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Modeling and simulation of atmospheric pressure low-temperature plasmas

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For the 2026 Ulrich Kogelschatz Lecture Award, the focus will be on the modeling and simulations of dielectric barrier discharges at atmospheric pressure. From his early work on ozone formation, U. Kogelschatz's work contributed a lot to improve the knowledge on dielectric barriers discharges [1,2] studied for a wide range of applications.

In this lecture, we focus on two different set-ups chosen as testbeds for the study of the physics and discharge dynamics of dielectric barrier discharges. First, a point-to-plane geometry in atmospheric pressure air in which a dielectric layer is set as an obstacle between both electrodes [3] is presented. Second, a helium kHz plasma jet powered by rectangular pulses of applied voltage impacting a target [4] is discussed. In the dielectric tube of the plasma jet, the dielectric surface contributes to the "guiding" of the discharge.

Different modeling and simulations approaches are presented, along with recent efforts for direct comparisons between simulations and measurements using advanced diagnostics tools. For both studied set-ups, we discuss the most fundamental physical quantities determining discharge dynamics, such as the electric field, the mean electron energy and the electron number density, as well as the charging of targets. Finally, the impact of a better understanding of dielectric barrier discharges on the further to further improvements of existing applications and new applications is discussed.

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Analysis of Spatio-Temporal Ignition Patterns in Sinusoidal-Driven Dielectric Barrier Discharges in a Multi-Filament Arrangement

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Dielectric barrier discharges (DBDs) operated at atmospheric pressure are relevant for ozone generation, air-pollutant degradation, CO_2 conversion, surface modification, decontamination, and plasma medicine. While pulsed-operated DBDs in single- and multi-filament arrangements have been studied extensively [1,2], sinusoidal excitation shows distinctly different discharge characteristics [3]. Here, we investigate the spatio-temporal ignition pattern of sinusoidal-driven filamentary DBDs in a spatially one-dimensional (1D) multi-filament arrangement and analyse the roles of surface and volume memory effects.

The experiments were performed in dry synthetic air (20 vol% O_2 in N_2) at 1 bar using a symmetric alumina-covered rod electrode configuration with 1 mm dielectric thickness on each electrode, a 1 mm gas gap, and a lateral discharge length of approximately 10–12 mm. A sinusoidal high-voltage (HV) waveform at 10 kHz and HV amplitudes between 11 and 14 kV_{pp} was applied. Synchronised electrical diagnostics (voltage and current probes) and optical diagnostics (iCCD and streak camera) were used to obtain the filament number, their positions, and ignition times during positive and negative half-cycles.

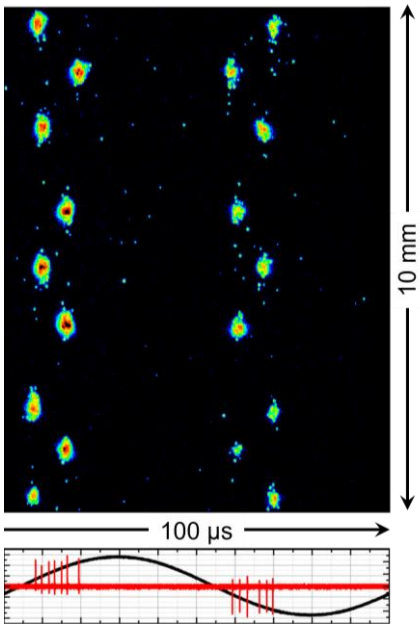

Fig. 1 Spatio-temporal ignition pattern of a sinusoidal-driven multi-filament DBD together with the corresponding HV and current waveforms (11 kV_{pp}, 10 kHz).

The filament positions remain fixed over one high-voltage period, and within each half-cycle the discharge appears in two stages at alternating positions. This indicates that previously deposited surface charges suppress reignition at the same lateral position for the same voltage polarity. The pattern observed in one half-period is mirrored in time in the next half-period, see Fig. 1. A statistical analysis of streak images shows that the ignition-time distribution is governed by local variations of the gap voltage, while the spatial pattern is controlled primarily by surface-charge deposition. However, this stable structure persists only for a limited number of periods and is lost for voltages of about 12 kV_{pp} and above, where more than one filament at the same lateral position occur within one half-cycle and spatial stability disappears. To interpret these findings, a data-driven equivalent electric circuit model and a self-consistent 1D fluid-Poisson model were employed. The simplified circuit model reproduces both the central tendency and dispersion of the ignition times and enables the estimation of effective capacitances, breakdown voltage, and initial gap-voltage conditions. Ongoing work focuses on modelling the surface-charge-induced local gap voltage for interacting filaments and transferring the results to plate-to-plate DBD configurations.

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Revisiting the memory effect in diffuse Nitrogen DBD using a fluid modeling approach

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Diffuse Dielectric Barriers Discharges (DBD) in nitrogen at atmospheric pressure have been studied for a few decades, yet some mechanisms are still not fully understood. Numerical simulations can be used to access data that are not experimentally accessible or to check the consistency of hypotheses based on experimental observations, leading to a better understanding of the discharge physics. The homogeneous or diffuse regime is only obtained if enough seed electrons are present in the gas gap between two discharges, allowing a Townsend breakdown to occur, otherwise the discharge is in the filamentary regime. The electron production mechanisms happening when the discharge is off originate from previous discharges and are referred to as the memory effect. The main candidate for this effect in pure nitrogen was proposed to be secondary electron emission induced by $N_2(A)$ metastable states at the dielectric surface [1]. However, a diffuse regime is still observed even at very low excitation frequencies, leading to a long time between discharges, during which the $N_2(A)$ density can drop significantly, as well as the aforementioned secondary emission [2]. Therefore, other electron production mechanisms are probably involved and have to be studied to explain this experimental result.

For that purpose, a time-dependent one-dimensional fluid model was developed to study the possible effect of oxygen impurities in so-called “pure” nitrogen (for example 99,999% purity). Hence, a specific reaction set takes into account the out-of-equilibrium plasma chemistry of oxygen/nitrogen mixture [3]. An electrical model of the DBD power supply is included, as it influences the discharge behavior [4]. Surface interactions are accounted for through a flux balance formulation at the dielectric surface, enabling the investigation of possible electron production mechanisms at the surfaces.

In the present work, our aim is to evaluate the relative importance of different memory effect mechanisms under conditions close to the experiments. Especially at frequencies as low as 50 Hz, mechanisms other than the secondary emission from $N_2(A)$ are examined to assess their potential contribution to the memory effect. These mechanisms include secondary emissions from other metastables, associative ionization due to the small oxygen impurities or spontaneous electron emission from the dielectric surfaces. The influence of other experimental parameters such as the dielectric properties or the gas gap value can also be explored. Based on the model results, we establish a framework to discriminate among the physical and chemical mechanisms identified as possible candidates for the memory effect, and to assess whether they can quantitatively reproduce the experimental observations in a self-consistent manner.

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Numerical Study of Filamentary Dielectric Barrier Discharges in Dry Air: Effects of Simulation Parameters and Model Dimensionality

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Dielectric barrier discharge (DBD) represents a versatile type of non-equilibrium atmospheric-pressure plasma and has been extensively applied in areas such as environmental and energy technologies, surface processing, and, more recently, medical and agricultural uses. In this study, we perform numerical analyses of DBD to quantitatively understand and control the reactive species generated by DBD. We focus on filamentary discharges in dry air between parallel-plate electrodes, both covered with dielectric layers. This configuration is motivated by applications involving the irradiation of plasma-generated reactive species onto seeds for germination control. Although numerous numerical studies of DBD, including surface discharges and glow discharges, have been reported [1,2], relatively few studies have addressed atmospheric-pressure air in such electrode configurations.

Fluid-model-based simulations were conducted under various conditions to reproduce filamentary discharges while accounting for dielectric surface charge accumulation. The effects of key parameters such as initial electron distribution, dielectric permittivity, boundary conditions, were investigated to identify reliable modeling conditions, and axisymmetric (r–z) and Cartesian (x–y) models were compared to assess the impact of dimensional assumptions. The DBD configuration (Fig. 1) consists of a 1 mm gap between electrodes, each covered by a 0.5 mm dielectric layer (ε_r=4, 10), with the left electrode grounded and a voltage applied to the right electrode. Discharges were initiated by seed electrons, whose number and distribution were treated as parameters due to their influence on breakdown voltage.

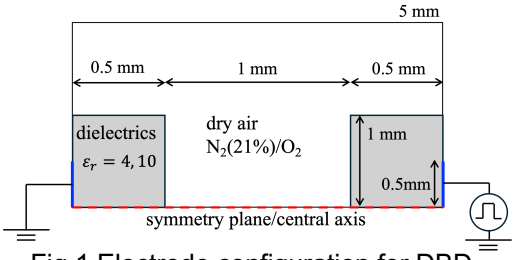

Fig.1 Electrode configuration for DBD.

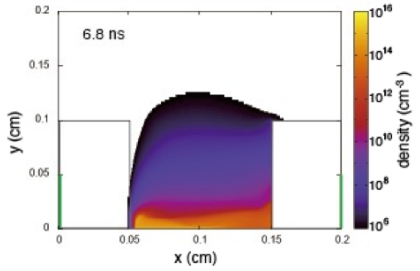

Fig. 2 Electron density distribution with applied voltage of 6,800 V using r-z system.

Fig. 2 shows the calculated electron density during cathode-directed streamer propagation in the r–z system. As the streamer approaches the cathode, the ion density increases, and these ions immediately accumulate on the cathodic dielectric surface (Fig. 3), leading to a rapid decrease in the gap voltage toward zero. A higher initial electron density leads to earlier streamer initiation, while the resulting electric field and electron density distributions are not significantly affected. Although minor differences are observed between the x–y and r–z models, the energy efficiency of radical generation remains largely unchanged under the present conditions, suggesting that the choice of dimensional model has a limited impact on this aspect.

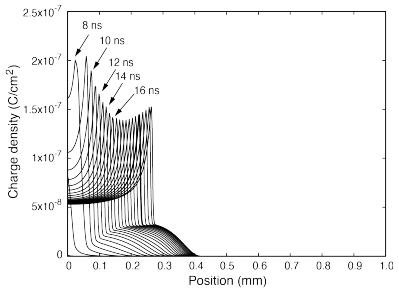

Fig.3 Charge density on the dielectric of cathode.

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On the Memory Effect and Discharge Characteristics of a Diffuse Dielectric Barrier Discharge in Various N_2/O_2 Mixtures

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Dielectric barrier discharges (DBDs) have been investigated and successfully applied in industry for many decades [1]. Typically, DBDs are filamentary discharges in which discrete filaments bridge the gap between the electrodes, further characterized by short-lived but intense bursts of current. In certain conditions, however, a diffuse discharge can be obtained. These diffuse discharges are spatially uniform and characterized by only one low-amplitude current peak per half period. Among the diffuse discharge regimes, the atmospheric pressure Townsend discharge (APTD) in pure N_2 is probably the most described and best understood [2].

To obtain an APTD, seed electrons are required to initiate gas breakdown at sufficiently low electric fields, preventing the formation of a streamer breakdown. These seed electrons are provided by charges stored in the dielectric and excited species that were generated during the previous discharge and drive the so-called memory effect. In pure N_2, it was shown that the metastable $N_2(A)$ species are essential to obtain an APTD [2]. It was also observed that even small additions of O_2 (hundreds of ppm) to the mixture can quench the $N_2(A)$ species, thus preventing an APTD from forming [3].

Nevertheless, a diffuse discharge was achieved in synthetic air, comprising 20 % O_2 in N_2 [4]. This previous work investigated the memory effects and the role of the dielectric material. It was shown that a diffuse discharge in air is possible even after replacing the gas completely in between subsequent discharges, indicating that the dielectric plays an essential role in sustaining the memory effect, although this behavior is highly dependent on the used dielectric. Despite these recent advances, the precise underlying discharge mechanisms enabling the diffuse discharge in air remain unclear.

In this work, a diffuse discharge is investigated in a variety of O_2/N_2 mixtures, going from 4 % up to 20 % O_2 in N_2. Optical emission spectroscopy and detailed electrical diagnostics are used to characterize the discharge in the different gas mixtures. It becomes clear that the discharge in N_2 behaves fundamentally differently from the discharge containing a substantial O_2 fraction. Furthermore, the role of secondary electrons emitted from the dielectric surface appears to change from the pure N_2 discharge to the O_2-containing one, as a significant change in the secondary electron emission coefficient is observed. In short, this work provides additional insights into the discharge mechanisms and possible memory effects driving the diffuse discharge in O_2/N_2 mixtures.

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Tunable diode laser absorption spectroscopy on a single-filament dielectric barrier discharge in argon at atmospheric pressure

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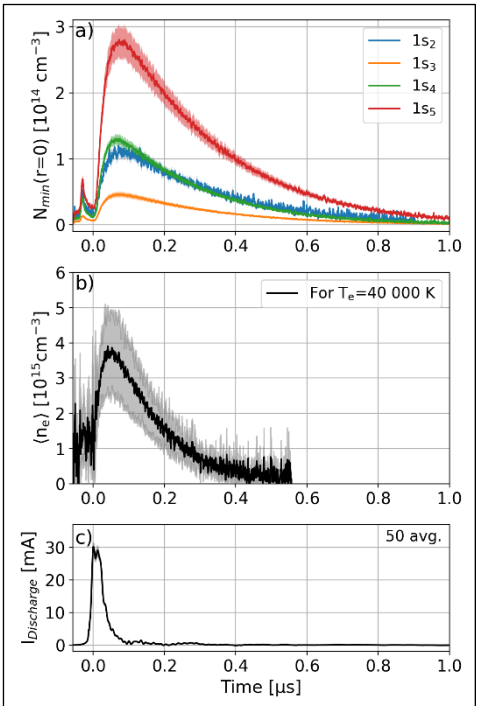
Atoms and molecules in excited states impact the discharge and chemical reaction kinetics by their contribution to the production of charge carriers, via, e.g., step-wise ionisation or chemi-ionisation processes. These processes are mainly driven in argon discharges by the energetically lowest excited states in the $3p^5 4s$ manifold, the two resonance states $1s_4$ and $1s_2$ and the two metastable states $1s_5$ and $1s_3$ (given in Paschen notation). Measurements of number densities of the four $3p^5 4s$ states, as well as other key plasma parameters such as the electron density and the gas temperature give insights into the discharge development and the initiation of plasma chemical processes. They are crucial for validating the reaction kinetics of numerical models through a direct comparison with the numerical results, see e.g. [1].

The measurements were performed in a two-sided dielectric barrier discharge (DBD) in a single-filament arrangement, consisting of a half-spherical powered metal top electrode in contact with a planar dielectric (Al_2O_3, thickness 0.6 mm, $\varepsilon_r \approx 9$) and a second dielectric on top of a grounded planar metal electrode. Both are separated by a gas gap distance of 3 mm. Operating the DBD with high-voltage (HV) sinusoidal waveforms leads to the ignition of an individual discharge event in each half-period of the HV-cycle [2]. The discharge was powered by a HV sinusoidal waveform with an amplitude of 2.5 kV and a frequency of 10 kHz, operated in argon at atmospheric pressure and a constant gas flow rate of 2 standard litre per minute argon through the discharge arrangement. Tunable diode laser absorption spectroscopy was utilised to measure the absolute number densities of the four $3p^5 4s$ states temporally resolved, in the center of the discharge arrangement using a single laser, probing transitions ($1s \rightarrow 2p$) in the near-infrared region between 790 and 830 nm. The densities reach up to 10^{14} cm^{-3} (Fig. a)). The line-shape analysis of the measured absorption spectra allows to estimate a gas temperature of (337±19) K from the resonance broadening [3] and maximum electron densities in the range between (10^{15}-10^{16}) cm^{-3} from the Stark broadening [4] of these lines (Fig. b)) for the measured discharge current shown in Fig. c).



Temporal density development of a) the resonant states ($1s_4$, $1s_2$) and the metastable states ($1s_5$, $1s_3$) and b) the electron density for the measured discharge current shown in c) of the discharge event in the positive half-period of the HV-cycle.

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Surface Engineering of Heterogeneous Bio-based Materials: Utilizing a Proprietary Hybrid Surface-to-Volume Dual-Frequency Discharge.

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While atmospheric pressure plasma is established in polymer processing, the transition to heterogeneous bio-based substrates is frequently hindered by complex surface morphologies and strict thermal constraints. This work presents previously unpublished results regarding the performance and diagnostic characterization of a hybrid plasma source utilizing a proprietary dual-frequency excitation scheme, a technology currently protected by a utility model.

By integrating a low-frequency pre-ionization stage (kHz range) with a high-frequency power component (MHz range), this IP-protected architecture achieves a stable, high-density ambient air discharge. To ensure the integrity of delicate biological structures, the MHz component employs a precision-modulated, low-duty-cycle pulse strategy, effectively optimizing the RONS (Reactive Oxygen and Nitrogen Species) flux while maintaining a low-gas-temperature regime if the high-power MHz frequency component is controlled.

This study expands upon prior experimental work by introducing new datasets obtained through high-resolution Optical Emission Spectroscopy (OES) and synchronized ICCD imaging. These results elucidate the synergistic effects of the dual-frequency harmonics on species evolution and discharge spatial distribution. Electrical characterization across a broader range of inorganic/organic conductive materials and insulating bio-materials demonstrates that this hybrid approach is topographically agnostic. The findings indicate that this dual-mode generation offers a robust, scalable pathway for the industrial-grade functionalization of the next generation of sustainable, bio-based materials.

Acknowledgement – this research was funded by the project GF25-20010L funded by the Czech Science Foundation and by the project LM2023039 funded by the Ministry of Education, Youth, and Sports of the Czech Republic and also supported by the Slovenian Research and Innovation Agency (ARIS) under research project No. N4-0267, “Plasma treatment of biobased porous heterogeneous substrates”, and under the research program funding No. P4-0015, “Wood and lignocellulose composites”.

Influence of Differently Sized Dielectric Beads on Plasma Properties in Plasma Catalysis

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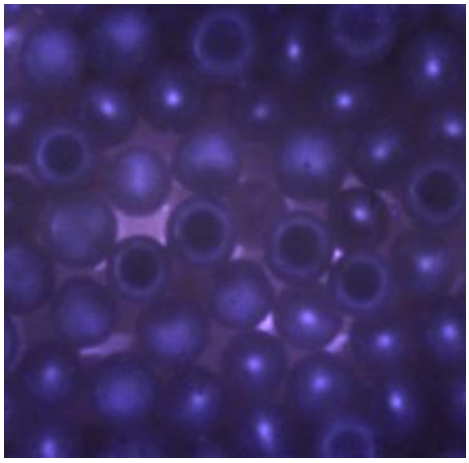
In plasma catalysis, dielectric beads are often used as carrier material for catalysts or as catalysts themselves. These beads can also possess porous structures or complex surface morphology to increase the available surface. The presence of these particles influences the plasma leading to changed discharge characteristics and properties. Besides the material properties, like the dielectric constant, we observed that the bead's size and morphology also have a significant effect on the plasma.

We designed a planar dielectric barrier plasma reactor which operates at atmospheric pressure with a H_2-CO_2 gas mixture to investigate this plasma-material interaction. The setup can be heated up to 600 °C to allow thermal catalysis experiments for comparisons. The plasma is ignited at 10-18 kV at 20 kHz while the plasma gap can be varied between 0.5 and 6 mm, allowing the investigation of a multitude of materials like differently shaped and sized beads or powders. By using a transparent indium tin oxide thin film electrode, the plasma region is optically accessible, allowing the plasma characterization with camera and optical emission spectroscopy measurements. Further analysis of the plasma is performed using current-voltage characterization. Mass spectrometry is used to quantify the gas conversion into CH_4, CO and CH_3OH.

The interplay between plasma and catalyst is highly complex. Therefore, the system is simplified by using spherical dielectric beads with no specific catalytic properties. This model system focuses only on physical plasma effects. Yttrium stabilized zirconium dioxide spheres with diameters in the rage from 0.1 to 2.1 mm are used as inert material. By varying the size of the beads, the gaps in between the spheres change, possibly reaching the minimal limit for the plasma formation. In the figure on the right, this limit can be observed for the spheres touching the glass dielectric. The plasma only ignites at a certain distance between the glass and bead, where the plasma gap is large enough. From optical analysis, this minimal gap needed can be estimated to be about 120 µm. For beads of smaller size, this gap size will be reached for inter-bead distances, which may result in a transition in the plasma characteristics.



ZrO_2 beads with a diameter of 0.9 mm in a H_2-CO_2 plasma viewed through the transparent electrode.

For the different bead sizes, the plasma properties are investigated at different temperatures and applied voltages, corresponding to different plasma powers. Here, significant changes in the characteristics of the plasma can be observed, since both parameters strongly influence the conditions for plasma formation. Finally, the observations made with the inert dielectric beads will be used to provide a possible explanation for the previously observed influence of particle morphology on plasma catalysis processes.

Physicochemical dynamics of atmospheric pressure streamer discharges: Numerical modeling and electric field measurement in DBDs

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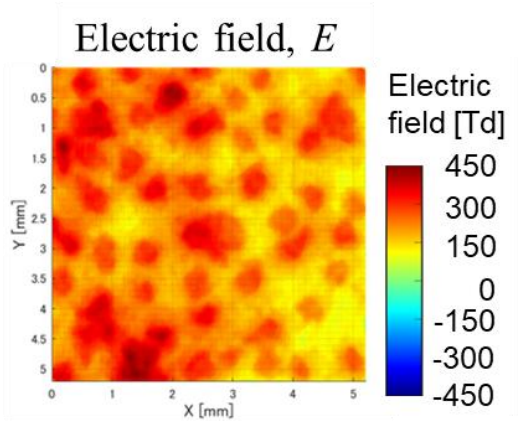
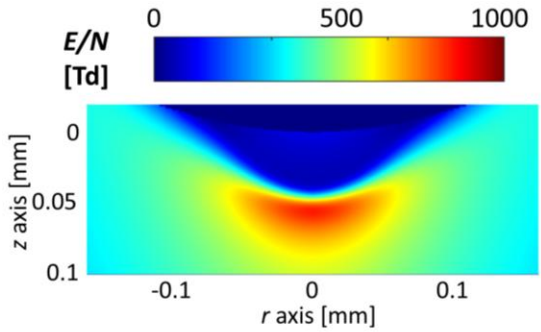
Streamer discharges are used in gas-treatment applications such as exhaust-gas purification, ozone generation, and semiconductor processing. Their behavior is governed by coupled transient phenomena involving electric fields, charged-particle transport, and plasma chemistry, which makes reactor optimization and scaling difficult. A better understanding of atmospheric-pressure streamer dynamics is therefore important for plasma reactor analysis and design. Although numerical simulations and experimental diagnostics of streamer discharges have advanced substantially, direct comparison between them remains limited, especially for quantities closely related to discharge physics. Among these, the electric field is particularly important because it governs electron energy, reaction rates, and plasma-chemical evolution.

This study presents our recent work on atmospheric-pressure streamer discharges using a combined approach based on electric-field measurement and self-consistent numerical modeling. Our earlier work focused mainly on point-to-plane streamer discharges, and more recently this approach has been extended to dielectric barrier discharge (DBD) systems that are more closely related to practical reactors. On the experimental side, we measured the net electric field in a parallel-plate DBD with high spatiotemporal resolution, as shown in Figure 1(a). In parallel, numerical simulations were developed to analyze streamer initiation, propagation, and branching under atmospheric-pressure conditions. Figure 1(b) shows a simulated electric-field distribution during primary streamer propagation in a point-to-plane DBD.

By comparing measured and simulated electric-field distributions, we aim to refine the physical interpretation of atmospheric-pressure streamer discharges and to assess the validity of plasma-chemical reaction models used in numerical analysis. This invited talk presents an overview of our recent work on electric-field diagnostics and numerical modeling for gas-treatment reactor studies.



(a)



(b)

Figure 1 (a) Experimentally obtained gap electric field measurement in parallel-plate dielectric barrier discharges in air [1]. (b) Simulated electric field during primary streamer propagation in point-to-plane dielectric barrier discharges in air [2].

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Defining the influence of electrical pulse parameters on atmospheric pressure plasma jet chemistry

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Cold atmospheric plasma (CAP) has emerged as a powerful tool for biomedical applications, ranging from cancer therapy to wound healing and infection control. Its therapeutic potential comes from the highly reactive mixture of reactive oxygen and nitrogen species (ROS/RNS) generated during its interaction with its environment. However, despite significant progress in plasma medicine, scant attention has been paid to the influence of plasma electrical pulsing characteristics on the production of these reactive species. A detailed understanding of these dependencies is vital for improving treatment precision, safety, and reproducibility.

To better understand the chemistry at the point of application, experiments are conducted using a custom-built cold atmospheric pressure plasma jet operating with humidified argon as the carrier gas driven by two different nanosecond pulsed power supply (2.6 ns FWHM, 1.4 ns rise time and 29.2 ns FWHM, 5.3 ns rise time). To probe the plasma's fundamental properties, four advanced optical diagnostic techniques are employed. Laser-Induced Fluorescence (LIF) provides absolute measurements of NO ground state density, VUV absorption spectroscopy to determine the O3 density, Thomson scattering for free electron density measurement, and improved Amplified Cross-beam Electric-field Induced Second Harmonic (ACE-FISH) technique [1].

The primary objective of this study is to identify specific electrical pulsing regimes and N2/O2 admixture ratios in a humidified Argon plasma jet that optimize the production of either ROS or RNS without compromising the plasma state. Preliminary characterization of Nitric Oxide (NO) was conducted by selectively targeting the NO ($A^2\Sigma^+$, v = 0) to NO ($X^2\Pi$, v = 2) transition [3], emitting fluorescence at approximately 247 nm following picosecond laser excitation at 226 nm. Current spatio-temporal NO-LIF mapping provides a critical baseline for the distribution of reactive species, quantifying the effect of pulse duration (3–30 ns) in its role as a primary lever for precise energy deposition pathways and RONS branching ratios. Furthermore, the integration of Thomson scattering and ACE-FISH measurements will allow for the correlation of local electric field strength and electron energy distribution function to be linked with the dissociation efficiency of molecular precursors. These insights will guide the optimization of operating parameters for targeted biomedical applications.

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The impact of metastable atoms on Penning dissociation of CO_2 in an atmospheric plasma jet

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The dissociation of carbon-dioxide (CO_2) is an important topic in the plasma community and is investigated in a variety of different plasma sources [1, 2]. Stewig et al. [3] found that the conversion of CO_2 into carbon-monoxide (CO) in an atmospheric pressure discharge increases from about 45% in pure helium to up to 85% when the amount of argon in the feed gas is increased (see Figure 1). Naturally the question arises, which process or which particle is causing this increase. The main candidates are the electrons via electron impact dissociation and the metastable atoms via Penning dissociation, since the ionisation energy and the excitation energy of the first metastable state for argon are lower than for helium. However, this question is yet to be answered.

To gain more insight into the process of the CO_2 dissociation via Penning collisions, we measured the helium 2^3S_1 and argon $1s_5$ (Paschen notation) metastable atom densities with and without CO_2 via tunable diode laser absorption spectroscopy (TDLAS). The investigated discharge is the COST-Jet, a micro-scaled atmospheric pressure plasma jet (µ-APPJ), developed as a reference for comparison between different atmospheric plasma sources [4].

Combined with the diagnostics, simultaneous measurements of both helium and argon metastable atom densities with high spatial resolution were performed. These 2D maps of the discharge channel for the respective species (see Figure 2) are giving an in-depth insight for the behaviour of the metastable atoms in presence of CO_2.

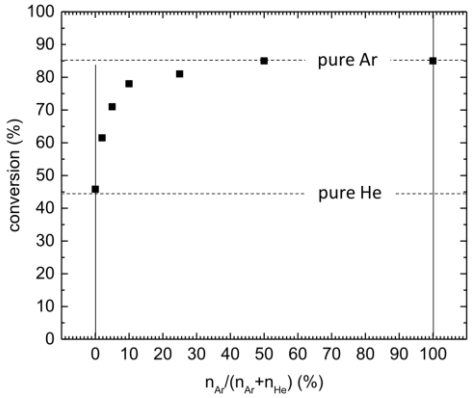

Figure 1 CO_2 conversion versus argon percentage in an atmospheric pressure plasma for an admixture of 0.125% CO_2 from [3].

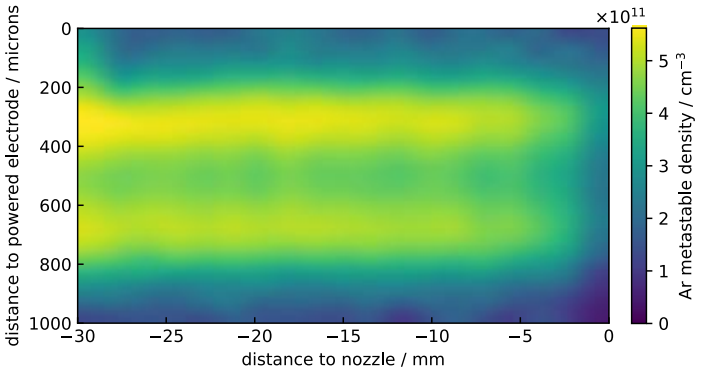

Figure 2 Argon metastable atom density map of the of the discharge channel of the COST-Jet for an argon admixture of 0.1% without CO_2.

Acknowledgement:
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Pulsed nanosecond discharge at heptane-water interface: influence of ambient pressure on bubble dynamics, interfacial instability, and emulsification efficiency

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Electrical discharges in liquid produce localized plasma channels that deposit intense thermal and mechanical energy, triggering cavitation bubbles that undergo a series of expansion-implosion cycles. When produced at ambient pressure at the interface of two immiscible liquids (e.g., water-heptane), this plasma-induced discharge produces an emulsion (droplets of heptane in water) [1, 2]. Emulsion formation is driven by instabilities that develop at the bubble-liquid interface. This study investigates the influence of ambient pressure, in the range of 200 – 1000 mbar, on plasma-initiated bubble dynamics, interfacial instability, and emulsification efficiency. The bubble dynamics and interfacial instability are investigated using a high-speed camera. Regarding the bubble dynamics, lower ambient pressure results in a larger maximum bubble diameter. A homemade algorithm was utilized to quantify instability development as a function of ambient pressure. We found a maximum boundary deformation regime at 400 mbar. This intense deformation is primarily driven by Rayleigh-Taylor instability resulting from violent collapse deceleration.

Interestingly, the conditions fostering maximum macroscopic instability inversely correlate with optimal microscopic mixing. Indeed, at 400 mbar, the system exhibits the poorest emulsification efficiency, generating the largest droplets with a Sauter mean diameter (D_{32}) of $21.7\mu m$. Conversely, optimal emulsification occurs at near-atmospheric conditions (1000 mbar, D_{32}= 11.5 μm). Crucially, the mean coupled electrical energy of the plasma discharge remains statistically constant (~1.5 – 1.7 mJ) across the entire ambient pressure range. This confirms that the initial plasma energy deposition is stable, and the observed non-linear kinematics are driven exclusively by external fluid mechanics and thermodynamics rather than variations in the initial electrical shockwave source. The true driving pressure and bubble kinematics underscore that deep vacuum environments fundamentally alter the energy transfer mechanisms, hindering the fine fragmentation process. This work provides critical insights into plasma-liquid interactions, offering pathways for utilizing nanosecond discharges as controllable tools for optimizing phase mixing in multiphase systems.

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Reproducible plasma columns sustained by EM field with a linearly decreasing axial electron density that depends solely on the gas pressure, field frequency and tube radius

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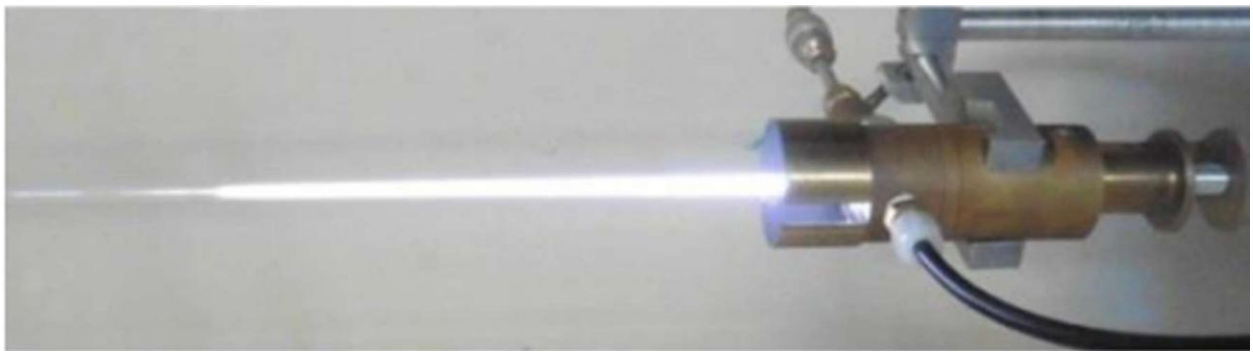
This plasma column, which utilises a patented generation method [1] and has subsequently been modelled [2], offers the widest range of operating parameters available in terms of the frequency f of the electromagnetic field sustaining the discharge (from a few MHz to at least 10 GHz), the carrier gas pressure p (from a few Pa tested up to twice atmospheric pressure) and the internal radius of the dielectric discharge tube R (from 0.5 mm to at least 150 mm), with an electron density spanning more than 18 orders of magnitude. This type of plasma is perfectly reproducible and can always be impedance-matched with RF and microwave power generators. Previously known as surface wave discharges (SWDs), they are now better identified as travelling wave discharges (TWDs).

It emerged as a novel method of plasma production [3]. It consists of a plasma column contained within a cylindrical dielectric discharge tube, which is maintained by the electric field component of radiofrequency (RF) and microwave (MW) waves. These waves propagate at the interface between the tube's outer surface and the ambient air (or vacuum). This plasma has the unique property of increasing in length in proportion to the RF and MW power absorbed. Its electron density decreases linearly along its axis until it abruptly stops at a non-zero value, marking the end of wave propagation. The slope of this distribution depends solely on the operating parameters p, f and R, which are operator-set. This makes it ideal for optimising plasma applications.



These are typical photographs of TWDs obtained using a 915 MHz Surfatron in argon gas at atmospheric pressure within a 6/8 mm id/od fused silica discharge tube. The absorbed power is 300 W, and the aluminium cavity at the launcher outlet prevents stray radiation in the room [4].

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Global Chemistry Modeling of Biogas Conversion in Surface Dielectric Barrier Discharges with Vortex-Induced Mixing

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Atmospheric pressure plasmas provide a promising route for the sustainable conversion of biogas (CO_2/CH_4) into value-added products. In this context, surface dielectric barrier discharges (sDBDs) possess low flow resistance and are particularly interesting for industrial processes. High conversion efficiencies have been reported in various applications and were linked to the induced flow field exhibiting vortex structures driven by electrohydrodynamic forces and gas heating. The induced velocity magnitudes can exceed the controlled external gas flow velocity and enhance conversion [1].

In this work, the process is investigated using a custom global chemistry model to calculate the species densities and electron temperature as a function of time. Electron-impact rate coefficients are obtained from BOLSIG+, a two-term Boltzmann solver, and are parameterized as a function of electron temperature for the considered gas mixtures. The energy input to the model is derived from the applied voltage waveform using a lumped-element approach that captures the strongly time-dependent electrical behavior of the sDBD.

Vortex-induced mixing is incorporated into the model via a power-driven effective increase of the plasma volume. As the volume expands, reactive species are diluted and replenished by entrained background gas, representing the continuous influx of untreated gas into the plasma by the vortices.

This 0D transport driven volume expansion model provides a computationally efficient yet physically grounded description of gas conversion in sDBDs, capturing the interplay between electrical driving, reaction kinetics, and flow-induced mixing that governs the overall conversion efficiency.

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Relative Humidity Role in Discharge Mode Probability for Nanosecond Plasmas with a Confined Water Droplet

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Nanosecond pulsed plasmas interacting with liquid water are significant for environmental remediation, sterilisation, and plasma-activated water production due to their ability to generate reactive oxygen and nitrogen species. Humidity critically influences these processes by affecting ionisation kinetics [1] and plasma–water chemistry [2]. However, its impact on discharge formation in the presence of a confined water droplet remains insufficiently quantified.

In this work, we investigate how ambient air humidity affects the initiation and stability of discharge modes in a pin-to-pin configuration, with and without a droplet in the gap. Understanding this influence is essential for interpreting experimental measurements and establishing reproducible plasma–liquid operating conditions.

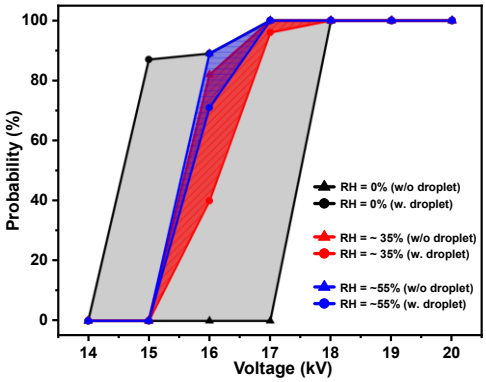

Fig. 1: Probability of spark discharge versus voltage at different relative humidities with and without a water droplet.

Experiments are performed in a small cavity with controlled temperature and humidity, using two horizontally aligned tungsten wire electrodes positioned above a glass substrate with a 7 mm gap between their tips. Nanosecond voltage pulses (400 ns) with peak amplitudes of 14–20 kV are applied at various repetition rates. In selected cases, a 3 µl droplet of deionised water is placed between the electrodes. Electrical diagnostics and ICCD imaging are combined with FTIR measurements of the surrounding environment to characterise the discharge behaviour and local gas composition.

In dry air, the expected enhancement of the electric field due to the presence of triple points [3] created by the droplet, is observed via the promotion of spark formation at lower voltages (<18 kV, see Fig. 1), the latter being facilitated by easier streamer initiation. Higher humidity reverses this trend: water vapor boosts electron attachment to oxygen and reduce the availability of free electrons (generation), thereby suppressing discharge probability.

FTIR analysis shows that the water droplet does not create a significantly enhanced local humidity field. This indicates that the observed change in discharge behaviour is dominated by the global ambient humidity rather than droplet-induced evaporation and by the liquid's properties. These findings demonstrate that humidity is a primary environmental parameter governing plasma formation, even in confined geometries, and must be carefully controlled in plasma–liquid studies. Future work will explore the role of convection and mass transport near the droplet between pulses.

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Pulsed RF Excitation in CO_2-CH_4 Mixtures: Electrical Characteristics of Power Modulation

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The method of power delivery is critical for creating ideal and efficient plasma chemical conditions for a given gas conversion reaction. Our group has been particularly interested in combining nanosecond (ns) pulsed and radiofrequency (RF) excitation sources to realize low to moderate temperature plasma conditions. In recent works, we performed a RF electrical characterization [1], as well as a RF plasma characterisation of our custom-built ns pulse – RF system [2]. We have recently been investigating the CO_2-CH_4 reaction system with the combined ns pulse – RF plasma source. High CH_4 content (mixtures greater than 20%) results in significant carbon formation in the plasma and deposition on reactor surfaces, leading to plasma instability and ultimately discharge extinguishing.

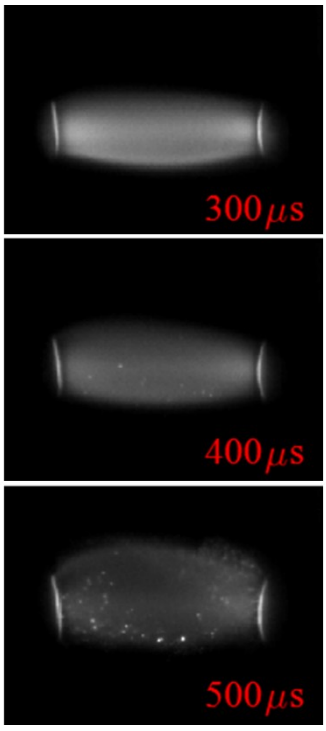

Figure 1: High-speed imaging frames of a RF discharge in CO_2 - CH_4 for 300, 400 and 500 μs RF pulses.

Early experimentation was done in a 40/60 (vol. %) CO_2/CH_4 gas mixture at atmospheric pressure. The 1 kHz pulsed excitation consisted of a ns pulsed burst followed by a RF pulse of 300, 400 or 500 μs. The ns pulsed source is used as an ignition source providing ionization for the RF field to utilize. High-speed imaging was performed to reveal carbon particle interactions in the RF discharge. Figure 1 shows three frames taken from the 300, 400 and 500 μs RF pulses. Carbon particles in the RF discharge are clearly visible for the 500 μs RF pulse as well as faintly visible for the 400 μs RF pulse. Not only does the level of carbon formation depend on the RF pulse length, but the level of carbon particulate observed is variable over the duration of the pulse. It was also observed that the quality of the RF signal changes depending on the amount of carbon deposition observed. Time and frequency domain measurements obtained temporally over the RF pulse show characteristics that correlate well with the levels of carbon observed during high-sped imaging.

Managing and mitigating the level of carbon formation and deposition during processing of high CH_4 content plasma is critical to ensuring stable operation over long periods of time. Modulation of the RF power during the RF pulse may allow for processing optimization while minimizing carbon formation and deposition. A feedback controller can be implemented by performing live electrical measurements of the RF discharge and modulating the applied RF power in an attempt to reduce the level carbon formation.

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Streamer diagnostics using a flexible fast pulse source

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Streamer discharges are present in nature as early stages of lightning. In the high-voltage industry, understanding streamer discharges is critical for spark protection and the design of high-voltage switchgear. For several decades, sulphur hexafluoride (SF6) has been used in high-voltage gas-insulated switchgear for the prevention and quenching of arcs. However, SF6 is also the most potent greenhouse gas, 23,600 times stronger than CO2 and therefore its usage should be reduced. Part of this research is about a candidate to replace SF_6: Perfluoro-iso-butyronitrile, C_4F_7N, or C4-FN for short. C4-FN has a lower global warming potential than SF6 and, mixed with CO2 it has comparable dielectric capabilities, reducing the global warming potential of the gas by more than 98% [1].

In this work, we study fundamental aspects of streamer discharges in various gases including air and CO2-C4-FN mixtures for both polarities using two techniques: first, by varying the voltage rise rate and second, by using double-pulse experiments. Both are made possible by the development and installation of an Impedance-matched Marx Generator (IMG) [2]. The IMG consists of a stack of solid-state voltage switches that can be triggered independently. By triggering each stage later than the previous one, the effective rise time of the voltage pulse – which is normally 8 ns – can be arbitrarily increased, as shown in figure 1. In streamer discharges in air, the rise time of the pulse greatly influences the streamer inception cloud, as well as the formation of the streamer branches, see figure 2.

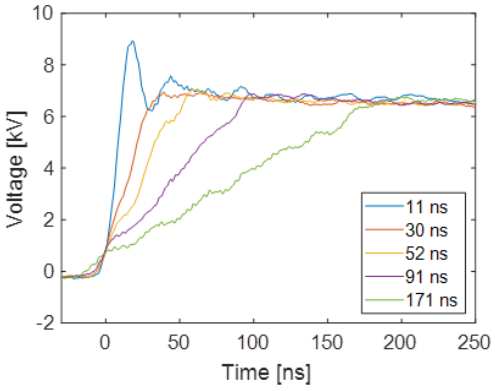

Fig. 1: Rising edge of the voltage pulse for varying rise times.

The IMG is also capable of making two pulses in quick succession, with delays between pulses as low as 30 ns. Using ICCD imaging, the behaviour of the second pulse is recorded as a function of the delay between the two pulses. In the past, this has proven to be an effective way to probe the memory effects of the gas [3]. In this way, we are able to get qualitative information on attachment and recombination rates of a gas mixture.

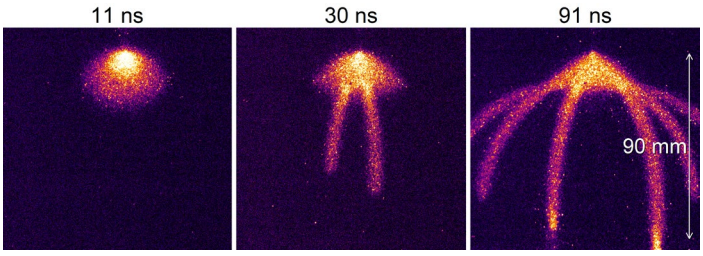

Fig. 2: Streamer images in 50 mbar air for varying pulse rise times

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Plasma Endpoint Detection for Wound Healing

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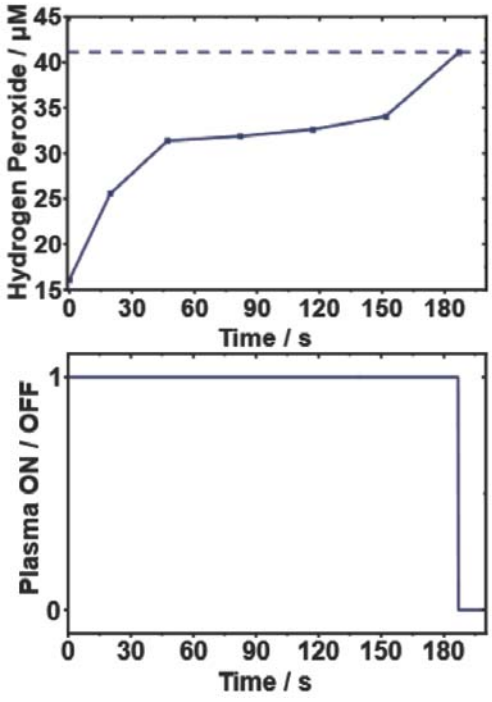
Cold atmospheric pressure plasma (CAP) is a promising treatment for chronic and hard to heal skin wounds and has been successfully used in human wound care. However, CAP dosing remains empirical because there are no immediate visible changes during the brief treatment time and biological outcomes are recapitulated hours to days later. While redox-relevant reactive oxygen and nitrogen species (RONS), the proposed effectors of CAP, can be measured with bulky and expensive equipment in the lab, it is impractical for a clinical setting. Two readily detectable RONS, H_2O_2 and NO, are physiologically relevant species. H_2O_2 serves as a key signaling molecule in regulated cascades that activate various metabolic processes involved in wound healing [3]. NO has antimicrobial properties and is an endogenous messen- ger that promotes angiogenesis, cell migration, and tissue remodeling [4]. ORP (oxidation-reduction potential) measures the overall redox state and the balance between oxidants and reductants. Besides measurements of CAP analytes, real-time monitoring of cellular effects could also serve as an important parameter for device control. Changes in calcium homeostasis are among the earliest changes in cells in response to environmental stressors. Ca^{2+} is a cen- tral regulator of proliferation, migration, and differentiation, as well as angiogenesis [5]. We report on the use of electro-chemical wire sensors to measure *in situ* H_2O_2 [1], ORP [1], NO [2], and Ca^{2+} [2] in real time in a wound bed. Coupled with a microcontroller, the sensor measurements can be used to control the CAP device, in order to terminate treatment once a threshold value is reached, e.g., when a desired concentration is reached with exceeding safe levels of H_2O_2. The controller was challenged and validated during CAP treatment of dorsal wounds on mice with three CAP devices: a 10 mm diameter volume DBD, a 5 mm diameter volume DBD, and a surface DBD.



In situ H_2O_2 measurement (top) and PWM signal (bottom) indicating plasma ON/OFF state. The controller terminates treatment once the setpoint is reached..

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The influence of cold plasma on dental prosthetic materials

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Denture stomatitis remains a common complication among patients using removable prosthetic restorations, largely associated with fungal colonization by species such as *Candida albicans* and *Candida glabrata*. This study aimed to evaluate the potential of cold atmospheric plasma (CAP) as a non-invasive and non-destructive method to limit fungal growth on commonly used dental materials, including acrylic, acetal, and prosthetic metal alloys. The investigation focused on how varying plasma exposure times (5, 10, and 20 minutes) influence the physicochemical and biological properties of these materials.

Comprehensive material characterization was performed using FT-IR spectroscopy, SEM-EDS analysis, and optical profilometry to assess chemical composition, morphology, and surface topography. Surface wettability and optical properties were evaluated using contact angle measurements and spectrophotometry. The susceptibility of both untreated and CAP-treated materials to fungal adhesion was also analyzed to determine their resistance to microbial colonization. The results demonstrated that CAP treatment is chemically safe for all tested materials, as no significant alterations in elemental composition were observed. However, material-dependent responses were evident. Acetal and metal alloy surfaces remained largely stable in terms of morphology, roughness, and color following plasma exposure. In contrast, acrylic resin exhibited notable changes, including increased surface roughness and altered optical properties, which may negatively affect its mechanical integrity and aesthetic performance in clinical applications. From a microbiological perspective, CAP proved highly effective in reducing fungal contamination. A single 10-minute helium-based CAP cycle reduced *Candida* populations by at least one logarithmic unit across all materials, with reductions reaching up to 98% for both *C. albicans* and *C. glabrata*. Statistical analysis confirmed significant effects of both material type and exposure time, with strong effect sizes observed, particularly for *C. glabrata*. Importantly, CAP treatment also reduced the water contact angle of the tested surfaces, enhancing wettability and potentially limiting fungal adhesion. These effects are attributed to plasma-induced surface activation, including the introduction of polar functional groups and micro- to nanoscale morphological modifications.

In conclusion, CAP represents a promising adjunct for improving prosthetic hygiene and reducing fungal colonization without compromising most material properties. However, its application should be carefully tailored, as acrylic materials may be adversely affected.

Acknowledgement:
We are grateful for the fruitful discussions in the following cooperative initiatives: NAWA Strategic Partnerships Programme agreement no BPI/PST/2024/1/00082/U/00001, COST CA20114 (Therapeutical applications of Cold Plasmas); CA23104 (Mainstreaming water reuse into the circular economy paradigm), and CEEPUS CIII-AT-0063.

Synthesis of early life's buildings blocks using NTP in microfluidic structures

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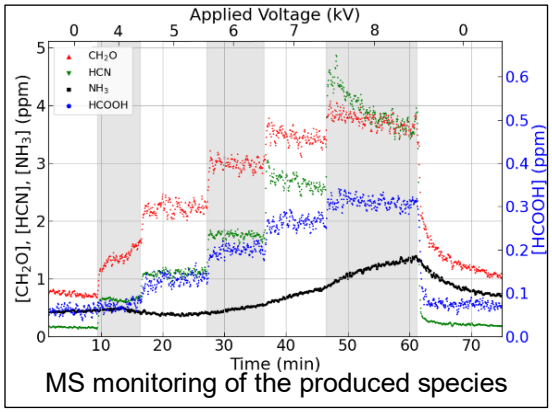
The origin of life was identified as one of the 125 most important scientific question by the journal *Science* in 2005 [1] and remains a complex topic due to its complexity and its interdisciplinary nature mixing chemistry, biology, physics, astronomy and Earth science. However, plasma discharges have proven to be valuable tools since it provides the necessary energy to synthetize the reactants for biological molecules. Indeed, plasmas were present in the early Earth environment (lightning) and are believed to be responsible for initiating essential prebiotic chemistry [2]. Since the pioneering experiments employing electrical discharges to simulate prebiotic conditions [3], several amino acids, nucleobases and sugars have been synthesized using plasmas [4].

Using a DC-pulsed micro-dielectric barrier discharge, we ignite a NTP inside a capillary with an inner diameter of 800 µm [5]. The plasma is ignited with different voltages applied to the µDBD, varying from 4 to 8 kV. The gas mix flowing through the capillary mimic the presumed prebiotic atmosphere ($CH_4/N_2/H_2$, 40%/40%/20%) diluted in He. Water vapor is then added to the gas mix. To monitor the chemistry involved, a real-time high sensitivity mass spectrometer (MS) CI-FTICR is set up at the exit of the tube [5].



MS monitoring of the produced species

First results provide promising insight into the potential of this plasma discharge for the synthesis of the reactants relevant to the origin of life. HCN and NH_3 are produced in the presence of the plasma (Figure). These two key precursors are involved in the Strecker synthesis of amino acids [6], in which CH_2O acts as the carbonyl compound leading to glycine formation. The formation of HCOOH in this gas mix is also relevant to amino acid production as the presence of carboxylic acids proves that oxidation, necessary to our application, is possible even in the strongly reducing prebiotic conditions recreated here. Figure also shows the concentration of NH_3 constantly increasing during the experiment whereas the concentration of the other detected products is directly correlated with the applied voltage. This behavior is likely due to the strong adsorption of NH_3, which makes its detection more difficult as only a fraction of it reaches the MS.

These first results are promising for the use of our micro discharge for the wanted application. The experimental set up will be presented with the latest additions to create a fluidic loop with a liquid phase, playing the role of Darwin's pond to better modelized the early Earth conditions. Heavier species will later be analyzed by LC-MS of the condensed water, allowing an exhaustive overview of the species produced during the experiment as non-volatile products cannot be detected by the MS.

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Numerical Modeling of Physiochemical Reactions Induced by Plasma Stimulation

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The effects of low-temperature plasma on cells and biomolecules have been extensively studied to date. Plasma is used in medical applications such as wound treatment, sterilization, and cancer therapy. In particular, its efficacy in cancer therapy has attracted particular attention. Many studies suggest that reactive species generated by plasma influence the “survival/death” fate of cancer cells [1,2]. Furthermore, it is known that plasma induces selective cell death in cancer cells while minimizing damage to normal cells [3,4]. However, the detailed mechanisms underlying these phenomena remain unclear. One reason for this is that almost all existing studies are experimental, with very few mathematical studies having been conducted. Therefore, quantitative elucidation using mathematical models is required. The authors previously developed a zero-dimensional intracellular signaling model to quantify the effects of plasma-induced reactive species on mitochondrial redox-mediated function and energy metabolism [5]. In this study, we constructed a numerical model of cell death induction by reactive species generated by plasma and performed simulations focusing on the selectivity and mode of cell death. Figure 1 shows a schematic diagram of the network of intracellular biochemical reaction pathways implemented in this model. This system includes death receptors, mitochondrial signaling cascades, initiator/executor caspases and their regulators, antioxidant enzymes, and nDNA. The effects of plasma irradiation are modeled as exogenous stress induced by reactive oxygen species (H_2O_2, OH, O_2^-, etc.) and reactive nitrogen species (NO, NO_2, $ONOO^-$, etc.). A quantitative analysis was conducted to examine the potential synergistic effects among multiple reactive species on cell death.

This work was partially supported by JSPS KAKENHI Grant Numbers 20KK0089, 23K26099, 24H00036, 24H02246 and 24H02249.

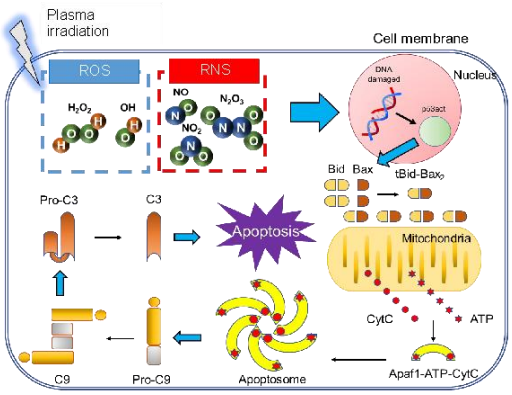

Fig. 1 Schematic diagram of the physiochemical reaction system for apoptosis induction.

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Combining microfluidics with cold physical plasma as a new theragnostic platform for personalized cancer redox therapy

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Non-equilibrium plasmas generate highly reactive oxygen and nitrogen species (RONS) at low temperatures, allowing safe biological tissue treatment. The effectiveness of plasma treatments results from the locally and temporally confined modification of the cellular redox environment modulated by RONS [1]. Many cell signaling pathways involved in pathologies, including cancer, are regulated by changes in redox chemistry [2]. Plasma redox therapy can selectively kill cancer cells and reduce tumor growth [3]. The concentration and the type of reactive species delivered to a tissue greatly influences its response. Precise tailoring of plasma-produced reactive species, as well as elucidating processes at the plasma-liquid interface are still unmet challenges but are essential to modulate tissue response.

To address this research gap, a plasma-microfluidic device is proposed that allows for precise studies of the effect of plasma-generated species on cancer models. Microfluidics offers many advantages for clinical oncology and precise control over plasma treatment conditions via control of flow rates and reaction conditions [4]. This novel laboratory-based platform uses defined flow chemistry that can be modeled and diagnosed to link plasma, liquid, and cancer biology. The plasma source geometry used for our studies is based on the COST-Jet [5], which serves as a benchmark for research and inter-lab comparability. This well-characterized device allows us to link biological responses to plasma reactivity. Plasma treated liquid is diagnosed using optical and colorimetric techniques, enabling the integration of experimental and modeling data: Hydrogen peroxide and hydroxyl radical concentrations are measured as a function of plasma power. A dual-phase flow of plasma effluent bubbles and liquid is used to increase the concentration of species being transferred into the liquid and the mixing of the liquid This dual-phase flow and its compatibility with biological models is assessed and shows no impact on cell viability. Preliminary results (Fig. 1) show a dose response of MB-231 spheroids (cultured, treated and analyzed entirely within the chip) to plasma treated media. The poster will present our platform, its characterization, first experiments integrating cell models, and how it aims to unravel fundamental processes in plasma-liquid-cell interactions. This work was supported by Québec-Flanders Bilateral Research Cooperation Program.

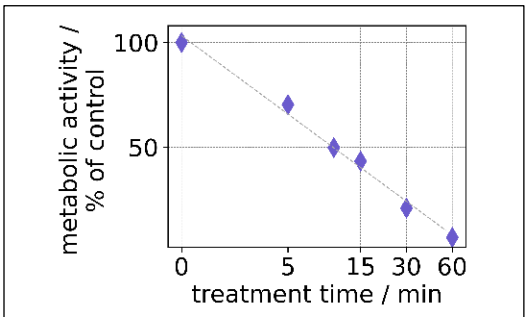

Figure 1: MB-231 cell response to plasma treated media (n=1)

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Non-thermal Plasma Inactivation of Airborne DNA Virus at Different AC Frequencies

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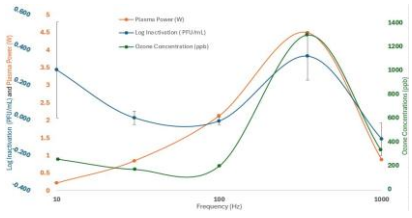
Airborne infectious diseases pose an environmental and public health concern. Since the worldwide COVID pandemic, there have been outbreaks of zoonotic (avian) influenza among birds, cows, and humans as well as measles, continuing the focus on development of newer technologies for preventing the spread of infectious viruses. Particulate filters and UV germicidal irradiation suffer from significant airflow restriction and long treatment times [1]. There have been studies regarding inactivating viruses on surfaces and in liquids, which are not to be confused for inactivating airborne viruses in flowing airstreams [2]. Nonthermal plasma (NTP) is a promising technology for a variety of applications. This research focuses on the use of nonthermal plasma to inactivate airborne viruses in a flowing airstream. Previous research used a RNA virus (MS2) as a surrogate for human viruses [3]. The current research focuses on ΦX174, a surrogate virus with DNA as its genetic material. Hong et al. conducted what is, to our knowledge, the first NTP inactivation of an airborne DNA virus in a flowing airstream [4].



PhiX174 inactivation, plasma power, and ozone readings for frequency sweep for 10, 30, 100, 350, 1000 Hz.

The inactivation efficiency of viruses has been very dependent on the frequency of the plasma power. It has been found that for the plasma setup, MS2 is optimally inactivated at an AC power frequency of 300 Hz, partly due to a large load capacitance in the plasma reactor and a low current threshold of the plasma power source used in this study. A series of inactivation trials for ΦX174 have been performed and the results are shown in the figure. These few trials have shown a similar peak inactivation of ΦX174 at 350 Hz, with another inactivation peak occurring at 10 Hz. But further study is needed to get a better understanding of the effect of frequency on inactivation of ΦX174. With an upcoming high-voltage power source addressing the capacitance issue, which enables operation at higher current (thus higher frequencies), the study could be extended to a wider range of AC frequencies and provide a more comprehensive picture of its effects on NTP inactivation efficiency, so more trials will be done.

In the packed-bed plasma reactor setup under study, there are some aerosol losses due to filtration through the packed bed and electrostatic precipitation. In our trials with the plasma off, the only losses through the reactor should be due to filtration. Our inactivation is calculated by the plasma-off subtracted from the plasma-on log concentration. Therefore, our reported log inactivation accounts for filtration. However, as the applied plasma power changes with frequency, the impacts on aerosol loss due to electrostatic precipitation have not been measured previously. The present study uses two condensation particle counters to count the number of particles at the NTP inlet and outlet. The change in particle counts between the NTP inlet and outlet with frequency will shed light on changing aerosol losses due to electrostatic precipitation. After each trial, microbiological assays are performed to assess inactivation efficiency.

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Effects of Non-thermal Plasma Treatment on Seed Germination Physiology in Native Plant species of Eastern Quebec

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Today, the impact of non-thermal plasma (NTP) on germination is not yet fully understood, as it is a relatively new area of study. Available data suggest that NTP can have a range of positive effects on germination, with these effects varying based on factors such as plasma type, exposure time, and plant species [1]. To date, NTP has primarily been used in agriculture to boost dry mass and speed up the germination of agricultural seeds. In this context, NTP is primarily known for altering the physical properties of the seed coat, making it more hydrophilic and significantly reducing the water contact angle [3]. This leads to faster water uptake, longer radicle growth, and better odds of successful root establishment, as demonstrated in Figure 1.

This research will focus on examining the impact of NTP utilizing surface analysis as a measure of treatment success. Scanning electron microscopy and micro-CT imaging techniques have been used for the inspection of both external and internal changes caused by treatment, while maintaining the seed's integrity. The tests have been done before and during germination. Because only a few studies have examined the effects of NTP on native plants (non-commercial) this work will focus on the impact of NTP on indigenous seeds. This has the potential to promote ecologically responsible reforestation of human-disturbed environments. Four native species from eastern Quebec were selected: *Alnus incana*, *Betula papyrifera*, *Chamaerion angustifolium*, and *Larix laricina*. These particular species play a pivotal role in ecological succession, as they are crucial for creating the necessary soil conditions for plants that follow. Results obtained are linked to the germination rate to better understand how it will possible to change the behavior of the seeds.

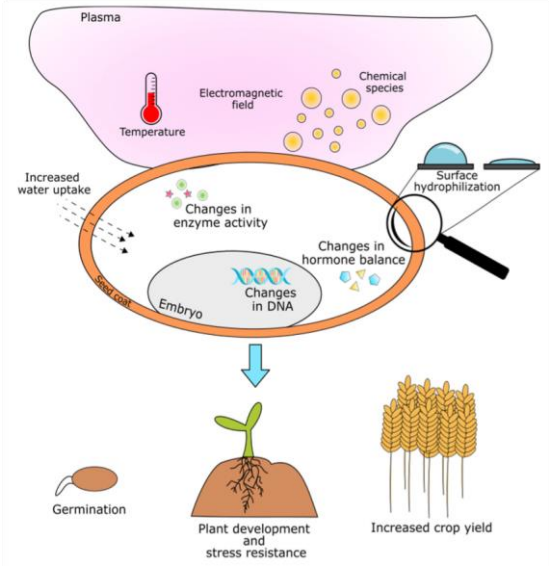

Figure 1: A schematic representation of non-thermal plasma effects on seeds [2]

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Applications of Plasma in Agriculture: Results of Polish-Japanese Cooperation

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More than 20 years past from the first joint publication of the teams from Japan and Poland on the non-thermal plasma-based technology for soil treatment [1]. Since then, research in this area has continued under cooperation agreements between the Japanese laboratory and universities listed in the affiliation, as well as the Lublin University of Technology. Research has also been conducted as part of national and international research projects [2]. Soil quality has a significant impact on the welfare and prosperity of countries.

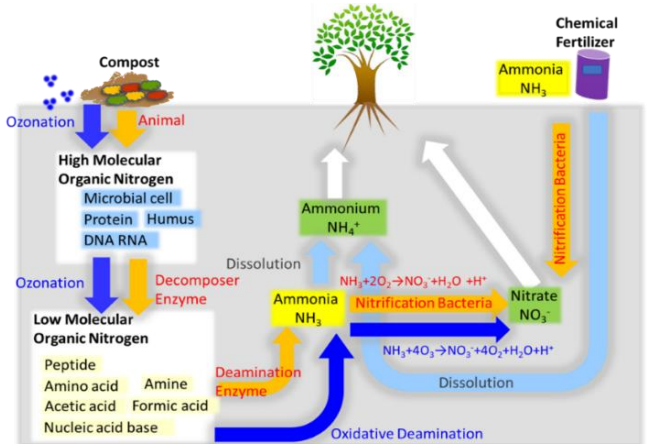

Figure 1 Ozone soil disinfection to enhance plant growth

Agriculture and soil protection involve issues related to the excessive use of chemicals, which degrade the soil and increase the content of pesticides in the soil, groundwater and food.
Chemical agriculture also affects the quality of cultivated seeds and their ability to germinate. It is also important to prevent microbiological contamination of soil and agricultural products during their processing, transport and storage [3]. Paper presents the results of collaborative research covering, amongst other things, the use of non-thermal plasma for soil treatment.

In particular it is related to: the direct application of ozone in agricultural crops, soil microorganisms and pathogens, a comparison of various soil disinfection methods, and advanced soil management techniques, sterilisation of agricultural product packaging, pest control and plant growth with deep learning technology [4].

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Control and diagnostic-based tailoring of plasma reactivity in health, environment, and agriculture

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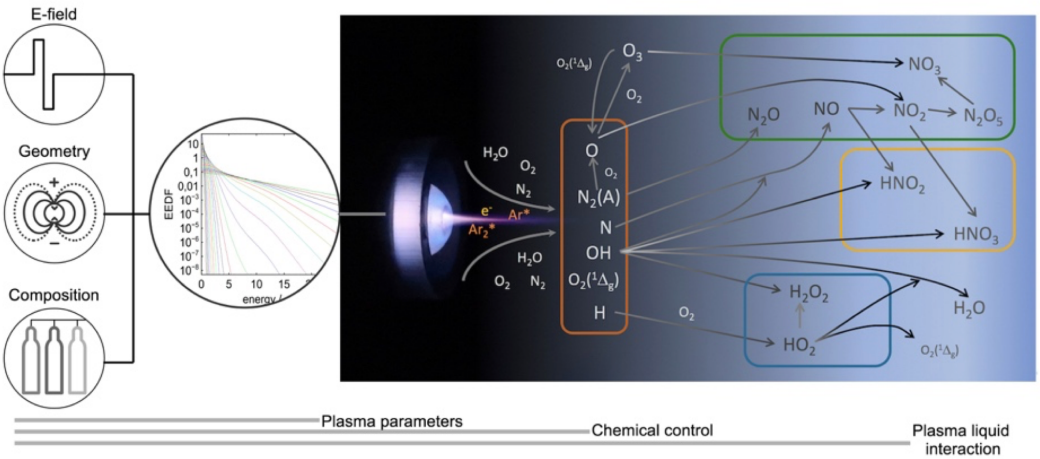
Cold plasmas play an increasingly important role in applications in health, environment, and agriculture. Especially plasmas interacting with liquids are studied in research labs worldwide [1, 2]. The benefits of plasma liquid systems are on-demand use as well as the potential to tailor the plasma chemical pathways to the desired application, for which a fine control over the plasma generated reactive species composition will need to be mastered.

The presentation explores how designing electric excitation, reactor geometry, and gas composition tailors the plasma reactivity and for the case of plasma liquid interaction, the chemical composition of liquids. The plasma's reactive species generation is characterized regarding the electric field, the atomic and molecular ground state and excited state species, as well as the flow field employing advanced diagnostics of ultrafast and ns laser-based spectroscopy as well as absorption spectroscopy and flow field imaging techniques.

Results demonstrate how tailored plasma chemistry effectuates the selectivity of plasma cancer treatment and wound healing [3] and increases energy efficiency in environmental applications for CO_2 dissociation [4], providing educts for added-value chemicals. In agricultural applications such as plasma assisted hydroponic systems, tailored plasma chemistry provides plants with nitrogen nutrients and at the same time kills plant pathogens [5].



Plasma operational parameters control chemical pathways and reactive species composition in plasma liquid interaction

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Characterization of H_2O_2 Production in an Undiluted O_2-H_2O DBD Reactor

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Hydrogen peroxide (H_2O_2) is an important and versatile oxidant having a high oxidation potential and that only produces water as by-product of oxidation reactions [1]. H_2O_2 has a global annual demand of over 4 million tons due to its utility in various applications: acting as a strong oxidizer, disinfectant, propellant in rocket, etc. [2]. Currently, over 95% of H_2O_2 is produced via the anthraquinone oxidation (AO) process which requires the hydrogenation of an alkylanthraquinone based working solution with a palladium catalyst followed by filtration, oxidation, and extraction of the produced H_2O_2. This process requires an energy input of ~17.6 kWh per kg H_2O_2, generates ~3 tons of CO_2 emissions per ton of H_2O_2, and causes degradation of the catalyst [3-4].

In an effort to contribute to lowering CO_2 emissions, alternative H_2O_2 production techniques are under investigation. Plasma-liquid interactions pose an interesting path for the production of H_2O_2. However, this method still requires improvement in understanding and optimizing the process. In this study, O_2 gas mixed with H_2O flows through a DBD reactor continuously producing H_2O_2. The effects of various interdependent parameters are studied with the goal of decoupling these interlinked effects and providing a path to an optimized process. Optical emissions spectroscopy (OES) is carried out for the characterization of the undiluted O_2 and O_2-H_2O plasma. Rotational and electron temperature are determined by Boltzmann plot of OH(A-X) band and from atomic hydrogen lines, respectively. Furthermore, electron density is characterized by the Stark broadening of the H_β line. The energy input is determined by electrical measurements. Finally, a colorimetric measurement method is used to measure the concentration of the produced H_2O_2 solution and determination of production rate and energy yield.

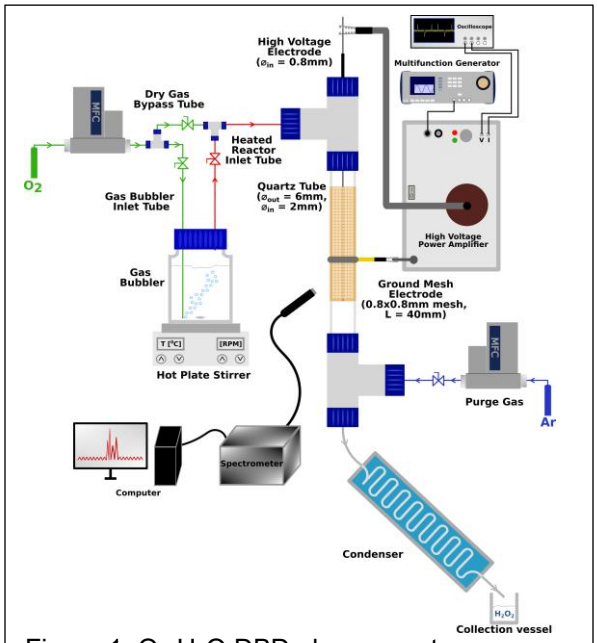

Figure 1: O_2-H_2O DBD plasma system

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Electrical control of plasma chemistry: Tuning reactive species production in atmospheric DBDs

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Atmospheric-pressure dielectric barrier discharges (DBDs) are widely used to produce reactive oxygen and nitrogen species (RONS) for applications such as plasma medicine and sterilization [1], plasma catalysis [2] or environmental remediation [3]. Despite extensive studies, establishing predictive relationships between electrical excitation and plasma-driven chemistry remains an open challenge, particularly under atmospheric conditions where discharge behaviour is highly sensitive to operating parameters and may exhibit distinct operating regimes [4,5].

In this work, we present a tunable high-voltage excitation system incorporating burst-mode operation, enabling independent control of frequency (1-50 kHz) and duty cycle for systematic investigation of DBD behaviour. Using a model reactor, we combine time-resolved electrical diagnostics, optical emission spectroscopy, and gas-phase Fourier-transform infrared spectroscopy to explore correlations between electrical excitation, discharge characteristics, and reactive species formation.

Particular attention is given identifying transitions in discharge behaviour through non-linear electrical responses and associated changes in optical emission spectra. These observations are complemented by gas-phase analysis targeting key long-lived RONS species, in order to elucidate the influence of excitation parameters on dominant chemical pathways.

This work establishes a direct link between power delivery, plasma behaviour, and reactive species formation under burst-mode excitation. The results highlight the role of electrical control in accessing distinct discharge conditions and tuning gas-phase chemistry, providing a basis for scalable plasma-based processes.

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Formation of Higher-Order Products from Liquid Organic Feedstocks in a Micro-second-Pulsed Gas-over-Liquid Dielectric Barrier Discharge

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Conventional methods for upgrading simple organic molecules into higher-value products are often energy-intensive and rely on catalysts prone to deactivation. This work presents experimental investigations using a microsecond-pulsed dielectric barrier discharge (DBD) in a pin-to-plate configuration to induce chemical transformations at ambient pressure and near-room temperature. Molecular growth is attributed at the interface through electron solvation and ion transport, a physical mechanism consistent with established roadmaps for plasma-liquid interactions [1]. This platform enables the catalyst-free processing of feedstocks including n-alkanes (hexane, octane, decane), alcohols (methanol, ethanol), and amines (butylamine).

Results demonstrate a capacity for chain extension and functionalization without added solvents. Processing of liquid hydrocarbons synthesized linear and branched compounds reaching up to C_{20} when using n-decane as a reactant, with primary product families identified as C_{n+1}, C_{n+2}, C_{n+3}, and C_{2n} dimers. Furthermore, the integration of alcohols with these hydrocarbon feedstocks resulted in a synergistic effect, increasing total conversion efficiencies and promoting the production of hydrogen-rich gas mixtures. Extending this process to butylamine enabled the direct synthesis of complex nitrogen-containing organic compounds (NOCs) such as aliphatic and aromatic amines, nitriles, and heterocyclic azoles, achieving a total NOC production efficiency of 49.4 g/kWh under optimized conditions.

These transformations are consistent with dissociation and dehydrogenation pathways initiated by energetic electron impact [2], within a kinetic framework supported by studies of non-equilibrium plasma-assisted oxidation. Ultimately, these results validate the potential of microsecond-pulsed plasma for converting electrical energy into stable chemical bonds [3], offering a scalable solution for the direct molecular upgrading of simple organic feedstocks under ambient conditions.

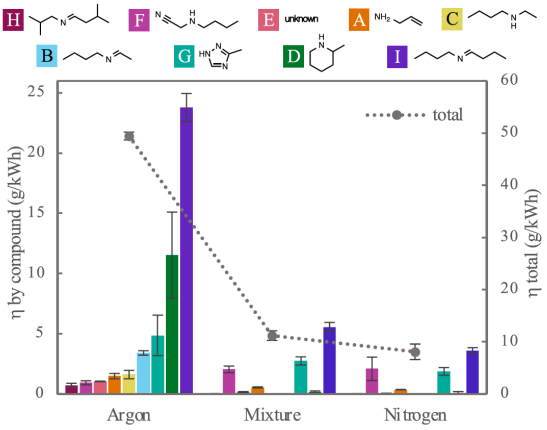

Fig. 1. Total production efficiency and production efficiency for nitrogen-containing compounds (g/kWh) with varying argon/nitrogen gas ratios.

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Plasma-liquid interactions for hydroponics farms: a multi-phase diagnostic framework for reactor scale-up

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The PLANET (Plasma-Electrification of Chemical Produce - net-zero carbon emission technology for sustainable greenhouses) project brings together over ten research groups alongside the largest greenhouse producers in Quebec and Ontario, with the goal of replacing energy- and carbon-intensive conventional chemical pathways in hydroponic agriculture with compact, plasma-based alternatives. In this context, cold atmospheric plasma sources interacting with liquids represent a promising route for the *in-situ* generation of reactive oxygen and nitrogen species (RONS), enabling electrically driven fertilization and disinfection of irrigation water under ambient conditions, without the need for external chemical inputs [1].

Building on previous proof-of-concept studies [2], this work aims to establish a reference diagnostic framework for plasma-liquid reactors, defined as a reproducible, multi-phase analytical baseline enabling systematic comparison of reactor designs and guiding scale-up strategies. The framework combines time-resolved electrical characterization of the discharge, providing real-time power deposition measurements and enabling the determination of overall energy yields. In the gas phase, optical emission spectroscopy (OES) is used to identify excited species, including OH, NO, N_2, and O, while Fourier-transform infrared spectroscopy (FTIR) enables the quantification of stable molecular species such as NO, NO_2, N_2O, O_3, HNO_2 and HNO_3. In the liquid phase, colorimetric assays (Griess reagent for NO_2^-/NO_3^-, and titanium oxysulfate for H_2O_2) quantify the long-lived RONS accumulated in the treated water as a function of operating conditions. In addition, the evolution of pH is monitored to characterize the formation of acidified nitrogen species such as HNO_2 and HNO_3.

By correlating gas-phase species fluxes with aqueous RONS accumulation, this framework provides indirect insight into the process occurring at the plasma-liquid interface and identify the key parameters governing nitrogen fixation efficiency and energy cost. This multi-phase diagnostic framework is designed with scale-up in mind, providing transferable process monitoring tools that bridge lab-scale plasma physics and industrial reactor deployment.

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New perspectives of dielectric barrier discharges for the deposition of thin films

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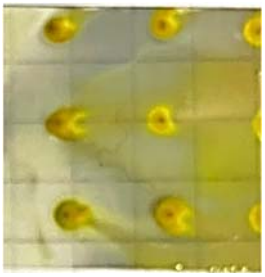
Dielectric barrier discharges (DBDs) allow generating atmospheric plasma at or near room temperature. For decades the main industrial application was for ozone generation thanks to the Siemens process [1]. Applications for surface modifications came later, first for surface activation. Deposition of coatings remained confidential, due to the poor control of the quality of the films. Indeed, the very small mean free path at atmospheric pressure leads to species with very low energies, and random processes due to moving filaments often occur. Taking advantage of the room temperature of DBDs, fragile surfaces such as polymers could be modified. Additionally, DBDs operating at atmospheric pressure do not require vacuum systems, and such processes could therefore present some economic advantages, as well as some positive input in the development of responsible sustainable surface engineering [2].

Thanks to decades of research, dielectric barrier discharges can now be used to deposit more and more sophisticated coatings. The talk will present, through selected examples, some current developments of DBDs for the deposition of organic and inorganic coatings.

We will show that by tuning the precursor chemistry and by controlling the plasma phase, one can design organic coatings with dedicated chemistries [3]. For years, achieving crystalline inorganic coatings using cold atmospheric plasma was challenging. We will show that, nowadays, one can deposit crystalline oxides [4], and that one can tune the average size of crystals [5]. Patterned coatings are usually achieved using mask techniques or laser addition. DBDs can nowadays be used to synthesize in a single step, without mask, chemically patterned organic and inorganic coatings [6,7]

Finally, the talk will explore the current limits of atmospheric DBDs for the deposition of thin films, including limits due to the low mean free path in the gas phase, the low energy of incoming particles, the limits of the Yasuda parameter approach, positive and negative streamer interferences in the polymerization and ablation process, effect of the nature of the inert plasma gas used.

Immobilized filaments in a DBD used to deposit chemically patterned inorganic and organic coatings.



Localized crystalline V_2O_5 coatings

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Accelerating the development of thin film deposition using an atmospheric pressure plasma torch through advanced optical diagnostics and digital twins

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The development of multifunctional thin films deposited by plasma-enhanced chemical vapor deposition (PECVD) at atmospheric pressure is a rapidly growing field, driven by applications in energy and environmental technologies. Among deposition devices, plasma torches represent an emerging solution offering high deposition rates and compatibility with industrial production lines [1]. However, the strong coupling between plasma physics, gas-phase chemistry, and surface processes remains poorly understood, particularly regarding plasma–substrate interactions during precursor injection, which limits process optimization and modeling.

This work aims to accelerate the understanding and development of atmospheric plasma-assisted thin film deposition through the construction of a digital twin (DT) framework [2]. To support this approach, comprehensive experimental datasets are required, motivating a detailed characterization of the plasma plume and its interaction with the substrate during the deposition of organosilicon thin films from hexamethyldisiloxane (HMDSO). Optical diagnostics combining conventional imaging and innovative hyperspectral imaging are employed to provide spatially resolved information on emission intensity and species distribution within the plume and near the substrate. The correlation of these optical measurements with deposition profiles and physicochemical film properties enables a deeper understanding of the process and provides structured datasets for modeling.

Because manual data collection remains a time-consuming and limiting step, a generative flow network (GFlowNet) [3] is employed to guide the design of experiments and efficiently explore the high-dimensional parameter space. This novel approach enables targeted and accelerated data acquisition, generating structured datasets that are subsequently used to train neural network models capable of predicting film properties, such as thickness and FTIR signatures. We compare these purely data-driven approaches with an innovative hybrid, physics-inspired model combining empirical knowledge of plasma processes with machine learning, improving interpretability while maintaining predictive capability. Overall, this combined experimental and modeling approach establishes new structure–process–property relationships and contributes to the development of predictive tools for the optimization and control of atmospheric plasma deposition processes.

Acknowledgements: This work was supported by an Exploratory Project program of the Institut Courtois, Université de Montréal.

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Plasma-surface effects in dielectric barrier discharges: investigating diffuse, filamentary and hybrid discharge modes for material processing

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Dielectric barrier discharges (DBD) at atmospheric pressure can operate in different discharge regimes. Commonly, two types of discharges are observed in DBDs: diffuse and filamentary [1]. The former regime produces more uniform plasmas, whereas the latter provides filaments that are stochastically distributed in both space and time. Although a diffuse discharge in N_2 is readily obtained in a planar DBD, it is easily disturbed by changing the gaseous environment or the operating parameters [2]. In some operating conditions of the DBD, a third intermediate (or hybrid) mode can appear, exhibiting properties of both the diffuse and the filamentary discharge. In the case of material processing (surface treatment, thin film deposition), coupling gas/liquid precursors with DBDs is effective but leads to issues in discharge control, i.e. oscillating between diffuse and filamentary regimes. The various operating parameters such as precursor injection mode, substrate type, and applied voltage will thus affect the discharge regime, which has a subsequent impact on the thin film quality [3]. In this work, the plasma/surface effects are discussed in the case of three regimes: diffuse, filamentary and hybrid discharges are proposed and compared both electrically and optically. The purpose of this study is to define the consequences of the different modes on the structure of various plasma treated surfaces and their evolution in time and plasma conditions.

Firstly, three operating regimes are defined for a plane-to-plane N_2 DBD at atmospheric pressure: by modifying the shape of the applied waveform (sine or square) and its frequency (from 1 to 6 kHz), the DBD regime can be tuned to a Townsend, a filamentary or a hybrid one. These three modes simulate possible discharge conditions for material processing. The electrical characterization of these modes is presented as well as iCCD imaging and OES measurements.

Secondly, SiO_2 (90nm) / Si substrates (a commonly used substrate in material processes) are subjected to these different regimes following increasing processing times, varying from one second to minutes-long discharges. The treated samples are then observed using SEM and AFM in order to assess the surface morphology variations induced by the DBD plasma treatment. After obtaining satisfying preliminary results, the study is extended to other materials such as polymers to understand how the various discharge modes affect substrates with different electrical and mechanical properties.

From a macroscopic to a microscopic scale, these imaging techniques reveal surface modifications caused by filaments in the discharge. Sub-micrometric impacts are covering the surface, arranged in the form of clusters. By studying the distribution of these impacts and their size over treatment time, additional knowledge on the behavior, distribution and intensity of (even slightly) filamentary discharges is obtained.

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Impact on surfaces of dual frequency pulsed+RF plasma jet in open air

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Dual-frequency configurations have demonstrated enhanced plasma heating performance relative to single low-frequency (LF), pulsed, or radio-frequency (RF) operation showing the possibility to independently control ionization and energy coupling. The approach is particularly promising in molecular gas excitation as CO, CO_2 and H_2 [1], in addition it was shown also to enable control over the ignition of the γ regime on facing surfaces [2].

These characteristic discharge properties are preserved in jet configurations. In a coaxial geometry, plasma operating in ambient air typically exhibit a filamentary structure in which ionization dynamics are dominated by the Ω regime; however, γ-mode operation can also be initiated on treated substrates, which effectively act as a third electrode [3,4].

Under specific operating conditions, locked modes can be established, and the spatial stability of the filaments can be modified on timescales of seconds, while the temporal jitter associated with γ-mode ignition is on the order of 10–20 ns. The resulting enhancement in plasma stability, together with the ability to regulate plasma–surface interactions through sheath control, is highly promising for advanced materials processing under open-air conditions.

In this work, we will present the principal advantages of such configurations, with emphasis on applications to both solid and liquid targets. The formation of a glow high-density plasma layer on the surfaces enables hydrogen incorporation into substrates, potentially leading to ion–exchange processes in sodalime glass. Simultaneously, a controlled ion flux can be exploited to introduce defects in two-dimensional materials in a highly controlled manner [5]. Moreover, the γ regime can also be established in liquids, creating a novel plasma–liquid interface environment with potential applications in chemical synthesis.

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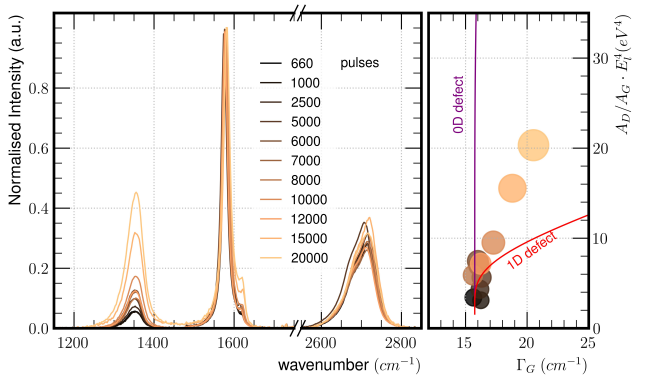

Defects induced in a graphene nanoplatelets by an Ar plasma jet in open air using coupled excitation RF and µpulse as a function of the number of pulses for comparison with other configurations [5].

The influence of key operating parameters of the three-electrode gliding arc reactor on the NO_x production efficiency

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Nitrogen oxides (NO_x) constitute important intermediates in a wide range of industrial applications, including the production of nitric acid, fertilisers, as well as certain medical and electronic processes. At present, NO_x is primarily generated via the Ostwald process, which involves high-temperature and high-pressure conditions and relies on noble metal catalysts, leading to substantial energy demand and elevated operational costs. These drawbacks have driven the exploration of alternative production routes capable of operating under milder conditions while offering enhanced energy efficiency [1].

Among the emerging approaches, plasma-assisted nitrogen fixation has attracted considerable attention, particularly when employing non-thermal plasma produced by gliding arc discharges [2]. In these systems, electrical energy is utilized to directly excite nitrogen and oxygen molecules in ambient air at atmospheric pressure, facilitating NO_x formation. In comparison with conventional thermal methods, gliding arc plasma reactors are characterised by lower bulk gas temperatures, higher electron energies, and increased flexibility in adjusting discharge parameters [3].

The effectiveness of NO_x generation in gliding arc reactors is governed by a complex interaction between electrical operating conditions, gas flow parameters, and reactor design. Variables such as discharge voltage, current, input power, and gas residence time have a direct impact on plasma characteristics, reaction mechanisms, and thermal behavior, rendering the process strongly non-linear. Consequently, thorough experimental evaluation combined with suitable data analysis techniques is crucial for determining optimal operating regimes [4].

This study reports an experimental investigation of NO_x formation in a three-electrode gliding arc plasma reactor operated under atmospheric conditions. The effects of electrical operating parameters and air flow rate on NO_x concentration and energy efficiency were systematically examined using a dedicated exhaust gas analysis system. The findings demonstrate that NO_x can be synthesized directly from ambient air without the use of a catalyst, achieving concentrations above 4500 ppm at low gas flow rates. An increase in airflow enhances both volumetric throughput and energy efficiency, but simultaneously leads to a decrease in NO_x concentration, indicating a trade-off between these performance metrics. Furthermore, a data-driven multi-criteria optimisation approach was applied to the experimental dataset to determine Pareto-optimal operating conditions. Overall, the results provide experimentally validated insights into reactor performance from both measurement and process optimisation perspectives.

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Plasma-Enhanced Siloxane Coating of Carboxymethylated Cellulose Films for Improved Hydrophobicity and Moisture Barrier Performance

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Carboxymethylated cellulose fiber (CMF) films were modified using dielectric barrier discharge (DBD) plasma with TMCTS/N_2 to tailor their surface chemistry and barrier properties. Such modifications are of particular interest for sustainable packaging applications, where cellulose-based materials are promising alternatives to petroleum-derived plastics but are limited by their intrinsic hydrophilicity and poor moisture barrier performance [1]. The key challenge is to achieve durable hydrophobicity while maintaining the structural integrity of the films.

In this study, plasma-enhanced deposition was carried out in a parallel-plate DBD reactor under atmospheric pressure using nitrogen as the carrier gas following the procedure described in our previous work [2]. TMCTS precursor (60 °C) was introduced via a controlled feed (0.3 mL/min) and transported into the plasma zone by a 5 L/min N_2 flow. The plasma was generated using a sinusoidal voltage (3.52 kHz, 17.6 kV peak-to-peak), with an electrode gap of ~1 mm. Treatment durations ranged from 30 s to 60 min.

Figure 1 – Optical image of plasma-treated cellulose film

Plasma treatment induced surface roughening and the formation of a siloxane coating, leading to reduced optical transparency. FTIR analysis revealed the emergence of Si–O–Si and Si–CH_3 bands together with attenuation of O–H groups, while systematic peak shifts (e.g., Si–O–Si redshift and spatial variations along the reactor) indicated progressive network rearrangement and non-uniform crosslinking under prolonged plasma exposure.

These chemical and morphological changes significantly enhanced hydrophobicity, with surface energy decreasing below 15 $mJ \cdot m^{-2}$ and water contact angles exceeding 140°. Moisture resistance was improved, as shown by reduced water adsorption (<7 wt%) and over 50% reduction in water vapor transmission rate after 30 min of treatment. However, excessive exposure (60 min) induced structural defects that slightly compromised barrier performance.

Overall, an optimal plasma duration (10–30 min) provides a balance between siloxane network formation and structural integrity, enabling the development of hydrophobic, moisture-resistant cellulose-based materials for advanced packaging applications.

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Aerosol-Assisted Thin Film Deposition in a Dielectric Barrier Discharge: Effect of the Precursor on the Deposition Mechanisms

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Plasma-enhanced chemical vapor deposition (PECVD) is a powerful technology capable of producing high-quality, controllable functional thin films [1]. However, conventional PECVD typically requires a controlled and high-vacuum atmosphere, limiting the compatible substrate types and dimensions and increasing the cost of the overall process, especially for high-throughput applications. Performing PECVD at atmospheric pressure (AP-PECVD) could overcome several of these limitations and enable low-cost and high-throughput thin film deposition by avoiding complex vacuum infrastructure.

A commonly used system for AP-PECVD is the dielectric barrier discharge (DBD) [2]. The low gas temperature in DBDs enables the deposition on heat-sensitive substrates, and the straightforward operation at atmospheric pressure holds great potential for upscaling. In addition to the conventional injection of precursor vapors, recent work has shown that precursors can also be injected into the discharge gap as an aerosol, expanding the range of available precursors and providing greater control over the injection rate [3]. Despite these advances, several questions remain regarding plasma-droplet interactions in the DBD and the driving mechanisms in aerosol-assisted thin-film deposition.

In this work, the aerosol-assisted thin film deposition process is characterized for the injection of hexamethyldisiloxane (HMDSO) and pentane. By varying the frequency of the applied voltage and the duty cycle, the energy provided to the system can be varied while keeping the precursor injection conditions fixed. The physical structure and chemical properties of the deposited films are characterized by optical microscopy and Fourier transform infrared spectroscopy, respectively. Our results indicate that depositions using HMDSO are mostly driven by direct droplet deposition, often leading to weakly polymerized films, whereas the deposition using pentane appears to be more vapor driven. Furthermore, by relating the amount of deposited material to the energy input, we observe that the deposition process using HMDSO becomes less efficient as the available energy increases, whereas the efficiency of the process with pentane remains largely unaffected.

These results highlight the complex nature of aerosol-assisted thin-film deposition in DBD and illustrate that multiple mechanisms contribute to deposition, which are strongly influenced by the precursor.

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In-flight reduction of iron oxides from various sources by hydrogen plasma

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The iron and steel industry, responsible for approximately 8% of the global CO_2 emission, must undergo rapid decarbonization to meet the Paris Agreement's goal of net-zero emissions by 2050 [1]. To significantly drop the emissions, hydrogen-based reduction technologies are under development, with hydrogen plasma (HP) being a promising route offering enhanced reactivity due to the active plasma species. Most studies utilize inert noble gases for plasma stabilization, with typical concentrations between 50-95% [2]. However, their high cost and slower reduction kinetics [3] can limit industrial applicability. The development of a stable undiluted hydrogen plasma is important for assessing the feasibility and scale-up potential of short residence time in-flight reduction. Furthermore, understanding the impact of gangue-elements on reduction kinetics is critical to assessing the industrial practicality of this technology. In parallel, iron combustion has emerged as a CO_2-free energy carrier [4], but combustion can damage particles (micro-explosions, cracks, densified shells, hollow spheres), complicating the subsequent reduction step and particle recycling to complete the iron power cycle.

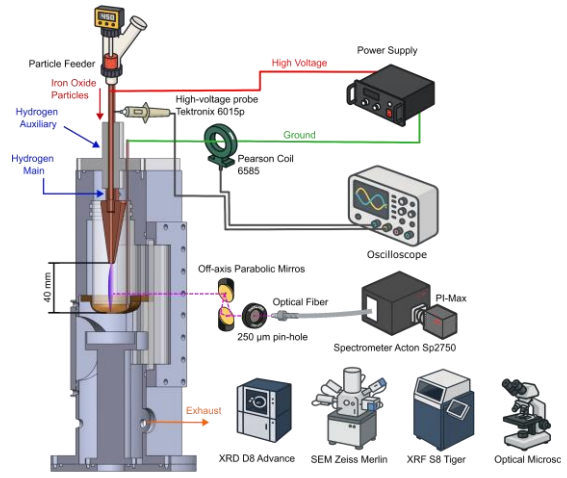

Figure 1: Elongated arc plasma reactor schematic and diagnostic techniques.

Motivated by these gaps, this study demonstrates in-flight reduction using a stable, elongated-arc hydrogen plasma for three iron-bearing feedstocks: pure hematite, combusted iron from the MC^2 burner in TuE Eindhoven, and goethite. Despite not being designed for process performance, a high absolute reduction degree was achieved (71-76% for hematite/combusted iron; 42% for aluminum-bearing goethite) at short residence times (18-30 ms) with an efficiency of 26.8 g_{iron}/kWh. SEM shows that in-flight melting modifies combustion-induced morphological defects in combusted iron particles (e.g., cracks and hollow-sphere structures), confirming technical feasibility for iron production and the iron-power cycle. Goethite-rich feed benefits from rapid dehydroxylation. However, even small gangue fractions, especially aluminum phases, promote iron-aluminum spinel formation that impedes fast reduction. Because gangues are not removed by this route, they must be managed separately. These results indicate clear paths towards practical application: enclosing the plasma-particle interaction zone, extending residence time, and systematically testing lower-grade ores with spinel formation mitigation strategies.

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An innovative process to synthesize gold/polymer nanocomposite thin films in a dielectric barrier discharge

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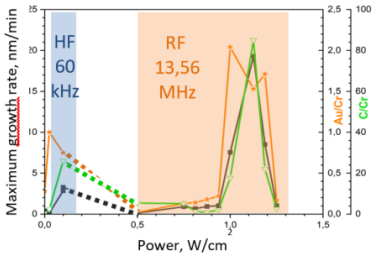
One of the advantages of AP-PECVD is its ability to use an aerosol of a solution as precursors for thin film deposition. In this work, an aerosol of a solution of gold salt (i.e., nanoparticles, NPs, precursor) in isopropanol (i.e. polymerizable solvent acting as a matrix precursor) is investigated using a dual frequency dielectric barrier discharge (DBD) [1]. A previous study [2] using an aerosol of a colloidal solution of TiO_2 NPs highlighted the benefits of alternating a high plasma frequency, responsible for matrix polymerization, and a low one used to control the transport of NPs onto the substrate. In this research, both high and low frequencies are alternated: the low frequency is applied continuously while the higher one is modulated.

In this study, the low frequency is always 800 Hz, while the high frequency is either 60 kHz or 13.56 MHz. At 60 kHz, the DBD is filamentary in Ar and could be a glow one in Ar+NH_3 Penning mixture. Thus, these two atmospheres are considered, by adding 133 ppm of NH_3 to Ar. However, due to the minimum isopropanol concentration required for stable aerosol generation, in this case 1.7%, the DBD remains filamentary even in the Ar/NH_3 mixture. The rate of salt and gold is 11 ppm.

The effects of process parameters on the nanocomposite morphology, chemical composition and optical properties are studied. Furthermore, aerosol formation and the aerosol-droplet size evolution are also characterized prior to plasma entrance.

First, properties of thin film made from $HAuCl_4 \cdot H_2O$ in Ar and Ar+NH_3 DBDs are compared [3]. Gold NPs are formed in both cases, however, the presence of NH_3 drastically reduces the plasmonic resonance related to electron oscillations in the NPs. This is explained by the reactivity of the salt with NH_3 and IPA leading to NPs aggregation while in pure Ar, a NPs carpet is deposited.

The use of radiofrequency voltage significantly increases the DBD power, which is expected to enhance the polymerization rate. The results reveal 3 distinct behaviors, as illustrated in the figure.



Effect of the average power of an Ar DBD with $HAuCl_4$ in isopropanol on the deposition rate and the amount of Au and C in the nanocomposite thin film determined by EDS on samples metalized with a Cr layer used as a reference. In the RF mode 3 different behaviors are observed.

Acknowledgement
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Surface Activation and Nitrogen-Based Functionalisation of Porous Materials by a Novel Linear Atmospheric-Pressure DCSBD Plasma Jet

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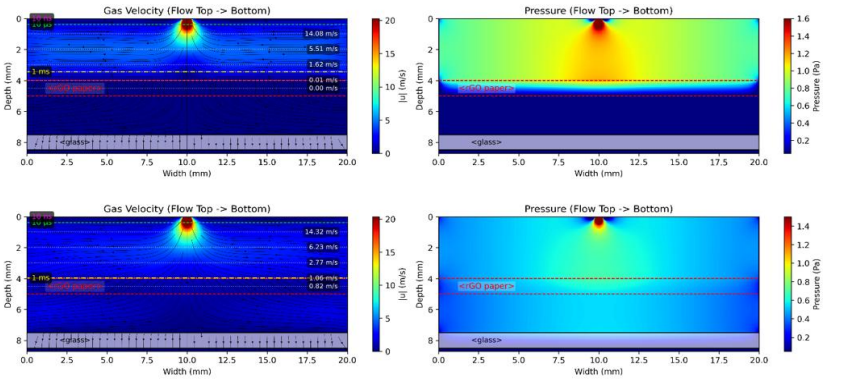
This contribution presents a novel exceptionally cold linear atmospheric-pressure DCSBD plasma jet [1,2] developed for the treatment of porous and temperature-sensitive materials. The main objective of the work is to demonstrate the potential of this newly designed plasma source for uniform surface processing of substrates with complex morphology and limited thermal stability, where conventional plasma treatment methods may be less suitable.

The plasma jet was applied to several classes of materials differing in chemistry, structure, and thermal sensitivity, including glass fabrics, polymeric PP nonwovens, and temperature sensitive and biodegradable polymers (PCL) as well as highly porous reduced graphene oxide. Particular attention was paid to the effect of material architecture, especially porosity, and accessibility of internal surfaces, on the interaction with the generated atmospheric afterglow plasma plume (AfPP) and on the resulting treatment efficiency.



Penetration of AfPP into two structures of different porosity (CFD simulation of gas flow distribution).

Besides general surface activation, the study also addresses nitrogen-based functionalisation of porous materials. Treatments were carried out mainly in pure nitrogen and, in selected cases, also in N_2/H_2 mixtures in order to assess conditions favourable for the incorporation of N-containing functionalities while preserving the low-temperature character of the process. XPS analysis indicated significant nitrogen incorporation, in some cases reaching about 10 at.% and up to 18 at.% under selected conditions, while NH_2 -related functionalities accounted for up to approximately 23% of the incorporated nitrogen species, depending strongly on the treated material and process parameters. This aspect is especially important for advanced applications requiring tailored surface chemistry without deterioration of the bulk properties of temperature-sensitive substrates. Direct experimental observations of the interaction between the linear plasma jet and porous materials were supplemented by simple CFD simulations. Although the simulations are intentionally simplified and serve only as a supporting tool, they provide useful insight into gas flow behaviour, penetration of the AfPP into porous structures, and the possible role of local transport conditions in the observed treatment outcome. The presented results indicate that the newly developed DCSBD linear plasma jet is a promising tool for the controlled modification and functionalisation of structurally complex materials under exceptionally mild treatment conditions.

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Anisotropic Hydrophilization of Resins Using Atomic Oxygen Produced by Laser Photolysis of O_3

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Atmospheric-pressure plasmas can generate highly oxidative radicals; however, their application is constrained by the short lifetime of the radicals and limited flexibility in processing geometry. In this study, we investigate localized surface modification using atomic oxygen (O) generated by UV laser photolysis of ozone (O_3) [1,2]. This approach enables spatially confined generation of atomic oxygen in the immediate vicinity of the target surface while allowing geometric control of the reaction field.

Hydrophilic surface treatment based on O_3 laser photolysis was applied to four polymer resins—HDPE, LDPE, PVC, and PVDF—to evaluate the feasibility of anisotropic surface modification. Experiments were conducted in a reactor, where an O_3/ O_2 gas mixture with the O_3 density of 3.0×10^{16} cm^{-3} was introduced at a flow rate of 1.0 L/min. A 266-nm-laser irradiation was applied near the resin surface to induce O production along the laser path. The laser energy was 0.5 mJ per pulse with a repetition rate of 10 Hz, and the treatment was repeated three times for 5 minutes each. The laser axis was arranged parallel to the resin surface and focused along the surface using a cylindrical lens with a 50-mm focal length. Surface hydrophilicity near the focal point was evaluated by measuring the contact angles of an ink with a surface free energy of 35 mN/m.

Figure 1 shows ink droplets on a PVC surface before and after treatment. The O_3 + UV laser treatment markedly enhanced surface hydrophilicity. In addition, the wettability was higher in the direction parallel to the laser beam axis than in the perpendicular direction, resulting in an elliptical droplet shape. This anisotropic wettability indicates that localized hydrophilization confined to the laser-irradiated region was successfully achieved. Figure 2 compares the contact angles of HDPE and PVC after treatments. Here, θ_L and θ_T denote the contact angles measured parallel and perpendicular to the laser axis, respectively. A significant reduction in contact angle was observed only under the combined O_3 + UV condition, whereas negligible changes were detected for the single-factor treatments. These results demonstrate that atomic oxygen plays a dominant role in surface hydrophilization. As for other resins, a clear difference between θ_L and θ_T was observed except for PVDF, indicating anisotropic modification. The degree of hydrophilicity along the laser beam direction followed the order PVC > LDPE > HDPE > PVDF, consistent with trends in bond dissociation energies characteristic of each polymer.

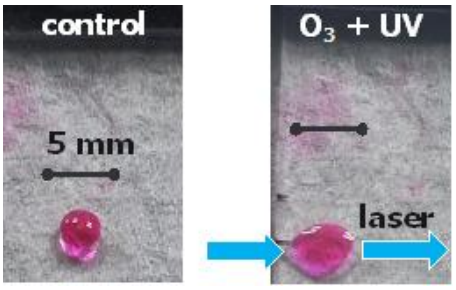

Fig. 1. Anisotropic treatment of PVC

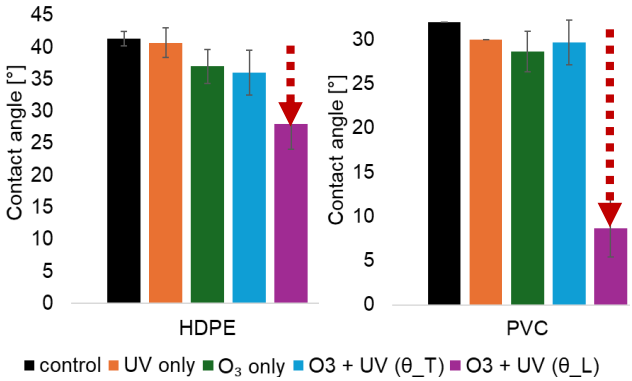

Fig. 2. Contact angle of resins after treatments

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Enhancing the Durability of PECVD Antifog Coatings for Mining Inspections

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Mining shafts require regular inspection to ensure its safety [1]. Traditionally performed through visual assessment, these inspections are increasingly conducted using automated inspection camera shown in **Figure 1**, offering improved efficiency and measurement precision [2]. However, harsh mining environments, characterized by variable temperature and humidity, promote the silica-based lens to fog, significantly degrading optical performance.

To address this issue, a plasma-enhanced chemical vapor deposition (PECVD) process based on tetramethylcyclotetrasiloxane (TMCTS) has been developed to produce superhydrophilic antifog coatings [3]. These plasma-deposited nano-films enable the formation of a continuous water layer rather than rounded-shape droplets, thereby minimizing light scattering and visual artifacts. The main limitation to this coating is therefore its long-term durability under mining conditions, resulting in optical degradation over time.

Figure 1 – Automated inspection camera Lazaruss of Point Laz [2]

This study investigates the effects of mining aging on the coating, with particular emphasis on the influence of substrate surface chemistry and topography on its adhesion and conformity. The silica-based coating was found to crack under thermal shock, induced by temperature fluctuations during inspection. This degradation can be mitigated through appropriate substrate preparation prior to deposition, with chemical and mechanical abrasion as well as plasma-based surface activation identified as effective pretreatments.

The antifog properties of the PECVD coating were investigated using a dedicated experimental setup developed for this study. Results showed that smooth nano-roughness provided better resistance to aging than sharp, irregular surfaces, indicating that good plasma conformity is closely related to coating durability [4]. The study also revealed that plasma activation did not enhance durability, suggesting that adhesion alone cannot explain the coating's performance. Residual reactive sites remaining at the surface may continue to evolve through interactions with the environment, thereby reducing the coating's effectiveness.

Surface preparation prior to PECVD is critical for ensuring long-term performance. These insights apply not only to TMCTS coatings but also to plasma-based coatings, promoting durability and uniform coverage.

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Mechanisms of Anisotropic Silver Growth in Pulsed Plasma–Liquid Discharges: Interfacial Confinement and Oxidative Etching

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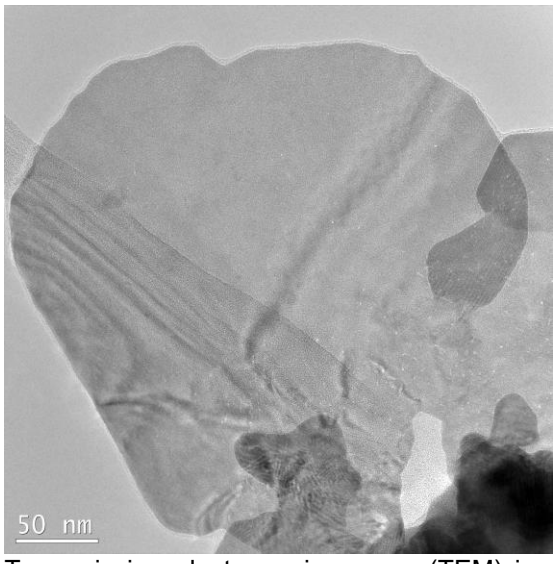
In this work, we investigate the formation mechanisms of silver nanostructures produced by nanosecond-pulsed electrical discharges generated in air above droplets of aqueous $AgNO_3$ solution. The discharge interacts with the curved liquid surface, creating a confined plasma-liquid interface where reduction reactions and oxidative chemistry occur simultaneously. Under these conditions, the system produces predominantly monocrystalline silver nanosheets that are less than tens of nanometers thick and hundreds of nanometers in length, synthesized without any surfactants, capping agents, or solid templates.

Experimental observations indicate that the resulting morphology is governed by a combination of interfacial confinement and plasma-driven oxidative processes. The reaction zone is restricted to a thin layer at the droplet surface, where the curvature of the liquid and the localized plasma contact region effectively create a quasi-two-dimensional growth environment. This spatial confinement limits vertical crystal growth while promoting lateral expansion along the interface.



Transmission electron microscopy (TEM) image of a thin silver nanosheet.

At the same time, the plasma generates reactive oxygen species, including hydrogen peroxide, which plays a key role in shaping the nanostructures. We propose that oxidative etching selectively destabilizes certain crystallographic facets, preventing isotropic growth and favoring the development of highly anisotropic sheet-like crystals. To test this hypothesis, controlled experiments were conducted with hydrogen peroxide added directly to the precursor solution. The presence of this oxidizing species significantly enhances the anisotropic growth, producing nanosheets with lateral sizes up to ~10 µm while preserving their monocrystalline structure.

These results highlight the importance of coupled physical and chemical effects at the plasma-liquid interface in directing nanomaterial growth. Understanding this interplay provides valuable insight into how plasma environments can be used to control crystal morphology and opens new possibilities for surfactant-free synthesis of two-dimensional metallic nanostructures.

Microwave Plasma Methane Pyrolysis: Carbon Collection and Quality Analysis

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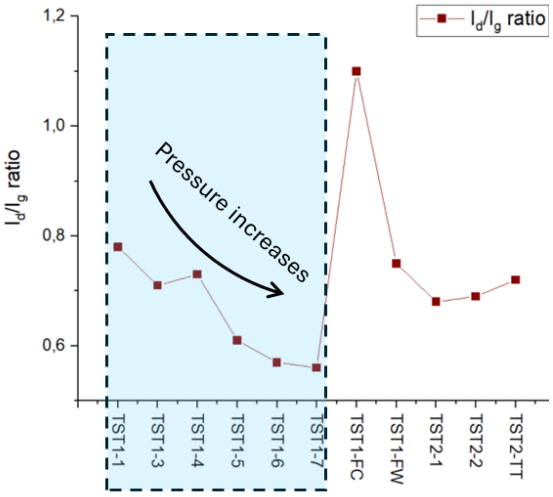
Plasma methane pyrolysis is a promising CO_2-free pathway for hydrogen production, simultaneously yielding solid carbon materials with tunable properties. However, carbon formation in microwave plasma reactors can be spatially heterogeneous, governed by local plasma conditions, temperature gradients, and flow dynamics. Understanding how these factors influence carbon deposition, transport, and final material properties remains a key challenge for process control and scalability [1, 2].

In this work, carbon produced during catalyst-free microwave plasma methane pyrolysis is systematically collected from multiple locations along the reactor. These distinct collection points enable differentiation between in-plasma deposited carbon, surface-grown films, and transported particulate (fluffy powder) phases.



This image shows Raman peaks intensity ratio as the variant of pressure and carbon collecting location from reactor.

The collected carbon samples are analyzed using a range of characterization techniques to evaluate structural, morphological, and compositional variations as a function of plasma condition and collection location. The results reveal differences in carbon properties across the reactor system. Analyzed carbon exhibits descent amount of structural ordering, with turbostratic domains and partially graphitic features. In addition, carbon shows higher hydrogen content, indicating formation via gas-phase nucleation and particle growth mechanisms. The variation in carbon quality highlights the strong coupling between plasma characteristics, reactor design, and material outcomes.

This study provides new insight into carbon formation, transport, and collection mechanisms in microwave plasma systems and underscores the importance of spatially resolved analysis for optimizing carbon quality and reactor performance in plasma methane pyrolysis processes.

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Quantifying Atomic Oxygen Flux in an Atmospheric-Pressure Microwave Induced Plasma Decapsulation System

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Atmospheric-pressure Microwave Induced Plasma (MIP) systems have emerged as high-performance alternatives to conventional acid and vacuum plasma decapsulation for semiconductor failure analysis. IC package encapsulants consist primarily of epoxy (10–30 wt%) and silica fillers (70–90 wt%), requiring selective removal of both organic and inorganic components without damaging copper bond wires or the silicon die [1,2]. Acid decapsulation induces copper corrosion, while vacuum RF plasma systems suffer from low etch rates and charging-related electrical damage [2]. The MIP configuration achieves molding compound etch rates exceeding 100 μm/min through its intense radical fluxes delivered to the substrate via the afterglow [2,3].

In the afterglow regime, surface reactions are governed by reactive neutrals rather than ions: oxygen radicals remove epoxy while fluorine radicals etch silica fillers, with optimal removal efficiency achieved at 30–60% CF_4 in the O_2/CF_4 mixture [2]. Process selectivity is highly sensitive to radical transport. When the residual molding compound thickness falls below ~30 μm, fluorine radicals penetrate porous layers and begin etching the Si_3N_4 passivation layer [2]. These observations confirm that industrial decapsulation performance is governed by radical flux delivery across the boundary layer, not by bulk discharge conditions. Despite this vital role, atomic oxygen flux delivered to the substrate has not been quantified in atmospheric-pressure MIP systems. Current process optimization relies on indirect parameters, microwave power and O_2 fraction, which do not represent the surface-reaching radical flux that governs the reaction kinetics.

Here we present a quantitative method to determine the atomic oxygen flux delivered by an Ar/O_2 MIP afterglow using Kapton polyimide as a calibrated chemical probe. The well-established Kapton erosion yield under atomic oxygen exposure [4,5] enables direct conversion of material loss into oxygen fluence. Experiments are performed at the industrial decapsulation position with defined exposed area. Systematic sweeps of O_2 fraction and absorbed microwave power establish the relationship between discharge conditions and surface-delivered oxygen flux. Atomic oxygen fluence is determined gravimetrically, by converting mass loss of the Kapton coupons into removed volume using Kapton density and the known erosion yield [5] and correlated with optical emission spectroscopy (OES) measurements employing a self-absorption technique with a single-mirror setup [6].

This approach provides a quantitative map of effective atomic oxygen flux under realistic atmospheric-pressure afterglow conditions. By linking neutral radical transport directly to epoxy erosion kinetics [1–3], the method establishes a physics-based framework for predictive optimization of industrial plasma decapsulation processes, built on actual surface chemistry rather than upstream discharge parameters alone.

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On the Characterization of Gliding Arc Discharges in Carbon Dioxide Containing Gases at Atmospheric Pressure

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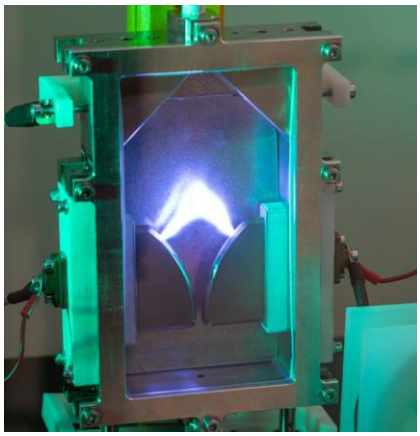
Nonthermal plasmas are one option for a plasma-based conversion of carbon dioxide (CO_2) by using intermittent renewable energy for new power-to-X approaches [1]. Among, microwave and dielectric barrier discharges, gliding arcs are one of the most studied plasma sources for the conversion of CO_2 [2-3]. Compared to DC operation, AC high-voltage operation allows for the use of less complex high-voltage power supplies. Furthermore, electrode erosion is reduced due to the shorter effective discharge duration.



Gliding discharge operated in pure carbon dioxide at 50 Hz.

This contribution presents electrical characterization studies of gliding discharges in the traditional “flat” (2D) geometry consisting of two divergent electrodes at frequencies of 50 Hz and 1 kHz, respectively. The measurements include voltage and current oscillography as well as voltage-current characteristics in combination with high-speed camera recordings. The operation frequency and the gas composition have a significant influence on the electrical signals, in particular the development of current and voltage maximal amplitude. In pure CO_2 at 50 Hz the signals appear regular, while at 1 kHz the high-voltage reverses several times during the upward expansion of the plasma channel leading to a gradual decrease of current but increase of voltage amplitude with the propagation and expansion of the plasma channel. However, the addition of methane (up to 60 vol.%) and reduction of the gas flow rate leads to regular discharge operation.

The influence of the nearest electrode gas gap (1; 2 and 3 mm), the electrode thickness (3 and 5 mm) and the gas flow rate are investigated also. The momentary and mean discharge power as well as the resistance of the plasma channel are determined. The maximum discharge channel length and propagation velocity are measured for different gas flow rates and electrode geometries. These findings are correlated with chemical analysis, namely carbon monoxide and oxygen generation in the plasma. There is a complex interplay between the gas flow and the specific input energy, the thicker electrode results in shorter and more resistive, but also less efficient discharge channels for CO_2-splitting.

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Etalon Spectrometry: Principles and Applications for High-Resolution Plasma Diagnostics

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Line-shape analysis is one of the few diagnostics available for atmospheric-pressure filaments and microplasmas too small or too transient for physical probes. Doppler, Stark, and collisional (van der Waals) broadening encode gas temperature, electron density, and gas density, respectively. However, at 1 atm, these features are compressed into only a few picometers – a regime where spectrometer design is itself the limiting factor in what can be measured.

Conventional instruments face a resolution-throughput-instantaneous spectral range trilemma. High-resolution gratings recover resolution by narrowing the slit. However, this collapses etendue precisely when photons are scarcest, typically forcing an average over many shots. This presents a non-ideal solution for a field increasingly focused on shot-to-shot variability. Conversely, scanning Fabry-Perot interferometers recover resolution and throughput but sacrifice single-shot operation and free spectral range.

We present a slit-based, cross-dispersed VIPA spectrometer designed to address these three constraints together rather than trading one for another. A VIPA element disperses the light angularly with substantially higher dispersion than a conventional grating. Cross-dispersing this output against a grating resolves order ambiguity and produces a two-dimensional spectral fingerprint captured in a single exposure. We detail the underlying optical physics of our spectrometer, particularly how the VIPA achieves its dispersion and why cross-dispersion is needed. We then outline where the resulting architecture lies within the resolution-throughput-range trade space relative to other gratings and scanning interferometers, and discuss applications to high-resolution diagnostics in atmospheric-pressure plasmas.

The scalability of streamer discharge generation for industrial air purification

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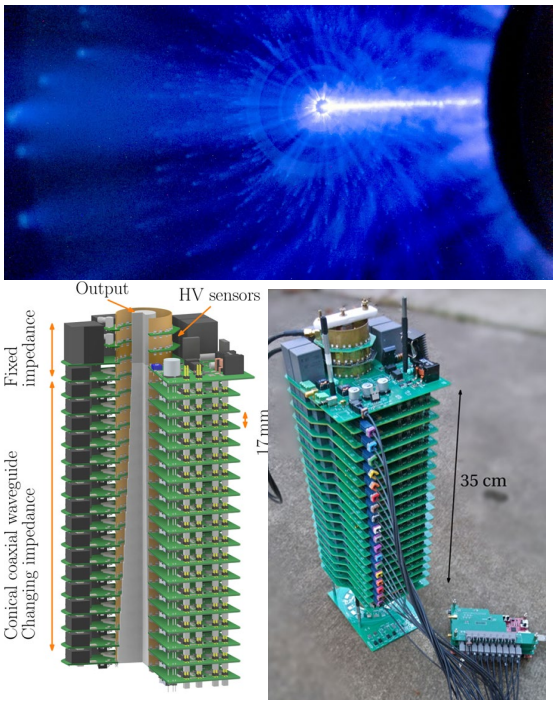
Streamer discharge generation by nanosecond high-voltage pulses in a cylinder-wire reactor is proven as an efficient method for air purification [1]. However, to upscale this technology to wide-spread use in industry, we need to answer the crucial question: which way of upscaling is the most efficient? Previous studies have shown that for this application short rise times and pulse durations are beneficial, but a large parametric study on optimizing reactor sizes and voltages over a very wide range of electrical parameters and physical dimensions has never been performed. To find an optimal scale for industrial application of these discharges, we have performed such a study.

Central in this study is to find what works best when upscaling; a few very large plasma reactors operated at high voltage (>100 kV), many plasma reactors operated at low voltages (<20 kV), or an in-between solution? Therefore, we tested with small cylinder-wire reactors to very large reactors (16-400mm) over a wide range of pulsed voltages (from a few kV to well over a hundred kV) with rise times in the order of tens of nanoseconds and pulse durations in the order of several tens to hundreds of nanoseconds. The resulting streamer discharges are inspected and measured using ICCD imaging, UV spectroscopy and electrical diagnostics with the aim of investigating (and optimizing) ozone generation.

A second theme in this contribution is to give an overview of what is required from a pulsed-power point of view when upscaling plasma air-purification applications. When we find which reactor diameter and pulse parameters work best, what kind of pulse source would be useful for such an operating regime? This is a story of how we went from spark-gap based systems to modern solid-state solutions that can cost-effectively scale to large plasma systems [2,3].



Top: streamer discharge generated with 400-kV pulses in a 400-mm wire-cylinder reactor. Bottom: 20-kV arbitrary waveform, solid-state, nanosecond pulse generator for transient plasma applications [2].

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The Role of Bubble Hydrodynamics in Plasma-based PFAS Treatment

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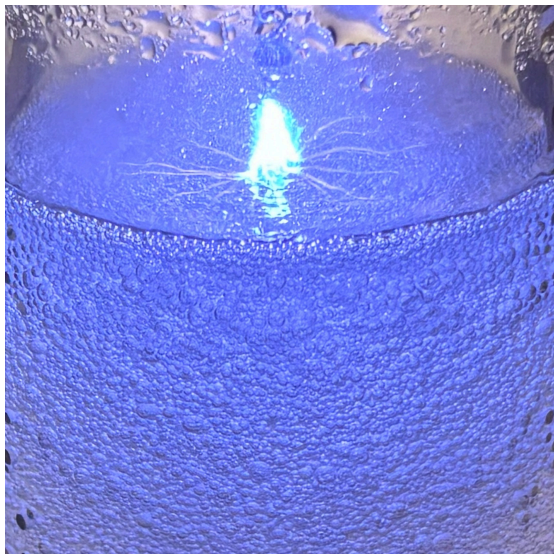
Per- and polyfluoroalkyl substances (PFAS) comprise a class of over 12,000 synthetic chemicals characterized by exceptionally strong carbon-fluorine bonds. Their environmental persistence is fundamentally linked to the C-F bond length and high bond dissociation energy, which make PFAS highly resistant to thermal, chemical and biological degradation. Commonly referred to as “forever chemicals”, PFAS are of increasing global concern due to their widespread occurrence and associated toxicity [1]. While standard advanced oxidation processes are unable to oxidize these compounds, plasma-based water treatment has proven to be an effective alternative for PFAS remediation. Specifically, non-thermal atmospheric pressure plasma leverages the surface-active nature of PFAS to enable targeted destruction at the plasma-liquid interface [2]. However, the overall efficiency of this interfacial mechanism depends strongly on mass transfer, which varies with PFAS chain length and transport conditions.

Gas sparging is known to enhance transport by increasing interfacial area, yet the specific role of bubble hydrodynamics, independent of solution chemistry, remains underexplored. Bubble size distributions, coalescence behavior, and population dynamics influence how effectively PFAS is delivered to the plasma region, but these hydrodynamic effects are not yet well quantified.



Argon bubble hydrodynamics coupled to a non-thermal electrical discharge plasma generated at the gas-liquid interface.

This work uses optical imaging to investigate the effects of gas bubble size, gas flowrate, physicochemical properties of the solution, and the presence of surface-active compounds including PFAS, on bubble population dynamics in a bubbling column reactor. The study also compares bubble behavior in the presence and absence of plasma. The aim is to identify the specific hydrodynamic conditions required to optimize mass transfer and maximize PFAS degradation. This work is expected to provide fundamental correlations required to upscale plasma reactors for the treatment of a broad range of PFAS compounds.

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Non-thermal plasma-Fe functionalized activated carbon coupling for PFOA removal in water

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Perfluorooctanoic acid (PFOA), a persistent and widely detected per- and polyfluoroalkyl substance (PFAS), resists conventional methods due to the high stability of its carbon–fluorine (C–F) bonds [1]. Non-thermal plasma (NTP) combined with heterogeneous catalysts is promising approach for its treatment [2–4]. In this study, plasma-activated carbon (AC) coupling was studied using two commercial granular ACs (L27 and L39 from Jacobi Carbons) with or without Fe functionalization prepared in-house, in a multi-pin over liquid dielectric barrier discharge.

Special attention was given to the effect of the plasma environment, as various gas mixtures favour the formation of reactive oxygen or nitrogen species. Accordingly, the influence of operating parameters, including gas composition (air, Ar/O_2 80/20, and Ar/N_2 80/20),was evaluated. Plasma treatment alone showed limited removal rate (<40% in air, <20% in Ar/O_2), while AC alone (with or without Fe) already achieved significant removal (up to ~60–90% depending on material and contact time), indicating a major role of adsorption, alongside other surface-related mechanisms. When combined with AC, plasma treatment substantially enhanced removal, particularly with Fe-functionalized materials: the L27-Fe/NTP system achieved > 96% PFOA removal after 10 min and up to 99% after 60 min whilst L39-Fe exhibited lower but still significant activity. TOC analysis showed enhanced TOC removal in the coupled systems, regardless of functionalization, compared with plasma alone, suggesting a combined effect of adsorption and plasma-induced oxidation, though their respective contributions remain to be clarified. uHPLC-MS analysis revealed the formation of several intermediate degradation products (PFHpA, PFHxA, PFpeA, PFBA) under selected conditions, with absolute peak intensities and distributions depending on the plasma environment and the AC. Plasma–AC coupling generated a wider spectrum of intermediates, indicating more complex transformation pathways.

Cytotoxicity of treated solutions was evaluated using a fibroblast wild-type cell line (MTT test). A slight transient increase in toxicity was observed in the presence of Fe-functionalized activated carbon probably due to the formation of degradation products, although further investigations is required to confirm this hypothesis.

Thermogravimetric analysis of post-treated ACs is required to define their role in the coupled process, especially to differentiate between adsorption and potential catalytic contributions. Overall, these preliminary experimental findings highlight the potential interest of plasma-AC coupling, with or without Fe-functionalization, for PFOA treatment at laboratory scale, and provide insight into the influence of plasma conditions and AC properties the process.

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PFOA Plasma Degradation in Water: Long-Time-Scale Modeling Investigation

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Per- and Polyfluoroalkyl Substances (PFAS), a sub-group of fluorinated organic compounds, are characterized by strong carbon-fluorine (C-F) bonds that render them highly persistent in the environment. Atmospheric pressure plasmas (APPs) have shown effective treatment of certain PFAS at the gas-liquid interface. APPs propagate on water as surface ionization waves which chemically activate the near-surface regions of the water. PFAS molecules can then be dissociated by the incident fluxes of electrons, ions, radicals and photons at the plasma-liquid interface and solvated electrons in the near-surface regions of the bulk liquid. The reactive species contribute to the decarboxylation−hydroxylation−elimination−hydrolysis (DHEH) pathway [2-5] generating byproducts of F^- and CO_2^-. A validated PFAS degradation mechanism would aid in optimizing PFAS degradation from water.

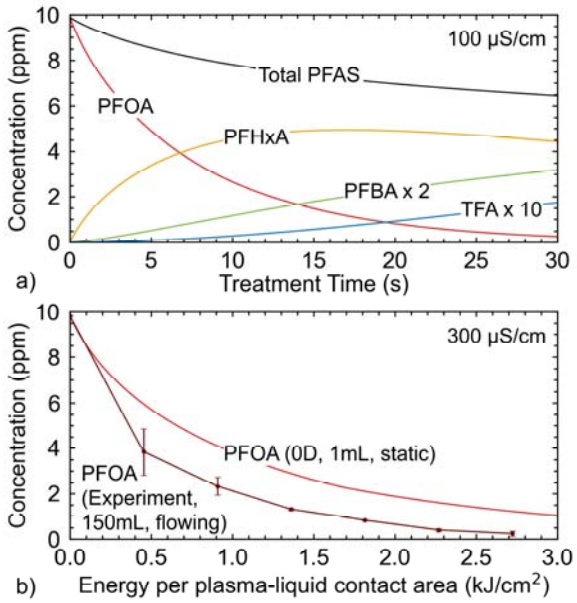

Figure 1 - Concentration of PFOA in water and DHEH fragments (PFHxA, PFBA, and TFA) during plasma exposure. a) *GlobalKin* results for 30 s and b) model and experiments vs. energy deposition.

In this work, a mechanism for PFOA degradation in water initiated by fluxes from an APP has been developed and implemented in a 0-dimensional (0-D) model *GlobalKin*. Plasma generated fluxes onto the water were obtained from a 2-dimensional (2-D) model *nonPDPSIM*. The initial 10 ppm of PFOA is degraded by 1 kHz, 200 ns discharge pulses. The fluxes produced by the 2-D model are for APP conditions of -30kV, 1.0 cm of water thickness and 100 µS/cm of water conductivity. A parametric investigation varied voltage and pulse repetition frequency, and water conductivity and thickness. The predicted PFOA degradation pathways are shown in Fig. 1a for a 30 s plasma exposure. When normalized by energy deposition onto the water surface, there is favorable agreement with experiments, shown in Fig. 1b.

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Synthesis of ammonia using atmospheric-pressure nitrogen and water vapor plasmas

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Ammonia is not perfect as a “green” energy carrier, if hydrogen, which is a raw material of ammonia, is produced from natural gas, since a large amount of carbon dioxide is emitted in its production process. Ammonia can be green if hydrogen produced from water is used as the raw material, but the high production cost of “green hydrogen” prevents the industry from using it in the production process of ammonia. This issue is solved if we can synthesize ammonia from water vapor instead of hydrogen. In this work, we compared the synthesis of ammonia using an atmospheric-pressure water vapor plasma with that using a hydrogen plasma.

We employed two atmospheric-pressure plasma-jet sources in the experiment. One was operated with nitrogen and the other was operated with the mixture of helium and water vapor. We also used the mixture of argon and hydrogen for comparison. The structures of the two plasma sources were the same. It was composed of a quartz tube with an inner diameter of 4 mm, a tungsten rod, and a copper ring. The tungsten rod was placed at the center of the quartz tube, and the copper ring was attached on the outside. The copper ring was electrically grounded, while the tungsten rod was connected to a high-voltage power supply. The effluents ejected from the ends of the quartz tubes irradiated the surface of a catalyst. The density of ammonia was measured by deep UV absorption spectroscopy, and the synthesis rate of ammonia was obtained from the density and the gas flow rate. We also measured the densities of atomic nitrogen, atomic hydrogen, and OH by laser-induced fluorescence spectroscopy.

The density of atomic hydrogen was approximately 5×10^{15} cm^{-3} in the effluent of the helium/water vapor plasma, whereas it was 2×10^{15} cm^{-3} in the effluent of the argon/hydrogen plasma. Even though a higher atomic hydrogen density was obtained using the helium/water vapor plasma, the synthesis rate of ammonia using the helium/water vapor plasma (2×10^{15} s^{-1}) was one-order of magnitude lower than that using the argon/hydrogen plasma, when we employed a ruthenium catalyst. We also detected NO in the deep UV absorption spectrum in the case of the helium/water vapor plasma. The production rate of NO was one-order of magnitude higher than the production rate of ammonia. When we employed an iron catalyst, the synthesis rate of ammonia using the helium/water vapor plasma was roughly independent of the atomic hydrogen density, while it was roughly proportional to the density of atomic nitrogen in the effluent from the nitrogen plasma. This result was different from our previous work using hydrogen [1], where the synthesis rate was not correlated with the density of atomic nitrogen but was correlated with the density of vibrationally excited molecular nitrogen.

Considering the experimental results, the issues with water vapor compared to hydrogen can be summarized in the following two points. One is the loss of vibrationally excited molecular nitrogen by the quenching collision with water vapor. Vibrationally excited molecular nitrogen is a major contributor to the ammonia synthesis using hydrogen, but it is lost in the presence of water vapor, resulting in the lower synthesis rate. The other is the oxidation of the catalyst surface. A major part of atomic nitrogen arrived at the surface of the catalyst is not converted to ammonia, and the main product is NO. We may obtain a better synthesis rate if we can avoid the oxidation of the catalyst surface.

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Characteristics of a Micro-cavity Plasma Array for Gas Conversion

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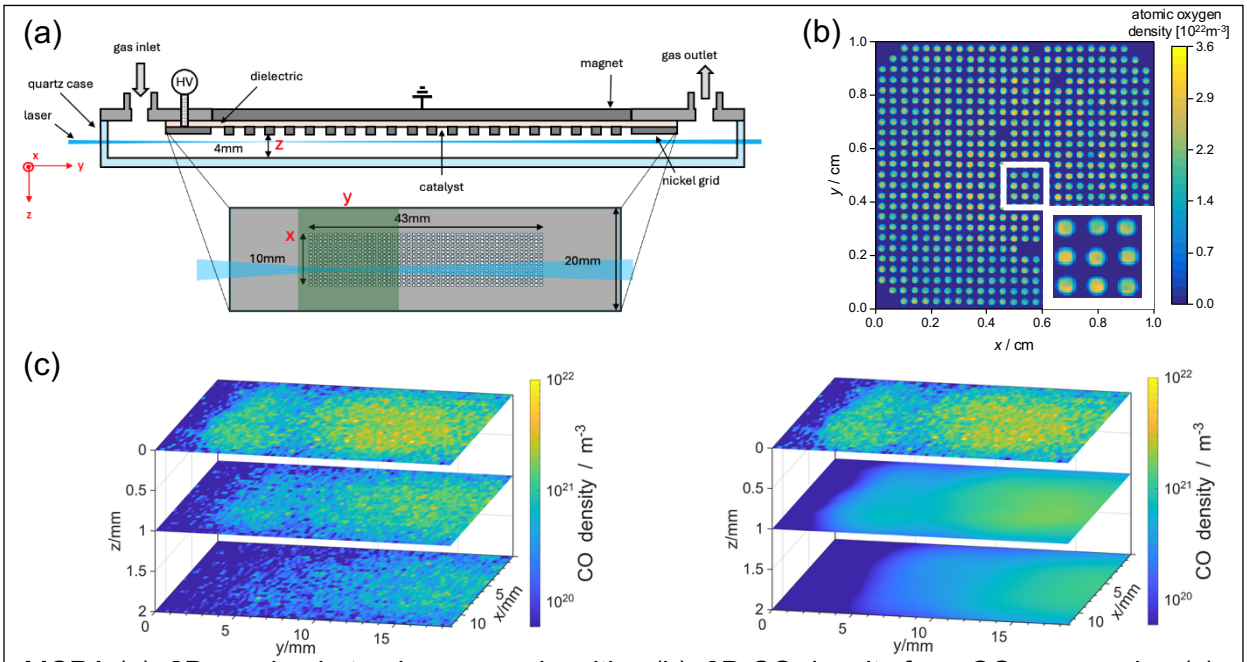
Micro-structured plasma discharges offer great prospects for a variety of technical applications, e.g., for applications requiring large-area treatment, catalytic conversion, or decomposition of volatile organic compounds. Therefore, arrays of dielectric barrier micro discharges in well-defined cavities are of high relevance from a scientific and technical point of view. To understand the underlying processes, fundamental knowledge about the discharge dynamics, generation and conversion of reactive species is necessary. In this work, we investigate modular constructed metal-grid micro-cavity [1] plasma arrays (MCPA), which allow for stable operation also at elevated temperatures and the incorporation of catalysts. One array consists of hundreds to thousands of small discharge cavities with dimensions in the range of 100µm each. Here, the plasma arrays are operated in helium with admixtures of reactive gases, typically in the percentage range and excited by triangular voltage amplitudes of 400-800V with frequencies in the kHz regime.



MCPA (a), 2D resolved atomic oxygen densities (b), 3D CO density from CO_2 conversion (c).

The basic discharge behavior, like discharge mode and expansion, electrical characteristics and dynamics will be discussed and accomplished by optical methods to determine electric fields (Stark shift), 2D resolved densities of produced species (state enhanced actinometry, two-photon absorption laser induced fluorescence in comparison with a basic drift diffusion model) [2,3]. Gas conversion results and the influence of catalysts will be presented for the case of C_4H_{10} and CO_2.

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Plasma and Plasma-catalysis coupling for hydrogen production from H_2S decomposition

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Hydrogen sulfide is a gas commonly found in many geological environments and is also generated as a by-product of various industrial processes. Each year, more than 10 Mt of H_2S are emitted worldwide [1]. Currently, the Claus process is widely used to convert H_2S into sulfur, but it leads to a substantial loss of hydrogen in the form of water vapor [2]. Direct decomposition of H_2S through thermolysis gives low H_2S conversion (15%) even at a temperature as high as 1130°C. In recent literature plasma appears as an attractive way for chemicals reaction and small molecule decomposition such as CO_2, NH_3, while H_2S decomposition was little studied. We investigated the decomposition of H_2S diluted into argon using a pulse plasma supply (NANOGEN1), the peak width was fixed at 150ns, at different voltage, residence time and H_2S concentration values. The voltage and current profiles are reported in Figure 1a). The linear increase of H_2S conversion with SEI, independently of whether SEI is varied via residence time or deposited power, suggests that recombination reactions are limited under the investigated plasma conditions. At a SEI of 4 kJ.L $^{-1}$ H_2S conversion reaches 38%. The addition of the MoS_2/Al_2O_3 catalyst favours the decomposition of H_2S into H_2 and solid S, achieving a conversion of 26% at 2 W (SEI = 1.2 kJ/L) compared to 7% without the catalyst.

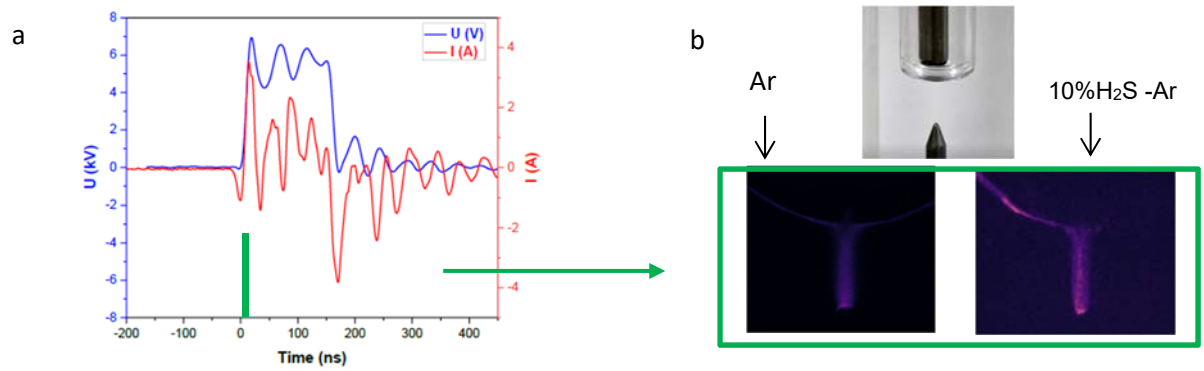

Figure 1: a) voltage and current profiles for 6kV applied, f= 5kHz, residence time 0.3s, 10%H_2S in Ar, b) ICCD analysis with Ar and 10%H_2S in Ar

In addition, a plasma diagnostic was initiated using ICCD imaging, as illustrated in Figure 1b), to monitor the time-resolved evolution of the discharge over 100 accumulated pulses. Images at the positive pulse shows that the presence of H_2S modifies the discharge propagation, it is narrower and less bright in the presence of H_2S. The propagation velocity has been estimated: it ranges from 3 × 10^5 m/s to 10.5 × 10^5 m/s, with Ar only and from 1.2 × 10^5 m/s to 9.9 × 10^5 m/s in the presence of H_2S.

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Plasma-driven upgrading of hydrocarbons with CO_2

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The rise in atmospheric levels of CO_2 poses a significant environmental threat, motivating the search for innovative methods to capture and reuse CO_2. In our work we target this reuse or "upgrading" of CO_2. To this end we will use a non-thermal plasma to have CO_2 react to energetic intermediates, have CO_2 react with compounds that can be made from CO_2, and have CO_2 react with waste products of the chemical industry. The products we aim to make are interesting in multiple areas; 1,3-dioxetane for example can be used in plastics to make them biodegradable over a period of years instead of hours or days. Other compounds are interesting for the pharmaceutical industry. Furthermore, plasma chemistry is uniquely suited to make strained ring structures, which are present in many natural products and have shown to have various biologically active properties but are challenging to make, especially on an industrial scale. [1]

In addition, these compounds can store a substantial amount of energy within their chemical bonds, making them suitable for further chemical functionalization, as well as for fuels.

We are optimizing this process by changing the residence time, pulse shape, pulse frequency, catalysts, quenching time and methods, changing Stoichiometric ratios and type of plasma reactor (Corona, DBD, plasma jet).

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Reverse water gas shift in microwave plasma for O_2 removal and CO_2 conversion enhancement

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Plasma conversion technology is investigated as a potential technology for conversion of gases, aiming at optimizing the efficiency of the process in order to complement current energy intensive technologies. One of the key challenges of the plasma process, in addition to increasing the CO_2 conversion and the process efficiency, is the gas separation in the plasma effluent. Several methods relying on sacrificial/reducing materials, membranes or admixing gases to remove oxygen have been reported in literature. Placing a carbon bed in the plasma effluent enables an effective removal of oxygen upon reaction with carbon atoms, and enhances the CO_2 conversion through the Boudouard reaction ($CO_2 + C \rightarrow 2\,CO$) [1, 2, 3]. Mixed ionic-electronic conductors, such as perovskite membranes, can be thermally activated in the plasma effluent resulting in removal of O_2 molecules [4]. Additionally, removal of O_2 can be achieved by adding H_2-containing molecules, such as H_2 or CH_4 invoking two reactions: CO_2 hydrogenation (or CO_2 methanation) or reverse water gas shift (RWGS).

An efficient removal of oxygen (>99 % removal) from the product gas stream in a 2.45 GHz microwave plasma reactor at atmospheric pressure is reported here [10]. This is achieved by addition of H_2 gas enabling the reverse water gas shift reaction. The addition of H_2 takes place either immediately after the microwave resonator, or inside the resonator, affecting the plasma size and optical emission in the latter case. The performance is comparable for both positions of H_2 addition.

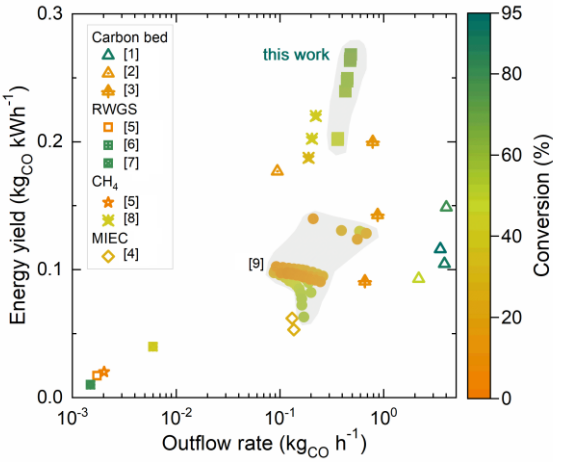

Figure 1. CO energy yield and CO outflow rate for this work and results from literature. The color coding of the data points corresponds to the CO_2 conversion shown on the right. The legend in figure groups the referenced papers based on the method used for O_2 removal.

Already 2 vol.% of H_2 admixture results in O_2 outlet concentrations below 0.1 vol.% from the product gas stream, however at the cost of lower CO_2 conversion. An increase of H_2 flow rate leads to a rise of the CO_2 conversion in accordance to the thermodynamics of the reverse water gas shift reaction driven by the heat of the plasma. CO_2 conversions of up to 65 %, and CO energy yields of up to 0.27 $kg_{CO}kWh^{-1}$ are achieved with less than 0.1 vol.% O_2 in the product gas. The $[H_2]/[CO]$ ratio in the product gas lies in the range between 1.8-2.2 which makes it suitable for synthetic fuel processes such as Fischer-Tropsch. The performance comparison (Figure 1) demonstrates that the presented method of O_2 removal by H_2 admixing to the microwave CO_2 plasma is a very efficient process with the highest energy yields compared to other O_2 removal methods using plasmas.

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Update on "Bottled Lightning" project

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Streamer discharges are self-organizing discharges which occur when a fast high voltage pulse is applied, leading to a local electric field above the breakdown field. These ionization waves can then penetrate areas below the breakdown field. Streamers occur as a precursor to sparks and lightning, but also as separate discharges, e.g. in sprite discharges. In recent years, both simulations and diagnostics of streamers have made great steps, so great that they allow us to compare simulation results now directly to experiments.

In this contribution, we discuss a new set-up which was recently commissioned for laboratory experiments on the fundamentals of lightning. This set-up consists of a large discharge vessel (> 6 m^3) in which long streamer discharges (nearly 1 m long) can be made in a controllable way in varying gas compositions and densities with optical access to the discharge path. Furthermore, a full electrical characterization is planned, i.e. the proper measurement of applied voltage and discharge current. This is a challenging task, since we intend to create > 500 kV pulses with rise-times on the order of 10 ns and repetition rates of tens of Hz. Using this setup, we will investigate how lightning initiates, how it propagates (including the evolution from streamers to leaders), and how it can emit x-rays and other types of high-energy radiation.

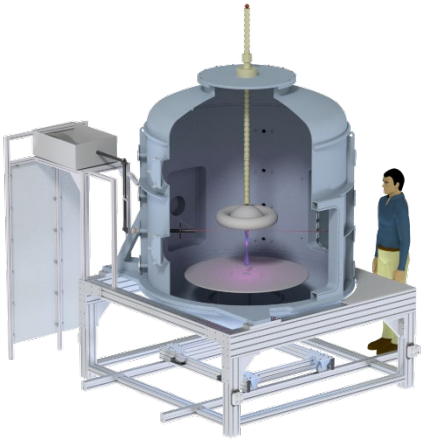

Fig. 1: Impression of the Bottled Lightning setup.

We will summarize results from the following first investigations using this setup:

1. Experiments on electric field measurements near such an ellipsoidal particle and its behavior during the initial moments of a discharge using EFISH [1]. EFISH uses Electric Field Induced Second Harmonic Generation to measure transient fields in gases through the third-order nonlinear susceptibility, $\chi(3)$.
2. The first set of results focused on electrical (discharge voltage and current measurements) and fast optical characterization (using an ICCD/ICMOS camera) of discharges generated in this set-up with an emphasis on identifying proper experimental parameters to compare our discharges to natural lightning. In addition, we will explore the possibility of electrode-less streamer discharge inception using pulsed lasers to investigate the streamer-to-leader transition without the effects of metal electrodes [2].
3. Measurements from an array of x-ray detectors with high energy, spatial, and temporal resolution. Previous theoretical and numerical work has provided us with promising explanations of the connection between the behavior of streamers and the emission of x-rays. These involve, for example, the collision of two streamers of opposite polarity [3] and streamers encountering a neutral plasma patch [4].

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Anomalous lifetime of hydrogen TALIF in a stainless-steel chamber equipped with atmospheric-pressure hydrogen-argon mixture plasma: possible contribution of impurities

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Atomic hydrogen is a typical radical species with unpaired electron, and in general, its lifetime is short in plasmas. The lifetime of atomic hydrogen in hydrogen-argon discharge at an atmospheric pressure is determined by three-body self-association reaction $H+H+M \rightarrow H_2+M$. This reaction has a rate coefficient of 4.3×10^{-33} cm^6/s for M=Ar at a temperature of 400 K. Hence, the lifetime of atomic hydrogen is estimated to be shorter than 0.1 s at an atmospheric pressure, if the density of atomic hydrogen is on the order of 10^{14} cm^{-3}. Contrary to this simple prediction, we recently detected two-photon absorption laser-induced fluorescence (TALIF) of atomic hydrogen even at several minutes after the termination of an atmospheric-pressure hydrogen-argon dielectric barrier discharge [1]. Before delving into the mechanism behind this anomalous phenomenon, in this work, we examined the possible contribution of impurities to the TALIF signal.

The plasma source was composed of a quartz tube with an inner diameter of 4 mm, a tungsten rod, and a copper ring. The tungsten rod was placed at the center of the quartz tube, and the copper ring was attached on the outside. The copper ring was electrically grounded, while the tungsten rod was connected to a high-voltage power supply. The mixture of argon and hydrogen flowed though the quartz tube. The plasma source was attached at the top of a stainless-steel chamber. We tried to measure the density of atomic hydrogen by adopting a standard TALIF technique. The output beam from a dye laser system was focused below the exit side of the quartz tube, and the laser-induced fluorescence was detected from the normal angle to the laser beam using an ICCD camera.

First of all, we examined the excitation and fluorescence spectra. As a result, the most intense TALIF signal was detected at the laser wavelength corresponding to the two-photon excitation from the n=1 to n=3 states of atomic hydrogen (205.08 nm). The fluorescence was composed of a single line emission at 656.3 nm, which is the wavelength of the transition from the n=3 to n=2 states of atomic hydrogen (the Balmer-α line). Therefore, the species we detected by TALIF is surely atomic hydrogen. The next possibility is the production of atomic hydrogen from an impurity molecule containing hydrogen atoms. Hydrogen atoms would be released from the impurity molecule by the irradiation of the dye laser beam (photodissociation), and hydrogen atoms produced by the photodissociation would be detected by TALIF. The impurity molecule is a discharge product and is not a molecule that is present in the chamber from the outset. This is because the TALIF intensity without the discharge was negligible. If a hydrogen atom is released from an impurity molecule, the intensity of TALIF should be proportional to the cube of the laser energy or more, since at least one photon is consumed by the photodissociation. However, we observed that the intensity of TALIF was proportional to the square of the laser energy, which rules out the contribution of an impurity molecule to the TALIF signal. We also examined the composition of gas species in the chamber using a quadrupole mass spectrometer. As a result, we confirmed that molecules which did not exist without the discharge were not newly generated by the discharge. The experimental results obtained to date do not agree with the contribution of impurities to the TALIF signal.

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Experimental and Numerical Investigation of Nanosecond Discharges in Air Gap with Hemispherical Dielectric Layer

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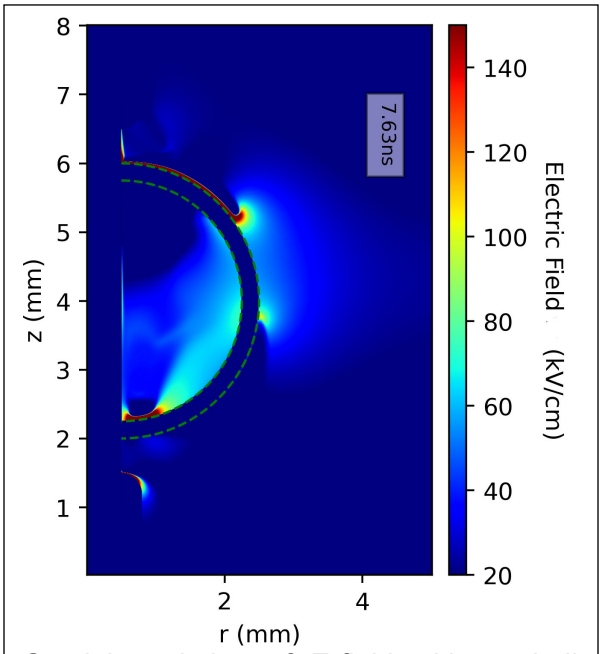
Electrical discharges are transient phenomena highly sensitive to the geometric and dielectric properties of their surrounding environment. Such a dependence directly influences plasma-surface interactions and the efficiency of a related application. This study investigates experimentally and by simulation the propagation dynamics of nanosecond discharge in air gap with the presence of a hemispherical dielectric layer (HDL). Experimentally, the HDL was fabricated using 3D printing of opaque resin that has a dielectric permittivity ε_r = 3. Its diameter and thickness can be finely adjusted during printing. Herein, we investigate the influence of HDL's thickness (100-1000 µm) on the dynamics of the discharge generated inside and outside of the HDL using an ICCD camera. To further determine the spatial and temporal properties of the discharge, numerical simulations are performed by adapting a 2D fluid model [1]. The simulation predicts the spatial evolution of electrons density and electric field inside and outside of the HDL. After being validated for the experimental cases, the model is employed to investigate the role of ε_r (3, 40, 80) on the discharge properties. The results offer new insights for understanding plasma-surface interactions which is highly needed for many applications.



Spatial evolution of E-field with a shell thickness of d=250 µm and ε_r = 3

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Space and Phase Resolved Optical Emission Spectroscopy of Pulse-RF Plasma

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Due to environmental concerns and the desire to go towards net-zero carbon emission, the reforming of carbon dioxide by plasma is a process that is investigated by research groups world-wide (e.g. [1]). The electrical conversion of CO_2 effectively stores renewable, clean energy in the chemical form as fuel or raw materials for industrial chemical processes while at the same time reducing CO_2 exhaust from industrial activities [2]. In particular, the usage of pulsed cold plasmas to dissociate CO_2 is a promising avenue that presents many advantages. Pulsed excitation e.g. in microwave plasmas shows high conversion efficiency, while the atmospheric pressure and ambient temperature working conditions allow for the use of intermittent energy sources, such as solar, wind or tidal power [2][3]. However, the underlying processes leading to dissociation are not well understood, showing the need for more characterization and diagnostics.

To contribute to the reduction of this research gap, a technique for optical emission spectroscopy resolved in space and time is used. Time resolution stems from the synchronization of short camera gating and the plasma oscillations. This technique, known as Phase Resolved Optical Emission Spectroscopy (PROES), is well documented (see e.g. [4]). In addition, the use of an imaging spectrometer allows for a spatially resolved emission profile in the same measurement [4][5]. This space-time resolved measurement has been previously proven, the key contribution of this work is its application of the diagnostic to Pulse-RF plasma.

In the first step, PROES analysis is established on an Argon/Helium/Oxygen plasma. The obtained data is a suite of images of the plasma at the wavelength of a pre-established atomic emission line. Each image corresponds to a certain time frame in the plasma excitation period. This set of images shows when and where the excitation of the observed atomic species occurs, forming a dataset that can be used for validation of numerical simulations. Notably, the plasma source used is the COST-jet, a standardized model useful for benchmarking [6]. In a second step, the spatially resolved PROES diagnostic will be used on Ar/CO_2 admixtures, observing the excitation dynamics under pulsed-RF excitation. The results from this work will then be used to optimize the parameters of the plasma, aiming to improve CO_2 dissociation efficiency.

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Hyperspectral Imaging for 2D spectroscopic characterization of atmospheric pressure Ar–CO_2 plasmas

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One of the most widely used methods for plasma characterization is Optical Emission Spectroscopy (OES) due to its simplicity, high sensitivity, and noninvasive nature. Despite its advantages, OES generally requires point-by-point measurements, making the acquisition of axial or radial profiles technically challenging. Even so, it is possible to obtain spatially resolved spectroscopic measurements by mounting the fiber on a micrometer screw and using a collimator [1], incorporating optical elements into the experimental setup [2], or using compact arrays of optical fibers. These procedures allow the acquisition of 1D profiles and 2D maps, although in a difficult and time-consuming manner which is not well-suited for routine measurements.

A good way to overcome these limitations is hyperspectral imaging technology, a spectroscopic technique that combines OES with 2D optical imaging to simultaneously obtain both spectral and spatial information from optical emissions. With this system, images are captured over a wide spectral range at small wavelength intervals, generating a two-dimensional map of the spectral distribution within a reasonable acquisition time. Each pixel contains its own spectrum, and together they form a hyperspectral data cube that includes both spatial and spectral information.

This technology has been used for the first time for the diagnosis of plasmas generated with molecular gases, with more complex kinetics than noble gas plasmas. Specifically, an Ar–CO_2 plasma sustained by a surfatron device has been characterized. Beyond emission intensities (Figure 1), this technology enables the generation of 2D maps of various plasma parameters, such as electron temperature, relative electron density and metastable states population, as has been done in previous studies on plasmas generated with pure Ar and Ar–Xe mixtures [4,5]. This study represents a significant step forward in the fundamental understanding (internal kinetics, excitation and dissociation mechanisms, etc.) of these plasmas, with promising applications in the plasma-assisted conversion of CO_2, a greenhouse gas, into value-added products such as CO and O_2, which can be further used for the synthesis of fuels and chemicals.

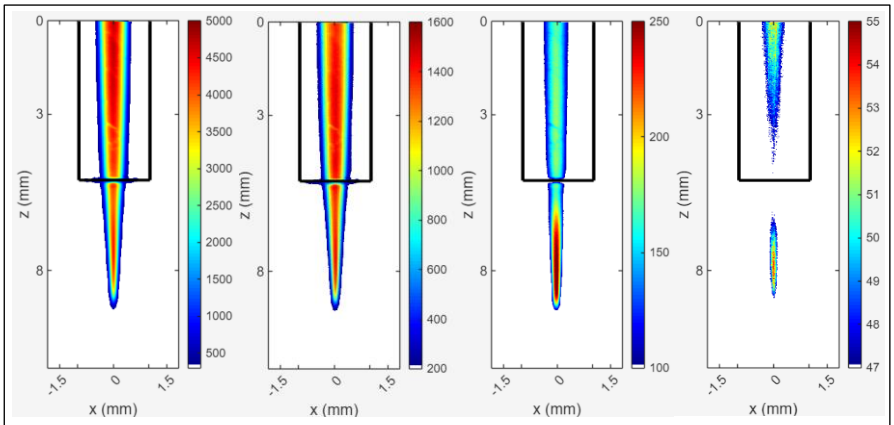

Figure 1: Atomic emissions observed in the Ar-CO_2 plasma. From left to right: Ar I 811 nm, C I 911 nm, O I 777 nm and N I 821 nm.

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A dual-zone discharge cell for probing memory effects in atmospheric pressure diffuse DBDs

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Achieving stable diffuse operation in atmospheric-pressure dielectric barrier discharges (DBDs) relies on the presence of seed electrons before the breakdown. This so-called memory effect enables homogeneous breakdown at reduced electric fields, thereby suppressing streamer formation and preventing transitions to filamentary regimes. Controlling the mechanisms governing this effect is therefore key to ensuring discharge uniformity and reproducibility in a wide range of plasma applications.

Despite its importance, the respective contributions of gas-phase and surface-driven processes to the memory effect remain poorly understood and strongly depend on gas composition and operating conditions. In nitrogen-based mixtures, long-lived $N_2(A^3\Sigma_u^+)$ metastable states play a major role by producing seed electrons prior to breakdown through associative ionization reactions involving $O(^3P)$ and $N(^2P)$ species [1,2]. In contrast, in air and CO_2, surface-related processes such as charge trapping and secondary electron emission are often considered dominant contributors [3,4], although competing gas-phase processes, including electron attachment to electronegative species such as ozone, may significantly modify the available pre-ionization level and thus alter discharge dynamics [5].

In this work, we propose a novel experimental strategy to decouple and quantify the respective roles of gas-phase and surface mechanisms. The approach relies on a dual-zone DBD configuration with independently driven regions, combined with duty-cycle modulation to control memory effects (Figure 1). The primary objective is to isolate the influence of species generated in the first discharge zone on the breakdown conditions in the second. In particular, it enables investigation of how reactive and metastable gas-phase species contribute to pre-ionization and trigger the first breakdown event in a subsequent discharge region.

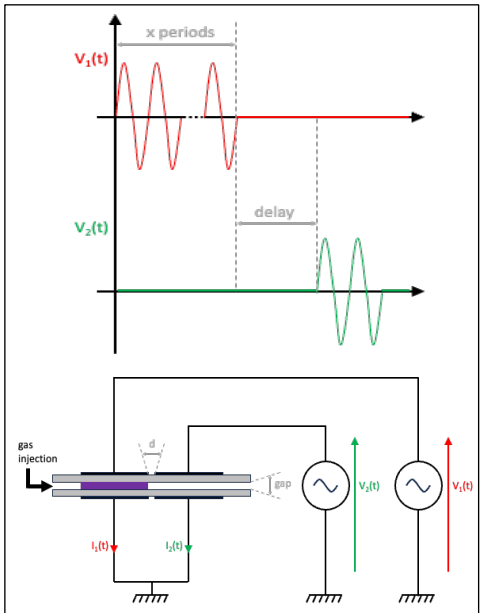

Figure 1: Schematic of the setup

Measurements are performed in N_2/O_2 mixtures ranging from pure N_2 to pure O_2, as well as in CO_2 atmospheres. Time-resolved electrical diagnostics combined with ICCD imaging characterize the spatiotemporal evolution of the discharges. This methodology provides new insights into the physical origins of the memory effect and clarifies the interplay between gas-phase and surface processes.

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Optical and Hyperspectral Characterization of the Plume of an Atmospheric Plasma Torch for Organosilicon Thin Film Deposition

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The development of multifunctional thin films deposited with PECVD is a rapidly growing field, attracting increasing interest from both the scientific community and industrial sectors. Among atmospheric plasma deposition devices, plasma torches represent an emerging technology offering unique advantages, including high deposition rates and compatibility with versatile industrial production lines [1], [2]. However, the literature on this technology remains sparse, particularly regarding plasma–substrate interaction during precursor injection, which is poorly understood.

This work aims to characterize the plasma plume environment and its interaction with the substrate with and without hexamethyldisiloxane (HMDSO) precursor injection. In addition to conventional visible-spectrum imaging of the plume, which reveals its overall emission intensity and shape during surface contact, hyperspectral imaging is employed. This innovative technique enables us to establish a spatial characterization of the intensity and species distributions within the plume and near the substrate, as was recently demonstrated for a microwave Ar jet [3], [4]. These analyses are conducted as a function of key input parameters such as torch–substrate distance and substrate nature.

The results show that correlating deposition profiles with optical characterization provides a novel and valuable approach for understanding deposition behaviour. In particular, hyperspectral imaging proves to be a highly relevant means of probing the process, as it reveals the spatial distribution of excited species within the spreading zone and opens a promising pathway for further exploration.

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Influence of gas residence time on breakdown characteristics in CO_2 Atmospheric Pressure Townsend Discharges

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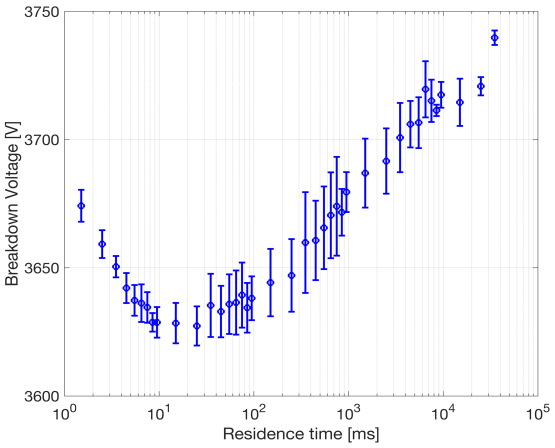
Given the need to reduce greenhouse gas emissions, numerous studies have been conducted over the past several years to explore the possibility of using plasmas to convert these gases - particularly CO_2 - into valuable molecules [1]. For this reason, it is particularly useful to have reliable and validated chemical kinetics models. Much research has therefore focused on low-pressure plasmas, particularly because they can be generated in a homogeneous and steady-state manner. At atmospheric pressure, most discharges obtained exhibit significant temporal and spatial variations, which complicates their characterization. In this context, the use of Townsend discharges at atmospheric pressure (APTD) greatly facilitates this process due to their stable and homogeneous nature, as well as the ease of determining the reduced electric field [2].

The generation of APTD was first reported in nitrogen, and subsequently in nitrogen with impurities (O_2, N_2O, etc.). It has been demonstrated that the gas composition plays a crucial role by enabling physicochemical processes to occur between two successive discharges. Among these, associative ionization reactions involving metastable states have been identified as strong candidates for the generation of the seed electrons required to initiate a Townsend breakdown, leading to an APTD [3]. On the contrary, in air or in CO_2, such processes are unlikely because of the efficient quenching of metastable states. In these mixtures, processes arising at the dielectric surfaces are more likely to dominate [4]. Nevertheless, a recent study conducted in air showed that even if the dominant effect is related to surface processes, the discharge development can also be influenced by changes in the gas composition along the gas flow, due to the formation of stable electronegative species such as ozone [5].



Evolution of the breakdown voltage as a function of the gas residence time in the discharge. (gas gap 1mm, 12 kVpp, 1 kHz).

In this study, the influence of gas composition changes on the electrical properties of plane-to-plane CO_2-APTD was investigated using a segmented electrode. We were thus able to demonstrate a non-monotonic evolution of the breakdown voltage along the gas flow (see figure). This likely reflects the competition between two mechanisms: one facilitating discharge initiation and the other hindering it. Possible candidates for these mechanisms will be discussed in the present contribution.

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Molecular excitation in plasma jets powered by ns-pulse sustain

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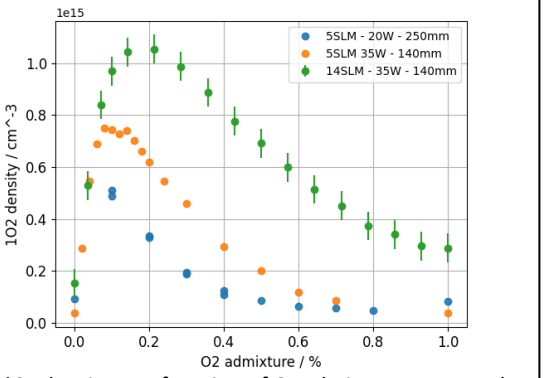
Non-thermal (NT) atmospheric pressure plasma jets (APPJs) are used in multiple application fields for their unique way to electrify chemistry. Notably, in biomedicine, NT plasmas are studied for their anti-cancer properties. While the specific chemical pathways that lead to cancerous cell apoptosis are still misunderstood, singlet delta oxygen ($O_2(a^1\Delta_g)$ or $^1O_2$ for short) is thought to play a key role [1]. Also, carbon dioxide (CO_2) dry reforming by NT plasmas has been largely demonstrated, but key efforts remain for a scalable and efficient process. Vibrational excitation leading to CO_2 reforming is a promising pathway as it takes less energy than thermal dissociation. In both these application fields, understanding and controlling molecular excitation is fundamental.



$^1O_2$ density as a function of O_2 admixture measured for different distances and total flow rates under RF excitation

Our work focuses on modifying electric waveform parameters of a ns-pulse combined with radio frequency (RF) excitation and quantifying the resulting production of $^1O_2$ in a macroscopic atmospheric pressure plasma jet (M-APPJ) and the CO_2 dissociation in the COST jet [2].

APPJs, powered by RF excitation result in an electronic temperature around 4-5 eV. This electron temperature (Te) is neither suitable for maximal $^1O_2$ production or vibrational excitation of CO_2 as their ideal Te is lower. A ns-pulse combined with sub-breakdown RF is used resulting in a lower, ideal Te for molecular excitation. In our work, such a power supply was built. The ns-pulse can reach 15 kV in amplitude, 75 ns to 5 µs pulse width and 500 Hz to 8 kHz pulse repetition frequency while the 13.56 MHz frequency is varied in amplitude from 0 to 300 Vpp.

The M-APPJ is composed of two rectangular stainless-steel electrodes of 100 mm length separated by a 1 mm gap. Helium is used with oxygen admixture. The effluent of the plasma jet is collected and directed by a glass tube to a glass cell, where NIR emission spectroscopy is conducted by an InGaAs photodiode mounted on a narrow bandpass filter centered at 1270 nm [3]. The signal is calibrated to absolute concentrations of $^1O_2$ by a conversion factor determined through a previously conducted ray-tracing Monte Carlo simulation. CO_2 dissociation is quantified with an FTIR measurement on the effluent of the COST-jet. Helium flows through the COST-jet with a CO_2 admixture. CO and CO_2 densities are calculated using the cross-sections from the HITRAN database and its associated interface, HAPI.

The results show that the electrical waveform has a significant impact on the species production. Measurements were performed in both setups for different admixture content, total flow rates, measurement distances and input powers.

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Nanosecond discharge in heptane-water emulsion: influence of droplet distribution on the discharge characteristics

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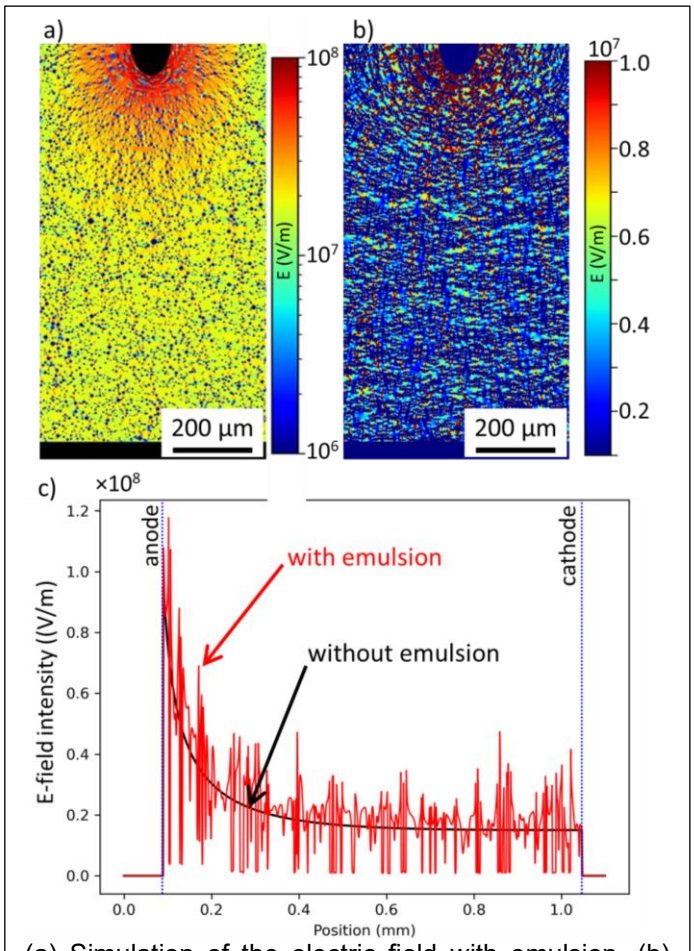
Discharges in discontinuous media, such as bubbles and aerosols, represent complex and fascinating phenomena in which plasmas interact with irregular environments. These media are characterized by regions with different properties, such as electrical conductivity and dielectric permittivity, where multiple interfaces exist. In addition to gas-liquid and solid-liquid discontinuities, liquid-liquid discontinuities can also occur when two immiscible liquids, such as water and oil, are mixed. Previous studies on this subject have demonstrated that the position of the liquid–liquid (hydrocarbon-water) interface relative to the electrode significantly influences discharge properties due to the intensification of the electric field.

In this work, we investigate the influence of a water-heptane emulsion on nanosecond-pulsed electrical discharges. The emulsion is first produced by generating discharges at the water-heptane interface. Once formed, discharges are generated within the emulsion, which has a defined droplet size distribution and density. We find that the electrical characteristics of discharges in the emulsion differ from those in a single liquid, as a pre-breakdown phase is identified in the voltage and current waveforms. Furthermore, we observe that discharges can be sustained over longer gap distances, up to 3 mm, whereas in a single liquid, discharges are obtained only over distances shorter than 0.5 mm, for same voltage pulses. Based on simulations, this behavior is attributed to the enhancement of the electric field at the multiple interfaces between heptane microdroplets and water.



(a) Simulation of the electric field with emulsion. (b) Electric field enhancement due to droplets only. (c) Electric field profile along the electrode axis: (red) with emulsion and (black) without emulsion.

We further investigate the influence of emulsion properties (droplet size and density) and gap distance on the discharge characteristics. The measurements are supported by the simulation of the electric field. We found that this latter is key to understanding the discharge behavior. The results highlight the importance of discontinuities in liquid media, and better understanding on their role provides valuable insight to further develop applications.

Investigation of Charged Particle Desorption Characteristics from Barrier Surfaces: Capable and Incapable of Generating APTD in Air

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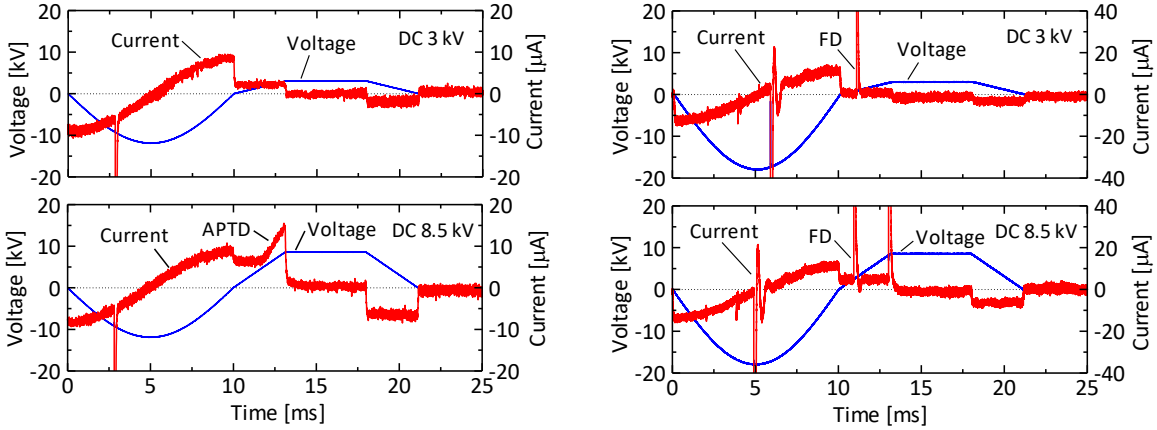
We successfully generated Atmospheric Pressure Townsend Discharge (APTD) in air by using a specific alumina barrier in the barrier discharge device [1]. To date, we have considered both the accumulation of negatively charged particles on the barrier surface and the desorption characteristics of these accumulated charges to be critical factors governing the generation of APTD in air [2]. In this study, we investigated the effect of barrier materials on the desorption characteristics of negative charges accumulated on the barrier surface.

A negative-polarity sinusoidal waveform was applied to generate filamentary discharge (FD) for accumulating electrons on the barrier surface, whereas a positive-polarity trapezoidal voltage waveform was applied to generate APTD. We examined whether APTD could be generated by varying the barrier material and evaluated the discharge inception voltage by applying a trapezoidal voltage. To keep the charge amount on the barrier surface constant, the peak value of the negative-polarity sinusoidal voltage was adjusted so that the surface potential remained between −4 kV and −5 kV, even when the barrier material was varied.

Fig. 1 shows the applied voltage and current waveforms for different barrier materials. As shown in Fig. 1(a), at 3 kV, only the displacement current was measured even when the trapezoidal voltage was applied. In contrast, at 8.5 kV, a proportional increase in current was observed in the rising region of the trapezoidal voltage waveform. This proportional increase in current is considered to indicate the generation of APTD. On the other hand, as shown in Fig. 1(b), at 3 kV, the pulse current was measured in the rising region of the trapezoidal voltage waveform, despite the same amount of charge accumulated on the barrier surface. This pulse current is considered to indicate the generation of FD. These findings suggest that barriers capable of generating APTD are expected to have material properties that make electron desorption more difficult.

This work was supported by JSPS KAKENHI Grant Number JP23K03824.



(a) barrier capable of generating APTD (b) barrier incapable of generating APTD

Fig.1 Voltage and current waveform.

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A multi-fluid Euler–Poisson scheme with discrete conservation of total energy

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The multi-fluid Euler–Poisson system describes each species as an independent fluid and couples them with a self-consistent electrostatic field through the Poisson equation. It can represent inter-species velocity differences, temperature differences, and charge separation that are difficult to capture in a single-fluid approximation. Because of this, it appears in the description of electrostatic transport and plasma phenomena such as low-temperature plasmas, discharges with space charge and sheath, semiconductor devices, and vacuum electronic devices.

This system is a mixed hyperbolic–elliptic system, where Euler-type conservation laws are strongly coupled with the Poisson constraint [1]. Therefore, it is important to keep the interaction between the fluids and the field consistent at the discrete level. In many conventional discretizations, the fluid part and the Poisson solver are treated separately. Then the total energy balance of the coupled fluid–field system, which holds at the continuous level, may not close automatically after discretization.

In a general finite-volume setting for electrostatic multi-fluid problems, a unified framework that closes the coupled total energy discretely is still limited. This point is directly related to the reliability of long-time simulations and energy diagnostics. In phenomena such as sheath acceleration, plasma oscillation, plasma expansion, and instability growth, the energy transfer itself between the field and each species is an essential part of the physics. If the discretization introduces numerical heating or cooling, it becomes difficult to distinguish physical energy conversion from numerical error.

In this work, we propose a multi-fluid Euler–Poisson scheme that satisfies local and global discrete balances of the coupled total energy of the fluids and the field. In the presentation, we will discuss the governing equations, the basic idea of the discretization, and representative benchmark problems, and report the conservation properties and numerical behavior of the proposed method.

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Investigation of Temporal Evolution in Surface Potential during Atmospheric Pressure Townsend Discharge in Air: Effects of Applied Voltage Waveform

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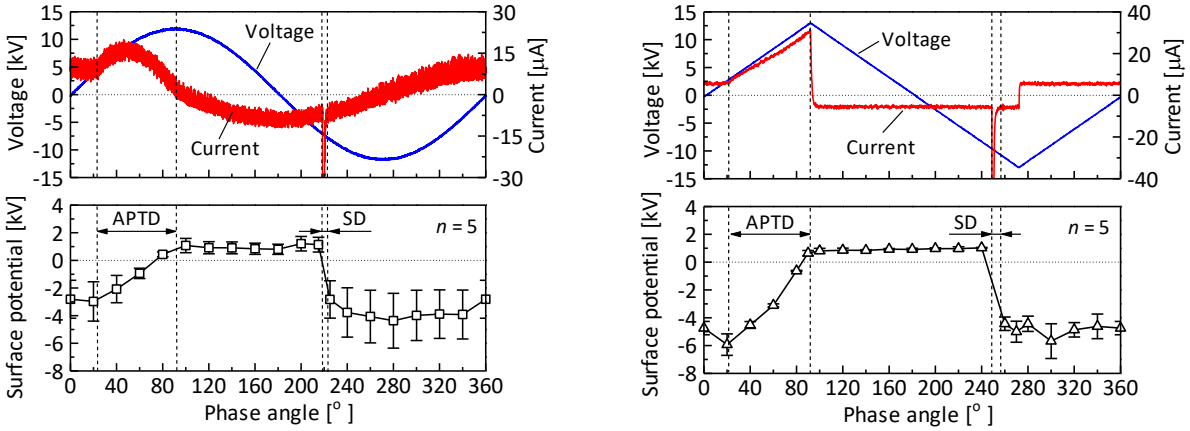
Atmospheric Pressure Townsend Discharge (APTD) is a promising technology for homogeneous surface treatment, material processing, and related applications [1]. So far, we have succeeded in generating APTD in air by using a specific alumina barrier [2]. To elucidate the correlation between surface charge density and the generation characteristics of APTD in air, we have developed a measurement technique capable of evaluating the spatiotemporal distribution of surface charge density during APTD. In previous studies, a sinusoidal voltage waveform has been employed as the applied voltage. However, under such conditions, the rate of rise of applied voltage during the non-discharge period varies with time, which complicates an investigation of the behavior of charged particles accumulated on the dielectric surface. Therefore, in this study, we investigated whether APTD can be generated using a triangular voltage waveform, whose voltage rise rate remains constant. Furthermore, we investigate the spatiotemporal evolution of the surface potential during APTD generation.

Fig. 1(a) and (b) show the voltage-current waveforms and the temporal evolution of the surface potential under sinusoidal and triangular wave applications, respectively. We confirmed that a continuous current was generated between 20° and 90°, regardless of the change in voltage waveform. According to the discharge emission analysis using a high-speed camera with an image intensifier, no streamer discharge was observed, and homogeneous emission was observed on the anode surface. These results indicate that APTD occurs under positive polarity even when the voltage waveform is changed. Analysis of the temporal evolution in the surface potential showed that the variation was more clearly observed under the triangular waveform than under the sinusoidal waveform. These results suggest that applying a triangular waveform may allow for more precise characterization of the temporal evolution of the surface charge density distribution, which is considered to play an important role in the occurrence of APTD.

This work was supported by JSPS KAKENHI Grant Number JP23K03824.



(a) sinusoidal voltage (b) triangular voltage

Fig. 1 Temporal evolution of surface potential during APTD and streamer discharge (SD).

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Modeling and Characterization of Low Flow Plasma Actuators

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Atmospheric pressure plasma jets are widely used e.g., for surface modification, plasma medicine and water treatment but highly rely on gas flow for plasma propagation [1]. On the other hand, plasma actuators are mostly used for modification of gas flow behavior for heat transfer control or applications in aerodynamics. Development of low to no input flow synthetic jets [2] by plasma actuators could provide paths for rapid highly precise spot modification of surfaces. In addition to accurate geometry, power tailoring from AC to ns-pulsed power refines the plasma distribution inside and outside the cavity of such plasma actuators.

Previous CFD modeling of flow has shown the impact of a small cavity with a pin-to-pin plasma actuator on atmospheric pressure air [3]. Our 2D modeling tries to improve on the plasma output and gas flow through the geometry of the cavity. Also, output temperature optimization plays a critical role in many applications. Flow and concentration mixing of Argon, Helium and Air is tailored to reach low enough temperatures and promote the desired plasma reactivity.

A key characteristic of such actuators is the induced flow. Schlieren imaging is a powerful diagnostic tool for electric wind or velocimetry characterization of such plasma actuators [4]. The modelled cavity geometries were tested with varying low input flows (0-100sccm). The impact of the plasma actuator on Ar, He and Air were characterized both inside and outside the cavity. This showed temperature and velocity evolution. At first, standard AC 22kHz, 3-10kVpp excitation power was used before looking at the flow response to ns-pulses 1-10 kV in amplitude at variable pulse width in the ns time range.

The encouraging modeling results show the feasibility of such a plasma actuator for active plasma surface interaction. Schlieren imaging provide experimental results on 3d printed cavities and the resulting output flow and mix with ambient air. Further development will lead to improvement to the actuator flow dynamics.

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Laser-Driven X-rays for Imaging Pulsed Discharges in Liquids

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High-pressure, low-temperature plasmas in liquids are of increasing interest for applications in environmental remediation, chemical synthesis, and medicine. Laser-driven x-ray imaging can be used to resolve plasma structures and dynamics in these environments. Our team has previously demonstrated their potential using a laser-wakefield accelerator betatron x-ray source (Figure 1). Here, we develop a compact laser-driven Molybdenum (Mo) X-ray source with tens of micrometer spatial resolution. These laser-driven x-rays are produced using an intense laser pulse incident on the Mo target, inducing a K-shell ionization and characteristic Kα radiation at 17.48 keV. The picosecond-scale pulse duration of the Mo X-ray source enables imaging of plasma filament evolution and subsequent bubble formation. This work outlines the status of the system implementation, focusing on the optimization of laser-target interaction parameters and the experimental geometry required to resolve plasma-liquid dynamics. X-ray imaging supports measurements of plasma density and structure dynamics, providing a novel method for investigating plasma-liquid environments.

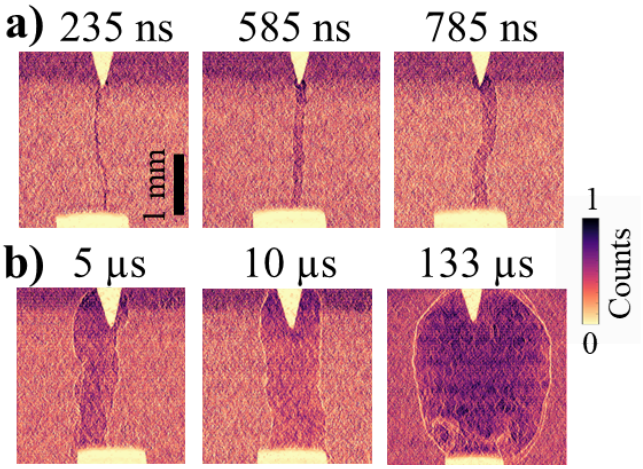

Figure 1. X ray images of plasma discharges at a liquid-liquid interface discharge propagation (a) and during the cavitation bubble expansion (b).

Minimization of Hazardous Byproducts During the Destruction of Hydrofluorocarbon Contaminated Oils via Liquid Injection Incineration Catalyzed by Non-thermal Gliding Arc

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Hydrofluorocarbons (HFCs), potent greenhouse gases, become contaminated with compressor oil throughout their operational lifetime in cooling systems. At the end of its operational life, the HFCs are reclaimed and recycled via distillation for continued use. A hazardous byproduct composed of HFC-contaminated oil is created through this distillation. Liquid injection incineration (LII) is one method approved by the United States Environmental Protection Agency (EPA) for destroying HFC wastes. However, this method generates a large concentration of hazardous by-products (COF_2 and COHF) [1]. Presented here, the C. & J. Nyheim Plasma Institute has developed a liquid-injection incinerator catalyzed by a non-thermal gliding-arc plasma (GAP) that suppresses the formation of these byproducts.

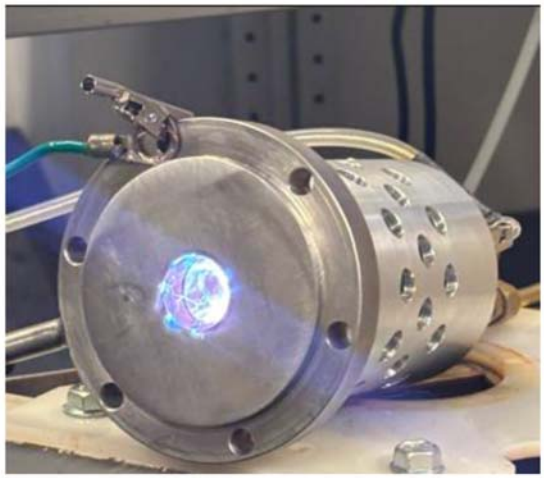

Figure 1: Photo of NPI's Non-thermal Gliding Arc Liquid Injection Incinerator for the destruction of HFC Contaminated Oils..

During Experimentation, operational parameters such as O/C ratio, supplied current, and concentration of R-134a were varied for the combustion reaction. The combustion byproducts were analyzed using two methods: in-situ FTIR gas sample analysis and a water trap in series with a NaOH solution trap for Fluorinated byproduct capture. In the traps, aqueous F-/NaF concentrations were analyzed to determine the efficiency of R-134a destruction. During the destruction of R-134a, the most desirable byproduct is HF and is miscible in the water trap. This is measured via an F-probe. The other byproducts are estimated to bypass the water and dissolve in the second trap, which contains a 15% NaOH solution by weight, thereby converting all other F-containing byproducts (COF_2, COHF, CF_4, etc.) to NaF. These concentrations were analyzed using UV-Vis liquid chromatography.

These experiments are ongoing. It is predicted that, compared to typical high-temperature incineration, the Gliding arc LII has a higher conversion efficiency to HF and reduces the effluent concentration of COF_2 and other hazardous by-products. This is theorized to be due to the reactive species (like H and OH) generated by the non-thermal gliding arc [2]. Further study is needed to determine the effects of non-equilibrium on the reaction to optimize the power minimization in the gliding arc reactor.

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Low temperature degradative desorption of perfluorooctanoic acid (PFOA) from granular activated carbon (GAC) induced by atmospheric plasma

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Contamination of water by per- and polyfluoroalkyl substances (PFAS) represents a global environmental concern and is commonly mitigated through filtration using granular activated carbons (GACs) to produce safe drinking water. Once GAC become saturated, they are regenerated by thermal treatment. However, this regeneration process requires extremely high temperatures, modifies the porous GAC structure, can only be repeated a limited number of times and is of concern for the possible emission of gaseous PFAS [1,2].

For these reasons, we are exploring the use of atmospheric plasma as an alternative approach to promote the degradative desorption of PFAS from GAC. A packed-bed dielectric barrier discharge (DBD) reactor was designed and constructed, employing a dual-frequency plasma configuration that combines low-frequency (LF, 15 kHz) and radio-frequency (RF, 27 MHz) power sources. The reactor consists of a coaxial quartz tube equipped with an internal stainless-steel rod acting as the LF electrode, while a copper tape wrapped around the outer surface of the tube over the sample region serves either as the ground electrode or as the RF electrode.

Experiments were carried out using both pristine GAC and GAC loaded with perfluorooctanoic acid (PFOA), which was selected as a model PFAS compound. Treatments were performed under both dual-frequency and single low-frequency plasma modes while varying the treatment duration. The dual-frequency configuration proved to be more effective and was therefore further investigated by modifying the applied power, the gas flow rate and the gas composition, by comparing experiments performed with pure argon and argon containing small amounts of water vapor or air.

During plasma operation, the outlet gas stream was bubbled through a NaOH solution. This solution was subsequently analyzed using an ion-selective electrode to determine the concentration of dissolved fluoride ions, and by LC/ESI-MS to detect and quantify both the desorbed, non-degraded PFOA and possible gaseous degradation products soluble in water. The treated GAC samples were analyzed by thermogravimetric analysis (TGA) to determine the percentage of PFOA degraded and/or desorbed during the plasma process. They were, moreover, subjected to desorption with two different solvents (i) to quantify fluorides, formed in the plasma process and remained adsorbed on GAC, and (ii) to estimate the fraction of PFOA as well as any degradation products that after the plasma treatment remained adsorbed on the material

The results showed that the presence of 1% of air in argon increases the efficacy of the process and that 29% of defluorination is reached after 60 min of treatment.

This work was supported by Veneto Region through European Social Fund (DGR n. 553, May 9, 2023) and by the University of Padova (P-DiSC#06BIRD2024-UNIPD). Support provided by Nadir s.r.l. is gratefully acknowledged.

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Degradation of Methylene Blue in Water Using Cold Atmospheric Plasma

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Methylene blue is a synthetic compound widely used in dyeing due to its complex chemical structure that ensures long-term color stability. Its remarkable solubility in water facilitates its spread in the environment and its long-term buildup, ultimately resulting in ecological consequences [1].

This problem has already been addressed in the literature using cold atmospheric-pressure plasma (CAPP) to remove blue methylene from the water surface [*e.g.*, [2]. This method outperforms traditional physicochemical techniques like adsorption [3], catalytic degradation or UV treatment [4]. This method allows for in situ generation of reactive species, including free electrons, ozone (O_3), hydroxyl radicals (•OH), hydrogen radicals (•H), hydroperoxyl radicals ($•HO_2$), and ionized water species ($•H_2O^+$). These reactive species facilitate the breakdown of organic contaminants in water [5]. However, key limitations remain, and the application of such water treatment is not yet reliable enough for commercial or industrial use.

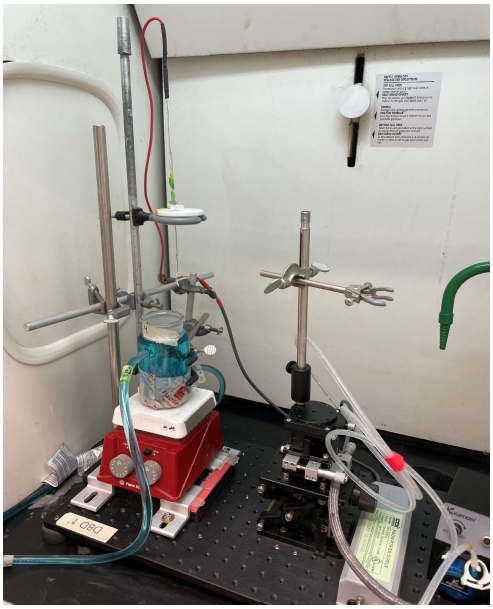

Figure 1—System for the degradation of methylene blue using CAPP.

The subject of this study is plasma-treated water systems that contain methylene blue and “dopant species”. In this work, we decided to focus on the chemical characterization of reaction products using Liquid Chromatography-Mass Spectrometry (LC-MS, Agilent), Ultraviolet-Visible spectroscopy (UV-Vis, Agilent) and Microwave Plasma Atomic Emission Spectroscopy (MP-AES, Agilent) techniques. In situ analysis was performed to clarify the chemical kinetics and correlate all results to the formation of by-products. Our custom-built system (Figure 1) was used to investigate degradation properties. The data suggests that exposure to cold atmospheric-pressure plasma (CAPP) boosts degradation rates. This effect is believed to be attributed to the activation of radicals into highly reactive intermediates. Moreover, the degradation process offers a promising avenue for generating nitrates (NO_3^-), a crucial component in other applications, by combining atmospheric nitrogen (N_2) and oxygen (O_2). The experiment’s design was also intended to clarify the treatment efficiency and scalability when processing large volumes of continuous water.

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Decoupling plasma-induced redox chemistry in liquids via space-resolved microfluidics for oncology applications

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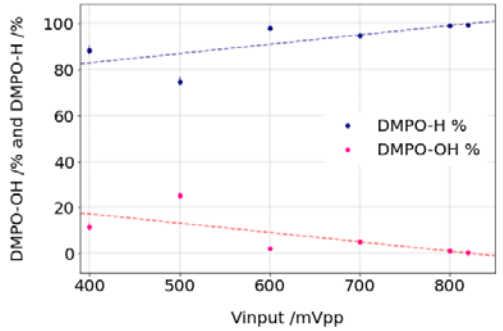
Cold atmospheric pressure plasmas are promising tools in oncology, capable of inducing selective cancer cell death through the production of Reactive Oxygen and Nitrogen Species (RONS). These species interact with biological targets via redox pathways to trigger selective apoptosis. However, it remains unclear whether these effects stem from the global redox potential or from specific RONS.[1] Decoupling the individual interactions of plasma-produced RONS on biomodels is thus an essential, yet unmet, challenge for developing optimized, targeted cancer treatments.

To address this gap, we propose a plasma-microfluidic platform designed for space-resolved treatment of biomodels. [2] This system exploits the spatiotemporal evolution of plasma-induced chemistry within microchannels, allowing cells to be exposed to distinct chemical environments depending on their position along the channel. The microscale ensures well-characterized physical forces, making the system both reproducible and amenable to numerical modeling. [3] A COST jet is employed as the plasma source to ensure inter-laboratory comparability and provide a well-documented reference.

As an initial validation, we implemented a set of diagnostics for both gas and liquid phases. The plasma is characterized electrically through power measurements, as power is a critical controllable parameter directly governing the resulting chemistry, and optically via Optical Emission Spectroscopy (OES) to identify gas-phase precursors. In the liquid phase, hydrogen peroxide (H_2O_2) is quantified by fluorimetry to monitor stable, oncology-relevant molecules. In parallel, short-lived hydroxyl radicals ($\cdot OH$) are detected using Electron Paramagnetic Resonance (EPR) spectroscopy, not only as key intermediates in H_2O_2 production, but also as a proof of concept for detecting short-lived species within the microfluidic environment. To capture the chemical dynamics within the microchip, a quantification method was implemented to decouple short-lived radical production in the liquid phase, combining EPR measurements with algorithmic analysis. Preliminary results demonstrate a dependence of short-lived species on plasma power under pure helium conditions.



Hydrogen and hydroxyl radical concentrations as a function of plasma power

Together, these findings validate the use of a microfluidic platform for systematically decoupling the fundamental physicochemical processes governing plasma-liquid-cell interactions. This work paves the way for a deeper understanding of the mechanisms underlying selective plasma-induced cancer cell killing and the development of more precise therapeutic protocols.

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An aerosol-assisted dielectric barrier discharge process for nanocomposite thin film deposition in N_2

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Nanocomposite thin films have attracted increasing interest due to their ability to combine the intrinsic properties of a host matrix with those of embedded nanoscale inclusions. By controlling the characteristics and dispersion of the inclusions, both the structural and functional behavior of the films can be adjusted, opening opportunities for advanced applications requiring tailored optical, electrical, or surface performances [1,2].

In this context, low-temperature atmospheric-pressure plasma technologies offer attractive routes for the synthesis of hybrid nanocomposites, enabling the incorporation of inorganic nanoparticles into an organic matrix. Recent studies have demonstrated that such materials can be deposited by coupling a plasma process with an aerosol containing preformed nanoparticles (NPs) dispersed in a polymerizable solution [3]. The direct use of pre-synthesized NPs is challenging due to potential health risks and their pronounced tendency to agglomerate, making their dispersion and incorporation difficult to control. An alternative approach is to replace them with solutions of metal salt precursors, enabling NPs formation in situ during plasma deposition.

As suggested in a previous work [4], a dielectric barrier discharge (DBD) in nitrogen can be associated with an aerosol of a solution of a gold salt (tetrachloroauric(III) acid trihydrate, $HAuCl_4 \cdot 3H_2O$) in a polymerizable solvent (isopropyl alcohol), allowing therefore the synthesis of the NC coatings in a single step. A dual-frequency excitation is typically used to independently control the growth of the matrix, the reduction of the gold salt, and the transport of the NPs [4,5].

This study investigates the influence of the main parameters of the process with a focus on a key parameter: the gold precursor concentration in the injected solution. By deliberately varying this concentration, its role in governing the nanocomposite structure and properties is demonstrated. In particular, changes in the precursor concentration significantly affect the nanoparticles density within the films, their spatial distribution and degree of uniformity, as well as the long-term stability of the deposited coatings. The chemical composition, morphology, and optical properties of the nanocomposite layers were characterized using complementary analytical techniques, including Fourier-transform infrared spectroscopy (FTIR), X-ray photoelectron spectroscopy (XPS), scanning electron microscopy (SEM), and UV–visible absorption spectroscopy.

Overall, these findings provide new insights into the potential of a single-step aerosol-assisted plasma process for the deposition of hybrid nanocomposite coatings on large areas at low cost and atmospheric pressure.

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Towards a data-driven Digital Twin for plasma-enhanced thin film deposition: combining neural networks, hybrid modeling and AI-assisted experimentation

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Atmospheric pressure plasmas offer versatile routes for the synthesis of functional thin films with applications in energy storage and CO_2 valorization. However, the strong coupling between plasma physics, gas-phase chemistry and surface processes makes these systems difficult to model and optimize, limiting their industrial applications [1].

In this work, we advance the development of a digital twin (DT) [2] framework for plasma-assisted thin film deposition, integrating experimental data, machine learning, and physics-informed modeling. An automated atmospheric pressure plasma jet reactor has been developed to enable reproducible and high-throughput deposition of organosilicon thin films on silicon substrates using hexamethyldisiloxane (HMDSO) as a precursor.

Preliminary experimental datasets have been collected and used to train neural network models capable of predicting selected physicochemical properties such as film thickness and FTIR signature as a function of controlled process parameters, including power input, plasma jet height, and nozzle velocity. These purely data-driven models are compared with a hybrid, physics-inspired approach combining empirical knowledge of plasma processes with machine learning, providing improved interpretability while maintaining predictive performance. To efficiently explore the high-dimensional experimental parameter space and accelerate data acquisition, a generative flow network (GFlowNet) is employed to guide the design of experiments towards regions of interest in the property space. This approach enables targeted sampling strategies, balancing exploration and exploitation in the construction of the DT [3].

The results from this combined framework demonstrate the potential of coupling automated experimentation, advanced machine learning, and physics-based insights to establish structure–process–property relationships in plasma-deposited materials. Ultimately, this work contributes to the development of predictive tools for the optimization and control of plasma manufacturing processes in applications related to energy and environmental challenges.

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Impact of temperature in surface treatment of ZnO nanoparticles by a low power blown arc plasma jet

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The tuning of semiconductor properties is of strong interest, particularly for systems incorporating nanoparticles whose characteristics depend on fabrication and post treatment processes. Atmospheric pressure plasma jets (APPJs) are promising tools for scalable surface engineering due to their versatility and industrial compatibility [1]. Among these, low power non transferred arc jets generate a reactive post discharge plume when a flowing gas—typically nitrogen or air—is electrically broken down between concentric electrodes under alternating high voltage. This plume contains reactive species such as metastables, neutrals, and radicals [2]. Although non thermal, the gas temperature may become sufficiently high for thermal effects to influence surface modification, making heat transfer a key factor in plasma–surface interactions.

In this study, we investigate the treatment by a nitrogen plasma jet of zinc oxide nanoparticles deposited on a microporous alumina membrane. The role of temperature in jet–surface interactions is examined using complementary diagnostics of the plasma jet and treated materials, combining electrical measurements, optical imaging and emission spectroscopy, in situ thermal sensing, and surface analysis by atomic force microscopy, scanning electron microscopy, and X ray photoelectron spectroscopy.

Electrical characterization indicates stable arc operation between 700 W and 1100 W, with no dependence of injected power on the gas flow rate. At 1000 W and a nitrogen flow rate of 50 L min^{-1}, preliminary XPS measurements reveal nitrogen incorporation into the surface of the microporous alumina membrane, suggesting the possibility of nitrogen doping of the deposited nanoparticles. Atomic force microscopy shows that the characteristic scale of surface modifications remains smaller than the membrane pore size. In addition, contact angle measurements reveal no measurable change in surface wettability, indicating that topography and porosity dominate over plasma induced surface energy modifications under the investigated conditions.

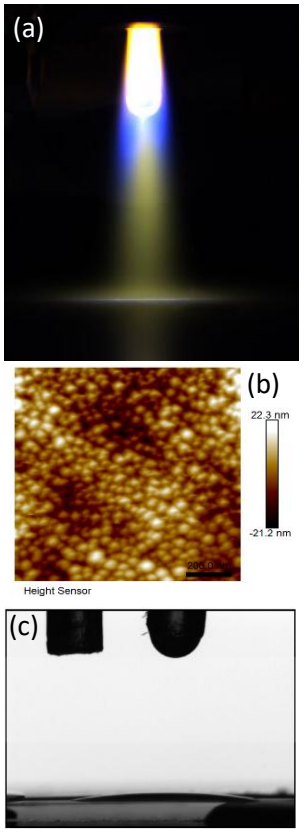

Figure 1 – (a) picture of the jet during treatment, (b) AFM image of the substrate after treatment (c) contact angle measurments before and after treatment.

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Investigation of the Products Resulting from the Application of a Streamer Discharge to a Liquid-Liquid Interface Containing Metal Salts with a Wide Range of Reduction Potentials

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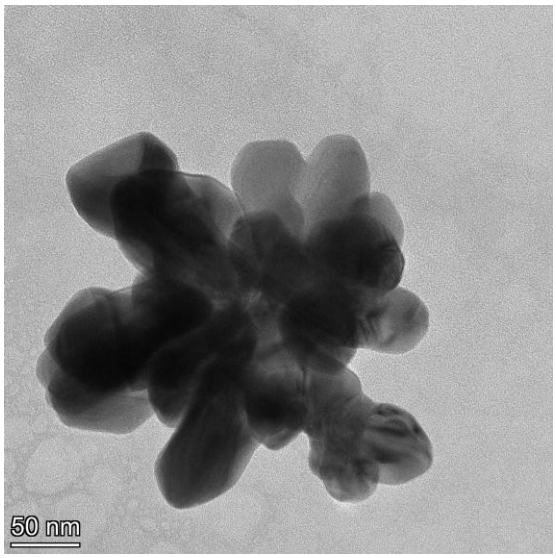
Currently, no robust, well-established method exists that can create high entropy alloy nanoparticles or microparticles consisting of any composition of elements. In this paper, we explore the flexibility of a plasma-based synthesis technique which consists of positive and negative polarity pulsed DC discharges at a voltage of 20 kV, a frequency of 10 Hz, and a pulse width of 500 ns in cyclohexane between a pin working electrode and an aqueous metal salt solution counter electrode.

This work is based on two previous papers from our group which used the same method but with only positive polarity discharges and with metal salts with close reduction potentials [1,2]. To test the limits of this method, metal salts were chosen specifically for their wide range of reduction potentials. Whether chromium can be reduced and whether the elements form one solid solution or remain segregated into separate crystal structures or separate amorphous domains after reduction reflects the robustness of the method.

Total concentrations of around 40 mM were used for all combinations of elements, and all combinations of chromium, cobalt, and silver were tested with positive and negative discharges. In addition, to test the effect of high concentration and high counter electrode conductivity, two 200 mM solutions of silver were treated with positive and negative polarity discharges.



EDS spectra of this image suggested an elemental composition of ~0.3 Cr, ~0.4 Co, and ~0.3 Ag. Upon further TEM investigation we discovered that the particle consisted of domains of Ag as individual crystals or amorphous sections rather than a single CrCoAg crystal lattice.

Electrode-electrode distance had to be continuously adjusted during experiments to maintain the discharge. To explain the fact that both positive and negative polarity discharges in cyclohexane are sensitive to minute changes in interelectrode distance, a simple model was created which showed that shorter electron mean free paths, like those expected in cyclohexane, require shorter interelectrode distances to maintain discharges and are more sensitive to changes in interelectrode distance.

Preliminary results show that for negative discharges at equimolar concentrations of chromium, cobalt, and silver, silver is unable to form shared crystalline domains with chromium and cobalt.

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Defect Formation in Graphene via Localized and Global Energy Deposition in Filamentary and Diffuse Dielectric Barrier Discharges

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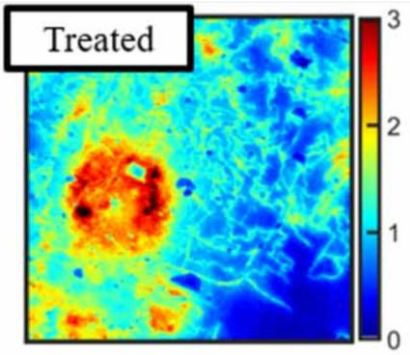
Understanding defect formation induced by non-equilibrium plasmas is essential for controlling material properties in applications from surface functionalization to thin-film processing [1]. In this work [2], we investigate energy deposition pathways in low-frequency (1 kHz) dielectric barrier discharges (DBDs), focusing on the contrast between filamentary and diffuse regimes. Unlike previous studies requiring pressure changes [3], a direct comparison is achieved by varying only the applied voltage waveform. Large-area CVD monolayer graphene is used as a model system, with defect generation characterized by hyperspectral Raman imaging to obtain high-resolution maps of defect density. This approach enables direct correlation between discharge behavior and spatial energy deposition, providing insight into how localized and distributed plasma inputs govern defect formation.

The filamentary and diffuse regimes are first compared using a fixed number of cycles (30,000), both yielding homogeneous modification. However, the filamentary regime strongly alters the atomic structure, converting graphene into amorphous carbon, whereas the diffuse regime largely preserves its Raman signature, indicating milder modification. To probe local energy deposition, a shorter filamentary treatment (1,000 cycles) is performed, revealing localized filament impacts with strong defect density gradients. Raman mapping shows defective regions of ~40 µm in diameter, while AFM reveals much smaller craters (~2 µm), highlighting highly localized damage alongside more extended defect formation.



130 x 130 μm^2 mapping of the I_D/I_G Raman ratio, which is linked to defect density, of the short treatment.

To understand the observed defect formation, a comprehensive analysis of energy deposition pathways is conducted. A discussion on localized versus global energy deposition is developed based on the various parameters extracted from both discharge diagnostics and graphene characterization. This fundamental study demonstrates, at the atomic scale, that localized energy deposition can lead to defect states equivalent to those produced by globally distributed energy input, provided that the total deposited energy is comparable. These findings provide a foundation for advancing atmospheric-pressure plasma processing, where atmospheric pressure DBDs offer unique opportunities to tailor material properties through controlled energy deposition pathways.

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Modulation of Localized PMMA Coatings by Carrier Gas in AP-PACVD

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This work investigates the localized deposition of poly(methyl methacrylate) (PMMA) films produced by atmospheric pressure plasma-activated chemical vapor deposition (AP- PACVD) operated in a dielectric barrier discharge (DBD) configuration. The study focuses on how the carrier gas composition—argon, nitrogen, and Ar/N_2 mixtures—affects the plasma chemistry and, consequently, the structure and optical behavior of the resulting coatings.

Chemical and optical analyses were performed using FTIR spectroscopy, UV–Vis, and XPS. FTIR analyses showed that all plasma-polymerized spots preserved the characteristic PMMA bands, with variations in peak broadening and intensity depending on the discharge gas. Ar-based plasmas preserved the ester structure more effectively whereas N_2-containing discharges induced broader, weakened ester peaks together with signatures of nitrogen incorporation and partial ester modification. This chemical modification resulted in a distinct yellow-orange color, associated with additional electronic transitions in the 320–340 nm region [1]. XPS analyses supported these findings, showing PMMA-like C 1s signatures for Ar-derived films and increased C–N/C=N contributions for N_2-based deposits.

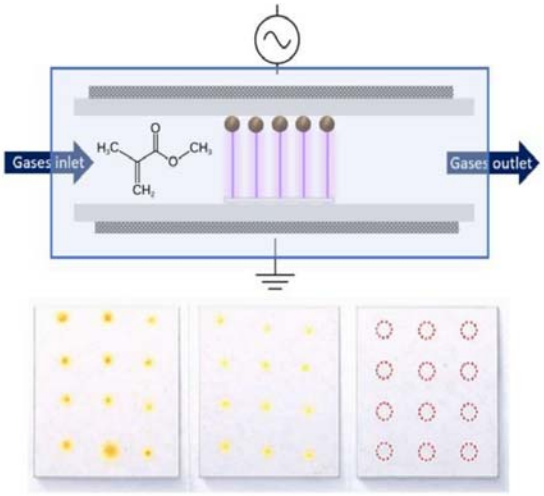

Figure 1. Localized AP-PCVD DBD setup for PMMA deposition.

The observed differences arise from the contrasting plasma activation mechanisms. Argon, being inert, primarily transfers energy through physical excitation and efficient ionization, promoting cohesive and homogeneous polymer networks [2]. In contrast, nitrogen introduces reactive species that modify surface functionalities but can also destabilize film growth under certain conditions [3]. These results demonstrate that the carrier gas composition is a crucial parameter for tailoring the chemical structure, crosslinking density, and optical response of PMMA coatings under localized APPCVD conditions [4].

This study highlights the versatility of plasma polymerization for microscale patterning and surface functionalization. Localized AP-PACVD enables micron-scale deposition and controlled chemical tuning without vacuum infrastructure [5], making it a promising technique for advanced surface engineering. The ability to modulate plasma chemistry through gas composition opens new perspectives for designing functional polymer coatings with spatially selective properties.

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Influence of plasma treatment conditions on the production of reactive species in water and on the modification of its surface tension

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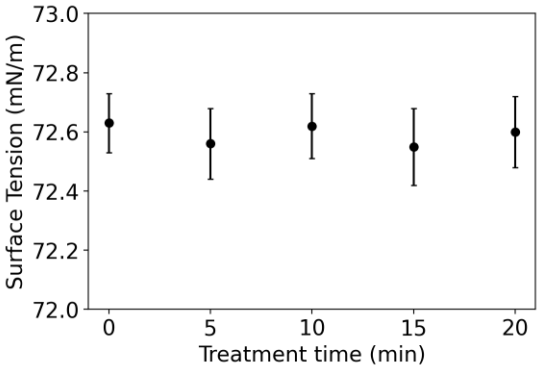
The processing of water with plasmas enriches it with reactive species, mainly NO_3^- and H_2O_2, with concentrations on the order of tens to hundreds of milligrams per liter. The presence of these reactive species in water makes it attractive for many applications such as medicine, agriculture or nanomaterial synthesis.

In this work, we investigate the reactive oxygen and nitrogen species produced by electrical discharges generated in air in contact with water. We study plasma-water interactions in two configurations: discharge in air in-contact with water and discharges with aerosol. In this contribution, we present a complete characterization of the plasma-modified water with a particular focus on water surface tension. Indeed, the consensus is that plasma-produced nitrate in water decreases the surface tension of plasma activated water. While plasma-produced NO_3^- concentrations are generally in the range of hundreds of milligrams per liter, the concentration of HNO_3 needed to significantly modify the surface tension of water is in the hundreds of grams per liter, i.e. three orders of magnitude higher. We performed measurement of water containing nitric acid with plasma-processed water in both configurations (discharge with water and with aerosol), and a striking discrepancy was observed. Experimental measurements of water processed by plasma show no change in surface tension. These results call into question the results of multiple studies reporting changes in water surface tension. If long-lived reactive oxygen and nitrogen species such as H_2O_2 and NO_3^- cannot account for the measured variations, other factors must be at play and remain to be identified.



Surface tension of plasma activated water as a function of treatment time

On the other hand, measurements performed on plasma-aerosol system showed that NO_3^- and H_2O_2 concentrations are independent of treatment time and depend instead on the flow rate of water. Furthermore, among different discharge types through water aerosols, preliminary results suggest that spark discharges are 20 to 30 times more efficient in the production of nitrate compared to streamer discharges. Additional findings on the effect of discharge frequency and initial conductivity of aerosol suggest an increasing trend in reactive species concentration as a function of frequency or conductivity, respectively.

These results highlight the importance of chemical analysis for the determination of plasma activated water properties. Understanding these results could allow for targeted delivery of reactive species using plasma discharges.

Impact of water-filled biofilm in plasma decontamination of endoscopes

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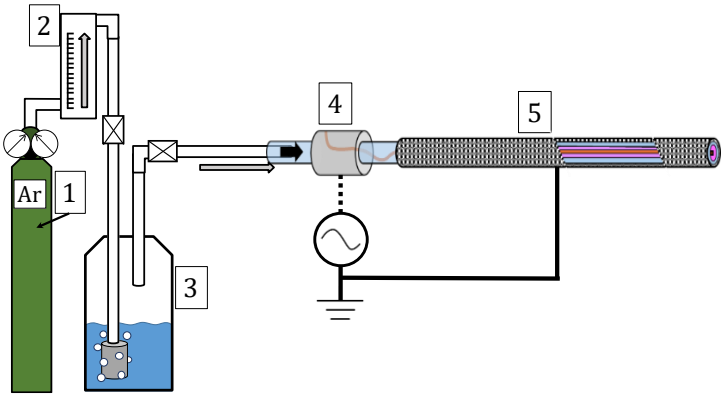
Endoscopic surgery is confronted with a significant challenge in the context of its decontamination procedures. A notable proportion of endoscopes have been observed to retain bacterial contamination and, more pertinently, biofilms following the cleaning process [1]

Cold atmospheric plasma (CAP) has the potential to play a significant role in public health. Indeed, plasma presents antibacterial properties [2]. The efficacy of CAP in decontaminating endoscopes, was studied. A plasma device was designed in order to offer an alternative for decontamination and plasma parameters such as gas mix (Ar/H_2O), flow (1.5 L/min) and power (15-17 W) were optimized for the purpose of anti-bacterial properties and biofilm etching properties [3]. The present study focuses on the impact of the presence within the channel of the endoscope of water-filled biofilm on plasma characteristics.

A combination of tubes was utilized to replicate the endoscope, with a soaked thread being inserted into the main tube, which was composed of PTFE to simulate the presence of a water-filled biofilm. As established by previous studies, Reactive Oxygen Species (ROS) play a major role in the plasma for the decontamination process [3]. The presence of hydroxyl radicals was therefore measured with OES, and the formation of H_2O_2 was followed using a titration method. The experiment involved the use of a high-speed camera to compare the volume of the plasma and its glow in the presence and absence of the soaked thread. The electrical characteristics of plasma (voltage, current, power) were analyzed using a high voltage probe and an oscilloscope.



Schematic view of the plasma device and the endoscope-like tubes 1: argon gas, 2: flowmeter, 3: water bubbler, 4: DBD discharge, 5: endoscope imitation

Results show that the gas flow and the heat generated by the plasma lead to the slow drying of the thread. The emission of hydroxyl radicals and H_2O_2 titrations exhibit a modest decline in intensity, followed by a notable escalation, culminating in a plateau phase. The values of the plateau are equivalent to the value when no soaked thread is present, suggesting that the thread is totally dried. However, the lower values recorded at the beginning suggest that the ROS are first absorbed into the water/ biofilm, which is consistent to the rapid decontamination of the bacteria. The images showed a similar pattern.

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Effects of Cold Atmospheric Plasma on Microbial Inactivation, and Quality Changes of Mechanically Fluidized Maize Flour

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Atmospheric cold plasma (ACP) is created by a strong electric field that accelerates free electrons, which in turn dissociate, excite, or ionize gaseous molecules [1]. As a result, it contains a vast array of reactive particles, as well as quanta of electromagnetic energy, photons, and visible light [2]. It is considered non-thermal as characterized by temperature close to the ambient one. ACP was found to successfully deactivate a varied range of microorganisms including fungi, spores and viruses in variety of food products. Cereals, such as rice (*Oryza sativa*), wheat (*Triticum aestivum* L.), and maize (*Zea mays* L.), are of paramount importance for human nutrition and are grown in many areas of the world [3]. However, cereal grains are susceptible to contamination during ripening, harvesting, processing and storage.

Controlling microbial contamination in flour remains a significant food safety challenge worldwide. Conventional and currently applied decontamination technologies often compromise product quality, provide uneven treatment, raise safety concerns, and mainly exert superficial effects on powders. To address these limitations, a prototype system integrating atmospheric cold plasma (ACP) with mechanical fluidization was developed and applied to naturally contaminated maize flour for 5, 10, 20, and 30 min.

Microbial inactivation, physicochemical properties, particle size distribution, and microstructural characteristics were systematically evaluated. Mesophilic aerobic bacteria were progressively reduced as treatment time increased, with complete inactivation achieved after 30 min; however, bacterial regrowth was detected after 16 days of storage. Filamentous fungi were fully inactivated after only 10 min, and although partial recovery occurred during storage, fungal loads remained consistently lower than those of the untreated control. ACP treatment also affected fungal diversity, with *A. flavus* showing greater sensitivity than *A. oryzae*. Longer plasma exposures resulted in slight reductions in moisture content and water activity, indicating limited dehydration effects. Changes in particle size distribution and surface morphology were observed, likely associated with plasma etching, electron bombardment, and surface erosion phenomena.

Overall, the effectiveness of ACP treatment depended strongly on exposure time and fungal species. These results highlight both the potential and the limitations of ACP combined with fluidization as a nonthermal strategy for flour decontamination, while largely preserving the essential physical quality attributes required for further processing and consumer acceptance.

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