combustion installation: or pin-to-pin with a few mm distance, or surface dielectric barrier discharge (SDBD) with a plasma divided on a few tens of microchannels providing multiple points of plasma pre-treatment for ammonia. Both systems will be developed, tested and compared in the near future.

Obtained set of quantitative data on electrical parameters of the discharge presented in this report – namely synchronized in time with an accuracy of 0.2 ns electrical current, electric field and specific delivered energy in the nanosecond FIW in ammonia, will be used, together with the time-resolved data on distribution of plasma emission in NH₃ over the cross-section of the discharge tube (see the data on ICCD emission and OES data above) as data for validation of kinetic mechanism suggested in T2.1 and plasma simulations of T3.2.

During this already complex experimental campaign at Lund, we have encountered also severe technical challenges: (i) a study from Princeton University reported in 2025, called into question the reliability of the cross-section ratio for two-photon absorption of Kr and H, which is required for the quantitative calibration of TALIF measurements; (ii) experimental efforts on calibrated H-TALIF at 205 nm in NH₃ plasmas have shown the experimental challenges linked to a strong absorption by ammonia itself – the way to potentially overcome these difficulties by a subsequent 3-photon LIF at longer wavelengths with additional calibration – has been suggested.

Data on optical emission spectra of FIW discharge in NH₃ are collected and analysed. Absolute calibration of emission data has been performed for NH(A³Π(v'=0)→X³Σ⁻(v''=0)) transition. G-value of NH(A³Π(v'=0)) production in pulsed nanosecond plasma in ammonia has been obtained for the first time experimentally and will be used as a dataset providing the efficiency of NH₃ dissociation in plasma. These are, to our knowledge, are the first available data on G-value of NH(A) production in ammonia plasma at high electric fields.

The results of simulations, together with experimental data described in this report, will be used to build, in the near future, the plasma system(s) for a combustion installation. Our expert conclusion at this stage is that two systems will be tested and compared: a pin-to-pin discharge with a few mm gap and a multi-point surface dielectric barrier (SDBD) discharge at atmospheric pressure. The electric fields will be between similar to those in kinetic experiments of this deliverable, while the specific energy delivered to plasma (SED) will be 1-2 orders of magnitude higher.

These results and the lessons learnt from T3.1 work form the basis for the planned work in the next few months under WP3 as a direct continuation of T3.1 activities under T3.2 and mainly T3.3. The planned timeline is the following:

- To finalize data treatment for the electrical parameters obtained for 6 different geometries of the FIW discharge cell – the unique data on discharge development in NH₃ at different reduced electric fields and SEDs: 1-15 September 2026;
- To finalize data treatment for [NH(A)] behaviour in time: 5-20 September 2026;
- To make additional analysis of (i) visible part of spectra; (ii) G-factor of [NH(A)] production as a function of the discharge parameters: 1 September – 31 October;
- To perform, during one additional experimental session in Lund, 3-photon TALIF measurements of H-atoms in NH₃; to provide a calibration using a known mixture without ammonia (f.e. 5%H₂:95%N₂ mixture): 15 September – 15 December.

Obtained data (synchronized in time voltage, current, electric field, electron density, and the NH(A) density as a function of time) will be used as (i) a validation dataset for numerical modelling of ammonia-containing plasma for validation of kinetic mechanism suggested in T2.1 and plasma simulations of T3.2; (ii) as a basis for adjustment of the optimal configuration of plasma system(s) in T3.3.