Electrical equivalent model of a long dielectric barrier discharge plasma jet for endoscopy

To cite this article before publication: Orianne Bastin et al 2023 J. Phys. D: Appl. Phys. in press https://doi.org/10.1088/1361-6463/acb603

Manuscript version: Accepted Manuscript

Accepted Manuscript is “the version of the article accepted for publication including all changes made as a result of the peer review process, and which may also include the addition to the article by IOP Publishing of a header, an article ID, a cover sheet and/or an ‘Accepted Manuscript’ watermark, but excluding any other editing, typesetting or other changes made by IOP Publishing and/or its licensors”

This Accepted Manuscript is © 2023 IOP Publishing Ltd.

During the embargo period (the 12 month period from the publication of the Version of Record of this article), the Accepted Manuscript is fully protected by copyright and cannot be reused or reposted elsewhere.

As the Version of Record of this article is going to be / has been published on a subscription basis, this Accepted Manuscript is available for reuse under a CC BY-NC-ND 3.0 licence after the 12 month embargo period.

After the embargo period, everyone is permitted to use copy and redistribute this article for non-commercial purposes only, provided that they adhere to all the terms of the licence https://creativecommons.org/licences/by-nc-nd/3.0

Although reasonable endeavours have been taken to obtain all necessary permissions from third parties to include their copyrighted content within this article, their full citation and copyright line may not be present in this Accepted Manuscript version. Before using any content from this article, please refer to the Version of Record on IOPscience once published for full citation and copyright details, as permissions will likely be required. All third party content is fully copyright protected, unless specifically stated otherwise in the figure caption in the Version of Record.

View the article online for updates and enhancements.
Electrical equivalent model of a long dielectric barrier discharge plasma jet for endoscopy.

Orianne Bastin$^{1,2}$, Max Thulliez$^{1,2}$, Teo Serra$^{1}$, Linus Nyssen$^{2}$, Thomas Fontaine$^{2}$, Jacques Dëvière$^{3}$, Alain Delchambre$^{1}$, François Reniers$^{2}$, Antoine Nonclercq$^{1}$

$^{1}$Bio-, Electro- and Mechanical- Systems (BEAMS), Blended Group, Ecole polytechnique de Bruxelles, Brussels, Belgium.
$^{2}$Chemistry of Surfaces, Interfaces, and Nanomaterials, ChemSIN, Université libre de Bruxelles, Faculty of Sciences, Brussels, Belgium.
$^{3}$Department of Gastroenterology, Hepatopancreatology, and Digestive Oncology, C.U.B. Erasme Hospital, Université Libre de Bruxelles, Brussels, Belgium.

E-mail: Orianne.Bastin@ulb.be, Antoine.Nonclercq@ulb.be

October 2022

Abstract. Cold atmospheric plasmas are a known source of reactive species enabling various treatments, from the healing of chronic wounds to the treatment of surface cancers. Therapeutic endoscopic procedures require developing specific flexible tools that can be used through or alongside endoscopes. Plasma devices for endoscopy have aroused significant research interest over the past few decades, but their electrical behaviour is not yet fully understood and predictable. There is thus a clear need for a robust model that provides a way to understand and optimize future devices. In this work, for the first time, an electrical equivalent model of a long plasma source (comprising plasma generation, transport and target interaction) was designed, implemented, and validated. System parameters were estimated based on the system geometry and independent measurements. The model reliably reproduces the double ignition (in the quartz chamber and at the treatment site) observed experimentally. Simulations globally agree with measurements taken for various gas gap distances and input voltages. Internal parameters that are difficult to measure, such as the electrical charge at the gas gaps, were inferred. The model can predict leakage current in the body and current at the target site. This work provides a new understanding of endoscopic plasma systems that could be used in the future to ensure patient and operator safety.

Keywords: Electrical equivalent, dielectric barrier discharge, plasma medicine, cold atmospheric plasma, endoscopy, model.

1. Introduction

Cold atmospheric plasmas (CAPs) are a known source of reactive oxygen and nitrogen species (RONs) and, consequently, can impact the redox biology equilibrium of living
cells by a natural mechanism called oxidative stress \cite{1,2}. Depending on the dose of plasma administered, various effects can be triggered by oxidative stress \cite{3} (e.g., cell proliferation, migration, apoptosis, necrosis), enabling various treatments such as healing of chronic wounds \cite{4,6}, sterilization of oral cavity and dental canals \cite{7}, tooth bleaching \cite{8}, or treatment of surface cancers \cite{9}. The selectivity of plasma treatment for cancer cells (over healthy cells) has been observed \cite{10,14}. This is associated with their intrinsically higher levels of RONS before treatment, making cancer cells more vulnerable to oxidative stress as the threshold for triggering apoptosis is reached more quickly. These treatments are part of the emerging field of plasma medicine \cite{15} which has grown significantly in the last 15 years. Simultaneously, there has been growth in the development of therapeutic endoscopy procedures, ranging from tumour resection to biliary stone removal \cite{16,19}. These procedures require developing specific flexible tools that can be used through or alongside endoscopes.

CAP devices for endoscopy have aroused significant research interest. The GREMI (Groupe de Recherches sur l’Energétique des Milieux Ionisés, from Orléans) has developed a plasma gun for endoscopic treatment in the area of anti-cancer therapy. It is a plasma device based on a dielectric barrier discharge (DBD) with sub-\(\mu\)s voltage pulses from 2 to \(20\,kV\) \cite{20} in various gases (He, Ar, Ne), with an outer electrode surrounding a dielectric tube containing the inner electrode and extended by a flexible tube. The Leibniz endoscopic plasma system, the kINPen MED, brings high voltage to the treatment site with two flat wire electrodes (high voltage and ground) wrapped around an inner tube and encased in an insulating material \cite{21}. To effectively transport CAP over long distances while avoiding bringing high voltage inside the body (as in the KINPen arrangement), Kostov et al. \cite{22} developed a plasma propagation system enclosed in long tubing for sterilization purposes. Its main feature is the use of a copper wire inside the catheter, which is left at floating electrical potential, i.e., it has no direct contact with the power supply or the ground. The plasma is ignited inside a DBD reactor composed of a high-voltage electrode embedded in a closed quartz tube, and greatly decreases in intensity when meeting the copper wire tip and all along the tube, to finally reignite at its extremity. A similar arrangement has been patented \cite{23} and studied by Bastin et al. upon sinusoidal \cite{24} and nano-pulsed \cite{25} excitation voltage. Finally, a device from Kobe University uses a sophisticated 3D printed titanium distal head (2.8 \textit{mm} in diameter), including an inner and outer electrode arrangement connected to high-voltage and separated by insulating material (alumina) in a DBD setup. In 2018, they reported the first CAP treatment by endoscopy \cite{26} \textit{in vivo}, i.e., not only using an endoscopic plasma solution on external tissues as for other endoscopic plasma sources.

This progress toward a solution for transporting active plasma is encouraging. However, long plasma jet behaviour upon different excitation signals is not yet fully understood and predictable. If plasma endoscopic devices are to be used in the hospital, there is a clear need for a robust model allowing us to (i) fundamentally understand the underlying mechanisms governing the device to allow for inference of internal parameters that are impossible to measure for practical reasons, (ii) optimize the device during its
An electrical model for predicting the behaviour of such a nonthermal plasma source suitable for endoscopy does not exist yet. However, DBD reactors have already been modelled as introduced by Manley in 1943 and are now widely accepted [27–30]. These basically consist of one power supply and a discharge reactor containing a dielectric. Figure 1a shows this electrical equivalent circuit for a single dielectric layer discharge. The dielectric layer, modelled by a capacitor $C_d$, is in series with the gas gap. The electric equivalent of this consists of a capacitor $C_g$ modelling the capacitive behaviour of the gas space, in parallel with a time-variable impedance modelling the conductive behaviour of the plasma. The impedance of the gas gap is large before plasma ignition, when the gas, not ionized, behaves as an insulator. Hence, in that situation, $R_p$ is large. As soon as the voltage applied at the gas limits $V_g$ exceeds the breakdown voltage $V_b$, the gas becomes partially ionized, and $R_p$ drops. The current flowing through the gas gap, when the plasma is not ignited, is called displacement current or capacitive current. The discharge current or conductive current appears when the plasma is ignited [31,32].

![Figure 1](image.png)

Figure 1: (a) Electrical equivalent of a DBD plasma reactor. $V_a$, $C_g$, $C_d$, and $R_p$ stand for applied voltage, gas and dielectric capacitors, and plasma time-variable resistor, respectively (b) Schematic of a typical QV-plot for the sinusoidal voltage applied. $C_{OFF}$ is the equivalent capacitance value of $C_g$ and $C_d$ in series, $Q(t)$ is the total charge obtained by integration of $I_{tot}(t)$ and $V_a(t)$ is the applied voltage. The passive (plasma OFF) phase is green, and the active (plasma ON) discharge phase is violet.
Electrical equivalent model of a long dielectric barrier discharge plasma jet for endoscopy.

By Kirchhoff’s laws, $I_{\text{tot}}$ is simply the sum of $I_{\text{disch}}$ and $I_{\text{disp}}$, and $V_a$ is the sum of $V_d$ and $V_g$. When the amplitude of the applied voltage is insufficient to induce a discharge, the resistance of $R_p$ is very large, and the gas behaves as an insulator. The system behaves capacitively with a value $C_{\text{OFF}}$ corresponding to $C_d$ and $C_g$ in series. In this approach, drawing the Lissajous diagram is particularly convenient since it allows for deduction of the internal parameters of any plasma system by only measuring the applied voltage $V_a$ and the total current $I_{\text{tot}}$. Indeed, the charge-voltage characteristic is, for the off-phase:

$$I_{\text{tot}} = C_{\text{OFF}} \frac{dV_a}{dt} \quad (1)$$

$$\Rightarrow \int_0^t I_{\text{tot}} \, dt = C_{\text{OFF}} V_a \quad (2)$$

$$\Rightarrow Q(t) \pm Q_0 = C_{\text{OFF}} V_a(t) \quad (3)$$

where $C_{\text{OFF}}$ is the equivalent capacitance value of $C_d$ and $C_g$ in series, $Q$ is the total charge obtained by integration of $I_{\text{tot}}$ and $Q_0$ is a constant charge (in absolute value) deposited on the plate of the dielectric capacitor. Equation 3 is visible in figure 1b. Then, when the applied voltage reaches a given value, the gas voltage overcomes the breakdown voltage, the plasma ignites, and the gas resistance drastically drops.

According to Manley’s theory [27], from this point, $V_g$ is constant (and equals $V_p$ in figure 1b) and only depends on pressure and inter-electrode gap distance (as predicted by Paschen’s Law [33]). Many alternatives have been proposed, based on Manley’s electrical equivalent circuit. More precisely, the dynamics of the time-variable impedance of figure 1a has been modelled in different ways by various teams [34–46]. However, these models do not simulate the behavior of a long plasma jet in a catheter of 2 meters.

This study describes a new electrical model of a long plasma jet suitable for endoscopy. The device consists of a cylindrical quartz chamber around which a copper electrode is wrapped and connected to a polytetrafluoroethylene (PTFE) tube of 2 meters. The plasma is generated outside the body (for safety reasons) and reignites two meters away. There is, therefore, a double plasma ignition (outside the body and at the target). Since the device is complex, we chose to first validate our model on a subpart of the system, simplifying the analysis. This first analysis covers the simple reactor, i.e., the quartz chamber near the high voltage electrode. Then, the model and analysis are extended to the entire device, including also the flexible tube, and the plasma plume applied to a conductive target.

2. Materials and methods

2.1. Methodology

The methodology followed to build both plasma jet models (the simple reactor and the entire device) is the following:

(i) A typical experimental current $I_{\text{tot}}(t)$ waveform obtained with a sinusoidal applied
Electrical equivalent model of a long dielectric barrier discharge plasma jet for endoscopy.

Voltage $V_a(t)$ at the electrode is qualitatively analysed to explain the physical phenomenon occurring in the system.

(ii) Based on (i), a model made of passive electrical components is derived along with an assumption of the curve profiles of internal variables such as the charge accumulating at the gas boundaries or the current flowing through the gas capacitor.

(iii) The model parameters are then quantitatively determined based on geometrical considerations and additional experiments (e.g., targeting the influence of the applied voltage amplitude).

Finally, with both implemented models, the simulations are compared to experimental measurements, and presented in the Results section. The model’s sensitivity to key parameters is assessed.

2.2. Experimental setup

Figure 2 depicts the device modelled in this work. It consists of a tubular DBD chamber made of quartz (outer diameter (OD) of 7 mm, inner diameter (ID) of 5 mm), where helium is flushed from the gas cylinder through an admission valve, a flowmeter, and enters the quartz chamber. The high voltage electrode consists of a copper tape wrapped around the chamber over 4 cm. This latter is plugged into a PTFE tube (with an outer diameter of 3 mm to enter the endoscope and a wall thickness of 0.75 mm to ensure electrical insulation) transporting the plasma post-discharge over 2 m. Please note that the distance upstream of the first reactor does not influence the plasma generation, since the plasma is not ignited at this level. The fluidic connection between the quartz chamber and the PTFE capillary is made with a heat shrinkable insulating sleeve. A copper rod (0.8 mm diameter), maintained at the centre by two machined PTFE parts (5 mm long cylinders drilled longitudinally with 9 holes), extends inside the quartz chamber and is soldered to a copper wire (0.2 mm diameter). This latter extends until the end of the PTFE tube, allowing for the maintenance of active plasma for several meters and sustaining a plasma plume at the outlet even at low power, similar to the work of Kostov et al. [22] or Bastin et al. [24,25,47]. The copper wire runs inside the PTFE capillary up to 5 mm before the capillary’s end. The AC-Sinusoidal high voltage source is a power-controlled AFS (GI0S-V) generator, operating at 18 kHz and delivering a peak voltage up to 15 kV. Any target reached by the plasma plume is an electrical component between the plasma and the ground reference, and will influence the electrical behaviour of the whole system. The human box (HB) is the electrical circuit shown in figure 2 and used to mimic the average impedance of a human body [48].

Electrical measurements were collected with a WaveSurfer 3024z oscilloscope connected to high-voltage probes (Tektronix P6015A x1000 3pF 100 MOhms) and current monitors (Rogowski coil Pearson model 2877 output 1V/A and 6595 output 2V/A). Probes were placed as shown in figure 2.

In contrast to other typical DBD reactors, in this system, plasma is observed to be ignited first inside the quartz chamber (between the quartz barrier and the copper rod),
Electrical equivalent model of a long dielectric barrier discharge plasma jet for endoscopy.

Figure 2: Schematic of the plasma system with probe positions. \( V_a(t) \) is the input applied voltage measured at the high voltage electrode, \( I_{\text{tot}}(t) \) is the instantaneous total current flowing from the generator to the high voltage electrode, \( I_{\text{tube}} \) is the current flowing inside the tube measured around the PTFE capillary, \( I_{\text{out}} \) is the current through the target and \( d \) is the gas gap distance.

then it is flushed all the way inside the PTFE capillary, to finally "reignite" at the copper wire end (the light emitted by the plasma fades out inside the tube but shines again at the end), as shown in figure 3. In terms of an electrical equivalent circuit, this specific configuration is schematically represented in figure 4 where the red rectangles highlight the two system subparts mentioned before. From left to right, the first pink rectangle indicates the plasma appearing inside the quartz chamber, connected to the copper wire running inside the capillary. A capacitor models the capacitive behaviour of this latter with its surroundings. Finally, the plasma plume at the tube exit is represented by a capacitor in parallel with a variable resistor.

The simple reactor (the quartz chamber with the first plasma discharge), shown in the first red rectangle, was analysed alone in the first instance (in section 2.3.1). To this end, a cylindrical reactor, much simpler, was built, as depicted in figure 5. The copper rod is directly connected to the ground to measure the applied voltage and input current flowing only through the plasma ignited in the quartz chamber. Then, in a second step, the capillary, the plasma plume bloc, and the target were added to the model to study the whole system (in section 2.3.2), corresponding to the second red rectangle in figure 4.

Figure 3: Copper wire, plasma reignition, and plasma plume at the end of the device.
Electrical equivalent model of a long dielectric barrier discharge plasma jet for endoscopy.

Figure 4: Electrical equivalent circuit of the endoscopic plasma jet. $I_{tot}$ is the input current. $V_a$ is the applied voltage. $I_{disch}$ represents the current flowing through the ignited plasma, and $I_{disp}$ the current without plasma. $C_{dq}$, $C_{dPTFE}$, $R_c$, $C_{probe}$, $C_g$, and $R_p$ are the dielectric capacitance values (of quartz and PTFE), the dielectric losses, the probe capacitance, the gas capacitance (between the quartz wall and the copper rod first, and then between the tip of the copper wire and the target), and the plasma variable resistance (at both ends of the copper central rod or wire), respectively.

Figure 5: (a) Cylindrical plasma reactor without capillary, for modelling the plasma inside the quartz chamber. (b) Dimension of the quartz chamber.

2.3. Model

2.3.1. Model of the simple reactor

(i) Experimental measurements. The total current was recorded in a system excited with a 5 kV 18 kHz sinusoidal voltage, as shown in figure 6. The corresponding Lissajous diagram is presented in figure 7. The voltage extrema can be seen on the blue parallelogram (4.77 kV and -4.83 kV, the two vertices corresponding to numbers 1 and 4) and are also indicated in the voltage temporal evolution in figure 6. From this
Electrical equivalent model of a long dielectric barrier discharge plasma jet for endoscopy.

Point, subscripts $a$, $p$, $n$, and $i$ stand for applied, positive polarity, negative polarity, and plasma ignition, respectively. Between the voltage peak value (4.77 kV) and the ignition value (3.78 kV), corresponding to the shaded zone in figure 6, the plasma is off, and the slope of the QV curve reflects the capacitance of the whole reactor without plasma. Then, at $t_{ip}$, a large current peak is visible. It appears when the absolute value of the applied voltage decreases and reaches a specific value (3.78 kV for positive and -3.57 kV for negative polarities). Those values correspond to the two other parallelogram vertices, indicated with numbers 2 and 3.

![Figure 6: Measured applied voltage $V_a$ and resulting total current $I_{tot}$ obtained with the simple reactor from figure 5a. $\Delta V_p$ and $\Delta V_n$ are the positive and negative applied voltage differences observed for plasma ignition.](image)

The system behaviour can be explained in terms of charge motion. At $t_{max}$, the applied voltage is maximal, and its slope equals zero. Therefore, there is no charge motion, and one can assume a specific charge distribution from previous discharges (or past system states). Then, this voltage starts to decrease, inducing a motion of charges inside the dielectric and a displacement current. During the time interval from $t_{max}$ to $t_{ip}$, this displacement current brings charges at the gas boundaries until a given threshold is reached at $t_{ip}$, where a discharge ignites. It will last as long as charges keep arriving through the reactor, so as long as the current through the dielectric layer is positive. The displacement current becomes null when the voltage slope equals zero, at $t_{min}$. Once again, a given charge distribution has been established, and the system is in relative equilibrium regarding charge motion. Then, from its minimal value, the voltage rises again, making the dielectric outer surface "less negative" until a specific value ($-3.57 V$)
Figure 7: Lissajous diagram or QV curve experimentally recorded. The total charge is obtained by total current ($I_{tot}$) integration, and the voltage is the applied voltage ($V_a$). Numbers correspond to a change of total capacitive behaviour of the system (i.e., plasma ignition or extinction).

at which enough charges have accumulated on the inner dielectric surface and are once again freed from the dielectric to flow into the gas. With this approach, we expect a constant maximal charge accumulation at the ignition point for a given reactor geometry made of given materials. It implies a constant current integral and, in turn, for a sine wave excitation, a constant $\Delta V$ between the maximal (respectively minimal) voltage and the ignition voltage as this difference would be the biggest voltage difference that the system (dielectric layer and gas gap) can afford without plasma ignition, whatever the absolute maximum applied voltage value is.

This interpretation of the motion of the charges led us to suggest a straightforward model described in the next section.

(ii) Suggested model The model proposed to represent this situation is shown in figure 8. It consists of a switch that would close when a given charge has accumulated, simulating plasma ignition. The capacitor $C_{dq}$ stands for the dielectric quartz layer. It is then connected to the capacitor $C_g$, which represents the non-ignited helium gas gap, with which the variable plasma resistor is in parallel. This variable resistor is modelled by the conditional switch in series with a constant resistance. The switch is controlled by
the applied voltage, rather than the accumulated charge, for practical reasons. Indeed, the applied voltage can be directly measured (which is not the case for the accumulated charge) and we have shown in the previous section the direct link between the applied voltage and the accumulated charge.

The expected behaviour for this simple model is schematically presented in figure 9 with sketches of the applied voltage, the corresponding total current, and the charge across gas boundaries over time. As indicated in the figure, starting from the beginning of zone 1, the applied voltage (blue curve) has a zero first derivative, resulting in a zero current (red curve), and one can assume that a given charge (green curve) is already present on the inner dielectric surface. Then, the voltage decreases, and a negative current flows through the system, leaving the gas boundary negatively charged. This negative charge increases until the threshold where plasma appears, i.e., the switch closes, and it is the beginning of zone 2. The voltage still decreases, giving a negative total current $I_{\text{tot}}$ and a given variable charge at the gas boundary. At $t_{\text{min}}$, the voltage-time derivative equals zero, as does the current, so there is no further charge brought to the reactor. When voltage starts to increase, the whole situation is repeated in the opposite polarity, with a positive current and a positive charge accumulating at the gas boundary (at the dielectric side).

![Electrical equivalent model implemented in Simulink MATLAB](image)

Figure 8: Electrical equivalent model implemented in Simulink MATLAB [49]. $C_{dq}$, $C_{\text{Probe}}$ and $C_g$ are the dielectric, probe and gas capacitance values, $R_p$ and $R_c$ are the ignited plasma and dielectric resistances, $V_a$ is the applied voltage and is an input of the model, $I_{\text{tot}}$ is the current flowing through the system.

With this model, we now can determine the parameters for each component.

(iii) Parameter determinations The parameters to be determined are the switch conditions (for closing and opening), the capacitance values, and the ignited plasma resistance value.

Switch condition
Figure 9: (left) Schematic of the applied voltage ($V_a$), the total current ($I_{tot}$), and the charges accumulated at the gas capacitor ports ($C_g$). Blue and pink dashed lines represent switch opening and closing, respectively. (right) corresponding states of the system, in zone 1 to 4. $C_{dq}$, $C_g$ and $R_p$ stand for the dielectric capacitance, the gas gap capacitance and the ignited plasma resistance, respectively.

Lissajous diagrams were drawn for various values of peak voltage (2.5 kV, 5 kV, 7.5 kV, and 10 kV), as represented in figure 10. Plain arrows indicate $\Delta V$. Dashed arrows indicate the width of the parallelogram-like shape when $Q = 0$, which depends on the peak applied voltage. Figure 11 gives $\Delta V$ as a function of the peak voltage applied. As
Electrical equivalent model of a long dielectric barrier discharge plasma jet for endoscopy. Expected (see plain arrows in figure 10), the difference $\Delta V$ between the highest applied voltage and the value at which the current peak appears (i.e., when plasma ignites) is constant independently of the voltage amplitude. However, this difference depends on the polarity and is slightly higher for negative polarity ($1250 \pm 74 V$ on average) than for positive one ($1014 \pm 27 V$ on average).

$$\Delta V_p = V_{a_{\text{max}}} - V_a(t_{\text{ip}}) = 1014V$$

$$\Delta V_n = -V_{a_{\text{min}}} + V_a(t_{\text{in}})_n = 1250V$$

As the system is not symmetrical across the gas gap, the second emission coefficient (probability to emit an electron when hit by an ion) is not identical for quartz and copper, explaining this different threshold for plasma ignition for each polarity.

Figure 10: Lissajous diagram or QV curve experimentally recorded for different applied peak voltages. Dashed arrows show the width of the QV diagram for $Q = 0$, and plain arrows show the $\Delta V$ when plasma is off.

**Capacitors**

The model capacitors $C_{dq}$ and $C_g$ were estimated based on measured QV curves. Please note that they can also be based on geometrical considerations or direct impedance measurement, as detailed in Appendix A. As shown in figure 10, Lissajous diagrams were recorded for several values of peak voltage, and the slopes of QV parallelograms were computed and averaged (the experiment was repeated on two different reactors and for four different peak voltages). The steep slope gives the value of $C_{dq}$ and the small one $C_{OFF}$. The gas capacitance $C_g$ is then deduced from those two values since
Electrical equivalent model of a long dielectric barrier discharge plasma jet for endoscopy.

Figure 11: Experimental values of \( \Delta V \) for positive and negative polarities, for values of peak voltage from 2.5 kV to 10 kV.

\[
\frac{1}{C_{OFF}} = \frac{1}{C_{dq}} + \frac{1}{C_g}. \quad \text{A constant value of } 12 \text{ pF was obtained for } C_{OFF} \text{ (the slope between 2 and 1 or 4 and 3 in figure [7]). When plasma is not ignited, the probe’s capacitance is not negligible (} C_{probe} = 3 \text{ pF), and it has to be subtracted from the } C_{OFF} \text{ value. The second slope (} C_{dq} \text{) was found to vary as a function of the applied voltage amplitude. Values obtained by curve fitting between the simulated QV curves and the experimental values are reported in figure [12]. A linear relation with } R^2 = 0.9996 \text{ (least square method) was found:}
\]

\[
C_{dq} = 0.52 \frac{pF}{kV V_{a-pp}} + 27.8 \text{ pF}
\]

where \( V_{a-pp} \) is the applied voltage peak to peak.

Plasma resistance value

The last unknown parameter is the constant resistance value of the plasma. Figure [13] shows the simulated input current and corresponding QV curves for different values of \( R_p \) and \( C_{dq} \). Changing the plasma resistance value mainly impacts the current peak when the plasma starts to ignite. In contrast, the capacitance value mainly influences the current when plasma is ignited, but after the main current peak. This behaviour can be explained by the dielectric reactance, estimated \( X_{Cd} = 1/(2\pi fC_{dq}) = 250 k\Omega \), typically larger than the resistance \( R_p \) around 10 k\Omega. However, the resistance value plays an important role in the current peak height as charges accumulated in the gas capacitor, during the phase without plasma, flow through the resistor as soon as the switch closes, creating this peak.

As in DBD, the ionization degree is low, and the current (indicating the presence of new charges) is limited by the dielectric barrier, the conductivity of ignited plasma is relatively stable during plasma on-phase. It can reasonably be assumed constant during this phase (i.e., the ionization degree does not drastically increase once the plasma is
Figure 12: Dielectric capacitance obtained by curve fitting as a function of the peak-to-peak values of the applied voltage.

Ignited) [34–40] and a resulting constant resistance value has, for example, been estimated as $V_b/I_{\text{peak}}$ [36,40].

Although this conductivity value is assumed to be constant over time when plasma is ignited, its resistance could still depend on the applied voltage amplitude. As explained in Appendix B, increasing the voltage amplitude extends the discharge outside the electrode zone and leads to extending the current path (increasing the conductivity). In addition, the ionization degree increases when the over-voltage increases, which lowers the conductivity, and hence the resistance [50]. However, a plateau is reached from a given applied voltage and we do not observe further resistance decrease. Two competing phenomena could occur as the probability for recombination of charges increases with ionization degree, potentially leading to a decrease in conductivity, as modelled by Bhosle et al. [45].

By fitting current peak height (with an error of less than 5%) between experimental and simulated data (at the plasma ignition time), we found values for $R_p$ as a function of the peak-to-peak applied voltage. The resistance value in the model, to fit the experimental current peak, decreases when the amplitude of the applied voltage increases. Then, it seems to stabilize and reach a plateau. The resistance value decrease was expected since both a wider plasma channel is obtained with higher applied voltage reducing the resistance and the ionization degree increases for higher voltage. The plateau reflects the limit at which increasing the voltage does not decrease the resistance further, since recombination probability increases with the ionization degree. The empirical law (equation 7) found to model this behaviour was a second-order polynomial with a determination coefficient of $R^2 = 0.97$ with the least square method. A first-order polynomial and a power function were also tested with a determination coefficient of
Figure 13: (a) Applied voltage, experimental total current and simulated current for different values of constant switch resistance values \( R_p \), with \( C_{dq} = 35 \text{ pF} \). (b) Corresponding QV curve. (c) Applied voltage, total experimental current, and simulated current for different values of dielectric capacitance \( C_{dq} \), with \( R_p = 20 \text{ kΩ} \). (d) Corresponding QV curve.

\[ R^2 = 0.72 \text{ and } R^2 = 0.91, \text{ respectively.} \]

\[ R_p = R_0 - a.V_{pp} + b.V_{pp}^2 \]  
\[ a = 2.6 \text{ kΩ } kV^{-1} \]  
\[ b = 0.08 \text{ kΩ } kV^{-2} \]  
\[ R_0 = 34 \text{ kΩ} \]

**Parameter overview**

At this point, a model of our simple plasma reactor, representing the device quartz chamber, has been developed. The inputs of this model are simply the high voltage applied and the two empirical laws (equations 7 and 6) for determining the dielectric capacitance and the plasma resistance value, both based on the voltage amplitude, for a
Electrical equivalent model of a long dielectric barrier discharge plasma jet for endoscopy. Given excitation voltage waveform, frequency, as well as set-up geometry and material. Table 1 summarizes the model parameters. Capacitance values must be adapted if different quartz dimensions are used. The switch conditions will change if the gas gap changes or for different quartz thicknesses.

<table>
<thead>
<tr>
<th>Simulink Component</th>
<th>Parameter</th>
<th>Law</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitor</td>
<td>$C_{dq}$</td>
<td>$C_{dq} = 0.52V_{a-pp} + 27.8$</td>
</tr>
<tr>
<td>Capacitor</td>
<td>$C_g$</td>
<td>$C_g = \frac{C_{dq} \cdot 9\text{pF}}{C_{dq} - 4\text{pF}}$</td>
</tr>
<tr>
<td>Plasma resistor</td>
<td>$R_p$</td>
<td>$R_p = R_0 - a.V_{pp} + b.V_{pp}^2$</td>
</tr>
<tr>
<td>Switch</td>
<td></td>
<td>Positive polarity</td>
</tr>
<tr>
<td>Closed to open</td>
<td>$V_a(t) = V_{max}$</td>
<td>$V_a(t) = V_{min}$</td>
</tr>
<tr>
<td>Open to closed</td>
<td>$V_a(t) = V_{max} - \Delta V_p$</td>
<td>$V_a(t) = V_{min} + \Delta V_n$</td>
</tr>
<tr>
<td></td>
<td>$\Delta V_p = 1014$</td>
<td>$\Delta V_n = 1250$</td>
</tr>
</tbody>
</table>

Table 1: Summary of parameters implemented to model the quartz chamber plasma reactor. $R_0 = 34\text{k\Omega}$, $a = 2.6\text{k\Omega kV}^{-1}$ and $b = 0.08\text{k\Omega kV}^{-2}$

2.3.2. Model of the whole plasma system

In the whole system (as presented in figure 4), the gas is flushed after the quartz chamber through the PTFE catheter over two meters. Then the plasma reignites and the plume impinges the target. An analysis of experimental measurements was performed to understand the influence of variables that have previously been proven to change plasma behaviour [24]. These variables are the applied voltage amplitude and the gas gap between the tip of the capillary and the target. From this point, the gas gap inside the quartz chamber will be referred to as gas gap** and the one at the target as gas gap**.

(i) Measurement observation The gas gap** between the tip of the copper wire and the human electrical equivalent (see figure 2) was varied. Figures 14a, b, and c show experimental voltages and currents for three distances (indicated on the graph). The total input current exhibits two peaks (for both polarities) in each half-period. The first one corresponds to the current peak observed with the simple reactor without the capillary. The second one, corresponding to the second zone where the plasma ignites, appears after a certain delay which, interestingly, increases with the gas gap** length. The second peak visible in the total current is also present in the output current, while the first one is visible in the total current, but does not appear in the output current.
The corresponding QV-diagrams are shown in figure 14d, with charge computed with $I_{\text{tot}}$. By analyzing this latter, one can see that starting from the minimum voltage applied ($-6 \text{kV}$), voltage and charge increase with an initial small slope (off phase) until a first vertex corresponding to plasma ignition somewhere in the system (first on-phase indicated by one *). The charge is still increasing, but with a larger slope. A second vertex is then reached, corresponding to the second current peak and the apparition of a second plasma into the system (second on-phase **). Finally, the maximum voltage applied is reached ($6 \text{kV}$), with a final larger slope.

Experimental QV curves for different gas gaps** and peak voltages are shown in figure 15. Under high-voltage amplitude or small gas gaps**, QV curves show a more complex shape (as seen in the blue and green curves in figure 15, respectively). Indeed, the QV shape is best described as a hexagon. When moving away from these conditions, i.e. decreasing the voltage or widening the gas gap**, the QV curve tends to become the simple parallelogram seen earlier (as seen in the red curve in figure 15). The complex shape obtained for high peak voltage or small gas gap** (blue and green curves, respectively, in figure 15) becomes a simple parallelogram, similar to the simple reactor of the previous section (red curve in figure 15). Visually, under these conditions (1.5 cm and 5 kV), the plasma plume did not reach the human box electrode, and the double current peak was, therefore, not observed, although a plume was present at the end of the capillary. This confirms that the second current peak is indeed induced by the ignition of a plasma channel "connecting" the capillary end and the human box.

(ii) Suggested model With these observations, the following electrical equivalent (figure 16a) was implemented. The capacitor $C_{g2}$ represents the gas gap**. It is connected to the previous simple reactor. The switch appears again to represent the second plasma ignition. In the capillary, the copper wire lies at the center of a coaxial configuration, surrounded by helium (partly ionized). This arrangement can be electrically assimilated to a transmission line [24, 51] typically used in cables (e.g., coaxial cables) designed to conduct high-frequency alternating current [52, 53]. A transmission line is generally modelled as a two-port distributed-element circuit designed to conduct an alternating current. A distributed element means that the primary constants of the system (resistance and inductance along the line and conductance and capacitance shunting the line) are all specified per unit of length. As the central element is a copper wire, for which the resistance is very small compared to other circuit elements (capacitors with reactance values above $M\Omega$), the copper wire resistance and inductance along the line were neglected. Therefore, the transmission line parallel elements (shunting the line) were only considered. They are represented by several capacitors $C_{d-PTFE}$ in parallel, connected to the ground. In a real scenario, the tube "connection" varies according to the experiment. In an in vivo experiment, it would be in contact with the endoscope or the patient, itself connected to the ground. The direct ground connection chosen here corresponds to the worst-case scenario since it maximizes the current leaking through the endoscope into the patient. Finally, the human body’s electrical equivalent (see figure 2)
Electrical equivalent model of a long dielectric barrier discharge plasma jet for endoscopy.

Figure 14: Experimental curves for the whole system. (a), (b), and (c) are current and voltage over time for gas gap** of 0.5 cm, 1 cm, and 1.5 cm, respectively, with a peak voltage of \( \approx 6 \text{kV} \). The red curve is the input current (\( I_{\text{tot}} \)), while the yellow curve is the current measured after the human box (see probe position in figure 2), called the output current \( I_{\text{out}} \). (d) Corresponding QV curves with arrows indicating the voltage difference between current peaks.

is added to the model.

In figure 16, the QV curves schematically represent the system’s different phases. According to the system’s state, different parts of the electrical equivalent show higher impedance, hence, less influencing its behaviour (in grey). Neglecting them, as a first approximation, allowed us to easily identify the values of the slopes \( C_{\text{OFF}} \), \( C_{\text{ON}**} \), and \( C_{\text{ON}***} \).

Figure 16 shows two voltage differences \( \Delta V^* \) and \( \Delta V^{**} \), determining the ignition conditions. Once again, the system behaviour can be described by the motion of the
Figure 15: Experimental QV curves with different gas gap** for different peak voltage, for the whole system (first on-phase is indicated by one * and second on-phase by **).

Charges. Starting from the minimum voltage, the voltage-time derivative is equal to zero, a relative equilibrium has been established in the system. Then, the applied voltage increases (becomes less negative), so negative charges are removed from the electrode, inducing a motion across the dielectric and reducing the bounding forces with positive charges previously accumulated on the dielectric inner surface. When this charge removal becomes sufficient, positive charges are freed, and helium inside the quartz ionizes, rendering this gas conductive. From this point, negative charges are still removed (the applied voltage still increases), leading to a global charge motion between the electrode and the copper wire tip at the very end of the capillary since helium is ignited and conductive inside the chamber. When enough charges have accumulated at the wire tip, the second gas gap** ignites. This is why $\Delta V^{**}$ is defined with the voltage at the first ignition as a reference instead of using $V_{\text{max}}$.

(iii) Parameter determinations The parameters that have to be determined are the switch conditions for both gas gaps, the capacitance values, and the resistance values of ignited plasma inside the chamber and at the plume.

Switch conditions
Figure 16: (a) Electrical equivalent of the whole system. (b) Schematic of the QV curve, with slopes $C_{OFF}$, $C_{ON^*}$, and $C_{ON^{**}}$, corresponding to the total capacitance of the electrical equivalent circuit during each phase. The grey parts of those small circuits show higher impedance (hence, less influencing its behaviour) during this system phase. The dashed parallelogram represents the behaviour observed when the plasma plume does not touch the human box (for a large gas gap**). (c) Schematics of the QV curves change when the gas gap** increases, as observed experimentally. $\Delta V^*$ corresponds to the first voltage difference from the minimum (respectively maximum) to the first current peak, and $\Delta V^{**} = V_5 - V_3$ (or $V_2 - V_6$) is the second voltage difference from the last ignition point to the second current peak.

Interestingly, the value $\Delta V^*$ (representing the first plasma ignition condition), which was constant for the simple reactor, regardless of the applied voltage, now slightly changes with the gas gap** at the end of the system. Figure 17 shows the values obtained from experimental data for different values of gas gap** and applied voltage. Each
Electrical equivalent model of a long dielectric barrier discharge plasma jet for endoscopy.

Measurement was averaged over 20 periods for different applied voltages (from 4.8 kV to 7.2 kV). The standard deviation of the measures ranged from 0.02 kV to 0.11 kV for the positive polarity and from 0.05 kV to 0.10 kV for the negative polarity, depending on the gas gap**. The voltage difference for the first plasma ignition follows a linear trend with the final gas gap**. This suggests that, when the whole system is in the off-phase, the parts of the circuit showing higher impedance (in grey in figure 16b), cannot be totally neglected. Otherwise, this block would not influence $\Delta V^*$. 

![Graph of Voltage difference vs Gas gap](image)

Figure 17: $\Delta V^*$ for each polarity for various gas gap** lengths.

Similarly, the values for $\Delta V^{**}$ (representing the second plasma ignition condition) were collected from experimental data (the same set), and the results are shown in figure 18. The standard deviation of the measures ranged from 0.05 kV to 0.49 kV for the positive polarity and from 0.04 kV to 0.53 kV for the negative polarity, depending on the gas gap**. To ignite the plasma channel between the tip of the copper wire and the human box, the total applied voltage has to increase (decrease, respectively) from $V_3$ to $V_5$ (from $V_2$ to $V_6$, respectively), where $V_k$ are the voltage values at the six vertices in figure 16b. The breakdown voltages computed with Paschen’s law at atmospheric pressure for helium as a function of the gas gap** were drawn on the same graph (figure 18). The voltage difference (between the first and second ignition) as a function of the gas gap** is quite close to this law. It suggests that the applied voltage drop between the first and second ignition induces an equivalent voltage difference at the gas gap** (between the copper wire end and the human box), leading to the gas breakdown as predicted by Paschen’s law. Besides, the voltage difference follows a relatively linear trend (the coefficient of determination, $R^2$, equals 0.94 both for positive and negative polarity). It is explained by the relatively linear behaviour of the Paschen law in that gas gap range. In addition, for the second ignition, the polarity seems to have less influence (or none at all) on the ignition condition, which was expected since both "sides" of the gas gap** are made of the same material (copper at the wire tip and for the human box...
Electrical equivalent model of a long dielectric barrier discharge plasma jet for endoscopy.

electrode).

Figure 18: $\Delta V^{**}$ as a function of the gas gap**. Dashed line represents Paschen’s law at 760 Torr for helium with $A = 3 \text{Torr}^{-1} \text{cm}^{-1}$, $B = 34 \text{V Torr}^{-1} \text{cm}^{-1}$ and $\lambda = 0.32$.

**Capacitors**

Figure 16 shows that three slopes are identifiable on the QV curves of the whole system. $C_{dq}$, $C_{d\text{-PTFE}}$, and $C_{g1}$ values can be deduced with values read on experimental QV curves for these slopes ($C_{\text{OFF}} = 12 \text{pF}$, $C_{\text{ON}*} = 29 \text{pF}$, and $C_{\text{ON}**} = 37 \text{pF}$) and equations detailed in Appendix C. These were equal to 34 pF, 16 pF, and 111 pF, respectively. Please note deducing these values from QV curves (rather than analytical calculation) allows taking into account tolerances in the components (e.g., the wire is not perfectly centred in the PTFE tube).

**Plasma resistance values**

Figure 19 shows the simulated current for various values of $R_{p*}$ and $R_{p**}$. The first plasma resistance $R_{p*}$ (inside the quartz chamber) was found to govern the height of both plasma peaks. This was expected as this first plasma defines the number of charges flowing through the system when plasma is ignited. The second plasma resistance $R_{p**}$ (in the plume) only impacts the height of the second current peak. This was also expected since, before the second gas gap** ignition, the switch for this gap is still open, and $R_{p**}$ is thus not involved for the first ON* phase. By visually fitting the height of the peaks, resistance values found are about 25 kΩ and 5 kΩ, respectively, for a peak voltage around 6 kV. For instance, with these values for typical conditions (6 kV and a gas gap** of 1 cm), the errors between the heights of the simulated and experimental peaks were 5.5% ± 3.4% (i.e., 1.8 ± 1.1 mA) and 1.7% ± 0.8% for the first and second peaks, respectively. These resistance values remain valid for the whole interval of gas gap** tested, as the errors were 5.5% ± 2.9% and 1.1% ± 1% (for each peak) with a gas gap** of 0.5 cm and 5.2% ± 3.8% and 1.7% ± 0.9% with a gas gap** of 1.5 cm. This
Electrical equivalent model of a long dielectric barrier discharge plasma jet for endoscopy.

suggests that the value of $R_p^{**}$ does not depend much on the gap** length once plasma ignites. However, the ignition condition on applied voltage for a "connecting" plasma (by opposition to a plume only flushed by the gas flow) to appear does depend on the gas gap** length (as discussed previously).

![Graph of $V_a$, $I_{tot}$, and $R_p^*$ for different $R_p^{**}$](image)

![Graph of $V_a$, $I_{tot}$, and $R_p^{**}$ for different $R_p^*$](image)

Figure 19: Applied voltage $V_a$, total experimental current $I_{tot}$, and total simulated current for (upper panel) several values of $R_p^*$ with $R_p^{**} = 5 \, k\Omega$ and (lower panel) several values of $R_p^{**}$ with $R_p^* = 25 \, k\Omega$.

Parameters overview

At this point, a model of the whole device has been developed. Its inputs are the applied voltage and the gas gap**, and parameters are determined as shown in table 2 for a given excitation voltage waveform, frequency, as well as set-up geometry and
Electrical equivalent model of a long dielectric barrier discharge plasma jet for endoscopy.

Table 2: Summary of parameters implemented to model the whole device (resistance values are valid for an applied peak voltage of 6 kV).

The Simulink files of the model can be found as supplementary materials.

3. Results

3.1. Simple reactor

Figures 20 and 21 compare, for the simple reactor, experimental curves to those simulated with the model presented in section 2.3.1. The simulation overall agrees with experimental curves concerning the general waveform at the ignition or during the off-phase. The absolute error (between the simulated curve and experimental data) was estimated over 8 periods (average ± standard deviation) and a relative value was obtained by dividing this by the average current in absolute value. This equalled 25.3% ± 0.2%, 11.5% ± 0.1%, 9.1% ± 0.1%, and 11.0% ± 0.2% for applied voltages of 2.5 kV, 5 kV, 7.5 kV, and 10 kV, respectively. The higher error value for the smaller applied voltage is explained by a small
Electrical equivalent model of a long dielectric barrier discharge plasma jet for endoscopy. The temporal shift of the main current peak, as seen in figure 20. The relative errors were also computed for the total charge (in figure 21) and values obtained were 9.5% ± 0.6%, 6.5% ± 0.1%, 6.6% ± 0.1%, and 7.2% ± 0.1%, respectively.

Figure 20: Comparison between the total experimental current and the simulated current with the sinusoidal applied voltage as the model input, for voltage amplitudes of about 2.5 kV, 5 kV, 7.5 kV, and 10 kV.

To verify our assumption that a given threshold of charge density is reached at the ignition time (as presented in figure 9), the simulated current flowing through the gas capacitor was extracted from the simulation and integrated to obtain the charge of the gas capacitor. These are shown in figure 22 along with the experimental applied voltage and the total simulated current. Consistently, the accumulated charge just before ignition is relatively constant (10.3 nC ± 0.3 nC for positive polarity and 8.0 nC ± 0.2 nC for negative) for the range of voltage amplitude studied, supporting our assumption. This provides a new approach to explaining DBD plasma jet physics based on charge
Electrical equivalent model of a long dielectric barrier discharge plasma jet for endoscopy.

Figure 21: Comparison between experimental and simulated QV curves (at the output of the generator) with the sinusoidal applied voltage as the model input, for voltage amplitudes of about $2.5\,kV$, $5\,kV$, $7.5\,kV$, and $10\,kV$.

density at the limit between gas and the dielectric layer.

3.2. Whole system

Simulated curves and experimental data are compared in figure 23. The data show that, overall, there was good agreement between experimental and simulated data obtained, suggesting that the hypotheses about the underlying physics are correct. Both current peaks appear in the total simulated current. Relative errors (computed as in section 3.1) equaled $15.2\% \pm 0.07\%$, $22.9\% \pm 0.4\%$, and $19.3\% \pm 0.2\%$ between simulated and experimental total current ($I_{tot}$) for gas gap** of $0.5\,cm$, $1\,cm$, and $1.5\,cm$, respectively. Again, these errors are mainly explained by a small temporal shift of both current peaks, as seen in figure 23. The relative errors of the total charge are $9.9\% \pm 0.5\%$, $7.9\% \pm 0.3\%$, $
Figure 22: (upper panel) Simulated charge at the gas boundaries \(Q_g\) with sinusoidal applied voltage \(V_a\) about 2.5 \(kV\) (purple), 5 \(kV\) (dark blue), 7.5 \(kV\) (light blue), and 10 \(kV\) (green), and (lower panel) total current and current through the gas capacitor \(C_g\). Coloured backgrounds represent the off-phase, and red arrows show the constant \(\Delta V^*\).

and 10.7\% ± 0.2\%.

The charge at the gas capacitors (for both gas gaps) was extracted from the simulation (by integrating the simulated current flowing through \(C_{g1}\) and \(C_{g2}\)). Figure
Electrical equivalent model of a long dielectric barrier discharge plasma jet for endoscopy.

Figure 23: Comparison between the total experimental current and the simulated current with the sinusoidal applied voltage as the model input, for voltage amplitude of about 6 kV, and different gas gap lengths (0.5 cm, 1 cm, and 1.5 cm), with corresponding QV curves.

...shows this charge at the gas gaps for several gap lengths. Please note that, for the combinations of excitation voltage and gas gap chosen for the figure, the plasma is in...
contact with the human box (i.e., the second plasma, at the plume, also ignites). The charge threshold for ignition of the first gas gap* is around $16 \text{nC}$, while this threshold is worth 10,000 times less, about $1.6 \text{pC}$, for the second gas gap**. However, in the first gas gap*, charges can accumulate on a surface of $40 \text{mm} \times 2\pi \times 2.5 \text{mm} = 630 \text{mm}^2$ while the surface of the copper wire tip is about $\pi(0.1 \text{mm})^2 = 0.03 \text{mm}^2$. If we consider the charge density (in $\text{nC/mm}^2$) by dividing this charge by the 'electrode' surface, the same order of magnitude is obtained for helium ignition.

The figure shows a distinct behaviour for the plasma at the electrode (top) and at the plume (bottom). Such a difference can be explained with our model, as schematized in figure 16. Regarding the first plasma ignition (top of figure 24), it always comes when the second plasma is not ignited. In that regard, when the first plasma starts to ignite, the second plasma can be considered a high impedance with little impact on the plasma, and the gas gap** does not influence much the first plasma ignition parameters. One can only note that the charge at the ignition point for the first gas gap* is slightly dependent on the second gas gap (from $14.5 \text{nC}$ to $17.5 \text{nC}$ for gas gap** from $0.5 \text{cm}$ to $1.5 \text{cm}$), which reflects the variation of $\Delta V^*$ observed in figure 17 and implemented in the model. Conversely, the second plasma ignition (bottom of Figure 24) is influenced by the gas gap**. In that regard, when the second plasma starts to ignite, its electrical characteristics have a key impact on the plasma. For instance, increasing the gas gap** distance decreases the value of the capacity $C_{g2}$ in the model, which in turn increases its impedance, decreases the current that flows in it, and increases the time needed to accumulate a given charge at the gas boundaries.

For the second gas gap**, the charge needed for ignition is found to be relatively constant ($1.59 \text{pF} \pm 0.06 \text{pF}$), regardless of the gas gap** length $d$. This was expected as, within the range of distance and pressure of this experiment, the Paschen curve can be assimilated to a line as a function of $d$ (see figure 18), giving:

$$C_{g2} \propto \frac{1}{d}$$

$$V_{b}^{**} \propto d$$

$$Q_{gb} = C_{g2}V_{b}^{**} = \text{cste}$$

where $V_{b}^{**}$, the breakdown voltage for the second gas gap**. This suggests that above a certain charge accumulated at the tip of the copper wire, helium ionizes, and a connection is established across the gas gap** regardless of its length. However, the voltage needed to accumulate this charge depends on the gas gap** length.

Figure 25 compares the experimental output current flowing through the target with the simulated output current. Overall, a good agreement between experimental and simulated data has been obtained, although the model overestimated the current administered to the patient (i.e., flowing through the human box), as the experimental peak height is about $40 \text{mA}$ while the simulated peak rises until $200 \text{mA}$. 
Figure 24: Simulated charge at the gas boundaries ($Q_g^*$ inside the dielectric chamber and $Q_g^{**}$ at the capillary tip) with sinusoidal applied voltage $V_a$, for different gas gap**.

Finally, figure [26] shows simulated currents flowing through the system at 25%, 50%, 75%, and 100% of the PTFE capillary length. Modelling this capillary as a linear capacitor (or capacitors in parallel) faithfully reproduces the fading of the first current peak along the tube observed with a similar system by Bastin et al. [24]. This fading is illustrated by a black arrow in figure [26] showing the currents measured between parallel
Electrical equivalent model of a long dielectric barrier discharge plasma jet for endoscopy.

PTFE capacitors. Consistently, during the first current peak (and before the second gap ignition), the plasma plume block has an important impedance (as not ignited), and current rather leaks through the tube wall (modelled by the parallel capacitors), leading to a decrease in the first peak height. Then, when the plume plasma ignites, its impedance drastically falls, leading to the second current peak in the whole system ($I_{tot}$). The overestimated current administered to the patient shown in figure 25 can also be explained by figure 26. In the model, capacitors which stand for the capillary are charged during the first on-phase (*), and discharge through the plasma plume once the switch closes. Each capacitor successively discharges, and reinforces the output current, progressively increasing the peak height as shown in the zoomed-out figure 25. In that regard, the model stores and restores the current in the capillary, without dissipation, resulting in an overestimation at this instant.

Figure 25: Comparison between the experimental and simulated output currents for sinusoidal applied voltage, with amplitude of about 6 kV and gas gap length of 1.5 cm.
Electrical equivalent model of a long dielectric barrier discharge plasma jet for endoscopy.

Figure 26: Simulated currents flowing through the PTFE capillary at 25% of its length ($I_{ptfe1}$), 50% ($I_{ptfe2}$), 75% ($I_{ptfe3}$), or 100% ($I_{out}$). Black arrows indicate the peak height tendency when the current probe position advances toward the plume in the model.

4. Discussion

4.1. Model outcomes

The electrical behaviour of a long plasma jet system designed for endoscopy, showing double ignition, has been analyzed and modelled. This system consists of one quartz chamber connected to a capillary. Since the device is complex, we first validated our model on a sub-section of the system. This first analysis covers the simple reactor, i.e., the quartz chamber near the high voltage electrode. The comparison between experimental data and the model provided an understanding of the DBD behaviour and an estimation of the system parameters. Three main observations were drawn from it:

(i) Plasma ignition occurs after a constant voltage drop (increase, respectively) from the maximum applied voltage (minimum, respectively), regardless of the maximum (minimum, respectively). Other studies have reported that the gas voltage (its absolute value) for plasma ignition varies with voltage rising time [54, 55] (or the over-voltage by comparison with the breakdown voltage). For example, Yehia et al. [56] reported a shift to the left for the ignition time for higher values of applied voltage (i.e., the plasma ignition appeared faster). They concluded that the value of the ignition voltage decreases because of charges accumulated on the dielectric surface. In this work, a new approach is proposed by considering, as the ignition condition, the charge accumulated by the applied voltage difference ($\Delta V$) between
Electrical equivalent model of a long dielectric barrier discharge plasma jet for endoscopy.

the maximum applied voltage (respectively minimum) and the applied voltage at the ignition instant $V_a(t_{ip})$ (respectively $V_a(t_{in})$). This voltage drop is a constant value, whereas the absolute voltage value at the ignition point is dependent on the maximum applied voltage.

(ii) The dielectric capacitance value clearly increases with the applied voltage, likely because of an extension of the discharge length.

(iii) When plasma appears, ignited helium can be modelled by a constant resistance over time. However, its value depends on the peak voltage applied.

For the whole system, the simple reactor is extended with the coaxial arrangement of the copper wire, surrounded by helium plasma, contained by the PTFE wall. It behaves as a transmission line, with a linear capacitor through which current leaks as long as no other low impedance paths are available. At the end of this capillary appears the plasma plume itself touching or not the human body electrical equivalent. This was modelled, similarly to the first gas gap*, by a switch in parallel with the gas capacitor. This last complete model compared and confirmed parameters from the first subsystem. The electrical behaviour of this kind of plasma device was described, and our observations led to several conclusions:

(i) The plasma regime (bright channel touching the target or plume in the free jet) can be discriminated with the number of peaks in the input current (or the vertices in the QV diagrams). The first one starts with a difference ($\Delta V^*$) between the maximum applied voltage and the ignition value, slightly related to the gas gap** length (see figure 17) but independently of the applied voltage. The second one appears for a voltage difference $\Delta V^{**}$ highly dependent on the gas gap** and follows the Paschen curve.

(ii) A condition linking the applied voltage and the gas gap** has been defined to predict this regime:

$$V_{pp} > \Delta V^*(d) + \Delta V^{**}(d) \rightarrow \text{bright channel}$$ (14)

$$V_{pp} < \Delta V^*(d) + \Delta V^{**}(d) \rightarrow \text{free jet}$$ (15)

where $d$ is the gas gap** at the end of the tube. Inversely, this distance could be deduced by monitoring the input current and knowing the applied voltage.

(iii) Derived from this last point, and similarly to the observations made on the simple reactor, a new approach for considering the breakdown voltage has been proposed, based on the system's charge density at the gas boundary, which determines the condition for plasma ignition, rather than on absolute voltage values.

(iv) In a DBD plasma jet with a low ionization degree, it is reasonable to assume a constant plasma resistance over time while plasma is ignited, leading to a simple model of the system.
4.2. Model limitations

Although the outcomes listed here are of interest for understanding plasma jet and future plasma medical devices for endoscopy, several limitations are worth mentioning.

For the whole plasma endoscopic system, modelling the PTFE tube as an ideal capacitor modifies this dielectric layer’s behaviour. Charges are not fully restituted when the plasma channel appears (i.e., during the second on-phase**) since the output current peak is similar to (and not larger than) the input one (see figure 14 or 25 in which the yellow current peak is similar to the red one). Modelling the energy dissipation through PTFE could avoid this discrepancy. The addition of a resistor that accounts for dielectric losses (tan δ = 0.0002 for PTFE) could be added. It would affect the impedance of the whole system, leading to a new parameter study (since equations C.1 - C.3 would have to include this new component). Please also note that the wire is not perfectly centred in the PTFE tube. In that regard, “hot spots” (i.e. high current density) could lead to increased losses compared to an evenly distributed current that flows into the previously mentioned resistor. It is worth mentioning that the capillary itself slightly glows, as shown in figure 3. The effect of modelling this weak plasma present inside the capillary (and emitting a dim light) could also be assessed to better simulate the experimental observations. Linked to that previous point, further investigations should bring light to the power dissipation mechanisms to assess, for example, if consequent power is lost by PTFE heating.

Secondly, although the model reliably describes the behaviour of the plasma jet for a well-established plasma channel between the capillary and the target (which is the worst case in terms of patient safety), it is not robust to effectively simulate a transient state between this channel and a plume in a free jet.

Finally, geometry strongly influences the model parameters, which are, therefore, sensitive to small changes, especially for dielectric materials dimensions (quartz and PTFE), as their capacitance values play a key role in the model. Indeed, a slight change of, for example, 0.2 mm of quartz thickness would change the dielectric capacitance of about 4 pF, which induces a non-negligible deviation between model and measurement, as seen in figure 13. A thorough study on the model sensitivity should thus be carried out for each parameter.

4.3. Model future improvement

Further improvements could be made to diminish the discrepancies between the model prediction and observed plasma behaviour. First, based on other teams’ work [43,45,47], one could refine this model by linking the constant resistor value to the applied voltage, the gas gap, or the number of charges inside the gas gap (by integrating the current, or through the ionization degree).

Broader ranges of electrical parameters should also be studied. In this study, the voltage generator was operating with a sine wave at a fixed 18 kHz frequency. Indeed, other frequencies or waveforms are known to change the electrical behaviour of plasma
Electrical equivalent model of a long dielectric barrier discharge plasma jet for endoscopy. 35

This parameter should be varied to see if the accumulated maximal charge at the gas boundary would differ, if our approach is robust, and if the voltage difference for ignition is indeed constant, regardless of the frequency. Such a model could first be challenged if conditions are modified but then could help determine the optimal applied voltage. In this study, a relatively low number of measurements were taken on one given setup (regarding geometry and material). On this model, or its future version (with previously cited features implemented), a statistical study with various device dimensions and materials, for example, should be carried out to confirm the results obtained here with small parameter sets. In this study, the (dis-)organized nature of our discharge under the form of “bullets”, as proposed by the GREMI [58] (see also the general comparison between bullets and jets by Lu et al. [59]), was not investigated. Further characterization, especially by high-speed imaging, would be highly interesting to get insights into the capillary’s discharge propagation. The addition of others gases as oxygen in different percentages has also been proved to modify the plasma chemistry [47], and could therefore change the electrical behavior. Finally, another target better mimicking the in vivo conditions (e.g., humidity, conductivity, or spatial configuration) could be considered to reproduce the plasma-target interface, for example with hydrogels [60].

The model could be used to predict the behaviour or even control a medical device. For example, the appearance of the second current peak occurs when a clear plasma channel is established between the catheter tip and the target, and as its timing has been proved to be dependent on this distance. Therefore, an excessive treatment could be avoided by monitoring these peaks and stopping operations if they are too close to each other. In addition, if a deviation from the modelled current, larger than a certain threshold, is measured by the system, operations could be automatically stopped, avoiding an unwanted electrical contact in the system.

To conclude, the electrical equivalent of a long plasma source suitable for endoscopy described here could take us one step closer to the therapeutic use of cold atmospheric plasma in hospitals. More specifically, cholangiocarcinoma in biliary ducts [51], pancreas or colon cancer [20], and lung cancer [61,62] could be treated with a synergistic treatment involving cold plasma. During endoscopic procedures, it could also be used to promote coagulation when bleeding occurs, as CAP coagulates anti-coagulated blood in a few minutes [63,64].

5. Conclusion

In conclusion, this work contributes to understanding the electrical behaviour of a long plasma jet system developed for plasma treatment by endoscopy. An electrical equivalent of a long plasma source was built, to simulate plasma generation, its transport inside a capillary, and its interaction on a target. The model can predict leakage current in the body and current at the target site. Simulated curves agree well with experimental data. This model could be used for safety to control treatment conditions in situ. Lastly, it provides an electrical equivalent circuit useful for explaining and discussing experimental
Electrical equivalent model of a long dielectric barrier discharge plasma jet for endoscopy. 36 results and deepens the understanding of plasma jet physics.

Acknowledgments

This work was supported by the Fondation Michel Cremer and by the PHENIX project, funded by the Université libre de Bruxelles.

Appendix A. Capacitance and dielectric losses value estimation based on geometry and by direct measurement

Based on chamber geometry: The dielectric capacitance $C_{dq}$ of the cylindrical quartz chamber can be computed as [65]:

$$C_{dq} = \frac{2\pi \varepsilon_{r,q} \varepsilon_0 l}{\ln (OD_q/ID_q)} = 24 \text{pF} \quad (A.1)$$

where $\varepsilon_{r,q} = 3.7$ for quartz and $\varepsilon_0 = 8.85 \times 10^{-12} \text{F.m}^{-1}$ are relative permittivity of quartz and vacuum permittivity, respectively. $L = 4 \text{cm}$ is the electrode's length, and $OD_q = 7 \text{mm}$ and $ID_q = 5 \text{mm}$ are the outer and inner diameters of the quartz chamber, respectively. The gas capacitance can be similarly estimated with:

$$C_g = \frac{2\pi \varepsilon_{r,he} \varepsilon_0 l}{\ln (ID_q/d_{Cu})} = 1.2 \text{pF} \quad (A.2)$$

where $\varepsilon_{r,he} = 1.055$, and the copper diameter $d_{Cu} = 0.8 \text{mm}$. When the plasma is not ignited, those two capacitors are in series, and the total capacitance value $C_{OFF}$ of the system without plasma is

$$C_{OFF} = \frac{C_{dq} C_g}{C_{dq} + C_g} = 1.1 \text{pF} \quad (A.3)$$

Finally, the parallel resistor, accounting for dielectric losses and representing the power dissipation by heating [66,67], is computed with equation [68] where the dielectric loss tangent coefficient is an intrinsic material property ($\tan \delta = 0.0005$ for quartz at $7.5 \text{kHz}$):

$$R_c = \frac{1}{\omega C_{dq} \tan \delta} = 7.4 \times 10^8 \Omega \quad (A.4)$$

Based on direct measurements: To confirm this estimated value, an impedance-meter (Wayne-Kerr Precision Component Analyzer 6425) was used without plasma ignition (the reactor was not connected to the generator nor to any helium gas flow). Two measures were taken with a frequency of 20 kHz and a peak voltage of 5 V: first, the total impedance ($C_{OFF}$) between the electrode and the copper wire, and second, the measure of quartz capacitance ($C_{dq}$) only by inserting a copper rod of 5-mm-diameter inside the quartz chamber along its whole length, therefore filling the quartz chamber. When the electrode length was doubled, the measured value for $C_{dq}$ followed the same tendency, as predicted by equation $A.1$.

The same orders of magnitude were obtained for the parameter estimation methods as shown in Table $A1$ Deviations can be discussed with limitations and assumptions.
Electrical equivalent model of a long dielectric barrier discharge plasma jet for endoscopy.

Table A1: Parameter values comparison depending on the method used.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Computation based on geometry</th>
<th>Impedance-meter</th>
<th>Based on QV curves (evaluated values with $V_{a-pp} = 10kV$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{dq}$</td>
<td>24 pF</td>
<td>18 pF</td>
<td>$C_{dq} = 0.52V_{a-pp} + 27.8 (33 pF)$</td>
</tr>
<tr>
<td>$C_g$</td>
<td>1.3 pF</td>
<td>2 pF</td>
<td>$C_g = \frac{C_{dq} - 9 pF}{C_{dq} - 9 pF} (12 pF)$</td>
</tr>
<tr>
<td>$C_{OFF}$</td>
<td>1.1 pF</td>
<td>1.8 pF</td>
<td></td>
</tr>
<tr>
<td>$R_c$</td>
<td>740 MΩ</td>
<td>92 MΩ</td>
<td>$\frac{1}{\omega C_{dq} \tan \delta} (534 MΩ)$</td>
</tr>
</tbody>
</table>

of each method. The computation based on geometry does not account for any effect induced by the high voltage applied and can be skewed by deviation in dielectric constant or dimension tolerances. The values given by the impedance meter are consistent with the computed ones. However, they were measured with a signal of 5 V, which is also far from the working voltage range, which can influence the equivalent capacitance of the system. Indeed, Sobota et al. [69] reported an increased capacitance for the whole system when increasing the imposed voltage amplitude. With a similar system and similar observations, Huang et al. [46] simulated the electrostatic potential distribution (with Comsol Multiphysics) with a constant voltage of 5 kV applied to an electrode of 2.5 cm. The resulting electrostatic field spreads and extends over distances greater than the electrode length. They found that the electric field intensity was higher than 200 V over a length of 3.75 cm, which they called discharge effective length. They then used this value to compute their dielectric capacitance, which increases with the applied voltage as the resulting field spreads more widely, resulting in a longer effective length. A similar simulation was run in this work and is available in Appendix B. Finally, the memory effect is the last phenomenon to explain those deviations between measurement methods, when plasma is not ignited [70]. Indeed, the dielectric constant of the gas gap can be highly modified [35], or charges can accumulate on the dielectric layer, explaining the differences between theoretical computations and measurement.

Appendix B. Comsol Simulation of Electrostatic potential

A simulation of the electrostatic potential distribution over the quartz chamber was undertaken with Comsol Electrostatics, with various applied constant voltages corresponding to the RMS values used in this work. Results are presented in figure B1. A threshold of 880 V (average value of positive and negative breakdowns) was chosen as the low limit of electric potential sufficient to ignite the gas. The effective electrode length obtained in simulation (figure B1a) is reported in figure B1b. The experimental capacitance values from figure 12 were then used to extract experimental effective lengths with equation A.1. These are reported on the same graph. Although
Electrical equivalent model of a long dielectric barrier discharge plasma jet for endoscopy.

This simulation is rather approximative (varying AC-voltage, absence of the copper rod at the centre, indicative threshold value,...), the orders of magnitude are relatively close to experimental results, suggesting that this effect of discharge extension could explain the increase of dielectric capacitance. Therefore, the effective discharge length seems important to consider in DBD models.

Figure B1: (a) 2D-axis Comsol simulation of the electrostatic potential when a constant voltage is applied at the copper electrode (from -2 to 2 cm). Helium and quartz dielectric constant are \( \varepsilon_{r,he} = 1.055 \) and \( \varepsilon_{r,q} = 3.7 \), respectively. Values for the voltage were chosen to correspond to the RMS voltage applied in experimental measures. (b) The effective length of the electrode as a function of RMS applied voltage (blue) computed from the dielectric capacitance given in [12] and (orange) coming from the Comsol simulation with a threshold of 880 V RMS.

Appendix C. Equations for determination of capacitance values

(i) During the first phase (plasma-off) (between 1 and 2 or 4 and 3), all switches are open. The branch representing the plasma plume can be neglected (as the gas gap** is 'long' and narrow, its capacitance value is very small (about 3.2 \( fF \) for a gas gap** of 0.5 \( cm \)) with regard to the one of the long PTFE capillary (estimated...
Electrical equivalent model of a long dielectric barrier discharge plasma jet for endoscopy. The slope of the QV curve \( C_{OFF} \) is approximately equal to:

\[
C_{OFF} \approx C_{probe} + \frac{C_{dq} C_{g1} C_{dPTFE}}{C_{dq} C_{g1} + C_{dq} C_{dPTFE} + C_{g1} C_{dPTFE}} \quad (C.1)
\]

(ii) When the first ignition voltage is reached (point 3 at \( V_{min} + \Delta V^* \) or point 2 at \( V_{max} - \Delta V^* \)), the first switch closes, and the gas capacitance \( C_{g1} \) can be neglected in front of the lower impedance path offered by the ignited plasma. The slope of this first on-phase \( C_{ON^*} \) is approximately equal to:

\[
C_{ON^*} \approx C_{probe} + \frac{C_{dq} C_{dPTFE}}{C_{dq} + C_{dPTFE}} \quad (C.2)
\]

(iii) Finally, when the second plasma ignites (point 6 or 5 at a voltage of \( V_{min} + \Delta V^* + \Delta V^{**} \) or \( V_{max} - \Delta V^* - \Delta V^{**} \)), all switches are closed, we are in the second on-phase and the total capacitance of the system \( C_{ON^{**}} \) is approximately just the sum of the probe and quartz capacitances:

\[
C_{ON^{**}} \approx C_{dq} + C_{probe} \quad (C.3)
\]

References

Electrical equivalent model of a long dielectric barrier discharge plasma jet for endoscopy. 40


Electrical equivalent model of a long dielectric barrier discharge plasma jet for endoscopy.


[33] Friedrich Paschen. Ueber die zum funkenübergang in luft, wasserstoff und kohlensäure bei verschiedenen drucken erforderliche potentialdifferenz... JA Barth, 1889.


Electrical equivalent model of a long dielectric barrier discharge plasma jet for endoscopy.


Electrical equivalent model of a long dielectric barrier discharge plasma jet for endoscopy.


