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ADVANCED PLASMA SOURCES FOR SPACE APPLICATIONS

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Abstract

A Helicon thruster is an electrical propulsion system where the plasma source, i.e. Helicon source, is a dielectric tube surrounded by coils generating a weak magneto-static field (up to 0.15 T), and a radio frequency antenna working in the range of frequencies 1-50 MHz that drives the discharge. The propulsive figures of merit of a Helicon thruster (e.g. specific impulse) depend on plasma parameters (e.g. plasma density), that are in turn related to the power deposited by the antenna into the plasma. A similar plasma source can be exploited in gaseous plasma antennas, devices that rely on a partially or fully ionized gas to radiate electromagnetic waves. Plasma antennas might offer several advantages with respect to conventional antennas that make them suitable for space communications. As far as plasma antennas are concerned, their performances (e.g. gain) are related to the discharge parameters (i.e. the plasma density, the neutral pressure), and so to the efficiency of the plasma generation system. Regardless the differences in shape, field of application, and working condition, Helicon thrusters and plasma antennas share the same physical problems, namely: (i) wave propagation, (ii) power deposition, and (iii) transport of charged particles within the plasma source. To solve the wave-plasma coupling, we relied on ADAMANT, a full-wave frequency domain tool that takes into account the plasma effect as a polarization current. By means of this tool, we numerically assessed the radiation properties of the simplest plasma antenna configuration, a *plasma dipole*. We numerically verified that a plasma dipole can feature the same current distribution of a conventional metal dipole, and found that the plasma density, and the neutral pressure are the main parameters driving the plasma antenna performances. To understand the equilibrium conditions of a plasma source, we coupled ADAMANT with a 0-D fluid solver. This new numerical tool was exploited to design, and realize several custom-made plasma sources. This new approach allowed us to explore several combinations of gases, background pressures, and geometries without any constraints related to commercially available sources. By means of a microwave interferometer, we measured the plasma density, and its distribution along the sources. One of these sources was exploited in one of the very first prototypes of plasma antenna working in the GHz regime. The plasma dipole has been tested in an open environment for the gain pattern, and value; these results are in good accordance with the simulation results. Nevertheless, the maximum gain of the plasma dipole is lower by the 57% than the gain of a conventional dipole antenna in same conditions. This is due to a high pressure level (i.e. 10 mbar), and a low plasma density (i.e. $4 \cdot 10^{19} \text{ m}^{-3}$) of the source exploited in the plasma dipole, that lead to low conductance, and high losses within the plasma discharge.

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List of Symbols

E	electric field	$[Vm^{-1}]$
J	current density	$[Am^{-2}]$
I	current intensity	$[A]$
q	charge	$[C]$
f	frequency	$[Hz]$
ω_p	plasma frequency	$[rad/s]$
ω_c	plasma gyrofrequency	$[rad/s]$
ε_0	vacuum electric permittivity	$[Fm^{-1}]$
μ_0	vacuum magnetic permeability	$[Hm^{-1}]$
ε	electric permittivity	$[Fm^{-1}]$
c	speed of light	$[ms^{-1}]$
n_0	plasma density	$[m^{-3}]$
λ_0	wavelength	$[m]$
D	electric flux density	$[Cm^{-2}]$
B_0	magneto-static field	$[T]$
G	Green's function	
σ	charge sign	
ν	plasma collisional rate	$[s^{-1}]$
Z	impedance	$[\Omega]$
m	mass	$[Kg]$
L	device length	$[m]$
R	device radius	$[m]$
Φ	device diameter	$[m]$
ω	angular frequency	$[rads^{-1}]$
k_0	free space propagation constant	$[radm^{-1}]$
G	antenna gain	$[dBi]$
S_{11}	reflection coefficient	

List of Acronyms

EM	ElectroMagnetic
IT	Ion Thruster
HET	Hall Effect Thruster
MPDT	Magnetoplasmadynamic Thruster
RF	Radio Frequency
HPT	Helicon Plasma Thruster
GPA	Gaseous Plasma Antenna
PAA	Plasma Antenna Array
SPA	Smart Plasma Antenna
RCS	Radar Cross Section
SPA	Smart Plasma Antenna
DC	Direct Current
PIC	Particle In Cell
VHF	Very High Frequency
UVHF	Ultra High Frequency
WKB	Wentzel-Kramers-Brillouin
HF	High Frequency
BP	Band Pass
PEC	Perfect Electrical Conductor
VEP	Volume Equivalence Principle
SEP	Surface Equivalence Principle
MoM	Method of Moments
PEC	Perfect Electric Conductor
RWG	Rao-Wilton-Glisson
SWG	Schaubert-Wilton-Glisson
HV	High Voltage
CCFL	Cold Cathode Fluorescent Lamp
PTFE	Polytetrafluoroethylene
V/I	Voltage/Current
CCD	Charge-Coupled Device
AUT	Antenna Under Test
Rx	Receiver
Tx	Transmitter

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Chapter 1

Introduction

Plasmas exhibit complex electromagnetic (EM) wave phenomena that can be exploited in a broad range of advanced applications. In the last two decades several new plasma based propulsion concepts have been proposed and developed, and now are beginning to challenge the monopoly of chemical thrusters in space propulsion. More recently, there has been a growing interest in the use of plasma as medium to realize antenna elements that look very promising in space communications. In what follows, we give a brief introduction about the state of the art of plasma sources for the aforementioned applications, and about this thesis work.

1.1 Plasma propulsion systems

Plasma propulsion systems use electric power to ionize the propellant and then impart kinetic energy to the resulting plasma. The main advantage of plasma based propulsion systems over chemical rockets, is the higher *specific impulse*, here defined as the total impulse (or change in momentum) delivered per unit weight of consumed propellant. In a chemical rocket, the specific impulse is mainly an intrinsic characteristic of the propellant, related to its calorific energy per unit of mass, and there are natural limitations to its maximum value. In an electric rocket, the specific impulse is extrinsic and depends on the electric or electromagnetic energy deposited into the plasma, which can attain very large values if compared with those obtainable by means of chemical combustion. For a given variation in velocity, to a higher specific impulse corresponds a lower propellant mass. This makes plasma propulsion systems very appealing. On the other hand, plasma propulsion systems are characterized by a lower thrust than chemical ones, and they operate on large propulsion time [1]. Plasma propulsion systems have been employed in interplanetary missions [2] and in the position and attitude control systems of missions requiring high variation in velocity [3].

Plasma propulsion systems can be classified according to the plasma acceleration technique, that can be accomplished by means of *electrothermal*, *electrostatic*, or *electromagnetic* mechanism [4].

Electrothermal thrusters rely on an electrical source to heat the propellant, and thus expand it thanks to a nozzle. A classical representative of electrothermal thrusters is

the arcjet, which is basically a chemical thruster where gas is super-heated employing a plasma arc. The arc is formed between a central rod (the cathode) on the upstream side of the nozzle, and the divergent nozzle wall, working as an anode. The arc stabilization is achieved by means of a constricted channel at the nozzle throat. Since most of the mass flow remains in the heated-neutral gas surrounding the low-density plasma arc, the thermodynamics of this device reside mainly in the domain of chemical rockets. The main issue of these devices is the electrode erosion, that limits the lifetime of the arcjet to ≈ 1000 h.

In electrostatic propulsion, the propellant is ionized and accelerated through electrostatic forces. The main examples of these devices are the Ion Thruster (IT), and the Hall Effect Thruster (HET). The IT consists of a plasma generation chamber and a set of at least 2 biased grids. The grids electrostatically extract ions from the production chamber, and accelerate them to energies typically of 1 - 2 kV [5]. The electric reaction force of ions on the grids constitutes the thrust. An external hollow cathode provides the electron current that makes the expelled beam quasineutral. One of the most critical aspects of ITs is the grid system. Grid transparency, and alignment should maximize the extracted current, while minimizing ion impacts onto the grid to ensure structural integrity, and limiting erosion. The electrical or structural failure of highly eroded grids is the main lifetime limitation of this kind of thrusters. Nevertheless, ITs feature a lifetime up to 30000 h in recent designs. On the other hand, the ion current is upper-bounded by the space-charge saturation at the grids. The maximum current is proportional to the inter-grid voltage gap, while it has an inverse relationship with the inter-grid distance. The grid separation is typically of the order of 1 mm with voltage drop of few kV, constituting a structural, electrical, and thermal challenge [4]. The HET partially overcomes the grid-system related issues. In these devices, the neutral gas (usually Xenon) is injected into an annular chamber through a metallic anode that serves also as propellant distributor [6]. An external cathode provides electrons that tends to move towards the anode inside the chamber. An applied radial magnetic field of hundreds of Gauss inhibits the inward flux of electrons, that in turn tend to deviate towards the $\mathbf{E} \times \mathbf{B}$. These electrons serves as primary electrons to ionize the propellant. The ionized gas is accelerated towards the external cathode, providing thrust. Once expelled, the ionized propellant is neutralized by the electrons coming from the external cathode. HET performance is quite sensitive to the magnetic field topology since it shapes the electric potential map. The lower voltages, the smaller number of electric points to control and the larger ion current density, make the HET simpler electrically and more compact than the IT. On the negative side, a HET, compared with an IT of a similar power, has a lower thrust efficiency in terms of ratio between thrust power, and available power (50–55% instead of 65–70%), about half the lifetime, a larger plume divergence, and high energy losses at the chamber walls.

The magnetoplasmadynamic thruster (MPDT) is the main example for the electromagnetic propulsion systems. It consists of an annular chamber with a central cathode and an anode ring, biased to a discharge voltage typically in the range 50 – 300 V. Usually, the shape of the anode ring is slightly divergent, in order to provide a nozzle effect on plasma acceleration, and reduce the energy dissipation there. The neutral gas is injected at the back of the chamber and becomes ionized by electron impact. The longitudinal plasma current density induces an azimuthal magnetic field. Plasma axial acceleration

is due to the combined effects of the thermal pressure gradient and the Lorentz force. Plasma density in a MPDT is usually of the order of $n_e \approx 10^{20} - 10^{21} \text{ m}^{-3}$, larger than in an IT or a HET, whereas the electron temperature T_e is below 10 eV. Moreover, no external neutralizer is required since the plasma flow along the MPDT chamber is net-current free. On the other hand, an efficient plasma acceleration requires high discharge current. The Lorentz force responsible for the electromagnetic plasma acceleration is related to the magnetic field induced by the plasma current itself. At low current density, the MPDT behaves as an electrothermal device, and operates in a very inefficient working regime compared to HET, and IT. The requirement of high discharge current makes the MPDT a high-power device only¹.

1.1.1 Helicon Plasma Thrusters

Recent advances in plasma-based propulsion systems have led to the development of Helicon Plasma Thrusters (HPTs), whose plasma generation system is derived from high-density industrial plasma sources [7]. The main elements of an HPT are: (i) a gas feeding system providing the neutral gas to be ionized; (ii) a dielectric tube in which the gas is ionized; (iii) a Radio Frequency (RF) antenna working in the MHz regime which convey the ionization and heating power; (iv) coils or permanent magnets surrounding the dielectric tube to create a quasi-axial magnetic field in the range of hundreds of Gauss. The magnetic field: (i) enhances the plasma confinement inside the source; (ii) allows for an efficient power deposition into the plasma, by means of the Helicon waves dumping [8]; (iii) creates a diverging magnetic field region at the dielectric tube exhaust, providing a magnetic nozzle effect. In a HPT we can distinguish two main stages: the Helicon source which works as plasma production stage, and the magnetic nozzle which works as acceleration stage, allowing for the conversion of plasma thermal energy into axial kinetic energy. HPTs are characterized by the absence of electrodes and neutralizers in contact with the plasma, and a reduced interaction of plasma with walls thanks to the magnetic field. These characteristics make HPT intrinsically feature some advantages over other plasma propulsion systems, such as a reduced erosion, and reduced heat losses. These aspects may potentially lead to longer lifetime, and a more efficient use of the available electric power with respect to other kind of electric thrusters. Helicon sources efficiently convey electromagnetic power into the plasma, reaching plasma density up to 10^{19} m^{-3} with a magnetic field lower than $< 100 \text{ mT}$ and a simple antenna geometry. HPTs are under study and development in some international research projects. Among them we found the American VASIMR [9] where a high-power Helicon source is coupled to an ion cyclotron resonance heating section to increase the specific impulse. In Europe, HPH.COM [10] regarding the development of a low power ($\leq 100 \text{ W}$) system. Other research centers which have developed HPTs prototypes are the Australian National University [11], the Massachusetts institute of technology [12], the Tokyo University [13], and the Madrid University [14].

As far as HPTs are concerned, the propulsive figure of merit (e.g. specific impulse, thrust/mass ratio, and efficiency) are related to the acceleration stage, but also to the

¹The current density level required depends upon the plasma density, the electron temperature, and the chamber dimensions. For instance, taking $n_e = 10^{21} \text{ m}^{-3}$ and $T_e = 3 \text{ eV}$, for an average chamber radius of 3 cm, an MPDT requires a power of $\approx 0.5 \text{ MW}$ to properly work as an electromagnetic thruster [4].

power deposited by the antenna into the plasma, which in turn depends on the discharge parameters (e.g. gas type, neutral pressure, applied magneto-static field). To increase the performance of an HPT, the source optimization is then required.

1.2 Gaseous Plasma Antennas

Gaseous Plasma Antennas (GPAs) are devices that rely on a partially or fully ionized gas to radiate EM waves, thus differing from the traditional antenna design that is based on metallic wires and/or surfaces. Though the idea is not new [15], only recently the feasibility has been demonstrated [16]. GPAs consist of a dielectric vessel filled with some neutral gas such as argon that is energized by any generation method to form a plasma. A metal circuit, here in after referred to as *signal coupler*, is wrapped around the tube or in contact with the plasma itself to inject the signal frequency into the plasma. In a GPA, the plasma is actually powered by two different frequencies simultaneously: a generation frequency to drive the plasma discharge and a working frequency to apply the signal so that it might be used for either transmission (both frequencies switched on) or reception (only the driving frequency switched on) [17].

The operation of a plasma antenna depends upon the interaction of EM waves with the plasma [18], and relies on the property of plasma to behave frequency-dependently when an EM wave impinges on a plasma volume. If the EM wave has frequency higher than the plasma frequency (see Appendix B), it passes through the plasma without attenuation. On the contrary, if the incident EM wave frequency is lower than the plasma frequency, the plasma behaves as a metal conductor. Thanks to this property, a plasma column can be used to radiate EM waves with frequency below the plasma frequency but offering more degrees of freedom than metallic antennas [19]. When the plasma is on, GPAs might offer several advantages, namely: (i) they are transparent to incoming EM waves whose frequency is greater than the plasma frequency, thus reducing interferences; (ii) they can be reconfigured with respect to frequency, gain and beam-width; (iii) they are reconfigurable electrically rather than mechanically on time scales the order of microseconds to milliseconds; (iv) they can be stacked to form arrays, as GPAs operating at different frequencies do not interfere with each other.

When the plasma is off, the GPA reverts to a dielectric tube with a very low radar cross-section, and such a feature makes GPAs appropriate for stealth communications; co-site interference and/or parasitic interference can be greatly reduced using plasma antennas because GPAs not in use can be turned off in micro to milliseconds with the plasma being extinguished. These features make GPAs very promising for space communication, where electric reconfigurability, and the possibility to stack several antenna in a small environment without interfering with each other can be very convenient.

A cluster of GPAs and possibly conventional metal antennas is usually referred to as Plasma Antenna Array (PAA) [20]. In addition to all the advantages of GPAs, PAAs allow (i) steering the beam in the direction of interest, and (ii) improving directivity by adding nulls to the radiation pattern [21]. A PAA endowed with smart signal processing algorithms, referred to as Smart Plasma Antenna (SPA), could achieve (i) the identification of the direction of an incoming signal, (ii) the tracking and locating of the antenna beam

on a mobile target, and (iii) the beam steering in the direction of interest while minimizing interferences.

Physical experiments and theoretical analysis have been carried out to investigate the performance of gaseous plasma antenna [22, 23, 24]. From a technology standpoint, plasma discharges to be used as antennas can come in different shapes (e.g., loops or rods), whereas the plasma can be generated by means of several methods, e.g. DC discharge [7], RF surface waves [25]. The plasma generation approaches have different efficiencies (i.e. plasma density reached with a given power consumption), and can introduce noise. As a result, the right choice in terms of plasma generation technique depends upon the specific application of the GPA. So far, various systems have been proposed to meet different requirements. Grewal and Hanson proposed a solid-state plasma leaky-wave antenna in which beam scanning features are achieved by tuning the density of an optically induced plasma [26], while Alexeff *et al.* constructed and studied different configurations of plasma discharges as plasma reflectors and plasma windows [22]. More recently, some research groups focused their activity on commercial fluorescent lamps to be used as a plasma antenna. In this effort, Barro and Himdi used a commercial fluorescent tube as a monopole plasma antenna working at frequencies $f \leq 600$ MHz [27], while Golazari relied on a commercial loop lamp to design a loop antenna operating in the Ultra High Frequency (UHF) band [28]. More studies focused onto a combination of metal antenna, and plasma elements used to shield, steer, or focus the beam radiated by one or more conventional antennas. A combination of metal patch antenna and commercial fluorescent was used tubes to achieve reconfiguration capabilities [29]. Several plasma discharges surrounding a metal radiating element were proposed, theoretically studied, and realized in different concepts, frequency bands, and discharge numbers by several groups [21, 30, 31, 32].

Regardless of the specific application, GPAs performances (e.g. gain, directivity, bandwidth, and radiated fields) are related to the discharge parameters, such as the plasma density (n_0), the background neutral pressure (p_n), and the magnetostatic field ($\mathbf{B}$).

1.3 Thesis work

Although different in shape, field of application, and working condition, HPTs and GPAs share the same physical problems, namely: (i) plasma generation, (ii) wave propagation, and (iii) plasma transport within the plasma source. The physics of power deposition and of wave propagation in a plasma source has been previously studied by many theoretical and experimental works. Simplified theoretical models of an Helicon plasma source for space application have been developed by Ahedo [33] and Laffleur [34]; these models are useful in the preliminary design but do not give sufficient insight to perform source optimization. Plasma fluid approaches have been widely employed to model industrial plasma sources [35], and Helicon sources [36]. Standard numerical approaches rely on EM solvers, which model the wave propagation and the power deposition therein, coupled to either kinetic [37] or Particle-In-Cell (PIC) [38] strategies to reproduce plasma response. However in high-power plasma sources, the plasma density can reach values higher than 10^{19} m^{-3} ; such values can not be handled by a PIC code, while could result in a computational burden for a kinetic approach. A simplified analysis of the electromagnetic wave equation

coupled to a fluid model of the plasma has been proposed recently, which is based on the asymptotic solution of the wave equation (WKB method) [39]. This has the advantage to handle with an accurate description of the macroscopic plasma quantities such as the density and temperature profiles as well as the structure of the magnetic field, giving more realistic deposition profiles. For what concerns GPAs, recently, the radiation theory of plasma antennas has been extended by taking into account the radiation mechanisms that govern metal and dielectric antennas [24], while numerical self-consistent models were developed to grasp the underlying physics, and to assess the dynamic reconfiguration [23, 40]. Though, most of the studies have focused on radiating plasma elements in the VHF frequency band [41], whereas not much has been said on plasma antennas working at higher frequencies (i.e., GHz regime) [22]. Moreover, most of the numerical, and experimental studies relied on commercial fluorescent lamps [27, 29, 30] because they are inexpensive, and no knowledge of plasma discharge technology is required; this approach allows to build prototypes with the discharge dimensions that are available from the market, and, more importantly, no information about the gas mixtures, and partial pressures thereof can be inferred, thus preventing any self-consistent analysis of the GPA or PAA performance.

1.3.1 Objectives

This thesis work intended to overcome the aforementioned limitations of the previous studies (e.g. the need for a numerical tool that copes with wave propagation, and plasma transport in high density plasma sources, the self-consistent analysis of a GPA made of custom-built plasma discharges) through the following objectives: (i) preliminary develop a numerical tool that couples the EM solution within the plasma transport inside a plasma source, (ii) clarify the behavior of GPAs when realistic excitation circuit and the transport of charged particles is taken into account, (iii) design, realize, and test plasma sources that will enhance the emission/reception of EM waves in GPA, and (iv) design, realize, and test a GPA working at high frequency ($f \geq 800$ MHz).

1.3.2 Outline

This thesis is organized as follows:

Chapter 2 describes the numerical tools used in this thesis work, and the numerical tool that couples the EM solution with the plasma transport within the plasma source. This tool will be helpful to understand the physics behind power deposition in a Helicon source, and/or in a GPA.

Chapter 3 presents the numerical results for the physical assessment on the radiation properties of a GPA in terms of input impedance, current distribution within the plasma discharge, and radiation pattern when different excitation circuit geometries, and plasma parameters are taken into account.

Chapter 4 describes the source design, realization, and testing. The results for the numerical design are presented, as well as the realization procedure, and experimental characterization of the plasma sources in terms of plasma density, and plasma density distribution.

Chapter 5 describes the plasma dipole design, realization, and testing. In this chapter, the results for the numerical analysis on the performance of GPAs are presented. These results were used to realize, and test a *plasma dipole*. The realization procedure, and the experimental characterization in terms of gain values, and pattern are described in detail.

Chapter 6 draws the conclusions of this thesis work.

1.3.3 My contribution

During my PhD, I developed the numerical tool presented in Chapter 2 that couples the EM solution with the plasma transport within a plasma source. Both the EM solver, and the Global Model were previously developed, and I coupled them to obtain the tool presented here. I did all the numerical analysis presented in Chapter 3, and 5 regarding GPAs, from the geometrical model design, to the simulations, and the post processing. Besides, I wrote the codes used for the post processing of the ADAMANT simulations, and optimized the post processing for the source characterization. With the help of my colleagues, I designed and manufactured the preliminary experimental set-ups (comprised of supports, electrodes, and coupler) used for the plasma sources, and the plasma dipole. I defined the requirements for the design of the final set-up that was used to characterize the plasma dipole. I supervised all the vessels manufacturing, and I did all the experimental source characterizations presented in Chapter 4, as well as the post processing . I also did all the site, and procedure validation for the plasma dipole experimental tests described in Chapter 5, the tests themselves, and the data post processing.

Chapter 2

Numerical Tools

In this chapter, the numerical tools used for this work are presented for the interested reader. In the first section, we present ADAMANT [42], a full-wave tool able to solve the EM problem self-consistently for arbitrary geometries of both plasma discharge, and metal circuit, that models the plasma by means of a permittivity tensor. In the second section a brief description of the 0-D fluid model [43] (Global Model) aimed to simulate the plasma transport inside the single plasma discharge is given. Both these tools were previously developed. In the last section, we presented a new numerical tool based on the aforementioned codes that couples the EM solution with the plasma transport. The numerical tool relies on an iterative loop: the Global Model simulates the plasma transport inside the single plasma discharge providing the average plasma density to be used in ADAMANT that, in turn, evaluates the power deposited into the plasma discharge to be used again in the Global Model. This tool will be helpful in the design, and optimization of plasma sources, either Helicon, or to be exploited in GPA applications.

2.1 ADAMANT

ADAMANT is a full-wave numerical tool aimed to study wave propagation in plasma. It relies on a set of coupled surface and volume integral equations that are numerically solved through the Method of Moments (MoM) in the form of Galerkin. The code solves for the surface electric current density on the metal surfaces driving the discharge in the case of the HPT and/or the signal in the case of a GPA, and the volume polarization current in the plasma volume. The latter can be inhomogeneous and anisotropic whereas the metal circuit can have arbitrary shape [42].

This approach allows the accurate analysis of the wave-plasma coupling, and the role of the excitation circuit, and the RF antenna in depositing power in the plasma column. Besides, knowing the current density distribution in the plasma column, it is possible to accurately evaluate the GPA performance in terms of radiation pattern, and input impedance as a function of plasma discharge parameters.

2.1.1 Problem formulation

A realistic EM model of a Helicon source, or a GPA should include (i) the plasma volume(s) V_P , and (ii) the metallic part(s) S_A , which are immersed in a background medium, as shown in Fig. 2.1(a). The plasma is considered cold, and collisional, and a time dependence in the form $\exp(j\omega t)$ for fields and sources is assumed.

We formulate the EM problem by applying the Volume Equivalence Principle (VEP), and the Surface Equivalence Principle (SEP).

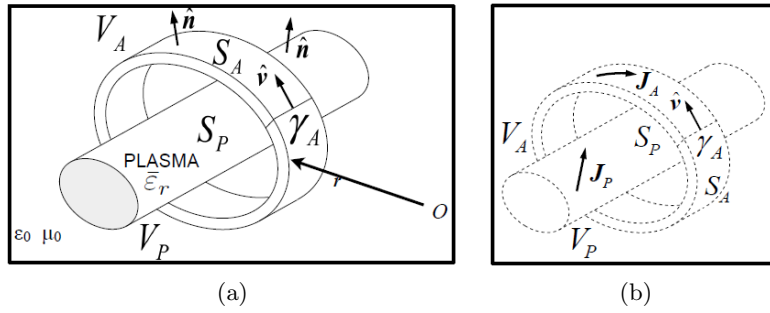


Figure 2.1: The EM model of an Helicon source and/or a GPA (a) before, and (b) after the application of the VEP, and SEP.

The VEP requires introducing a set of polarization currents

$$\mathbf{J}_P = j\omega(\mathbf{I} - \epsilon_r^{-1}) \cdot \mathbf{D}_P \quad (2.1)$$

The tensors ϵ_r denote the plasma permittivity relative to free space. In a system of Cartesian coordinates with $\mathbf{B}_0 = B_0 \hat{\mathbf{z}}$, the dyadics $\bar{\epsilon}_{rk}$ take the form

$$\bar{\epsilon}_{rk} = \begin{bmatrix} S_k & jD_k & 0 \\ -jD_k & S_k & 0 \\ 0 & 0 & P_k \end{bmatrix}, \quad (2.2)$$

with the Stix parameters defined as follow:

$$S = 1 - \sum_{\xi} \frac{\omega_{p\xi}^2 (\omega - j\nu_{\xi})}{\omega \left[(\omega - j\nu_{\xi})^2 - \omega_{c\xi}^2 \right]} \quad (2.3a)$$

$$D = \sum_{\xi} \frac{\sigma_{\xi} \omega_{c\xi}}{\omega} \frac{\omega_{p\xi}^2}{\left[(\omega - j\nu_{\xi})^2 - \omega_{c\xi}^2 \right]} \quad (2.3b)$$

$$P = 1 - \sum_{\xi} \frac{\omega_{p\xi}^2}{\omega (\omega - j\nu_{\xi})} \quad (2.3c)$$

where $\omega_{p\xi} \equiv \left(n_\xi q_\xi^2 / \varepsilon_0 m_\xi\right)^{1/2}$ is the plasma frequency, σ_ξ indicates the particle charge sign, $\omega_{c\xi} \equiv \sigma_\xi q_\xi B_0 / m_\xi$ is the gyrofrequency, and ν_ξ is the collision frequency. The subscript ξ refers to the index of the plasma species.

We apply the SEP to the metallic parts. We assume all the metallic parts as Perfect Electrical Conductor (PEC), and we model the metallic circuit excitation by means of the so-called *voltage gap*, which requires setting the voltage V_G at the circuit port and computing the current I_A therein [44], [45], [46]. It is worth recalling that the voltage gap model can be applied as long as the actual excitation port is small as compared to (i) the operational wavelength in the background medium, and (ii) the circuit size. As a result of SEP application, the metallic parts are replaced with an unknown electric surface density $\mathbf{J}_A$.

The currents $\mathbf{J}_A$ and $\mathbf{J}_P$ are the unknowns to be determined.

2.1.2 Governing equations

We apply the boundary conditions on the metal surface S_A , which states that the tangent component of the electric field upon a PEC surface is zero, and we express the total electric field in the plasma region as

$$\mathbf{E}_P(\mathbf{r}) = \mathbf{E}_{PA}^S(\mathbf{r}) + \mathbf{E}_{PP}^S(\mathbf{r}), \quad \mathbf{r} \in V_P \quad (2.4)$$

where $\mathbf{E}_{PA}^S$ ($\mathbf{E}_{PP}^S$) represents the secondary electric field produced by $\mathbf{J}_A$ ($\mathbf{J}_P$) within V_P . By enforcing the boundary condition for S_A , and Eq. 2.4 we arrive at a set of coupled surface and volume integral equations

$$\begin{aligned} \mathbf{E}_A^i(\mathbf{r}) + \omega^2 \mu_0 \overline{\mathbf{G}}(\mathbf{r}) \cdot \left[\sum_{k=1}^{N_P} \overline{\boldsymbol{\alpha}}_k(\mathbf{r}) \cdot \mathbf{D}_{Pk}(\mathbf{r}) \right] \\ - j\omega \mu_0 \overline{\mathbf{G}}(\mathbf{r}) \cdot \mathbf{J}_A(\mathbf{r}) \Big|_{tan} = 0, \quad \mathbf{r} \in S_A, \end{aligned} \quad (2.5)$$

$$\begin{aligned} \overline{\varepsilon}_r^{-1} \cdot \mathbf{D}_{Pk}(\mathbf{r}) = -j\omega \varepsilon_0 \mu_0 \overline{\mathbf{G}}(\mathbf{r}) \cdot \mathbf{J}_A(\mathbf{r}) \\ + k_0^2 \overline{\mathbf{G}}(\mathbf{r}) \cdot \left[\sum_{l=1}^{N_P} \overline{\boldsymbol{\alpha}}_l(\mathbf{r}) \cdot \mathbf{D}_{Pl}(\mathbf{r}) \right], \quad \mathbf{r} \in V_{Pk}, \end{aligned} \quad (2.6)$$

where $\mathbf{E}_A^i$ is the impressed electric field at the metal surface port, $\overline{\mathbf{G}}(\mathbf{r})$ is the dyadic Green's function in free space, and $\cdot^*$ denotes 3D spatial convolution and scalar product.

2.1.3 Numerical solution

The system of Eqs. 2.5, 2.6 is numerically solved by means of the Methods of Moments (MoM) in the form of Galerkin. To this purpose, S_A is modeled with a 3D triangular-faceted mesh, and V_P with a tetrahedral mesh. Surface and volume div-conforming vector linear element $\mathbf{f}(\mathbf{r})$ and $\mathbf{v}(\mathbf{r})$ are respectively associated with the inner edges of the

triangular mesh, and with all facets of the tetrahedral mesh [42], in order to expand the unknowns as follow:

$$\mathbf{J}_A(\mathbf{r}) \approx \sum_{n=1}^{N_A} \mathbf{f}_n(\mathbf{r}) I_n, \quad \mathbf{r} \in S_A \quad (2.7a)$$

$$\mathbf{D}_P(\mathbf{r}) \approx \sum_{p=1}^{N_P} \mathbf{v}_p(\mathbf{r}) D_p, \quad \mathbf{r} \in V_P \quad (2.7b)$$

Substituting Eqs. 2.7(a),(b) into Eqs. 2.5, 2.6, and projecting them respectively onto $\mathbf{f}_m$, $m = 1, \dots, N_A$, and onto $\mathbf{v}_q$, $q = 1, \dots, N_P$, we obtain the final algebraic system of rank $N_A + N_P$. In matrix form, it reads

$$\begin{bmatrix} [Z_{AA}] & [Z_{AP}] \\ [Z_{AP}] & [Z_{PP}] \end{bmatrix} \begin{bmatrix} Z_0 [J_A] \\ [D_P] / \varepsilon_0 \end{bmatrix} = - \begin{bmatrix} [V_G] \\ [0] \end{bmatrix} \quad (2.8)$$

where Z_0 and ε_0 have been factored out and paired with the vectors of unknown coefficients to improve the conditioning of the matrix. With this positions, $Z_0 [J_A]$ and $[D_P] / \varepsilon_0$ carry the physical dimensions of an electric field. The column vectors $[J_A]$ and $[D_P]$ contain the coefficients of $\mathbf{J}_A$ and $\mathbf{J}_P$ respectively. The entries of the excitation vector $[V_G]$ and of the four blocks in which the system matrix is naturally partitioned are detailed in [42].

2.2 Global Model

In this section, we give a brief overview of the Global Model developed in order to support the investigations on argon plasmas, carried out at CISAS research center. In this model, densities and temperatures are spatially averaged and only their time dependency is considered. This model is aimed to solve the plasma transport, and diffusion either in the case of magnetized or unmagnetized plasmas, and in closed systems (i.e. in GPA application), or system with inflow and outflow (i.e. HPTs). The inputs of the model are: (i) the dimensions (radius R and length L) of the cylindrical discharge, (ii) the electrical power deposited into the plasma P_{abs} , and (iii) the mass flow rate entering the system $\dot{m}_{in}$, and (iv) the nozzle throat-to-chamber section ratio ϱ^* when present. The output parameters are the density of each species n_i , the electron temperature T_e and the homogeneous neutral-ion temperature inside the chamber T .

2.2.1 Problem Formulation

The model geometry is a cylindrical discharge having diameter D , and length L with an injection aperture of negligible area. If an outflow is present, as in the HPT case, an exhaust section at the end of the cylinder is defined by means of the ϱ^* exhaust-to-chamber section ratio. If present, the magnetic field is assumed to be axial and uniform.

The electron temperature is determined by solving the time-dependent electron energy equation:

$$\frac{d}{dt} \left(\frac{3}{2} n_e k_b T_e \right) = P_{abs} - P_{col} - \Gamma_w \cdot \varepsilon_w - \Gamma_{exh} \cdot \varepsilon_{exh} \quad (2.9)$$

where P_{abs} is the power absorbed by the plasma, P_{col} is the loss by elastic and inelastic collisions, Γ_w and Γ_{exh} are the wall and exhaust flux of electrons, ε_w and ε_{exh} are the wall and exhaust energy loss for each electron leaving the boundaries of the discharge [47]. In the case of closed systems, the terms Γ_{exh} , and ε_{exh} vanish. The species densities are determined solving the time dependent mass balance equations:

$$\frac{dn_i}{dt} = \Phi_i + \dot{m}_{in} - \dot{m}_{out} \quad (2.10)$$

in which Φ_i is a source term containing production and loss of the i -th species by volume and surface reactions, and $\dot{m}_{in}$ and $\dot{m}_{out}$ are the mass flow entering and exiting the system, equal to zero in case of closed systems.

In this model, the neutrality is assumed, so that $n_i \approx n_e$, and Eq. 2.10 is sufficient to solve both the ion, and electron density. Besides, neutral and ion particles are assumed to share a common temperature $T = T_i$. Atomic plasmas are not subjected to considerable heating in low pressure non equilibrium discharges; a value for the gas temperature can be assumed based on estimation from literature, numerical formulas, experimental measurements (use of the wall temperature is common approach). In any case, in atomic low pressure non equilibrium plasmas, the neutral gas temperature has a weak influence on the chemistry of the discharge, which instead is controlled by the electron temperature T_e [43].

2.2.2 Surface plasma process

The rate of electron-ion recombination at the wall is proportional to the ion density at the sheath. Charge density at the sheath is evaluated with semi-empirical solutions of the diffusion equation developed by Godyak, and reported also for electropositive and electronegative gases in [7, 47].

h_L and h_R are the ratio of the sheath to bulk positive ion densities in the axial and radial diffusion direction, the sheath densities can be calculated from the bulk charge densities.

For the sake of clarity, we will refer with the subscript ' p ', ' n ', and ' e ' respectively to positive ions, negative ions, and electrons; the formulas reported here are implemented for the general case of a electronegative discharge, with $\alpha = \sum n_{n,i}/n_e$ the *electronegativity* parameter of the discharge (i.e. the negative ion to electron density ratio). If the parameter $\alpha \rightarrow 0$ the formulas for electropositive discharge are recovered.

In a unmagnetized electronegative discharge, the h_L and h_R parameters read:

$$h_L = \left[\frac{n_p^s}{n_p} \right]_{l=L} = \frac{1 + 3\bar{\alpha}/\gamma}{1 + \bar{\alpha}} \frac{0.86}{[3 + L/(2\lambda_p) + (0.86Lu_b/(\pi D_a^p))^2]^{1/2}} \quad (2.11)$$

$$h_R = \left[\frac{n_p^s}{n_p} \right]_{r=R} = \frac{1 + 3\bar{\alpha}/\gamma}{1 + \bar{\alpha}} \frac{0.8}{[4 + R/\lambda_p + (0.8Ru_b/(2.405J_1(2.405)D_a^p))^2]^{1/2}} \quad (2.12)$$

where u_b , λ_p are the Bohm velocity and the mean free path of the positive ion; $\gamma = T_e/T$ and $\bar{\alpha}$ is the average value of α [47]. D_a^p is the effective ambipolar coefficient for the positive ion diffusion, and it yields:

$$D_a^p = D_p - \mu_p \frac{D_p(\bar{\alpha} + 1) - \bar{\alpha}D_n - D_e}{\mu_p(\bar{\alpha} + 1) + \bar{\alpha}\mu_n + \mu_e} \quad (2.13)$$

The expression for D_a^p results from conservation of charge fluxes and quasi-neutrality condition, it implements the diffusion and mobility coefficients for positive, negative charges and electrons; in the limit of electropositive discharge ($n_n \rightarrow 0$) becomes the classic ambipolar coefficient [7].

Ion and electron mobilities are calculated as $\mu_e = e/(m_e\nu_e)$, $\mu_{p,n} = e/(m_{p,n}\nu_{p,n})$; diffusivity is related to mobility by the *Einstein relation* $D/\mu = k_bT/e$. The ion collision frequency is calculated as the ratio between thermal velocity and mean free path $\nu = v_{th}/\lambda$; electron collision frequency is evaluated with the electron elastic scattering rate constant $\nu_e = nK(T_e)$, with n the neutral background density.

The ion mean free path results from elastic scattering and charge transfer, the cross sections for elastic scattering, $\sigma_{ES}/2$, and charge transfer, σ_{CT} , are estimated with the Langevine cross section formula, as explained in [7].

The rate of loss of positive ions by diffusion toward the surface is then expressed by

$$\Gamma_p = n_p u_b A_{eff} \quad (2.14)$$

The Bohm velocity of a electronegative discharge is modified as reported in [7, 43]. Being α_s the electronegativity at the plasma-sheath interface, the Bohm velocity is:

$$u_b = \left[\frac{(1 + \alpha_s)}{(1 + \alpha_s\gamma)} \frac{eT_e}{m_p} \right]^{1/2} \quad (2.15)$$

The rate of loss of negative ions on the wall is proportional to the Γ_n and is:

$$\Gamma_n = \frac{\Lambda_{ne}^s}{1 + \Lambda_{ne}^s} \Gamma_p \quad (2.16)$$

in which $\Lambda_{ne}^s = \Gamma_n^s/\Gamma_e^s$ is the ratio of negative ion to electron flux at the sheath interface

$$\Lambda_{ne}^s = \frac{n_n^s v_{th,n}}{n_e^s v_{th,e}} = \alpha_s \left(\frac{m_e}{\gamma m_n} \right)^{1/2} \quad (2.17)$$

The rate of loss of electrons on the wall comes from the continuity of charge flux condition: $\Gamma_e = \Gamma_p - \Gamma_n$.

The energy loss associated to the wall loss of electrons, is given by the potential drop in the sheath and the pre-sheath region plus the average thermal energy $2T_e$ [43]. The loss term results:

$$\epsilon_w = 2T_e + \frac{T_e}{2} \left[\frac{(1 + \alpha_s)}{(1 + \alpha_s \gamma)} + \ln \left(\frac{m_p}{2\pi m_e} \right) \right] \quad (2.18)$$

2.2.3 Plasma exhaust

Since the gas is exhausted into the vacuum chamber, the neutral flow exiting through the diaphragm is assumed to be choked. The flow rate of each neutral species is given by the isentropic relation of the mass flow through a choked section:

$$\Gamma_i = n_i \left[\frac{k_b T k_i}{m_i} \left(\frac{2}{k_i + 1} \right)^{\frac{k_i + 1}{k_i - 1}} \right]^{1/2} \quad (2.19)$$

Where k_b is the Boltzmann constant, n_i , m_i and k_i are the density, mass and specific heat ratio of the neutral i-th specie.

The model is described in more detail in the PhD thesis of Bosi [43], and it is based on the work of Lee, and Lieberman [47, 7].

2.3 EM Code and Fluid Solver Coupling

To model the coupling between wave propagation, and plasma transport, we implemented an iterative loop between the global model, and ADAMANT, a schematic of which is shown in Fig. 2.2. From a physical standpoint, this approach is justified considering the different time scaling at which the two phenomena occur: the wave propagation is by far faster than the plasma diffusion. In the study of the plasma transport, the wave propagation can be thus modeled as a source term by means of the power deposited by the plasma generation circuit into the discharge P_{abs} . On the other hand, the plasma parameters can be considered as stationary in the solution of wave propagation.

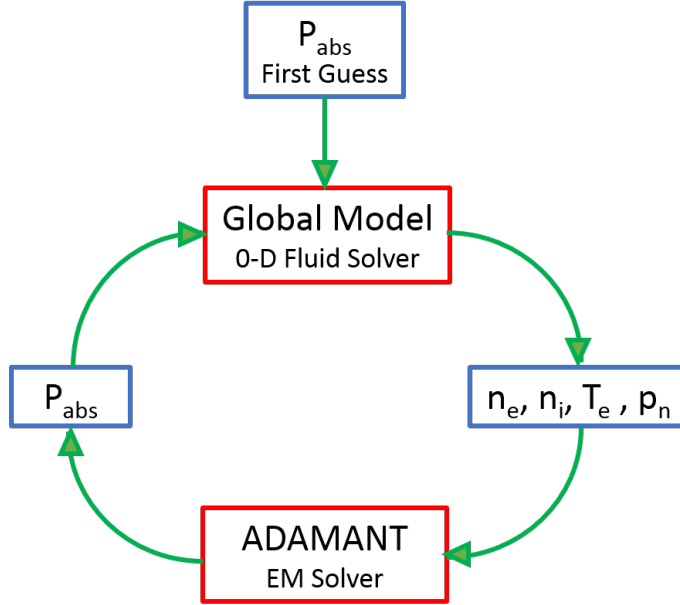


Figure 2.2: Schematic of the iterative loop: P_{abs} is the power deposited in the plasma discharge, n_e , and n_i are the electron, and ion densities, T_e is the electron temperature, and p_n is the neutral pressure.

The input of the iterative loop are the geometry of the source, the neutral pressure p_n , the magneto-static field B_0 , and the excitation voltage ΔV ; the output are the ion, and electron densities n_i , n_e , the electron temperature T_e (evaluated by the Global Model), and the power deposited in the discharge P_{abs} (evaluated by ADAMANT). The Global Model runs first, being initialized with a first guess P_{abs} . The Global Model calculates n_e , n_i , p_n , and T_e , that are used as input for ADAMANT to solve again for P_{abs} . The loop restarts until the source reaches the equilibrium conditions.

The choice of the first guess P_{abs} is critical: its value must be higher than the lowest P_{abs} that sustains the discharge. In order to choose a proper first guess P_{abs} value, a preliminary analysis has to be done to identify the minimum P_{abs} value that sustains the discharge for the different configurations of p_n and B_0 . This parameter can be estimated by means of the Global Model.

Chapter 3

Physical Assessment on GPAs

In this chapter we assess the physical behavior of GPAs. To this purpose, we considered a *plasma dipole*, and a *bipolar plasma dipole*, respectively comprised of a plasma column, and a half-nagoya coupler, and 2 plasma columns, driven by means of 2 plate electrodes connected by a metal strip. We simulated them for the input impedance, and the electric displacement field within the plasma discharges. We numerically verified that a plasma column can feature the same current distribution of a conventional metal dipole. We then considered the *plasma dipole* since it is easier to realize, and we simulated it for the gain pattern on varying the plasma density, the magnetostatic field, the neutral pressure, and the gas type.

3.1 Gaseous Plasma Antennas

An antenna can be defined as a device that radiates or receives radio waves. In other words, the antenna is the transitional structure between free-space and a guiding device (i.e. coaxial line, waveguide) [48]. The radiation of EM wave is accomplished by the electric charged motion in a conductive medium, such as a metal wire. More specifically, to create radiation there must be an acceleration (or deceleration) of charge. To accomplish the acceleration (or deceleration) of charge, the wire must be curved, bent, discontinuous or truncated. A time-varying current can be created also with a time-harmonic oscillation of charge, in which case a wire radiates even if straight. The simplest antenna configuration is the *half-wavelength dipole*. A conventional half-wavelength dipole is comprised of 2 thin-wire segments excited at the midpoint at the operational frequency f_0 , as shown in Fig. 3.1. To properly radiate EM waves, a conventional half-wavelength dipole has to resonate. In resonance condition, the current distribution on the 2 wire-segments takes the form of the dashed line in Fig. 3.1. To feature such a current distribution, the half-wavelength dipole has to be truncated at a length $L = \lambda_0/2$, where $\lambda_0 = c/f_0$ is the wavelength at the operational frequency. At the feeding port of the half-wavelength dipole, we can define the input impedance as $Z = V/I$, that it is usually a complex number. At the resonance frequency, $Im(Z)$ vanishes, and the input impedance at the port is purely real.

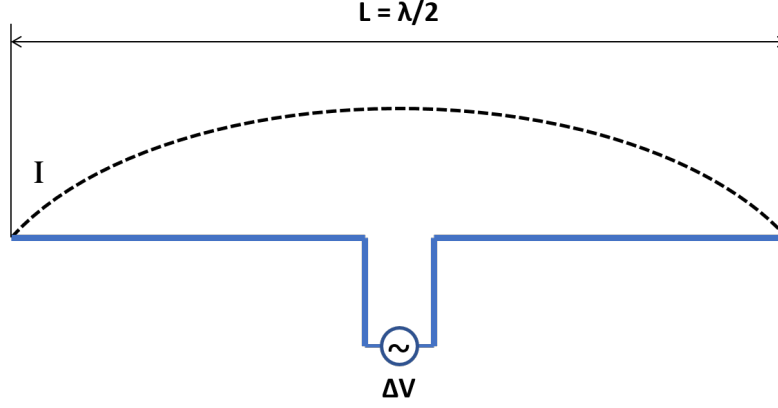


Figure 3.1: Schematic of a metal half-wavelength dipole connected to the feeder, and its current distribution in resonance conditions.

In a similar fashion, we can define the impedance at the port of the feeder Z_g . To maximize the power transfer between the feeder, and the half-wavelength dipole, the impedance at the port of the dipole Z should be equal (matched) to that of the feeder as viewed from its output terminals $Z_g = Z$. Otherwise, part of the power coming from the source is reflected back¹. The reflected power is:

$$P_{ref} = P|S_{11}|^2 \quad (3.1)$$

where P is the power actually generated by the feeder, and S_{11} is the *reflection coefficient*. The reflection coefficient it is usually a complex number, and it is defined as:

$$S_{11} = \frac{Z_g - Z}{Z_g + Z} \quad (3.2)$$

Under certain conditions, a plasma can be considered as a conductive medium. More specifically, if the angular frequency of an incoming EM wave ω is lower than the plasma frequency ω_p , the plasma behaves as a metal conductor (see Appendix B). GPAs rely on this property to exploit a plasma discharge as radiating/receiving antenna element instead of metal.

To assess the properties of a GPA, we considered a cylindrical plasma column, since it is more similar to a wire antenna such as the half-wavelength dipole. Besides, a cylindrical geometry is the simplest to be studied, and realized. Since similar to a metal rod, a plasma column is expected to behave in a similar fashion to the conventional dipole antenna, and thus to feature the same current distribution of Fig. 3.1 within the plasma column at the resonance frequency. In order to obtain such a current distribution, the plasma column has to be excited. Being impossible to excite it in the same way as in the simpler case of a metal dipole, in the case of a plasma column a proper excitation circuit has to

¹We are assuming that the dipole is transmitting the signal generated by the feeder, but the same is true for an antenna receiving a signal to be transferred to a spectrum analyzer.

be designed with the aim to "inject" the signal in the plasma column. Such a circuit is referred to as *signal coupler*. It is worth to be noticed that the signal coupler is in addition to any plasma generation circuit, which is neglected in this analysis. In the effort to retrieve the half-wavelength dipole behavior in terms of current distribution, and input impedance, we considered the systems pictured in Fig. 3.2, and in Fig. 3.5, hereinafter referred to as *plasma dipole*, and *bipolar plasma dipole*, and we simulated them by means of ADAMANT for the input impedance, and the electric displacement field distribution. The electric displacement field $\mathbf{D}$ is related to the current within the plasma $\mathbf{J}_P$ by the following relation:

$$\mathbf{J}_P = \varepsilon \mathbf{D} \quad (3.3)$$

where the permittivity $\varepsilon = \varepsilon_0 \varepsilon_r$, with ε_r the plasma permittivity relative to free space (see Appendix B).

3.1.1 The antenna input impedance

We considered the plasma dipole pictured in Fig. 3.2(a). The plasma dipole is comprised of a cylindrical preformed plasma column whose axis is aligned with the z-axis of the Cartesian system of coordinates, plus a signal coupler placed midway along the plasma cylinder shown in Fig. 3.2(b).

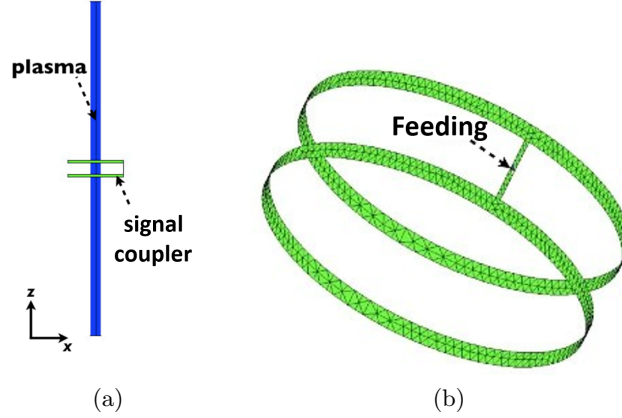


Figure 3.2: The *plasma dipole* model (a), and the *signal coupler* CAD model (b).

The plasma column has length and diameter of 75 mm and 2.5 mm, respectively. The length was chosen according to the behavior of a conventional half-wavelength dipole resonating at 2 GHz ($\lambda_0 = 150$ mm), while the diameter was selected keeping in mind the ideal half-wavelength dipole (infinitesimal diameter) but also the technical difficulties related to a plasma column with a thin diameter. The considered plasma is an argon plasma with plasma density $n_0 = 10^{19} \text{ m}^{-3}$, an electron temperature $T_e = 3 \text{ eV}$, and a neutral background pressure $p_n = 0.02 \text{ mbar}$. To design a signal coupler, we looked at the most common configurations of circuit used to couple power to the plasma in well known devices such as Helicon sources. The signal coupler was chosen to be a *half nagoya*,

a circuit comprised of two loops connected by means of a strip. The half nagoya loops have a radius of 6.25 mm and width of 0.625 mm, and they are connected by a strip with length and width of 2.5 mm and 0.21 mm, respectively. The coupler is modeled as PEC, and it is excited midway along the strip connecting the loops by means of the so-called *voltage-gap* approximation. The voltage gap model requires setting the voltage V_G at the circuit port and computing the current I_A therein. It is worth recalling that the voltage gap approximation is valid as long as the actual antenna port is small as compared to (i) the operational wavelength in the background medium, and (ii) the antenna size. The port is fed with 1 V at frequencies comprised between $0.1 \text{ GHz} \leq f \leq 6 \text{ GHz}$. The real and imaginary parts of the antenna input impedance as a function of frequency are plotted in Figs. 3.3(a), and (b).

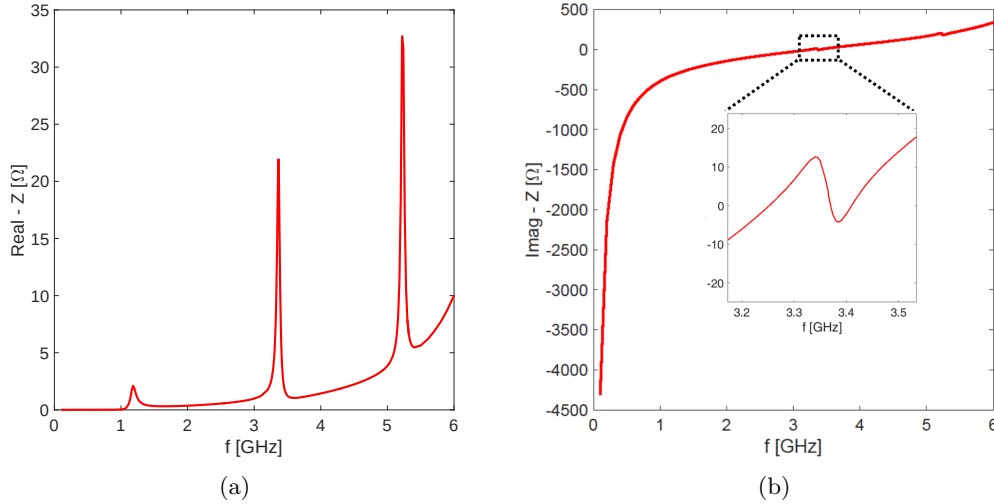


Figure 3.3: (a) The real, and (b) the imaginary parts of the input impedance of the plasma dipole. The inset in the imaginary part of the input impedance highlights 3 different but closed frequencies at which $\text{Im}(Z) = 0$. The argon plasma parameters are: $n_0 = 10^{19} \text{ m}^{-3}$, $B_0 = 0 \text{ mT}$, $p_n = 0.02 \text{ mbar}$, $T_e = 3 \text{ eV}$.

The plasma dipole resonates between 3 and 3.5 GHz, in which range it exhibits a real impedance of about 22 Ω . In that frequency range, the electric length of the plasma dipole is $0.8\lambda_0$, with λ_0 the wavelength in free space. Between 3, and 3.5 GHz, both the real, and the imaginary parts of the input impedance change rapidly: $\text{Re}(Z)$ exhibits a peak, while $\text{Im}(Z)$ shows dips and negative slope. As a results of the oscillation in $\text{Im}(Z)$, the plasma dipole resonates at 3 different but close frequencies. Figs. 3.4 show the electric displacement field $\mathbf{D}$ along the plasma column at the resonance frequencies $f = 3.25 \text{ GHz}$. It is evident that $\mathbf{D}$ is distributed in 3 bands of high field, spaced by regions of low field, instead of 1 band, as in Fig 3.1.

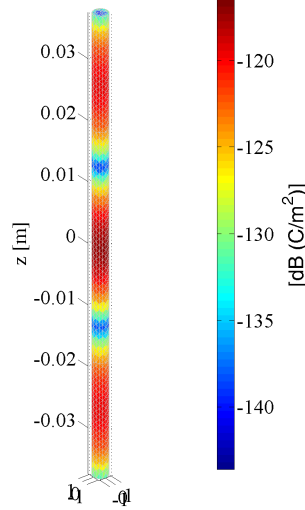


Figure 3.4: Electric displacement field $\mathbf{D}$ along the plasma column in Fig. 3.2(a), driven by the coupler in Fig. 3.2(b) at $f = 3.25$ GHz.

We then considered a *bipolar plasma dipole* shown in Fig. 3.5. The bipolar plasma dipole is comprised of 2 plasma columns having length $L = 60$ mm, and diameter $\Phi = 4$ mm each, and placed at a distance $D = 6$ mm, filled with a pre-formed argon plasma with $n_0 = 5 \cdot 10^{18} \text{ m}^{-3}$, $T_e = 3 \text{ eV}$, $p_n = 2 \text{ mbar}$. These plasma parameters were chosen because more feasible with respect to the previously analyzed plasma dipole. The signal is injected by means of 2 PEC plates with a diameter $\Phi_c \approx 4.2$ mm placed between the discharges at a distance $d \approx 0.5$ mm from each plasma column. The plates are connected by means of a strip 1 mm wide excited at the midpoint.

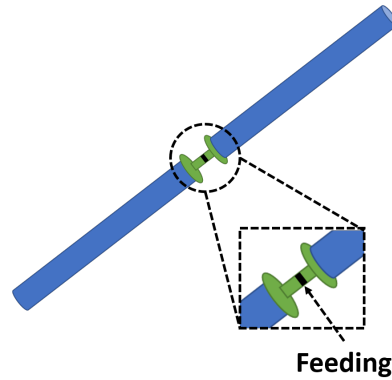


Figure 3.5: The *bipolar plasma dipole*, comprised of 2 plasma columns driven by the coupler in the inset.

We simulated the bipolar plasma dipole in Fig. 3.5 by means of ADAMANT. The results for the input impedance are shown in Fig. 3.6. The bipolar plasma dipole resonates at a frequency $f = 860$ MHz, where $Im(Z) = 0$. Fig. 3.7 shows the electric displacement field $\mathbf{D}$ at the resonance frequency $f = 860$ MHz.

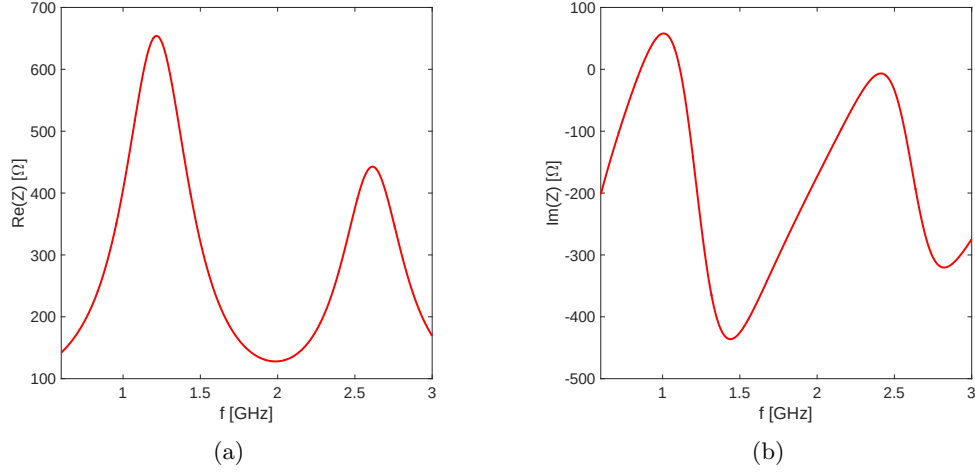


Figure 3.6: (a) The real, and (b) the imaginary parts of the input impedance of the bipolar plasma dipole. The argon plasma parameters are: $n_0 = 5 \cdot 10^{18} \text{ m}^{-3}$, $B_0 = 0 \text{ mT}$, $p_n = 2 \text{ mbar}$, $T_e = 3 \text{ eV}$.

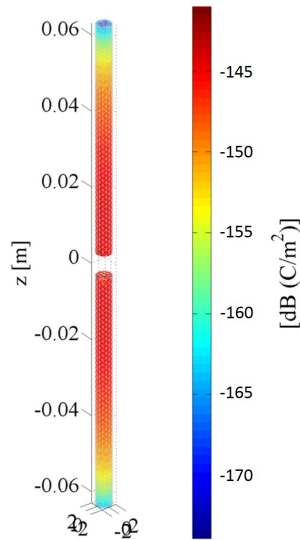


Figure 3.7: Electric displacement field $\mathbf{D}$ along the bipolar plasma dipole in Fig. 3.5 at $f = 860$ MHz. The argon plasma parameters are: $n_0 = 5 \cdot 10^{18} \text{ m}^{-3}$, $B_0 = 0 \text{ mT}$, $p_n = 2 \text{ mbar}$, $T_e = 3 \text{ eV}$.

It is evident that $\mathbf{D}$ is distributed in one band of high density field that fades toward the edges of the column. The current distribution in correspondence of the resonance frequency is therefore similar to that of a conventional metal dipole, pictured in Fig. 3.1.

3.2 Radiation properties

The plasma dielectric permittivity depends on the plasma frequency ω_{pe} , the collision frequency ν_e , and the gyrofrequency ω_{ce} , that are in turn related to the plasma parameters such as plasma density n_0 , discharge gas, external magneto-static field B_0 , and neutral pressure (see Appendix B). The electro-magnetic behavior of the plasma dipole is therefore expected to vary according to the plasma parameters. In order to assess the effect of the plasma parameters, we considered the plasma dipole of Fig. 3.2, since it is easier to realize in terms of geometries of both plasma, and coupler. We simulated it for the polar gain pattern on varying the aforementioned parameters. Besides, we simulated a PEC dipole of same dimensions of the plasma column to fix a term of comparison.

3.2.1 The PEC dipole

In order to have a term of comparison, we considered a *PEC dipole* of same dimensions of the plasma column (length and diameter 75 mm and 2.5 mm respectively), and we simulated it in a frequency range $0.1 \text{ GHz} \leq f \leq 5 \text{ GHz}$. The PEC dipole is fed along the axis line $(\pm R, 0, L/2)$ by means of the voltage-gap approximation. The considered geometry is shown in Fig. 3.8.

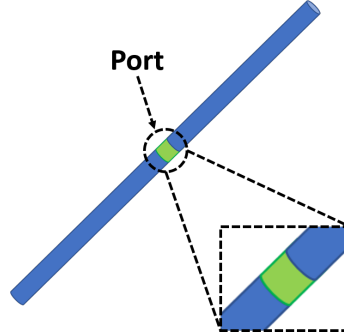


Figure 3.8: The considered PEC dipole. It has length and diameter of 75 mm and 2.5 mm respectively, and it is fed along the axis line $(\pm R, 0, L/2)$ by means of the voltage-gap approximation.

As is well known, an ideal metallic dipole of finite length L has its first resonance at a frequency such that the wavelength in free space $\lambda_0 = 2L$. At this frequency, an ideal metallic dipole should have a real part of the input impedance $Re(Z) = 73 \Omega$ [48]. Since the length of the considered dipole is 75 mm, the PEC dipole should resonate at $f \approx 2 \text{ GHz}$, at which $\lambda_0 = 150 \text{ mm}$. Though, this is true for an ideal half-wavelength dipole, which has infinitesimal diameter, and infinitesimal feed point dimension. Both parameters affect

the input impedance, and the radiation pattern. Specifically, the presence of a finite-length feed point can affect the input impedance behavior, while a finite radius moves the resonance towards lower frequencies [48]. The results for input impedance as a function of frequency, and for the polar gain pattern onto the E, and H planes at $f = 2$ GHz are respectively shown in Figs. 3.9, and Figs. 3.10.

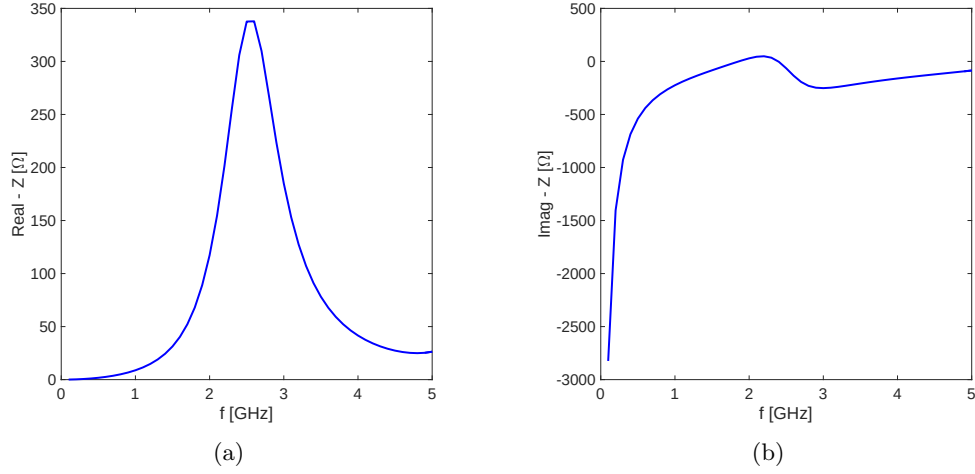


Figure 3.9: The (a) real, and the (b) imaginary parts of the input impedance of the PEC dipole.

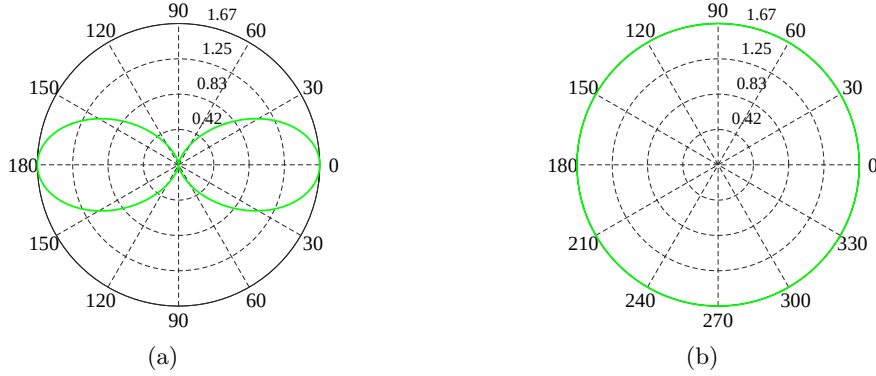


Figure 3.10: The antenna gain $g(\vartheta, \varphi)$ projected onto the (a) E-plane, and (b) H-plane of the PEC dipole at a frequency $f = 2$ GHz.

The PEC dipole resonates at $f \approx 1.86$ GHz, where $\text{Im}(Z) = 0$, and $\text{Re}(Z) \approx 80 \Omega$ that is higher of what expected. Moreover, the imaginary part of the input impedance shows an oscillation with amplitude lower with respect to that asserted by the theory for an ideal half-wavelength dipole. This is well explained when considering the thickness of the

considered PEC dipole, far higher than that of an ideal half-wavelength dipole. Besides, the finite length of the feeding point concurs to further drive away the input impedance trend from the behavior expected according to theory. At $f = 2$ GHz, the antenna gain has a toroidal shape as expected, with a maximum gain $G_{max} = 1.66 = 2.21$ dBi.

3.2.2 Effect of the plasma density

The plasma dielectric permittivity strongly depends on the density through the plasma frequency ω_{pe} and the collision frequency ν_ε ; more specifically, both ω_{pe} and ν_ε increase as the density does so. To assess the effect of the plasma density n_0 on the EM behavior of the plasma dipole, we computed the antenna gain function $g(\vartheta, \varphi)$ for different values of the uniform plasma density n_0 in the range $10^{18} - 10^{21} \text{ m}^{-3}$ the operational frequency $f = 3.25$ GHz. The results are shown in Fig. 3.11.

As shown by Fig 3.11, it is not necessarily true that increasing the density makes the plasma behave as a good conductor. On the contrary, the performance of the plasma dipole at higher plasma densities departs from that of the PEC dipole of the same size, and this result supports the argument that the plasma is not accurately described by a PEC medium.

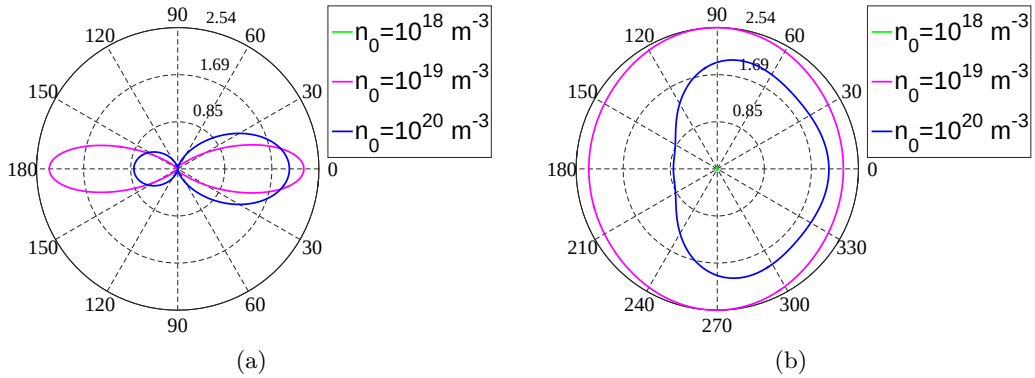


Figure 3.11: Effect of the uniform plasma density (n_0) on the antenna gain $g(\vartheta, \varphi)$ onto the (a) E-plane, and (b) H-plane, driven by the signal coupler in Fig. 3.2(b) at the operational frequency $f = 3.25$ GHz. The argon plasma parameters are: $B_0 = 0$ mT, $p_n = 0.02$ mbar, $T_e = 3$ eV.

3.2.3 Effect of the magneto-static field

An axial magneto-static field B_0 is often applied to plasma sources in order to reduce wall losses (magnetic confinement), and thus the power required to ignite and sustain a discharge. The presence of an external B_0 may influence the radiation properties of the plasma dipole. In particular, in unmagnetized plasma the relative permittivity is a scalar (isotropic medium), and the injected signal propagates within the plasma column as a *surface wave*, a wave propagating along the interface between plasma, and the surrounding medium. The presence of an axial magnetic field makes the plasma behave as an

anisotropic medium, and the signal propagates as a *volume wave*. Moreover, the dielectric permittivity depends upon the gyrofrequency, that is in turn related to the magnitude of the magnetic field. We assessed the influence of the magneto-static field onto the antenna performance of the plasma dipole by computing the gain function $g(\vartheta, \varphi)$ at the operative frequency $f = 3.25$ GHz for different values of B_0 in the range 0 mT - 100 mT. The results onto the E, and H-planes for the plasma dipole with $n_0 = 10^{19} \text{ m}^{-3}$, at a pressure $p_n = 0.02$ mbar are plotted in Figs. 3.12. As evident from the results of the analysis, the effect of the magneto-static field is negligible for densities higher than $n_0 > 10^{18} \text{ m}^{-3}$.

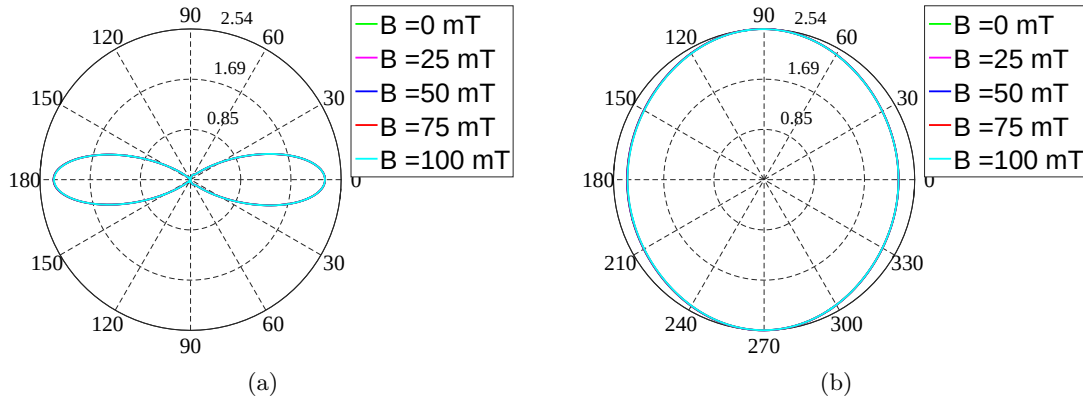


Figure 3.12: Effect of the magneto-static field (B_0) on the antenna gain $g(\vartheta, \varphi)$ onto the (a) E-plane, and (b) H-plane, driven by the signal coupler in Fig. 3.2(b) at the operational frequency $f = 3.25$ GHz. The argon plasma parameters are: $n_0 = 10^{19} \text{ m}^{-3}$, $p_n = 0.02$ mbar, $T_e = 3$ eV. The effect is negligible, and all different cases perfectly superpose.

3.2.4 Effect of the neutral pressure

As already said, the electric permittivity of a plasma discharge depends on the collision frequency, that is in turn related to the neutral-background pressure. We considered the effect of the neutral background pressure on the performance of the plasma dipole by computing the gain function $g(\vartheta, \varphi)$ at the operative frequency $f = 3.25$ GHz for different values of p_n in the range 0.02 mbar - 0.2 mbar. As can be seen by the results plotted in Fig. 3.13, the antenna gain lowers values as the neutral pressure increases from 0.02 to 0.2 mbar. This behavior is well explained when considering the relation between neutral pressure, and losses in plasma: as the pressure increases, so does the collision frequency between charged and neutral particles. This in turn leads to higher power losses within the plasma discharge. To higher losses corresponds a decrease of the radiated power, and thus of the gain function.

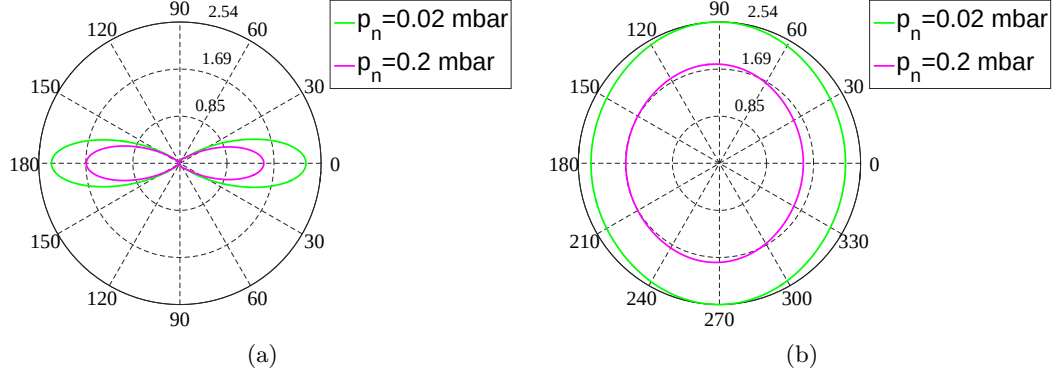


Figure 3.13: Effect of the gas neutral pressure (p_n) on the antenna gain $g(\vartheta, \varphi)$ onto the (a) E-plane, and (b) H-plane, driven by the signal coupler in Fig. 3.2(b) at the operational frequency $f = 3.25$ GHz. The argon plasma parameters are: $n_0 = 10^{19} \text{ m}^{-3}$, $B_0 = 0 \text{ mT}$, $T_e = 3 \text{ eV}$.

3.2.5 Effect of the gas type

We already noticed the importance of the neutral pressure on the collision frequency, and thus on the performance of a plasma antenna, but the collision frequency is related also to the cross-section of the atoms comprising the discharge. Furthermore, the ionization energy, and thus the amount of power required to ignite and sustain the discharge, are related to the gas used. For these reasons, we investigated the performance of the plasma dipole when different gases are used, namely argon, helium, and neon. The results pictured in Figs. 3.14 show that the gas type has a small, but still noticeable effect on the antenna performance.

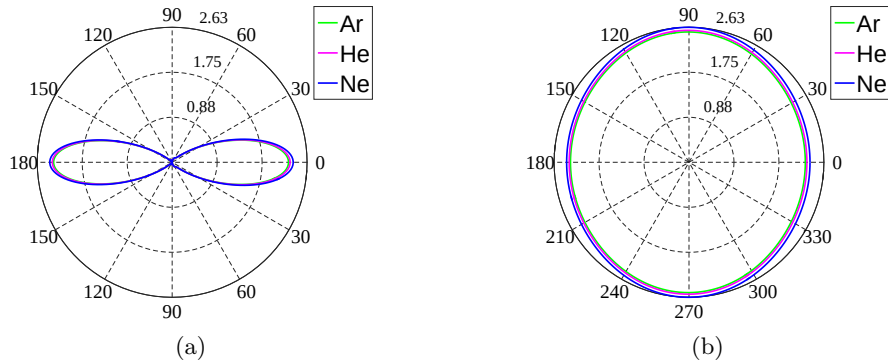


Figure 3.14: Effect of the neutral gas on the antenna gain $g(\vartheta, \varphi)$ onto the (a) E-plane, and (b) H-plane, driven by the signal coupler in Fig. 3.2(b) at the operational frequency $f = 3.25$ GHz. The plasma parameters are: $n_0 = 10^{19} \text{ m}^{-3}$, $B_0 = 0 \text{ mT}$, $p_n = 0.02 \text{ mbar}$, $T_e = 3 \text{ eV}$.

Chapter 4

Design, Realization, and Testing of the Plasma Source

In this chapter, we describe the design, realization, and testing of plasma sources to be used as GPAs, with several gases, background pressure levels, and geometries. We relied onto 2 different plasma generation methods, namely (i) RF-power generation with external electrodes, and (ii) HF-generation with immersed electrodes. We extensively tested the sources for the plasma density, and for the axial density profiles along the plasma sources by means of a microwave interferometer.

4.1 Numerical Analysis

From the physical assessment of previous chapter, we identified the neutral background pressure, and the plasma density as the main drivers of the antenna performances. The plasma source should provide a high plasma density ($n_0 \geq 10^{18} \text{ m}^{-3}$) in order to assure a conductance high enough to efficiently radiate EM waves. On the other hand, the neutral pressure has to be low enough to avoid a highly lossy plasma ($p_n \leq 10 \text{ mbar}$). In the effort to design a plasma source to be used as a plasma antenna, we considered:

- the power requirements to ignite and sustain the plasma discharge;
- the antenna properties of the radiating element.

For the assessment of the power requirements to ignite and sustain the discharge, we exploited the Global Model, a 0-D numerical fluid model that allows for the calculation of (i) the plasma density, and (ii) the electron temperature when (i) the RF power delivered to the discharge, (ii) the discharge geometry, and (iii) the initial neutral gas pressure are specified (see Section 2.2). We developed an optimization tool that couples the Global Model, and the genetic algorithm from the optimization tool of Matlab. The input parameters of this model constitute the decision-space throughout the genetic algorithm searches, which have been reported in Table 4.1 with objectives for the optimization design tool. As a preliminar analysis, we set a range for each parameter as summarized by Table 4.2, and we identified the more efficient combination of individuals and generation for this design

in 150 individuals for 70 generations of the evolutionary algorithm. In other words, for each combination of plasma radius, plasma length, and neutral pressure in the range of Table 4.2, the algorithm calculates the input power needed to reach the target plasma density, and discards the results with out-of-range input powers. Then, the algorithm selects the configuration featuring the lowest input power. The results of the analysis have been reported in Table 4.3. These results were used as a guideline for the realization of the first prototypes of plasma sources.

Decision-space variable	Optimization parameters
Plasma Radius Plasma Length	Plasma density of 10^{19} m^{-3}
Neutral Pressure Input Power	Minimize input power

Table 4.1: Decision-space variables, and target parameters of the optimization design tool.

Parameter	Range of values
Plasma Radius [mm]	5 - 10
Plasma Length [mm]	50 - 75
Neutral Pressure [mbar]	0.06 - 0.5
Input Power [W]	20 - 100

Table 4.2: Ranges for the decision-space variables that have been used in the preliminary analysis with optimization parameters in Table 4.1.

	Case 1	Case 2	Case 3	Case 4
Plasma Radius [mm]	8.7	6.6	7.5	6.42
Plasma Length [mm]	54.6	56.2	78.9	72.5
Neutral Pressure [mbar]	0.75	0.39	0.09	0.4
Input Power [W]	84.1	23.8	94.2	28.9

Table 4.3: Plasma discharge dimensions (radius and length), neutral pressure and RF power to ignite the plasma discharge. The identified cases refer to different sets of the decision-space variables that satisfy the optimization parameters in Table 4.1 with the ranges of Table 4.2.

4.2 Plasma Source Realization

To be used as a plasma antenna, the plasma source should:

1. be as much free as possible from metal electrodes that can shield or disturb the radiation coming from the plasma column;
2. generate the plasma with a frequency as much lower as possible with respect to the signal frequency in order to not perturb the signal, and be easily filtered with a proper Band Pass (BP) filter.

Moreover, the plasma discharges identified by the numerical analysis are low pressure, thus needing a vacuum vessel to contain them. The vessel must also be made of a high temperature, high dielectric strength insulating material, intended to:

1. resist to the pressure differential between the plasma and the external atmosphere;
2. resist the heating produced by the plasma, both by radiation and by high-energy particle impacts on inner walls;
3. resist the strong electric fields employed for plasma generation;

We decided to employ Pyrex glass, which combines the aforementioned characteristics with a low price and ease of manufacturing. Fig. 4.1(a) shows the realization setup. A Pyrex tube of the desired dimensions, and sealed at one end by glass-blowers was connected to a vacuum system. An Edwards E2M28 pump provided the background vacuum level (i.e. 10^{-2} mbar), that was monitored by means of an Edwards APG-100 Pirani vacuum gauge. The selected operating gas was injected in the vessels via an MKS 1179A or Bradford IOF-200-AAD-11-V-S mass flow controllers. Once reached the desired background-pressure level, the tube was sealed as shown in Fig. 4.1(b). Cold-Cathode-Fluorescent-Lamp (CCFL) commercial electrodes, shown in Fig. 4.2, were included in the design, and sealed to the glass tube when needed for the plasma generation. We manufactured, and tested several configurations of plasma antenna sources, with different cylindrical geometries, gases, and pressure levels. Table 4.4 summarizes the parameters, and ranges explored during the experimental campaign.

Parameter	Range of values
Diameter	3 – 10 mm
Length	50 – 130 mm
Gas	Ar, Ne, Kr
Pressure	0.4 – 10 mbar

Table 4.4: The range of parameters explored in the experimental campaign.

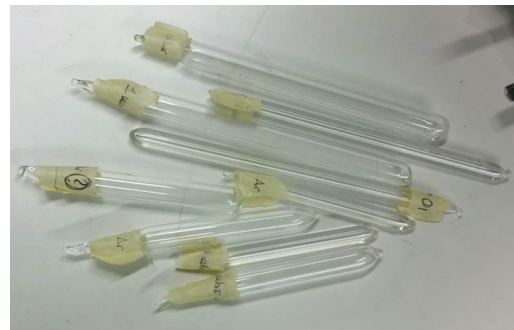
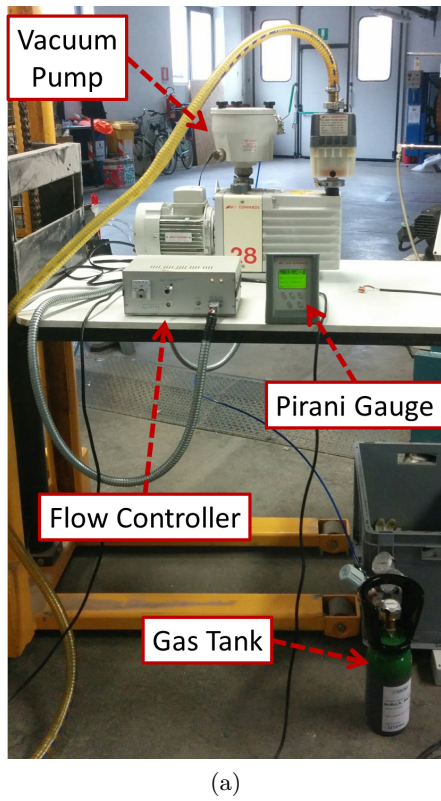


Figure 4.1: (a) The plasma realization set-up, (b) the sealing process, and (c) examples of vessels obtained.

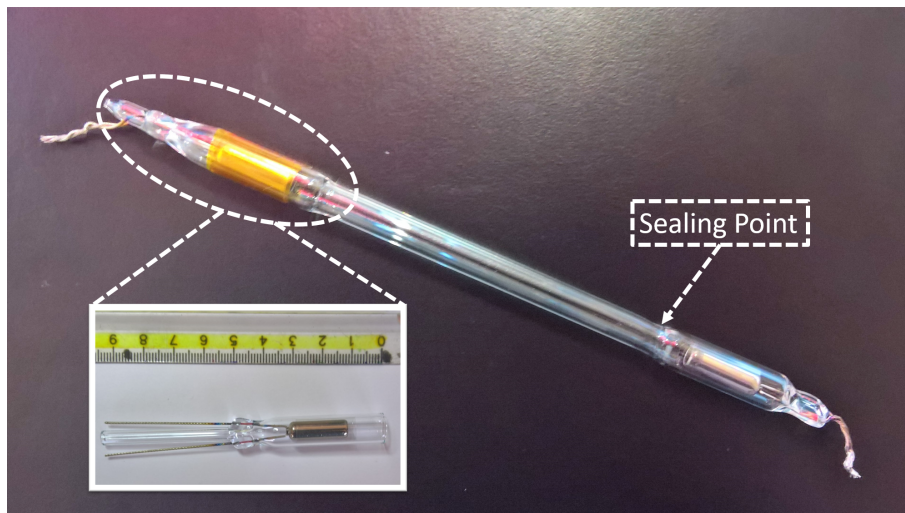


Figure 4.2: A vessel with a CCFL commercial electrode included in the design. The electrode, pictured in the insight, is sealed to the glass vessel where shown by the white arrow.

In order to ignite, and sustain the plasma discharge, we took into considerations 2 methods, namely (i) RF-generation system, (ii) HF-generation system.

The first method relies on 3 external-RF electrodes: a central ring-shaped one, and two plate electrodes connected together. The electrodes were manufactured employing a 0.5 mm thick copper foil. The ring electrode has diameter $\Phi \approx 15$ mm, the plates have length, and width of nearly 45 mm, and 30 mm respectively. The electrodes were encased in Polytetrafluoroethylene (PTFE) to provide electrical insulation. The electrodes are fed with RF power by the system schematically shown in Fig. 4.3.

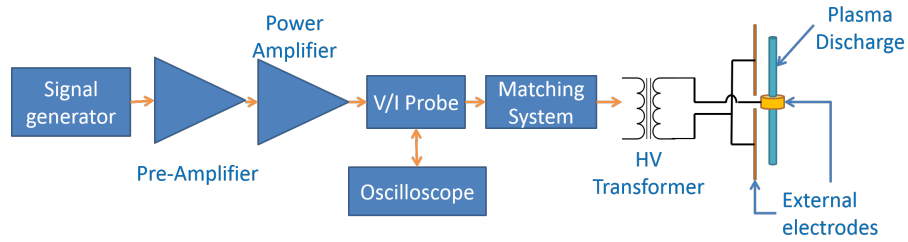


Figure 4.3: Schematic of the RF-generation system.

The RF generation system is comprised of:

- a HP8648A signal generator provides an RF sine wave at the chosen generation frequency;
- the signal is fed to a low power pre-amplifier, which in turn increases its strength in order to trigger an HFPA-300 RF power amplifier, with a maximum power output of 300 W;
- the RF power output from the amplifier is conveyed to a custom built matching system, which provides the impedance matching between the amplifier itself and its load;
- a transformer is connected to the output port of the matching system and provides high voltage output which is applied to the electrodes on the plasma element. The current set-up features an 1 : 10 transformer capable of producing 1000-1500 V on the electrodes;
- the impedance and power coupling of the load (matching system, transformer and plasma element) is monitored by means of a custom built V/I probe, placed at the input port of the matching system and connected to an oscilloscope, which enables vector measurements of the voltage and current flowing to the load.

RG-58 coaxial cables carry the signals, while RF power is conveyed via RG-214 coaxial cables. The operating frequency of the system can span between 1.8 MHz – 15 MHz, but it is usually comprised in the range $9 \text{ MHz} \leq f \leq 12 \text{ MHz}$. PTFE was chosen also to build the vessel housing thanks to its electrical insulation properties, and its low tangent

loss. The support is schematically shown in Fig 4.4. It features a PTFE base at the ends of which 2 columns with diameter ≈ 20 mm, and height ≈ 80 mm are mounted. On top of the columns the plate electrodes with the PTFE insulation are fixed by means of screws. Between the 2 columns, 2 rectangular brackets are mounted. The latter feature a hole with diameter ≈ 12 mm to support the discharge at a height ≈ 100 mm from the base surface. Fig. 4.5 shows 2 discharges housed on the PTFE support.

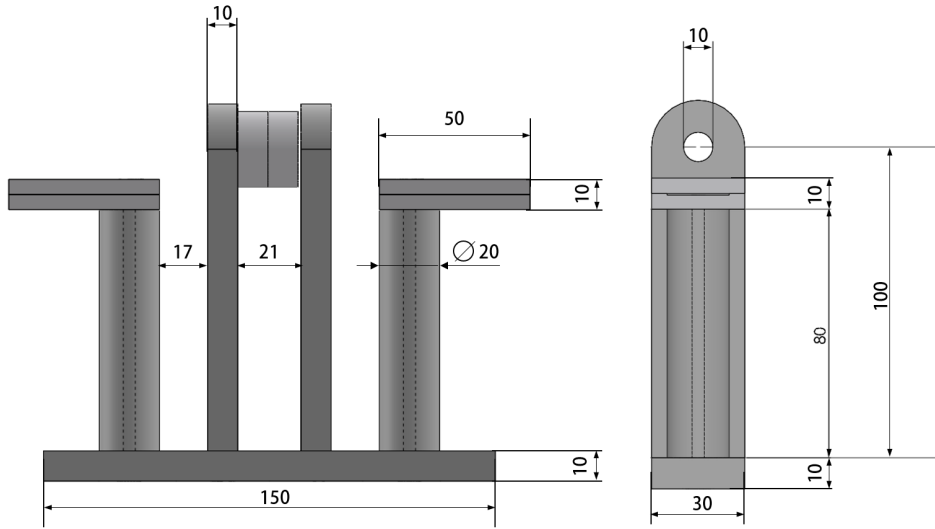


Figure 4.4: A sketch of the PTFE support for a plasma antenna excited by the RF-generation method. Dimensions are expressed in millimeters.

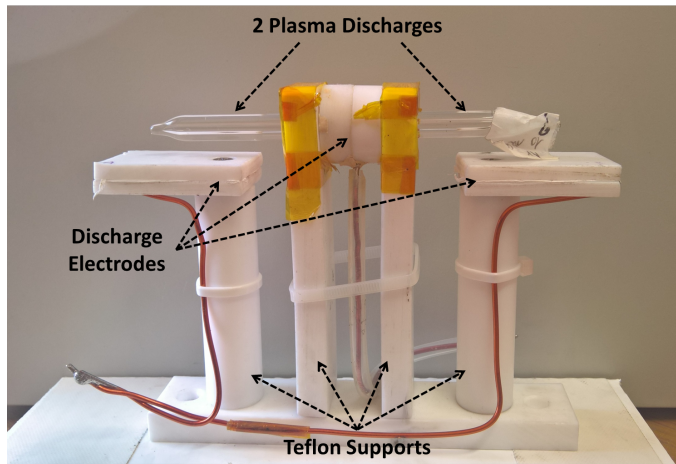


Figure 4.5: A photo of the PTFE support with 2 vessels.

The density of the plasma inside each plasma element is determined by the power coupled to it, which in turn is directly related to the voltage applied to the RF electrodes. By regulating the output voltage of the RF amplifier, and thus of the transformer feeding the electrodes, it is possible to effectively tune the density inside the vessel. The effective power coupled to the plasma element depends on the electrical efficiency of the transformer and matching network, which in turn depends on the impedance of the plasma element itself. This parameter was estimated by means of a lumped-parameters electrical model of the system, calibrated and verified by means of comparison between the numerically estimated input impedance of the system, seen by the V/I probe, and the experimentally measured one.

The HF-generation method relies on a commercial HV transformer, connected to 2 CCFL electrodes immersed at the end of the Pyrex vessel, and thus in contact with the gas, and the plasma itself. The transformer is a MIDI ECG 2100 model produced by the Italian company E.L.Elettronica Per Luce (S.R.L) as a power supply for fluorescent lamps. The technical features of the device are listed in Table 4.5. The commercial HV transformer was designed for fluorescent lamps longer than the plasma discharges for GPA applications, and thus with higher impedance. The poor impedance matching between the HV transformer, and the plasma led to low power coupled to the discharge, and the HV overheating. To improve the impedance matching, and the power deposited into the plasma, we used a single power supply to feed two plasma elements connected in series, as shown in Fig. 4.6. After an experimental optimization process, we included in the design a ≈ 1.5 nF capacitance to further improve the impedance matching. The overall schematic of the plasma generation system for one couple of plasma discharges is reported in Fig. 4.7.

Parameter	Value
Input Voltage	200 - 250 V
Input Current	Up to 400 mA
Input Power	Up to 90 W
Input Frequency	50/60 Hz
Output Voltage	2 kV max
Output Short-circuit Current	95 mA
Output Current to Load	84 mA (nominal)
Output Frequency	19 kHz

Table 4.5: The MIDI ECG 2100 features.

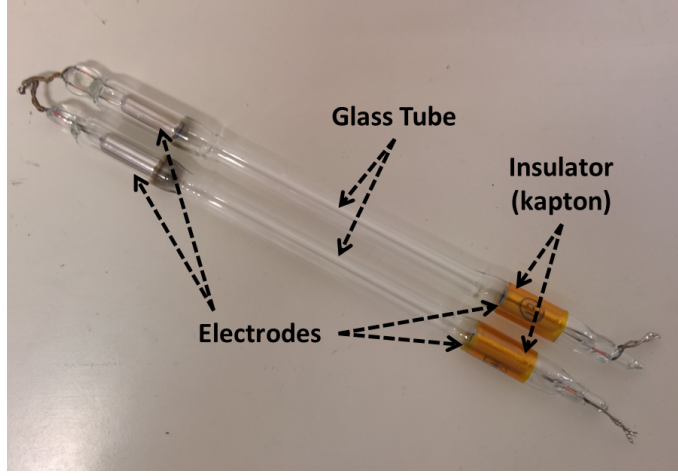


Figure 4.6: Two plasma element connected in series to improve impedance matching with the commercial HV transformer.

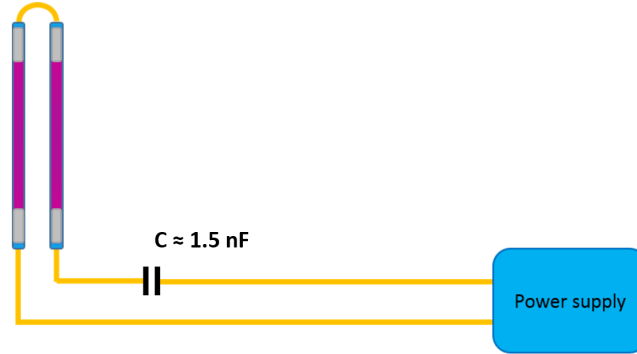


Figure 4.7: A schematic of the HF plasma generation system for one couple of plasma discharges.

4.3 Plasma Source Testing

The characterization of the plasma source is performed by determination of the electron density, its distribution along the plasma source, and the power required to sustain the discharge. To measure the plasma density inside the discharge, and to estimate its distribution, we relied on a microwave interferometer [49], which is capable of plasma density measurements regardless of the gas type. The instrument is movable along the plasma source, and measures the average electron density in a plasma slab having length $L_{horns} = 15$ mm, and height $h_{horns} = 10$ mm.

The error evaluation takes into account (i) geometrical parameters (i.e. accuracy in the diameter estimation, and the measurements section positioning), and (ii) the phase

noise. In particular, the phase noise can be severe for low diameters, and low densities. In these cases, the phase shift may be of the same order of the phase noise, leading to high errors, and low precision. These aspects were taken into account during the plasma source characterizations.

Being the plasma density related to the power coupled to the discharge, by means of the RF-generation method it is possible to effectively tune the plasma density by varying the amplifier output power. We then measured the plasma density as the power increases. Fig. 4.8 shows the plasma density measured along the line of sight of the interferometer as a function of the power coupled to the discharge for a vessel with diameter $\Phi = 10$ mm, length $L = 130$ mm, filled with argon at a neutral pressure $p_n = 1$ mbar, and excited by means of the RF generation method. Fig. 4.9 shows the plasma density as a function of the net power for a discharge with diameter $\Phi = 3$ mm, length $L = 130$ mm, filled with argon gas at a neutral pressure $p_n = 10$ mbar, and excited by means of the RF generation method. The plasma density in the discharge increases as the power does so. In Fig. 4.9 an asymptotic trend is evident. The plasma density is in fact related to the actual power coupled to the discharge, and so to the electrical efficiency of the transformer. The efficiency depends on the discharge impedance, that is related to the plasma density again. At higher densities correspond lower values of the input impedance that lowers the efficiency of the HV transformer.

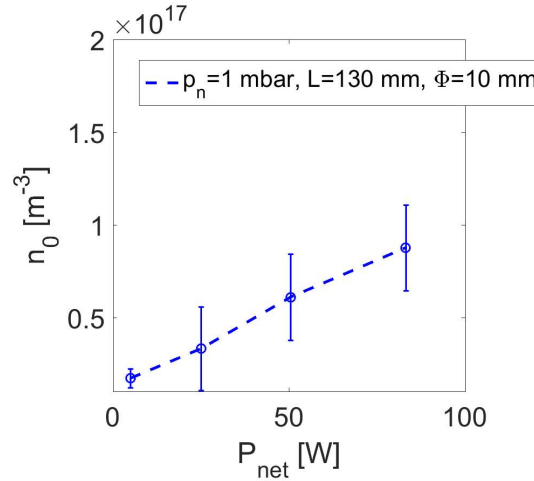


Figure 4.8: Plasma density against the power coupled to the plasma for an argon discharge having diameter $\Phi = 10$ mm, length $L = 130$ mm, and a neutral pressure $p_n = 1$ mbar, excited by means of the RF generation method.

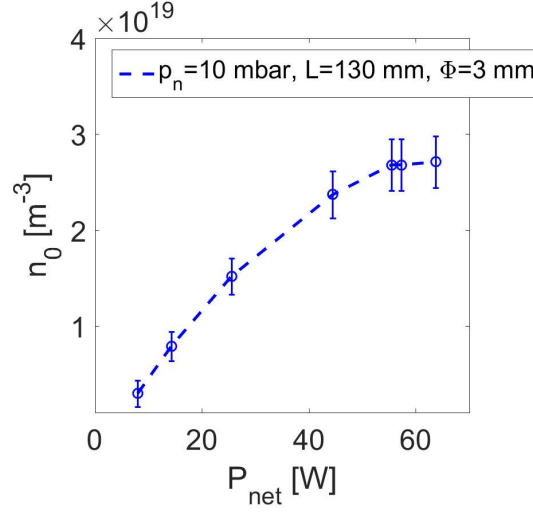


Figure 4.9: Plasma density against the power coupled to the plasma for an argon discharge having diameter $\Phi = 3$ mm, length $L = 130$ mm, and a neutral pressure $p_n = 10$ mbar, excited by means of the RF generation method.

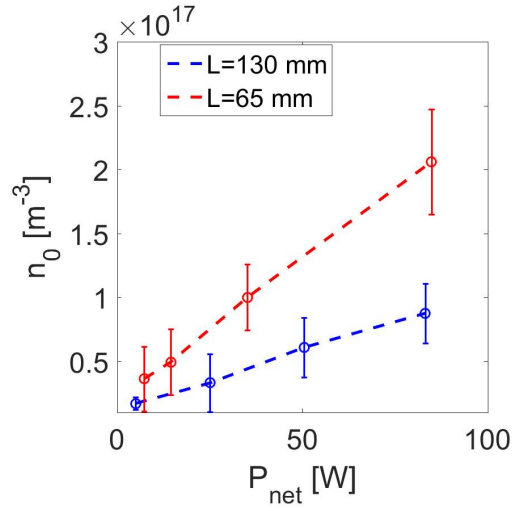


Figure 4.10: Plasma density against the power coupled to the plasma for 2 argon discharges having a neutral pressure $p_n = 1$ mbar, and a diameter $\Phi = 10$ mm but different lengths, namely $L = 130$ mm, and $L = 65$ mm, excited by means of the RF generation method.

Coupling the same power, the reached density value is higher as the source length decreases. This can be seen by Fig. 4.10 that shows the results of the analysis for 2 argon discharges excited by means of the RF generation method with diameter $\Phi = 10$ mm,

and a neutral pressure $p_n = 1$ mbar, but having 2 different lengths $L = 130$ mm, and $L = 65$ mm. This behavior is well explained when the volume power density is taken into account: to shorter discharges correspond a higher volume power density.

Keeping in mind the design of a bipolar plasma dipole as described in Section 3.1.1, we tested several combinations of 2 separate discharges featuring the same dimensions, gas type, and pressures, housed together in the PTFE support, and excited at the same time. In this configuration, each of the 2 discharges has one tip inside the ring-shaped electrode, and the other above the plate electrode, as shown in Fig. 4.5. Several tests showed that it is impossible to obtain the same plasma density into 2 discharges with same dimensions, gas type, and pressure, even if housed on the PTFE support, and excited together. Fig. 4.11 shows the plasma density against the net power for 2 argon vessels having both $\Phi = 10$ mm, $L = 65$ mm, and a neutral pressure $p_n = 1$ mbar, excited together on the PTFE support. The density reached in the 2 vessels is different, and for net power higher than $P_{net} \geq 30$ W, the difference between the density obtained in the 2 vessels is greater than the uncertainty.

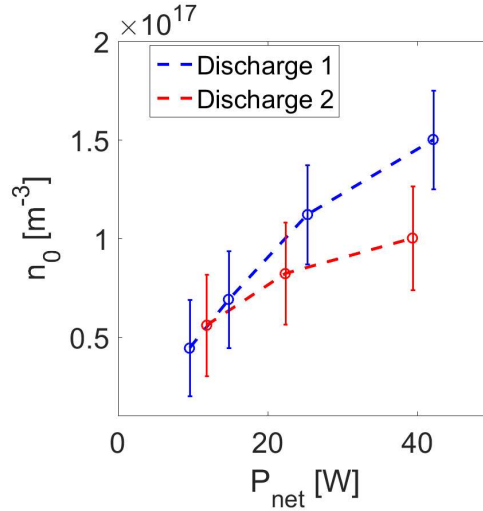


Figure 4.11: Plasma density against the power coupled to the plasma for 2 argon discharges having a neutral pressure $p_n = 1$ mbar, and diameter $\Phi = 10$ mm, and length $L = 65$ mm, excited together by means of the RF generation method.

To assess the axial distribution of n_e , we sampled the plasma density along the plasma source. We then evaluated the ratio n_e/n_{max} , where n_e is the plasma density at the sample point, and n_{max} is the maximum value of plasma density measured for each source. For neutral pressures $p_n < 10$ mbar, and for radii $R > 3$ mm, the RF generation method leads to strongly not-uniform plasma-density distribution, with estimated value of n_e/n_{max} ranging from 0.2 to 1 axially. For $p_n \geq 10$ mbar, and $R \leq 3$ mm, the density distribution features higher uniformity, with value of the n_e/n_{max} ratio remaining between 0.5 and 1 axially. To have a rough idea of the density distribution, we employed a Basler

SCA1400-30fc CCD camera, equipped with a BP filter centered on an emission line of Ar II ions (488 ± 5 nm). In this range, few emission lines of ArII are present, the strongest being ArII [$^2D_{5/2} - ^2P_{3/2}$] at $\lambda = 488$ nm. Figs. 4.12, and Figs. 4.13 show the filtered images of 2 discharges 130 mm long, but respectively having a diameter $\Phi = 10$ mm with a neutral pressure of $p_n = 1$ mbar, and $\Phi = 3$ mm with $p_n = 10$ mbar. It is evident that the low-pressure discharge features strongly not-uniform luminosity, with 2 regions of high luminosity under the ring-shaped electrode (on the left of the discharge), and just above the plate electrode (on the right of the discharge). A lower diameter, and a higher neutral pressure partially improve the luminosity distribution along the discharge. This may be due to the configuration of the electrodes that shapes the electric field, and so the plasma density inside the vessels. Moreover, there is no magnetic field enhancing the plasma confinement. Increasing the pressure, so does the collision frequency, and the contribution of charged-neutral collisions becomes significant with respect to the electromagnetic interactions. This can explain the higher uniformity in the vessels featuring $p_n = 10$ mbar.

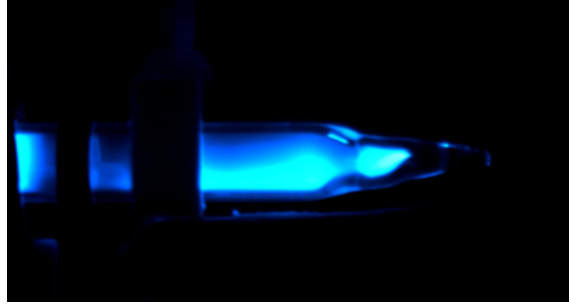


Figure 4.12: Filtered image of an argon plasma discharge having diameter $\Phi = 10$ mm, length $L = 130$ mm, and a neutral pressure $p_n = 1$ mbar, excited by means of the RF-generation method.

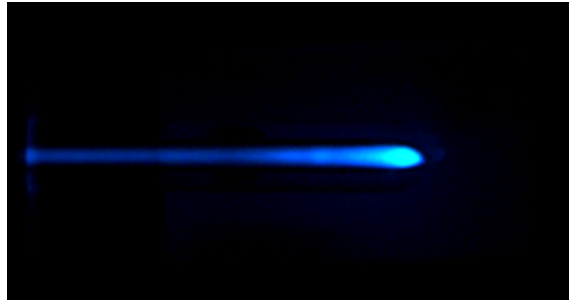


Figure 4.13: Filtered image of an argon plasma discharge having diameter $\Phi = 3$ mm, length $L = 130$ mm, and a neutral pressure $p_n = 10$ mbar, excited by means of the RF-generation method.

The HF-generation system is not tunable: being the power coupled to the plasma fixed by the transformer, and the matching capacitors, it is not possible to control, and vary the plasma density inside the vessels. We measured the power supply absorption from the electric line to be $P \approx 30$ W, but it wasn't possible to estimate the power actually coupled to the plasma. We performed several measurements on discharges excited by means of the HF-generation method, that were found to have a more uniform density distribution with respect to the discharges driven by the RF-generation method at same neutral pressure, with values of n_e/n_{max} ranging from 0.75 to 1 in the most severe case. This can be qualitatively seen by Fig. 4.14.

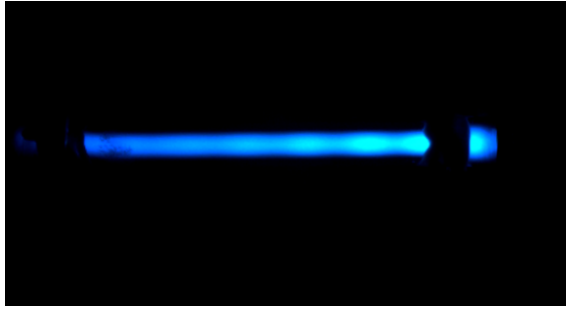


Figure 4.14: Filtered image of an argon plasma discharge having diameter $\Phi = 6$ mm, length $L = 100$ mm, and a neutral pressure $p_n = 2$ mbar, excited by means of the HF-generation method.

On the other hand, the internal electrodes are subjected to performance degradation during time. This was observed thanks to continuous plasma density measurements for ignition time ranging from 40 s to 200 s. Fig. 4.15 shows an example of phase shift as a function of time for an HF generated discharge during an ignition of $t \approx 160$ s. The first phase shift occurs at the ignition of the discharge, and it is equal to $\Delta\varphi_{ON} = 0.13 \pm 0.005$ rad that corresponds to a plasma density $n_0 = 5.08 \cdot 10^{18} \pm 3.38 \cdot 10^{17} \text{ m}^{-3}$. During the test the density tends to lower, until the second phase shift when the discharge was turned off. The phase jump at the turning off instant is $\Delta\varphi_{OFF} = 0.073 \pm 0.01$ rad, and corresponds to a plasma density $n_0 = 2.83 \cdot 10^{18} \pm 4.11 \cdot 10^{17} \text{ m}^{-3}$, that is 40% less than the density measured at the ignition. In the effort to stabilize, and raise the density in the plasma source, we explored different gas pressures, and mixture. In fluorescent lightning applications, adding few drops of mercury close to the electrode is a common practice. Since the heat developed by the electrode vaporizes the liquid mercury, the atmosphere inside the vessel results as a mixture of a noble gas and mercury vapour that lowers the breakdown voltage with respect to the noble gas only. This effect can be obtained also with a proper mixture of noble gasses [50]. To take advantage of this effect, and a better impedance matching with the HV transformer, we explored the effect of a mixture of 50% argon and 50% neon, and of few drops of mercury close to the CCFL electrode in a vessel filled with argon at 1, and 2 mbar. Table 4.6 summarizes the main results for the HV discharges in terms of plasma density along the line of sight of the interferometer horns. All the reported results refer to discharges having length $L = 100$ mm, diameter

$\Phi = 6$ mm. It was noticed that a mixture of argon and mercury at an argon pressure of 1 mbar leads the plasma density to lower in a shorter time with respect to a pure argon gas. It is worth to be noticed that the addition of mercury lowers the uncertainties (error bars) with respect to the noble gas only.

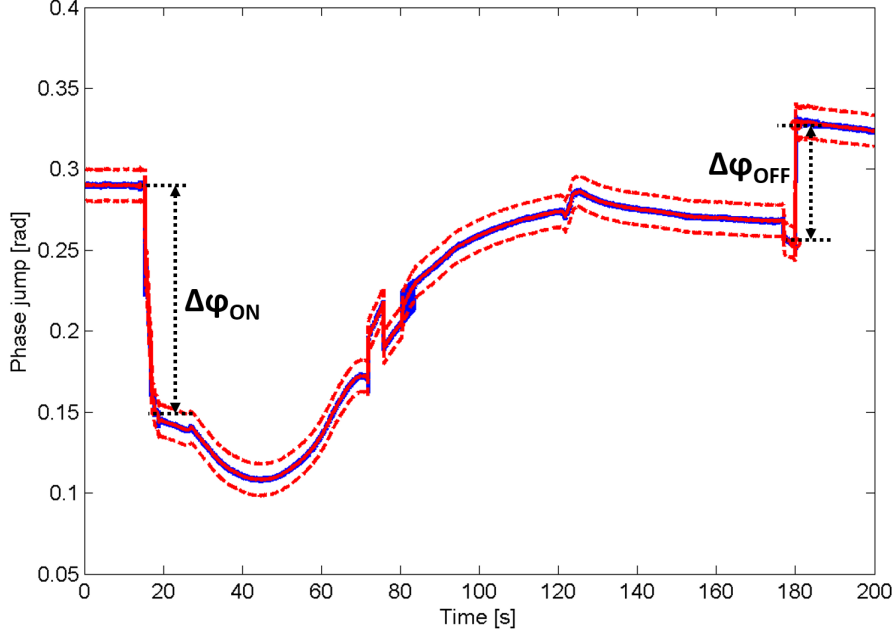


Figure 4.15: Phase shift as a function of time for a HF-generated discharge ignited for a time $t \approx 160$ s. The phase shift at the turning off $\Delta\varphi_{OFF}$ corresponds to a plasma density lower by the 40% with respect to the phase shift at the ignition $\Delta\varphi_{ON}$.

Gas Type	p_n [mbar]	n_0 [m^{-3}]
Argon	1	$3.70 \cdot 10^{18} \pm 1.84 \cdot 10^{17}$
Argon - Neon	2	$3.84 \cdot 10^{18} \pm 8.57 \cdot 10^{16}$
Argon	2	$4.40 \cdot 10^{18} \pm 5.09 \cdot 10^{17}$
Argon - Mercury	2	$3.18 \cdot 10^{18} \pm 5.88 \cdot 10^{16}$
Argon - Mercury	1	$2.59 \cdot 10^{18} \pm 1.50 \cdot 10^{17}$

Table 4.6: Main results in terms of plasma density for the HV discharges. All the reported results refer to discharges with length $L = 100$ mm, and diameter $\Phi = 6$ mm.

Chapter 5

Design, Realization, and Testing of the Plasma Dipole

In this chapter, we describe the design, realization, and testing of a plasma dipole working in the GHz regime. We used the results coming from the plasma source characterization to simulate the electrical behavior, and antenna properties of a plasma dipole when several signal couplers, antenna configurations, and plasma parameters are considered. We realized a plasma dipole comprised of a plasma discharge driven by the RF generation method, and a coupler to inject the signal into the plasma. We tested the plasma dipole for the gain pattern, and values in the range of frequency $860 \text{ MHz} \leq f \leq 920 \text{ MHz}$.

5.1 Numerical Analysis

We considered several configurations of signal coupler, plasma discharge, and plasma parameters, and we analyzed their electrical, and antenna properties (e.g. input impedance, reflection coefficient, antenna gain etc.) as a function of frequency in the range $0.9 \text{ GHz} - 1.8 \text{ GHz}$ by means of ADAMANT. The plasma parameters, and antenna geometry were chosen according to the results obtained for the plasma source design of the previous chapter. The electron temperature was selected according to considerations found in literature [51]. Table 5.1 summarizes the plasma parameters used for the numerical simulations.

Parameter	Value
Diameter Φ	3 - 10 mm
Length L	50 - 130 mm
Plasma density n_0	$10^{17} - 10^{19} \text{ m}^{-3}$
Neutral pressure p_n	0.4 - 10 mbar
Electron Temperature T_e	3 eV
Gas Type	Ar, He, Kr

Table 5.1: Summary of the plasma source parameters used to simulate the behavior of a radiating plasma antenna.

5.1.1 Effect of the coupler configuration

In order to inject the signal in the plasma discharge, and excite the proper current distribution within the plasma volume, a proper signal coupler has to be designed. In this effort, we considered two different coupler configurations, namely (i) half-nagoya couplers, and (ii) sleeve couplers, examples of which are shown in Figs 5.1. In choosing these geometries, we took inspiration from the RF antennas used for Helicon sources. For each coupler configurations we considered several length, and diameter values in the ranges reported in Table 5.2. In half-nagoya case, we also evaluated the effect of several loop widths, and strip lengths.

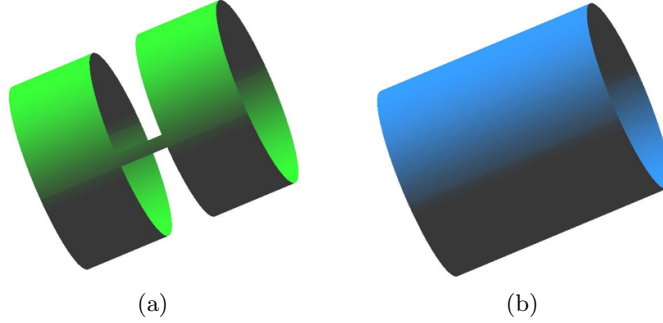


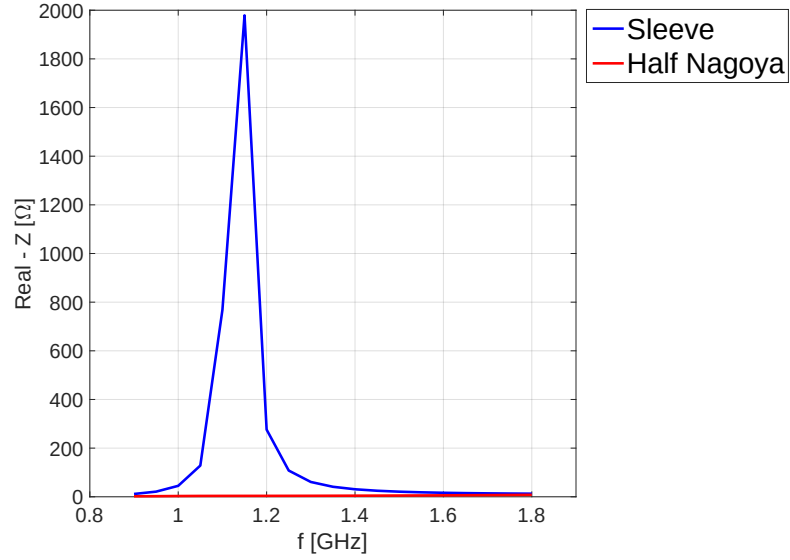
Figure 5.1: An example of (a) half-nagoya coupler, and (b) sleeve couple.

Parameter	Value
Diameter Φ	13 - 28 mm
Total Length L_{tot}	15 - 45 mm
Loop Width S_{loop}	2 - 15 mm
Strip Length L_{strip}	3 - 35 mm

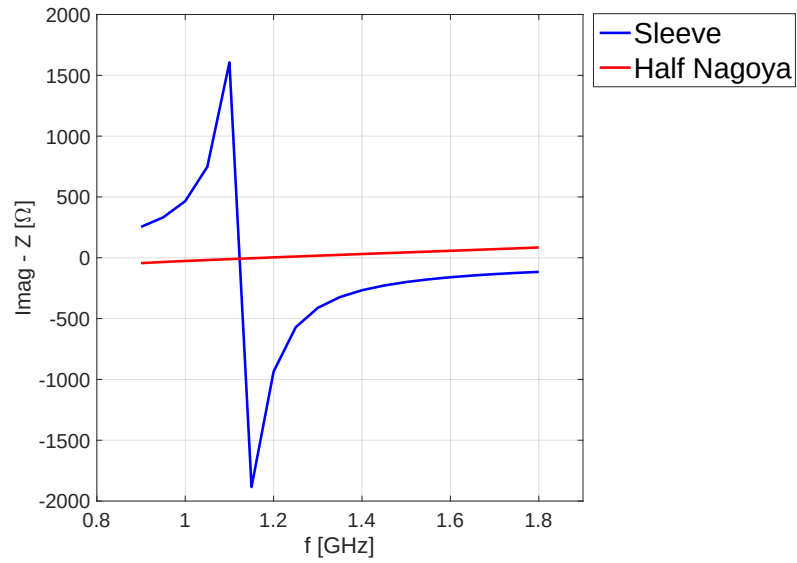
Table 5.2: Summary of the plasma source parameters used to simulate the behavior of a radiating plasma antenna.

We then fixed the plasma column geometry, and the plasma parameters, and we simulated its behavior when driven by several couplers. The plasma column has diameter $\Phi = 10$ mm, and total length $L = 100$ mm, and it is filled with an argon plasma having $n_0 = 3 \cdot 10^{18} \text{ m}^{-3}$, $p_n = 1$ mbar, and $T_e = 3$ eV. The couplers are modeled as PEC. The half-nagoya couplers are excited by a voltage gap applied at the middle point of the leg connecting the loops at $(+R, 0, 0)$, while the sleeve along the axial line $(+R, 0, \pm L/2)$.

Figs. 5.2, and 5.3 show a comparison between the plasma column driven by a sleeve coupler, and by a half-nagoya coupler. The couplers have both a diameter $\Phi = 28$ mm, and length $L = 30$ mm, while the half-nagoya loops has a width $S_{loop} = 12$ mm.

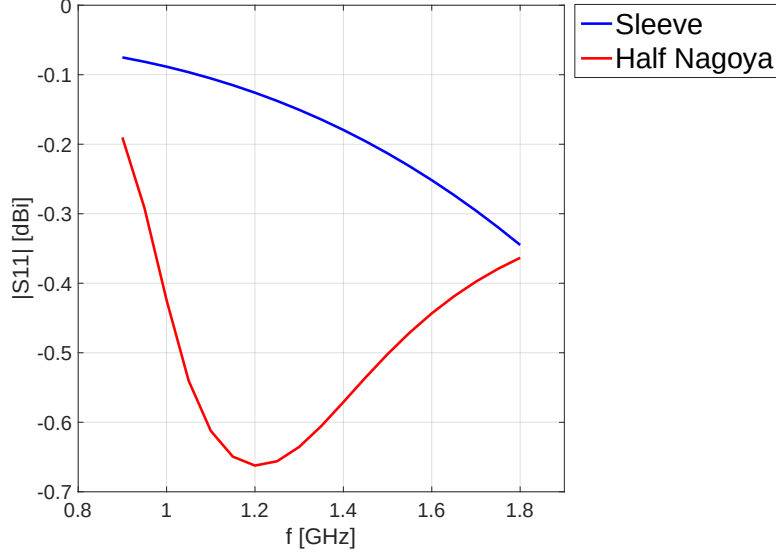


(a)

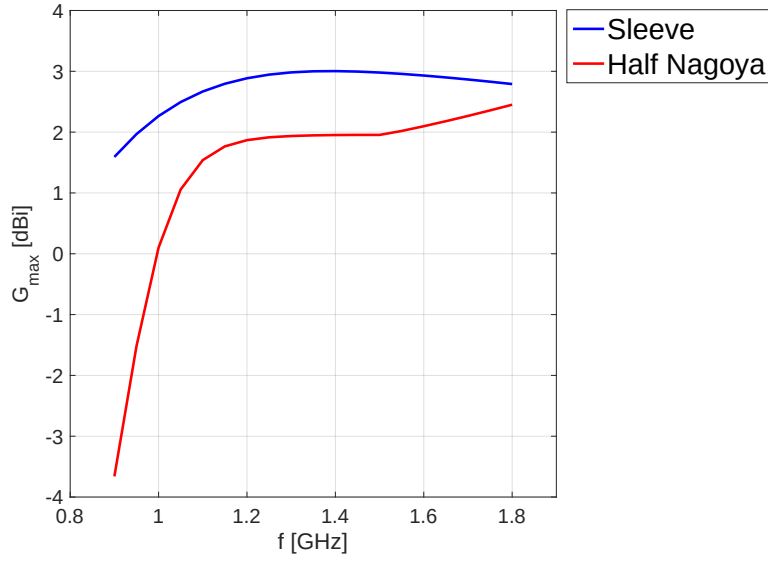


(b)

Figure 5.2: (a) Real, and (b) imaginary parts of the input impedance as a function of frequency for a monopolar plasma dipole driven by the sleeve coupler, and the half nagoya coupler. The couplers have both a diameter $\Phi = 28$ mm, and length $L = 30$ mm. The half-nagoya loops has a width $S_{loop} = 12$ mm. The plasma dipole have $\Phi = 10$ mm, and $L = 100$ mm, and it is filled with an argon plasma with $n_0 = 3 \cdot 10^{18} \text{ m}^{-3}$, $p_n = 1$ mbar, and $T_e = 3$ eV.



(a)



(b)

Figure 5.3: (a) Magnitude of the reflection coefficient, and (b) maximum gain as a function of frequency for a monopolar plasma dipole driven by the sleeve coupler, and the half nagoya coupler. The couplers have both a diameter $\Phi = 28$ mm, and length $L = 30$ mm. The half-nagoya loops has a width $S_{loop} = 12$ mm. The plasma dipole have $\Phi = 10$ mm, and $L = 100$ mm, and it is filled with an argon plasma with $n_0 = 3 \cdot 10^{18} \text{ m}^{-3}$, $p_n = 1$ mbar, and $T_e = 3$ eV.

Even if the half-nagoya coupler leads to lower gain value with respect to the sleeve one, the plasma dipole does not resonate in the considered range when driven by a sleeve coupler. This can be because of a resonance frequency higher than $f > 1.8$ GHz, or because of a low real part of the input impedance. A low $Re(Z)$ can actually affect the frequency behavior of loop antennas such as the sleeve couplers considered here, and make them having only one antiresonance and no resonances [48]. On the other hand, it is evident that the half-nagoya drives the plasma dipole to resonate at $f \approx 1.18$ GHz, where $Im(Z) = 0 \Omega$, and $Re(Z) \approx 3.8 \Omega$.

Thanks to several simulations with different half-nagoya couplers but fixed plasma geometries, and parameters, we found as the best coupler configuration in terms of antenna gain, and resonance frequency the half-nagoya circuit shown in Fig. 5.4. The half nagoya has a diameter $\Phi = 14$ mm, a total length $L_{tot} = 42$ mm, and a loop width $S_{loop} = 5$ mm.

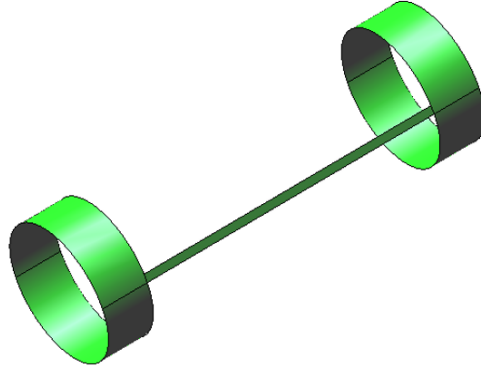


Figure 5.4: The half-nagoya coupler chosen after an optimization process by means of ADAMANT simulations. The half nagoya has a diameter $\Phi = 14$ mm, a total length $L_{tot} = 42$ mm, and a loop width $S_{loop} = 5$ mm.

5.1.2 Effect of the antenna configuration

We considered 2 different conventional antenna configurations, namely monopolar dipole, and bipolar dipole, respectively shown in Figs. 5.5(a), and (b). Both the plasma dipoles have diameter $\Phi = 10$ mm, and total length $L = 100$ mm, but the bipolar plasma dipole is comprised of two discharges with $L_{cols} = 47$ mm, and placed at a distance $D = 6$ mm along the z-axes. We fixed the coupler geometry as shown in Fig. 5.4, and we simulated the chosen configurations for the input impedance, the reflection coefficient, and the maximum antenna gain as a function of frequency. The computed input impedance, magnitude of the reflection coefficient, and maximum antenna gain for the monopolar, and the bipolar plasma dipoles with an argon plasma having $n_0 = 7 \cdot 10^{18} \text{ m}^{-3}$, $p_n = 0.4$ mbar, and $T_e = 3$ eV are shown in Figs. 5.6, and 5.7.

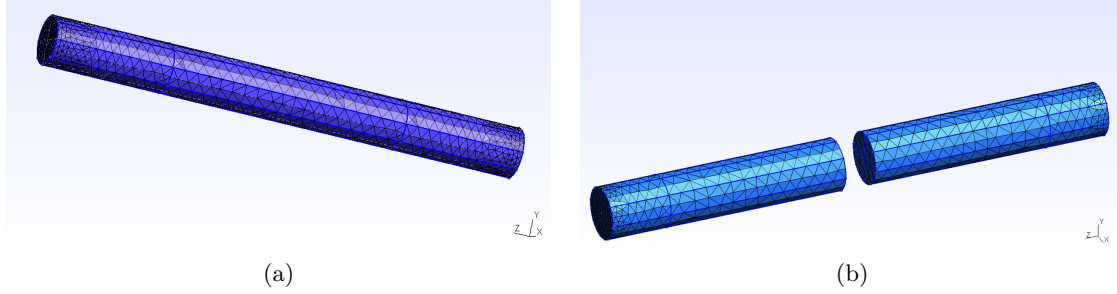
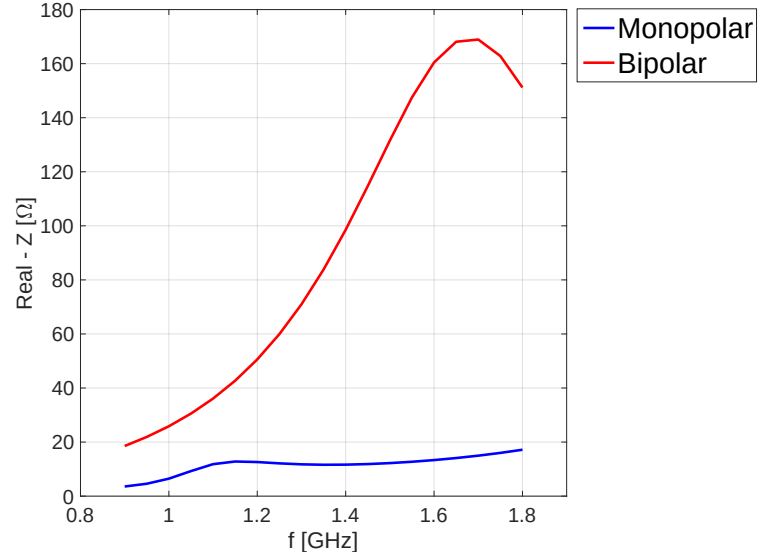
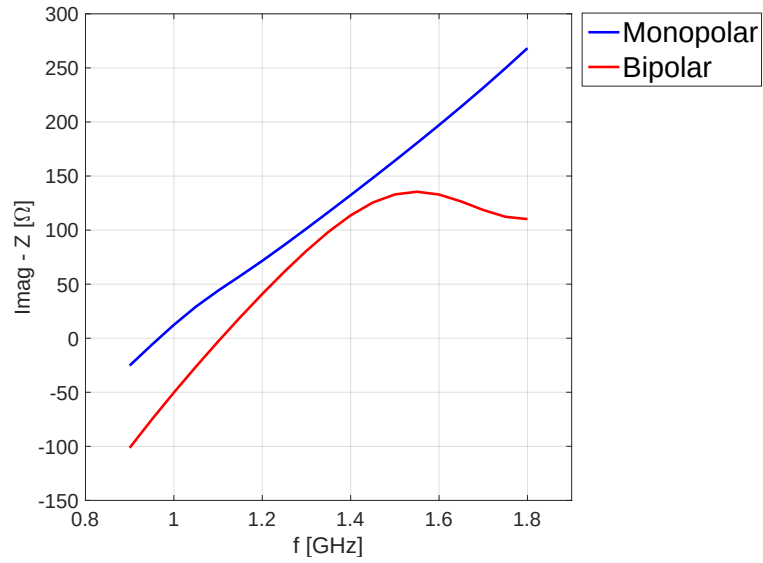


Figure 5.5: The simulated plasma discharge geometries: the monopolar dipole (a), and the bipolar dipole (b). Both have diameter $\Phi = 10$ mm, and total length $L = 100$ mm, but the bipolar plasma dipole is comprised of two discharges with length $L_{col} = 47$ mm, and placed at a distance $D = 6$ mm.

Both the real, and the imaginary parts of the input impedance strongly depend on the plasma discharge configuration. In the monopolar configuration, the real part of the impedance shows a peak at $f \approx 1.15$ GHz, where $Re(Z) \approx 18 \Omega$, while in the bipolar configuration the peak increases, reaching $Re(Z) \approx 170 \Omega$ at $f \approx 1.65$ GHz. For the bipolar configuration, the real part of the input impedance is higher with respect to that of the monopolar discharge, and the half nagoya coupler in all the frequency range. This is well explained when considering the presence of a small gap between the 2 discharges of which the bipolar plasma antenna is comprised of. In the gap the conductivity is lower with respect to that of plasma, resulting in an enhancement of the real part of the input impedance. It is worth to be noticed that the imaginary part of the input impedance shows an oscillation in correspondence of the peak in the real part of the input impedance for both the configuration considered. This behavior in the monopolar plasma antenna is less evident with respect to the bipolar. The maximum gain of the bipolar configuration is higher with respect to the gain of the monopolar configuration for frequencies higher than $f > 1.4$ GHz, and lower than < 1.1 GHz.

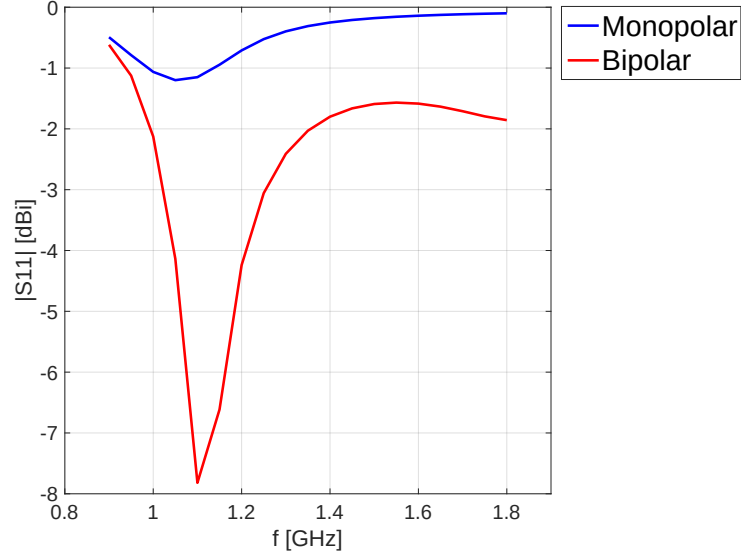


(a)

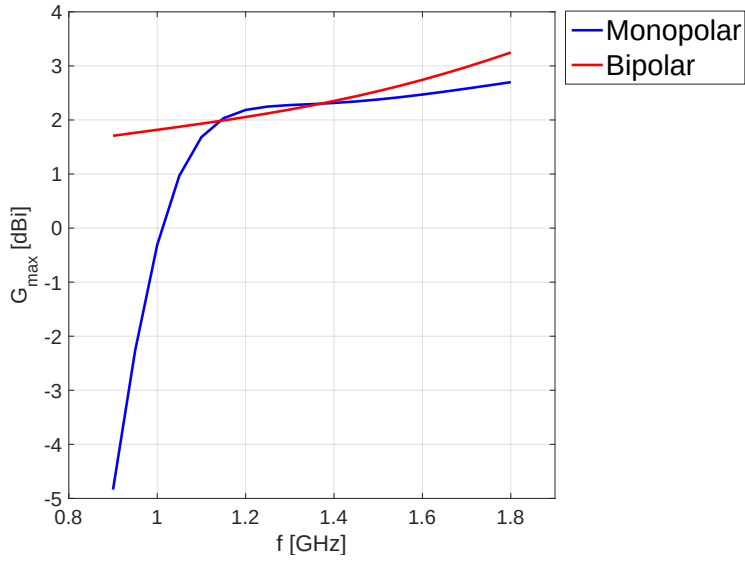


(b)

Figure 5.6: Real (a), and imaginary (b) parts of the input impedance as a function of frequency for a monopolar plasma dipole, compared to a bipolar plasma dipole. Both the plasma dipoles have diameter $\Phi = 10$ mm, and total length $L = 100$ mm, but the bipolar plasma dipole is comprised of two argon discharges with $L_{cols} = 47$ mm, and placed at a distance $D = 6$ mm. The considered plasma parameters are: $n_0 = 7 \cdot 10^{18} \text{ m}^{-3}$, $p_n = 0.4$ mbar, and $T_e = 3$ eV.



(a)



(b)

Figure 5.7: (a) Magnitude of the reflection coefficient, and (b) maximum gain as a function of frequency for a monopolar plasma dipole, compared to a bipolar plasma dipole. Both the plasma dipoles have diameter $\Phi = 10$ mm, and total length $L = 100$ mm, but the bipolar plasma dipole is comprised of two argon discharges with $L_{cols} = 47$ mm, and placed at a distance $D = 6$ mm. The considered plasma parameters are: $n_0 = 7 \cdot 10^{18} \text{ m}^{-3}$, $p_n = 0.4$ mbar, and $T_e = 3$ eV.

5.1.3 Effect of the plasma parameters

We already assessed the effect of the plasma parameters on the polar gain pattern in the previous chapter. We then explored the influence of the neutral pressure p_n , and of the plasma density n_0 onto the frequency behavior of the radiating plasma antennas shown in Figs. 5.5 when driven by the coupler in Fig. 5.4, taking into account the results for the plasma source realization, and testing. We considered an argon plasma having 2 different values of neutral pressure, $p_n = 0.4$ mbar, and $p_n = 1$ mbar, and 2 different plasma densities, $n_0 = 3 \cdot 10^{18} \text{ m}^{-3}$, and $n_0 = 7 \cdot 10^{18} \text{ m}^{-3}$, obtaining the 4-element test matrix shown in Table 5.3. These values come from the source design, and testing as explained in the previous chapter. Figs. 5.8, and 5.9 show the results for the monopolar plasma antenna having a diameter $\Phi = 10$ mm, and total length $L = 100$ mm, and pictured in Fig. 5.5(a).

$n_0 = 3 \cdot 10^{18} \text{ m}^{-3}, p_n = 0.4 \text{ mbar}$		$n_0 = 7 \cdot 10^{18} \text{ m}^{-3}, p_n = 0.4 \text{ mbar}$
$n_0 = 3 \cdot 10^{18} \text{ m}^{-3}, p_n = 1 \text{ mbar}$		$n_0 = 7 \cdot 10^{18} \text{ m}^{-3}, p_n = 1 \text{ mbar}$

Table 5.3: The plasma-parameter test matrix chosen for the ADAMANT simulations of the plasma antennas shown in Figs. 5.5 when driven by the coupler in Fig. 5.4.

From Fig. 5.8(a), it is evident that the trend of $Re(Z)$ is more affected by the plasma density than the neutral pressure. A lower density corresponds to a higher input impedance, and the already noticed peak enhances with respect to higher densities. On the other hand, the neutral pressure affects the magnitude of the real part of the input impedance, that reaches higher values when the discharge is driven at higher pressure. This behavior is in accordance with the plasma conductivity, that is lower for lower densities, and higher pressures. The effect of the neutral pressure, and plasma density on $Im(Z)$ is less evident with respect to that on $Re(Z)$. Looking closely at Fig. 5.8(b), one can notice that the aforementioned oscillation for frequency lower than $f < 1.1$ GHz enhances for the lowest tested value of $n_0 = 3 \cdot 10^{18} \text{ m}^{-3}$. The variation in the oscillation is responsible of the slight shift of the resonance frequency, that can be noticed also in the reflection coefficient. The results for G_{max} are in accordance with those shown in terms of polar gain pattern in the previous section. Similar trend were found also for the bipolar configurations, whose results are omitted for the sake of brevity.

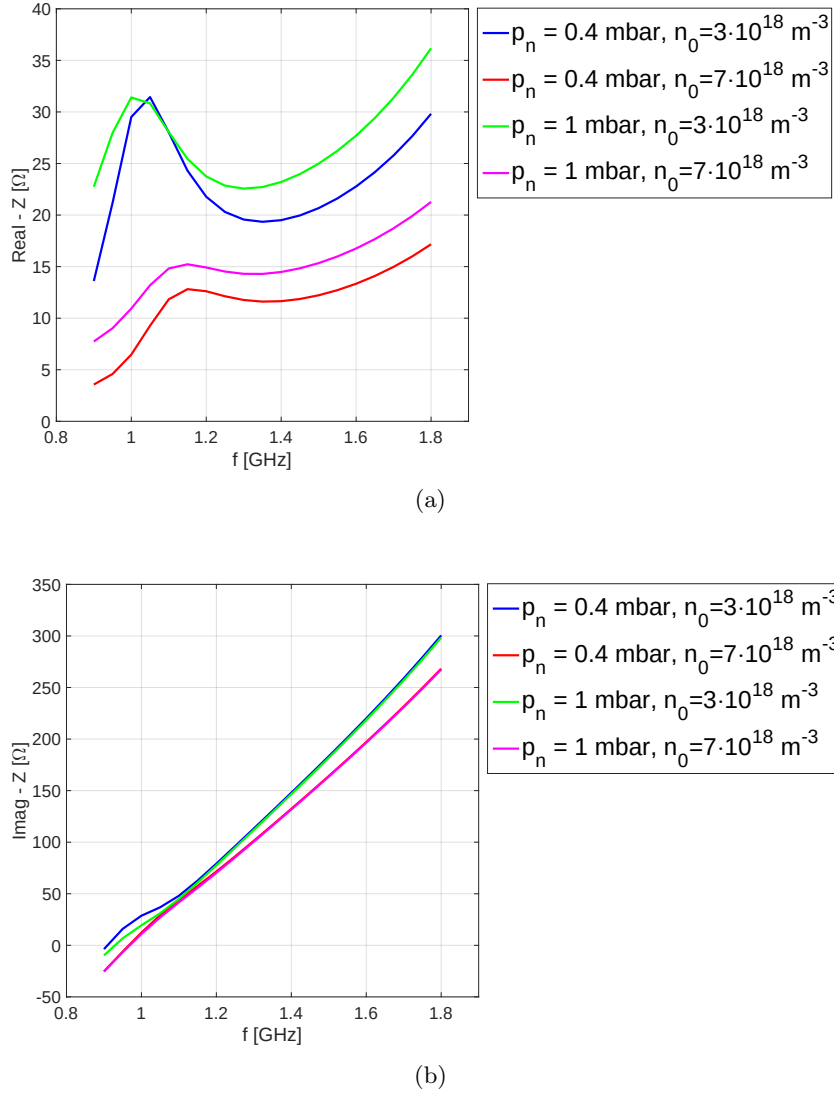


Figure 5.8: (a) Real, and (b) imaginary parts of the input impedance as a function of frequency for the monopolar plasma dipole having diameter $\Phi = 10$ mm, and length $L = 100$ mm. The considered plasma column is an argon discharge having $T_e = 3$ eV.

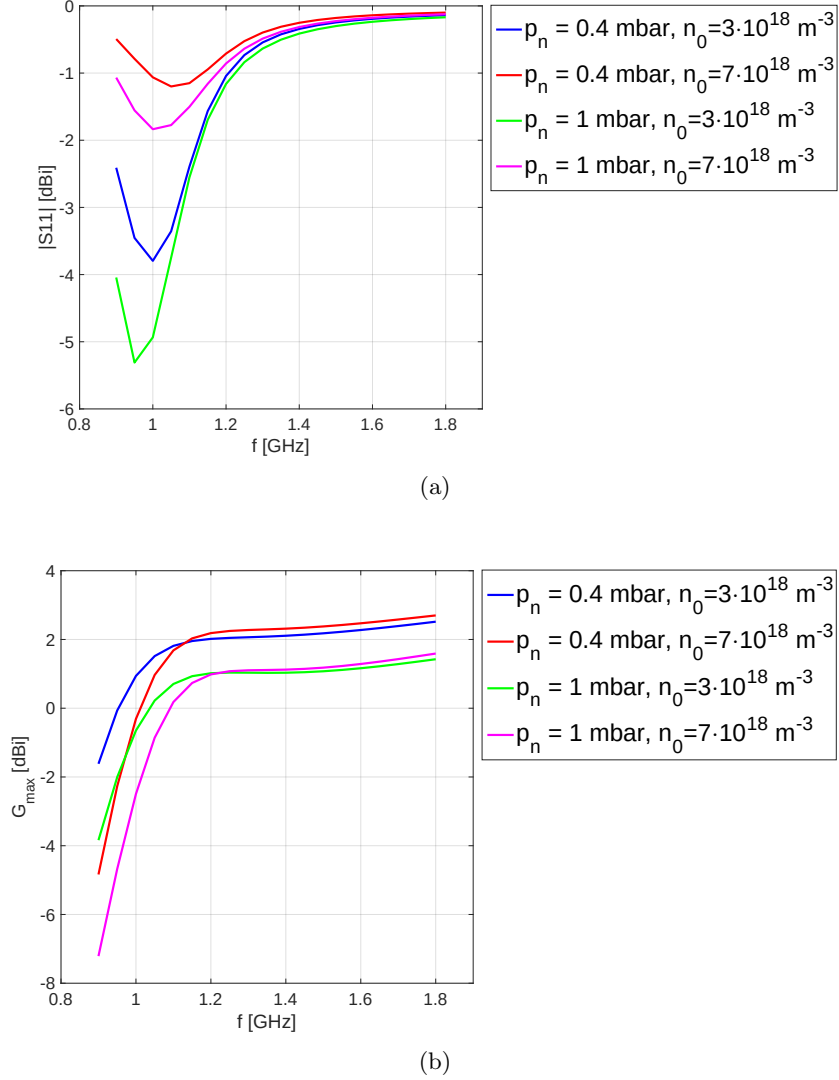


Figure 5.9: (a) Magnitude of the reflection coefficient, (b) and maximum gain as a function of frequency for the monopolar plasma dipole having diameter $\Phi = 10$ mm, and length $L = 100$ mm. The considered plasma column is an argon discharge having $T_e = 3$ eV.

5.1.4 Effect of the source geometry

Since we realized and tested several source-geometrical configurations, we wanted to evaluate the effect of the source geometry in the electrical behavior of the plasma dipole. In this section we will take into account a variation in length of the bipolar plasma dipole, considering both a variation of the plasma-column length, and of the mutual distance at which they are placed. Figs. 5.10, and 5.11 show the results for different plasma column length of the bipolar plasma dipole with an argon plasma having $n_0 = 3 \cdot 10^{18} \text{ m}^{-3}$, $p_n = 1$ mbar, and $T_e = 3$ eV. The plasma columns are placed at a fixed mutual distance of

$D = 6$ mm. As can be noticed from Figs. 5.10, the peak in $Re(Z)$, and the correspondent oscillation in $Im(Z)$ move towards lower frequency as the column length is increased. This is in accordance with the behavior of a metal half-wavelength dipole, whose length L and free-space wavelength at the resonance frequency λ_0 are related by $L = \lambda_0/2$.

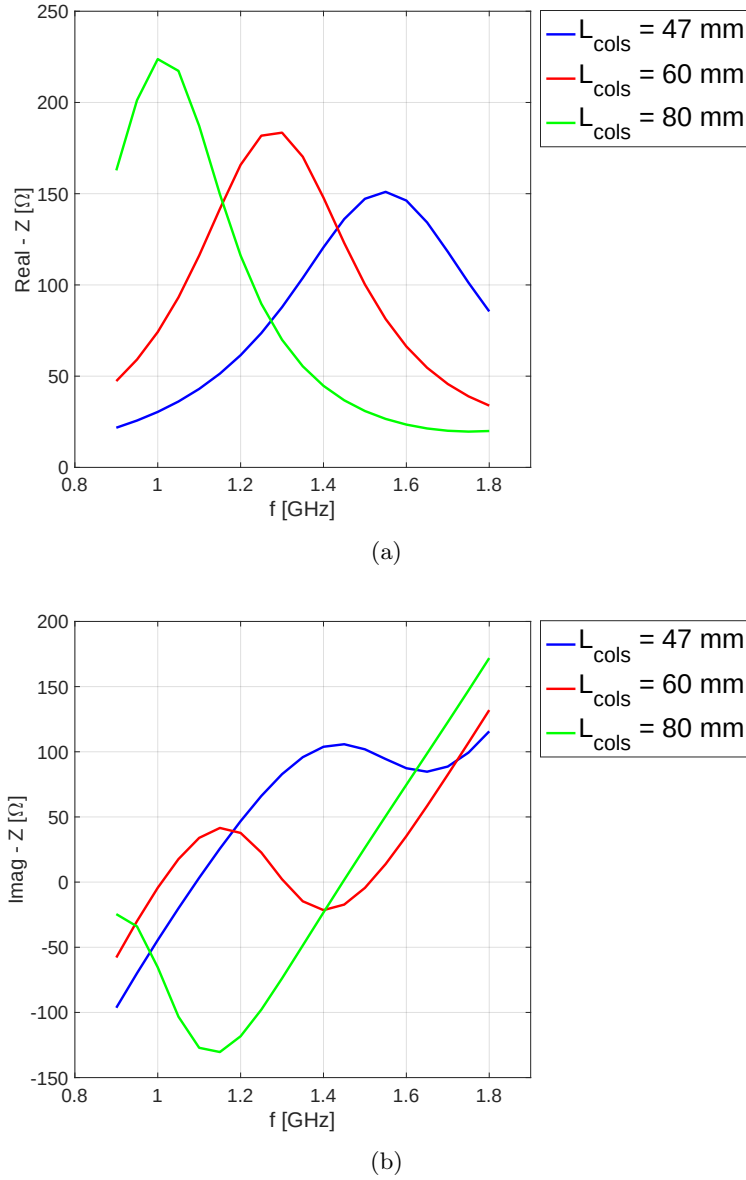
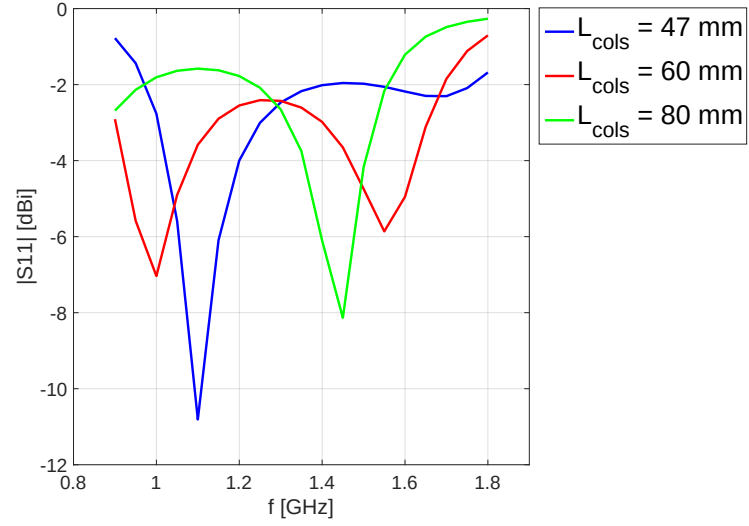
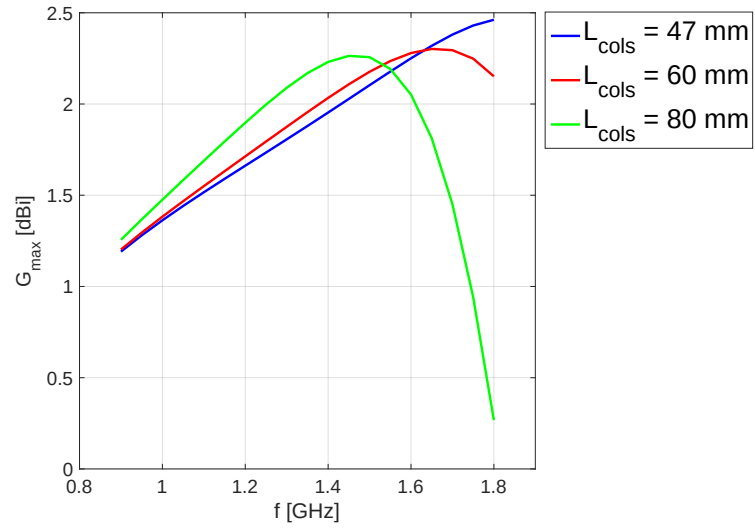


Figure 5.10: (a) Real, and (b) imaginary parts of the input impedance as a function of frequency of the bipolar plasma dipole for different plasma column length. The argon discharges have diameter $\Phi = 10$ mm, and are placed at a distance $D = 6$ mm. The considered plasma parameters are: $n_0 = 3 \cdot 10^{18} \text{ m}^{-3}$, $p_n = 1$ mbar, and $T_e = 3$ eV.



(a)



(b)

Figure 5.11: (a) Magnitude of the reflection coefficient, (b) and maximum gain as a function of frequency of the bipolar plasma dipole for different plasma column length. The argon discharges have diameter $\Phi = 10$ mm, and are placed at a distance $D = 6$ mm. The considered plasma parameters are: $n_0 = 3 \cdot 10^{18} \text{ m}^{-3}$, $p_n = 1$ mbar, and $T_e = 3$ eV.

To evaluate the effect of the mutual distance between the plasma columns onto the radiation, and electrical properties of the bipolar plasma dipole, we varied the distance between the two plasma columns of which the bipolar plasma dipole is comprised of. We considered two plasma columns having diameter $\Phi = 10$ mm, and length $L = 47$ mm placed at 3 different distances, namely $D_1 = 3$ mm, $D_2 = 6$ mm, and $D_3 = 12$ mm, and

we simulated them for the input impedance, the reflection coefficient, and the antenna gain. The results for an argon plasma with $n_0 = 3 \cdot 10^{18} \text{ m}^{-3}$, $p_n = 1 \text{ mbar}$, and $T_e = 3 \text{ eV}$ are shown in Figs. 5.12, and 5.13.

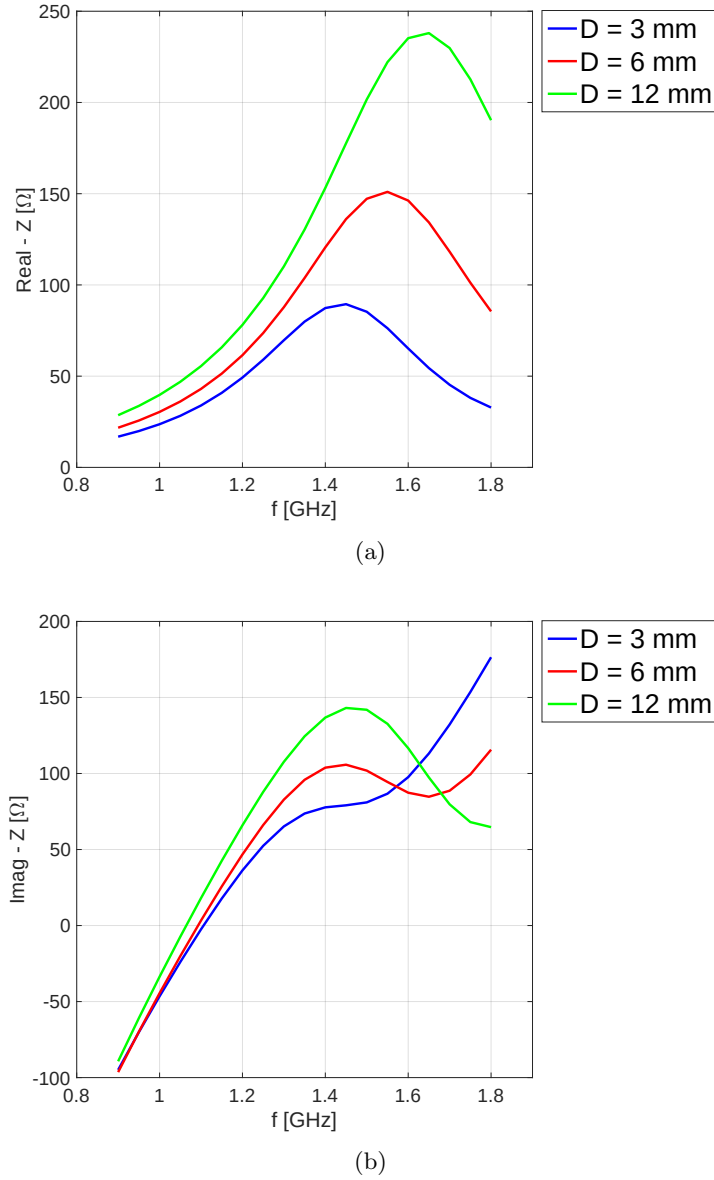
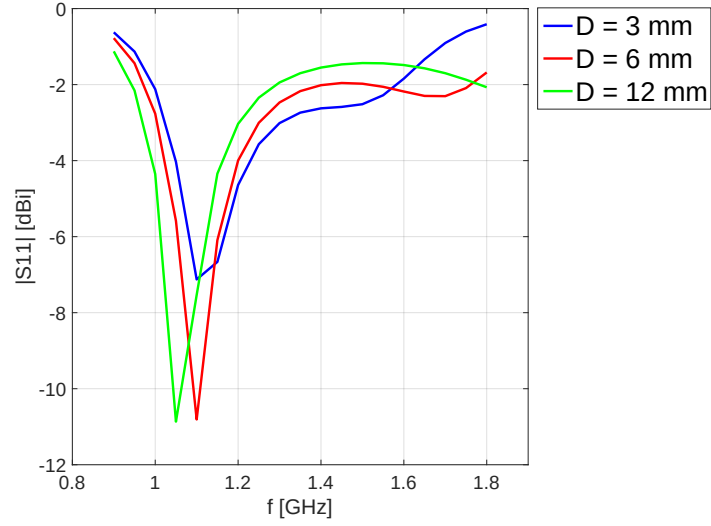
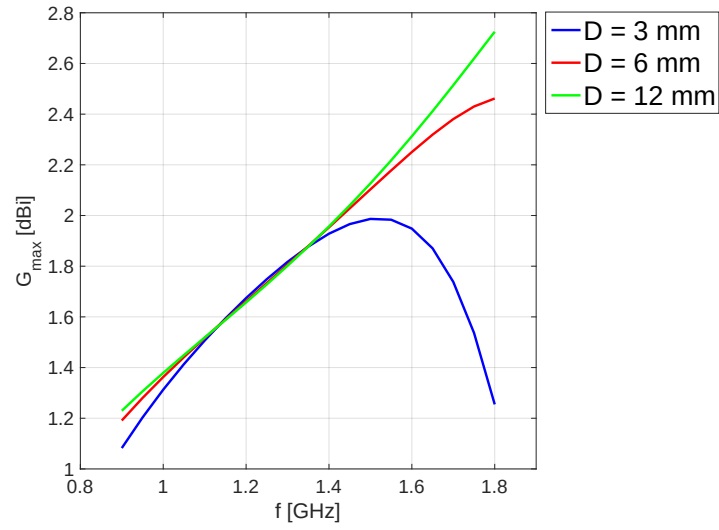


Figure 5.12: (a) Real, and (b) imaginary parts of the input impedance as a function of frequency of the bipolar plasma dipole for different values of distance D between the two plasma discharges. The discharges have: $\Phi = 10 \text{ mm}$, and length $L_{cols} = 47 \text{ mm}$ each. The argon plasma parameters are: $n_0 = 3 \cdot 10^{18} \text{ m}^{-3}$, $p_n = 1 \text{ mbar}$, and $T_e = 3 \text{ eV}$.



(a)



(b)

Figure 5.13: (a) Magnitude of the reflection coefficient, (b) and maximum gain as a function of frequency of the bipolar plasma dipole for different values of distance D between the two plasma discharges. The discharges have: $\Phi = 10$ mm, and length $L_{cols} = 47$ mm each. The argon plasma parameters are: $n_0 = 3 \cdot 10^{18} \text{ m}^{-3}$, $p_n = 1$ mbar, and $T_e = 3$ eV.

As can be seen from Fig. 5.12, the real part of the input impedance shows a similar trend for all the configurations tested, but the absolute value of $Re(Z)$ increases as the distance grows. The already noticed peak is enhanced, and it moves towards higher frequencies as the distance is increased, reaching $Re(Z) \approx 238 \Omega$ at $f \approx 1.65$ GHz for $D_3 = 12$ mm. The imaginary part of the input impedance shows an oscillation with period, and amplitude lower for lower distances. For what concerns the maximum value of the gain function, in the case of $D_1 = 3$ mm it is evident a peak at $f = 1.5$ GHz, where $G_{max} \approx 2$ dBi. As the distance is increased, the gain peak moves towards frequencies higher than the tested frequencies. This behavior can be noticed also for higher densities, and lower pressures once considered the antenna parameters dependence on the plasma status.

Finally, we evaluated the effect of the diameter of the source in the electrical, and antenna parameters. We simulated several monopolar plasma dipoles having length $L = 100$ mm, but different radii, namely $R = 5, 7$, and 9 mm. The plasma columns are driven by the same coupler that was chosen in order to fit every considered geometry. The coupler is a half-nagoya having a diameter $\Phi = 28$ mm, a total length $L_{tot} = 30$ mm, and a loop width $S_{loop} = 12$ mm. The results for radii $R = 5, 7$, and 9 mm with an argon plasma having $n_0 = 3 \cdot 10^{18} \text{ m}^{-3}$, $p_n = 1$ mbar, and $T_e = 3$ eV are pictured in Figs. 5.14, and 5.15.

The plasma column radius affects the imaginary part of the input impedance, moving the resonance frequency towards lower frequencies while the radius is increased. On the other hand, the real part of the input impedance grows when the radius is decreased. Note that maximum gain value decreases as the radius is increased, and this is particularly evident for the highest tested value $R = 9$ mm.

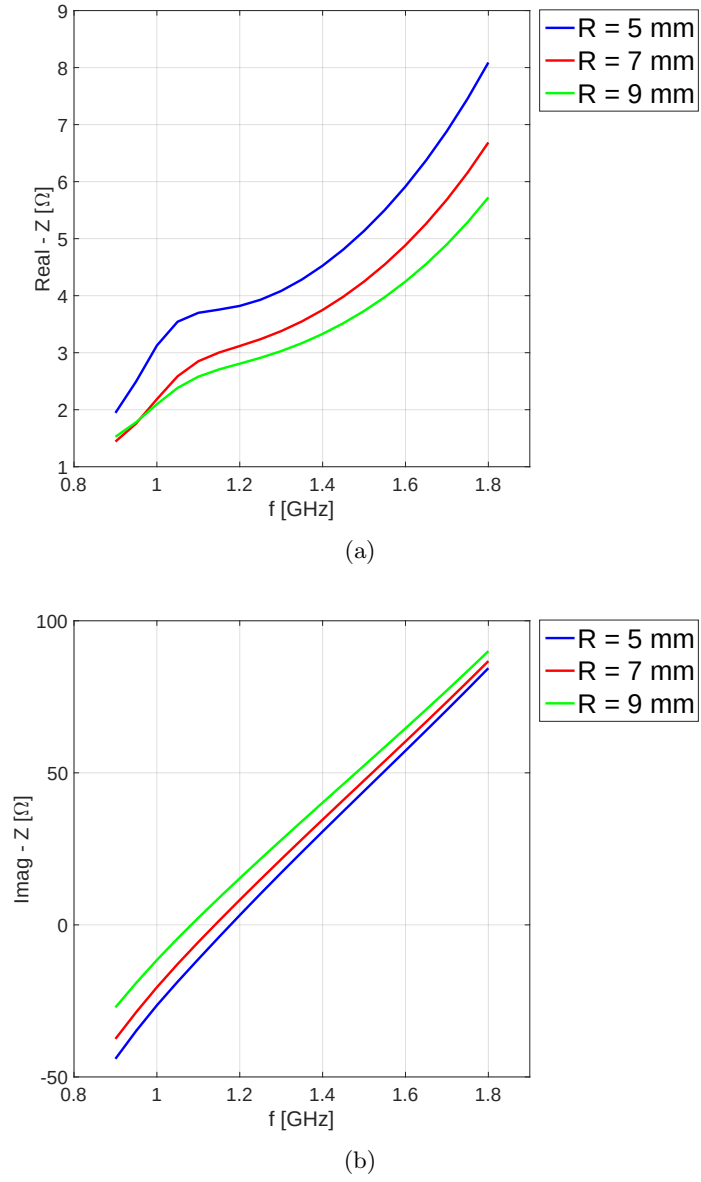


Figure 5.14: (a) Real, and (b) imaginary parts of the input impedance as a function of frequency for different radius of the monopolar plasma dipole having length $L = 100$ mm. The considered plasma column is an argon discharge with $n_0 = 3 \cdot 10^{18} \text{ m}^{-3}$, $p_n = 1$ mbar, and $T_e = 3$ eV.

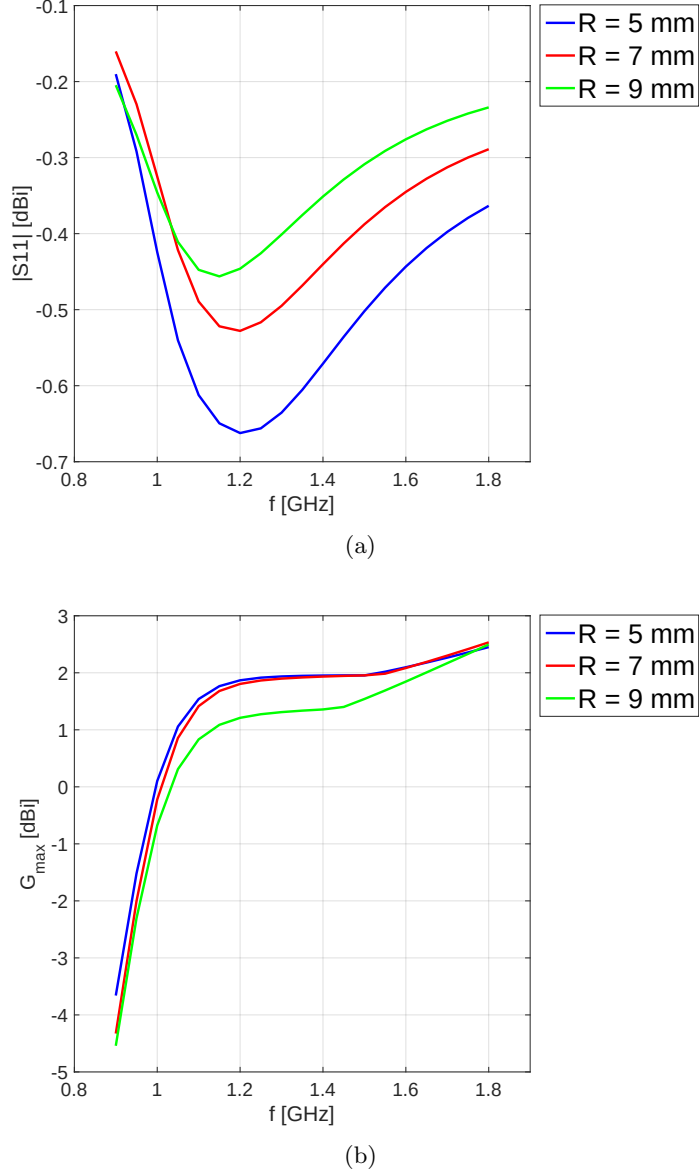


Figure 5.15: (a) Magnitude of the reflection coefficient, (b) and maximum gain as a function of frequency for different radius of the monopolar plasma dipole having length $L = 100$ mm. The considered plasma column is an argon discharge with $n_0 = 3 \cdot 10^{18} \text{ m}^{-3}$, $p_n = 1$ mbar, and $T_e = 3$ eV.

5.1.5 Effect of the gas type

We already established that the gas type chosen for the discharge can affect the gain values of a plasma dipole in the previous chapter, but we still need to evaluate the effect onto the electrical behavior as a function of frequency. To this purpose, we considered

the plasma dipoles when filled with different gas type, namely argon, xenon, and krypton. The results for a bipolar plasma dipole comprised of 2 columns with diameter $\Phi = 10$ mm, length $L_{cols} = 60$ mm, and placed at a distance $D = 6$ mm for different discharge gas are shown in Figs. 5.16, and 5.17. The considered plasma parameters are: $n_0 = 3 \cdot 10^{18} \text{ m}^{-3}$, $p_n = 1$ mbar, $T_e = 3$ eV.

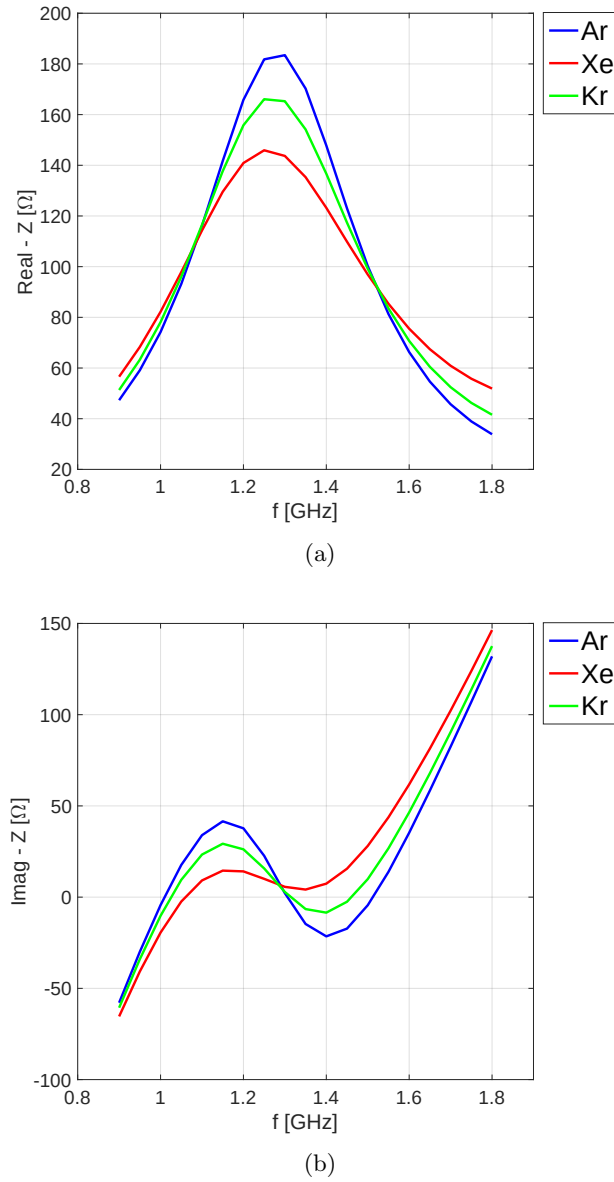


Figure 5.16: (a) Real, and (b) imaginary parts of the input impedance as a function of frequency for several ionized gas in the bipolar plasma dipole configuration. The bipolar dipole has $\Phi = 10$ mm, $L_{cols} = 60$ mm, and $D = 6$ mm. The plasma has: $n_0 = 3 \cdot 10^{18} \text{ m}^{-3}$, $p_n = 1$ mbar, $T_e = 3$ eV.

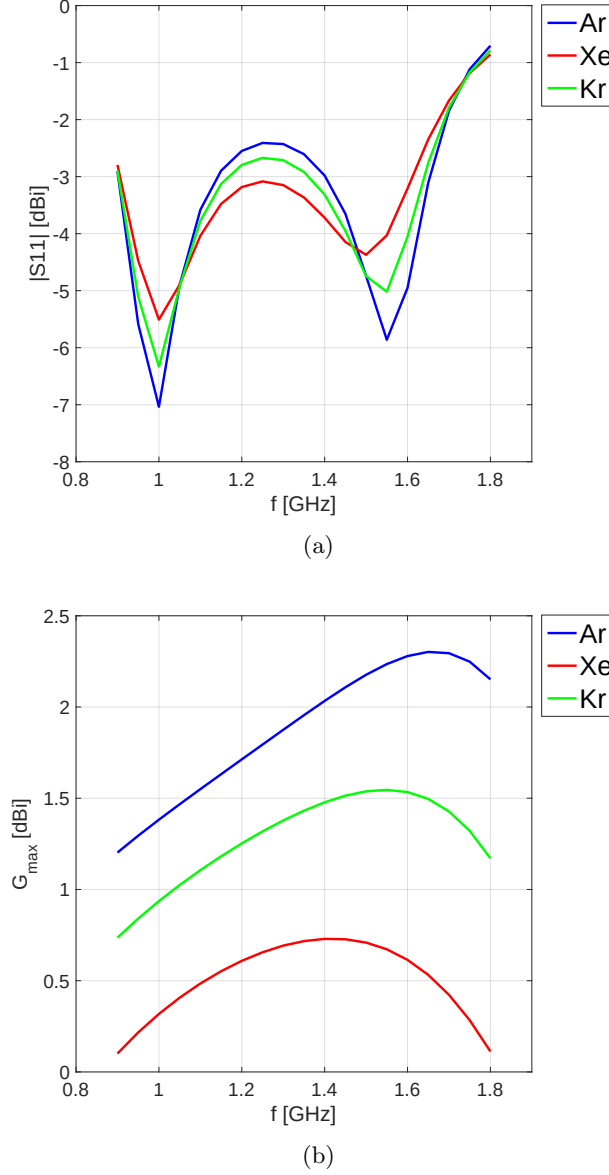


Figure 5.17: (a) Magnitude of the reflection coefficient, (b) and maximum gain as a function of frequency for several ionized gas in the bipolar plasma dipole configuration. The bipolar dipole has $\Phi = 10$ mm, $L_{cols} = 60$ mm, and $D = 6$ mm. The plasma has: $n_0 = 3 \cdot 10^{18} \text{ m}^{-3}$, $p_n = 1$ mbar, $T_e = 3$ eV.

The frequency behavior is affected by the gas type used for the plasma antenna. The argon plasma leads to higher $Re(Z)$, and higher gain values with respect to the other gasses considered. Note that the imaginary part of the input impedance, and thus the resonance frequencies, depends on the gas type. In the case of the argon, and the krypton discharges, $Im(Z) = 0$ at 3 frequencies, while in the case of xenon gas only at one frequency.

5.2 Plasma dipole realization

We wanted to realize a plasma dipole antenna comprised of (i) a plasma discharge, and the plasma generation system, and (ii) a coupler, and we wanted to measure the antenna gain pattern, and to compare it to the simulation.

From the numerical design, we identified the neutral pressure, and the plasma density as the main parameters driving the antenna performances. Besides, a bipolar plasma antenna comprised of 2 discharges leads to higher antenna performances. On the other hand, the source design showed that the performance of the source in terms of plasma density, and plasma density uniformity are strongly related to the pressure, and the diameter of the vessel: to higher pressures, and lower diameters, corresponds a higher, and more uniform plasma density (see Section 4.3). As a compromise, we relied onto the discharge featuring the highest plasma density among those realized, and tested. Moreover, we wanted to compare the experimental results to the numerical ones, in order to validate the model adopted for this work. Due to difficulties in the estimation of the actual plasma density profile to be implemented in the simulation, we discarded the sources featuring highly not-uniform plasma density within the discharges. Similar considerations were done about the bipolar configuration: the source testing showed that it is impossible to obtain the same plasma density onto both the discharges, leading to a further not-uniformity, and uncertainty.

For these reasons, we relied onto a plasma discharge with an inner diameter $\Phi = 3$ mm, a length $L = 130$ mm, filled with argon at $p_n = 10$ mbar to realize the GPA. At this pressure losses are severe, but a plasma density higher than in other cases can be reached by means of the RF generation system. Moreover, the plasma source features a more uniform plasma density with respect to lower pressure sources.

The plasma was ignited, and sustained by means of the RF-generation system, coupling a RF power of $P \approx 100$ W into the plasma discharge, that corresponds to an average density value of roughly $n_0 \approx 4 \cdot 10^{19} \text{ m}^{-3}$.

The RF-generation system is comprised of (i) the PTFE support with the RF-external electrodes of Fig 4.5, (ii) the HV transformer, (iii) the current/voltage sensor, (iv) the RF generator, amplifier, and the oscilloscope to feed the plasma, and (v) cables. To avoid power losses, the HV transformer, and V/I sensor had to be placed as close as possible to the plasma discharge. On the other hand, the presence of metal parts would produce uncontrollable interference with the field radiated by the plasma discharge. To cope with these issues, we enclosed the HV transformer, and the V/I probe in a grounded metal box, while the PTFE support was mounted directly on top of the box, as shown in Fig. 5.18. This allowed us to simplify the geometry of the metal parts, and to include them in the simulations to better reproduce the experimental setup.

From the numerical analysis, we identified the coupler of Fig. 5.4. Due to the presence of the central ring-shaped electrode, we had to modify the coupler geometry. The coupler loops still have a diameter of 14 mm and width of 5 mm, but they are connected by means of two vertical strips with length of 20 mm, and an horizontal strip of 40 mm to make room for the central ring-shaped electrode; the strips have width of 1 mm. To collect the signal coming from the coupler, we used a spectrum analyzer connected by means of a coaxial cable to the coupler. Being coupled to the plasma discharge, the coupler collects power at

2 separate frequencies: (i) the plasma generation frequency, and (ii) the signal frequency. Moreover, the coupler collects a balanced signal, while the spectrum analyzer requires it to be unbalanced. We then included in the design a circuit board, hereinafter referred to as *board*. The board features a balun, and a BP filter. The balun converts the balanced signal at the operative frequency coming from the coupler into an unbalanced one to meet the spectrum analyzer input requirements. The BP filter protects the spectrum analyzer from the RF signal used to ignite, and sustain the discharge. The BP filter lowers signals with frequency $f < 800$ MHz by 50 dBm. The coupler horizontal strips were soldered directly onto the board, as shown in the inset of Fig. 5.18.

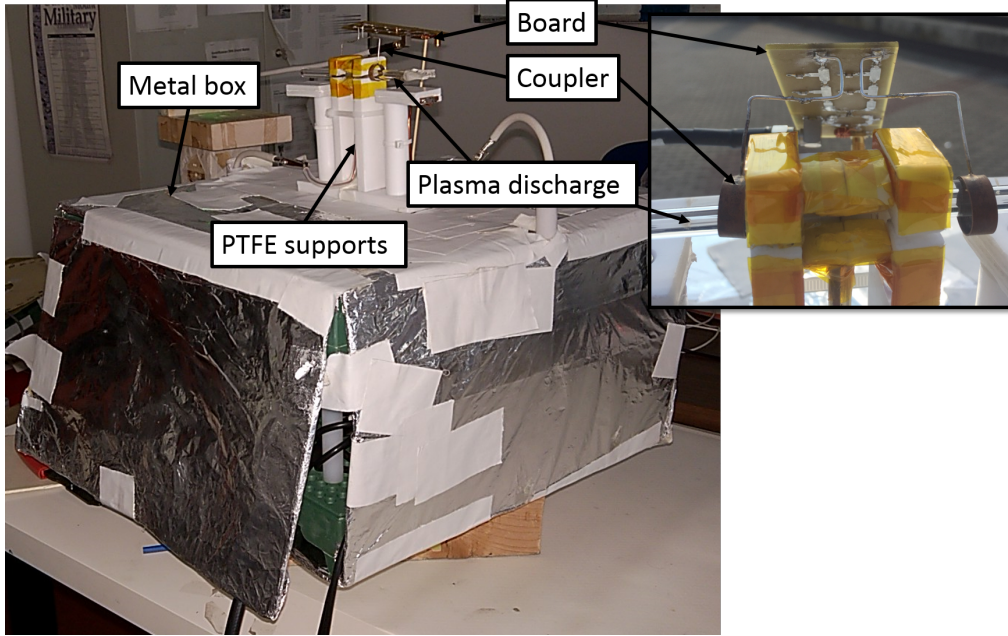


Figure 5.18: The plasma dipole comprised of: (i) the plasma discharge, (ii) the coupler, (iii) the grounded metal box. The inset shows a detail of the coupler, and the board.

5.3 Plasma dipole testing

We characterized the plasma dipole in terms of realized gain (i.e. the antenna gain reduced by the losses due to impedance mismatching), and gain pattern, and we compared the results to the numerical simulation. We measured the antenna gain pattern of the plasma dipole in an open environment (i.e. not anechoic). For site, and procedure validation see Appendix A.

To measure the radiation pattern of the plasma dipole, the latter was used as receiver (Rx) antenna¹, and a well-known log-periodic RKB LOG-HALLO antenna was used as a

¹It is worth recalling that metal, and plasma antennas have the reciprocity property. Reciprocity states that the receive and transmit properties of an antenna are identical. Hence, plasma antennas do not have distinct transmit and receive radiation patterns.

transmitter (Tx). We placed the plasma dipole on a revolving plate, under which a fixed plate with a protractor was mounted. We connected the board to a HP 8920B spectrum analyzer through 4 m of CO-100AF coaxial cable (cable losses are nearly 1 dB). The RF power was delivered to the sensor, and HV transformer by means of 5-meter-long cables. To mitigate disturbances coming from cables, instrumentation, and the human operator, we (i) twisted the cables in a single braid that included 2 cables for the voltage and current signals, respectively, the RF-power cable, the receiving-signal cable and the ground cable for the metal box, and (ii) we placed the instrumentation at nearly 3 m from the Antenna Under Test (AUT). The Tx antenna was placed at a distance of 10 m from the AUT. The signal was generated by the HP 8648A signal generator, which was amplified by means of the TAMP-112-2W+ Minicircuits amplifier, and a resulting transmitted power of approximately 21 dBm. The output section of the amplifier was connected to the Tx antenna by means of nearly 5 m of CO-100AF coaxial cable (1.4 dB of cable losses). Both the Tx, and the AUT were placed at a height $h \approx 1.85$ m from the ground.

Preliminary measurements of the normalized gain pattern on the E-plane of the plasma dipole are shown in Fig. 5.19. In this plot, the plasma-dipole axis is aligned along the $(-90^\circ, +90^\circ)$ direction. The Tx antenna works at 880 MHz with a gain of 9 dBi.

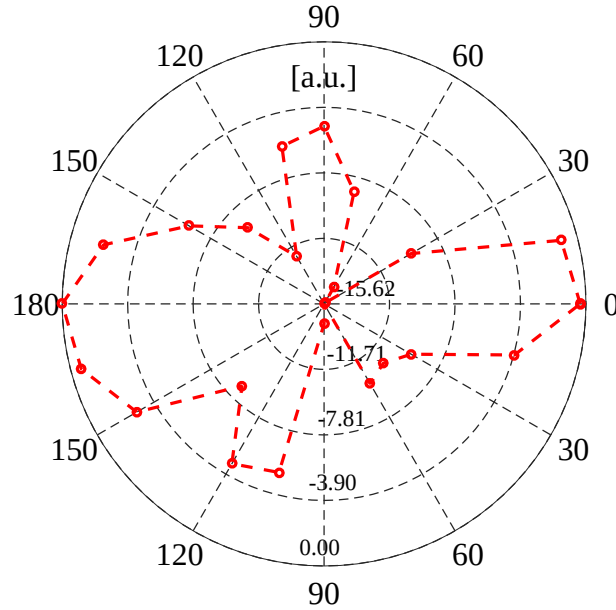


Figure 5.19: The normalized gain pattern of the plasma dipole at a frequency equal to 880 MHz on the E-plane of a conventional dipole. The maximum gain value is $G_{max} \approx -5$ dBi.

Fig. 5.20 shows the simulation result for the normalized gain pattern onto the the E-plane. In the simulation we took into consideration (i) the metal box, and the RF electrodes, (ii) the actual plasma-discharge radius experimentally estimated, (iii) the actual

coupler geometry. Besides, we estimated the plasma density axial profile, and we calculated the average plasma density that was used as uniform density value in the simulation. Since we didn't include in the design any impedance matching circuit, the simulated gain was multiplied by $(1 - |S_{11}|^2)$ to take into account the reflection losses (realized gain).

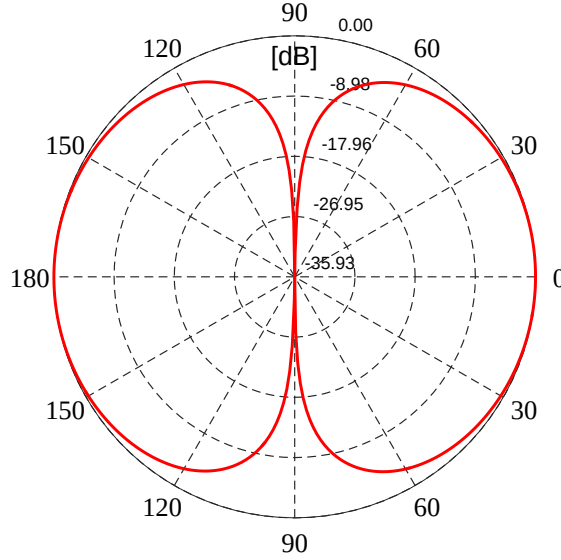


Figure 5.20: The results of the simulation for normalized gain pattern of the plasma dipole at a frequency equal to 880 MHz on the E-plane of a conventional dipole.

The results for the gain shape are in good accordance with the simulation results, when the axis scale are considered. The experimental gain pattern features 2 main lobes at 0° , and 180° , as expected, but 2 side lobes that were not predicted by the simulation results. The side lobe level was estimated to be ≈ -4 dB. Besides, the experimental gain pattern is not symmetric. These discrepancies may be due to the presence of the board, and the PTFE supports that were not included in the simulation. We then measured the maximum gain on the E-plane in a range around the working frequency. The results for the maximum gain onto the E-plane as a function of frequency in the range $860 \text{ MHz} \leq f \leq 920 \text{ MHz}$ for the experimental plasma dipole, compared to the results coming from simulations are shown in Fig. 5.21. The results for the maximum gain values are in good accordance with the simulations. Discrepancies may be due to the same problems affecting the radiation pattern, such as the presence of the PTFE supports, and the board that couldn't be included in the simulation.

It is worth to be noticed that the gain value reached by the plasma dipole is low compared to a conventional dipole antenna in the same conditions (i.e. above a metal box). A metal dipole placed at the same distance from a metal box with same dimensions of the one we used, features a maximum gain on the same plane $G_{max} \approx -0.32$ dBi. This value was estimated by means of numerical simulation, and it is well justified considering that the metal box tends to steer the gain pattern towards the H-plane. The plasma source used for the plasma dipole suffers from a high pressure level, and low plasma density at

this pressure level. This led to a plasma discharge with low conductance, and high losses that can't efficiently radiate. At the state of the art, it wasn't possible to couple more power to the plasma discharge to reach a higher density value, or a similar density in a lower pressure vessel. Though, the accordance between experiment, and simulations was verified, and better performing configurations were numerically simulated. A further optimization of the plasma source is required.

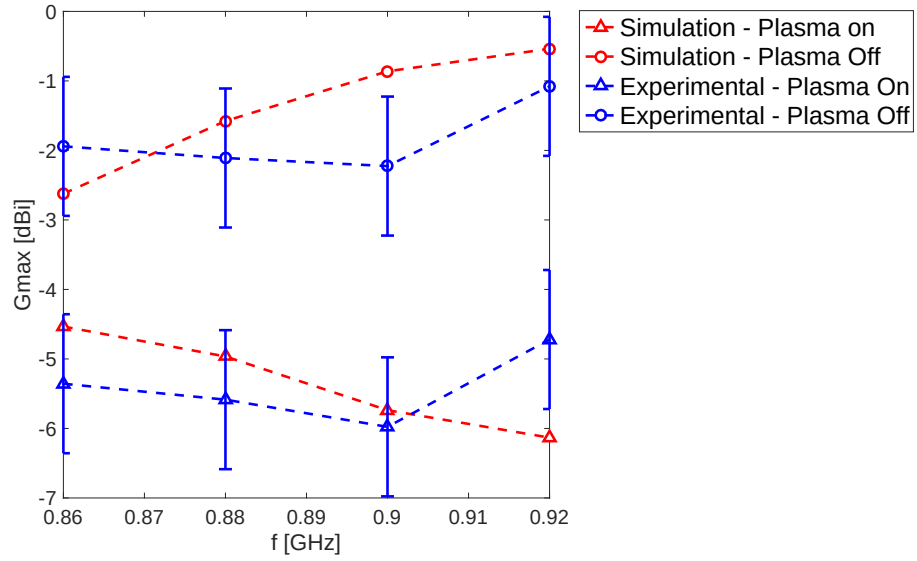


Figure 5.21: The maximum realized gain as a function of frequency for the plasma dipole when the plasma is turned off, and on compared to the simulation results. The simulated plasma dipole has a diameter $\Phi = 2.8$ mm, and a length $L = 130$ mm. We considered a uniform argon plasma having $n_0 = 4.09 \cdot 10^{19} \text{ m}^{-3}$, $p_n = 10$ mbar, and $T_e = 3$ eV.

Chapter 6

Conclusions

In this work, we:

- presented a numerical tool aimed to study the equilibrium conditions (i.e. absorbed power, reached plasma density) in Helicon sources, and in sources for GPAs;
- assessed the radiation properties of a GPA when realistic excitation circuits, and plasma parameters are taken into account;
- realized, and tested several plasma sources to be exploited as a GPA;
- realized, and tested a plasma dipole working at frequencies higher than $f \geq 800$ MHz.

The numerical tool couples the EM solution with the plasma transport. The tool is based on an iterative loop between ADAMANT [42], a full-wave tool able to solve the EM problem self-consistently for arbitrary geometries of both plasma discharge, and metal circuit, and the Global Model [43], a 0-D fluid solver for the plasma transport within the source. This tool gives insights about the equilibrium conditions of a plasma source driven by an RF antenna, and it will be helpful in the design, and optimization of plasma sources that could be exploited either in an HPT, or a GPA.

We then took into consideration GPAs in the effort to design, and realize a prototype of GPA working in the GHz range of frequency. Since the physics governing a GPA wasn't clear, we began our design work from the physical assessment onto the radiative, and electrical behavior of the simplest plasma antenna configurations. To this purpose, we considered a *plasma dipole*, and a *bipolar plasma dipole*, respectively comprised of a plasma column, and a half-nagoya coupler, and 2 plasma columns, driven by means of 2 plate electrodes connected by a strip. We simulated them for the input impedance, and the electric displacement field within the plasma discharges. We numerically verified that a plasma column can feature the same current distribution of a conventional metal dipole, and thus that it can radiate EM waves in a similar fashion. We considered the *plasma dipole* since easier to realize, and we simulated it for the gain pattern on varying the plasma density, the magnetostatic field, the neutral pressure, and the gas type. Thanks to this physical assessment, we found that the plasma density, and the neutral pressure are the main parameters driving the antenna performances.

Starting from the results coming from the physical assessment, and from a preliminary numerical design by means of the Global Model coupled to the genetic algorithm from the optimization tool of Matlab, we designed, and realized several types of plasma sources to be exploited in the plasma dipole, with several gases, background pressure levels, and geometries. Such sources are enclosed in a Pyrex vessel providing the neutral gas, and plasma confinement. This approach allowed us to explore several geometries, pressure levels, and gas mixture without any constraints related to commercially available sources (i.e. commercial fluorescent lamps). We relied onto 2 different plasma generation methods, namely (i) RF power generation with external electrodes, and (ii) HF generation with immersed electrodes based on a commercial HV transformer. We extensively tested the sources for the plasma density, and for the axial density profiles along the plasma discharges by means of a microwave interferometer.

The results obtained were used in an extensive numerical campaign to evaluate the performance of a plasma dipole based on such sources. Unlike many previous studies, our work is based onto custom-made plasma sources, that allowed us to analyze self-consistently the plasma antenna behavior when realistic plasma parameters, and geometries of both plasma, and signal coupler are considered. We considered several configurations of plasma dipole in terms of plasma discharge geometry, plasma parameters, signal coupler geometries, and antenna configurations, and we simulated them for the input impedance, the maximum gain, and the reflection coefficient. The numerical campaign guided the realization of a prototype of plasma dipole comprised of a plasma discharge driven by the RF generation method, and a half-nagoya coupler to inject the signal into the plasma. The plasma dipole realized in this work is one of the very first prototypes of plasma antenna working in the GHz range ever realized, and tested. We relied onto a plasma discharge with an inner diameter $\Phi = 3$ mm, a length $L = 130$ mm, filled with argon at $p_n = 10$ mbar. At this pressure, losses are severe, but a plasma density higher than in other cases can be reached by means of the RF generation system. Moreover, the plasma source features a more uniform plasma density with respect to lower pressure sources, reducing the uncertainties related to the plasma density value to be used in the simulation. The plasma was ignited, and sustained coupling a RF power of $P \approx 100$ W into the plasma discharge, that corresponds to an average density value of roughly $n_0 \approx 4 \cdot 10^{19} \text{ m}^{-3}$.

We extensively tested the plasma dipole for the EM reception in open environment (i.e. not anechoic). We measured the gain pattern on the E-plane at a frequency $f = 880$ MHz, and the maximum gain in a range of frequency, $860 \text{ MHz} \leq f \leq 920 \text{ MHz}$, and we compared the results with the simulations. The experimental results for the gain pattern shape, and values are in good accordance with the simulation results.

The maximum gain value reached by the plasma dipole in this range is lower by the 57% than the gain of a conventional dipole antenna in same working conditions, since the plasma source used for the plasma dipole suffers from a high pressure level (i.e. 10 mbar), and a low plasma density (i.e. $4 \cdot 10^{19} \text{ m}^{-3}$). This led to a plasma discharge with low conductance, and high losses that can't efficiently radiate, and a further optimization of the source is required. At the state of the art, it wasn't possible to couple more power to the plasma discharge to reach a higher density value or to lower the pressure. Regardless the performance of the plasma dipole, the accordance between the simulated, and the experimental gain pattern shape, and values states that the numerical tools used,

developed, and optimized during this work are reliable, and based on realistic models. These tools can be used to further optimize the source, and to identify better performing configurations of plasma parameters, geometries, and couplers. Besides, we experimentally proved the feasibility of GPAs working at frequencies higher than $f \geq 800$ MHz.

Appendix A

Gain pattern measurements: procedure, and site validation

The Friis transmission equation yields:

$$\frac{P_r}{P_t} = G_r G_t \left(\frac{\lambda^2}{4\pi R} \right)^2 \quad (\text{A.1})$$

where P_r , and P_t are respectively the received, and transmitted powers, G_r , and G_t are respectively the Rx antenna, and the Tx antenna gain along the line of sight, λ is the wavelength, and R is the distance between the Tx and Rx antennas. In logarithmic units, and solved for the Rx gain, the [A.1](#) becomes:

$$G_r = P_r - P_t - G_t - 10 \log_{10} \left(\frac{\lambda^2}{4\pi R} \right)^2 \quad (\text{A.2})$$

By means of [A.2](#) it is possible to calculate the gain of the Rx antenna using a well-known antenna as Tx. By rotating the AUT used as Rx antenna, one can calculate the gain at several angular position, thus leading to the gain pattern. Note that [A.1](#) is valid in the far-field region only.

In order to validate both the environment and the procedure, we used 2 well-known RKB LOG-HALLO Antennas, one as Rx antenna, and the other one as Tx antenna. The goal was to retrieve the antenna characteristics (e.g. gain pattern) that can be found in the datasheet shown in Fig. [A.1](#). The maximum gain level, and the normalized gain pattern were retrieved from the data-sheet. Both the antennas have a frequency bandwidth of 790-1800 MHz, a maximum gain of 9 - 11 dBi, and an input impedance of 50 Ω .

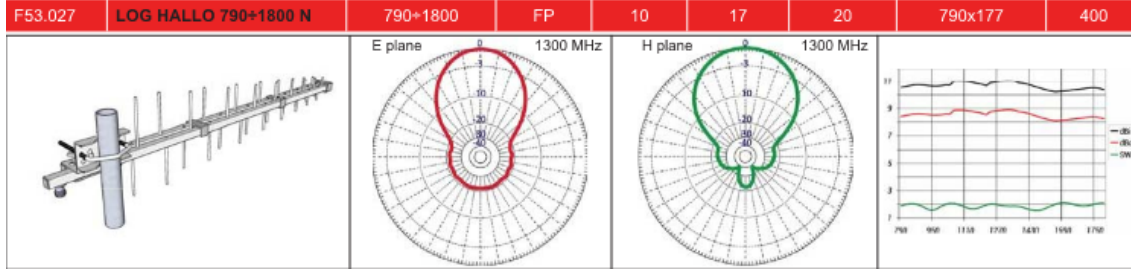


Figure A.1: RKB LOG-HALLO Antenna datasheet.

The Rx antenna (AUT) was mounted onto a rotating plate to sample the radiation pattern. Under the rotating plate, a plate with a protractor is fixed to the antenna-support system. The sampling angle was chosen to be 15° . The Tx antenna was connected to a signal generator HP 8648A through a 3.00 m long RG58 coaxial cable. The transmitted power was set as $P_t = 12$ dBm at a frequency $f = 900$ MHz. The AUT was connected to a spectrum analyzer HP 8920B through 3.00 m of RG316 coaxial cable. Both the antennas were placed at a height of 1.85 m with respect to the ground. We measured the AUT gain with the Tx placed at 3 different distances from the AUT, respectively $R_1 = 14$ m, $R_2 = 10$ m, and $R_3 = 7$ m. Test info are summarized in A.1, while Fig. A.2 shows the results for the normalized-gain pattern of the AUT compared to the nominal one retrieved from the datasheet (power losses due to cable connections have been taken into account).

Parameter	Value
Tx Power Out [dBm]	12
Rx/Tx Gain [dBi]	9-11
Transmission Losses [dB]	1.5
Reception Losses [dB]	2.7
Tx/Rx Distance [m]	7, 10, 14
Frequency [MHz]	900

Table A.1: Validation-test parameters.

The maximum gain values measured for each distance are: 10.8 dBi (R_1), 9.5 dBi (R_2), 8.8 dBi (R_3). The results are in good agreement with the nominal gain pattern. Note that the gap between the experimental, and the nominal data is higher when the gain is expected to be low; this is due to the presence of the spectrum analyzer, and of the human operator. When the AUT was placed at $R_1 = 14$ m, we measured higher gain values with respect to the nominal data. This might be due to unwanted ground reflections, thus following tests were performed at distances $R < 14$ m.

Appendix B

Plasma physics

Plasma can be defined as a *quasineutral gas of charged and neutral particles which exhibits a collective behavior* [52]. In other words, a plasma is an ensemble of ions, and electrons in equal number (quasineutrality), together with neutral particles, whose physic, and motion are mostly governed by electromagnetics, rather than collisions as in a neutral gas (collective behavior). The motion of charged particles generates an electric current that affects and is affected by the fields created by the other charges.

Let's now define some parameters and quantities useful in plasma physics. The specie (ions, electrons, or neutrals) density n_ξ is defined as the number of particle of each specie (indicated by the subscript ξ) per unit of volume, and it is measured in m^{-3} . In plasmas, $n_i \approx n_e$. The kinetic energy of each specie is referred to as specie temperature T_ξ , and it is expressed in eV. A plasma is defined *cold* if $T_e \gg T_i$, where the subscripts e , and i denote respectively electrons, and ions. The specie thermal velocity is given by $v_{th,\xi} = (2T_\xi/m_\xi)^{1/2}$. In a cold plasma, the thermal motion of ions can be ignored.

The ionization degree α is defined as

$$\alpha = \frac{n_i}{n_i + n_0} \quad (\text{B.1})$$

where n_i is the ion density, and n_0 is the density of neutrals. A plasma is considered *weakly ionized* when $\alpha \leq 10^{-6}$, and *fully ionized* if $\alpha = 1$. For what this work is concerned, we consider a cold, and weakly ionized plasma. In a weakly ionized plasma, the fraction of ionized particles is so small compared to the neutral density, that the latter can be considered equal to the density before the ionization process.

A weakly ionized cold plasma can be represented by means of the cold fluid model [53]. In the presence of a magnetic field $\mathbf{B}_0$ aligned along the $\hat{\mathbf{z}}$ direction, the plasma permittivity relative to free space ε_{rk} takes the form

$$\varepsilon_r = \begin{bmatrix} S & jD & 0 \\ -jD & S & 0 \\ 0 & 0 & P \end{bmatrix}, \quad (\text{B.2})$$

where S , D , and P are the Stix parameters, defined as follow:

$$S = 1 - \sum_{\xi} \frac{\omega_{p\xi}^2 (\omega - j\nu_{\xi})}{\omega \left[(\omega - j\nu_{\xi})^2 - \omega_{c\xi}^2 \right]} \quad (\text{B.3a})$$

$$D = \sum_{\xi} \frac{\sigma_{\xi} \omega_{c\xi}}{\omega} \frac{\omega_{p\xi}^2}{\left[(\omega - j\nu_{\xi})^2 - \omega_{c\xi}^2 \right]} \quad (\text{B.3b})$$

$$P = 1 - \sum_{\xi} \frac{\omega_{p\xi}^2}{\omega (\omega - j\nu_{\xi})} \quad (\text{B.3c})$$

In the latter, $\omega_{p\xi} = \left(n_{\xi} q_{\xi}^2 / \varepsilon_0 m_{\xi} \right)^{1/2}$ is the specie plasma frequency, σ_{ξ} indicates the particle charge sign, $\omega_{c\xi} \equiv \sigma_{\xi} q_{\xi} B_0 / m_{\xi}$ is the specie gyrofrequency, and ν_{ξ} is the specie collision frequency. Note that ε_r depends on the frequency of the EM wave ω , thus the plasma is considered as a dispersive medium. In the absence of a magnetostatic field $D = 0$, and $S = P$. In this conditions, plasma is isotropic, with permittivity:

$$\varepsilon_r = 1 - \sum_{\xi} \left(\frac{\omega_{p\xi}^2}{\omega^2 + \nu_{\xi}^2} \right) - j \sum_{\xi} \frac{\nu_{\xi}}{\omega} \left(\frac{\omega_{p\xi}^2}{\omega^2 + \nu_{\xi}^2} \right) \quad (\text{B.4})$$

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