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New insights on the propagation of pulsed atmospheric plasma streams: From single jet to multi jet arrays

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Atmospheric pressure plasma propagation inside long dielectric tubes is analyzed for the first time through nonintrusive and nonperturbative time resolved bi-directional electric field (EF) measurements. This study unveils that plasma propagation occurs in a region where longitudinal EF exists ahead the ionization front position usually revealed from plasma emission with ICCD measurement. The ionization front propagation induces the sudden rise of a radial EF component. Both of these EF components have an amplitude of several kV/cm for helium or neon plasmas and are preserved almost constant along a few tens of cm inside a capillary. All these experimental measurements are in excellent agreement with previous model calculations. The key roles of the voltage pulse polarity and of the target nature on the helium flow patterns when plasma jet is emerging in ambient air are documented from Schlieren visualization. The second part of this work is then dedicated to the development of multi jet systems, using two different setups, based on a single plasma source. Plasma splitting in dielectric tubes drilled with sub millimetric orifices, but also plasma transfer across metallic tubes equipped with such orifices are reported and analyzed from ICCD imaging and time resolved EF measurements. This allows for the design and the feasibility validation of plasma jet arrays but also emphasizes the necessity to account for voltage pulse polarity, target potential status, consecutive helium flow modulation, and electrostatic influence between the produced secondary jets. © 2015 AIP Publishing LLC.

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I. INTRODUCTION

The impressive development in the past years of biomedical applications of plasma, spanning from sterilization, decontamination, processing of biomaterials to cell, tissue and in vivo plasma treatments for therapeutics issues, still appears as a two-sided innovative, exciting but questioning new field of research in plasma science. At the same time, a large effort is paid for the analysis of the mode of action of plasma requiring a detailed diagnostics of the gas and liquid phase chemistries, energetic photon generation, and electric field (EF) characteristics but also for the development of plasma sources tailored for specific applications.

This work is a contribution to this effort with two main objectives: the first is the development of plasma jet arrays based on the use of a single primary plasma jet device. The second is the measurement and analysis of transient electric field associated with atmospheric pressure plasma propagation in long capillaries. Both topics have been already addressed by other research groups, showing evidence for the potentialities of nonthermal atmospheric pressure (NTP) multi jet generation and reporting preliminary EF characterization associated with single NTP plasma jet or dielectric barrier discharge (DBD) operation. Nevertheless, both a new method for bi-directional EF measurement and new schemes for multi jet generation have been achieved in this study.

Dealing with multi jets or plasma array, one of the pioneer reports is probably that from Weltmann and co workers where the design and implementation of plasma module composed of a several RF-driven argon plasma jets was demonstrated for large surface plasma treatment. Significant contribution was also achieved in Refs. 2 and 3 where honeycomb arrays of seven helium fed AC driven (30kHz) were proposed and studied in detail. In this latter work, the strong self-influence between individual jets in a densely arranged structure was reported and discussed with respect to the unique or individual ballast powering of the plasma array. An interesting and demonstrative development based on a bench of individual RF-driven He jets including their interaction with human body was reported in Ref. 4, allowing for the delivery of 9 or 18 jets each fed with 600 sccm of helium and the assembly being powered with a 600 W RF generator. The distance between individual jets was around 1 cm, and the plasma temperature was estimated around 400 K. The limitations but also potential benefits from individual jet self influences were recently reported in Refs. 5 and 8, where benches of individual plasma reactors were used. The strong interplay between gas flow and discharge, the possibility for individual jet monitoring through individual ballast, or the effect of gas admixtures was shown to allow for multi jets delivery in such combinations of several single jets devices.

While of strong interest for a large number of biomedical applications based on direct plasma interaction with tissue or cells, the diagnostics of EF delivered in DBD or plasma jets has so far been quite limited. Besides modeling studies, experimental measurements based on the intensity ratio of excited nitrogen ions and molecules have been introduced and applied for surface DBD plasmas and tentatively to He jets. In the latter case, peak EF amplitudes as high as 100 kV/cm were reported suggesting same order of magnitude as those measured in air for volume DBD. Recent
approach based on the use of a Pockels technique was introduced to assess EF amplitude resulting from He plasma jets delivery on a dielectric target, leading to peak value of 11.6 kV/cm during the negative half period of a 30 kHz AC cycle.\(^{13}\) Using stark polarization spectroscopy, a nonintrusive time resolved measurement of EF generated by helium plasma jet reveals that peak EF amplitude between 10 and 20 kV/cm exists in the plasma ionization front.\(^{13}\) Correlation between the front propagation velocity and EF was demonstrated\(^{14,15}\) and generalized to argon and air plasmas.\(^{14}\)

New insights on the helium and neon atmospheric pressure ionization wave propagation in dielectric tubes and the associated transient EF generation and propagation are proposed in the first part of this work. To begin with, time and space resolved EF measurements with a new device (bi component EOP Kapteos probe) for the diagnostics of pulsed atmospheric-pressure plasma streams\(^{16}\) inside long dielectric tube, produced by the Plasma Gun (PG) are reported. The key role of the voltage pulse polarity and the drastic impact of the presence of a target in front of the plasma jet are then briefly documented and discussed from representative time-integrated Schlieren images of helium jets in ambient air. In the second part of this work, the development and experimental analysis, based on Intensified charge-Coupled Device (ICCD) imaging and EF measurements, of multi jet devices derived from a single PG primary source are documented.

The generation of multi jets is reported with both metallic and dielectric tubes and is shown to rely either on the synchronized secondary jets generation and propagation in ambient air or on time-shifted successive splitting of the primary plasma stream during downstream propagation.

**II. RESULTS**

**A. Single plasma gun experiments**

**1. Experimental setup**

Figure 1 presents the schematic of the experimental set up used for the study of the helium and neon plasma propagation inside a dielectric tube. The PG is a coaxial dielectric barrier discharge reactor with a quartz capillary, flushed with rare gas and powered, in this work by μs duration voltage pulses in the kHz regime. A 42 cm long dielectric quartz capillary with a 4 mm inner diameter and a 6 mm outer diameter is used. The inner electrode, 2 cm long, is set inside the capillary. The rare gas (helium or neon) buffer (1 l/min) is injected through the inner hollowed electrode (0.8 mm inner diameter). A 5 mm wide grounded ring electrode is set on the outer surface of the quartz capillary centered with the tip of the inner electrode. A Pockels effect based fiber-like sensor equipped with an isotropic crystal probed by a laser beam gives simultaneous access to two orthogonal components of the EF. In this work, a specially designed 1.75 mm in diameter, 1 mm long crystal embedded in an alumina tube, set at one end of an optical fiber was used as a sensor. The orientation between the capillary tube and the probe is a very sensitive parameter as two orthogonal EF components are measured. A preliminary experiment is performed with a dedicated plane-plane static EF chamber allowing for both, the identification of both axes, as well as the absolute EF amplitude calibration. The sensor was moved vertically along the quartz capillary, with a constant 2 mm gap from the quartz outer surface. This corresponds to a distance between the capillary axis and the crystal center of 6 mm. This 2 mm gap setting was checked, through ICCD measurement, to induce no detectable modification of the plasma front propagation emission pattern and velocity. Thus, the probe allows for the nonintrusive, nonperturbative measurement of the longitudinal (LEF) and radial (REF) EF components. The EF amplitude necessarily reflects a space averaged value while the full detection system affords nanosecond temporal resolution. Light emission from the plasma was measured with an optical fiber and a fast risetime photomultiplier tube (R955 Hamamatsu). Visualization of helium flows in ambient air was performed on a Z-type Schlieren optical test bench, available at ISAE (Toulouse), equipped with a 3 W green LED light source, a set of parabolic mirrors, a knife-edge mounted on a precision translation stage, and a high frame rate camera.\(^{17}\) In this work, time integrated, with 1 ms exposure time, Schlieren images are documented in various setups including different voltage polarity and targets. Schlieren visualization has been performed during the steady state regime of operation of the PG. The steady state regime is achieved after a first step, involving helium flow channeling previously reported in Ref. 17 and mostly concerning with the first tens of voltage pulses after PG ignition.

**2. Electric field measurements with single PG**

Figure 2 presents the voltage pulse waveform and the temporal evolutions of longitudinal and radial EF measured for helium and neon gas buffers at different distances from the inner electrode tip. With the helium buffer and for the probe set 10 cm downstream the inner electrode, the LEF peak amplitude, –5 kV/cm, is measured with a 1800 ns delay from the voltage onset. This delay should be assigned to the combination of the discharge ignition delay and the consecutive plasma propagation along the first 10 cm path. For the
EF induced through the plasma column following the ionization front. The voltage applied to this plasma column is controlled by the voltage applied across the PG inner electrode. Both the longitudinal and radial EF measured 6 mm from the capillary axis exhibit the amplitudes of a few kV/cm with no direct relationship with the EF imposed across the PG electrodes. The latter is essentially intense in the electrode zone and nearly undetectable a few cm away from this region without plasma propagation. This confirms that transient intense EF could be delivered a few tens of cm away from the DBD reactor and may play a critical role for biomedical applications. With helium buffer but for the probe set 25 cm away from inner electrode, very similar EF signals are measured with a delay associated with the propagation of the plasma along the 15 cm additional length inside the quartz capillary. At the instants when peak LEF amplitude is detected at 10, respectively, 25 cm from electrode tip, the voltage amplitude is about 14 and 11.5 kV. The voltage applied at the ionization front position is a few kV smaller than that imposed at the powered electrode, due to voltage drop across the plasma column. Typical voltage drop value for positive polarity voltage pulse was calculated to be around 0.5 kV for a typical 10 cm long plasma column in Ne/Xe plasma. 18 With this voltage drop amplitude and with the rough assumption for linear voltage drop dependence on the plasma column length, the instantaneous voltage at the ionization front head should be about 9 kV, respectively, around 13 kV at 25 cm, respectively, 10 cm from the electrode tip. This 30% reduction of the instantaneous voltage at the front head may partly be at the origin of the decrease of the LEF peak amplitude measured at the longest distance from the PG electrode.

At a first glance, the EF components behavior and amplitudes are relatively similar for helium and neon buffers. The faster propagation of neon plasma is confirmed by the sooner rise of the EF components for the same downstream positions (10 or 25 cm). Sudden rise of radial EF holds true for neon plasma which exhibits slightly higher EF amplitude, shorter duration, and steeper rising front partly associated with the faster propagation velocity in front of the EF probe. The measurements in long tubes for neon plasma indicate that the EF amplitudes are almost constant along a few tens of cm propagation, in agreement with prior calculation. 18 Here again, only a slight decrease of the LEF peak amplitude is measured from the 10 cm to 40 cm positions, while REF peak amplitude is almost constant. Neon plasma is ignited with a smaller delay than for helium regarding the voltage pulse onset and the neon propagation velocity is higher for the same set of parameters. The neon ionization front propagation over the first 40 cm from the electrode tip occurs during the rising part of the voltage pulse. This gradual increase of the instantaneous applied voltage may partly compensate the higher voltage drop as the ionization front travels downstream. Thus during the plasma propagation inside the capillary, the LEF peak amplitude gradually decreases. Depending on the voltage pulse waveform and ionization front dynamics, the LEF peak amplitude may be preserved above a threshold ensuring plasma expansion along meters with microsecond duration HV pulses. As
previously reported, plasma velocity monitoring through the voltage pulse modulation or charged deposition along the wall\textsuperscript{19} may also involve the modulation of LEF amplitude at the ionization front. This confirms the specific nature and peculiar interest of plasma streams generated in confined dielectric tubes, having the ability to preserve some of plasma parameters along very long distances.

3. Role of voltage polarity and target

While detailed analysis of the interplay between helium gas flow and plasma discharge for various parameters is far beyond the scope of this work, representative Schlieren images are documented in Figure 3 to highlight the key roles of the voltage pulse polarity and the target on the helium flow patterns with the PG, i.e., including a first step during which helium flows inside 10 cm long capillary before its expansion in ambient air. In Fig. 3(a), the helium flow pattern measured with no plasma ignition expands over about 7 mm in ambient air towards the grounded target set 2 cm away from the capillary outlet. Due to the low density of helium, the gas then diffuses in the ambient air and dilutes upwards due to buoyancy force. The situation is drastically different when PG is turned on, as documented in Figs. 3(b) and 3(c) for positive, respectively, negative polarity voltage pulses of same amplitude (16 kV peak) delivered at the same pulse repetition rate (2 kHz). In Figs. 3(b) and 3(c), the helium flow patterns are those visualized after a 50 ms operation of the plasma gun. It is measured that with positive polarity (PP), the almost cylindrical helium flow channel is a little bit longer, about 9 mm from capillary outlet, and that helium streams cross the 2 cm gap before leading to helium flow on the target. For PP polarity, the helium flow on the target is rather unstable, the impact area over the target moving during typical time scale ranging from a few seconds to a few minutes. On the contrary, for the negative polarity (NP), the helium channel is straight, bridging the capillary outlet to the target. The position of the helium channel is measured very stable during minutes of operation of the PG, which leads to a constant flow of helium over the target on which a steady state helium rich layer is present due to the PG operation. Work is in progress to analyze the mode of action of the different ionic species generated inside and at the boundary of the helium jet on the helium gas flow. There exist plenty of evidences that thermal effect plays a very minor role in our experimental conditions, unlike the situations encountered with other plasma jets,\textsuperscript{20} while the key role of ionic species and EF probably induce most of the effects revealed from Schlieren diagnostics in agreement with other author analysis.\textsuperscript{21}

In Figs. 3(d) and 3(e), the specific role of the target is documented and provides one example of the key role of EF on the development of the helium flow pattern in ambient air. Images in Figs. 3(d) and 3(e) are obtained after a 125 ms operation of the plasma gun and are representative for the steady state regime of the helium flow patterns. It is measured that depending on the grounded or floating potential state of the target, helium channeling and flow over the target are very different while all other parameters were kept constant. The critical role of the target nature on the gas flow over surfaces facing helium plasma jets has been already reported in Ref. 22 from Schlieren diagnostics, but for nanosecond driven positive polarity voltage pulses. Our results confirm and broaden the parametric study previously reported with a different helium plasma jet setup. They also indicate that many parameters are correlated, namely, voltage amplitude, pulse repetition rate and polarity, presence of a target, nature of the target, etc. The drastic modification of gas flow pattern and mixing with ambient air play a key role for biomedical applications, resulting in specific reactive species generation and transport on the target. Once again, the analysis of the main physical phenomena involved in the helium flow patterning and successive plasma propagation is under process, but it will be shown in Sec. II B, that the knowledge of the significant role of such plasma-induced helium flow modification should be accounted, for instance, for multi jets generation.

B. Multi jets generation from single PG

This section presents the development of plasma multi jets based on the implementation of hollowed dielectric or metallic tubes at the outlet of a primary single PG device. Recent evidence of the significant action of plasma discharge on the rare gas\textsuperscript{17,20–23} flow at the outlet of capillary structure, together with previously reported propagation in small diameter capillary,\textsuperscript{24–26} splitting and transfer\textsuperscript{27–31} opportunities of atmospheric pressure plasma in dielectric assemblies or through metallic tubes allow for the development of two different setups. Both will be shown to allow for the generation of tens of jets from a single PG device, i.e., a single DBD.
reactor flushed by a rare gas flow ranging, in this work, from one to two liters per min. While both setups may be strictly identical, except the nature of the tubes, the generation of the multi jets relies either on the splitting of the primary plasma stream through the successive dielectric channels and outlets in ambient air or on the contrary for metal based multi jets setup where synchronized generation of the jets is induced at the outlet of the metal assembly. These two strategies for multi jet generation lead to specific features of the multi jets with the two setups resulting in different potentialities for applications and upscaling opportunities for large surface or volume multi plasma jet treatment.

The operation of plasma jet arrays consisting in up to one hundred of secondary jets originating from a single PG device was achieved with either dielectric and metallic tube setups or their combination both for free plasma plume generation in ambient air but also on different dielectric or metallic targets. As an illustration, Figure 4 illustrates the delivery of 34 multi jets through two sub assemblies of dielectric tubes having 0.5 mm in diameter orifices with either 5 or 3 mm inter orifice separation. As observed with a conventional camera, time exposure was of 125 ms, the vast majority of 34 multi jets appear quite similar among each of the two sub assemblies, impacting at a constant distance from the tube axis with an almost identical intensity. Even with the smaller 3 mm orifice separation, in the right hand side tube in Fig. 4, no indication for significant self influence of the 21 individual jets is observed, leading to a quasi line impact of the jets on the grounded target.

1. Experimental setup

Figure 5 presents a simplified schematic of the experimental setup used for the generation and diagnostics of the multi jets. The multi jets are generated using one of the two, 20 cm long tubes having inner/outer diameters of 4/6 mm, whose end on outlet was sealed, and equipped with side on outlet channels drilled perpendicularly to the wall. For the dielectric tube, 13 holes, 0.5 mm in diameter, were drilled each 5 mm. The metallic tube was equipped with 16, 0.8 mm in diameter, holes with a 3.3 mm step. These tubes were alternatively connected through an air-tight dielectric part equipped with two o-seal rings, to the outlet of the 10 cm long glass capillary of the PG. The distance between the PG inner powered electrode tip and the first upstream hole of the multi jet tube is of 135 mm. The rare gas flow rate was set to 1300 sccm, respectively, 1600 sccm when using the dielectric, respectively, metallic tube so that in a first approach the gas flow rate through any orifice could be estimated to be around 100 sccm.

The same PG driver as described in Sec. A 1, was used delivering microsecond duration 20 kV peak amplitude voltage pulses at a constant one kHz pulse repetition rate. The drastic influence of voltage polarity on multi jets generation will be documented, in situation where either positive or negative 20 kV peak amplitude voltage pulses are applied on the inner PG electrode. A PiMax3 Roper Scientific ICCD camera was used with 10 ns gating for time-resolved plasma expansion diagnostics, or with a 5 μs gating for time-integrated visualization and analysis of the multi jets. While multi jet generation was successfully achieved in ambient air, this work focuses on the measurements where a metallic flat (15 × 5 cm²) target was set 3 cm apart the orifices as shown in Fig. 5. Both the multi jet tubes and target were set horizontally, the target being grounded in the baseline configuration reported in this work, except otherwise indicated. The EF probe described in Sec. II A 1 was set on a motorized platform affording a precise positioning along the multi jet tubes. The radial distance between the EF probe tip and the jet axis was of 3 mm, so that the EF of the multi jets is not captured on their own expansion axis but about 4 mm apart, to ensure a non-intrusive, non-perturbative characterization. The EF probe allows for time-resolved measurement of the vertical LEF and REF induced by the multi jet propagation to the 3 cm apart grounded target. The EF probe was
horizontally moved in the middle of the gap, i.e., 15 mm downstream the tube orifices. Both the ICCD camera and the EF probe were synchronized with the PG driver. Both, images and EF measurements were averaged over 100 shots once the steady-state regime of the PG was reached.

2. ICCD multi jets analysis

Figures 6 and 7 present 10 ns snapshots representative for the ignition and propagation of the multi jets in the air gap through the 16 orifice metal assembly for negative and positive voltage pulse polarities. The first observation, is that synchronous ignition of multi jets is detected with a delay from voltage onset of 2400 ns (NP) and 2300 ns (PP) including primary plasma generation delay and propagation in the 13.5 cm glass capillary to the metal tube inlet. These two delays are documented as $t_0$ in Figs. 6 and 7, and confirm the slower propagation velocity of negative PAPS. For NP, the multi jet propagation then lasts during about 500 ns before they simultaneously all vanish.

In these preliminary experiments, the plasma emission intensity variation between the different jets is partly associated with some slight geometrical differences in the orifices on both sides of the drilled channels. The inlet from the main tube and the outlet to ambient air are not perfectly identical after the machining of the tube. One of the jet, the twelfth from the left hand side in Figs. 6 and 7, was unfortunately inoperative due to partial obstruction of this orifice. Same technical limitation was also faced with dielectric tubes. The development of jets in PP drastically differs from that in NP. While for NP the jets extend on 5 mm from the orifices, in PP the jets impact over the grounded target about 300 ns after their ignition at the orifices. Two different steps for multi jets propagation to the target in PP are evidenced in Fig. 7. During the first 150 ns after their ignition, the jets develop on a straight vertical axis and extend over about 10 mm from the orifices. Then, in a second step, the jets bend from their axis, e.g., for delays 200 and 250 ns in Fig. 7, and plasma emissions from the different jets, more or less mix together before reaching the target. As the helium fraction gradually decrease downstream, plasma branching in air may be suspected. At the same time plasma front moves closer to the target, so that EF might be enhanced between this front and the target. As during the first step the jets appears almost
straights, the bending of the jets in the second step, even over the first 10 mm downstream the orifices, is suggested to reflect mostly electrostatic self-influence between the jets rather than disturbed helium gas channels. Strong self influence between synchronized jets with negative and more drastically with positive polarity pulses has already been reported in Refs. 6 and 8.

Figures 8 and 9 present 10 ns ICCD snapshots revealing the multi jet operation with the 13 orifice dielectric tube for the two voltage polarities at the different delays after the detection of plasma emission at the orifice outlets (t₀).

With the dielectric tube, t₀ was, respectively, measured to be of 2225 and 2100 ns from the voltage pulse onset for NP, respectively, PP. For both polarities, the development of the plasma jets is shown not to operate in the synchronized mode as for the metallic tube, but with a time delay between the appearances of the successive plasma jets. In NP, the secondary jets appear consecutively one after the other. For NP, for the 100 ns delay, only the first four jets are generated, while two new additional jets are then produced each 100 ns increment. The 13 jets are generated in NP around 550 ns and then gradually vanish also in the downstream direction as shown at delays 650 ns and 800 ns in Fig. 8 where only the right hand side (downstream region) of the dielectric tube still generates a few jets. The same downstream time-shifted jet ignition, propagation in the gap and vanishing is also measured for PP. As for the metallic tube setup, the plasma jets expand only a few mm downstream the orifices for NP while for PP plasma jets impinge on the grounded target.

While helium channeling is more efficient for NP, as illustrated in Figs. 3(b) and 3(c), the plasma propagation length is much less reduced for NP in comparison with inhomogeneous but longer propagation distance of the plasma stream resulting from PP excitation. Peak EF amplitudes for NP and PP driven plasmas have been nevertheless measured to be very close for same operating conditions of PG. More influent is probably the instantaneous potential applied at the ionization front which is suspected to be lower for NP. In Ref. 18, the voltage drop calculated for NP in Ne/Xe mixtures was indeed reported to be the order of 2 to 3 kV for a 10 cm long column in comparison with the 0.5 kV amplitude for PP already discussed in Sec. II A 2.

The time shift between successive orifice jet ignition is associated with the plasma propagation, inside the main tube, and resulting delay from one orifice to the next. At the difference of the metallic tube, plasma propagation occurs in the 4 mm inner diameter dielectric tube with a typical velocity of about 10⁷ cm s⁻¹. The nearly constant 50 ns increment required for the appearance of a new jet downstream corresponds to the propagation delay along a 5 mm long helium channel inside the dielectric tube. This time-shifted operation of dielectric multi jets cannot be achieved with the metallic tubes where electric potential applied to the PG inner electrode is transferred across the plasma column to the metallic part as soon as the ionization front connects to it. With metallic tubes, the synchronized operation of the multi jets is mainly associated with the instantaneous polarization of the tube. The time-shifted operation of the multi jets with dielectric tube offers an additional advantage correlated with the spatial separation of the time-shifted ionization fronts produced in the orifices. One observes in Fig. 9, that the straight development of the multi jets is preserved all across the 3 cm wide air gap with neither no significant branching nor no obvious self-influence in between the different jets in comparison with the situation for metallic tube (Fig. 7). Such straight propagations were also measured in other assemblies even having a much smaller (down to 2 mm) separation between the different orifices. On the contrary to the metallic setup, successive jets operation with the dielectric tube relies on the successive plasma splitting for each new orifice. While the plasma splitting is inherently associated with some energy balance between the two plasma generated after plasma branching, it has been measured that the emission intensity and patterns collected with ICCD camera are almost similar for all the
jets. It is speculated that only a limited fraction of the input energy is transferred to each new jet, the main part being associated with the plasma propagation inside the main tube (see Fig. 5).

Time-integrated ICCD images of multi jets generated with the metallic and dielectric tubes and powered in PP or NP are shown in Figure 10 with the same experimental conditions including the presence of a grounded metal target 3 cm apart from the jet orifices. An additional time integrated image is included in Fig. 10 where the target was left at floating potential. Time-integrated images for NP with metallic, respectively, dielectric tubes confirm the generation of 15, respectively, 13 jets expanding in ambient air over about 4 mm from the orifices. For NP, the jets are almost straight with no indication for any significant self-influence between them even with the metallic tube associated with synchronized multi jet generation. For PP, time-integrated images confirm the impact of the multi jets over the grounded target with obvious strong self-influence for the metallic tube setup leading to plasma generation over a large volume and surface on the target. For PP and dielectric tubes, the jets develop almost straightly towards the target with much less self-influence between them leading to a less pronounced plasma mixing during air gap propagation and a multi spot target impact. The key role of the target electrical potential is shown for PP and metallic tube. With the target at floating potential, the jets only travel about half of the air gap and exhibit almost straight line propagation paths. It is important to note that this much less bended pattern of the plasma jets coincides with what is observed during the first 150 ns period after ignition at the orifices in presence of a grounded target. This probably confirms that jet bending during the second step occur due to self-influence of the jets as they approach the grounded target. The critical influence of the target potential on the helium flow channeling, as shown in Figs. 3(d) and 3(e), probably plays a key role on the successive plasma development not only for single but also for multi jet setups.

3. Electric field diagnostics for synchronized and time-shifted multi jets

Figure 11 presents EF measurements performed with the optical-based probe. The probe was moved perpendicularly to the multi jets at a distance of 3 mm from their expansion plan, along the horizontal direction in the middle of the gap, i.e., 15 mm from the jet orifices.

Figs. 11(a) and 11(b) present the superposition of 6 longitudinal EF waveforms collected for different horizontal positions of the probe, starting from the first downstream orifice position and then with a one cm spatial step sampling with the metallic, respectively, dielectric multi jet assembly. Considering the diameter of the sensitive crystal of the EF probe, and the relatively short separation between the different orifices, it was checked experimentally that the probe mainly sense the EF contribution of 3 individual plasma jets. This means that the comparison of the amplitude of EF
associated with each individual jet was not processed in this work.

Nevertheless, Figure 11 confirms that for the jets generated through the metallic tube the longitudinal EF components, i.e., along the jet axis propagation towards the target, are synchronized, having their peak amplitudes ranging from 5 to 6 kV/cm and detected around 2250 ns after voltage pulse onset along the middle gap direction. The time-shifted generation of the jets with the dielectric tube is confirmed in Fig. 11(b) where the LEF signals are detected from 2 to 3 μs after voltage pulse onset as the probe is moved along the middle gap direction. The REF measurements with dielectric tube, Fig. 11(c), also evidence the time-shifted jet generation mode. The REF peaks appear from 2000 to 2500 ns along the 6 cm wide scan length of the EF probe, in agreement with the plasma ionization front velocity determined from ICCD acquisitions. In the experimental conditions for EF measurement in Fig. 11, the LEF peak intensity is reached within a 20% range of amplitude for the metallic tube set up. This modulation may be partly correlated with the bended patterns in PP and the non homogenous distribution of plasma jets along the tube axis due to machining issues. With the dielectric tube setup, the gradual decrease of the peak LEF amplitude along the downstream direction, leads to a 50% reduction of the LEF peak intensity. With this latter setup, the REF is on the contrary almost constant along the tube axis, confirming in multi jet configuration, that the REF detected right after the ionization front is tightly correlated with the plasma column potential. With the dielectric tube setup, the gradual decrease of the LEF amplitude following the successive splitting of the plasma, may lead to some limitations for the upgrading of multi jet devices for the generation of tens or hundreds of plasma jets. This limitation can nevertheless be largely moderated for plasma array development if plasma jets are distributed in sub assemblies of multi orifice tubes allowing in a first time for jet splitting in a few secondary jets, each of them being in a second step divided again in multi orifices tubes, as was shown in Fig. 4. Such limitation appears less relevant for the generation of multi jets with metallic tube setup where synchronized mode of operation is shown to induce a much balanced LEF peak amplitude distribution among the different multi jets. It should nevertheless be pointed out that the strong self influence between individual multi jets with metallic tube may be a severe limitation if multi spot operation of the multi jets is required. The strong self influence between the jets with metallic tube was confirmed through EF measurement. The measurements, not shown in this work, evidence large variations of both the amplitude and direction of the REF signals which only preserve a constant delay with voltage pulse onset. This behavior is suspected to reveal a continuous on-axis twisting of the individual jets, due to their self influence, leading to some continuous modulation of the REF features.

III. CONCLUSIONS

The first part of this work reports on the measurement of electric fields associated with propagation of ionization wave in dielectric tubes downstream the plasma gun DBD reactor powered with microsecond duration high voltage pulses. As a first step, these first time reported measurements, are documented in the so called “free jet” operation of both neon and helium fed plasma gun. Time-resolved non intrusive and non perturbative measurement of longitudinal and radial EF components associated with helium and neon atmospheric pressure plasma propagation in long dielectric tubes has been achieved using a new probe based on Pockels effect. Peak EF amplitudes of a few kV/cm have been measured for both components a few mm apart from the capillary axis, for both rare gas buffers. The experimental measurements reveal that plasma propagates in region where an intense longitudinal EF component exists a few cm ahead the ionization front. The latter is usually reported in the literature from optical diagnostics as an intense and transient plasma emission along the plasma propagation. Correlated with the ionization front propagation, the extension of a plasma tail connecting this latter with the powered electrode of the plasma jet device, induces the sudden generation of an intense radial EF component. These observations are in good agreement with previous model calculations and confirm that EF amplitudes are almost constant along the full plasma propagation, i.e., over distances of a few tens of cm. Dealing with biomedical applications of plasma gun, or other plasma jet devices, the role of intense transient EF, having amplitudes in the kV/cm range, should probably be considered with more attention. It is then speculated that plasma treatment could be a unique way to deliver synchronously intense transient EF and chemical reactive species. The further development of EF measurement and modeling would be valuable to assess the role of EF and chemical species during plasma treatments.

The key role of voltage polarity and target nature on the plasma jet development is then documented through Schlieren images. The major impact of voltage polarity and target potential status is demonstrated from helium gas flow patterns analysis. While no detail analysis on the mechanism involved in helium flow channeling at the capillary outlet are proposed, the experimental evidences for severe helium flow modifications depending on the plasma jet operation conditions, are then encountered for the development of multi jets in the second part of this work.

The plasma gun device is then used as a single primary discharge reactor likely to drive the operation of tens of secondary plasma jets. Two modes of generation of multi jets are documented and analyzed using ICCD imaging and EF measurements. The use of dielectric or metallic tubes equipped with outlet channels having sub millimetric orifices connected at the outlet of the plasma gun capillary allow for the time shifted or synchronized operation of tens of secondary plasma jets. In the time shifted mode, plasma jets are produced with a time delay in between them, resulting from the successive plasma splitting during downstream propagation in the tube. For synchronized mode, the metallic tube is polarized as soon as the primary ionization front connects the tube leading to simultaneous secondary plasma jets ignition and propagation in ambient air. These two modes of operation revealed with ICCD imaging have been confirmed through EF measurements. For the two setups, negative voltage polarity result in short, 5 mm in length, plasma plume...
generation while for positive polarity plasma jets expand over a few cm in ambient air or on metallic target. The use of a dielectric tube with small orifices and powered with positive polarity PG lead to the generation of straight plasma jets showing small self influence in between them even for small separation down to a few mm, and lead to multi spot impact on the target. Contrarily, with metallic tube and positive polarity PG, strong self influence is measured both from ICCD and EF analysis and lead to some mixing of the different secondary jets before they reach the target. The development of plasma arrays based on combination of plasma splitting within dielectric tubes and plasma transfer across metallic tube is reported leading to the generation of 34 secondary jets from a single PG device, i.e., a single DBD reactor flushed with 2 l/mn of helium. Further optimization of plasma source operating conditions may lead to the generation of hundreds of secondary jets, each of them being developed in very low gas flow rate, a few tens of sccm. This would allow for large surface but also low gas flow rate plasma delivery in comparison with most of previously published results.

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