PARAMETRIC ANALYSIS OF PLASMA ANTENNAS

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Abstract

This thesis is a study of different plasma antennas through a parametric analysis. The goal is to understand the particularities of plasma antennas. Such devices use an energized gas as a conductor to transmit and receive electromagnetic waves. By altering the properties of the gas, the radiation and reception properties of the antenna can be modified.

Plasma antennas were first conceived in the early twentieth century. However, they still present some implementation challenges. In this thesis, models ranging between different degrees of complexity are simulated and studied.

Finally, some conclusions regarding the implementation, applications and widespread use are drawn. The results obtained along with publications about the state-of-the-art are a glimpse into the many possibilities of plasma antennas.

Resum

Aquest TFG és un estudi de diferents antenes de plasma mitjançant l'anàlisi paramètric. L'objectiu era entendre les particularitats de les antenes de plasma. Aquest tipus de dispositius utilitzen un gas energitzat com a conductor per a transmetre i rebre ones electromagnètiques. Alterant les propietats del gas, es poden modificar els paràmetres de transmissió i recepció de l'antena.

Les antenes de plasma es van concebre a començaments del segle vint. Tot i això, encara presenten obstacles a l'hora de ser implementades. En aquest TFG se simulen i estudien models amb diferents nivells de complexitat

Finalment, s'obtenen algunes conclusions sobre la implementació, aplicacions i ús generalitzat. Els resultats obtinguts juntament amb publicacions sobre l'estat de l'art són resum sobre les àmplies possibilitats de les antenes de plasma.

Resumen

Este TFG es un estudio de diferentes antenas de plasma mediante el análisis paramétrico. El objetivo era comprender las particularidades de las antenas de plasma. Este tipo de dispositivos utilizan un gas energizado como conductor para transmitir y recibir ondas electromagnéticas. Alterando las propiedades del gas, se pueden modificar los parámetros de radiación y recepción de la antena.

Las antenas de plasma fueron concebidas a principios del siglo veinte. Sin embargo, todavía presentan retos a la hora de ser implementadas. En esta tesis, se simulan y estudian modelos con diferentes grados de complejidad.

Finalmente, se obtienen algunas conclusiones sobre la implementación, aplicaciones y uso generalizado. Los resultados obtenidos junto con artículos sobre el estado del arte, conforman un buen resumen sobre las muchas posibilidades de las antenas de plasma.

A todos los que me han traído hasta aquí: Francho, Carbu, Luis y Mario por su inestimable consejo y valiosa amistad. A Javi por enseñarme que cuando uno está agotado, siempre puede más. A Pablo, Belottos, Joel, Zapa y Albert por estar siempre. A Geri y Víctor por acompañarme al principio. A Isabel por su orientación. A Nuria, Eric, Soufi y Pol por su compañía en la uni. A Nuria por darme consejo todas y cada una de las muchísimas veces que se lo he pedido. A los de la paz por los buenos momentos que han hecho que volver al estudio fuese más fácil y entre ellos, especialmente a Cris y Sara. A Gerard, Álvaro y Song por enseñarme y porque trabajar con ellos es un placer. To Maud, Roxanne, Cille and Zlata for making my stay in Italy a lot of fun while writing this project.

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I would like to thank Professor Capobianco for giving me the opportunity to do this work. I would also like to show my deepest gratitude to professor De Carlo, who has guided me through the process, answered my questions and explained so many things carefully.

Revision history and approval record

Revision	Date	Purpose
0	08/09/2020	Defining contents and scope of the thesis.
1	23/10/2020	Posing questions about articles regarding the state-of-the art, introduction to CST models.
2	09/11/2020	Discuss results of simulations, highlight mistakes and answer more questions.
3	20/11/2020	Discuss corrections from previous work, decide simulations for crossed dipole and explanation about CST.
4	02/12/2020	Discuss crossed dipole simulations, choose plasma configurations for array simulations and tips for writing the report.
5	18/01/2020	Review the final draft.

DOCUMENT DISTRIBUTION LIST

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1. Introduction

a. **Statement of purpose (objectives).** The goal of this thesis is to study the antenna parameters and particularities of plasma antennas by simulating different designs.

b. **Requirements and specifications.** The requirements are knowledge on the fundamentals of antennas, a software to perform simulations and basic understanding of the state-of-the-art.

c. **Methods and procedures, citing if this work is a continuation of another project or it uses applications, algorithms, software or hardware previously developed by other authors.** The student performed simulations based on the supervisor's recommendations and models and then a discussion of the results ensued and the next steps were decided.

d. **Work plan with tasks, milestones and a Gantt diagram.**

Project: First contact the Drude model	WP ref: (WP0)	
Major constituent: simulations performed on CST studio and PowerPoint.	Sheet 1 of 1	
Short description: Perform simulations in CST studio using the simplified dipole model provided by the supervisor. Change plasma parameters and draw conclusions from the effects on the plasma parameters.	Planned start date: 12/10/2020 Planned end date: 27/10/2020	
	Start event: 30/10/2020 End event: 10/11/2020	
Internal task T1: Read about Drude model and state-of-the-art research on plasma antennas. Internal task T2: Perform simulations tweaking parameters.	Deliverables: PowerPoint with the results.	Dates:

Project: Read about the state-of-the-art	WP ref: (WP1)	
Major constituent: Understanding the current state of research and previous work.	Sheet 1 of 1	
Short description: Read papers on the current state of research in plasma antennas and related topics.	Planned start date:15/08/2020 Planned end date: 15/01/2021	
	Start event: 15/08/2020 End event: 15(01/2021	
Internal task T1: L-Band Plasma Turnstile Antenna for GPS applications (Paper) Internal task T2: Analytical and Numerical Study of a gaseous Plasma Dipole in the UHF Frequency Band (Paper) Internal task T3: Hybrid Metal-Plasma Yagi-Uda Antenna for Microwave Applications (Paper). Internal task T4: Introduction to Plasma physics – Chapter 1(Book chapter)	Deliverables: None	Dates:

Internal task T5: Introduction to Plasma physics – Chapter 3(Book chapter) Internal task T6: Experimental and Theoretical Results With Plasma Antennas - Alexeff et al. (paper) Internal task T7: Physical Characteristics of Plasma Antennas - Rayner et al. (paper)		

Project: Simulate crossed dipole	WP ref: (WP2)	
Major constituent: Simulation results with CST	Sheet 1 of 1	
Short description: Perform multiple frequency domain simulations in CST for a crossed dipole with a resonance frequency close to 0.5 GHz.	Planned start date: 27/10/2020 Planned end date: 31/10/2020	
	Start event: 22/10/2020 End event: 23/11/2020	
Internal task T1: Add materials to the CST material library. For every condition of pressure, plasma density and gas type, a new material has to be used. Internal task T2: Perform simulations. Internal task T3: Set up a far field monitor at the frequency of resonance and run CST's Setup Solver to get far field results. Internal task T4: Present all the gathered data in a PowerPoint. Internal task T5: Draw conclusions and discuss them with the supervisor.	Deliverables: CST simulations, simulation results and conclusions	Dates:

Project: Theoretical background	WP ref: (WP3)
Major constituent: text about plasma and antennas basic theory.	Sheet 1 of 1
Short description: Writing about the theoretical background of antennas and plasma.	Planned start date: 15/11/2020 Planned end date: 01/01/2021
	Start event: 15/11/2020 End event:10/01/2021

Internal task T1: Review notes on antennas and microwaves. Internal task T2: Search for sources. Internal task T3: Write. Internal task T4: Review with supervisor. …	Deliverables: A comprehensive description of antenna and plasma basics.	Dates:

e. **Description of the deviations from the initial plan and incidences that may have occurred**. In the first meeting, the possibility of creating a model specifically for a satellite link was discussed. However, the supervisor proposed different models which were very interesting and the goal shifted from analysis to design. We believe that was the best course of action since there are many intricacies related with plasma and its practical implementations.

1.1. Plasma

According to Oxford's Dictionary of Physics, plasma is "an ionized gas consisting of positive ions and free electrons in proportions resulting in more or less no overall electric charge, typically at low pressures (as in the upper atmosphere and in fluorescent lamps) or at very high temperatures (as in stars and nuclear fusion reactors)" . (1)

To fully understand this, it is paramount to understand the concepts of gas, ionization and charge:

1.1.1. Gas

Matter is any "physical substance in general [...] which occupies space and possesses rest mass, especially as distinct from energy" (2) The following diagram represents the classification of matter:

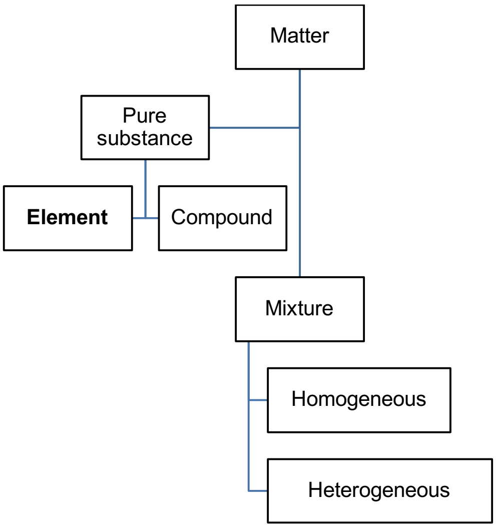


Figure 1 Classification of matter. (3)

The scope of this work is concerned with pure substances, specifically elements. According to Oxford Languages, an element is each of more than one hundred substances that cannot be chemically interconverted or broken down into simpler substances and are primary constituents of matter. Each element is distinguished by its atomic number, i.e. the number of protons in the nuclei of its atoms."

In theory, every single element can be found in three different states: solid, liquid and gas. In plain terms, by modifying the conditions of temperature and pressure, atoms can be put together or set apart.

For example: if ice (solid water) is warmed it becomes liquid water (assuming normal pressure conditions around 1 atmosphere). If liquid water is boiled it becomes water vapour (gas). A gas is "a substance or matter in a state in which it will expand freely to fill the whole of a container, having no fixed shape (unlike a solid) and no fixed volume (unlike a liquid)". (2)

1.1.2. Ion

According to Oxford's Physics dictionary, an ion is "an atom or molecule with a net electric charge due to the loss or gain of one or more electrons" (2)Atoms are the smallest units of matter which form chemical elements. Their diameter is in the range of picometres and their behaviour is described by quantum physics. Atoms have a nucleus composed of protons and neutrons and electrons bound to it.

Particle	Electric charge (C)	Mass (kg)
Proton	1.602176634e-19 (CODATA)	1.67262192369e−27
Neutron	0	1.67492749804e−27
Electron	1.602176634e-19 (CODATA)	9.1093837015e-31 (CODATA)

Table 1 Mass and electric charge of proton, neutron and electron.

If an atom has more protons than electrons, it has a positive charge and is known as a cation (4). On the other hand, if the atom has more electrons than protons, its charge is negative and it shall be named anion. (2)

Electromagnetic forces keep the electrons bound to the nucleus and nuclear forces attract neutrons and protons. When an electromagnetic force is stronger than the nuclear force that keeps the nucleus together, the nucleus splits resulting in different elements. (1)

1.1.3. Electric charge

According to Oxford's Dictionary (2), (electric) charge is "the property of matter that is responsible for electrical phenomena, existing in a positive or negative form." Charges can be either positive or negative. The former is associated with protons and the latter with electrons. These are some key particularities:

1. Two charges of equal sign repel each other.

2. Two charges of different signs attract each other.
3. A piece of matter with the same amount of positive charges and negative charges has a net charge equal to zero.
4. Coulomb's law describes the forces between two stationary charged particles.
5. **Coulomb's law and electric field generated by a charge**

Coulomb's law defines the force of attraction between two charges as proportional to the product of their charges divided by the square of the distance between them:

$$F_e = k_e \cdot \frac{q_1 \cdot q_2}{r^2}$$

Where $k_e \approx 8.988\text{e}+9\ \text{N}\cdot\text{m}^2\cdot\text{C}^{-2}$

If q_1 and q_2 are of the opposite sign, F_e will be negative, which means that the charges attract each other.

The electric field that a charge q_1 in vacuum generates at some point x_0 can be described with the following equation:

$$E(x_0) = \frac{F}{q_0} = \frac{1}{4\pi\varepsilon_0} \cdot \frac{q_1}{(x_1 - x_0)^2} \cdot \boldsymbol{r}_{1,0}$$

Where:

- $\mathbf{r}_{1,0}$ is the unitary vector from the charge to x_0.
- x_1 is the location of the charge in space.

1.1.4. Plasma parameters

With this basic knowledge, let's define the following plasma parameters:

- Electron density: $n_e = \frac{number\ of\ free\ electrons}{volume}\,[m^{-3}]$
- Ion density: $n_i = \frac{number\ of\ free\ ions}{volume}\,[m^{-3}]$
- Neutral density: $n_0 = \frac{number\ of\ neutrons}{volume}\,[m^{-3}]$
- Ion charge: $Z_i = electrical\ charge\ of\ ions\ [C]$
- Electron temperature: $T_e = kinetic\ energy\ of\ electrons\ [eV]$
- Ion temperature: $T_i = kinetic\ energy\ of\ ions\ [eV]$
- Neutral temperature: $T_0 = kinetic\ energy\ of\ neutrons\ [eV]$

A more rigorous definition of plasma is the following: plasma is a quasineutral gas of charged particles which exhibits a collective behaviour. (4)

where, in this definition, quasineutral means:

$$n_i \approx n_e$$

Therefore, the plasma can be globally considered neutral.

Francis F. Chen explains collective behaviour as follows:

“Consider the forces acting on a molecule of, say, ordinary air. Since the molecule is neutral, there is no net electromagnetic force on it, and the force of gravity is negligible. The molecule moves undisturbed until it makes a collision with another molecule, and these collisions control the particle's motion. A macroscopic force applied to a neutral gas, such as from a loudspeaker generating sound waves, is transmitted to the individual atoms by collisions. The situation is totally different in a plasma, which has charged particles. As these charges move around, they can generate local concentrations of positive or negative charge, which give rise to electric fields. Motion of charges also generates currents, and hence magnetic fields. These fields affect the motion of other charged particles far away. [...]By "collective behaviour" we mean motions that depend not only on local conditions but on the state of the plasma in remote regions as well. “ (4)

Another paramount parameter is the **plasma frequency** (ω_P):

If the electrons in a plasma are displaced from a uniform background of ions, electric fields will be built up in such a direction as to restore the neutrality of the plasma by pulling the electrons back to their original positions. Because of their inertia, the electrons will overshoot and oscillate around their equilibrium positions with a characteristic frequency known as the plasma frequency. This oscillation is so fast that the massive ions do not have time to respond to the oscillating field and may be considered as fixed. (4)

$$\omega_P = \sqrt{\frac{n_e \cdot e^2}{\varepsilon_0 \cdot m_e}}$$

(4)

Where:

- **e** is the charge of the electron.
- $\mathbf{m_e}$ is the mass of the electron.
- ε_0 is the vacuum permittivity.

Last but not least, collision frequency:

Collisional Frequency is the average rate in which two reactants collide for a given system and is used to express the average number of collisions per unit of time in a defined system. (5)

1.2. Antennas

Whatever the kind, all antennas share a series of parameters which define their performance. By understanding their meaning and implications, engineers can produce better designs or choose the optimal antenna for an application from a catalogue.

1.2.1. Transmission specific parameters

1.2.1.1. S11 parameter

The scattering parameters of a microwave circuit describe the relation between the inbound and outbound waves of such circuit and characterise it from the outside. A circuit with N ports has NxN parameters which are usually expressed in a matrix. The Snn parameter is a measure of how much the antenna reflect powers in the port ‘n’.

If P_{in} [W] is the input power in the port, then:

S11 (linear)	Power reflected [W]
1	P_{in}
0	0

1.2.1.2. Impedance

The antenna must be connected to a transmitter and radiate as much power as possible. In order to do so, they must be adapted in terms of impedance of the antenna itself and of the transmitter/receiver. The connection is made with a transmission line or waveguide, which also takes part in the process of adapting the antenna. Therefore, the connection’s impedance, attenuation and longitude must be taken into account. (6)

The input impedance of an antenna in permanent sinusoidal regime has a real part $R_e(\omega)$ and imaginary part $X_e(\omega)$. Both depend on frequency. If the imaginary part of the input impedance at a certain frequency is zero, such antenna is called “resonant”. Given that the antenna radiates energy, there is a net power loss due to radiation which can be assigned to a radiation resistor R_r, defined as the resistor which would ohmically dissipate the same power as the amount radiated by the antenna. (6)

Thus, the power delivery to an antenna can be defined by the following equation, where P stands for power in watt and I for intensity in ampere:

$$P_{delivered} = P_{radiated} + P_{losses} = I^2 \cdot R_r + I^2 \cdot R_{ohm}$$

If $P_{delivered}$ and $P_{radiated}$ are know, antenna efficiency can be calculated as:

$$\mu_l = \frac{P_{radiated}}{P_{delivered}} = \frac{R_r}{R_r + R_\Omega}$$

(6)

1.2.1.3. Radiation pattern

A radiation pattern is a graphical representation of an antenna's radiation properties in terms of the different directions of space at a fixed distance. It is usually displayed in a spherical coordinates system with the antenna at the origin, the electric field is expressed in terms of azimuth θ and elevation ϕ. (6).

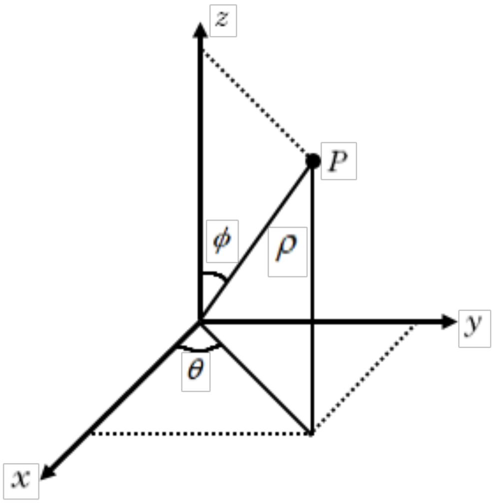


Figure 2 Cylindrical coordinate system (MathWorks).

While a three-dimensional representation can be useful, it is most commonly represented in two figures, one with fixed θ and another with fixed ϕ. These plots are also very useful to determine the beam width at -3dB, NPLS (side lobe level), front-to-back ratio and if the antenna is omnidirectional (it is if the radiation pattern presents revolution symmetry in an axis). (6)

The example below shows the radiation pattern of a half-wave dipole at 1GHz. The results have been obtained with CST STUDIO SUITE:

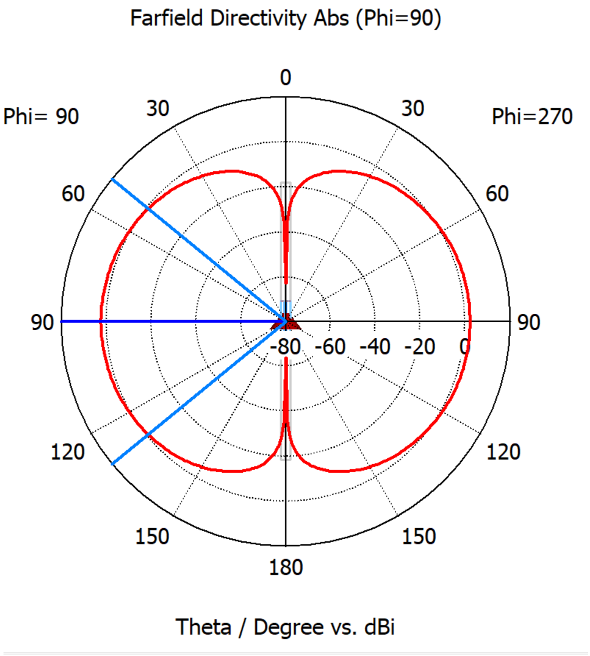


Figure 3 Radiation pattern of a dipole for phi = 90º.

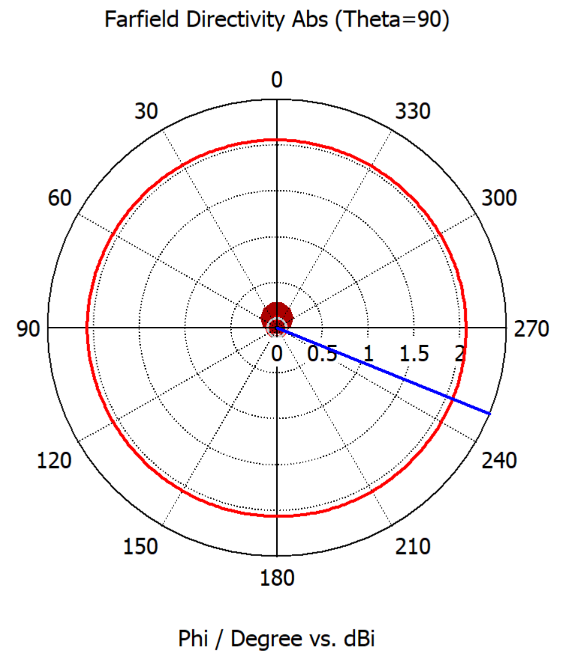


Figure 4 Radiation pattern of a dipole for theta = 90º.

The first plot displays the radiation pattern for ϕ=90 degrees, which corresponds to the XY plane. The second plot displays the radiation pattern for θ=90 degrees, which corresponds to the Z axis (the pattern has revolution symmetry). In the latter, the magnitude of the radiation pattern is constant. Putting these together we can easily imagine a radiation pattern with a toroidal shape.

Directivity is slightly above 2dB.

1.2.1.4. Directivity

The directivity of an antenna is defined as the relation between the power density radiated in a certain direction at a given distance and the power density that would be radiated at the same distance by an isotropic antenna which would radiate as much power as the antenna of interest. This can be expressed as:

$$D(\theta,\varphi) = \frac{\wp(\theta,\varphi)}{\frac{P_r}{4\pi r^2}}$$

To compute the maximum value, the angular direction can be ignored and the Poynting vector has to be substituted by its modulus:

$$D_{max} = \frac{\wp_{max}}{\frac{P_r}{4\pi r^2}}$$

(6)

1.2.1.5. Gain

It is a measure that takes into account the efficiency of the antenna as well as its directional capabilities (7). The absolute gain on an antenna (in a given direction) is defined as "the ratio of the intensity, in a given direction, to the radiation intensity that would be obtained if the power accepted by the antenna were radiated isotropically. The radiation intensity corresponding to the isotropically radiated power is equal to the power accepted (input) by the antenna divided by 4π" (7).

$$G(\theta,\varphi) = e_{cd} \cdot D(\theta,\varphi)$$

where e_{cd} is the antenna radiation efficiency (dimensionless) (7).

1.2.1.6. Polarization

The field vector of an electromagnetic wave is a function of position and time. Polarization is an indication of the field vector's orientation at a certain moment and point in space. The polarization of a wave is the geometrical shape described over time by the end of the electric field vector at a fixed point in space over a plane orthogonal to the direction of propagation. For permanent sinusoidal regimes, the shape is usually an ellipse. However, it can also be a line or a circle. (6)

The Axial Ratio (AR) of an elliptically polarised wave is defined as the ratio between the major and minor axes of the ellipse. (6)

In mathematical terms, given a wave like

$$\boldsymbol{E} = (A\boldsymbol{x} + jB\boldsymbol{y}) \cdot e^{j(\omega t - kz)}$$

the axial ratio can be defined as

$$20 * \log\left(\frac{A}{B}\right)$$

Therefore, the axial ratio is zero for a circularly polarize wave and infinity for linearly polarised waves. Knowing this, representing the axial ratio in Cartesian axes is a very simple yet effective way to see if the antenna can transmit and receive circularly polarised waves. It is considered that circular polarisation can take place if the axial ratio is below 3dB.

Let's see and example with the simulation of a turnstile antenna in phase-quadrature, which is a well-studied example of a circularly polarised antenna:

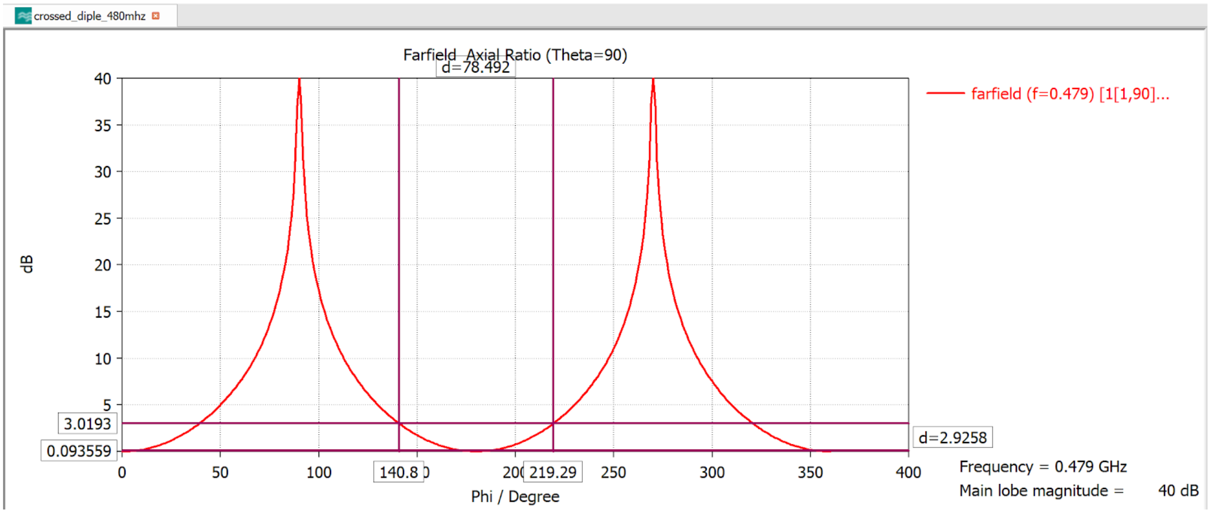


Figure 5 Axial ratio plot of a circularly polarised antenna.

Between 140.8 and 219.9 degrees, the axial ratio is below 3dB

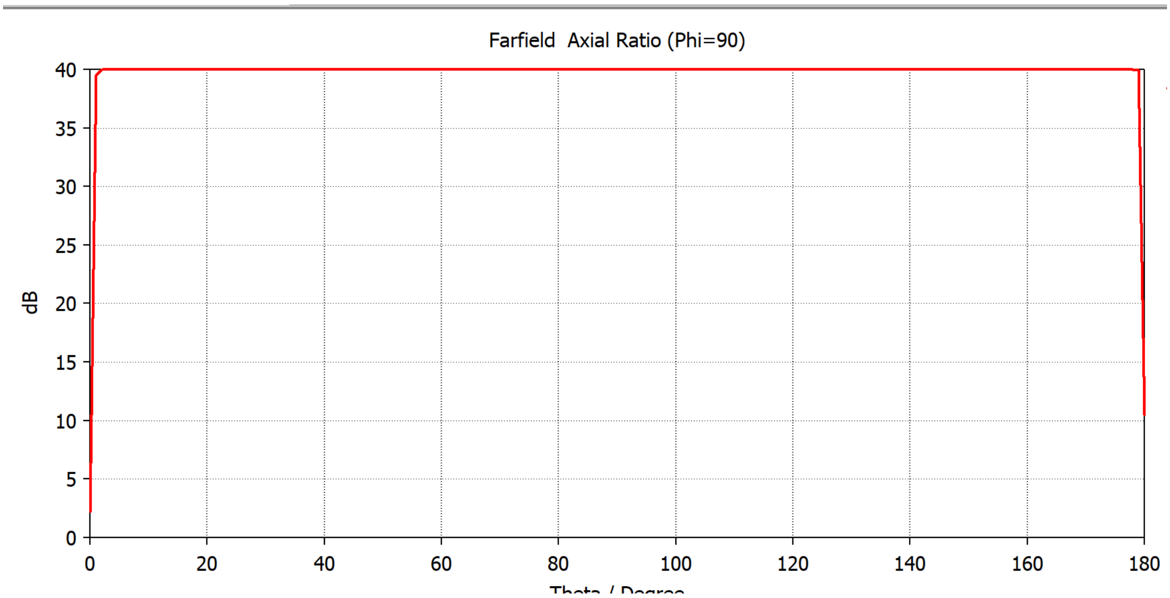


Figure 6 Axial ratio plot of a linearly polarised antenna.

1.2.1.7. Bandwidth

Given their limited geometry, resonant antennas are limited to operate satisfactorily in a band or range of frequencies. This range of frequencies in which a parameter of the antenna does not surpass certain pre-set limits, is known as the antenna's bandwidth.

It can be expressed mathematically as a ratio between the range of frequencies and the central frequency:

$$BW\_ratio = \frac{f_{max} - f_{min}}{f_0}$$

where:

- **BW** is the bandwidth.

- **f_{max}** and **f_{min}** are the upper and lower bounds for the frequency range.
- **f_0** is the optimal operation frequency.

(6)

The bandwidth is calculates as follows:

$$BW = fmax - fmin$$

1.2.2. Reception specific parameters

1.2.2.1. Impedance matching

When receiving, the antenna is connected to a transmission line or directly to a receiver. For maximum power transfer, the antenna's impedance $Z_a = R_a + j \cdot X_a$and the load's impedance $Z_L = R_L + j \cdot X_L$must be complex conjugate $Z_L = Z_a{}^*$. In this case:

$$P_{Lmax} = \frac{|V_{ca}|^2}{4R_a}$$

(6)

If operating at the resonance frequency, the rule is simplified and becomes as follows:

$$R_a = R_L$$

2. State of the art of the technology used or applied in this thesis

Antennas are at the core of the workings of human society in the twenty-first century. By transmitting and receiving radio signals, they make thousands of applications and services real. There are dipoles, monopoles, patches, Yagi-Uda, parabolic reflectors, fractal antennas etc. as well as 1D and 2D arrays of all the above mentioned. Some are used to open garage gates and others are used to steer space probes millions of kilometres away from earth (8). Others are used to make millions of payments every single day (9).Others are used to support fast data streams available in almost every single corner of any busy and chaotic modern city. (10)To sum it up, in the field of antennas, one size does not fit all. Therefore, creativity and engineering along with some ingenuity and effort have produced a very wide family of designs which can be adapted to fit a specific need. According to Oxford Languages (2), an antenna is "a rod, wire or other device used to transmit or receive radio or television signals". "Or other device" is key in that definition.

In 1888, Heinrich hertz created the first antennas (11). In 1895 Meucci made wireless telegraphy a reality (12). Today, millions of people carry one or more tiny small wideband fractal antennas in their phones (13). It took many years and a lot of research to reach this point. Nevertheless, it is by no means the end of the road. Nowadays, there is a great amount of research in the field of antennas. A lot of it is concentrated in applications which have possibilities of being commercially produced at large scale. The fields of antennas for wearable devices (14) or energy harvesting (15) fit that category. Other lines of research delve deeper in fields whose commercial applications are rather non-existent or hard to imagine at first glance. One of such fields would be plasma antennas. Gaseous Plasma Antennas (GPAs) are devices that rely on a plasma to transmit/receive EM (Electromagnetic) waves. In GPAs a neutral gas is confined in a dielectric tube (e.g. glass) and ionized by means of a dedicated circuit. The signal is then injected into the plasma by another circuit, usually referred to as “signal coupler”. They were first conceived by J. Hettinger. In 1919 he was granted a patent for an “aerial conductor” (16). Nevertheless, these kind of devices require complex hardware to generate plasma. Because of this and because classic antennas made of metallic conductors are cheap and well understood (17).

First and foremost, plasma antennas can become invisible to the same EM waves they seek to receive or transmit as well as others (18). To understand this behaviour, it is paramount to be aware that energised plasma behaves as a conductor. On the other hand, de-energised plasma does not. This behaviour can be of interest for stealth communications which require antennas with low radar cross-section. If a constant link is not required, data can be transmitted in short bursts, thus having de-energised plasma most of the time and protecting human life and material goods such as equipment, stations, vessels etc. (19)

Moreover, this ability to almost instantly energise or de-energise plasma brings another great advantage. In classical antenna arrays, elements of the array can be turned on and off at will. However, while turned off, they still affect other elements because of cross impedance. Unlike metallic elements, de-energised plasma elements in an array do not affect other elements. (19) This has further implications in structures which hold antennas for different applications: be it the mast of a warship or a big communications post housing antennas for many fields, by switching off antennas, coupling can be avoided.

Furthermore, another interesting property exists. The applied RF (Radio Frequency) power to generate the plasma can change the plasma density, and consequently the effective length of the antenna. By changing the effective length of the antenna, the transmitting frequency can be varied. (19)

The energising and the energising of the plasma can be performed in time spans in the order of microseconds. (19)

In terms of noise, Rayner et al. describe the following noise sources in a “low-pressure glow discharge excited by a dc or low frequency ac current” (19):

1. Thermal noise due to the random motion of electrons.
2. Shot noise due to the dc current or spectral density.
3. Cathode processes including thermionic and secondary emission.
4. Noise in the vicinity of the ion plasma frequency.

They also point that “the plasma itself is a crucial issue when considering the use of plasma antennas for reception and transmission. Plasmas are well-known sources of noise through to microwave frequencies particularly for dc, or mains driven ac” (19). Finally, they conclude that “total antenna noise temperature is a function of both the antenna efficiency and the weighted temperature of the radiation field compared and the plasma noise temperature". However, they point out that "whether or not the plasma noise is a significant factor depends on the circumstances" (19).

In (18), Alexeff and his colleagues state that "plasma-generated noise is in general not a problem". In the same paper, they explain different methods for noise reduction.

To sum it up, all these properties are very exciting in their own right and promising when combined. Plasma antennas could be put to very good use in the fields of space communications, earth observation and warfare communications. (19)

Some researchers propose hybrid models to use plasma technology. In (20) researchers study a Yagi-Uda antenna in which "the directors of the antenna are constituted of microplasma discharges that allow to realize very thin and short plasma tubes, thus overcoming some issues related to the use in the GHz regime of classic thick plasma discharges."

3. Methodology / project development:

3.1. Reading about the state-of-the-art

The first step was to read and understand papers about the state of the technology. This was a continuous process during the production of this work.

3.2. Simulating with CST STUDIO SUITE

According to 3ds, the owner and distributer of CST STUDIO SUITE, the software "offers accurate and efficient computational solutions for electromagnetic designs" (21). The steps followed to simulate a model were the following:

1. Load or create model (frequency domain solver).
2. Choose plasma configuration.
3. Run Setup Solver.
4. Observe the (1D) results.
5. Find resonance frequency.
6. Add (18) field monitors for:
    a. E-Field
    b. H-Field
    c. Farfield/RCS
7. Run Setup Solver.
8. Observe the (Farfields) results.
9. Gather data and discuss with the supervisor.
10. Review and correct mistakes.
11. Draw conclusions and compare the behaviour of the antenna for different plasma configurations.

4. Results

4.1. Plasma parameters

One of the many powerful tools of CST Studio is its wide range of options to model materials. A Drude model (22) can be used for plasma if the plasma frequency and collision frequency are known. The physics behind these parameters are explained in the "Theoretical background" section of this work. Both parameters have been calculated with a MatLab script provided by the supervisor for different conditions of plasma density and pressure and multiple gases. These are the results:

4.1.1. Argon | 1500 mTorr | Variable density

Plasma density **[m^3]**	**Plasma frequency** **[rad/s]**	**Collision frequency** **[Hz]**
1e18	5.6415e+10	4.911e9
4e18	1.1283e+11	4.9276e+09
6e18	1.3819e+11	4.9383e+09
8e18	1.5956e+11	4.9488e+09
1e19*	1.7840e+11	4.9591e+09

Table 2 Plasma parameters for Argon at different plasma densities constant pressure.

This is the relationship between the plasma density and the plasma frequency:

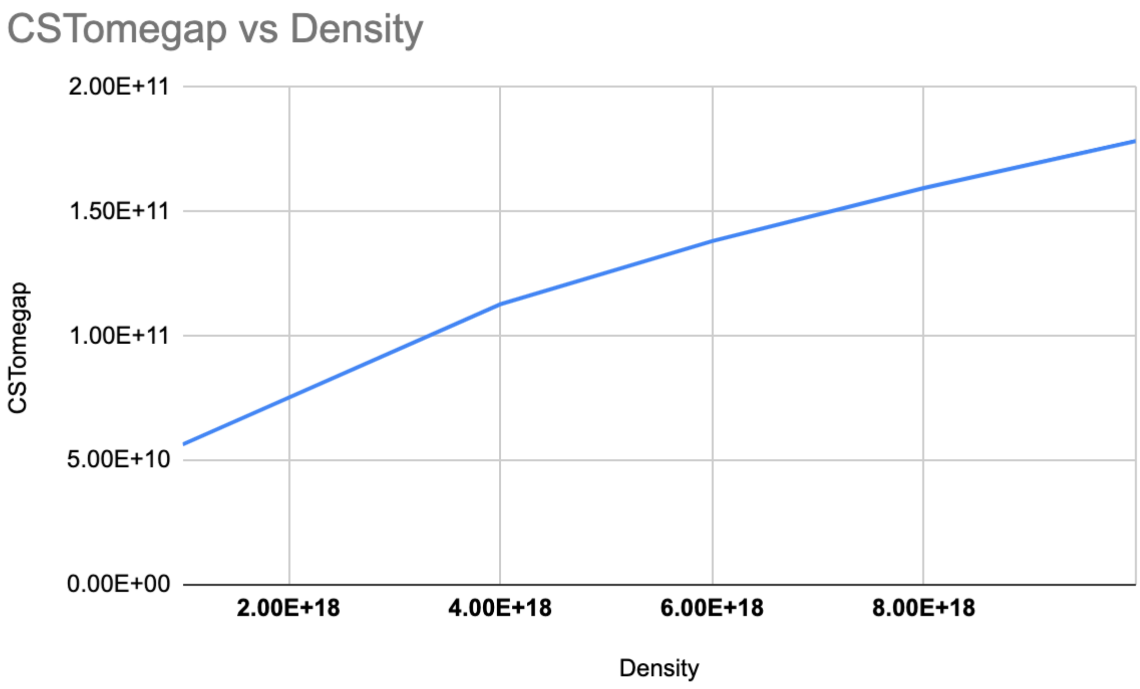


Figure 7 Plasma frequency in terms of plasma density at constant pressure.

This is the relationship between the plasma density and the collision frequency:

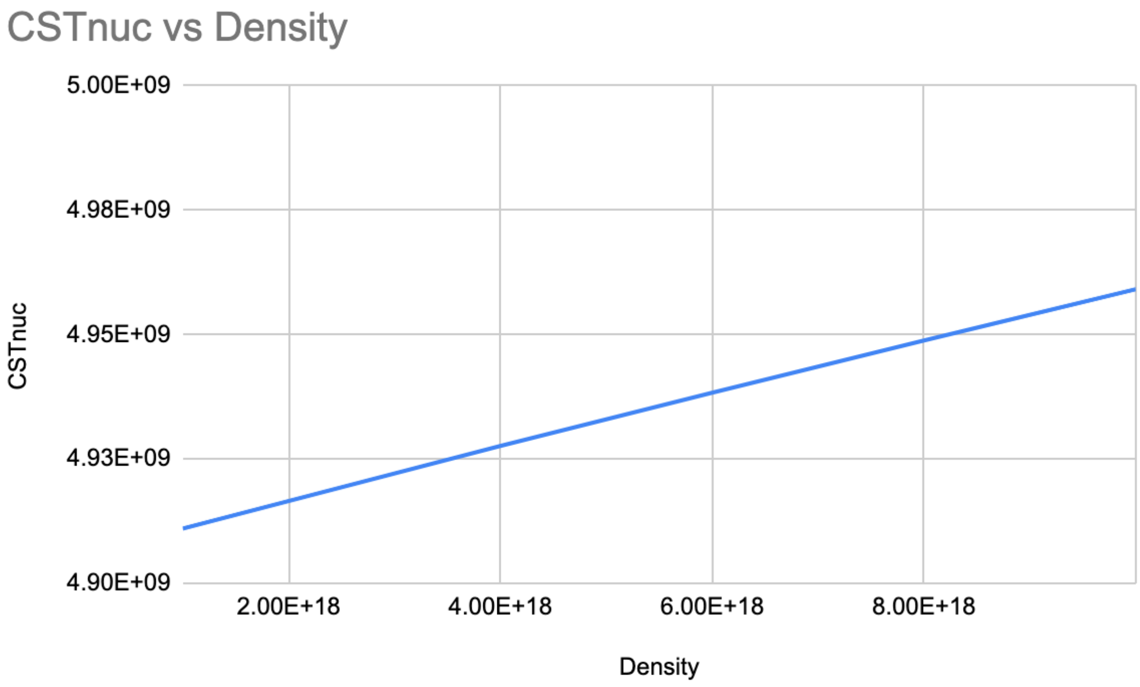


Figure 8 Plasma collision frequency in terms of plasma density at constant pressure.

4.1.2. Argon | Variable pressure| 1e19 e^-/m^3

Pressure [mTorr]	Plasma frequency [rad/s]	Collision frequency [Hz]
750	1.7840e+11	2.5067e+09
1500*	1.7840e+11	4.9591e+09
2250	1.7840e+11	7.4116e+09

Table 3 Plasma parameters for Argon at different plasma pressures and constant density.

Plasma pressure has no effect on plasma frequency at constant density.

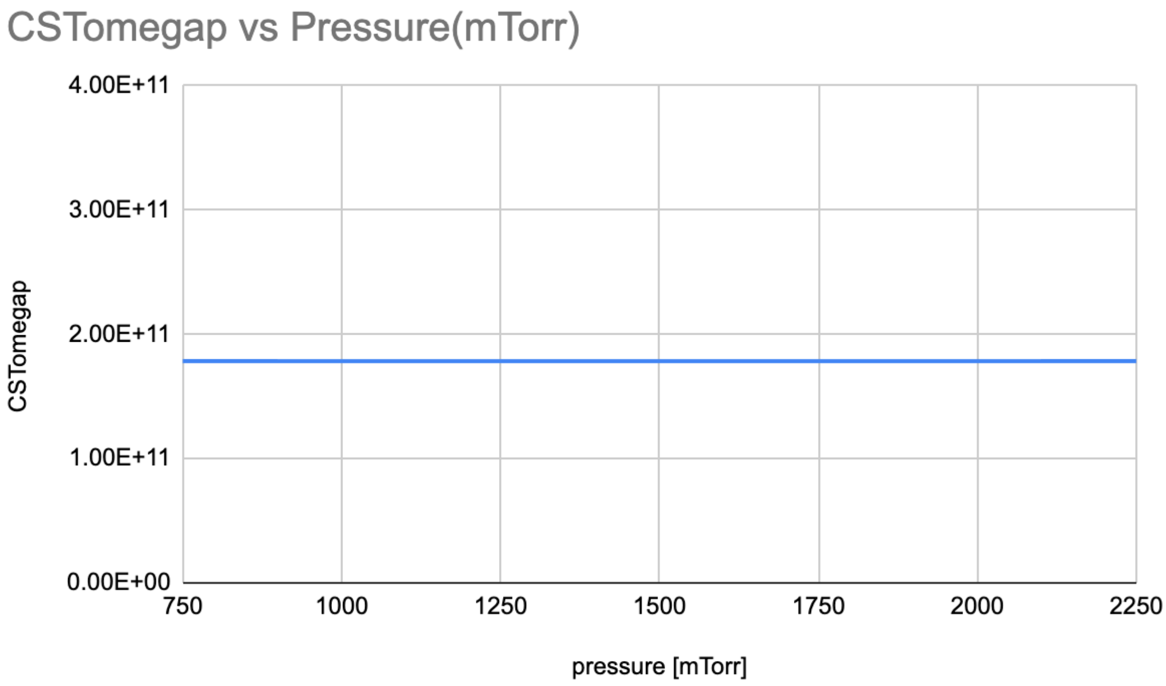


Figure 9 Plasma frequency in terms of plasma pressure at constant density.

Relationship between pressure and collision frequency:

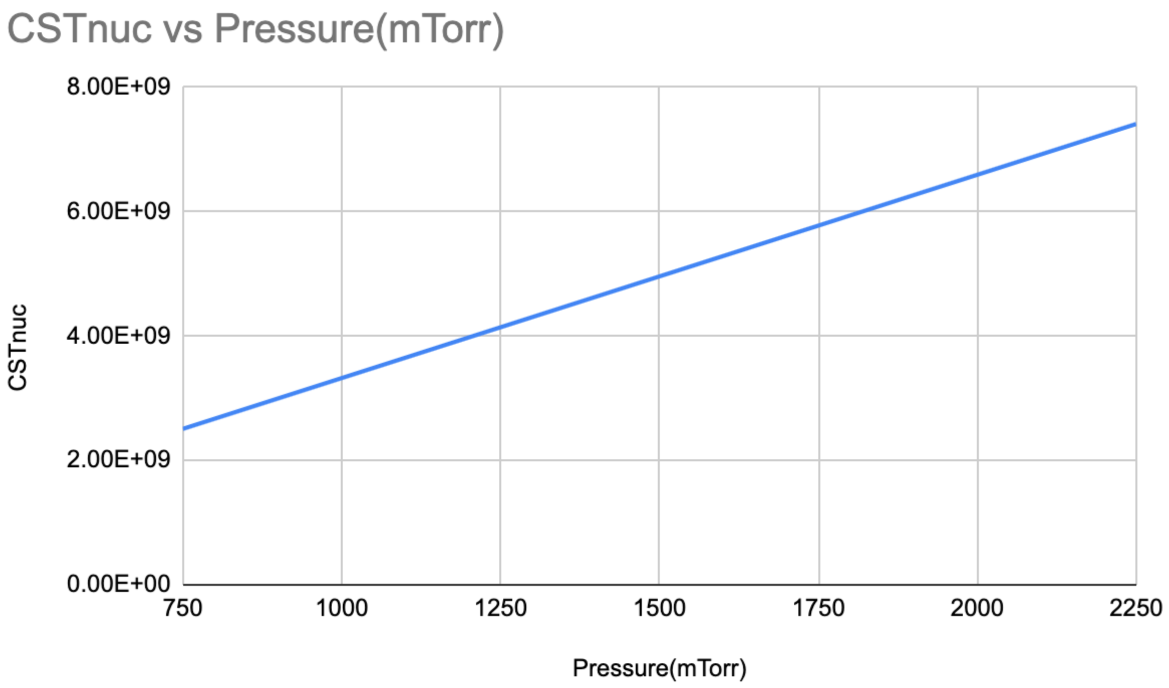


Figure 10 Plasma collision frequency in terms of plasma pressure at constant density.

4.1.3. Argon, Neon, Xenon and Krypton | 1500 mTorr | 1e19 e^-/m^3

Gas	Plasma frequency [rad/s]	Collision frequency [Hz]
Argon*	1.7840e+11	4.9591e+09
Neon	1.7840e+11	1.3473e+09
Krypton	1.7840e+11	8.1181e+09
Xenon	1.7840e+11	1.3247e+10

Table 4 Plasma parameters for Argon, Neon, Krypton and Xenon at identical pressure and density conditions.

Collision frequency for every gas:

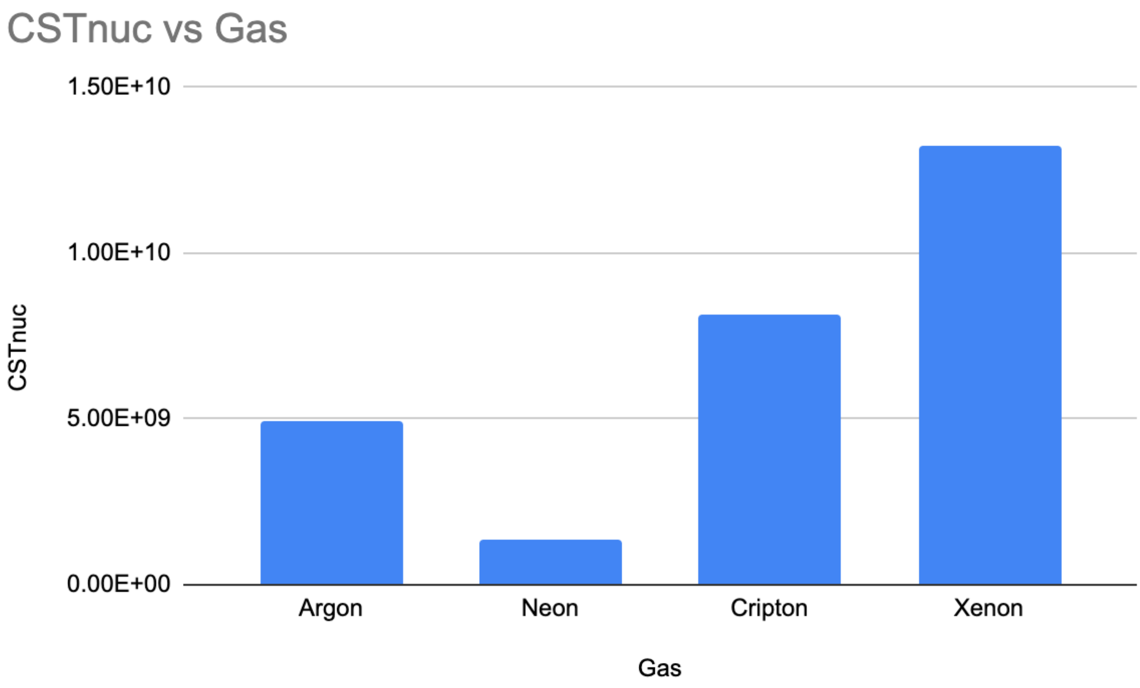


Figure 11 Plasma frequency for Argon, Neon, Krypton and Xenon at identical pressure and density conditions.

In CST, creating a new material from these parameters is as simple as navigating to

Materials → New Material → Dispersion

and choosing the **Drude** dispersion model in the **Dielectric dispersion** column. CST will compute the dielectric constant for the range of frequencies set when creating the project. The material can now be added to the material library.

4.2. Simplified dipole

4.2.1. Classic dipole

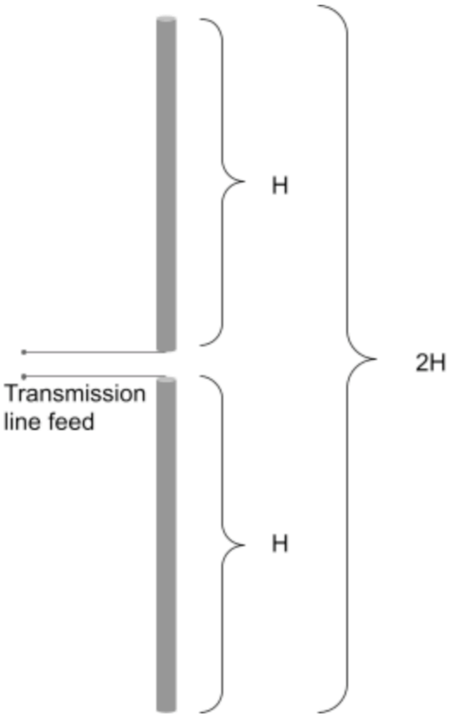


Figure 12 Schematic of a classic dipole.

A dipole is one of the simplest antenna designs. It consists of two metal wires aligned on the same axis separated by a gap. Its most common form is the lambda/2 dipole, where the length of every arm of the dipole is lambda/4.

Its radiation pattern presents revolution symmetry. Therefore, it is a good type of antenna for broadcasting.

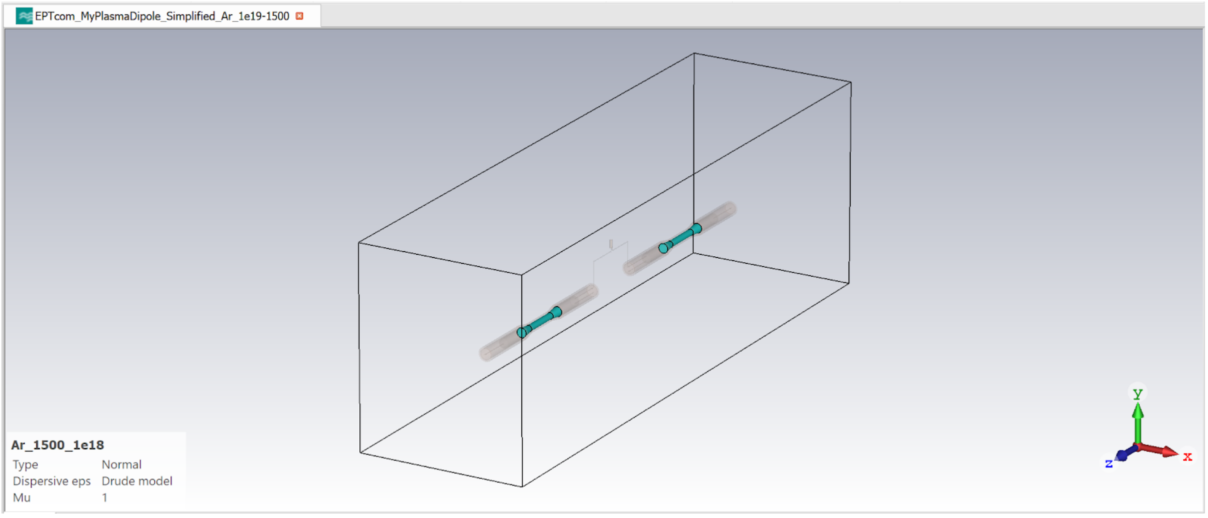
The values of the <3dB beam width ($\Delta\Theta_{-3dB}$) and directivity(D) of this dipoles are well known and can be consulted in the table below:

H	$\Delta\Theta_{-3dB}$(º)	D
$\lambda/4$	78	1,64
$3\lambda/8$	64	1,94
$\lambda/2$	48	2,41
$5\lambda/8$	33	3,33

Table 5 Parameters of a classic dipole for different arm lengths.

The $\Delta\Theta_{-3dB}$ is the beam width of the main lobe at -3dB.

4.2.2. Plasma dipole



EPTcom_MyPlasmaDipole_Simplified_Ar_1e19-1500

Ar_1500_1e18

Type	Normal
Dispersive eps	Drude model
Mu	1

Figure 13 CST model of the simplified dipole.

The first step was to simulate a bare-bones model of a plasma dipole as seen in the image above. This model represents the smallest plasma dipole that could be practically implemented with the plasma generating hardware available at the lab.

It was designed to have the shortest length possible in order to maximize its operating frequency.

It was simulated for all the cases specified in the section above. The following tables show the results where:

wp = plasma frequency in rad/s

wc = collision frequency in Hz

s11 = s11 at resonance frequency in dB

f_res = resonance frequency

z11_real = real part of the input impedance at resonance frequency

z11_imag = imaginary part of the input impedance at resonance frequency

main_lobe = Maximum gain in dB

4.2.2.1. Argon | 1500 mTorr | Variable density

Density [m^{-3}]	wp [rad/s]	wc [Hz]	s11 [dB]	f_res [Hz]	z11_real [Ω]	z11_imag [Ω]	main_lobe [dB]
1E+18	5.64E+10	4.91E+09	-4.585714	0.74447	146.036309	-59.510907	-4.9
4E+18	1.13E+11	4.93E+09	-5.6115658	0.39287	126.5323	-42.311018	-3.6
6E+18	1.38E+11	4.94E+09	-7.4649633	0.39578	102.77819	-24.363496	-2.46
8E+18	1.60E+11	4.95E+09	-8.900205	0.39738	89.676069	-17.580201	-1.79
1E+19	1.78E+11	4.96E+09	-10.077982	0.3987	81.786215	-13.863454	-1.34

Table 6 Antenna parameters of the Argon-filled simplified dipole at constant pressure and different plasma densities.

As plasma density increases:

- The s11 parameter decreases.
- There is a slight shift to upper frequencies.
- The absolute value of the real part and of the imaginary part of z11 decrease.
- The antenna directivity increases.

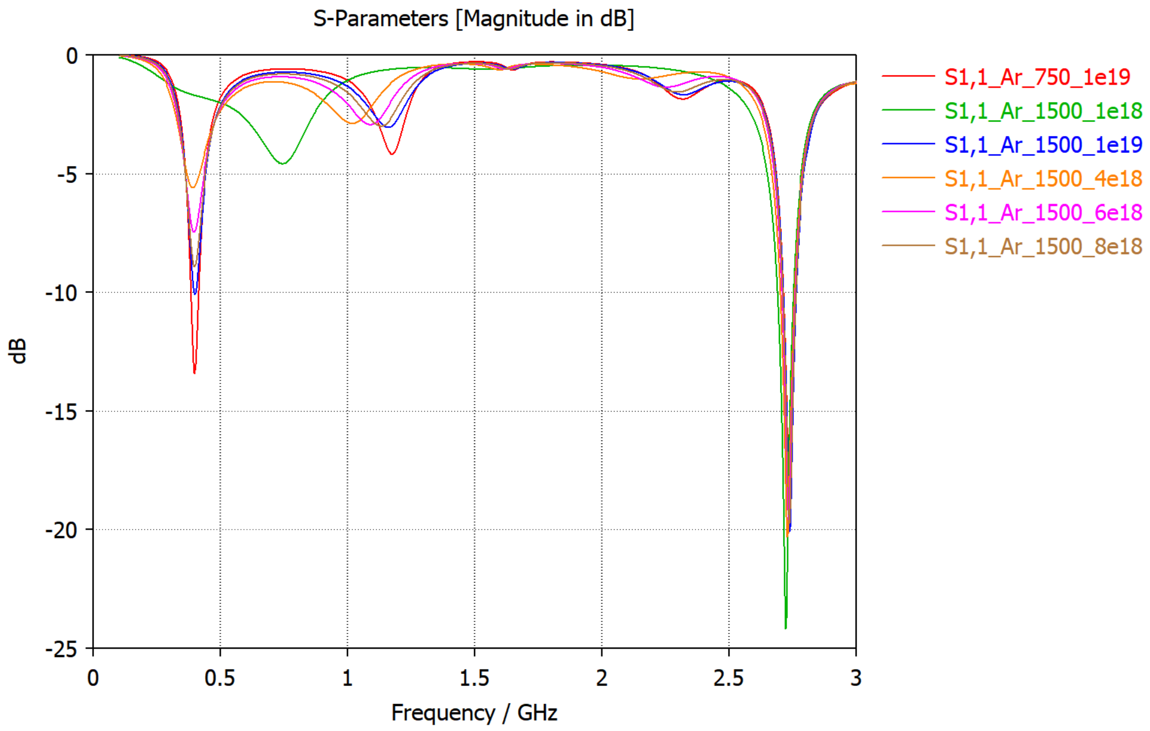


Figure 14 Magnitude of the reflection coefficient S11 of the Argon-filled simplified dipole at constant pressure and different plasma densities.

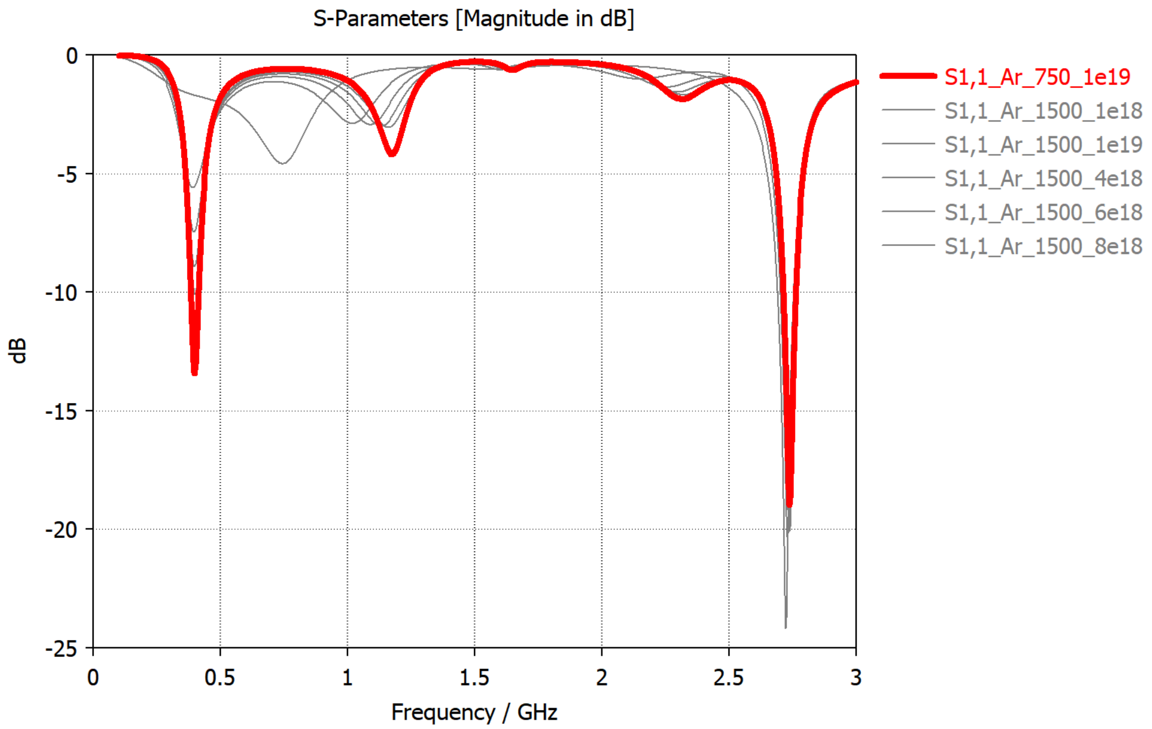


Figure 15 Magnitude of the reflection coefficient S11 of the Argon-filled simplified dipole at 750 mTorr and 1e19 m^{-3}*..*

Deepest S11 parameter is for Argon at 750 mTorr and density 1e19.

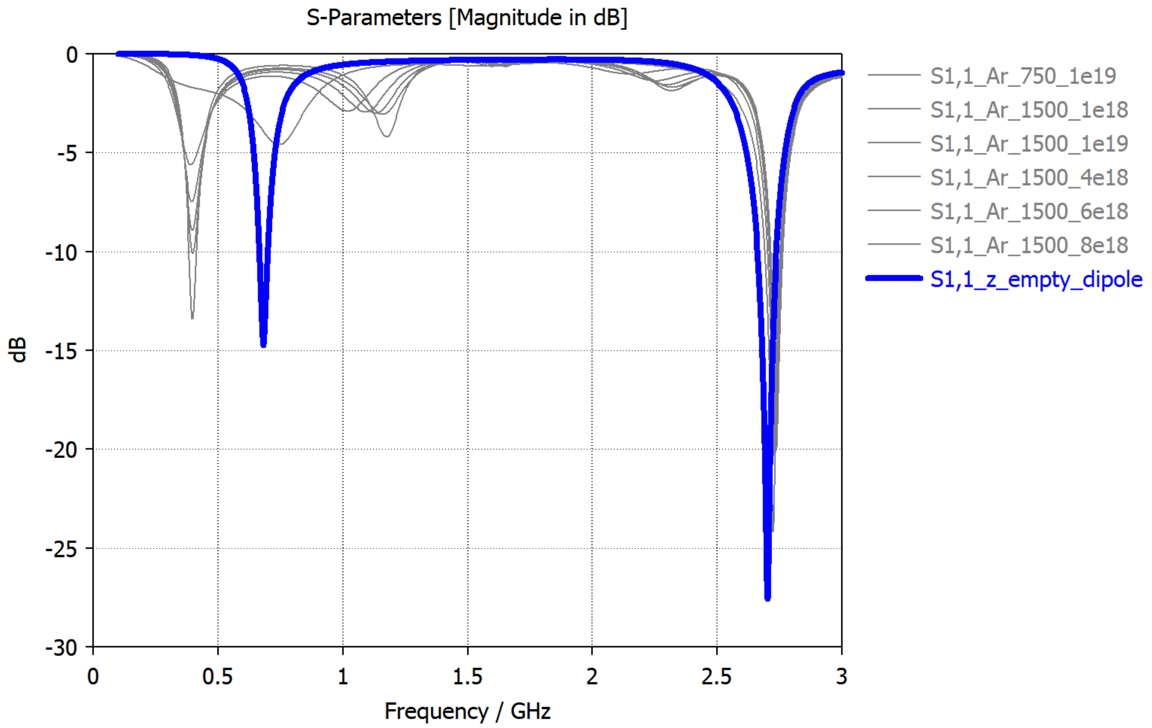


Figure 16 Magnitude of the reflection coefficient S11 of the empty simplified dipole.

S11 parameter of the empty dipole. Clearly, there is no well at any frequency close to the other S11 parameters (around 400MHz).

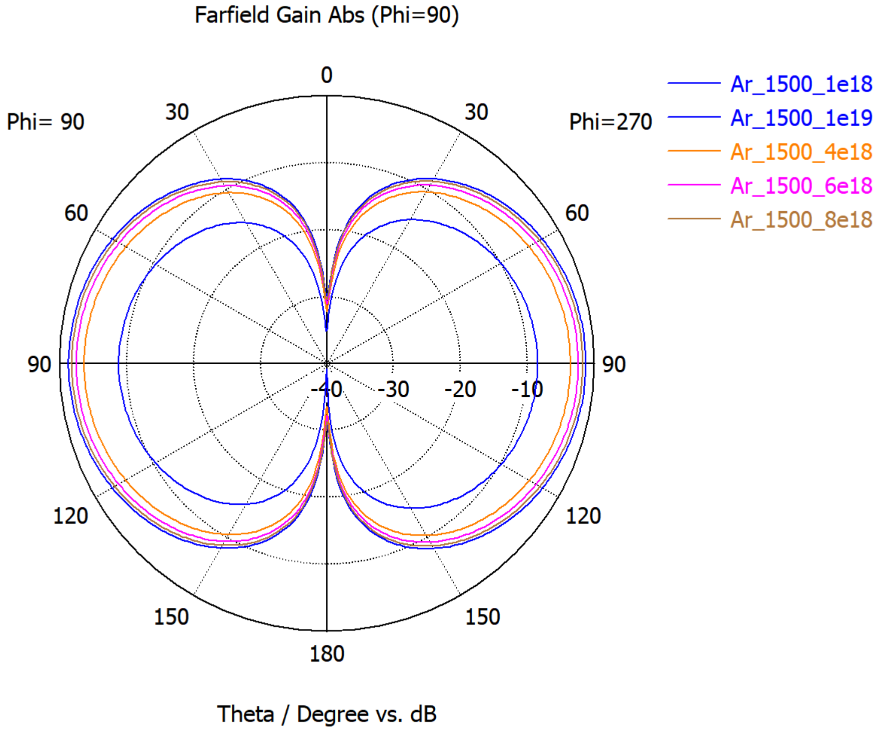


Figure 17 Gain of the Argon-filled simplified dipole at constant pressure and different plasma densities for phi = 90º. The maximum gain value is -1.34 dB for the Argon plasma at a density of 1e19 m^{-3}.

For constant pressure, the higher the density, the greater the gain.

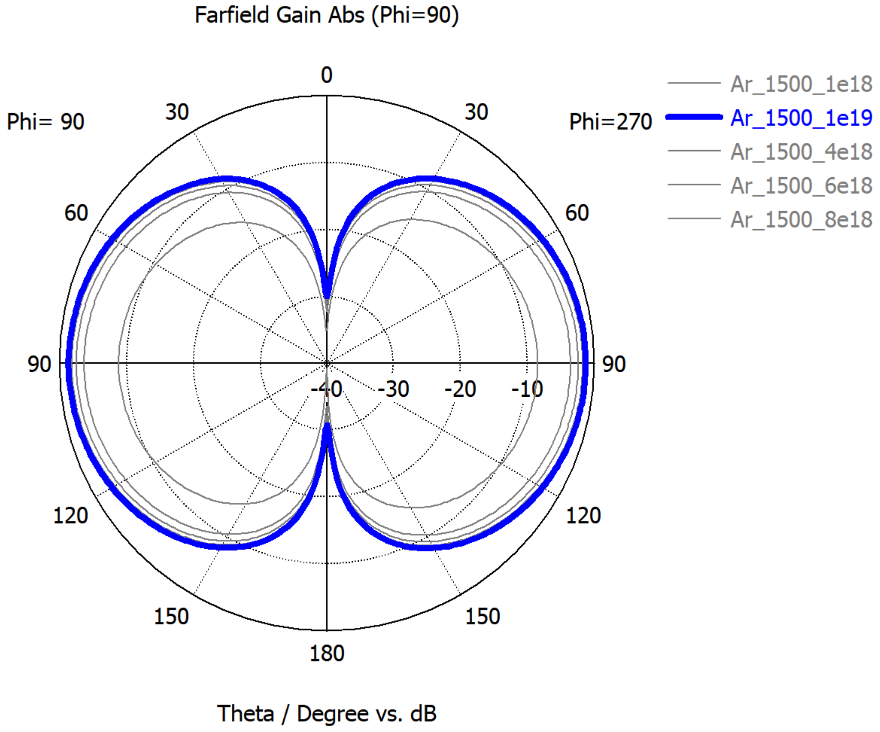


Figure 18 Highest S11 value of the Argon-filled simplified dipole at constant pressure and different plasma densities for phi=90º. The maximum gain value is -1.34 dB for the Argon plasma at a density of 1e19 m^{-3}.

4.2.2.2. Argon | Variable pressure | 1e19 e^-/m^3

Pressure [mTorr]	wp [rad/s]	wc [Hz]	s11 [dB]	f_res [Hz]	z11_real [Ω]	z11_imag [Ω]	main_lobe [dB]
750	1.78E+11	2.51E+09	-13.418788	0.3987	67.926611	-5.0984071	-0.386
1500	1.78E+11	4.96E+09	-10.077982	0.3987	81.786215	-13.863454	-1.34
2250	1.78E+11	7.41E+09	-8.1541016	0.39998	95.118242	-22.144893	-2.1

Table 7 Antenna parameters of the Argon-filled simplified dipole at constant density and different pressure.

As pressure increases:

- The s11 parameter increases.
- There is a very slight shift in frequency.
- The absolute value of the real part and of the imaginary part of z11 increase.
- The antenna directivity decreases.

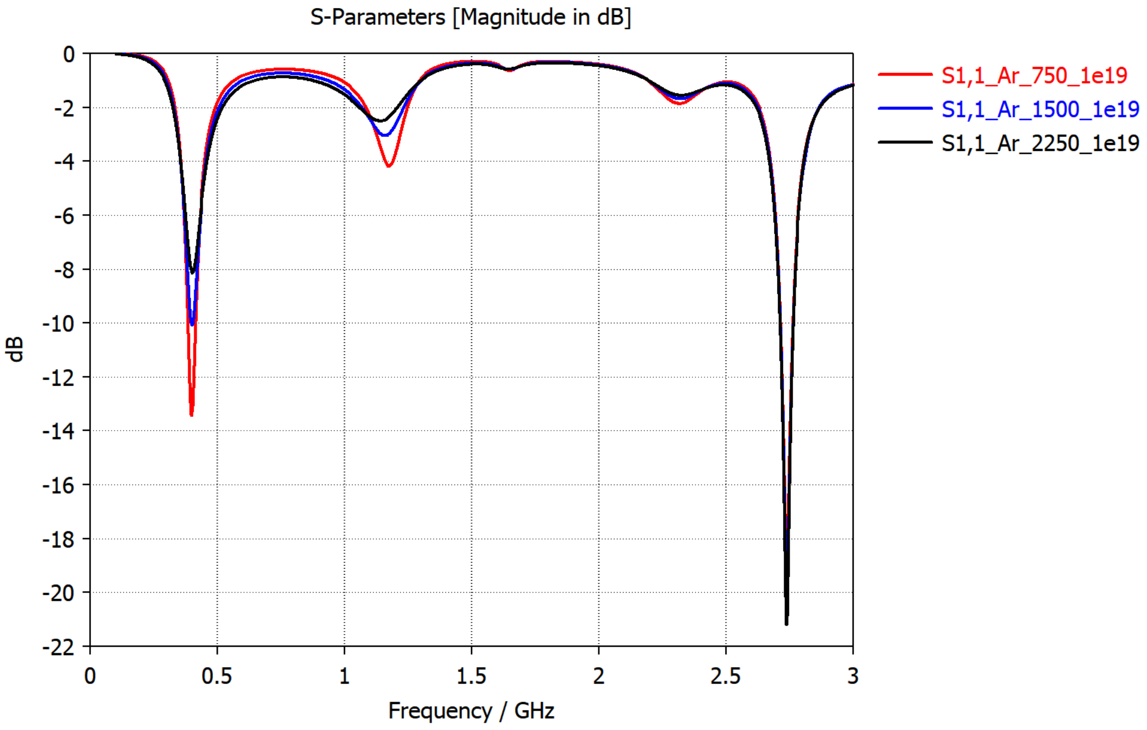


Figure 19 Magnitude of the reflection coefficient S11 of the Argon-filled simplified dipole at constant density and different pressure.

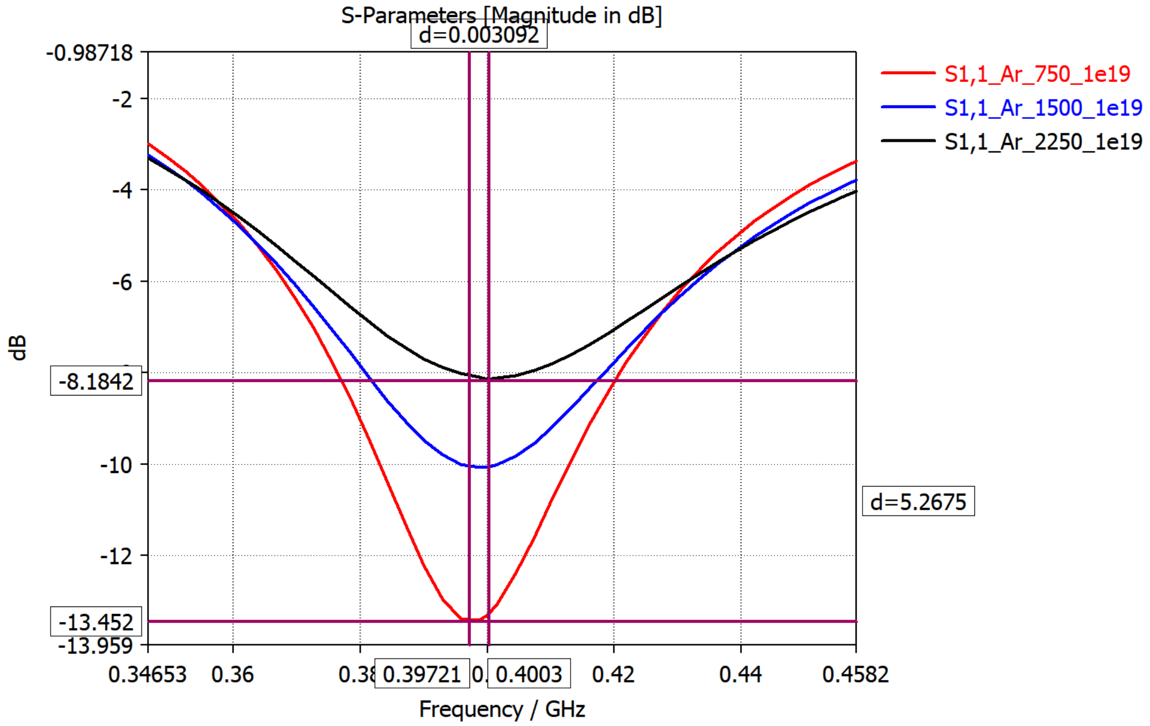


Figure 20(Detail) Slight frequency shift to higher pressure as plasma pressure increases.

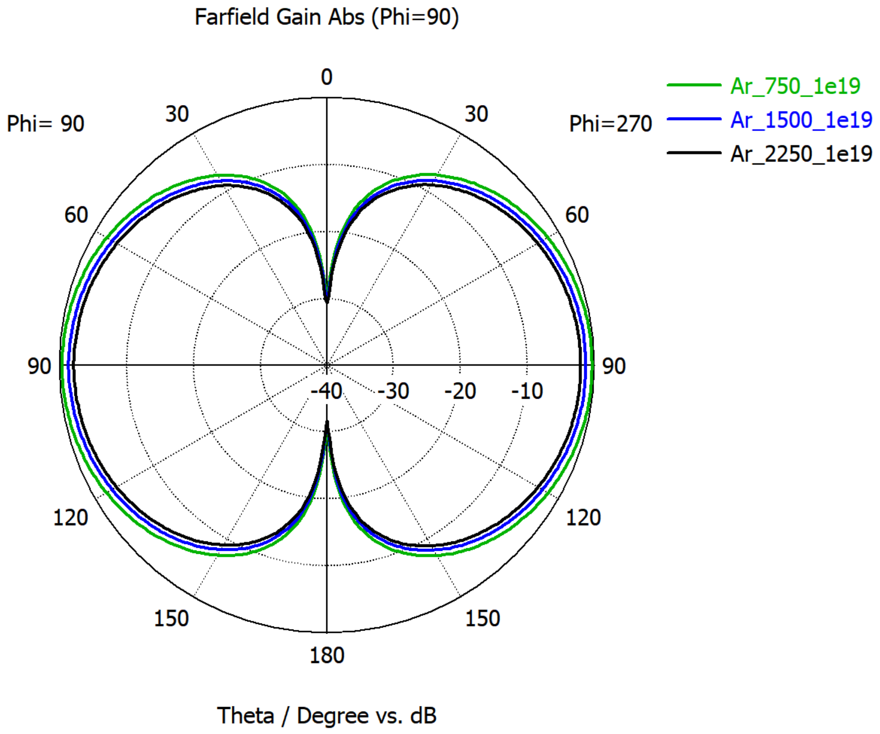


Figure 21 Gain of the Argon-filled simplified dipole at constant density and different pressure for phi = 90º. The maximum gain value is -0.386 dB for the Argon plasma at a pressure of 750 mTorr.

4.2.2.3. Argon, Neon, Xenon and Krypton | 1500 mTorr | 1e19 e^-/m^3

Gas	wp [rad/s]	wc [Hz]	s11 [dB]	f_res [Hz]	z11_real [Ω]	z11_imag [Ω]	main_lobe [dB]
Argon	1.78E+11	4.96E+09	-10.077982	0.3987	81.786215	-13.863454	-1.34
Neon	1.78E+11	1.35E+09	-16.254547	0.39596	58.950476	-6.578189	0.111
Krypton	1.78E+11	8.12E+09	-7.7432227	0.40158	99.660458	-23.18649	-2.27
Xenon	1.78E+11	1.32E+10	-5.7496109	0.40745	123.14495	-41.86863	-3.38

Table 8 Antenna parameters of the Argon-filled simplified dipole at constant density and pressure for Argon, Neon, Krypton and Xenon.

- Neon produces a smaller s11 parameter and the lowest resonance frequency.
- Xenon produces a larger s11 parameter and the highest resonance frequency.
- Xenon produces a more directive antenna.
- The input impedance of the antenna varies significantly for every gas.

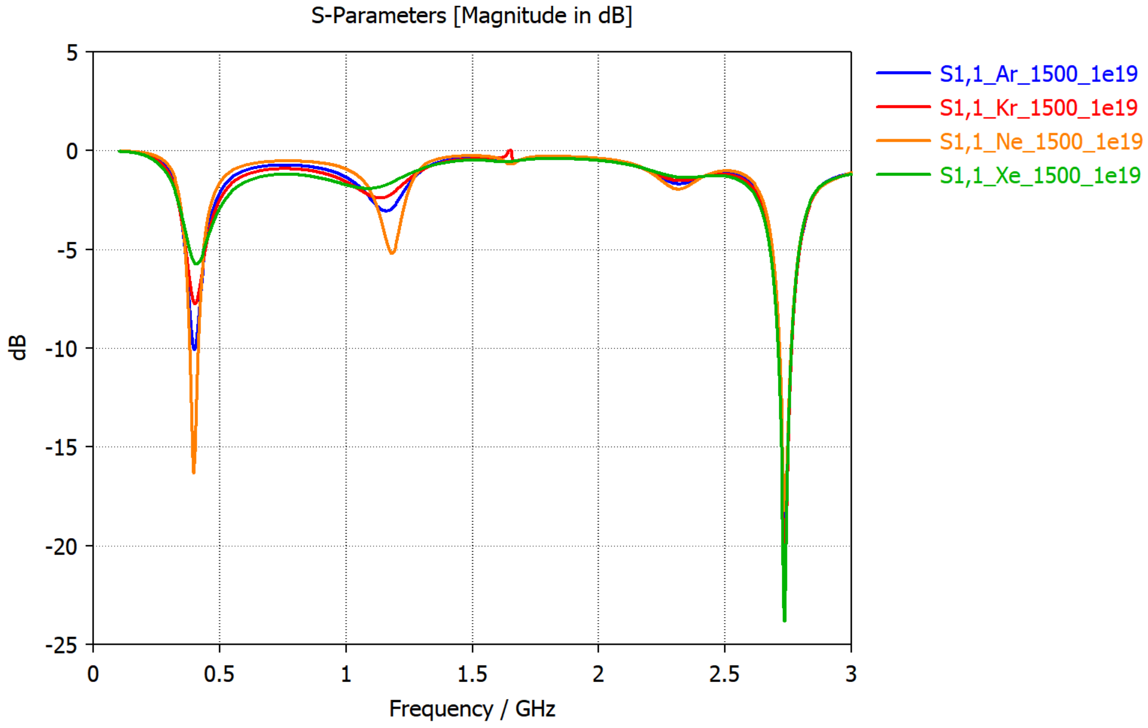


Figure 22 Magnitude of the reflection coefficient S11 of the Argon-filled simplified dipole at constant pressure and plasma density for Argon, Neon, Krypton and Xenon.

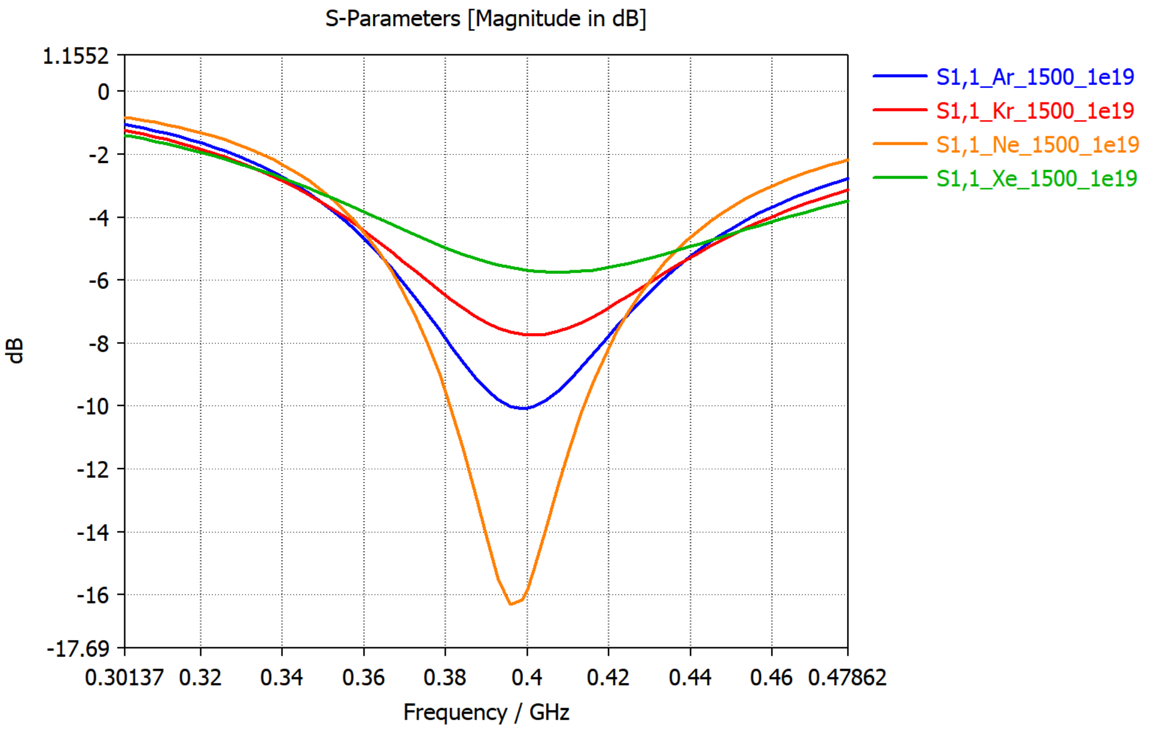


Figure 23 (Detail) Magnitude of the reflection coefficient S11 of the simplified dipole at constant pressure and plasma density for Argon, Neon, Krypton and Xenon.

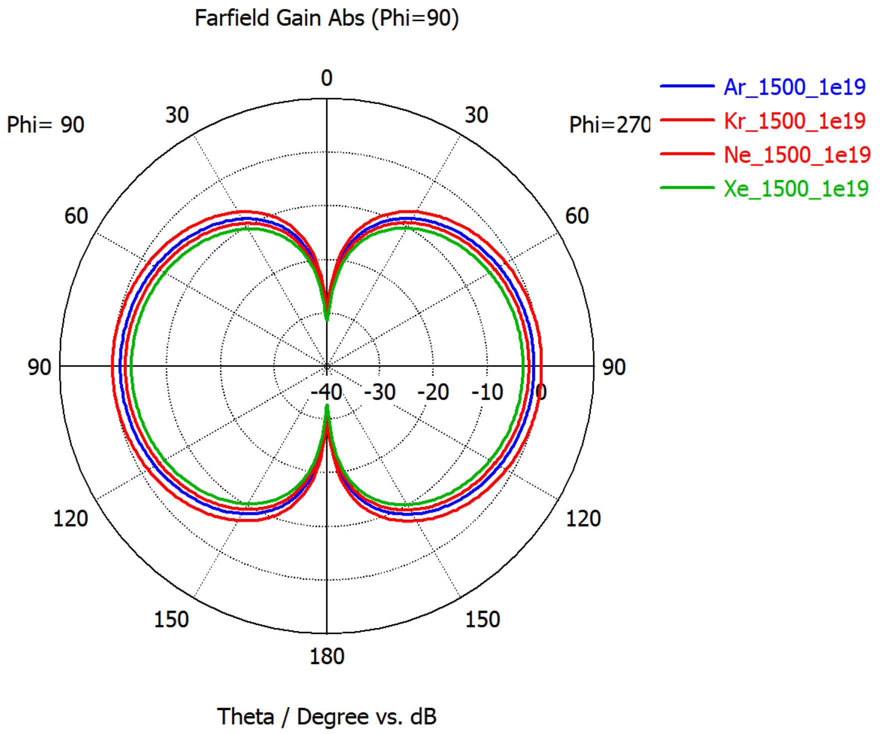


Figure 24 Gain of the simplified dipole at constant pressure and plasma plasma density for Argon, Krypton, Neon and Xenon for phi = 90º. The maximum gain value is 0.111 dB for the neon plasma.

Neon produces the highest gain and Xenon the smallest. This is because Xenon has the highest collision frequency (See Figure 11). Collisions result in losses in terms of radiated power.

These findings do not produce evident results on which plasma configuration is best without a definition of what “best” means. The best configuration will depend on the needs of the user, the location of the antenna, the available technology and other factors. Notwithstanding, the results shine a light on how all the variables involved in this simulation interact. For example: if the goal is to implement a more directive antenna, according to the data we would choose Xenon. Nevertheless, the s11 parameter is the biggest for Xenon. By reducing the pressure of the plasma, the s11 parameter can be decreased. Reducing the pressure increases the directivity (Figure 21), but that does not help if the goal is to design an omnidirectional antenna. Nevertheless, Xenon produces an input impedance far from 50 Ω while. On the other hand, Neon produces an input impedance much closer to the 50 Ω standard (Table 8).

This is just an example of how intricate the relation between the plasma parameters and the antenna parameters is. At the end of the day, having very clear the purpose of the antenna to be designed, one should review the relationships between parameters and run more specific simulations.

Crossed-dipole

4.2.3. Classic crossed-dipole

The cross-dipole, also known as turnstile antenna, consists of two dipoles at 90º fed with a phase difference of 90º. It can receive and transmit circularly polarised waves.

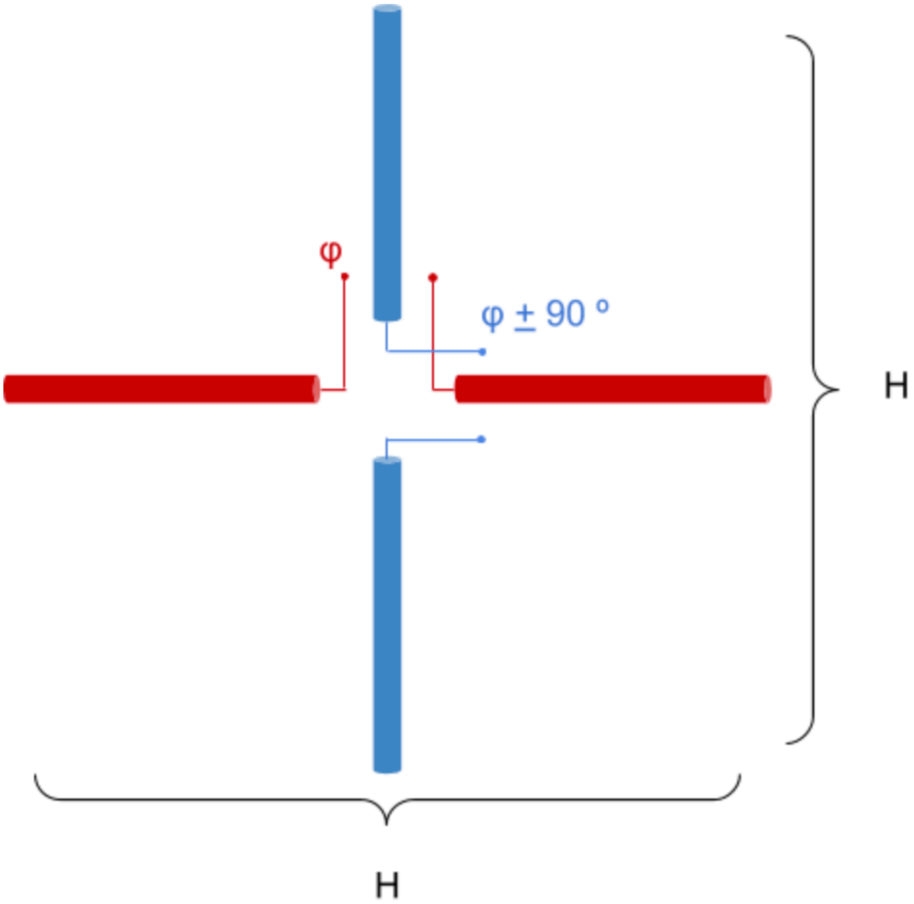


Figure 25 Schematic of a crossed-dipole.

4.2.4. Plasma crossed-dipole

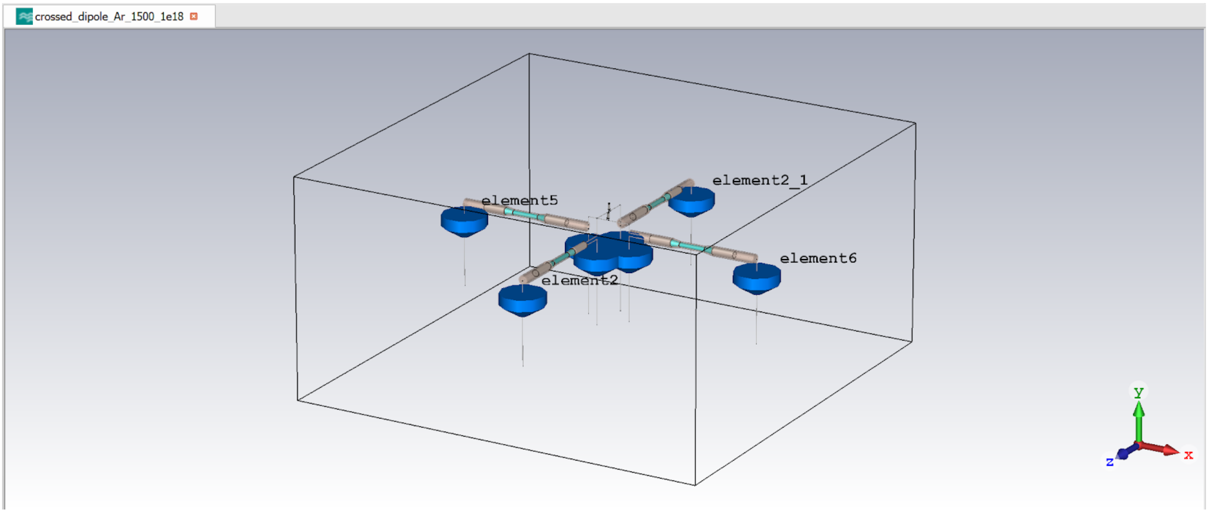


Figure 26 CST model of the crossed-dipole.

In the plasma model of the crossed-dipole every arm has two ports: one for the signal and another to energise and de-energise the plasma. There are lumped elements between the arms of the dipoles and the connections to the power source to truncate the antenna. Otherwise, the frequency operating frequency would be off.

These are the results after simulating the model:

4.2.4.1. Argon | 1500 mTorr | Variable density

Density [m^{-3}]	**wp** [rad/s]	**wc** [Hz]	**s11** [dB]	**f_res** [Hz]	**z11_real** [Ω]	**z11_imag** [Ω]	**main_lobe** [dB]	**AR<3dB** [º]
1E+18	5.64E+10	4.91E+09	-11.337266	0.30408	27.33107	-9.213922		69.696
4E+18	1.13E+11	4.93E+09	-6.3400523	0.47605	110.79225	-39.337448	1.701	62.406
6E+18	1.38E+11	4.94E+09	-8.2842868	0.4799	94.681541	-20.534305	1.76	57.541
8E+18	1.60E+11	4.95E+09	-9.801828	0.4799	80.294361	-19.771991	1.753	55.912
1E+19	1.78E+11	4.96E+09	-11.085483	0.4828	77.505524	-8.7764133	1.797	49.98

Figure 27 Antenna parameters of the Argon-filled crossed-dipole at constant pressure and different plasma densities.

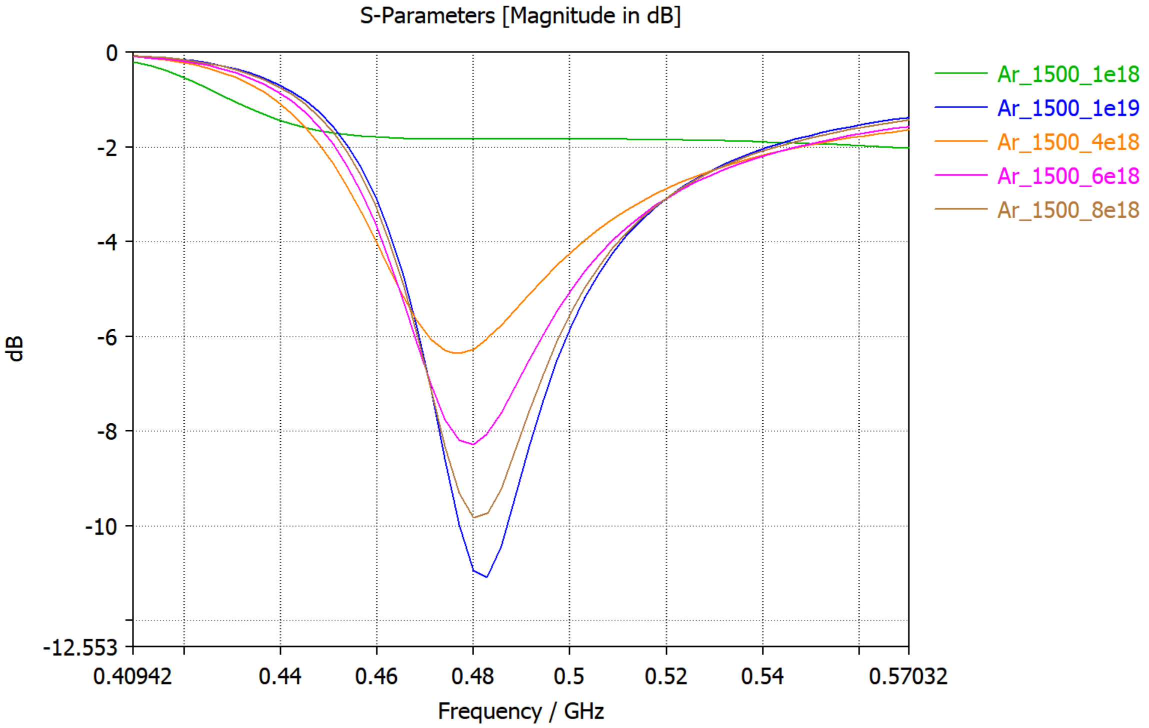


Figure 28 (Detail) Magnitude of the reflection coefficient S11 of the Argon-filled crossed-dipole at constant pressure and different densities.

The higher the plasma density, the deepest the S11 parameters. This coincides with the conclusions drawn from the simulation of the simplified dipole.

Figure 29 shows the results for the axial ration on varying the plasma density. Plasma density is related to the <3 dB axial ratio of the antenna. In fact, the lowering the plasma density improves it. In this case, a tenfold decrease in plasma density produces, approximately, a |10º| improvement in <3 dB axial ratio.

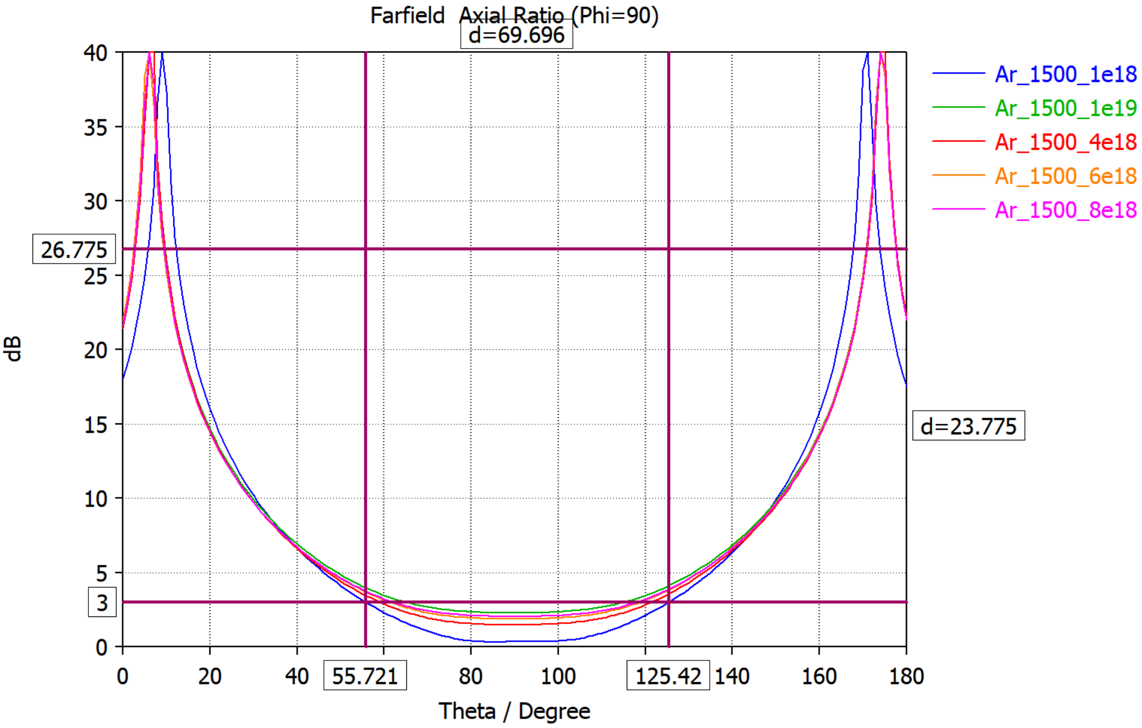


Figure 29 Magnitude of the axial ratio of the Argon-filled crossed-dipole at constant pressure and different densities.

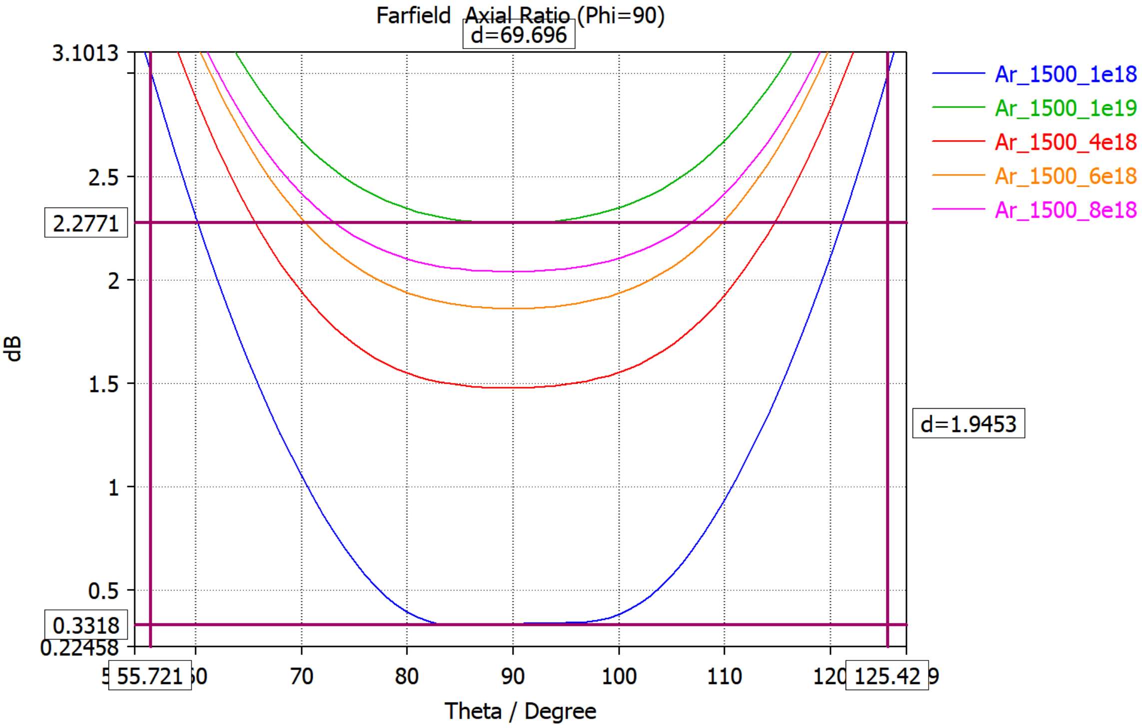


Figure 30 (Detail) Magnitude of the axial axial ratio of the Argon-filled crossed-dipole at constant pressure and different densities.

4.2.4.2. Argon | Variable pressure| 1e19 e^-/m^3

Pressure [mTorr]	**wp** [rad/s]	**wc** [Hz]	**s11** [dB]	**f_res** [Hz]	**z11_real** [Ω]	**z11_imag** [Ω]	**main_lobe** [dB]	**AR<3dB** [º]
750	1.78E+11	2.51E+09	-14.707592	0.48279	64.256367	-3.1907833	1.793	43.15
1500	1.78E+11	4.96E+09	-11.085483	0.4828	77.505524	-8.7764133	1.797	49.98
2250	1.78E+11	7.41E+09	-9.0113484	0.48291	89.447492	-16.358286	1.802	55.594

Table 9 Antenna parameters of the Argon-filled crossed-dipole at constant density and different pressure.

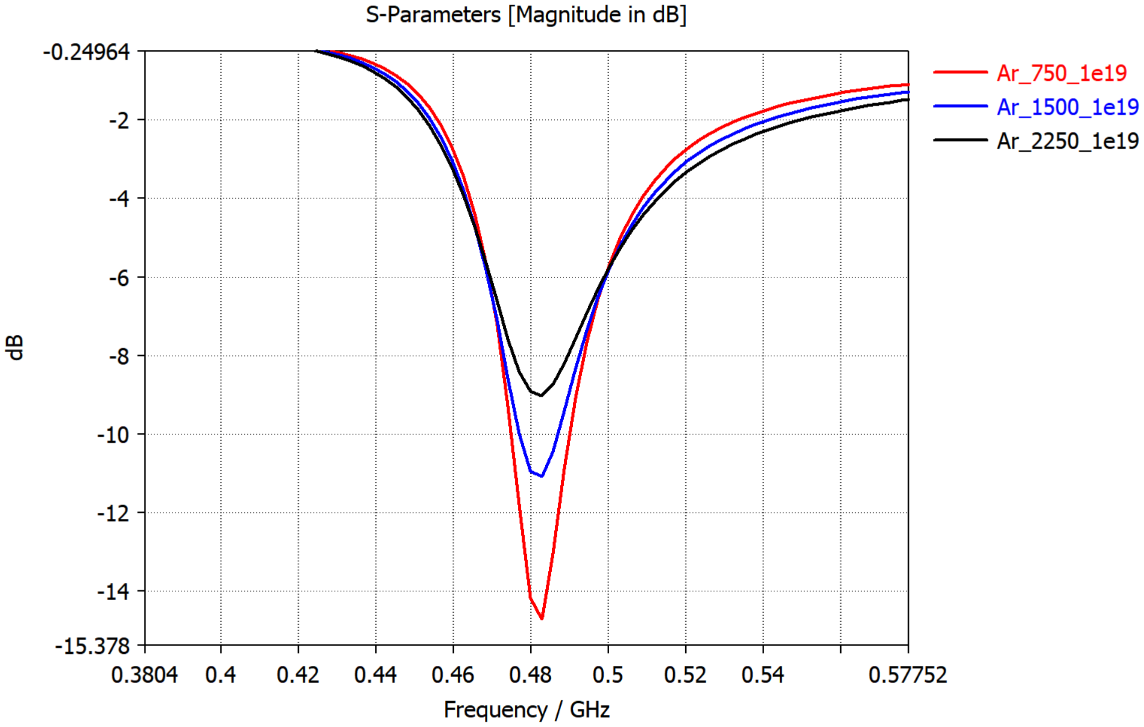


Figure 31 (Detail) Magnitude of the reflection coefficient S11 of the Argon-filled crossed-dipole at constant density and different pressure.

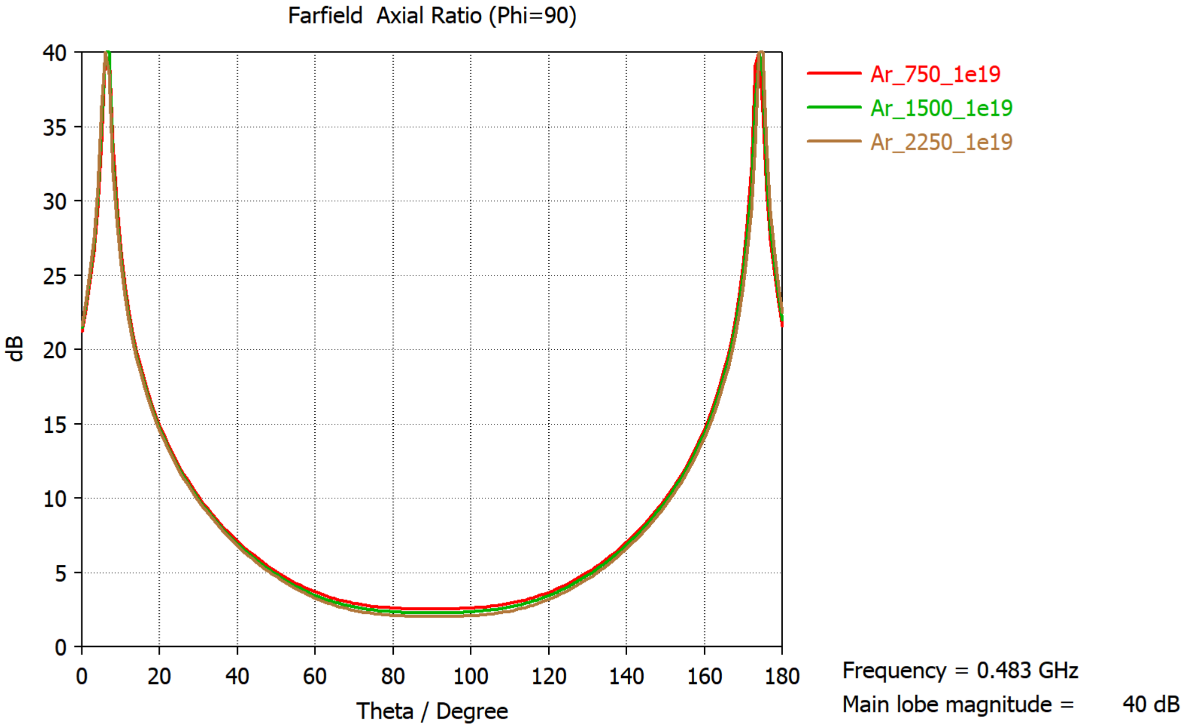


Figure 32 Magnitude of the axial ratio of the Argon-filled crossed-dipole at constant density and different pressure.

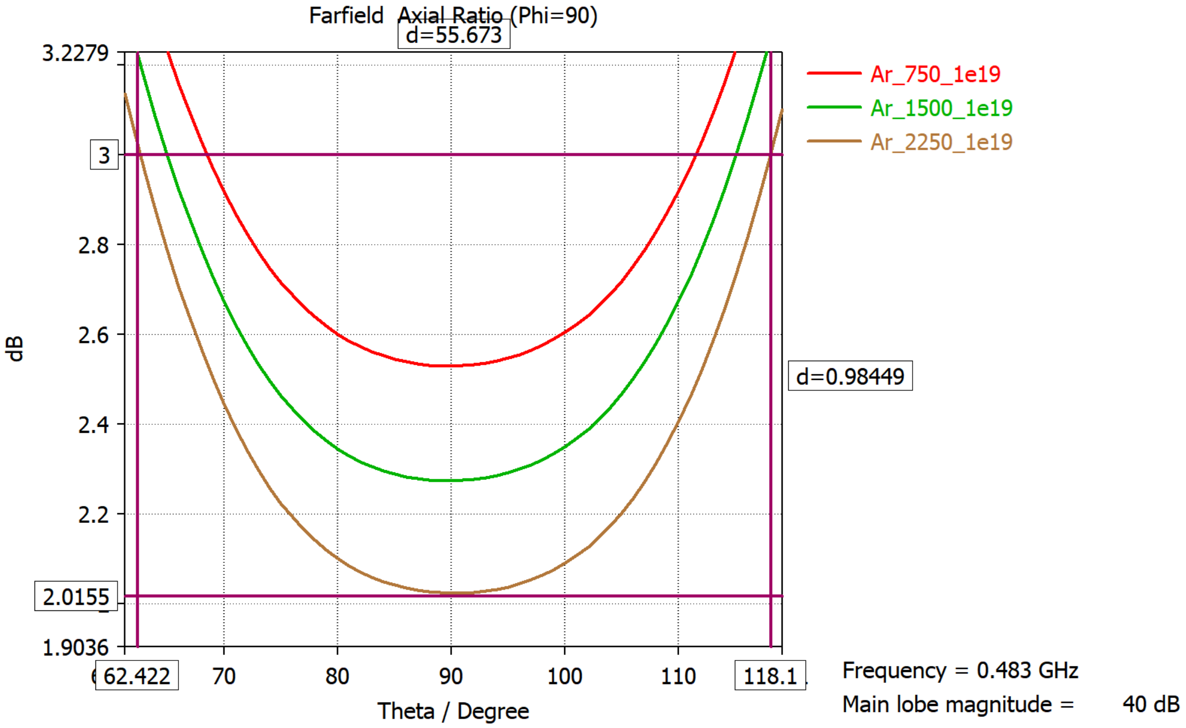


Figure 33 (Detail) Magnitude of the axial ratio of the Argon-filled crossed-dipole at constant density and different pressure.

The higher the pressure, the wider the range in which the antenna can receive circularly polarised waves.

4.2.4.3. Argon, Neon, Xenon and Krypton | 1500 mTorr | 1e19 e⁻/m³

Gas	wp [rad/s]	wc [Hz]	s11 [dB]	f_res [Hz]	z11_real [Ω]	z11_imag [Ω]	main_lobe [dB]	AR<3dB [º]
Ar	1.78E+11	4.96E+09	-11.085483	0.4828	77.505524	-8.7764133	1.797	49.98
Ne	1.78E+11	1.35E+09	-18.170008	0.483	55.175471	-6.1902016	1.756	43.811
Kr	1.78E+11	8.12E+09	-8.6417281	0.483	90.467358	-20.955578	1.794	60.091
Xe	1.78E+11	1.32E+10	-6.374303	0.483	110.51694	-39.190619	1.81	62.774

Table 10 Antenna parameters of the Argon-filled crossed-dipole at constant density and pressure for Argon, Neon, Krypton and Xenon.

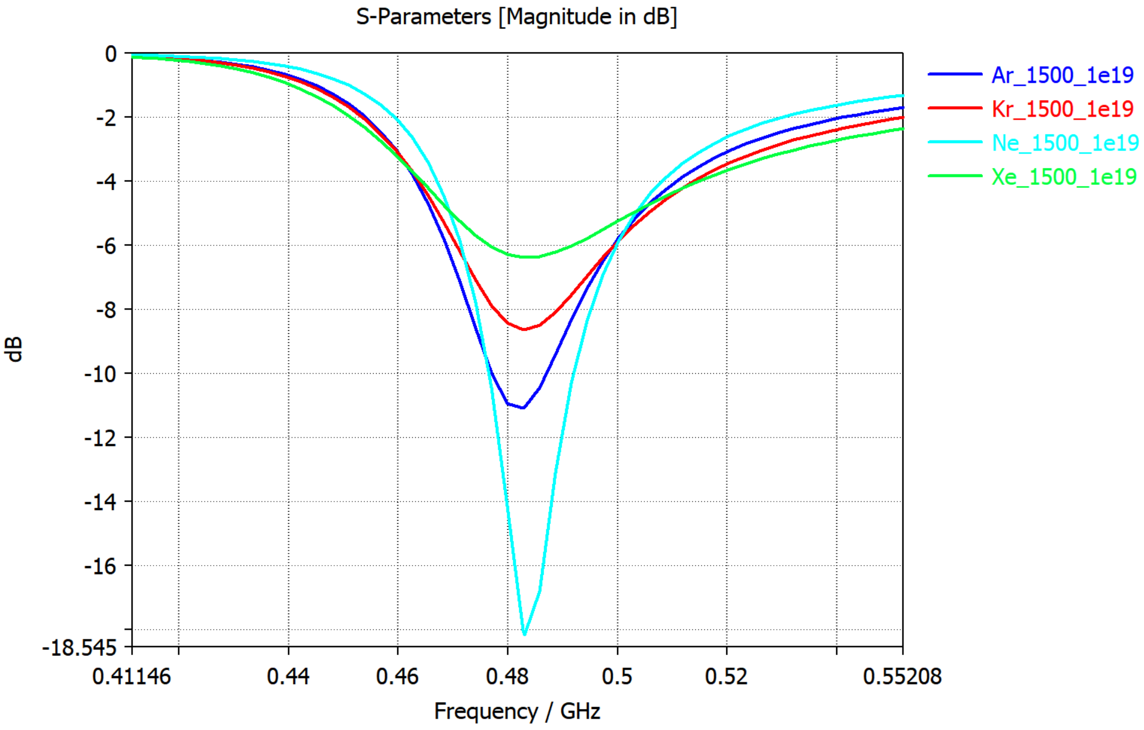


Figure 34 Magnitude of the reflection coefficient S11 of the crossed-dipole at constant pressure and plasma density for Argon, Neon, Krypton and Xenon.

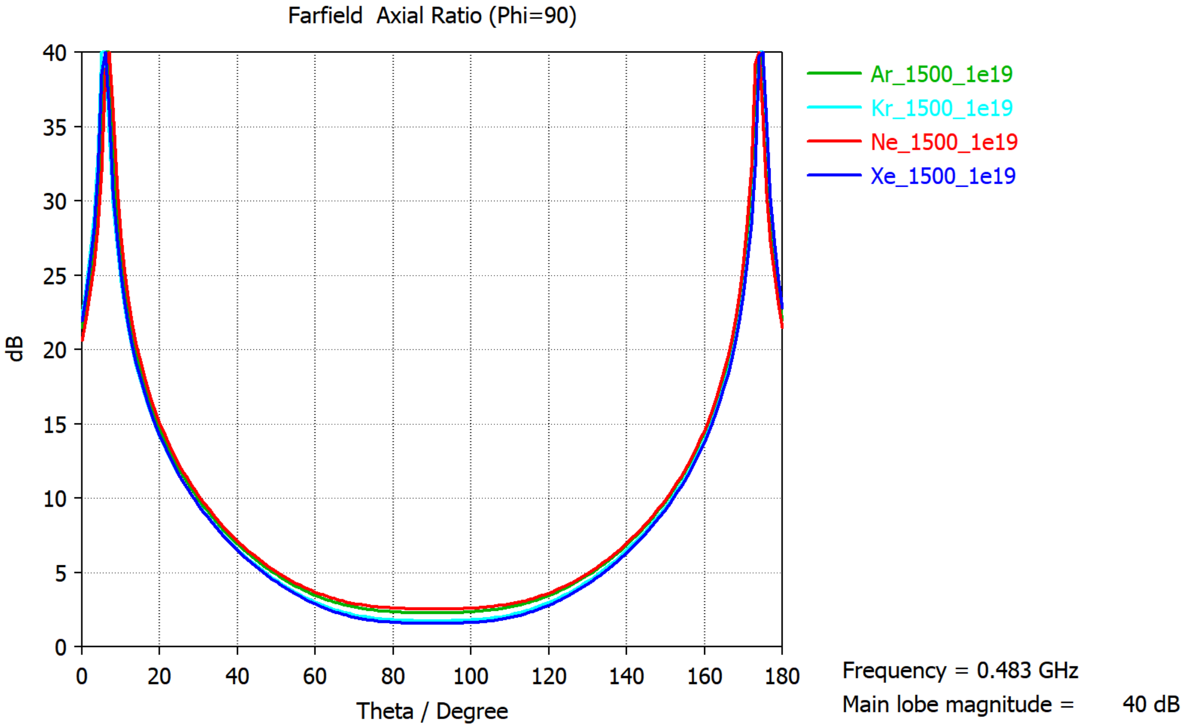


Figure 35 Magnitude of the axial ratio of the crossed-dipole at constant pressure and plasma density for Argon, Krypton, Neon and Xenon.

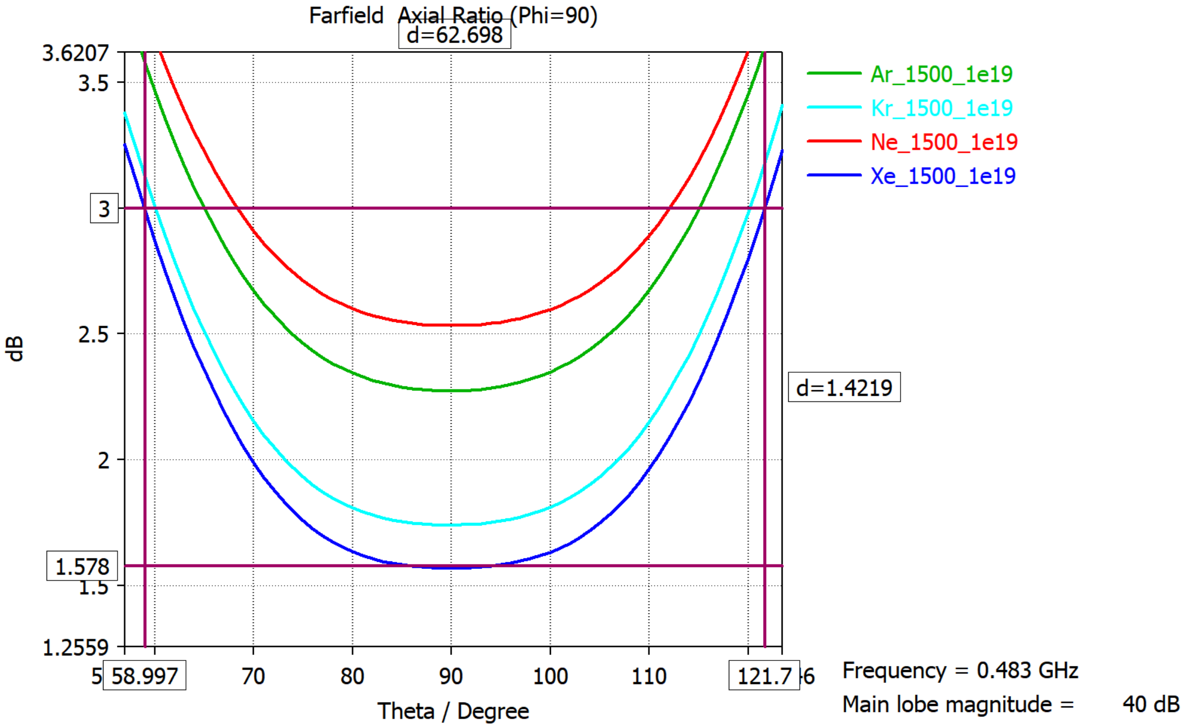
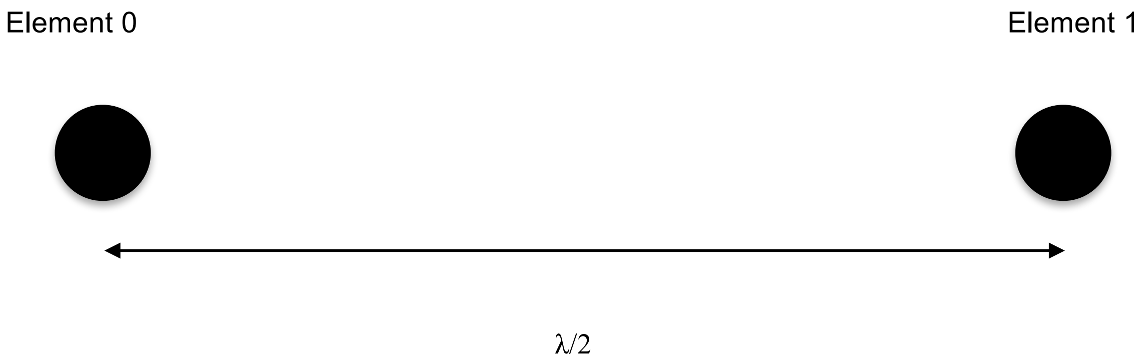


Figure 36 (Detail) Magnitude of the axial ratio of the crossed-dipole at constant pressure and plasma density for Argon, Krypton, Neon and Xenon.

Xenon would provide the best axial ratio in terms of receiving circularly polarised waves.

4.3. Crossed-dipole array



To simulate a two element array, we chose the following plasma configuration:

Gas: Neon

Pressure = 1500 mTorr

Density = 1e19 e^-/m^3

Table 10 is very helpful to understand the choice.

1. Neon has the smallest S11 parameter.
2. Re{Z11} ≈ 50 Ω
3. Im{Z11} ≈ 0 Ω
4. The main lobe gain is almost equal to the biggest one (Ar). This is under the assumption that we wish to design a more directive antenna.
5. Neon is cheaper than Krypton and Xenon (23).

There are drawbacks, of course. The axial ratio is worse and, in practical terms, Neon requires much more power than Argon to reach the same density,

4.3.1. Two energised elements

4.3.1.1. Method 1: CST far field Calculation of Antenna Arrays

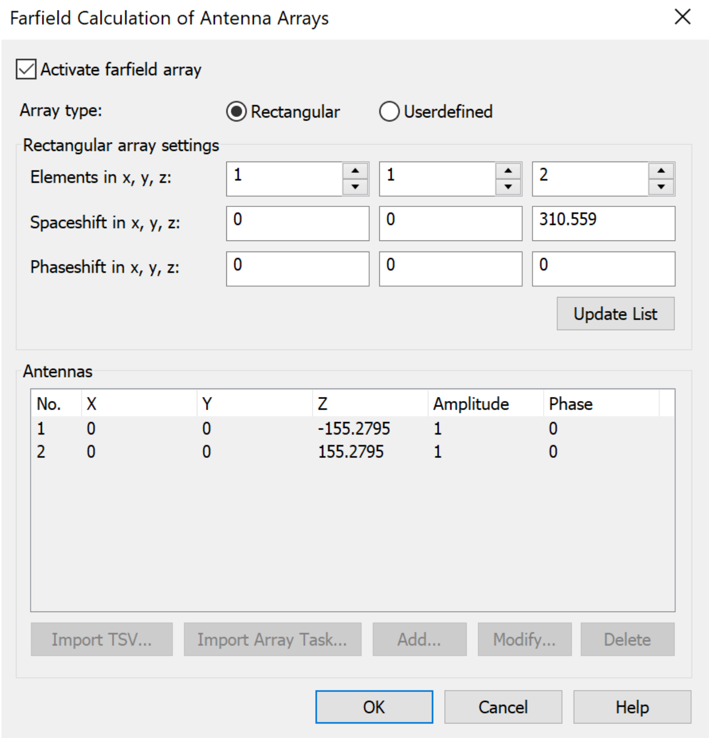
This first method uses CST's capabilities to quickly compute far fields after having simulated the antenna. The parameters can be seen below:

The wavelength is:

$$\lambda \ = \frac{c}{f} = \frac{3 \cdot 10^8}{483 \cdot 10^6} = 0.621\, m = 621\, mm$$

And the spacing is:

$$\frac{\lambda}{2} = 0.310599\, m = 310.599\, mm$$



☑ Activate farfield array

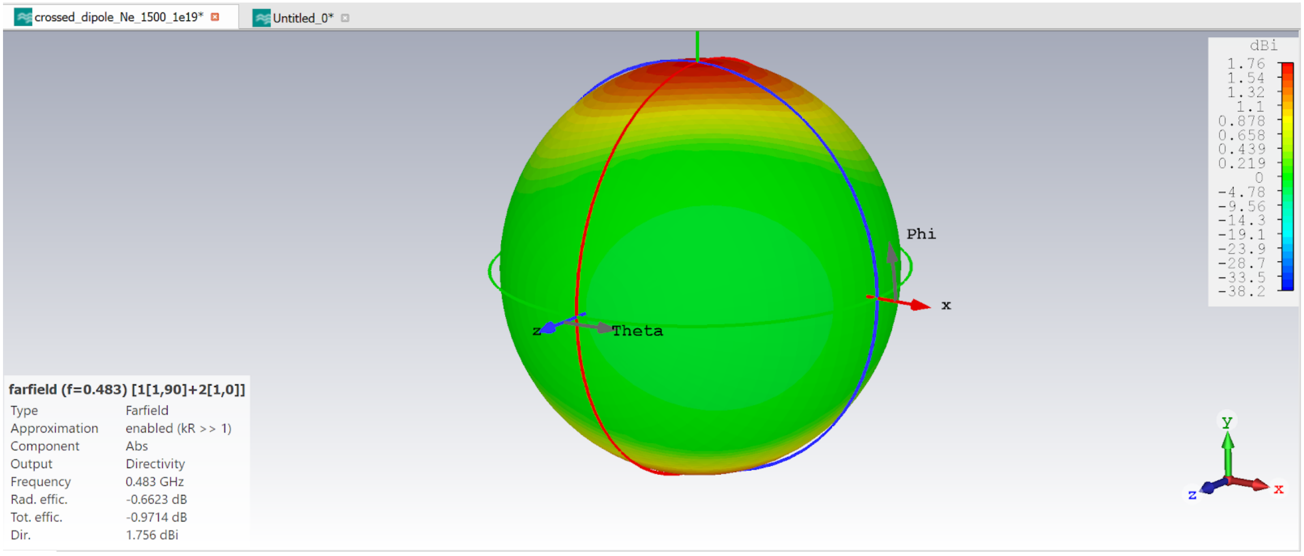
Array type: ● Rectangular ○ Userdefined

	x	y	z
Elements in x, y, z:	1	1	2
Spaceshift in x, y, z:	0	0	310.559
Phaseshift in x, y, z:	0	0	0

No.	X	Y	Z	Amplitude	Phase
1	0	0	-155.2795	1	0
2	0	0	155.2795	1	0

Figure 37 Configuration of the two energised crossed-dipole array in CST.

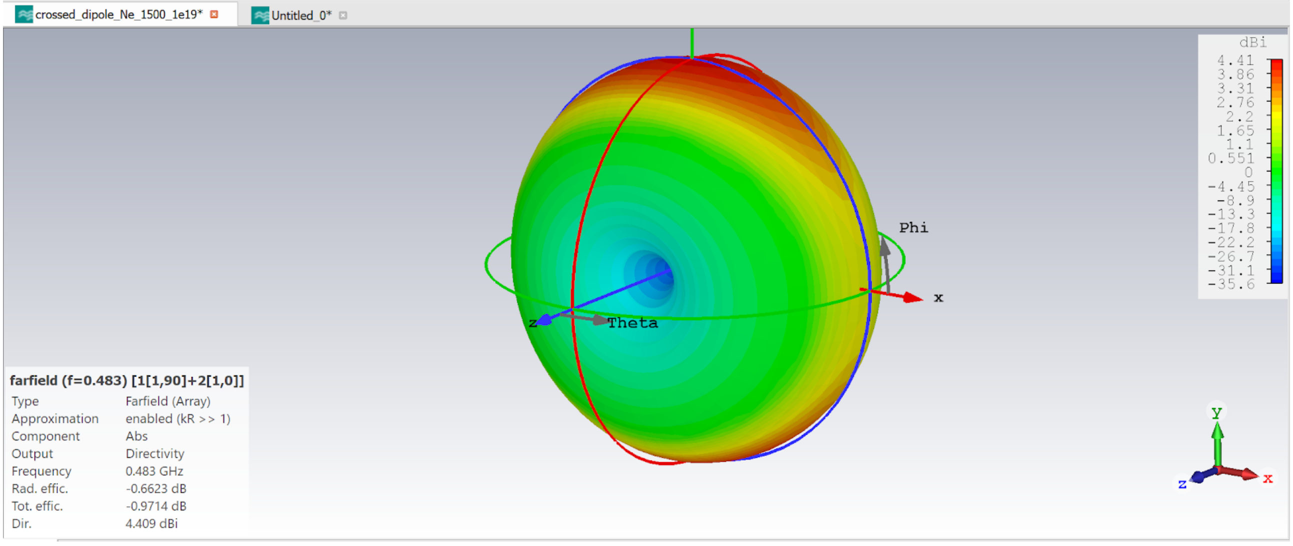
The following radiation patterns show that plasma antennas can be arranged in arrays like any classic antenna. The first picture is the radiation pattern of a single element. The second corresponds to the array. The array is much more directive (see the colour scale).



farfield (f=0.483) [1[1,90]+2[1,0]]

Type	Farfield
Approximation	enabled (kR >> 1)
Component	Abs
Output	Directivity
Frequency	0.483 GHz
Rad. effic.	-0.6623 dB
Tot. effic.	-0.9714 dB
Dir.	1.756 dBi

Figure 38 3D radiation diagram of the energised plasma crossed-dipole.



farfield (f=0.483) [1[1,90]+2[1,0]]

Type	Farfield (Array)
Approximation	enabled (kR >> 1)
Component	Abs
Output	Directivity
Frequency	0.483 GHz
Rad. effic.	-0.6623 dB
Tot. effic.	-0.9714 dB
Dir.	4.409 dBi

Figure 39 3D radiation diagram of a two energised plasma crossed-dipole array.

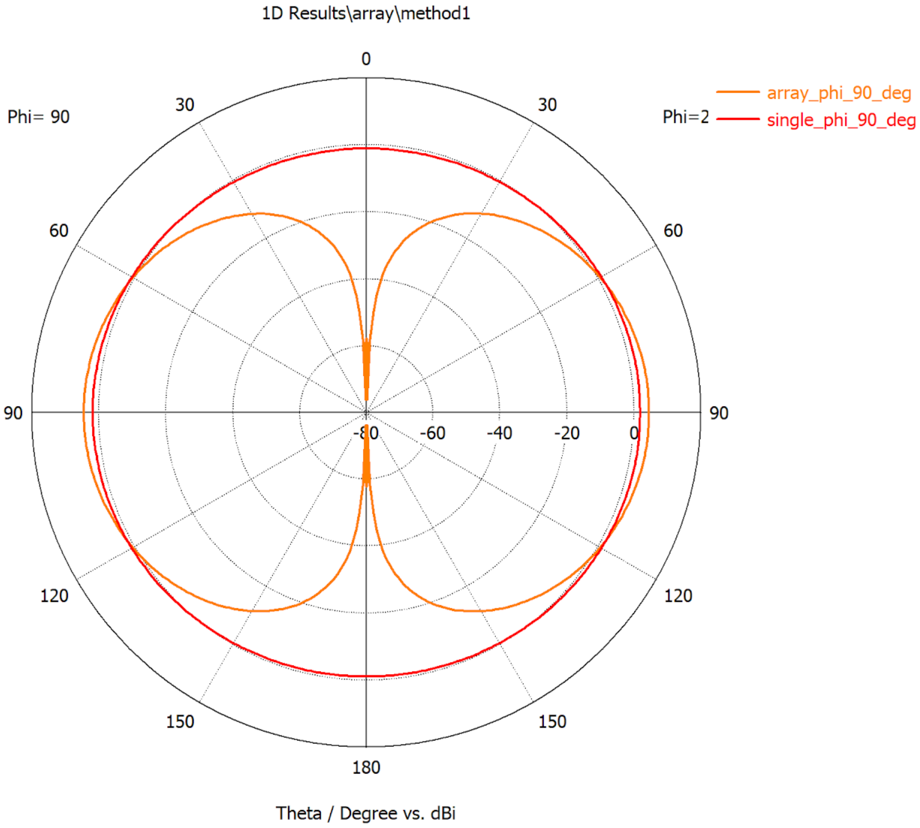


Figure 40 Radiation pattern of the single element and the array for phi = 90º.

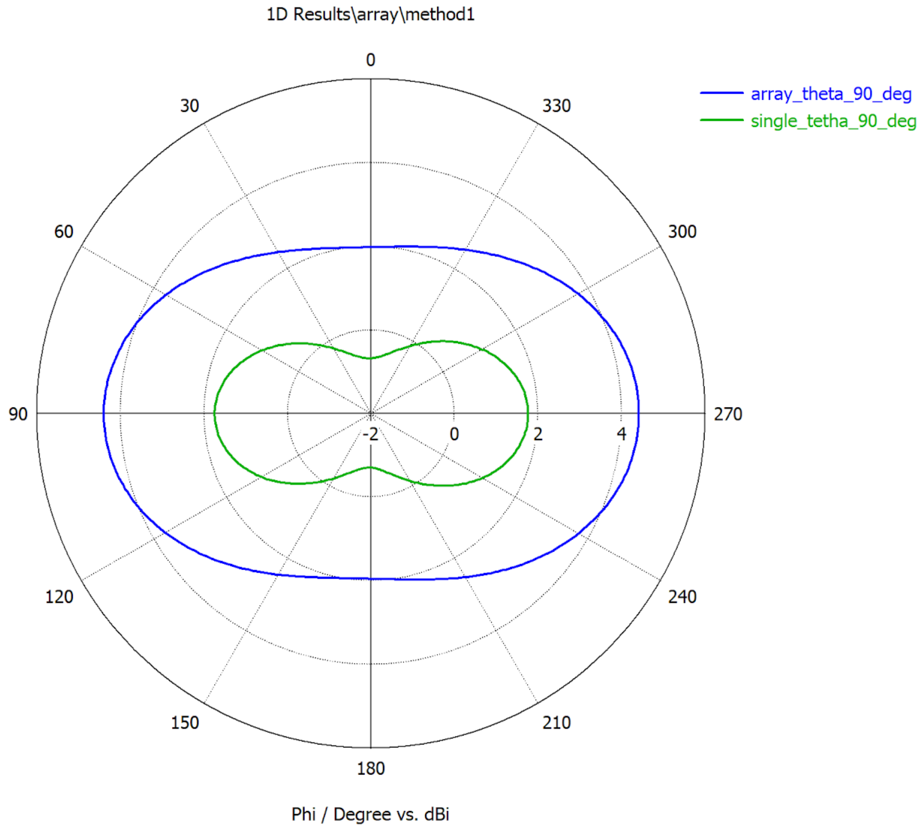


Figure 41 Radiation pattern of the single element and the array for theta = 90º.

5. Budget

The duration of this work was of 4.5 months with a dedication of 25 hours per week(1 ECTS). Assuming a salary of 9 €/hour[1], the compensation for a junior engineer would be of 4050 €.

“Seguridad social” taxes are approximately 30% of the compensation under Spanish law. In this case, 4050 € * 0.3 = 1215 €.

CST STUDIO SUITE is free for students with an institutional “.edu” email address. 3DS, the owner of the software, only discloses the price to those interested in buying the software. By searching online[2], a CST STUDIO SUITE license has an estimate cost of 2500 € for members of degree granting institutions.

The computer we used has a price tag of 1300 €. If we assume that it has a lifespan of 6 years and that after that time its value is 60% of the original price, its cost is 130 € per year:

1300 € * 0.6 / 6 year = 130 €/year

Concept	Price (€)	Lifespan	Cost (€)
Compensation	4050		4050
“Seguridad social”	1215		1215
CST STUDIO SUITE	2500	1	2500
Computer	1300	6	130
		Total	7895

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[1] Recommended salary by ETSETB for degree internships.
[2] https://www.edaboard.com/threads/price-of-hfss-cst.166061/

6. Environment Impact

Argon, Krypton, Xenon and Neon belong to a group of cases called “noble gases”. According to Encyclopaedia Britannica, noble gases are “any of the seven chemical elements that make up Group 18 (VIIIa) of the periodic table. The elements are helium (He), Neon (Ne), Argon (Ar), Krypton (Kr), Xenon (Xe), Radon (Rn), and Oganesson (Og). The noble gases are colourless, odourless, tasteless, non-flammable gases.” Also according to Encyclopaedia Britannica, “several of these elements are quite abundant on Earth and in the rest of the universe”. Therefore, none of the gases proposed in this work are harmful for the environment.

As a general rule, the more complex a piece of equipment is, the shorter its lifespan. Plasma antennas and the equipment to operate them are complex. Therefore, they will, most likely, have a shorter lifespan than their traditional counterparts. Nevertheless, since plasma antennas will be used in very specific applications -at least in the upcoming years- we must not fear that the activity derived from their development and operation will produce any significant amount of waste. What is more: since the equipment is expensive, it will most likely be recycled.

7. Conclusions and future development:

“One size fits all” is generally not true when talking about antenna design. This is why engineers have come up with models ranging from very simple to very intricate to provide solutions for multiple systems which required an antenna. Plasma antennas are one of such solutions and a ground-breaking one, indeed. At the beginning of this document, we listed applications of interest and particularities of this technology. Through simulations, we have been able to delve into two of them: reconfigurabilty and EM invisibility.

As seen in the result obtained with CST, different plasma configurations produce antennas which behave slightly different. Moreover, antennas with identical structures can behave differently by changing the properties of the conducting material.

The results of our simulations showed some cases in which the differences were significant. For example, Neon produces S11 parameters much smaller than Xenon. In the case of the simplified dipole model, there was a difference of 10dB in the S11 parameter between both gases (See Figure 34). In order to design the best antenna for a system, an engineer involved in the field of plasma antennas should be very much acquainted with this sort of findings. However, differences are not always so clear and budget requirements have to be met. In Figure 21, a comparison of the gain for the same gas in different pressure conditions shows little improvement in the gain of the simplified dipole model. In addition to that, increasing frequency produces a frequency shift towards higher frequencies and vice versa. Therefore, the designer should have a good reason to use Argon over Neon. Such reason could be that Argon produces better axial ratios for circularly polarised antennas. Figure 36 backs this statement. Yet, again, the engineer should evaluate the trade-offs. One important trade-off is that reaching high densities with Neon requires much more power than Argon.

Choosing one gas or another is one of the various questions engineers would need to ask themselves, of course. Nevertheless, the pressure and density of the plasma are also key in the performance of the antenna. They also affect the S parameters, gain, axial ratio and others. Figure 33 shows a difference of around 2x6º = 12º from main beam in <3dB axial ratio for the crossed-dipole. In a high noise, power constrained service where the information is transmitted in two orthogonal components, such difference could need to be taken into account. Again, studying the particular goal of the antenna is paramount. An antenna on the surface of the Earth receiving a circularly polarised wave like from a satellite in orbit needs a sufficiently good axial ratio because of Faraday rotation happening in the ionosphere. Especially in the VHF (Very High Frequency) and UHF (Ultra High Frequency) bands (6). GPS (Global Positioning System) signals are circularly polarised (24), for example. However, axial ratio could be sacrificed to benefit another parameter in an Earth-Earth radio link with fixed stations where this kind of phenomenon is not present and the antennas do not change position nor rotate.

The property of invisibility is harder to implement in practice than in theory. For example: the crossed-dipole array model contains many of the elements that its practical implementation would contain as well. Both structurally (support) and electrically (filters and power). Nevertheless, when one of the two elements is not energised, the conductive pieces that make it will still interfere with the wave produced by the energised element.

Therefore, the opportunity of being able to modify the antenna parameters comes at a cost. Designers need a bigger budget to design more complex systems for an application for which many antennas are already available (without the particular properties of plasma antennas, of course). A classic metallic dipole may consist of metal rods, some screws, a coaxial port and a plastic piece to keep the structure together. On the other hand, a plasma dipole requires gas, precision made containers for the gas, hardware to generate plasma, hardware to couple the signal with the plasma and filters amongst other elements. Most of the elements in this list are expensive and are mostly exclusive to expensive laboratories filled with experts. Despite these hardships and obstacles, there are good reasons to keep track of the advances of plasma antennas in the upcoming years. A lot has been learned through simulations, practical implementations and empirical studies. The research has come a long way since plasma antennas were first conceived. Researches are producing more models with better performance. When the technology fits commercial or military needs, even greater advancements will be made. This is key in this field. Plasma antennas, in the current state of technology, are best fit for very specific applications in the worlds of academia, military and space communications. It is in these fields where their development will thrive even more as they are used in specific applications.

Last but not least, a note about future work in relation to the scope of this work. Almost any conducting element in a classic antenna can be substituted by a plasma structure. Therefore, more antenna designs could be simulated and studied.

In (18), Alexeff et al. experiment with plasma frequency selective surfaces (FSS). The purpose of this surfaces is to filter EM waves, not to transmit or receive them. Simulating this kind of structures in combination with antennas would be, without a shadow of a doubt, very interesting. For example: a dihedral reflector is made of a conducting surface and an active element. The reflecting surface could be an FSS and the active element metallic a dipole. Thus, if the FSS were off, the resulting antenna would be a dipole. If it were on, the result would be a very directive antenna. Or the FSS could be kept on and by varying its plasma parameters, it would filter or not the dipoles radiation. To sum it up, there are many antennas to study given the peculiar properties of plasma. Therefore, there is a lot of room for studying the effects of plasma properties in many antennas, arrays and combinations.

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Glossary

A list of all acronyms and the meaning they stand for.

- **Ar**: Argon
- **AR**: Axial ratio
- **CST**: Electromagnetic field simulation software
- **CSTnuc**: Plasma collision frequency (Hz)
- **CSTomegap**: Plasma frequency (rad/s)
- **EM**: Electromagnetic
- **FSS**: Frequency Selective Surface
- **GPA**: Gaseous Plasma Antenna
- **He**: Helium
- **IEEE**: Institute of Electrical and Electronics Engineers.
- **Kr**: Krypton
- **Ne**: Neon
- **Og**: Oganesson
- **RF:** Radio Frequency
- **Torr**: Unit of pressure based on an absolute scale. 1 Pa = $7.5 \cdot 10^{-3}$ Torr. (25)
- **UHF**: Ultra High Frequency
- **VHF**: Very High Frequency
- **Xe**: Xenon