# Multipurpose microwave plasma source

ENRIQUE CAMPS, OSCAR OLEA, GERARDO ANGUIANO,
RICARDO ONDARZA AND CÉSAR R. GUTIÉRREZ
*Instituto Nacional de Investigaciones Nucleares*
*Gerencia de Investigación Básica, Apartado postal 18–1027, 11801 México, D.F., México*

Recibido el 13 de marzo de 1992; aceptado el 15 de diciembre de 1992

ABSTRACT. Electron ciclotron resonance (ECR) plasma devices have an important place among the electrodeless cold plasma sources, due to their potential applications in industry. Many different devices of this type are now under research around the world. This paper deals with the design description of a microwave ECR plasma source, in which an overdense plasma will be generated, making use of the plasma eigen modes to induce wave conversion.

RESUMEN. Dentro de las fuentes de plasma frío sin electrodos, los dispositivos generadores de plasma mediante resonancia ciclotrónica de los electrones ocupan un lugar importante, debido a sus posibilidades potenciales de aplicación en la industria. Existe una gran variedad de dispositivos de este tipo que se encuentran en estudio actualmente. En el presente trabajo se hace la descripción del diseño de una de estas fuentes de plasma. En este dispositivo, haciendo uso de los modos propios del plasma para inducir transformación de ondas, se creará un plasma supercrítico.

PACS: 52.50.Dg; 52.35.–g

## 1. INTRODUCTION

Potential applications of plasma in materials processing [1], which include from thin film deposition, plasma polimerizators and microcircuit fabrication to welding, tool hardening, synthesis of pure and ultrafine powders has led to a sharp raise of interest in developing different kind of plasma producing devices. Otherwise, there are many interesting physical phenomena, like linear and nonlinear wave conversion [2], isotope separation [3], that could be object of research in these type of devices.

Commercially available devices are based on low frequency ($rf$) parallel plate reactors and dc plasma sources of the Kaufman type. Many other applications requiring high film deposition velocities, operation with chemically active gases or high beam currents need the development of devices different from the commercially available ones. Some of those problems can be solved by the use of microwave discharges which actually are in their research stage. The frequencies usually used in this technology cover the range from 300 MHz to 10 GHz. This paper describes the design of such a device, which actually is under construction. In this device, in order to generate the discharge will be used a cylindrical cavity working in single mode excitation. This cavity is situated in an external static magnetic field, used for ignition and confinement of the plasma. The working parameters of the magnetic field will allow the generation of overdense plasma.

The organization of the paper is as follows: in Sect. 2 the main points under which the design was made are discussed. In Sect. 3 the description of the design is given.

## 2. OVERDENSE PLASMA

During the last years many different microwave plasma or ion sources have been proposed to solve specific problems [4]. An attempt to make a classification of these devices by the way the plasma is created and in dependence on the type of created plasma is given in Ref. [5]. Following this classification the design we are going to describe finds its place among the overdense plasma sources. The principal difference of this machine is that the working regime is not the resonance, but lower values of the magnetic field. Experimentally we have shown the possibility of overdense plasma generation in these regimes [6]. The purposes and the ways for creating such plasmas are the most different. As we previously determined [7], with microwave overdense plasma it is possible to produce some material treatments faster than with underdense plasma.

The overdense plasma is going to be generated in our device by making use of the eigenmodes of a magnetized plasma. The creation of microwave overdense plasma, when the density may greatly exceed its critical value ($n > n_{\rm cr} = m\omega^2/4\pi e^2$, where $e$ and $m$ are the electron charge and mass, $\omega = 2\pi f$ is the pump frequency) under the condition $\omega_{\rm c} > \omega$ ($\omega_{\rm c} = eB/mc$ is the electron ciclotron frequency in the magnetic field $B$), when the plasma can be penetrated by electromagnetic waves is well known. However, overdense plasma can be maintained at $\omega_{\rm c} < \omega$. In this case the pump electromagnetic wave can not propagate, and the mechanism of energy transfer to the plasma can be related only to a linear wave conversion near the boundary (in other words, as we will use the frequency $f = 2.45$ GHz, then the upper hybrid eigenmode is excited).

An important feature in the linear wave conversion theory, is the problem related to the effectiveness of the conversion. By this we understand, how much of the electromagnetic energy is transfered to the plasma waves. According to some theoretical calculations [2], the effectiveness of the conversion depends on the parameter $l$, which determines the density scale length at the point where the conversion takes place, it depends also on the coefficient, characterizing the deepness of penetration of the field into the plasma. The influence of these parameters is determined by the characteristic dimensions of the plasma ($L$).

Let us suppose that we have an external static magnetic field along the $z$ axis, a gradient of plasma density on the $x$ axis and an electric field of the electromagnetic wave oscillates along the $y$ axis, then the dielectric constant can be written as

$$\epsilon = 1 - \frac{\omega_p^2}{\omega^2}\frac{\omega^2 - \omega_p^2}{\omega^2 - \omega_h^2},$$

where $\omega_p$ is the plasma frequency ($\omega_p^2 = 4\pi e^2 n/m$) and $\omega_h^2 = \omega_p^2 + \omega_c^2$ is the upper hybrid frequency. The cutoff ($\epsilon = 0$) is reached when

$$\frac{\omega_{p1}^2}{\omega^2} = 1 - \frac{\omega_c}{\omega}. \tag{1}$$

As the wave propagates into the region of increasing density it will find the resonance at ($\epsilon = \infty$)

$$\frac{\omega_{p2}^2}{\omega^2} = 1 - \frac{\omega_c^2}{\omega^2}, \tag{2}$$

which describes the upper hybrid resonance.

Dividing (2) by (1) we get

$$\frac{\omega_{p2}^2}{\omega_{p1}^2} = 1 + \frac{\omega_c}{\omega} = \frac{n_2}{n_1} \approx 1 + \frac{\Delta x}{l}, \tag{3}$$

where $\Delta x$ is the distance between the cutoff and the resonance layer, and is directly related to the parameter $L$. From (3) we have

$$\Delta x = \frac{\omega_c}{\omega} l. \tag{4}$$

If $\lambda \ll L$ the wave cannot reach the resonance point, because $\Delta x$ will be many wavelengths thick, and the wave conversion effectiveness is determined only by the grade of penetration of the wave into the plasma. Eq. (4) shows that in this case $\Delta x$ can be diminished by reducing $B$, nevertheless a big reduction of $B$ can affect the confinement of plasma. A formal analysis [2] shows that the more proper conditions for conversion are reached when $L$ is comparable with $\lambda$. It is shown in that work that for these conditions a reduction of $B$ will improve the effectiveness of conversion.

Under the influence of a strong electromagnetic field, when the plasma particles obey the relation

$$V_E \leq V_{Te}, \tag{5}$$

(where $V_E = eE/m\omega$, $E$, $m$ are respectively the electric field intensity and the electron mass, $V_{Te}$ is the electron thermal speed) plasma parameters begin to vary with time, and this makes possible the development of parametric instabilities, which are non-linear effects. In this case, the dielectric constant of the plasma (the reaction of the medium) cannot be more considered proportional to the intensity of the strong electromagnetic field, the dependence turns more complex. The coupling of external strong fields in the plasma can lead to the excitation of plasma oscillations and to the nonlinear interaction of the plasma waves with the external field. The nonlinear processes can be essential even with small values of electric field (easy to obtain in an experiment), it depends on the conditions of interaction (*e.g.* when there exist resonances).

Parametric decay is related to a certain threshold value of the electric field, these values are different for different parametric processes. The threshold values for the case of an homogeneous magnetized plasma are given in Ref. [8]. When the frequency of the external field is near to the plasma frequency of electrons, the parametric instabilities can appear with threshold values of the electric field **E** considerably lower [9]. In these conditions a parametric decay will take place if relation (5) holds.

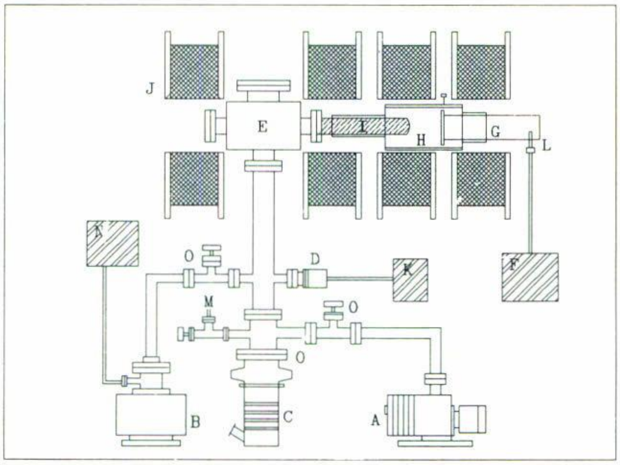

FIGURE 1.

Taking into account the considerations about linear and nonlinear wave conversion we have done, we can establish, in our case some important criteria necessary for the design of the device we are constructing.

1. The plasma will be ignited at the ECR. As the frequency of the magnetron generator is fixed and equal to 2.45 GHz, then the magnetic system of the device will have to be able to create a static external field of 850 gauss, at the region where the plasma will be generated.
2. The magnetic system has to be made in such a way that the value of the magnetic field can be easily reduced, in order to improve the conversion effectiveness. In accordance to the effectiveness criteria of linear conversion, the device will form a cylindrical plasma whose diameter will be aproximately $\lambda/2$. This value is also conditioned by constructing limitations.
3. A cylindrical cavity of high quality factor ($Q$) must be constructed, in which the plasma will be created. In this cavity, the electric field of the external wave will be increased (in the resonance) in order to reach the value given by (5), and the parametric decay can take place. As we will see later, if $Q = 800$, then the value of electric field in the resonant cavity is aproximately 700 V/cm for a power of 100 W, which is enough to satisfy relation (5).
4. Cleaness requirements during some material treatments or thin film deposition, establish the vacuum criteria. The design of the device is made under the condition that the maximum value of the basic vacuum will have to be $10^{-7}$ torr. The values of the working pressure will be in the range between $10^{-4}$ to $10^{-3}$ torr.

## 3. DESIGN DESCRIPTION

The device will consist of three main parts: the vacuum system, the external magnetic field system and the microwave system. In Fig. 1 a scheme of the device is shown.

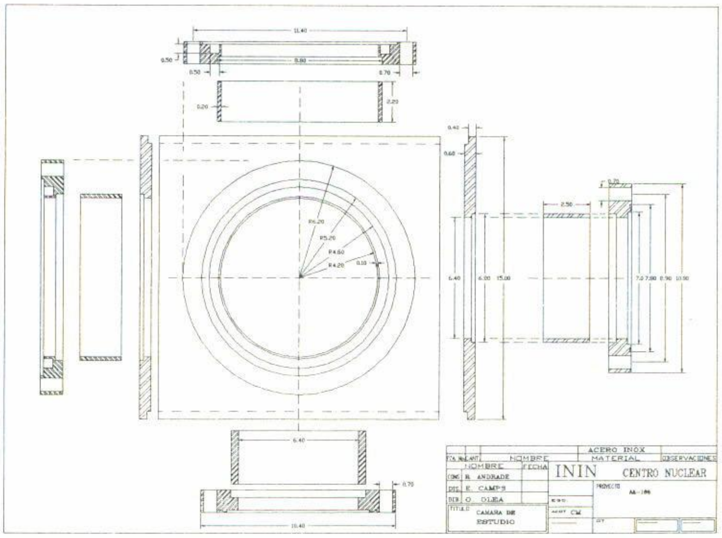

FIGURE 2. Reaction chamber.

### *3.1. Vacuum system*

The vacuum system includes the equipment for displacement of residual gases, the reaction chamber (E in Fig. 1) and the pyrex glass tube (I in Fig. 1), which will contain the gas to be ionized. The reaction chamber will be made of a stainless steel non-magnetic 15 cm i.d. cylinder of 15 cm in length. The chamber will have six accesses, four of them can be closed by quartz or pyrex windows, supporting the vacuum with viton o-rings. The fifth access will be connected to the vacuum equipment and the sixth will be used to connect the glass tube container of the gas, here a 304 stainless steel to 7740 pyrex tube will be used. In these two cases the connection to the chamber will be carried out through copper o-rings. The details of construction of the reaction chamber are shown in Fig. 2.

The vacuum equipment that will be used consists of:

1. A mechanical vacuum pump Balzers DUO 060 A (A in Fig. 1) with a capacity of 60 $m^3/h$. This pump will be used for a first step vacuum.
2. A PLS 063 H Balzers diffusion pump system. This pump will be used for the maintenance of the working pressure (C in Fig. 1).
3. An Ionic vacuum pump *Maglon Andar* MI-75 with capacity of 70 l/s, which will be used for the evacuation of residual gases and formation of the basic vacuum (B in Fig. 1).

Manual locks (O in Fig. 1) will be used to keep working the vacuum equipment while the chamber is opened. The input gas will be introduced into the discharge region through a needle valve, at the first stage situated as shown in Fig. 1 (M in Fig. 1). A different feeding gas system, connected directly to one of the accesses of the reaction chamber is now under design.

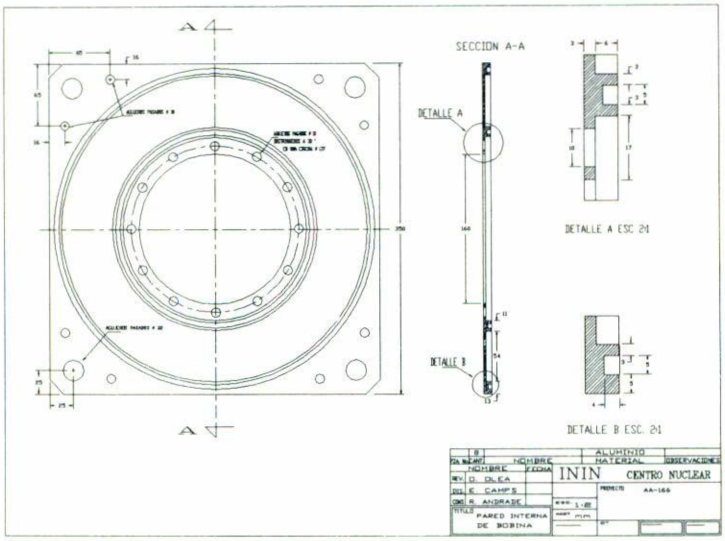

FIGURE 3. Internal wall of solenoid.

The pressure meassurements will be done by means of the standard Pirani Cold Cathode Vacuumeter PKG 020 Balzers, which allows meassurements in the range $10^2$–$5 \times 10^{-8}$ m-bar.

### *3.2. Magnetic field system*

The external magnetic field system will be made up of four 16 cm i.d. and 8.8 cm in wide solenoids (J, in Fig. 1), with 400 turns of AWG-6 copper wire, covered by aminadel (special thermal covering). The copper wire is rolled in an aluminum square shape holder, whose walls are water cooled, here we have to point out that the solenoids will work mainly in continuous regime. The construction details of the aluminum holder are shown in Fig. 3.

The coils were designed using a computer program specially written for this purpose. This program allows to change coil parameters (*i.e.* internal diameter, total number of turns, which is divided into number of layers and number of turns per layer, wire diameter, distance among solenoids and the value of current) and calculate the magnetic field intensity in the region within the internal diameter of the coils. In this program each solenoid is simulated by a collection of spires of different diameter. The program has been described in detail earlier [10].

The magnetic field values obtained from the program were compared with some experimental measurements, for this purpose a small 5.8 cm i.d. coil with 88 turns of AWG-6 copper wire distributed in 4 layers was constructed. The field measurements were performed with a BELL 620 Gaussmeter. The results of this comparison are displayed in Fig. 4 and it shows that the difference between theoretical and experimental cases do not overcome 10 %. In this figure the zero value in the horizontal axis corresponds to the center of the test coil, NC is the number of layers, NV is the number of turns in each layer and RI the internal radius.

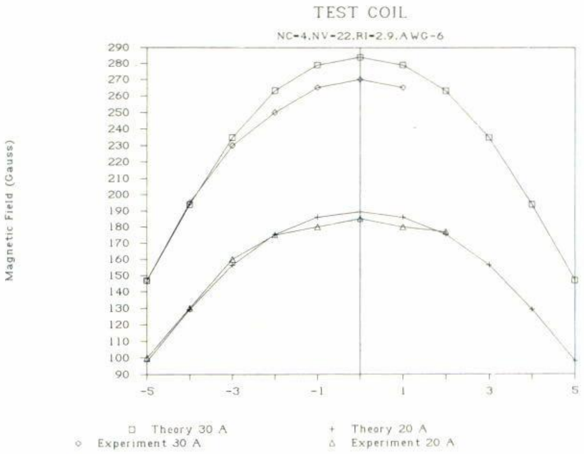

FIGURE 4. Comparison of results.

Fig. 5 shows the profile of the field along the device, obtained with the program, the displayed values correspond to the central part of the solenoid. In this figure it is possible to see that the value of the field at the region where the resonant cavity is going to be located (≈ 40 cm, the central part of the resonator) reaches the resonant value of 850 gauss, at which the discharge will be ignited. In this figure, CR denotes the value of the current, measured in amperes, and the Z's define the position of the center of each solenoid, the rest of the notation is the same as in Fig. 4. The radial variation of the field at this region is shown in Fig. 6. The horizontal axis of this figure denotes different positions within the internal diameter of the solenoids, the zero corresponds to the center. The different curves correspond to different positions along the device. This figure shows that the region that will be occupied by the plasma (the plasma diameter will be approximately 6 cm) is a region of almost homogeneous field.

### *3.3. Microwave system*

This system will consist of a microwave (magnetron) generator, a waveguide and a resonant cavity.

A Raytheon PG10x1 of fixed frequency ($f = 2.45$ GHz) and variable power output ($\leq 100$ W in CW) will be used. The high frequency field will be transported into the resonant cavity through a 8.5 cm i.d. brass cylindrical waveguide (G in Fig. 1, C in Fig. 7). In this guide an $H_{11}$ electromagnetic mode will be excited, which is the basic one for this kind of guides.

The critical wavelength is determined from the relation [11]

$$\lambda_c = \frac{\pi D}{j'_{mn}}, \tag{6}$$

where $D$ is the internal diameter of the guide and $j'_{mn}$ is the $n$–th root of the derivative of the Bessel function $J_m(x)$. Accordingly to these values ($j'_{11} = 1.84$) we get $\lambda_c = 14.5$ cm.

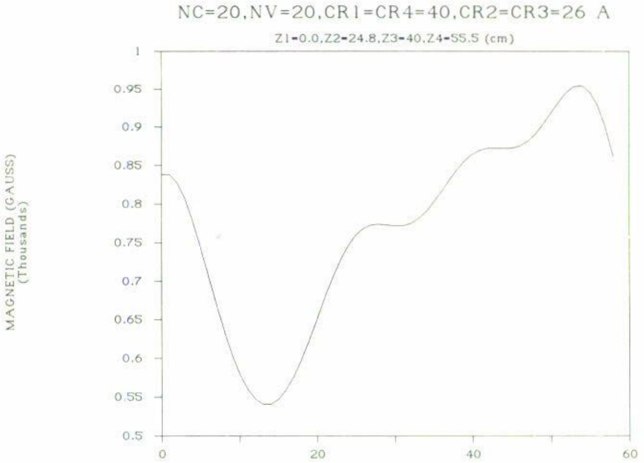

FIGURE 5. Distance along the device (cm).

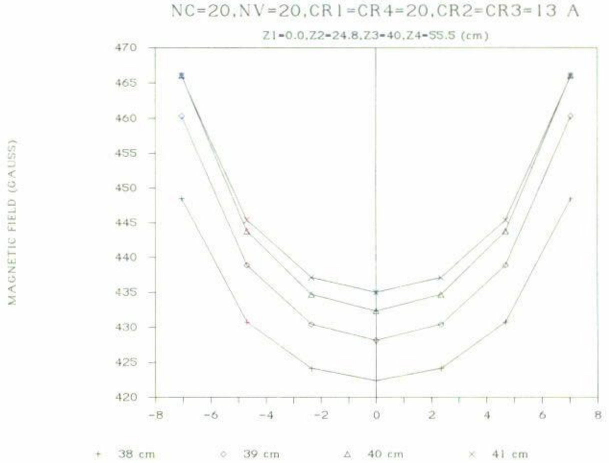

FIGURE 6. Magnetic field radial variation.

The wavelength of the pump frequency is $\lambda = 12.24$ cm then $\lambda < \lambda_c$ and the wave of type $H_{11}$ will propagate along the waveguide.

A brass 14 cm i.d. cylindrical $TE_{111}$ cavity will be used (H in Fig. 1, B in Fig.7). This cavity was designed to have a variable height $h$ ($h$ is the distance between the walls of the resonator) in order to provide the tuning required. The resonant value of the height was determined from the following relation [11]:

$$h = \frac{\lambda S}{\sqrt{4 - \left(\frac{\lambda}{a}\right)^2 \left(\frac{j'_{mn}}{\pi}\right)^2}},$$

where $a$ is the resonator radius and $S$ is the number of halfwavelengths in the resonator. In our case $a = 7$ cm, $S = 1$ and $j'_{11} = 1.84$. Then we get

$$h = 7.13 \text{ cm}.$$

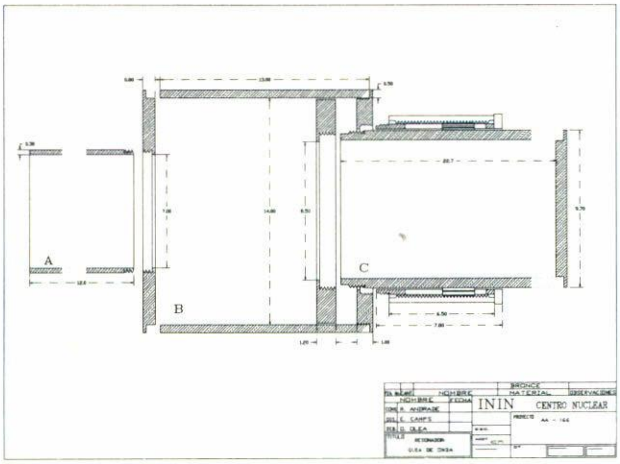

FIGURE 7. Resonant cavity's details.

It is possible to find the electric field intensity in the resonator tuned to the generator's frequency, using the expresions which determine the field distribution in the $TE_{111}$ resonator [12]:

$$E_\phi = E_0 J_1'\left(1.84\frac{r}{a}\right)\cos\phi \operatorname{sen}\pi\left(\frac{z}{h}+\frac{1}{2}\right),$$

$$E_r = E_0\frac{J_1\left(1.84\frac{r}{a}\right)}{1.84\frac{r}{a}}\operatorname{sen}\phi \operatorname{sen}\pi\left(\frac{z}{h}+\frac{1}{2}\right),$$

$$E_z = 0,$$

where $E_{\phi,r,z}$ are the components of the electric field in cylindrical coordinates, $E_0$ is the maximum value of the field and $J_1$ is the first order Bessel function. Accordingly to the definition of the electromagnetic wave power absorbed in the resonant cavity we have

$$P = \frac{\omega}{Q}\int_v W\,dv,$$

where $v$ is the volume of the resonator, $Q$ is the quality factor of the resonator, $\omega$ is the wave frequency, $W = \frac{1}{2}\epsilon E^2 + \frac{1}{2}\mu H^2$ is the electromagnetic wave energy density ($\epsilon = 10^7/4\pi c^2$ [Farad/m], $\mu = 4\pi \times 10^7$ [Henry/m], and $c$ is the light speed), using these values we can get an expression for the density of the electric field energy, which takes the form

$$W_E = \tfrac{1}{2}\epsilon E^2 = \frac{QP}{0.238\,\pi a^2 h\omega}. \tag{7}$$

When we suppose that all the output energy of the generator is introduced into the resonator (*i.e.* when $P = 100$ W.), it is possible to obtain from (7) the value of $E_0$, if $Q = 800$ (this is a value commonly obtained in experiments, the theoretical value is

11800, the difference is caused by the holes on the walls of the resonator and the glass tube, which contains the gas) then

$$E_0 = 676 \text{ V/cm}.$$

This value allows an easy ignition of the discharge. On the other hand, relation (5) is satisfied, indeed $V_{Te} = 18.4 \times 10^5$ m/s (here we supposed an electron temperature equal to 20 eV, which is a characteristic value of temperature for this type of devices, see *e.g.* Ref. [6]) and $V_E = 7.64 \times 10^5$ m/s. With these expected values parametric processes are possible.

The resonant cavity will have, in the opposite side to the input waveguide, another guide working in the cutoff regime, *i.e.* its diameter is such that $\lambda > \lambda_c$. The object of this second guide is to supply an access to the resonant cavity, which will be used to introduce the glass tube containing the gas for ionization (I in Fig. 1, A in Fig.7). The guide works in the cutoff regime in order to avoid the escape of electromagnetic energy from the cavity.

The components of the electromagnetic field vary as

$$E = E_0 e^{-\alpha z} e^{i\omega t}; \qquad H = H_0 e^{-\alpha z} e^{i\omega t},$$

where the decay constant is given by

$$\alpha = \frac{2\pi}{\lambda_c}\sqrt{1 - \left(\frac{\lambda_c}{\lambda}\right)^2}.$$

The relation between the input and output magnitudes of the electric field in the guide is

$$|E_{\text{out}}| = |E_{\text{in}}| e^{-\alpha l},$$

where $l$ is the waveguide length. The decrease in the magnitude of the electric field is defined by

$$L = 20 \log \frac{|E_{\text{in}}|}{|E_{\text{out}}|} = 20 \log e^{\alpha l} \simeq 8.7\alpha l \text{ [db]},$$

in our case $D = 7$ cm and $l = 12$ cm, then from (6) we have

$$\lambda_c = 1.71 D = 11.97,$$

as $\lambda = 12.24$ cm then $\lambda > \lambda_c$. Finally we get

$$L = 8.7\alpha l = 8.7 \frac{2\pi}{\lambda_c}\sqrt{1 - \left(\frac{\lambda_c}{\lambda_0}\right)^2} \cdot l,$$

and $L = 11.83$, the last means that the decrease of the signal in power will be of 15-fold.

## 4. CONCLUSIONS

The main point while making the design of the plasma source, was to have enough versatility in order to make possible the arrangement of different experiments, particularly those related to deposition of different kind of thin films, and the study of overdense plasma formation, in which we are interested. However these kind of devices do not limit their possibilities to those experiments, and can be useful in many other applications.

Some of the results that can be obtained in this device, can have industrial applications, but it is necessary to point out that the present design is an experimental one, and industrial applications will need industrial designs, which would consider some economical improvements, that are still possible.

## ACKNOWLEDGEMENTS

The authors would like to thank Ing. Roberto Andrade and Pedro Alonso Jiménez for many helpful discussions and invaluable technical support during the construction of the device.

## REFERENCES

1. J.L. Shohet, *Phys Fluids B* **2**, 6 (1990) 1474.
2. V.E. Golant, A.D. Pilia, *Sov. Phys. Uspekhy* **104**, 3 (1971) 413.
3. J.M., Dawson *et. al., Phys Rev. Lett.* **37** (1976) 1547.
4. Int. Conf. on Ion Sources. Berkeley, July 10-14, 1989.
5. M. Dahimene, J.A. Asmussen, *J. Vac. Sci. Technol. B,* **4**, 1 (1986) 126.
6. A.A. Balmashnov, K.S. Golovanivsky, E. Camps, International Conference on Plasma Physics, T.2 Kiev, USSR April 6-12 (1987).
7. A.A. Balmashnov, K.S. Golovanivsky, E. Camps *et. al., Sov. Phys. Doklady,* **297**, 3 (1987) 580.
8. I.R. Gekker, Interacción de campos electromagnéticos fuertes con el plasma. Moscú, Atomizdat, 1978.
9. N.E. Andrieev, A. Yu. Kiri, V.P. Silin, *Sov. Phys. JETP* **57**, 3 (1969) 1024.
10. E. Camps, A. Muñoz, Research Report, IBA-DF-90-03, May 1990.
11. J. Meinke, F.M. Gundlaj, *Radiotechnical Handbook.* Moscow, Gozenergoizdat (1960).
12. M.A. Heald, C.B. Wharton, *Plasma Diagnostics with Microwaves.* John Wiley & Sons Inc. (1968).