Tuning in the medium frequency (0.3 to 3 MHz) range to control the secondary emission of a dielectric barrier discharge in helium at atmospheric pressure

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Abstract: It was recently shown that homogeneous dielectric barrier discharges can be generated in the medium frequency range at atmospheric pressure. The present paper discusses the advantages of the medium frequency range over the low frequency (30 to 300 kHz) and high frequency (3 to 30 MHz) ranges, namely the capability of tuning the secondary emission via the control of the Townsend-like and glow-like modes.

Keywords: dielectric barrier discharge, atmospheric pressure, helium, medium frequency

1. Introduction
Widely studied in the low frequency (LF; between 30 and 300 kHz) [1] and the high frequency (HF; between 3 and 30 MHz) [2] range, diffuse DBDs are nowadays known for their capability to be operated at atmospheric pressure. In the last decade, many atmospheric cold plasma sources were developed. Whether it is a direct plasma device or a plasma jet, most of the atmospheric cold plasma sources are based on a DBD configuration [3-5]. As far as applications are concerned, an important issue is the versatility of the plasma device, i.e., the latitude allowed for the plasma parameters. The aim of this paper is to show that the available plasma parameters cover a wider range in the MF range than in the LF or the HF range for similar experimental conditions. Furthermore, it will be shown that the secondary emission can be switched on and off simply by a flip of the applied voltage.

2. Experimental setup
A plane parallel DBD setup operated in atmospheric helium is used for this study. Helium is injected at a constant flow rate of 8.3×10^-6 m^3/s through the 2 mm interdielectric gap distance previously pumped to a primary vacuum.

Fig. 1 shows the experimental setup. It includes the reaction chamber as well as the electrical circuit. Medium frequencies can be obtained using a waveform generator (Agilent 33220A) and a power amplifier (Prâna GN500) connected to the discharge cell via a customized air core transformer [6]. Changing either the capacity (via different cable lengths) of the discharge cell or the transformers, it is possible to tune different frequencies of the MF range. This enables to test 4 frequencies in the MF range, namely 1.48, 1.97, 2.61 and 2.65 MHz.

3. Townsend-like and glow-like modes
It has now become clear that, like in Ar [6], two very different discharge modes can be obtained in atmospheric helium DBD using a MF excitation waveform [7]. For example, Fig. 2 displays both Townsend-like and glow-like discharges pictures in the interdielectric gap during the maximum voltage amplitude of a discharge at 2.65 MHz. The gray stripes represent the dielectric barriers while the black stripes represent the electrodes. The light emission is recorded only in the wavelength range close to 337 nm (FWHM of 10 nm) which corresponds to the emission of the molecular band N_2(C^3Π_u - B^3Π_g) of the nitrogen molecules present as impurities in the plasma.

The intensity of the 337 nm molecular nitrogen emission is usually observed in helium plasmas containing traces of nitrogen. Even for low concentrations of such impurities (less than 10 ppm), the density of nitrogen ions (atomic or molecular) can be significant [8]. On the other hand, in atmospheric pressure helium plasmas, the upper state of the N_2(C^3Π_u - B^3Π_g) transition is known to be populated by direct electronic collision from the N_2 ground state [9]. This means that the light emission associated to 337 nm is proportional to the electron density. The picture at the top of Fig. 2 indicates that the region close to the cathode corresponds to a high electron density. This is very
similar to the glow discharge that can be obtained in DBDs generated in helium with LF excitation waveform [10] or in DC discharges [11]. The capability of generating glow discharges in helium at atmospheric pressure in the MF range is not unexpected. However, at such frequencies, the light is continuously emitted (all observed emissions between 200 and 750 nm). Unlike the LF glow discharge, there is no plasma relaxation between two half period. In other words, the lifetime of the long-lived species is equal or greater than the time between two half period.

The picture at the bottom of Fig. 2 shows that the light emission is concentrated close to the anode during the maximum applied voltage. The emission intensity is more than one order of magnitude weaker than in the glow-like mode (the normalization does not allow to see this feature in Fig. 2 but every emission is roughly 10 times brighter in the glow-like mode than in the Townsend-like mode). This behaviour is very similar to the Townsend discharge that can be obtained with a LF excitation waveform in nitrogen DBD [12] or with a DC discharge [11], or with a MF excitation in an Ar DBD [6]. However, the Townsend discharge was never observed in LF DBD produced in helium. In contrast, the Townsend-like mode is inherently obtained in the MF range at low power densities. It switches to glow-like mode by increasing sufficiently the power density. The transition from Townsend-like to glow-like is accompanied by a voltage drop across the gas gap [7], similarly to the transition from Townsend to glow in the DC discharge.

4. Advantage of the MF over LF and HF ranges

From comparison with the known plasma parameters obtained with DBDs or capacitively coupled discharges in helium at atmospheric pressure, one can conclude that the medium frequency range enables to reach the widest range of plasma parameters. This is indicated in Table 1 where the LF, MF and HF range are compared. Data in the LF [1] and HF [13, 14] range were taken from the literature respectively dealing with glow DBD and capacitively coupled discharges (excluding the gamma mode). Data in the MF range are evaluated experimentally from electrical measurements. The power density is calculated via:

$$P_d = \frac{1}{\tau V} \int_{0}^{T} V(t) \cdot I(t) \, dt$$

where $\tau$ is the oscillating period, $V$ is the volume of the discharge $V(t)$ is the measured voltage and $I(t)$ is the measured current. The electron density is calculated with:

$$n_e = \frac{j_\mathbf{g}}{e \mu_e E_g}$$

where $j_\mathbf{g}$ is the conduction current density, $e$ is the electron charge, $\mu_e$ is the electron mobility and $E_g$ is the electric field across the gas gap. The MF parameters are obtained for fixed operating conditions (same dielectric barriers and interdielectric distance in helium) and for a fixed frequency in the MF range.

<table>
<thead>
<tr>
<th>Light emission</th>
<th>LF</th>
<th>MF</th>
<th>HF [13, 14]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency, $f$ (MHz)</td>
<td>$&gt; 0.01$</td>
<td>$0.3 &lt; f &lt; 3$</td>
<td>$&gt; 1$</td>
</tr>
<tr>
<td>Electron density, $n_e$ (m$^{-3}$)</td>
<td>$10^5$ to $10^7$</td>
<td>$10^5$ to $10^7$</td>
<td>$10^5$ to $10^7$</td>
</tr>
<tr>
<td>Current density, $j$ (A/m$^2$)</td>
<td>$10^1$ to $10^2$</td>
<td>$10^1$ to $10^2$</td>
<td>-</td>
</tr>
<tr>
<td>Power density, $P_d$ (W/cm$^3$)</td>
<td>$10^1$</td>
<td>$10^1$ to $10^3$</td>
<td>$10^2$ to $10^3$</td>
</tr>
</tbody>
</table>

As indicated in Table 1, the electron density spreads over 3 orders of magnitude in the MF and HF ranges. That is one order more than in the glow DBD in the LF range. On the other hand, the power density spreads over 2 orders of magnitude, which is one order of magnitude wider than in the HF range and two orders as compared to the LF range. This wide range of parameters results from the possibility to operate the discharge either in the Townsend-like mode or in the glow-like mode.

5. Control of the secondary emission

The fundamental difference between Townsend-like and glow-like modes deals with the role of the secondary emission when a large enough flux of ions flows to the dielectric barriers. In atmospheric pressure plane parallel discharges, the oscillation amplitude (the displacement length over which a particle can travel before the reversal of applied field) is larger than the discharge height (about 1 mm) in the LF range and smaller than the discharge height in the HF range. However, in the MF range, the oscillation amplitude of the electrons is of the order of the discharge height while the ion oscillation amplitude is about one order of magnitude smaller. In the Townsend-

Fig. 2. Filtered pictures of the glow-like and the Townsend-like modes during the maximum voltage of the excitation waveform for the discharge at 2.65 MHz.

| Table 1. Comparison of some plasma parameters between LF, MF and HF helium discharge in a plane parallel geometry. |
|---------------|----|----|-------------|
| Light emission | LF | MF | HF [13, 14] |
| Frequency, $f$ (MHz) | $> 0.01$ | $0.3 < f < 3$ | $> 1$ |
| Electron density, $n_e$ (m$^{-3}$) | $10^5$ to $10^7$ | $10^5$ to $10^7$ | $10^5$ to $10^7$ |
| Current density, $j$ (A/m$^2$) | $10^1$ to $10^2$ | $10^1$ to $10^2$ | - |
| Power density, $P_d$ (W/cm$^3$) | $10^1$ | $10^1$ to $10^3$ | $10^2$ to $10^3$ |
like mode, the electric field is uniform across the discharge. The ionization rate is low and only a few ions reach the solid dielectrics. In contrast, in the glow-like mode, a cathode fall is formed. Therefore, the electric field is concentrated close to the cathode. The cathode fall occurs over about the same length than the ion oscillation amplitude. In other words, once the glow-like mode is triggered, many ions can then reach the dielectric barrier, which enables the emission of a large quantity of secondary electrons.

Switching from the Townsend-like mode to the glow-like mode, it is consequently possible to control in some way the secondary emission. Furthermore, by adjusting the applied voltage or by tuning the excitation waveform frequency the cathode fall length is modified [7]. As the secondary emission depends on the oscillation amplitude of the ions relative to the gap height of the actual electric field, tuning the frequency and the applied voltage enables to control the amount of secondary emission via the regulation of the cathode fall length.

6. Conclusion

In helium at atmospheric pressure, a DBD generated by an excitation waveform in the medium frequency range results in an electron density and a power density that spread over three orders of magnitude. This wide range of parameters significantly outmatches those achieved in the LF and HF ranges. This advantage is mainly due to the capability to generate two discharge modes, namely the Townsend-like one and the glow-like one by only varying the applied voltage in otherwise identical operating conditions (gas mixture, applied frequency, electrode geometry and pressure).

7. Acknowledgements

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8. References

[7] J.-S. Boisvert, J. Margot and F. Massines. "Transition from Medium Frequency (0.3 to 3 MHz) to High Frequency (3 to 30 MHz) in Atmospheric Helium Dielectric Barrier Discharge". unpublished