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Represented by

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Plasma Sources for Biomedical Applications: cyclotron radiation in plasma (ICP) torche

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Dedication

To those who planted in my heart the love of knowledge, were a support, and helped me at every step…

To my dear parents, the source of love and giving, who taught me patience and determination, and from whose prayers the landmarks of success were drawn…

To my esteemed teachers who did not spare their knowledge and guidance, as they were a light in the journey of knowledge, illuminating my path …

To my brothers and friends, who were the best companions on this journey, with their encouraging words and standing by my side at every moment…

To everyone who contributed to my support, with a word, or advice, or encouragement…

I dedicate this fruit of my effort, hoping it will be the beginning of a future full of giving and success.

Acknowledgement

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General introduction

Plasma is the highest energy state of matter. It consists of a collection of free electrons, positive ions, and neutral particles [1]. Although it is closely related to the gas phase in that it has no definite shape or volume, it differs from several ways [2]. Advances in plasma technology have enabled its use in diverse medical fields, including wound healing, cancer treatment, sterilization, and tissue engineering [3].

Cold atmospheric plasma (CAP) is one of the most commonly used plasma sources in biomedical research. It generates reactive species, including oxygen and nitrogen radicals, which play a crucial role in microbial inactivation, cell signaling, and controlled tissue modification[4]. Various plasma sources, such as dielectric barrier discharge (DBD) and plasma jets, have been developed to deliver targeted therapeutic effects without causing significant thermal damage [5].

Sterilization was the first application of plasmas in the biomedical field. Today, there are a multitude of devices for sterilizing instruments as well as parts of the human body, such as hands. Atmospheric plasmas are widely used in medicine: accelerate coagulation, accelerate the healing process in surgery, and ablate certain tissues. It used in dentistry (effectiveness of plasmas for tooth whitening), root canal treatment, oral cavity disinfection. In addition, it have the power to accelerate the healing. The use of plasmas for oncology has garnered significant interest in the last five years. The results of using plasma to treat cancer cells in lab tests, outside the body, and in living organisms show very encouraging outcomes, which might change cancer from a long-lasting illness into a treatable one soon

A thorough grasp of the ignition mechanism and the electromagnetic principles regulating plasma formation are essential for the creation and operation of Inductively Coupled Plasma (ICP) torches. ICP torches are now essential instruments in many fields of science and industry, especially materials processing, plasma-assisted synthesis, and analytical spectroscopy. They are perfect for applications needing precise control and large energy densities because of their exceptional capacity to produce high-temperature, stable, and contamination-free plasmas.

The purpose of our study is to explore the different parameters of ICP plasma sources, used in biomedical applications, which enhance the radiation produced power. This work contains three chapters.

In the first chapter, we will present general information about the plasma (types and parameters). In the second chapter, we will describe main types used plasma technic in medicine domain, and we will focus our attention on the inductively coupled plasma (ICP). The third chapter contains the theoretical and numerical treatments of the cyclotron-produced radiation caused by plasma electrons. Finally, we will finish with a general conclusion and perspectives

Chapter 1

General concepts of plasma

1.1 Introduction:

Plasma, often referred to as the fourth state of matter, is an ionized gas consisting of free electrons and ions that exhibit collective behavior due to long-range electromagnetic interactions. Unlike solids, liquids, and gases, plasma does not have a definite shape or volume and responds strongly to electric and magnetic fields. It is the most abundant form of matter in the universe, found in stars, interstellar space, and many laboratory and industrial applications. Understanding the fundamental properties of plasma, including its formation, classification, and governing principles, is essential for various scientific and technological advancements. This chapter provides an overview of the basic concepts of plasma, its defining characteristics, and its significance in both natural and artificial environments.

1.2 Definition of plasma:

The plasma is one of the four principal states of matter. It can be generally defined as an ionized gas, but it has unique properties. Here, "ionized" means that at least one electron is freer to move and is not bound to the atom or molecule. Therefore, the atom or molecule Plasma is an ionized state of matter composed of free electrons, ions, neutral atoms, and excited molecules, collectively exhibiting electromagnetic interactions [1]. It forms when a gas is energized sufficiently—through heat, electricity, radiation, or electromagnetic waves—causing electrons to detach from atoms, creating a highly conductive and reactive medium [2]. Unlike solids, liquids, or gases, plasma exhibits unique characteristics such as electrical conductivity, responsiveness to magnetic fields, and the ability to generate reactive species [3].

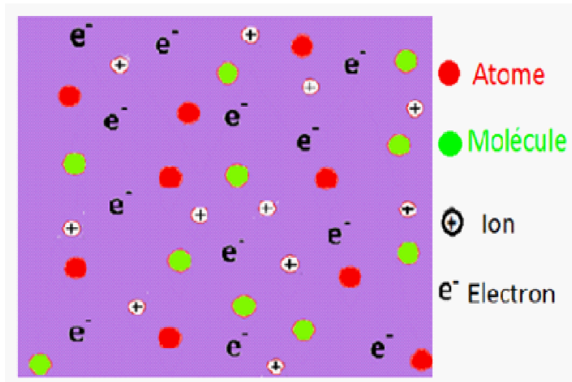


Figure 1-1: The constitutions of plasma

Plasma is the most abundant component of matter in the universe, comprising over 99% of visible celestial bodies, including stars, nebulae, and the interstellar medium [6]. It exists in two primary forms: thermal (hot) plasma, where electrons and heavy particles share the same high temperature, and non-thermal (cold) plasma, where electrons are highly energetic, but ions and neutral atoms remain near room temperature, making it suitable for biomedical applications [7].

Due to its distinct physical and chemical properties, plasma has diverse applications in medicine, industry, energy research, and space science [8].

1.3 The collective effect of plasma

The collective effect of plasma refers to the behavior of charged particles influenced by long-range electromagnetic interactions rather than individual collisions, leading to unique phenomena such as plasma oscillations, wave propagation, instabilities, and self-organization. Unlike neutral gases, where interactions occur mainly through short-range collisions, plasma exhibits plasma oscillations, where electrons oscillate around a uniform background of positive ions due to electrostatic forces.

Another key effect is Debye shielding, in which plasmas naturally shield external electric fields, forming a characteristic screening length known as the Debye length. Additionally, plasma waves, such as Langmuir waves and Alfvén waves, propagate due to collective particle interactions. Plasma can also experience instabilities, including Rayleigh-Taylor and Kelvin-Helmholtz instabilities, which impact plasma dynamics in astrophysical and fusion environments. These collective behaviors are crucial in fields such as fusion energy, space physics, astrophysics, and plasma-based technologies like ion thrusters and plasma accelerators.

1.4 Important parameters in plasma

The study of the physical and especially electrodynamic properties of plasma is today one of the largest and most difficult research areas in physics. To understand the properties of plasma, it is important to detect the electrons, ions, neutrals, and other active species present in plasma and to measure or deduce their parameters.

1.4.1 Plasma temperature

The plasma temperature is defined as the average of the energies of the charged and uncharged particles in the discharge. Given the mass difference that exists between electrons and heavy species, these two particles are often considered as two systems, each in their own thermodynamic equilibrium.

This is why, when talking about plasma, we often hear about several temperatures (electronic, ionic, gas) that can all be different. The electronic temperature is often considered the most important to determine and demonstrate the phenomena in the plasma since they are the most active agents for the ionization of the gas and also the creation of radicals. In general, in cold plasmas we have $T_e >> T_i > T_n$, where Te is the electronic temperature, Ti the ionic temperature, and Tn the temperature of the neutrals, close to room temperature.

1.4.2 Plasma density

Plasma density refers to the concentration or number of ionized gas particles in a given volume. This is also sometimes used to discuss the percentage of gas in a volume that is in the ionized state. The electric fields that generate plasmas give their energies to electrons, which heat up, and then transfer their energy to ions and other heavy particles (atoms, molecules) through collisions.

Since the density of plasma can vary, the properties of plasma vary depending on its density. Even a weakly ionized gas with a very low plasma density is still considered plasma and has the characteristics of plasma.

1.4.3 The radius of the ionic sphere a (Wigner-Seitz radius):

The radius a is the radius of the sphere that contains, on average, one electron if the ions forming the positive background are continuous, as is the case in our model. It is of the order of the average inter-electronic distance [9]:

$$a = \left(\frac{3}{4\pi n_e}\right)^{1/3} \tag{1.1}$$

where n_e is the electron density, which represents the number of electrons per unit of volume: $n = N/\Omega$, where N is the number of electrons and a is the total volume of plasma.

1.4.4 Longueur de Landau (longueur critique d'interaction binaire) :

The Landau length l_L is the distance at which two electrons approach each other so that their potential binary interaction energy is of the same order of magnitude as their thermal agitation energy. This translates into [10]:

$$k_B T = \frac{q_1 q_2}{4\pi\varepsilon_0 r_0} \tag{1.2}$$

Where r from:

$$r_{0=}\frac{q_1 q_2}{4\pi\varepsilon_0 k_B T} \tag{1.3}$$

where T is the temperature, K_B is the Boltzmann constant, and q_1 and q_2 are the electric charges of the intersecting particles.

The Landau length is involved in the analysis of collision phenomena and position correlations in a plasma.

1.4.5 Debye screening length:

Any charged particle in a plasma attracts other particles with an opposite charge and repels those with the same charge, thus creating a net cloud of opposite charges around it. Seen from the outside, this cloud shields the particle; that is, it causes the particle's Coulomb field to decay exponentially at large radii, instead of decaying as $1/r^2$.

In plasma physics, the Debye length λ_D (also called the Debye radius or critical length collective interaction), with reference to the physical chemist Peter Debye, is the length scale on which electric charges (for example, electrons) screen the electrostatic field in a plasma. In other words, the Debye length is the distance beyond which a significant separation of charges can take place. This length can be demonstrated and quantified as was done by Debye Hückel in the framework of the theory of strong electrolytes: let us consider a charge union Z_{ie} surrounded by an electron cloud; the potential Φ obeys the Poisson equation [11]:

$$\nabla^2\Phi = -4\pi\rho \tag{1.4}$$

ρ is the charge density at the point considered.

Using the Poisson Equation, the Debye potential can be extracted and given by:

$$\Phi(r) = \frac{Ze}{r}e^{-\frac{r}{\lambda_D}} \tag{1.5}$$

which is Debye's potential with:

$$\lambda_D = \sqrt{\frac{k_B T}{4\pi n \times e^2}} \tag{1.6}$$

If we consider that the electrons are on a uniform positive background, then the Deby length will have the following form:

$$\lambda_D = 6.9\sqrt{\frac{T}{n}} \tag{1.7}$$

we present the difference (due to the screening effect) between the potential of an electric charge of 1 Coulomb in a vacuum, in a density plasma $n = 1.6 \times 10^{14}\,\mathrm{m}^{-3}$, and temperature $Te = 30800\,\mathrm{K}$. We note that the decrease in the potential created by a charge is faster in a plasma than in a vacuum, that is to say that there is screening.

1.4.6 Coupling Γ:

Coupling is nothing but the ratio of the interaction energy between two electrons separated by the average distance a to the thermal energy K_BT and is equal to the Landau length l_L over the average distance a [9].

$$\Gamma = \frac{l_L}{a} = \frac{\beta e^2}{a} \tag{1.8}$$

where: $\beta = 1/K_BT$

If $\Gamma << 1$, the coupling is weak, and the kinetic energy is greater than the Coulomb interaction energy.

If $\Gamma > 1$, the coupling is strong, and the Coulomb interaction energy is greater than the kinetic energy.

1.4.7 Debye Sphere:

The number of electrons located in a sphere of radius equal to the Debye length is called the Debye number N_D[9]

$$N_D = n_e \frac{4\pi}{3} \lambda_D^3 \tag{1.9}$$

If $N_D << 1$, the Debye sphere is sparsely populated, which corresponds to a strongly coupled plasma (independent particle regime).

If $N_D >> 1$, the Debye sphere is very populated, which corresponds to a weakly coupled plasma (collective behavior regime).

1.4.8 The degree of quantitative η:

Quantum effects are very different and completely unique depending on whether they are electrons or ions because the ratio of the ion mass to the electron mass is of the order of 2.10^3. If T

is the plasma temperature, the degree of electron quantumness η is characterized by the fraction of the Louis *De* Broglie thermal wave λ_T on the average distance a between two electrons [12, 13]. Therefore:

$$\eta = \frac{\lambda_T}{a} = \frac{h}{a\sqrt{2\pi m_e k_B T}} \tag{1.10}$$

where h is Planck's constant and m_e is the mass of the electron.

If $\eta = \lambda_T/a << 1$, that is to say, at high temperature, we can treat the behavior of electrons classically.

If $\lambda_T/l_L << 1$, that is to say, at low temperature, we can also do a classical treatment since under these conditions the quantum effects at short distances are then negligible.

1.4.9 plasma frequency

A second important phenomenon related to the screening effect is the collective motion of electrons, the plasma oscillation or plasmon. When an inhomogeneity of charges is created in a gas of electrons, the latter set in motion to reestablish neutrality under the effect of the electrostatic field thus produced. Since electrons have inertia, they acquire an oscillatory motion around the perfectly neutral equilibrium state.

What has just been said can be demonstrated by the following elementary argument: At equilibrium, the electron density neutralizes the charged background at each point. Now suppose that we move a two-dimensional electron layer of thickness d by a distance $r > 0, r << d$, In doing so, we create a charge defect on the left and an excess of negative charge on the right. The surface charge density of these two charged planes is $\sigma = \pm e r n_e$, and it gives rise (as in a capacitor) to an electric field $E = \sigma/\varepsilon = \rho e r/\varepsilon$. Thus, each electron in the displaced layer obeys Newton's law:

$$m_e \frac{d^2 r}{d^2 t} = -eE = -\frac{1}{\varepsilon_0}\rho r e^2 \tag{1.11}$$

This is the equation of motion of a frequency oscillator:

$$\omega_p = \left(\frac{\rho e^2}{\varepsilon_0 m_e}\right)^{1/2} \tag{1.12}$$

The electrons in the shell therefore perform a collective oscillation of a well-determined frequency p. In this reasoning, we have neglected the shocks between electrons and their Coulomb interaction. Note that this frequency of plasma oscillations depends only on the density of the plasma n_e and not on the temperature or the strength of a magnetic field that could be present. Note that if we define the electronic thermal velocity at $\nu_e \equiv (k_B T_e/m_e)^{1/2}$

So

$$\omega_p \equiv \nu_e/\lambda_D \tag{1.13}$$

1.5 Types of plasma:

Plasma is classified into different types based on temperature, energy distribution, and physical conditions. The two main categories are thermal (hot) plasma and non-thermal (cold) plasma.

1.5.1 Thermal (Hot) Plasma

Thermal plasma, also known as equilibrium plasma, is characterized by electrons, ions, and neutral particles existing at the same high temperature. This type of plasma is typically found in extreme conditions, such as stars and fusion reactors, where the high energy levels lead to near-complete ionization.

Examples of Thermal Plasma:

• The Sun and Stars—Nuclear fusion reactions generate high-energy plasma that radiates immense heat.

• Lightning—A natural electrical discharge that ionizes air molecules.

• Plasma Arc Welding—Used in industrial applications for high-temperature metal cutting.

• Tokamak Fusion Reactors—Devices that confine high-temperature plasma for controlled nuclear fusion.

1.5.2 Non-Thermal (Cold) Plasma

Non-thermal plasma, or non-equilibrium plasma, consists of highly energetic electrons while the ions and neutral atoms remain at much lower temperatures, often close to room temperature. This makes it suitable for biomedical applications, as it can interact with biological tissues without causing thermal damage.

Examples of Non-Thermal Plasma:

• Cold Atmospheric Plasma (CAP)—Used for wound healing, sterilization, and cancer treatment.

• Dielectric Barrier Discharge (DBD) Plasma—Commonly used for air and water purification, as well as surface treatment of materials.

• Plasma Jets—Used in biomedical treatments and dentistry.

• Gliding Arc Plasma—A hybrid of thermal and cold plasma used for water purification and disinfection.

1.6 Plasma classification

Typical values of temperature and electron density for natural plasmas and those produced in laboratories are shown in an equilibrium diagram in T, N_e coordinates.

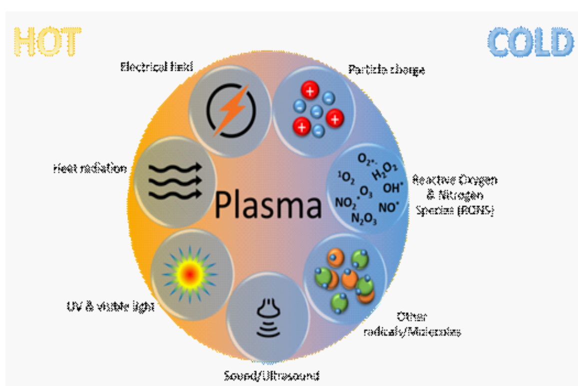


Figure 1-2: The main types of plasma.

Two categories of plasmas are defined: natural plasmas that make up 99% of the universe and human-made plasmas. As we have seen, plasma is made up of electrons, ions, and neutral particles. The medium is characterized by the densities: N_e for electrons, N_i for ions, and N_e for neutrals. Generally, the kinetic state of different species is characterized by the three temperatures, T_e, T_i, and T, respectively, the temperature of electrons, ions, and neutrals.

Often, the electron density and the electron temperature are used to classify plasmas. Given this classification, plasma physics covers an electron density range from $10\,\mathrm{m}^{-3}$ (interstellar space) to 10^3 (plasmas in metals, stars). The electron temperatures can vary from $10^2\,\mathrm{eV}$ (interstellar space, discharge plasmas) to $10^4\,\mathrm{eV}$ (interior of stars, fusion plasmas). Some typical plasmas include:

• Ultradense (hot) plasmas, corresponding to temperatures above $10^2\,\mathrm{K}$ and electron densities between 10^{23} and 10^{26} particles per cm^{-3}. They are produced nowadays in the laboratory using high-power lasers.

• Cold laboratory plasmas, where the ions remain at temperatures below $10^3\,\mathrm{K}$ while the electrons are at high temperatures. They are created by electrical discharges in gases (z-pinch discharge plasmas) or obtained in plasma reactors where the plasma is magnetically confined, or those generated by inductive coupling with a "radiofrequency" system.

• Thermal plasmas: characterized by operating temperatures above $3000\,\mathrm{K}$ (use of arc discharges for welding, cutting, material projection, etc.).

• Astrophysical plasmas with an electron density greater than 10^{23} particles per cm^{-3}.

1.7 Plasma in a constant uniform magnetic field:

The movement of a free charged particle in a magnetic field constant (i.e. not varying over time) is determined by the Lorentz force which is perpendicular to both the speed $\mathbf{v}$ of the particle and the magnetic field B. If we assume the movement is not relativistic, the equation of motion is:

$$m\frac{d\mathbf{v}}{dt} = q(\mathbf{v} \times \mathbf{B}) \tag{1.14}$$

where q its charge and B is the magnetic field vector. By multiplying scalarly both sides of this equation by $\mathbf{v}$ we obtain:

$$\frac{d}{d\mathbf{t}}(\frac{mv^2}{2}) = 0 \tag{1.15}$$

That is to say:

$$\frac{mv^2}{2} = \varepsilon = cte \tag{1.16}$$

Thus, kinetic energy ε of a charged particle deploying into a static magnetic field is constant and this irrespective of the spatial dependency $\mathbf{B}(\mathbf{r})$ of that field.

Suppose now that the magnetic field is not static settlement but also uniform (independant de r). The equation (1.14) can then also be written:

$$\frac{d\mathbf{v}}{dt} = \mathbf{\Omega} \times \mathbf{v} \tag{1.17}$$

or we introduced the constant vector, called cyclotron frequency:

$$\mathbf{\Omega} = -\frac{q}{m}\mathbf{B} \tag{1.18}$$

The equation (1.17) is a classical equation of a vector **v** anime of a rotation around an axis. To be able to write equations valid for both electrons and ions, we also introduce the algebraic value of the cyclotron frequency

$$\overline{\Omega} = -\frac{q}{m}B \tag{1.19}$$

or **B** is assumed positive.We can now show that the most general trajectoryof a particle is a helix obtained by superposition of the rotation around and a translation $\mathbf{\Omega}$ has the speed $v_{\parallel}$ in the direction of $\mathbf{\Omega}$. For this, take the Oz axis as an axis parallel to **B** and oriented in the same sense. The movement in the z direction is therefore:

$$v_z = v_{\parallel} = cte \tag{1.20}$$

$$z = z_0 + v_{\parallel}t \tag{1.21}$$

In x and y directions, equations can be combined in writing. So we have:

$$v_x = v_\perp \cos(\overline{\Omega}t + \varphi) \tag{1.22}$$

$$v_y = v_\perp \sin(\overline{\Omega}t + \varphi) \tag{1.23}$$

$$v_x^2 + v_y^2 = v_\perp^2 = cte \tag{1.24}$$

so that perpendicular energy remains constant as requires equation (1.16). The position of the particle is obtained by integration

$$x = X_0 - \overline{\rho}\cos\alpha(\overline{\Omega}t + \alpha) \tag{1.25}$$

$$y = Y_0 + \overline{\rho}\sin\alpha(\overline{\Omega}t + \alpha) \tag{1.26}$$

$$x = x_0 - \overline{\rho}\cos\alpha \tag{1.27}$$

$$y = y_0 + \overline{\rho}\sin\alpha \tag{1.28}$$

$$\overline{\rho} = \frac{v_\perp}{\Omega} \tag{1.29}$$

In general, the particle has a non-zero initial speed parallel to **B** and the trajectory in space is a helix, like the one represented on Figure (1-3).

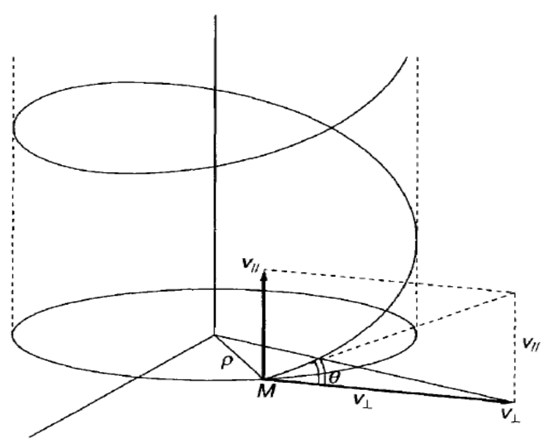


Figure 1-3: Helicoidal trajectory for ρ Larrnor radius, and θ angle of inclination.

1.8 Conclusion

The fourth state of matter, or plasma, is an ionized gas made up of free electrons and ions that behave collectively as a result of long-range electromagnetic interactions. Plasma reacts aggressively to electric and magnetic forces and lacks a defined shape or volume, in contrast to solids, liquids, and gases. It is the most prevalent type of matter in the universe and can be found in many industrial and laboratory settings, as well as in stars and interstellar space. Numerous scientific and technological developments depend on an understanding of the basic characteristics of plasma, such as its genesis, classification, and guiding principles.

Chapter 2

Study of Inductively Coupled Plasma (ICP) for Biomedical Applications

2.1 Introduction:

The development and operation of Inductively Coupled Plasma (ICP) torches rely heavily on a comprehensive understanding of both the ignition process and the electromagnetic principles governing plasma generation. ICP torches have become indispensable tools in various scientific and industrial domains, particularly in analytical spectroscopy, materials processing, and plasma-assisted synthesis. Their unique capability to generate high-temperature, stable, and contamination-free plasmas makes them ideal for applications requiring precise control and high energy densities.

This chapter focuses on two fundamental components that underpin the functionality of ICP systems: the ignition of the plasma and the electromagnetic interactions responsible for its maintenance. Plasma ignition is the initial phase in which a neutral working gas typically argon is ionized to create a conductive medium. This process often requires an auxiliary ignition source, such as a Tesla coil or spark, to generate the first free electrons and ions. Once the ionization threshold is surpassed, the externally applied radio-frequency (RF) electromagnetic field couples energy into the system, sustaining and intensifying the plasma through inductive heating.

In the sections that follow, the physical mechanisms of plasma ignition are explored in detail, followed by an in-depth discussion of the electromagnetic theory relevant to ICP operation. Emphasis is placed on the interdependence between the torch's electrical parameters and the resulting plasma characteristics. Through this analysis, the chapter aims to provide a foundational understanding necessary for both the design and control of advanced ICP systems.

2.2 Examples of plasma applications in the medical field

One of the first devices certified and used in the biomedical field is the kINPen (2-1)[14, 15]. A multitude of devices certified for use in surgery have begun to emerge recently, such as the J-Plasma, PlasmaJet, and Helica (2-2). Among the certified devices, we can mention Plasmacure, the photo of which is shown in Figure (2-3).

Figure 2-1: Image of the kINPen MED device.

Sterilization was the first application of plasmas in the biomedical field; today, there are a multitude of devices for sterilizing instruments as well as parts of the human body, such as hands.

Sterilization is any process or procedure designed to entirely eliminate microorganisms from a material or medium. Plasma sterilization operates synergistically via three mechanisms:

Figure 2-2: Image of the PlasmaJet device

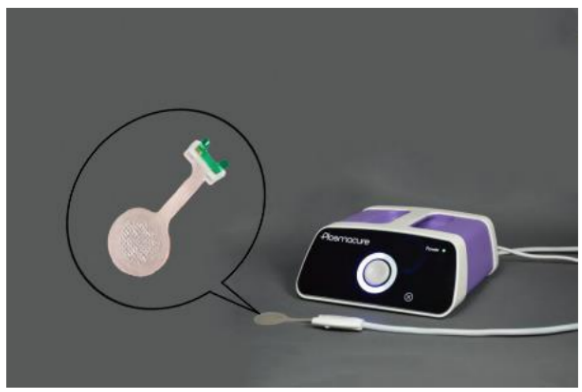


Figure 2-3: Image of the Plasmacure device

- Free radicals interactions

- UV/VUV radioactive effects

- Volatilization

Atmospheric plasmas are widely used in medicine.

Cold plasmas:

- accelerate coagulation

- accelerate the healing process in surgery [16, 17, 18]

- ablate certain tissues [19].

- used in dentistry (effectiveness of plasmas for tooth whitening)[20, 21, 22, 23], root canal treatment[24], oral cavity disinfection [25, 26].

- have the power to accelerate the healing process [27].

-The use of plasmas for oncology has garnered significant interest in the last five years [28, 29]. The results of using plasma to treat cancer cells in lab tests, outside the body, and in living organisms show very encouraging outcomes, which might change cancer from a long-lasting illness into a treatable one soon[30, 31, 32, 33].

2.2.1 Methods of plasma in medical field

Four main methods can produce the plasma that is suitable for medical uses:

- Dielectric Discharge Barrier (DBD).
- Inductively Coupled Plasmas (ICP).
- Atmospheric Pressure Plasma Jet (AAPJ).
- Microwave (MW) Plasmas.

Microwave (MW) Plasmas

- Gas enters through an inlet.
- Interacts with incoming microwaves from a waveguide.
- kW magnetron power supply.

Dielectric discharge barrier (DBD)

- High AC voltage (1.2 kV), atmospheric pressure, 200-300 W.
- Dielectric layers allow for plasma discharge to reach material surface.

2.3 Atmospheric Plasma Jets

A plasma jet is a flow of highly ionized gas generated at atmospheric pressure. This ionization originates from the passage of this gas, which is inert in most cases, through a discharge zone. Contact between the filaments created and the gas passing through the discharge zone leads to the ionization of the latter and the formation of the plasma jet.

In medical plasma applications, one of the most studied areas is the creation of plasma sources that better meet the needs of their use on living beings, especially humans. Among these sources, atmospheric pressure plasma jets (APPJ) are the most promising because they are simple to use in normal conditions, pose little risk to people and the environment, and can target specific areas for treatment. Indeed, one can modulate the size of a plasma jet and easily produce a small section, thereby enabling a highly localized treatment. Atmospheric pressure creates plasma jets, which can produce multiple species with strong bactericidal effects, making them useful for the treatment of biological cells. These species include UV radiation, charged particles, reactive oxygen species (ROS), and reactive nitrogen species (RNS). They can damage living cells by affecting their structure and DNA, thus leading to their destruction.

2.3.1 Classification of Plasma Jets

Classification by Temperature

Plasma jets are divided into two categories:

•Cold plasma jets:

whose gas temperature is very close to, or even equal to, ambient temperature.

• Hot plasma jets:

whose temperature is very high, around a few hundred degrees.

Classification by Excitation Mode

Plasma jets are divided into two categories:

• Capacitively coupled plasma jets:

These jets are created using metal electrodes subjected to a potential difference of around a few kilovolts.

• Inductively coupled plasma jets:

also called trochees, are the product of an intense magnetic field generated using a generally cylindrical coil.

2.4 Inductively Coupled Plasma (ICP)

The ICP torch, also known as an applicator, is an industrial tool that can produce temperatures much higher than those achieved by conventional methods (gas, coal, etc.). The plasma torch, on the other hand, is a physical method of chemical analysis (the analysis takes a few minutes, excluding preparation). This torch constitutes a spectroscopic source. The heat of the plasma stimulates all the atoms and ions in it for analysis.

2.4.1 Application of inductively coupled plasma (ICP) in medicine field

The inductively coupled plasma (ICP) has several applications in different scientific domains. We focus particularly on the main applications in biomedical and medical domains for example for cosmetics or pharmaceuticals and blood analyses.

Introduced in the mid-1980s, the inductively coupled plasma mass spectrometer (ICP-MS) is an instrument of choice for inorganic analyses. An ICP-MS consists of a sample introduction system that transforms the sample into gaseous form and transmits it to the inductively coupled plasma (ICP). High-temperature (8000 to 10000 K) and highly ionized argon gas decomposes the matrix, atomizes, and ionizes the introduced species before transferring them to the mass spectrometer (MS), which detects and quantifies the ions after selecting them based on their mass-to-charge ratio using the analyzer. The response of different chemical elements depends greatly on the plasma temperature, the density of ions, atoms, and electrons in the plasma, and the ionization energy of these elements. From the Saha equation (1), we can estimate that 51 elements naturally present in the periodic table are ionized at more than 90% and only9 at less than 1%.

The detection limits obtained for all elements are very low (generally ng/L). Furthermore, ICP-MS is also a multi-element technique that can analyze the entire periodic table (except for a few elements such as C, N, O, F, and the noble gases) in just a few minutes. This technique is usable for the elemental analysis of commonly analyzed biological matrices, i.e., blood, serum, and urine. The instrument has the capability to perform screening analyses, isotopic analyses, or speciation analyses [34].

Using O_2,N_2 RF inductively coupled plasma to sterilize Geobacillus Stearothermophilus is a main application of this technology. The effectiveness of sterilization using different mixtures of $O_2$and N_2 is compared with the characteristics of the plasma and images of the treated spores taken with a scanning electron microscope. The results show that the time it takes to achieve complete sterilization is more connected to the amount of O atoms than the strength of UV light, meaning that complete sterilization is more about wearing away the spore than damaging DNA like in UV sterilization.

2.5 Construction of Inductively Coupled Plasma (ICP) torches

The torch consists of three concentric tubes with a small annular distance between them (2-4).Quartz typically makes up the outer tube, also known as the plasma confinement tube. Its cooling depends on the dissipated power.In the discharge zone, the confinement tube is wrapped with a short copper (or Inconel) coil that runs on RF current, is cooled by water or air, and has either 3 or 7 turns based on the type of RF power supply used.The intermediate tube, made of either quartz or segmented metal, cooled by circulating water, extends approximately to the level of the first turn. The main job of this tube is to help the plasma gas, known as peripheral gas, move quickly along the inside wall of the quartz tube to minimize heat loss and prevent it from getting too hot. The central gas, called flow plasmagen, is introduced between the intermediate tube and the central tube, either longitudinally; it is in this gas that the discharge takes place. The gas that moves in the middle of the torch, known as the carrier gas, can be added using a cooled probe that goes into the torch, and its presence allows for the addition of either the chemicals (like $SiCl_4$ and O_2) or the materials to be processed (samples).

Depending on the power used and the operating RF frequencies, the ICP torch operates over a wide power range, from 1 kW to 1 MW, with gas flow rates ranging from 10 to 200 slpm (standard liters per minute).

The figures above represent two types of torches designed according to power. The first type features a quartz containment tube (2-5), which is externally air-cooled and capable of power outputs ranging from 20 kW to 3 MHz. Quartz enclosures, even water-cooled ones, do not allow power outputs exceeding 120 kW. A second, with a cold metal cage (2-6), internally

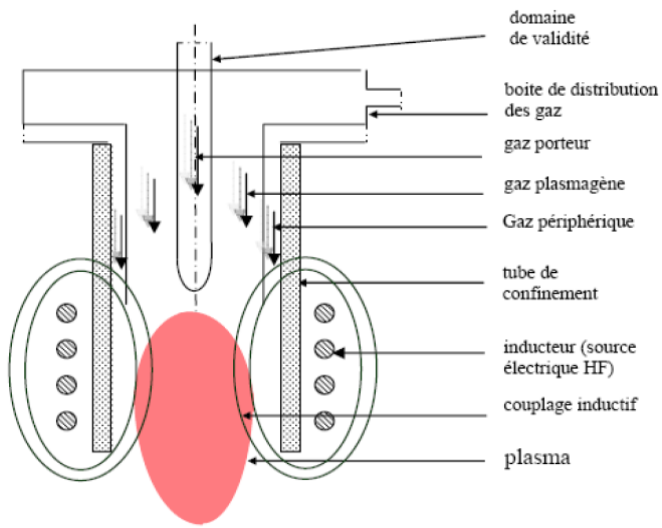


Figure 2-4: Schematic diagram of an ICP torch.

reproduces the magnetic field created by the inductor it sees externally. This technology makes it possible to achieve very high power outputs.

Another way to increase torch power is to widen its radius and, consequently, lower the operating frequency (f). However, because it's more challenging to study plasma in high-power torches, it's clear that these torches are researched less than analysis torches that use clear, insulating, and uncooled quartz tubes.

Regardless of the reactor type (cold metal cage, cooled double tube, uncooled single tube), the test gas is injected into a quartz tube surrounded by 2 to 7 copper coils cooled by demineralized water. Due to the low electrical conductivity of gases, high power (depending on the gas mass flow rate) is required to create a plasma initiated by a pre-ionization process. This can be achieved using an external high-voltage electrode applied to the quartz tube or by a ground electrode placed in the creation zone and removed when the plasma is ignited (the same effect can be obtained with a heated graphite rod). However, in the case of low-pressure studies such as those carried out for atmospheric entry problems, the applied electric field is the source of the seed electrons. When the high-frequency current flows through the solenoid, an oscillating

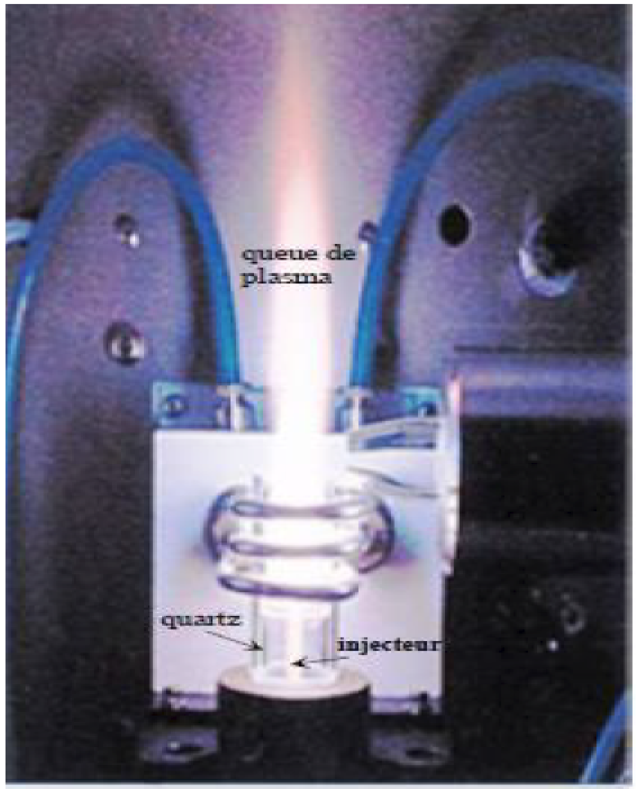


Figure 2-5: Inductively coupled plasma torch with quartz tube.

magnetic field and an induced electric field also oscillating take place in the quartz tube. The two fields are linked by the Maxwell-Faraday law and are used to accelerate the first electrons in the plasma. Collisions of these fast electrons with heavy particles generate new electrons by ionization, and so on. The plasma is self-sustaining if the ionization rate remains higher than the recombination rate.

Inside the tube, the electromagnetic field is not homogeneous: a skin thickness d occurs near the quartz tube. This quantity appears in the calculations when solving the Maxwell-Faraday equation. The field is at its maximum at this distance from the turns. The thickness of this layer is a few millimeters and depends on the electrical conductivity of the gas s and the oscillation frequency f according to the following expression:

$$f = (\pi \mu \sigma f)^{-1/2} \tag{2.1}$$

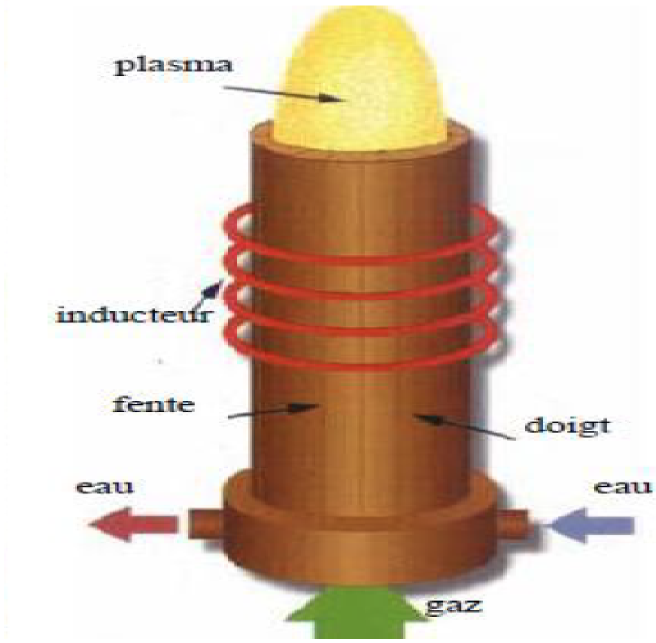


Figure 2-6: Quartz inductively coupled plasma torch with a metal cold cage.

where μ is the magnetic permeability. The main part of the injected power is in this layer close to the quartz tube. The central region is heated by conduction, convection and radiation. A lower frequency would better distribute the energy throughout the volume, but the penetration thickness must not be greater than the radius of the tube, otherwise the electromagnetic field will be canceled. In addition, the power density is higher with high frequencies. Indeed, the injected power can be written as follows:

$$P = \pi I^2 \frac{a}{l} n^2 (\frac{\pi \mu f}{\sigma}) \tag{2.2}$$

where I is the injected current, a and l are the radius and length of the medium respectively, and n is the number of turns of the solenoid. A compromise must therefore be found, and the frequencies used are between 0.4 and 2.7 MHz. On the other hand, since the thermal conductivity of polyatomic gases is greater than that of monatomic gases, air and carbon dioxide require more power than argon to generate a plasma. Monatomic gases are therefore often used for ignition. However, this phase can be thermally critical because the skin thickness is therefore so small that the plasma ends up very close to the quartz tube.

2.6 ICP Torch Ignition and Electromagnetic Aspects

At the time of plasma ignition, the RF generator does not provide sufficient energy to create ionization directly from the plasma gas. The initial ionization is created by thermionic discharge, either:

A graphite tip is dipped inside the torch near the inductor and then removed immediately after ignition,

by a spark from a Tesla transformer.

The electrons thus released are accelerated by the RF field and trigger the plasma reaction by collision with the atoms of the plasma-forming gas. Argon is often used for ignition because it ionizes at lower energy than other plasma-forming gases (N2, H2, He). The plasma is then maintained by heating the gas by induction, provided that the power supplied by the RF generator allows it at a given working pressure. The minimum power required to maintain an induction plasma depends on the frequency and pressure.

The dots on the dashed line show the holding powers at 3 MHz. It can be seen that the holding power must become lower as the frequency decreases and the pressure increases. For example, the minimum power required to maintain an argon plasma is less than 1 kW at atmospheric pressure for a frequency of 3 MHz. At this frequency, the required power is almost 8 kW at 2 atm.

The first energy transfer occurs between the electric field and the plasma. The electric field in an inductor is zero along the axis, so energy dissipation occurs in the annular region of the plasma, the area where the electric field is strongest.

Since the electrical conductivity of plasma is relatively high, the oscillating electromagnetic field cannot penetrate the plasma, especially at high frequencies. This phenomenon is quantified by introducing the concept of the skin effect.

Since skin thickness depends on electrical conductivity, it is likely to change depending on temperature and the degree of thermal imbalance.

In HF plasma, the skin depth is a few millimeters. The figure below shows the radial variations in induced current density, electric field, and electrical conductivity.

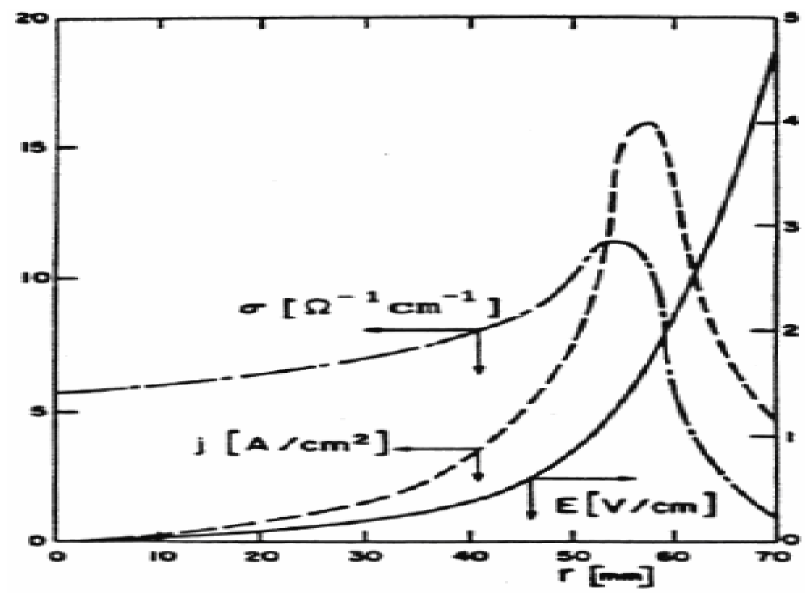


Figure 2-7: Radial distribution of electric field, induced current density, and conductivity.

The study of the coupling efficiency η, defined by the ratio between the power dissipated in the discharge (transferred active power P_0) and the electrical power of the source P_e:

$$\eta = \frac{P_0}{P_e} \tag{2.3}$$

η is the coupling coefficient as a function of two coefficients. It is the ratio between the average radius of the discharge and the thickness of the skin $\frac{r_n}{\delta}$ and the second, is the ratio between the average radius of the discharge and the radius of the torch $\frac{r_n}{r_e}$.

It can be seen in Figure below that the best coupling in power η is obtained for a report $\frac{r_n}{\delta}$ between 2.5 and 4, while $\frac{r_n}{r_e}$ as close as possible to unity (discontinuous). Then the best way is to decrease the radius of the inductor r_B to that of the r_e torch for proper frequency. But this adjacency creates constraints on the inductor (it is generally taken ≈ 0.75). Indeed, the choice of frequency is important, because the minimum power required to maintain the discharge increases very rapidly with the decrease in frequency f .

2.7 Conclusion

In summary, the ignition and electromagnetic characteristics of ICP torches are fundamental to their performance and reliability. Effective plasma ignition initiates the transition from a neutral gas to a highly conductive state, while electromagnetic induction sustains and controls the plasma through efficient energy transfer. Understanding the interplay between RF power, coil design, and plasma behavior is essential for optimizing torch operation across a range of applications. This foundational knowledge serves as a basis for further advancements in ICP technology and its expanding role in scientific and industrial processes.

Chapter 3

Cyclotron radiation in plasma (ICP) torche

3.1 Introduction:

The central gas, called flow plasmagen, is introduced between the intermediate tube and the central tube, longitudinally; it is in this gas that the discharge takes place. The induced plasma releases the jet with great energy as particle kinetic energies (electrons, ions. . .) and electromagnetic energies (radiation energies). This chapter focuses on the theoretical and numerical treatments of the cyclotron-produced radiation caused by plasma electrons. This treatment requires a deep analysis of the radiation plasma system and the magnetic affectation. The power is the ideal quantity that can be used as a critical concrete estimation for the radiation plasma evaluation.

3.2 The magnetic field created for the solenoid (induction).

Magnetic fields are produced by all charged particles in motion. Electrons and other moving point charges create complex yet well-known magnetic fields that are dependent on the particles' charge, acceleration, and velocity.

A cylindrical current-carrying conductor, like a piece of wire, is surrounded by concentric rings of magnetic field lines. The "right-hand grip rule" (see figure at right) can be used to determine the direction of such a magnetic field. As one gets farther away from the wire, the magnetic field's strength diminishes. The strength of a wire with an infinite length is inversely proportional to its length.

When a current-carrying wire is bent into a loop, the magnetic field weakens outside the loop and becomes concentrated inside. Creating a coil or "solenoid" by bending a wire into several closely spaced loops intensifies this effect. A device that is constructed in this way around an iron core has the potential to function as an electromagnet, producing a powerful, precisely regulated magnetic field. A cylindrical electromagnet that is indefinitely long has no external magnetic field and a homogenous magnetic field inside. The strength and polarity of the magnetic field generated by a finite-length electromagnet, which is influenced by the current passing through the coil, resembles that of a homogeneous permanent magnet.

The Biot–Savart law explains the magnetic field produced by a steady current I_c, which is a continuous flow of electric charges that doesn't accumulate or run out any point.

$$\mathbf{B} = \frac{\mu_0 I_c}{4\pi} \int_{wire} \frac{d\mathbf{l} \times \mathbf{r}}{r^3} \tag{3.1}$$

where μ_0 is the magnetic permeability, r is the distance between the location of $d\mathbf{l}$ and the location where the magnetic field is calculated, $\mathbf{r}$ is the direction, and vector $d\mathbf{l}$ is the vector line element with direction in the same sense as the current I_c. The integral is then summed over the wire length. For instance, if the wire is long enough and straight, this turns into:

$$B = \frac{\mu_0 I_c}{2\pi r} \tag{3.2}$$

where $r = |\mathbf{r}|$ The direction is tangent to a circle perpendicular to the wire according to the right hand rule.

Along the axis of the solenoid carrying current I_c with n, uniform number of loops of currents per length of solenoid; and the direction of magnetic field as shown figure (3-1).

$$B = \frac{\mu_0 n I_c}{2}(\cos\theta_1 + \cos\theta_2) \tag{3.3}$$

or

$$B = \frac{\mu_0 n I_c}{2}\left(\frac{r}{\sqrt{R^2 + r^2}} + \frac{L - r}{\sqrt{R^2 + (L - r)^2}}\right) \tag{3.4}$$

To simplify our estimation, we suppose that $\theta_1 = \theta_2 = \theta$ so $r = \frac{L}{2}$

$$B = \mu_0 n I_c \cos\theta \tag{3.5}$$

where

$$\cos\theta = \frac{L/2}{\sqrt{R^2 + \frac{L^2}{4}}} \tag{3.6}$$

We can write

$$B = \frac{\mu_0 n I_c L}{2\sqrt{R^2 + \frac{L^2}{4}}} \tag{3.7}$$

L and R are the dimentions of solenoid.

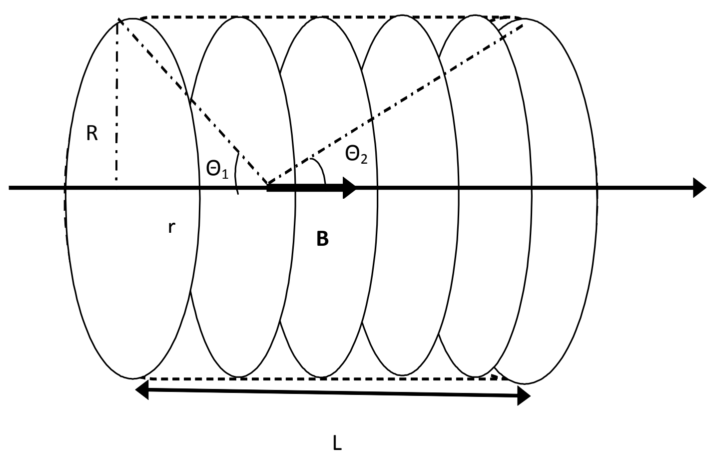


Figure 3-1: Solenoid carrying current I with uniform number of loops n.

3.3 Moving charge radiation in plasma (ICP) torches:

The particles can accelerate to extremely high energies when they interact with scattering centers, which are other particles or fields. Electromagnetic waves are created when charged particles accelerate. Electromagnetic energy flows irreversibly from the source, or charges, to infinity in the form of radiation.

We consider a radiating charge q moving with velocity $v << c$ in the direction of $l(t)$. Assume that at time t and $\mathbf{u} = \frac{\mathbf{R}}{R}$ is the unit vector of the distance vector $\mathbf{R}$, we wish to measure the radiation field at point M.

The magnetic force is given by the Lorentz force

$$\mathbf{F} = q(\frac{\mathbf{v}}{c} \times \mathbf{B}) \tag{3.8}$$

The radiation fields are defined as

$$\mathbf{E}_{rad}(r,t) = \frac{q}{4\pi\varepsilon_0}\left[\frac{\mathbf{u}}{R} \times \frac{1}{c^2}(\mathbf{u}\times\dot{\mathbf{v}})\right] \tag{3.9}$$

if we let θ be the angle between $\mathbf{R}$ and $\dot{\mathbf{v}}$, then

$$|E_{rad}| = c\,|B_{rad}| = \frac{q}{4\pi\varepsilon_0}\frac{\dot{v}}{Rc^2}\sin\theta \tag{3.10}$$

or

$$\mathbf{B}_{rad}(r,t) = \frac{\mathbf{u}}{c} \times \mathbf{E}_{rad}(r,t) \tag{3.11}$$

where ε_0 permittivity of free space, c speed of light in vacuum and R is the separation between the field point and its source point. Observe that the plane containing the vectors $\mathbf{u}$, $\dot{\mathbf{v}}$, and $\mathbf{E}_{rad}$ is perpendicular to $\mathbf{B}_{rad}$.

Let θ be the angle between $\mathbf{u}$ and $\dot{\mathbf{v}}$, the Poynting vector $\mathbf{S}$ is in the direction of $\mathbf{R}$ with

$$S = \frac{1}{\mu_0 c}E_{rad}^2 = \frac{c}{\mu_0}B_{rad}^2 = \frac{\mu_0}{16\pi^2 c}\frac{q^2\dot{v}^2}{R^2}\sin^2\theta \tag{3.12}$$

We can write

$$dA = R^2 d\Omega \tag{3.13}$$

where Ω is the solid angle about the direction $\mathbf{R}$ of $\mathbf{S}$,

$$d\Omega = \sin\theta d\theta d\varphi \tag{3.14}$$

since S is the EM energy dW emitted per unit time dt per unit area dA.

$$S = dW/(dtdA) \tag{3.15}$$

Thus, the amount of power released per solid angle equals

$$\frac{dW}{dtd\Omega} = SR^2 = \frac{\mu_0}{16\pi^2 c} q^2 \dot{v}^2 \sin^2\theta$$

where S is the electromagnetic energy dW emitted per unit time dt per unit area dA

$$S = \frac{dW}{dtdA} \tag{3.16}$$

Take note of the distinctive dipole pattern $\propto \sin^2$, which shows that the highest radiation is emitted perpendicular to the acceleration and that no emission occurs in the direction of acceleration. Integrating this yields the total electromagnetic power released into all angles. By combining this, the total electromagnetic power released into all angles can be found:

$$\begin{aligned} P &= \frac{dW}{dt} = \int_A \frac{\mu_0}{16\pi^2 c} \frac{q^2 \dot{v}^2}{R^2} \sin^2\theta dA = \left(\frac{\mu_0}{16\pi^2 c} \frac{q^2 \dot{v}^2}{R^2} \sin^2\theta \right) R^2 (\sin\theta d\theta d\varphi) \\ &= \frac{\mu_0}{16\pi^2 c} q^2 \dot{v}^2 \int_0^{2\pi} \int_0^{\pi} \sin^2\theta \sin\theta d\theta d\varphi \end{aligned} \tag{3.17}$$

The electromagnetic power released by an accelerating charge using the Larmor formula:

$$P = \frac{dW}{dt} = \frac{\mu_0 q^2 \dot{v}^2}{6\pi c} \tag{3.18}$$

3.4 Cyclotron radiation

When non-relativistic charged particles accelerate in a magnetic field, usually in a circular trajectory, they create electromagnetic radiation known as cyclotron radiation. Synchrotron radiation is another name for this kind of radiation. It results from the particle being accelerated by the magnetic force, and the spectrum of the radiation that is released is connected to the cyclotron frequency of the particle.

A charged particle, like as an electron, encounters a force that directs its motion in a circular pattern when it is in a magnetic field. According to the laws of electromagnetism, speeding charged particles release electromagnetic radiation, and this circular motion is an acceleration.

Cyclotron radiation is seen in a number of settings. Particle accelerators, often known as cyclotrons, are devices that accelerate charged particles to extremely high energies. Astrophysical phenomena; charged particles in magnetised plasma, such as those surrounding black holes or in the interstellar medium, emit cyclotron radiation. Cyclotron have a main applications in medicine; radioactive isotopes for imaging and treatment are created by cyclotrons.

Electron moving perpendicular to a magnetic field feels a Lorentz force.

According to the relativistic Lorentz factor,

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \tag{3.19}$$

two types of radiation can be defined:

- Non-relativistic electrons: ($\gamma \sim 1$) - cyclotron radiation
- Relativistic electrons: ($\gamma >> 1$) - synchrotron radiation

Our investigation is related with the cyclotron radiation that create by the charge particles (electrons or ions).

Particle of charge q moving at velocity v in a magnetic field B feels a force:

$$\mathbf{F} = q\mathbf{v} \times \mathbf{B} \tag{3.20}$$

Let $\mathbf{v}$ be the component of velocity perpendicular to the field lines (component parallel to the field remains constant). Force is constant and normal to direction of motion.

In this circular motion, the acceleration is identified as

$$a = \frac{qvB}{m} \tag{3.21}$$

for particle mass m.

Let ω_c be the rotation's angular velocity. Start with the application of Newton's first law.

$$ma = F = m\frac{v^2}{r} \tag{3.22}$$

but:

$$\omega_c = \frac{v}{r} \tag{3.23}$$

and

$$\Rightarrow m\frac{qvB}{m} = mv\omega_c \tag{3.24}$$

so

$$\omega_c = \frac{qB}{m} \tag{3.25}$$

In a constant magnetic field, the electron moves along the magnetic field line on a uniform helical path with constant linear and angular speeds. An external oscillating field matching the cyclotron frequency, ω_c will accelerate the particles, a phenomenon known as cyclotron resonance. This resonance is the basis for many scientific and engineering uses of cyclotron motion.

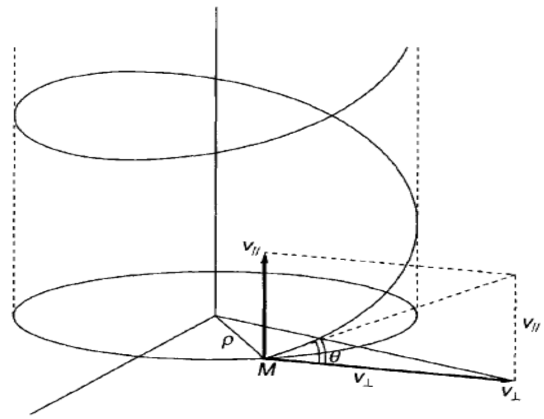


Figure 3-2: Cyclotron particle path.

For this case, the Larmor radius defined as

$$r_c = \frac{v_\perp}{\omega_c} \tag{3.26}$$

Note that $v_\parallel$ is the velocity component parallel to B and $v_\perp$ is the perpendicular component, it comes:

$$v_\perp = v\cos\theta \tag{3.27}$$

$$v_\parallel = v\sin\theta \tag{3.28}$$

Supposing approximately that θ is a weak angle, the Taylor development of the first order of the functions $\sin\theta$ and $\cos\theta$ can be written

$$\sin\theta \simeq \theta \tag{3.29}$$

$$\cos\theta \simeq 1 \tag{3.30}$$

which lead to

$$v_\perp^2 \simeq v^2 = \frac{2K_BT}{m} \tag{3.31}$$

thus,

$$r_c = \frac{v_\perp}{\omega_c} = \frac{\sqrt{2mK_BT}}{qB} \tag{3.32}$$

$$r_c = \frac{v}{\omega_c} = \frac{\sqrt{2mK_BT}}{qB} \tag{3.33}$$

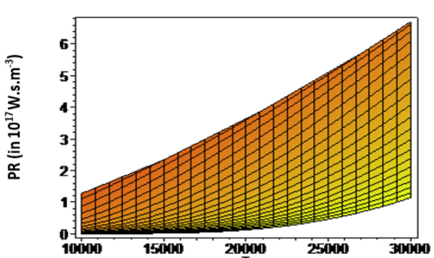
Using the acceleration a according to the formula (3.21), Power given by Larmor's formula:

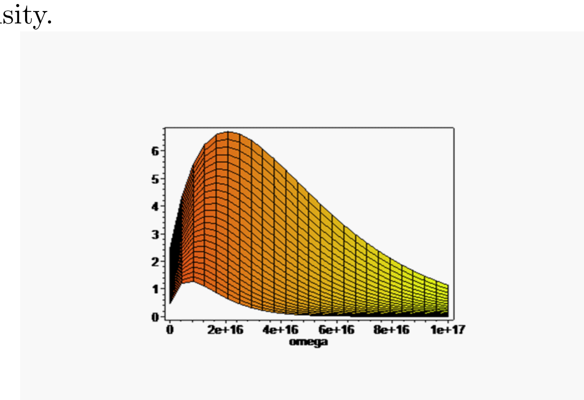
$$P = \frac{dW}{dt} = \frac{\mu_0 q^2}{6\pi c}\dot{v}^2 = \frac{\mu_0 q^2}{6\pi c}\left(\frac{qvB}{m}\right)^2 = \frac{\mu_0 q^4 v^2 B^2}{6\pi m^2 c} \tag{3.34}$$

so

$$P = \frac{\mu_0 q^4 v^2 B^2}{6\pi m^2 c} \tag{3.35}$$

The figures (3-3) and (3-4) show the variations of the cyclotron radiation power for the (ICP) plasma torches system PR as a function of radiation pulse ω. Meanwhile, in these figures, the influences of the temperature T when $N_e = 10^{22}\ \mathrm{m}^{-3}$ and the affectation of N_e electron density when $T = 10^4\,\mathrm{K}$ are treated in the case where $n = 2$, $I_c = 20\,\mathrm{A}$, $L = 4\,\mathrm{mm}$, and $R = 1.5\,\mathrm{mm}$. As a function of radiation pulse ω, the profile of cyclotron radiation power appears as a spectral line with a noticeable width and significant peak. We notice that the system radiation power grows with both temperature T and electron density N_e. Thus, both width and peak are increased when we increase the electron temperature and density.





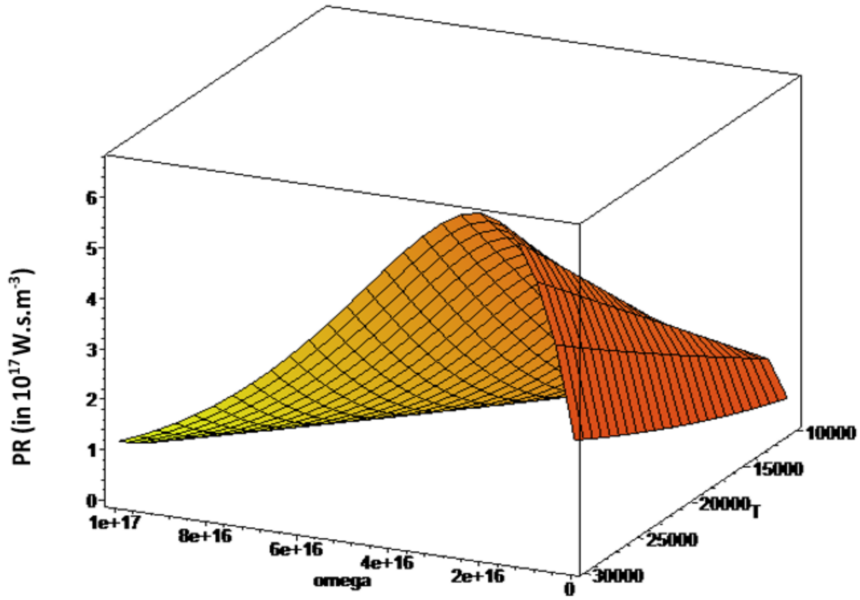
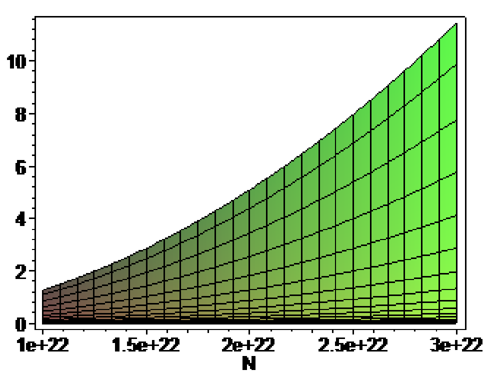
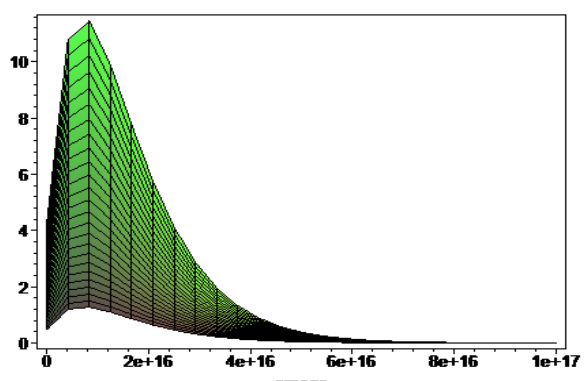


Figure 3-3: Cyclotron radiation power for the (ICP) plasma torches as a function of radiation pulse ω and temperature T for $N_e = 10^{22}$ m^{-3}, $n = 2$, $I = 20\,\mathrm{A}$, $L = 4\,\mathrm{mm}$, and $R = 1.5\,\mathrm{mm}$.





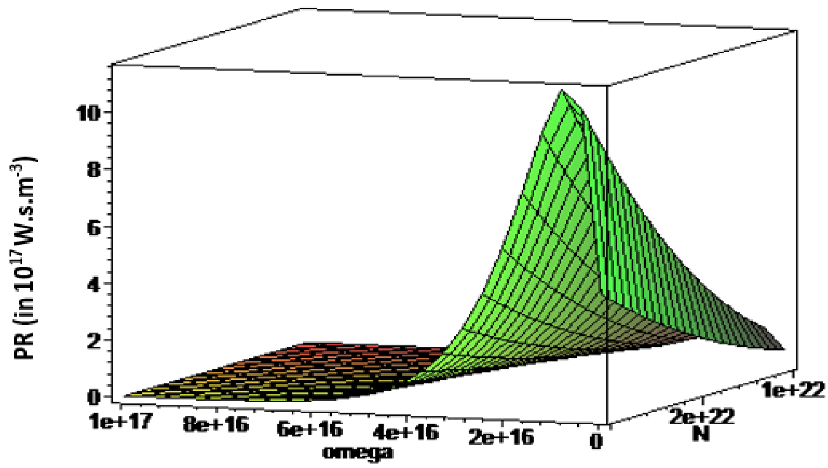


Figure 3-4: Cyclotron radiation power for the (ICP) plasma torches as a function of radiation pulse ω and electron density N_e for $T = 10^4$ K, $n = 2$, $I = 20$ A, $L = 4$ mm, and $R = 1.5$ mm.

The cyclotron radiation power variations for the (ICP) plasma torches system PR as a function of radiation pulse ω are illustrated in figures (3-5) and (3-6). Meanwhile, in the instance where $N_e = 10^{22}$ m^{-3}, $T = 10^4$ K, $L = 4$ mm, and $R = 1.5$ mm, these figures treat the effects of the electric current I_c carried on the solenoid when $n = 2$ and the influence of the n uniform number of loops when $I_c = 20$ A. The profile of cyclotron radiation power is shown as a spectral line with an apparent peak and an important width as a function of radiation pulse ω. We see that both electric current I_c and number of loops n increase the system radiation power. Therefore, increasing electric current and number of loops results in a rise in both width and peak.

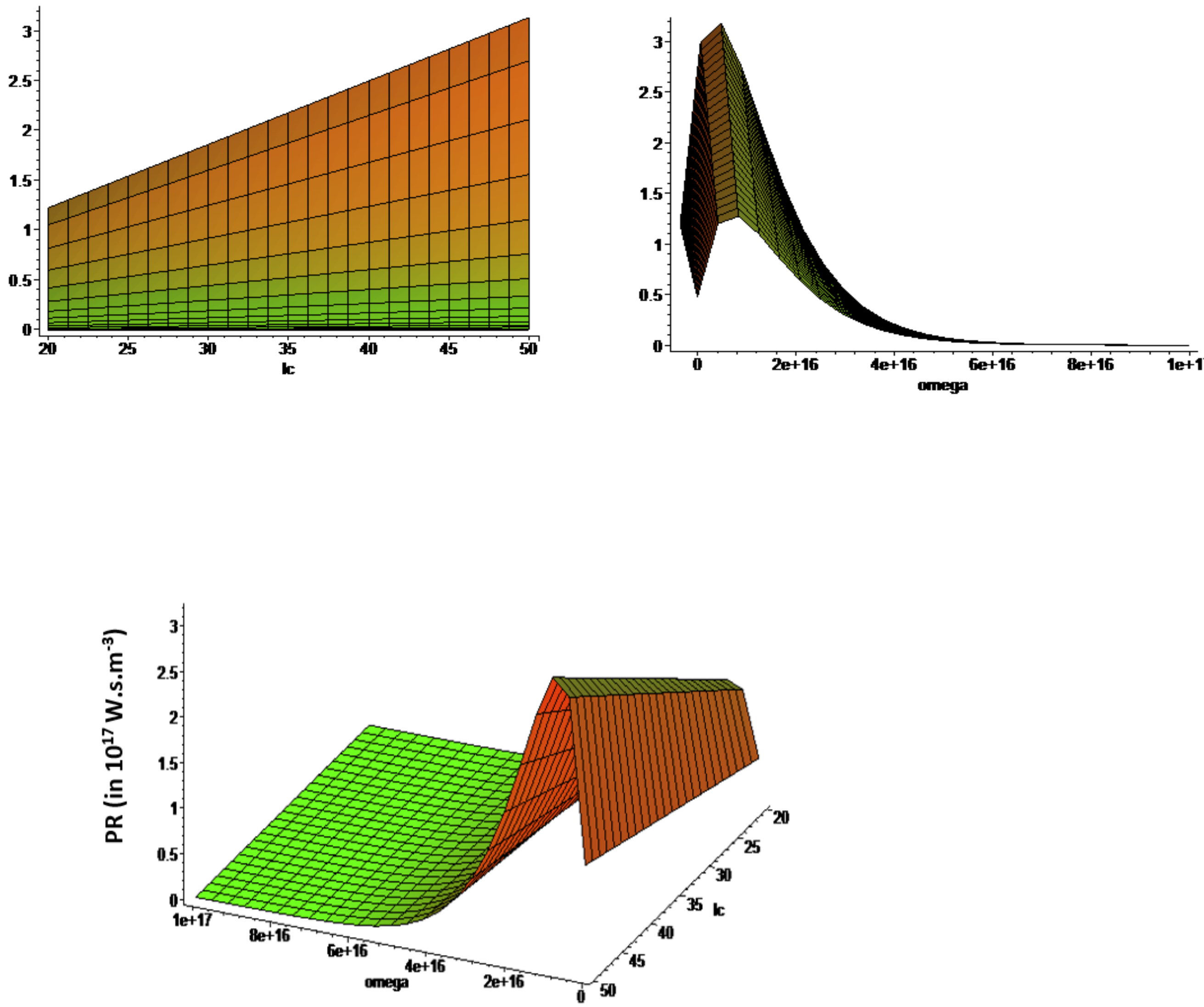


Figure 3-5: Cyclotron radiation power for the (ICP) plasma torches as a function of radiation pulse ω and the electric current I for $n = 2$, $N_e = 10^{22}\ \mathrm{m}^{-3}$, $T = 10^4\,\mathrm{K}$, $L = 4\,\mathrm{mm}$, and $R = 1.5\,\mathrm{mm}$.

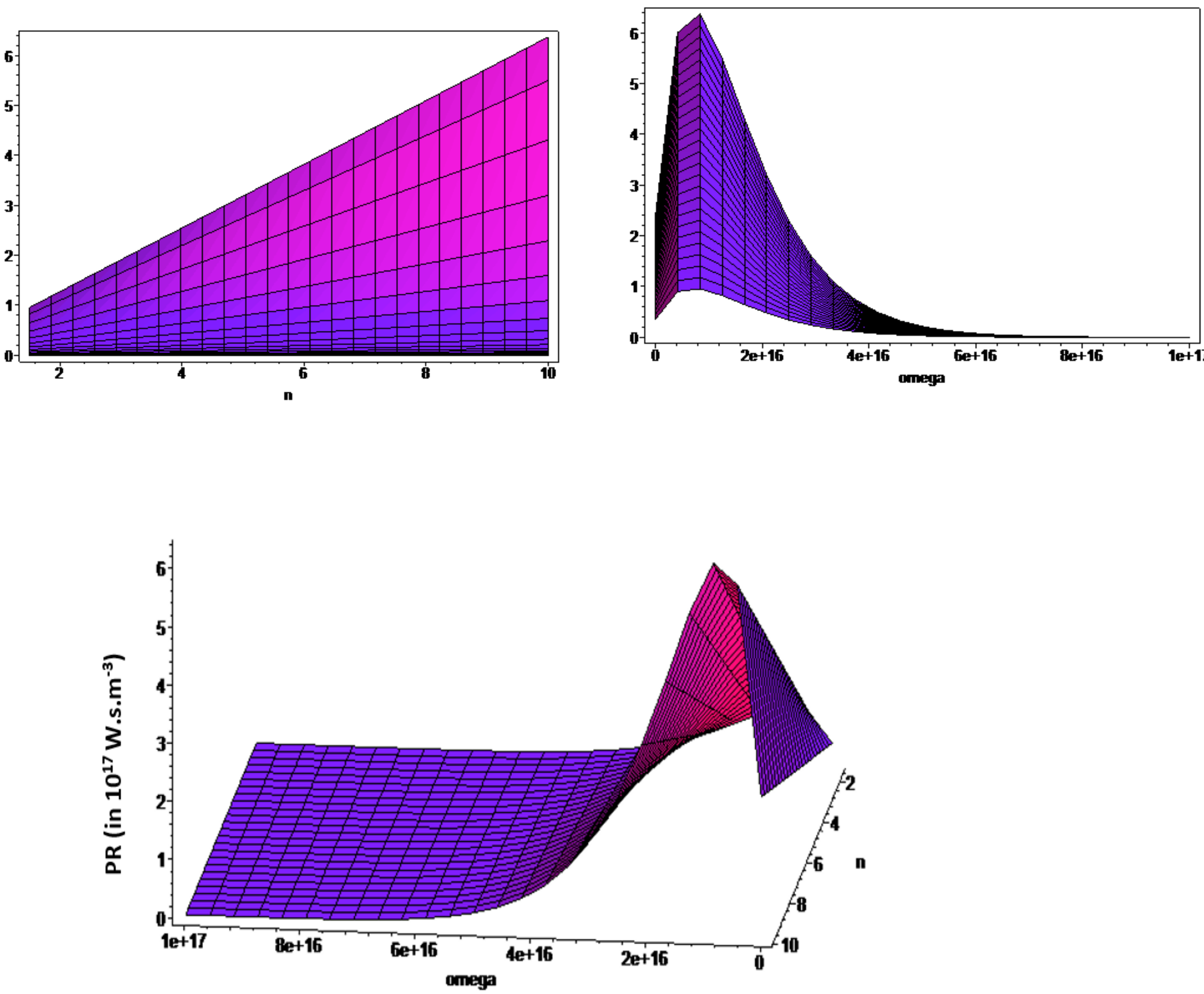
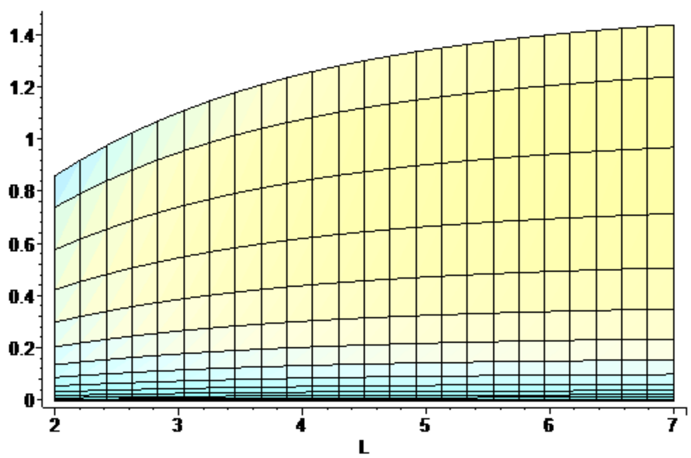
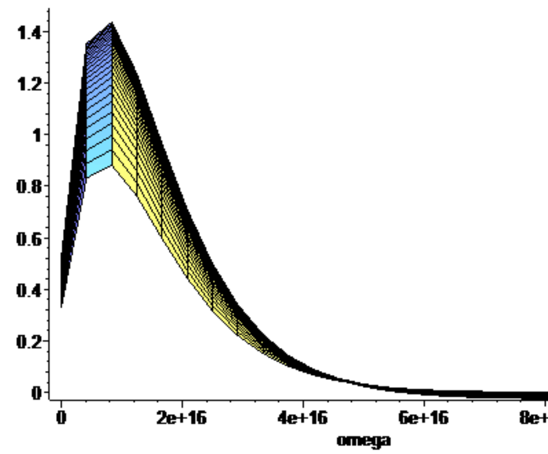


Figure 3-6: Cyclotron radiation power for the (ICP) plasma torches as a function of radiation pulse ω and number of loops n for $I = 20\,\mathrm{A}$, $N_e = 10^{22}\ \mathrm{m}^{-3}$, $T = 10^4\,\mathrm{K}$, $L = 4\,\mathrm{mm}$, and $R = 1.5\,\mathrm{mm}$.

Figures (3-7) and (3-8) show the changes in cyclotron radiation power for the (ICP) plasma torches system PR as a function of radiation pulse ω. In addition, the figures in the case where $n = 2$, $N_e = 10^{22}\ \mathrm{m}^{-3}$, $T = 10^4\,\mathrm{K}$, and $I_c = 20\,\mathrm{A}$, address the effects of L, the length of the solenoid when $R = 1.5\,\mathrm{mm}$, and the radius of the solenoid when $L = 4\,\mathrm{mm}$. As a function of radiation pulse ω, the profile of cyclotron radiation power is seen as a spectral line with an apparent peak and a significant width. We observe that the growing of the length of the solenoid L raises the radiation power of the system. In contrast, the growing of the radius of the solenoid decreases the radiation power of the system. According to our observed numeric result, the increasing of solenoid length leads to a rise in both width and peak. Conversely, both decrease with the growing of the solenoid radius.





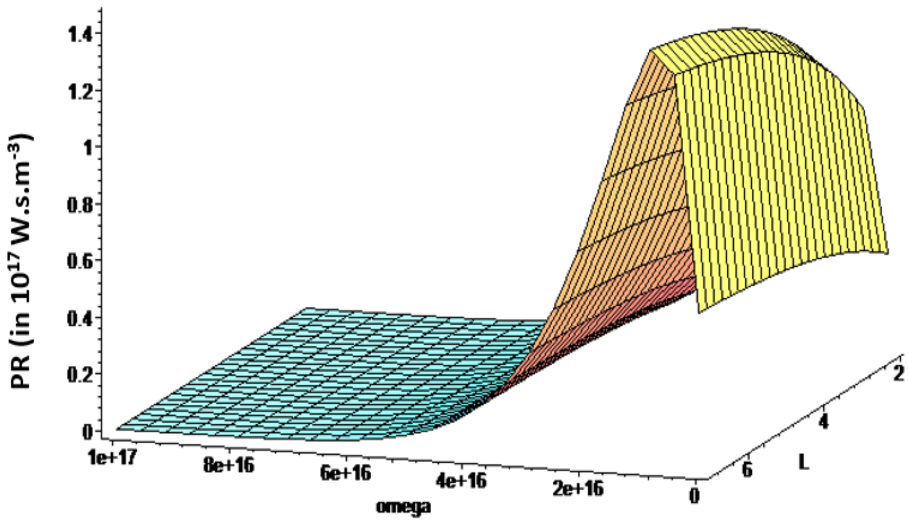
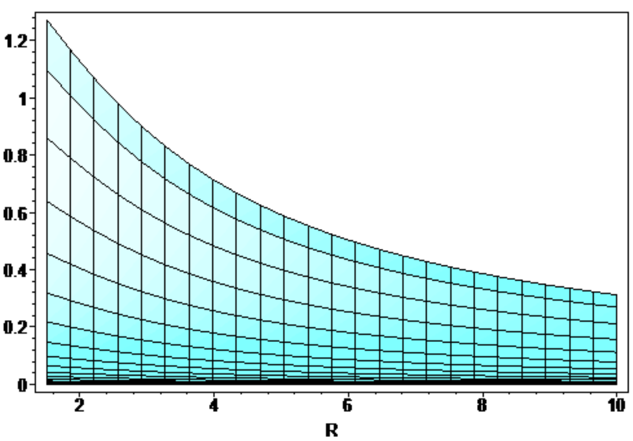
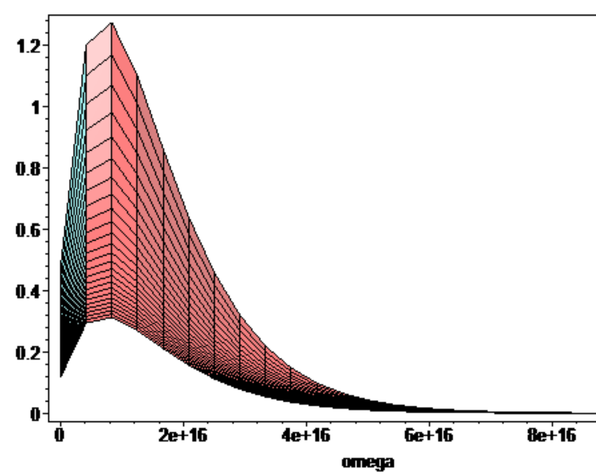


Figure 3-7: Cyclotron radiation power for the (ICP) plasma torches as a function of radiation pulse ω and length of solenoid L for $I = 20\,\mathrm{A}$, $n = 2$, $N_e = 10^{22}$ m^{-3}, $T = 10^4\,\mathrm{K}$, and $R = 1.5\,\mathrm{mm}$.





3.5 Conclusion

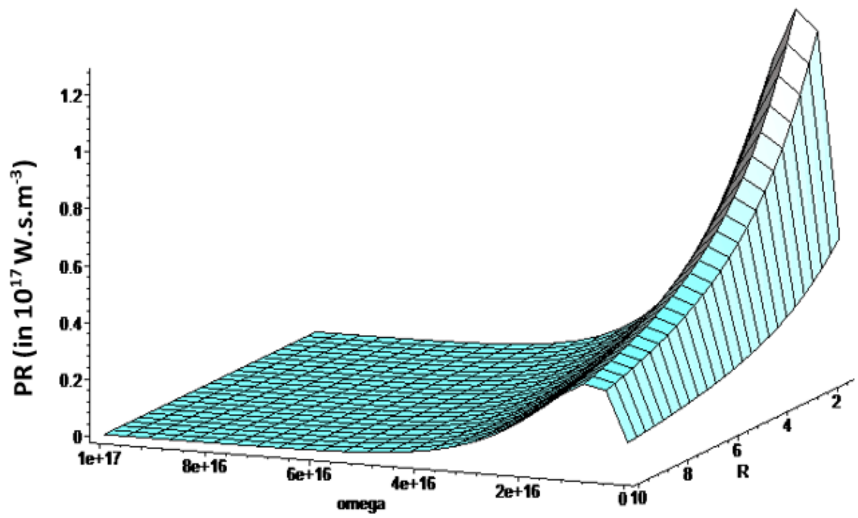


Figure 3-8: Cyclotron radiation power for the (ICP) plasma torches as a function of radiation pulse ω and radius of solenoid R for $I = 20\,\mathrm{A}$, $n = 2$, $N_e = 10^{22}\ \mathrm{m}^{-3}$, $T = 10^4\,\mathrm{K}$, and $L = 4\,\mathrm{mm}$.

The discharge occurs in the central gas, also known as flow plasmagen, which is introduced longitudinally between the central tube and the intermediate tube. The jet is released with a lot of energy in the form of electromagnetic (radiation) and particle kinetic (electrons, ions, etc.) energy from the generated plasma. The theoretical and numerical study of the radiation generated by plasma electrons in cyclotrons is the main topic of this chapter. A thorough examination of the magnetic affectation and radiation plasma system is necessary for this treatment. The best number to use as a crucial, tangible estimate for the radiation plasma assessment is the power. As a function of radiation pulse ω, the profile of cyclotron radiation power appears as a spectral line with a noticeable width and great peak. We notice that the system radiation power grows with temperature T, electron density N_e, electric current I_c, the length of the solenoid L, and the uniform number of loops n. Thus, all these parameters are directly proportional to the width and peak. Conversely, the system radiation power decreases with R the radius of the solenoid; the last is inversely proportional to the width and peak.

General conclusion

The greatest energetic state of matter is called plasma. It is made up of neutral particles, positive ions, and free electrons. It is similar to the gas phase in that it lacks a defined shape and volume, but it is different in a number of respects. Plasma technology advancements have made it possible to use plasma in a variety of medical applications, such as tissue engineering, cancer treatment, wound healing, and sterilizing.

One of the most often used plasma sources in biomedical research is cold atmospheric plasma (CAP). It produces reactive species, such as nitrogen and oxygen radicals, which are essential for cell signaling, microbial inactivation, and regulated tissue alteration. Different plasma sources have been created to give specific therapeutic effects without inflicting major thermal damage, including plasma jets and dielectric barrier discharge (DBD).

The earliest use of plasmas in the biomedical industry was sterilization. Instruments and human body parts, including hands, can now be sterilized using a variety of techniques. In medicine, atmospheric plasmas are utilized extensively to ablate certain tissues, speed up coagulation, and speed up the healing process following surgery. It is utilized in dentistry for root canal therapy, oral cavity cleansing, and the efficiency of plasmas for teeth whitening.

It also has the ability to hasten the healing process. Over the past five years, there has been a lot of interest in the use of plasmas for oncology. Very promising results have been obtained from treating cancer cells with plasma in lab tests, outside the body, and in real beings; this could soon turn cancer from a chronic disease into a curable one.

The development and functioning of Inductively Coupled Plasma (ICP) torches require a solid understanding of the electromagnetic principles controlling plasma production as well as the ignition process. In several scientific and industrial domains, including materials processing, plasma-assisted synthesis, and analytical spectroscopy, ICP torches are now indispensable tools.

Their remarkable ability to generate high-temperature, stable, and contamination-free plasmas makes them ideal for applications requiring precise control and high energy densities.

Our goal is to investigate the various ICP plasma source settings that increase the power generated by radiation in biomedical applications. There are three chapters in this work.

We provided general information about plasma (types and parameters) in the first chapter. In the second chapter, we discussed the primary types of plasma techniques utilized in the medical field, with a particular emphasis on inductively coupled plasma (ICP). The theoretical and numerical treatments of the radiation generated by plasma electrons in cyclotrons are presented in the third chapter. We've concluded with a broad conclusion and some final thoughts.

As a function of radiation pulse ω, the profile of cyclotron radiation power appears as a spectral line with a noticeable width and great peak. We notice that the system radiation power grows with temperature T, electron density N_e, electric current I_c, the length of the solenoid L, and the number of loops n. Thus, all these parameters are directly proportional to the width and peak. Conversely, the system radiation power decreases with the radius of the solenoid R; the last are inversely proportional to the width and peak.

Bibliography

[1] Chen, F. F. (2016). Introduction to Plasma Physics and Controlled Fusion. Springer.

[2] Fridman, A. (2008). Plasma Chemistry. Cambridge University Press.

[3] Lieberman, M. A., & Lichtenberg, A. J. (2005). Principles of Plasma Discharges and Materials Processing. John Wiley & Sons.

[4] Laroussi,■M. (2015).■Low-Temperature Plasma Jet for Biomedical Applications: A Review.■IEEE Transactions on Plasma Science,■43(3),■703–711.

[5] Scholtz,■V., Hruška,■K., Rázik,■F., Lukeš,■P., & Julák,■J. (2021). Non■thermal plasma treatment of ESKAPE pathogens: a review. Frontiers in Microbiology, 12, 737635.

[6] Gurnett, D. A., & Bhattacharjee, A. (2005). Introduction to Plasma Physics: With Space and Laboratory Applications. Cambridge University Press.

[7] Piel, A. (2010). Plasma Physics: An Introduction to Laboratory, Space, and Fusion Plasmas. Springer.

[8] Bittencourt, J. A. (2013). Fundamentals of Plasma Physics. Springer.

[9] M.Baus,J.P.Hansen,Phys.Rep59,11-94(1980).

[10] J.L.Delcroix,A.Bers,Physiquedesplasmas1,InterEditions/CNRSEdi-tions,Paris,(1994).

[11] P. Debye, and Hückel, E. (1923) De la theorie des electrolytes. I. Abaissement du point de congelation et phenomenes associes. Phys. Zeit., 24, 185-206.

[12] E.Dufour,A.Calisti,B.Talin,M.Gigosos,M.Gonzalez,T.delRoGaztelur-rutiaetJ.W.Dufty,Phys.Tour.E71,066409(2005).

[13] B.Talin,A.Calisti,J.W.DuftyetI.V.Pogorelov,Phys.Tour.E77,036410(2008).

[14] K. Weltmann et al., “Atmospheric Pressure Plasma Jet for Medical Therapy: Plasma Parameters and Risk Estimation”, Contributions to Plasma Physics, 49(9), (2009), pp.631–640.

[15] http://neoplas-tools.eu/files/neoplas_tools/public/bilder/slider/20170628-IMG_0043.jpg.

[16] G. Fridman et al., “Applied Plasma Medicine”, Plasma Processes and Polymers, 5(6), (2008), pp.503–533.

[17] G. Fridman et al., “Blood Coagulation and Living Tissue Sterilization by FloatingElectrode Dielectric Barrier Discharge in Air”, Plasma Chemistry and Plasma Processing, 26(4), (2006), pp.425–442.

[18] J. Raiser, M. Zenker, “Argon plasma coagulation for open surgical and endoscopic applications: state of the art”, Journal of Physics D: Applied Physics, 39(16), (2006), p.3520.

[19] G. Lloyd et al., “Gas Plasma: Medical Uses and Developments in Wound Care”, Plasma Processes and Polymers, 7(3–4), (2010), pp.194–211.

[20] H. Lee, S. Nam, A. Mohamed, G. Kim, J. Lee, “Atmospheric Pressure Plasma Jet Composed of Three Electrodes: Application to Tooth Bleaching”, Plasma Processes and Polymers, 7(3–4), (2009), pp.274–280.

[21] J. Pan et al., “A Novel Method of Tooth Whitening Using Cold Plasma Microjet Driven by Direct Current in Atmospheric-Pressure Air”, IEEE Transactions on Plasma Science, 38(11), (2010), pp.3143–3151.

[22] H. Lee et al., “Tooth Bleaching with Nonthermal Atmospheric Pressure Plasma”, Journal of Endodontics, 35(4), (2009), pp.587–591.

[23] G. Kim et al., "Dental Applications of Low Temperature Nonthermal Plasmas", Plasma Processes and Polymers, 10(3), (2013), pp.199–206.

[24] X. Lu et al., "An RC Plasma Device for Sterilization of Root Canal of Teeth", IEEE Transactions on Plasma Science, 37(5), (2009), pp.668–673.

[25] C. Jiang et al., "Nanosecond Pulsed Plasma Dental Probe", Plasma Processes and Polymers, 6(8), (2009), pp.479–483.

[26] R. Sladek, E. Stoffels, R. Walraven, P. Tielbeek, R. Koolhoven, "Plasma Treatment of Dental Cavities: A Feasibility Study", IEEE Transactions on Plasma Science, 32(4), (2004), pp.1540–1543.

[27] J. Heinlin et al., "Plasma medicine: possible applications in dermatology", Journal der Deutschen Dermatologischen Gesellschaft, 8(12), (2010), pp.968–976.

[28] D. Yan, J. Sherman, M. Keidar, "Cold atmospheric plasma, a novel promising anticancer treatment modality", Oncotarget, 8(9), (2017), pp.15977–15995.

[29] M. Keidar, "Plasma for cancer treatment", Plasma Sources Science and Technology, 24(3), (2015), p.033001.

[30] J. Kim et al., "Apoptosis of lung carcinoma cells induced by a flexible optical fiberbased cold microplasma", Biosensors and Bioelectronics, 28(1), (2011), pp.333–338.

[31] S. Ja Kim, H. Min Joh, T. Chung, "Production of intracellular reactive oxygen species and change of cell viability induced by atmospheric pressure plasma in normal and cancer cells", Applied Physics Letters, 103(15), (2013), p.153705.

[32] R. Walk et al., "Cold atmospheric plasma for the ablative treatment of neuroblastoma", Journal of Pediatric Surgery, 48(1), (2013), pp.67–73.

[33] .D. Graves, "Low temperature plasma biomedicine: A tutorial review", Physics of Plasmas, 21(8), (2014), p.080901.

[34] Darrouzes, J. (2007). Spectromètre de masse à plasma à couplage inductif (ICP-MS) à cellule de collision/réaction (CC/R) pour l'analyse clinique. Performances et applications

à l'analyse élémentaire et à la spéciation. In Annales de Toxicologie Analytique (Vol. 19, No. 1, pp. 103-111). EDP Sciences.

[35] Griffiths, David J. (2017). Introduction to Electrodynamics (4th ed.). Cambridge University Press. ISBN 9781108357142.

Abstract

Atmospheric cold plasmas are the most widely used in the biomedical field. They are simple to generate and handle, posing no major risks to the operator, the patient, or the samples under treatment. Today, there are several applications of atmospheric plasmas in medicine, such as accelerating coagulation and the healing process in surgery, tooth whitening, treatment of cancer cells, and sterilization. Our investigation aims to theoretically treat the plasma jet for the purpose of identifying the optimal parameters that enhance its radiation-produced power of cyclotron radiation of the (ICP) plasma system. As a function of the radiation pulse ω, we have obtained that the profile of cyclotron radiation power appears as a spectral line, containing a noticeable width and a significant peak. Our result manifests that the system radiation power grows with temperature T. Thus, both width and peak are increased, as are electron density Ne, electric current Ic, the length of the solenoid L, and the number of loops n. In addition, the larger the radius of the solenoid, the less the cyclotron radiation power for the (ICP) plasma torches.

Keywords: (ICP) plasma torches, cold plasmas, cyclotron radiation.

ملخـــص

البلازما الباردة الجوية هي الأكثر استخدامًا في المجال الطبي الحيوي. فهي سهلة التوليد والتعامل، ولا تُشكل أي مخاطر كبيرة على المُشغّل أو المريض أو العينات المُعالجة. يوجد اليوم العديد من تطبيقات البلازما الجوية في الطب، مثل تسريع التخثر وعملية الشفاء في الجراحة، وتبييض الأسنان، وعلاج الخلايا السرطانية، والتعقيم. يهدف بحثنا إلى معالجة نفث البلازما نظريًا لغرض تحديد المعلمات المثلى التي تُعزز قدرتها المُنتجة إشعاعيًا من إشعاع السيكلوترون لنظام البلازما (ICP). وكدالة لنبضة الإشعاع ω، حصلنا على أن مخطط قدرة إشعاع السيكلوترون يظهر كخط طيفي، يحتوي على عرض ملحوظ وقمة ملحوظة. تُظهر نتيجتنا أن قدرة إشعاع النظام تزداد مع درجة الحرارة T. وبالتالي، يزداد كل من العرض والذروة، وكذلك كثافة الإلكترونات Ne، والتيار الكهربائي Ic، وطول الملف اللولبي L، وعدد الحلقات n. بالإضافة إلى ذلك، كلما كان نصف قطر الملف اللولبي أكبر، كلما كانت قوة إشعاع السيكلوترون لمصابيح البلازما (ICP) أقل.

الكلمات المفتاحية: : (ICP) مشاعل البلازما، البلازما الباردة، إشعاع السيكلوترون.

Résumé

Les plasmas froids atmosphériques sont les plus utilisés dans le domaine biomédical. Simples à générer et à manipuler, ils ne présentent aucun risque majeur pour l'opérateur, le patient ou les échantillons traités. Aujourd'hui, les plasmas atmosphériques trouvent de nombreuses applications en médecine, comme l'accélération de la coagulation et du processus de cicatrisation en chirurgie, le blanchiment dentaire, le traitement des cellules cancéreuses et la stérilisation. Notre étude vise à traiter théoriquement le jet de plasma afin d'identifier les paramètres optimaux qui augmentent la puissance de rayonnement produite par le rayonnement cyclotronique du système plasma (ICP). En fonction de l'impulsion de rayonnement ω, nous avons obtenu que le profil de puissance du rayonnement cyclotronique se présente sous la forme d'une raie spectrale, présentant une largeur notable et un pic significatif. Nos résultats montrent que la puissance de rayonnement du système augmente avec la température T. Ainsi, la largeur et le pic augmentent, tout comme la densité électronique Ne, le courant électrique Ic, la longueur du solénoïde L et le nombre de boucles n. De plus, plus le rayon du solénoïde est grand, plus la puissance du rayonnement cyclotron des torches à plasma (ICP) est faible.

Mots-clés : torches à plasma (ICP), plasmas froids, rayonnement cyclotron.