



PULSE – Plasma reconfigUrabLe metaSurface tEchnologies

*This project has received funding from the European Union under the call EIC
Pathfinder Open 2022 (Project n. 101099313)*

Deliverable: Report on generation techniques for plasma and related EM description

Deliverable number	D1.2
Due date	29 February 2024
Delivery date	
Type ¹	R
Dissemination Level ²	PU
Work Package	WP1- Physical Investigations
Deliverable Related No	D1.2
Lead Beneficiary	FORTH
Contributing Beneficiaries	All

¹ **Type:** R = Report, P = Prototype, DEM = Demonstrator, DMP = Data Management Plan, O = Other

² **Dissemination Level:** PU = Public, SEN = Sensitive

Table of Contents

1. Introduction.....	3
2. Plasma generation techniques and sources	4
2.1 DC excitation	4
2.2 Pulsed excitation	6
2.3 AC/RF excitation	6
2.4 Microwave excitation	8
3. Plasma discharge regimes.....	9
3.1 Glow discharge.....	9
3.2 Microplasma discharge	9
3.3 Others: Corona discharge, plasma jets.....	10
4. Associated plasma electromagnetic properties.....	12
4.1 Characteristics of plasma discharge	12
4.2 Electromagnetic properties of plasma discharge	13
References	15

1. Introduction

Plasma, also known as the fourth state of matter, is an ionized medium consisting of charged particles (e.g. electrons and ions) and excited atoms and molecules in a neutral gas. There are two main groups of plasmas that can be generated under lab conditions – equilibrium thermal plasmas, and non-equilibrium cold plasmas [1]. Thermal plasmas are in thermal equilibrium, usually produced under high pressures, where all the species in the plasma (electrons, ions and neutral particles) have the same temperature (typically 1-2 eV, with 1eV representing 11600 K) [1]. On the other hand, cold plasmas are not in thermal equilibrium state, and the electrons in the plasma have much higher temperature than the other heavier particles. Typically with low-power source cold plasmas, the electron temperature is within 30000 – 40000 K [2], with ion/neutral temperature within 300 – 1000 K. Cold plasmas are the focus of the PULSE project and also of this deliverable.

A conventional approach to generate plasma is by applying an electric field to a volume of neutral gas, which contains a small number of free electrons due to, for instance, cosmic radiation. The electrons are accelerated by the electric field, and inelastic collisions between electrons and gas particles lead to ionization and excitation, i.e. transitions to higher energy states, which can be considered as primary reactions. As the applied electric field approaches the breakdown requirements, avalanches of charged particles occur, which results in plasma generation. In some of the plasma discharge regimes that will be discussed in later sections, e.g. DC glow discharge, self-sustained plasma discharges are formed based on secondary reactions between ions and the electrodes. In such cases, the ions generated are accelerated by the electric field towards the cathode, producing secondary electrons that contribute to the multiplication of charged particles.

Plasma discharges have a wide range of applications, including plasma displays, surface and material processing [1, 3], environmental decontamination [4-6], biomedical applications [7, 8] etc. In this deliverable, electromagnetic (EM) properties of the plasma discharges related to the PULSE project will be summarized.

2. Plasma generation techniques and sources

A few commonly used plasma generation techniques are introduced in this section. In particular, generation through the DC excitation (Section 2.1), pulsed excitation (Section 2.2), AC/RF excitation (Section 2.3), and microwave excitation (Section 2.4).

2.1 DC excitation

Constant DC voltages can be applied to plane electrodes to create plasma discharges in closed vessels. Different discharge voltage-current relationships characterize various DC plasma discharge regimes [9], as shown in Figure 1. The normal glow discharge, which is more relevant to the project, is characterized by relatively low voltages.

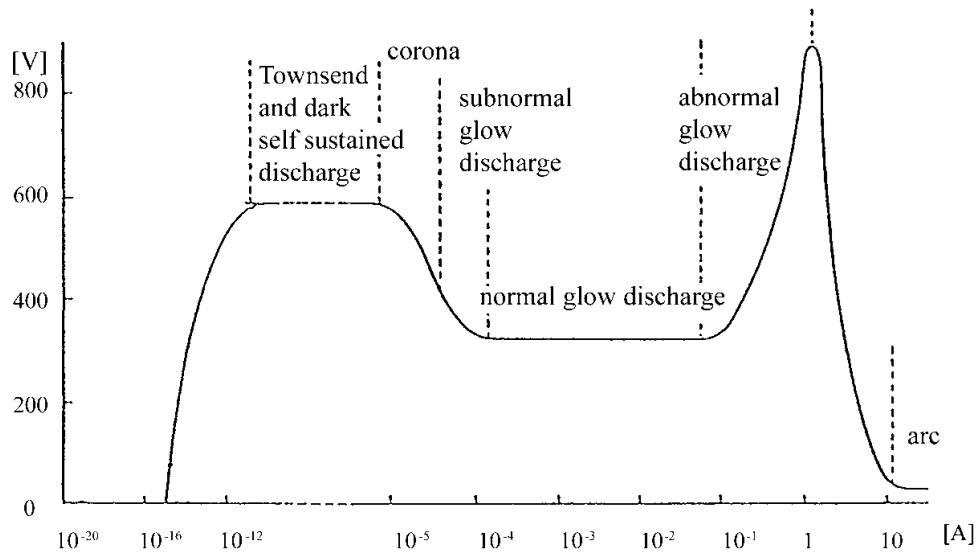


Figure 1: Relationship between discharge voltage and current for DC plasma discharges in different regimes, for Ne with pressure 1.3 mbar, from [9].

A DC normal glow discharge, formed between the electrodes in a cylindrical discharge tube, exhibits spatial variations in the plasma parameters along the tube axis, which is shown schematically in Figure 2. The dimensions of each region are not drawn to scale. It can be seen that the light intensity is approximately axially uniform in the positive column.

The product of the pressure and the separation between the electrodes pL characterizes the plasma discharge. The dependence of the required breakdown voltage V_B on pL gives the Paschen curve, which is different for various discharge gas types. The Paschen curves for several gas types [10] are shown in Figure 3.

Practical characterization of the breakdown voltage for DC plasma discharges is easier compared to AC discharges which will be introduced in Section 2.3. Nonetheless, DC device lifetime and flexibility are often lower than with AC excitation [11].

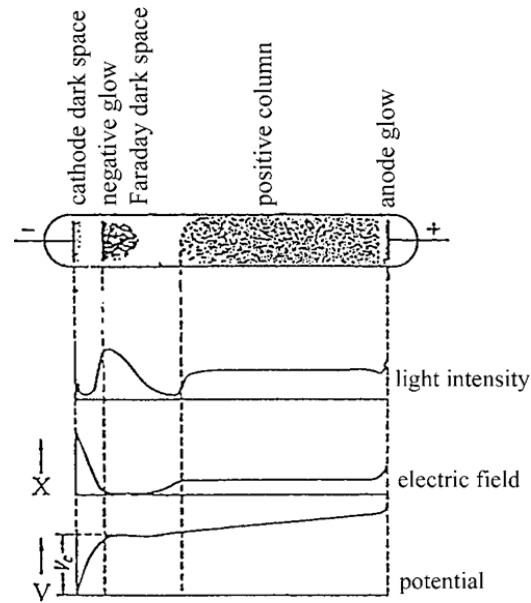


Figure 2: Variation of light intensity, electric field and potential along the length of a DC glow discharge with electrodes, from [9].

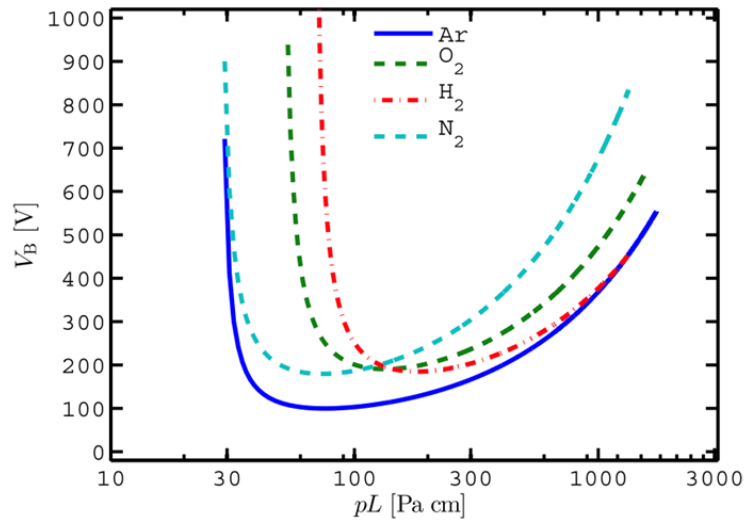


Figure 3: The relationship between the required breakdown voltage V_B and the reduced electrode distance pL for different gases, where p is the gas pressure, L is the distance between the electrodes, from [10].

2.2 Pulsed excitation

Compared to DC plasma sources, pulsed sources allow more freedom in controlling the plasma parameters, e.g. by varying the duty cycle or the shape of the pulses. In addition, pulsed sources provide higher instantaneous power for the same average power in DC discharge sources, and therefore can be considered to be more efficient than DC discharges [12-14]. The pulses can be either unipolar or bipolar, where bipolar pulses have the polarity of the applied voltage reverted every half-cycle. When the pulse is on, the system resembles a DC discharge, while it enters an afterglow period when the pulse is off [14].

The durations of the pulses are in the milli- or microsecond range for conventional pulsed sources [15, 16]. Nanosecond pulsed sources are also available [17], although characterization is more complicated due to EM interference from the environment.

2.3 AC/RF excitation

When at least one of the electrodes is not conductive, e.g. covered by a dielectric barrier as will be discussed later, plasma discharge cannot be sustained by DC voltages due to charge accumulation on the electrodes. Alternating voltages or sources in the radiofrequency (RF) range are required to overcome this issue. RF sources of 13.56 MHz are widely used, though the frequency range for RF discharges is typically within 1-100 MHz. There are two main mechanisms in coupling the power from RF sources to the plasma discharge, capacitive and inductive, generating capacitively coupled plasma (CCP) and inductively coupled plasma (ICP) respectively.

2.3.1 Capacitively coupled plasma (CCP)

CCP is also called E-field discharge. Parallel electrodes may be in direct contact with the plasma discharge or could be covered by insulating layers [18]. Dielectric barrier discharge (DBD) can be considered as a special case of CCP with one or both of the electrodes covered by dielectric layers as insulating barriers.

Typical configurations of DBD are mainly volume discharge and surface discharge [19], as shown in Figure 4. In volume discharge, plasma is formed in the space between the electrodes, where at least one of which is covered by a dielectric barrier. In contrast, both electrodes are in contact with the dielectric barrier in the surface discharge, and plasma is formed along the surface of the dielectric layer.

DBD can operate in two different discharge regimes or modes, namely the filamentary or the diffuse mode. In the filamentary mode, usually under medium or higher pressures, thin discharge channels are formed [19]. Whereas in the diffuse

discharge, the plasma discharge almost covers the entire surface of the dielectric barrier, although the discharge may not be homogeneous. Whether the discharge is diffusive or filamentary may be affected by operational conditions, for example the discharge gas type. It should be noted that filamentary discharge might appear as being in the diffuse mode to naked eyes, and cameras of short exposure time might be needed to distinguish the two modes.

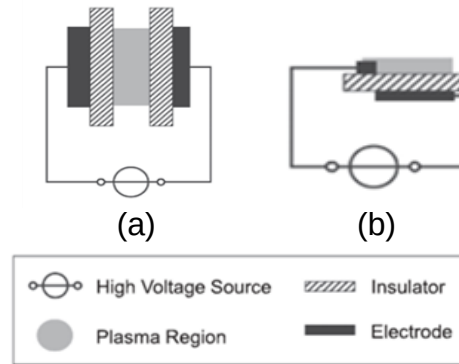


Figure 4: Basic DBD configurations of (a) volume discharge and (b) surface discharge, from [19].

2.3.2 Inductively coupled plasma (ICP)

The second type of RF discharge, the ICP, is also called the H-field discharge. An induction coil connected to a RF source generates a time-varying magnetic field, which then induces an electric field that ignites the plasma. ICP sources in both cylindrical geometry (with a helical induction coil surrounding the discharge chamber) and in planar geometry (with a planar spiral coil above the chamber) are shown in Figure 5 [14].

ICP sources generally require more complicated structures and setups compared to CCP RF sources, but discharges with higher electron density may be generated using ICP.

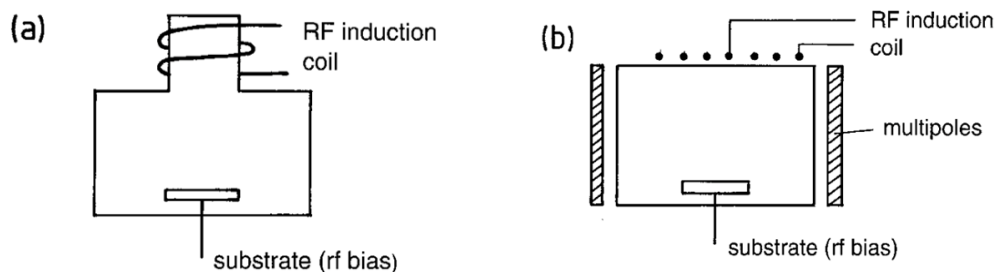


Figure 5: Schematics for ICP sources in (a) cylindrical and (b) planar configuration, from [14].

2.4 Microwave excitation

Plasma generation using microwaves, with a typical frequency of 2.45 GHz or other frequencies within 1-10 GHz, has also been reported. This technique is less relevant to the current project and will only be introduced briefly, with references.

Microwave-induced plasmas can be categorized based on the mechanisms of how the microwaves are coupled to the plasma [20]. Examples of microwave discharge configurations include cavity, waveguide, as illustrated in Figure 6 [20], or surface wave microwave plasma generators. In the cavity mode [21], a plasma tube is typically inserted into a resonator cavity where there are standing waves formed, and the energy is coupled to the plasma discharge. Microwave energy from waveguides can also be coupled into the plasma volume [22]. Generating surface waves that propagate along the interface of the plasma discharge and its surrounding dielectric tube is another approach to sustain microwave-induced plasma [23]. Microwave plasmas can generally operate at both low and high pressures.

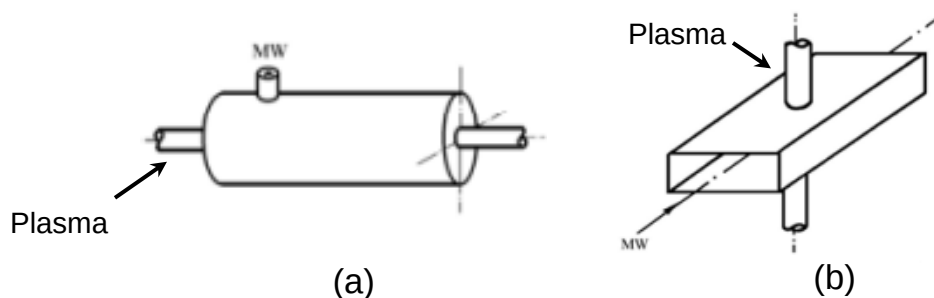


Figure 6: (a) Cavity microwave plasma generator, where plasma is in the horizontal cylindrical volume, and (b) waveguide microwave plasma generator, where plasma is generated in the vertical tube, from [20].

3. Plasma discharge regimes

Different discharge regimes are discussed in this section. Glow discharges (Section 3.1) and microplasma discharges (Section 3.2) under low pressure conditions are more relevant to the project, though they can also operate under high pressures. Other discharges (Section 3.3), such as the corona discharge and plasma jets, typically operating under high pressure, will be discussed briefly as well.

3.1 Glow discharge

Glow discharges can operate over a wide range of pressure, from low pressure (<1 Torr) to near atmospheric pressure (760 Torr) or even higher. DC, pulsed, or AC/RF sources can be used for glow discharge generation.

Conventional DC glow discharges operate under low pressure, less than 1 Torr, although higher pressure conditions are also possible [24, 25]. Recall that the product term pL discussed in Section 2.1 is an important parameter for characterizing stable DC glow discharge operation. Pulsed glow discharges [26] are similar to the DC glow discharges, where the glow discharges are generated during the ‘on-period’ of the pulse.

CCP or ICP structures can be used to generate RF glow discharges [27], typically operating under low or moderate pressure, e.g. up to about 7.5 Torr.

Atmospheric pressure glow discharges [28] are also available, for instance using the DBD structure mentioned in Section 2.3. Characterized by the pL term, miniaturization of the discharge chamber is another approach for realizing high pressure discharges, and such micro-discharges will be discussed in Section 3.2.

3.2 Microplasma discharge

Miniaturization of plasma discharge is one way to generate stable glow discharges at atmospheric pressure. Such microplasmas have dimensions below 1 mm, and enable stable operation avoiding glow-to-arc transitions [29, 30]. DBD can be used for microplasma generation under atmospheric pressures.

Microhollow cathode discharge (MHCD) is another type of device for microplasma generation. A typical structure has a cylindrical opening in the cathode, as shown in Figure 7 [29], and DC or pulsed sources can be used to power MHCD.



Figure 7: Schematic of a typical microhollow cathode discharge (MHCD), with a cylindrical cavity in the cathode, from [28].

Despite the extensive studies of using MHCD for generating atmospheric pressure plasma with high electron density, microplasmas can also operate under moderate or low pressures [31]. Scaling down to the micrometer range, microplasma arrays were studied in [32] as controllable elements interacting with EM waves in the GHz frequency range. Operating under lower pressures results in lower achievable electron densities, and it was shown in [32] that, as pressure rises from 30 to 80 Torr, the electron density increases by a factor of 60 to reach a peak value of $4.7 \times 10^{20} \text{ m}^{-3}$. In [33], a range of low to moderate pressure conditions (from 3.5 to 56 Torr) was studied for MHCD, showing different voltage-current characteristics. It was suggested [33] that MHCD can operate under a range of pD values (D being the cathode hole diameter), and for argon the minimum pD is 0.026 Torr cm.

Metamaterial-based structures can also be used to generate microwave-induced microplasmas or microplasma arrays [34, 35], though it is generally difficult to characterize the plasma properties due to the experimental setup required.

3.3 Others: Corona discharge, plasma jets

Some other types of plasma discharges, such as corona discharges and plasma jets, will be discussed briefly in this section and related references will be listed. These discharges operate at high pressures, and are not relevant to the current project.

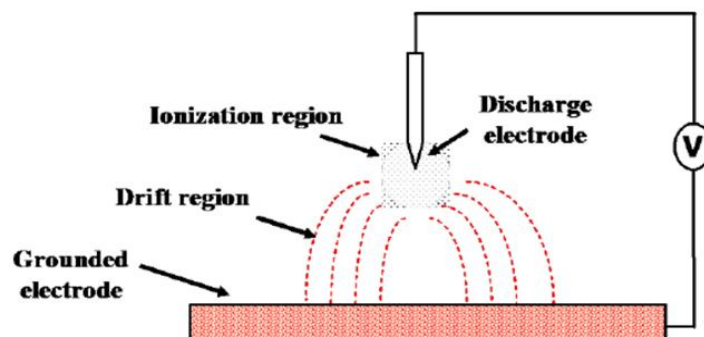


Figure 8: Schematic of pin-to-plate configuration for corona discharge, from [36].

Corona discharges typically are generated using pin-to-plate configurations [36, 37], with a schematic diagram shown in Figure 8. Pulsed sources can be applied to the pin or wire electrode, and depending on the polarity of the applied voltage, negative or positive corona discharges can be produced.

Plasma jets [38] can be ignited in a source consisting of two concentric electrodes, as shown in Figure 9. The gas discharge exits through a nozzle. Compared to other atmospheric pressure discharge sources, breakdown voltage for plasma jets is much lower.

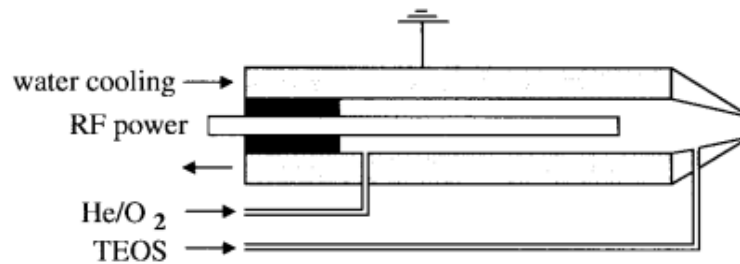


Figure 9: Schematic of atmospheric pressure plasma jet structure, from [38].

4. Associated plasma electromagnetic properties

4.1 Characteristics of plasma discharge

The typical characteristics of the aforementioned plasma discharge types are summarized in Table 1.

Type	Generation		Pressure	$n_e [m^{-3}]$	Remarks
Glow discharge	DC		low to atmospheric (atm.)	(At low pressure) $\sim 10^{17}$	pL characterizes the discharge
	Pulsed		0.75 Torr typical		similar to DC glow discharge
	Capacitively coupled	RF	low to moderate < 7.5 Torr	$10^{15} - 10^{17}$	
		DBD, AC/pulsed	0.1-1 atm., lower pressure possible	$10^{16} - 10^{21}$	dielectric barrier discharge, dimension 1- 20 mm
	Inductively coupled, RF		low pressure < 7.5 Torr	$10^{17} - 10^{18}$	more complex than capacitively coupled plasma, but higher n_e
Corona discharge	DC, pulsed DC		1 atm.	$10^{15} - 10^{18}$	high pressure
Micro-plasma	1-100 kHz, pulsed		low to atmospheric pressure	$10^{20} - 10^{22}$	< 1 mm (range based on available setup: pressure from pump 0.04-760 Torr, dimension 300-400 μm)

Table 1: Characteristics of different plasma discharge types.

4.2 Electromagnetic properties of plasma discharge

In order to analyze the interactions between electromagnetic (EM) waves and the plasma medium, the plasma effective permittivity ε should be determined, and can be written as in Eq. 1 [17].

$$\varepsilon = 1 - \frac{\omega_p^2}{\omega(\omega - j\nu_m)}, \quad (1)$$

where the angular plasma frequency ω_p is dependent on the electron density in the plasma discharge, ν_m is the effective electron momentum-transfer collision frequency (in rad/s) with other particles (typically neutrals, neglecting Coulomb collisions). Assuming a uniform plasma volume, ω_p can be expressed as,

$$\omega_p = \sqrt{\frac{e^2 n_e}{\varepsilon_0 m_e}}, \quad (2)$$

with n_e being the electron density in the plasma, with unit m^{-3} , e the electron charge, ε_0 the vacuum permittivity, and m_e the electron mass. By substituting the constant values, e , ε_0 , m_e , the following can be obtained:

$$\omega_p = \sqrt{3180 n_e}. \quad (3)$$

Note that the unit for the plasma frequency in Eq. 3 is in rad/s. Eq. 3 shows that the plasma frequency can be tuned or modulated by changing the electron density. Based on some typical numbers of n_e from Table 1, the plasma frequency can be calculated. $n_e = 10^{18} m^{-3}$ gives $f_p = \omega_p/2\pi = 8.97$ GHz, and $n_e = 10^{19} m^{-3}$ gives $f_p = 28.4$ GHz, showing that increasing the electron density by one order of magnitude approximately triples the plasma frequency.

The effective momentum transfer collision frequency ν_m in Eq. 1 is typically derived from solutions of the Boltzmann equation (e.g. under the two-term approximation) using adequate cross sections for momentum transfer. Usually, such solutions allow one to obtain the electron mobility, μ_e , as a function of the electron mean energy, and relate to the momentum transfer frequency (as for DC fields, $\mu_e = e/(m_e \nu_m)$, where ν_m is in $1/s$). It is thus electron energy dependent (or similarly reduced-field dependent) and it strongly depends on the gas pressure p (or the gas density, which dictates the mean free path for collisions) and on the gas composition. The electron energy dependence is rather weak for small variations in reduced electric fields, and thus the assumption of considering only the pressure dependence of ν_m is justified from the EM interactions point of view. A more accurate estimation could be made by evaluating the mean electron energy inside a plasma discharge, and linking this to ν_m . Simplified expressions for the gas pressure dependence exist for air: $\nu_m/2\pi = 5.3 \times 10^9 p$ (p is in the unit of

Torr), and for argon: $\nu_m/2\pi = 3.5 \times 10^9 p$. Taking $p = 0.1$ Torr gives a collision frequency of 0.53 GHz for air, and 0.35 GHz for Argon. An example of the reduced momentum transfer collision frequency (ν_m/N , units of m^3/s , where N is the gas density) versus the mean electron energy for Argon, as calculated by the two-term Boltzmann solver BOLSIG+, is shown in Figure 10. Note that in case of high-frequency plasma excitation, the plasma mobility is a complex quantity and this should be properly accounted for when calculating the momentum transfer frequency (see Sec.3.4 of [39]).

The pressure, and therefore the momentum transfer collision frequency, determines the Ohmic losses in the plasma, as ν_m contributes mainly to the imaginary part of ε (see Eq. 1), which represents the losses. Assuming atmospheric pressure condition, with $p = 760$ Torr, the collision frequencies for common gases are in the THz frequency range, much higher than the interested frequency range in the project, and possibly higher than the achievable plasma frequency as well. This results in ranges of values of ε close to 1, which is not desirable for the project. Therefore lower pressure conditions with lower losses are more favorable for the current project.

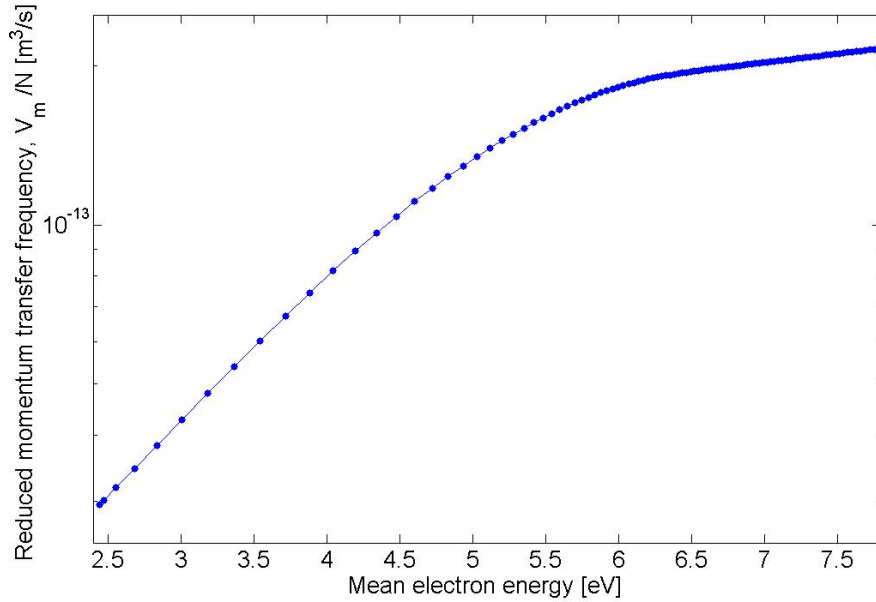


Figure 10: Reduced momentum transfer frequency over the mean electron energy, calculated in the Boltzmann solver BOLSIG+.

References

- [1] Samal, Sneha. "Thermal plasma technology: The prospective future in material processing." *Journal of cleaner production* 142 (2017): 3131-3150.
- [2] Wiesemann, K. "A short introduction to plasma physics." *preprint arXiv:1404.0509* (2014).
- [3] Graves, David B. "Plasma processing." *IEEE transactions on Plasma Science* 22.1 (1994): 31-42.
- [4] Hammer, Th. "Application of plasma technology in environmental techniques." *Contributions to Plasma Physics* 39.5 (1999): 441-462.
- [5] Machala, Z., et al. "Emission spectroscopy of atmospheric pressure plasmas for bio-medical and environmental applications." *Journal of Molecular Spectroscopy* 243.2 (2007): 194-201.
- [6] Becker, K., et al. "Environmental and biological applications of microplasmas." *Plasma physics and controlled fusion* 47.12B (2005): B513.
- [7] Park, G. Y., et al. "Atmospheric-pressure plasma sources for biomedical applications." *Plasma Sources Science and Technology* 21.4 (2012): 043001.
- [8] Laroussi, Mounir. "Low-temperature plasma jet for biomedical applications: a review." *IEEE transactions on plasma science* 43.3 (2015): 703-712.
- [9] Francis, G. "The glow discharge at low pressure." *Gas Discharges II / Gasentladungen II*, Springer Berlin Heidelberg, 2012, pp. 53-208.
- [10] Gudmundsson, Jon Tomas, and Ante Hecimovic. "Foundations of DC plasma sources." *Plasma Sources Science and Technology* 26.12 (2017): 123001.
- [11] Iza, Felipe, and Jeffrey A. Hopwood. "Low-power microwave plasma source based on a microstrip split-ring resonator." *IEEE transactions on plasma science* 31.4 (2003): 782-787.
- [12] Shao, Tao, et al. "Atmospheric pressure pulsed discharges and plasmas: mechanism, characteristics and applications." *High voltage* 3.1 (2018): 14-20.
- [13] Conrads, H., and M. Schmidt. "Plasma generation and plasma sources." *Plasma Sources Science and Technology* 9.4 (2000): 441.
- [14] Bogaerts, Annemie, et al. "Gas discharge plasmas and their applications." *Spectrochimica Acta Part B: Atomic Spectroscopy* 57.4 (2002): 609-658.
- [15] Zhang, Qian, et al. "Analysis of discharge characteristics of pulsed plasma power source in the microsecond scale." *Journal of Physics: Conference Series*. Vol. 2313. No. 1. IOP Publishing, 2022.

- [16] Su, Zhi, et al. "Characteristics of a dielectric barrier discharge plasma actuator driven by pulsed-DC high voltage." *Journal of Physics D: Applied Physics* 55.7 (2021): 075203.
- [17] Chng, Tat Loon, et al. "Pulsed nanosecond discharges and their applications." *XXXIV International Symposium on Plasma Chemistry (ICPIG) and 10th International Conference on Reactive Plasmas (ICRP-10)*. 2019.
- [18] Lieberman, Michael A., and Allan J. Lichtenberg. "Principles of plasma discharges and materials processing." *MRS Bulletin* 30.12 (1994): 899-901.
- [19] Brandenburg, Ronny. "Dielectric barrier discharges: progress on plasma sources and on the understanding of regimes and single filaments." *Plasma Sources Science and Technology* 26.5 (2017): 053001.
- [20] Lebedev, Yu A. "Microwave discharges: generation and diagnostics." *Journal of physics: conference series*. Vol. 257. No. 1. IOP Publishing, 2010.
- [21] Asmussen, J., et al. "The design of a microwave plasma cavity." *Proceedings of the IEEE* 62.1 (1974): 109-117.
- [22] Nowakowska, H., M. Jasiński, and J. Mizeraczyk. "Electromagnetic field distributions in waveguide-based axial-type microwave plasma source." *The European Physical Journal D* 54.2 (2009): 511-518.
- [23] Moisan, M., and Z. Zakrzewski. "Plasma sources based on the propagation of electromagnetic surface waves." *Journal of Physics D: Applied Physics* 24.7 (1991): 1025.
- [24] Chiad, Bahaa T., et al. "Construction and characterization of a low pressure plasma reactor using DC glow discharge." *Journal of Optoelectronics and Biomedical Materials* 1.3 (2009): 255-262.
- [25] Staack, David, et al. "Characterization of a dc atmospheric pressure normal glow discharge." *Plasma Sources Science and Technology* 14.4 (2005): 700.
- [26] Bussiahn, R., et al. "Pulsed excitation of low-pressure He–Xe glow discharges." *Journal of Physics D: Applied Physics* 39.1 (2005): 66.
- [27] Surendra, M., D. B. Graves, and I. J. Morey. "Electron heating in low- pressure rf glow discharges." *Applied physics letters* 56.11 (1990): 1022-1024.
- [28] Trunec, David, Antonín Brablec, and Jiří Buchta. "Atmospheric pressure glow discharge in neon." *Journal of Physics D: Applied Physics* 34.11 (2001): 1697.
- [29] Becker, K. H., K. H. Schoenbach, and J. G. Eden. "Microplasmas and applications." *Journal of Physics D: Applied Physics* 39.3 (2006): R55.

- [30] P Papadakis, A., S. Rossides, and A. C Metaxas. "Microplasmas: A review." *The Open Applied Physics Journal* 4.1 (2011).
- [31] Chiang, Wei- Hung, et al. "Microplasmas for advanced materials and devices." *Advanced Materials* 32.18 (2020): 1905508.
- [32] Qu, Chenhui, et al. "Properties of arrays of microplasmas: Application to control of electromagnetic waves." *Plasma Sources Science and Technology* 26.10 (2017): 105006.
- [33] Schoenbach, Karl H., et al. "Microhollow cathode discharges." *Applied Physics Letters* 68.1 (1996): 13-15.
- [34] Singh, Pramod K., Jeffrey Hopwood, and Sameer Sonkusale. "Metamaterials for remote generation of spatially controllable two dimensional array of microplasma." *Scientific reports* 4.1 (2014): 5964.
- [35] Kim, Hyunjun, Stephen Parsons, and Jeffrey Hopwood. "Spatially adjustable microplasma generation in proto-metamaterials using microwave radiative power transfer." *Plasma Sources Science and Technology* 27.1 (2018): 015010.
- [36] Ould Ahmedou, S. A., O. Rouaud, and M. Havet. "Electrohydrodynamic enhancement of heat and mass transfer in food processes." *3rd International Symposium on Food and Agricultural Products*. 2007.
- [37] Chang, J-S., Phil A. Lawless, and Toshiaki Yamamoto. "Corona discharge processes." *IEEE Transactions on plasma science* 19.6 (1991): 1152-1166.
- [38] Schutze, Andreas, et al. "The atmospheric-pressure plasma jet: a review and comparison to other plasma sources." *IEEE transactions on plasma science* 26.6 (1998): 1685-1694.
- [39] Hagelaar, G. J. M., and L. C' Pitchford. "Solving the Boltzmann equation to obtain electron transport coefficients and rate coefficients for fluid models." *Plasma sources science and technology* 14.4 (2005): 722.