Theoretical and experimental studies of a planar inductive coupled rf plasma source as the driver in simulator facility (ISTAPHM) of interactions of waves with the edge plasma on tokamaks

To cite this article: V. Ghanei et al 2017 JINST 12 P11024

View the article online for updates and enhancements.

Related content
- Theoretical and experimental investigations of the electromagnetic field within a planar coil, inductively coupled RF plasma source
  I M El-Fayoumi and I R Jones
- EEDF measurements and plasma parameters in ICP
  V A Godyak, R B Piejak and B M Alexandrovich
- Chlorine plasma and polysilicon etch characterization
  Marwan H Khater and Lawrence J Overzet
Theoretical and experimental studies of a planar inductive coupled rf plasma source as the driver in simulator facility (ISTAPHM) of interactions of waves with the edge plasma on tokamaks

V. Ghanei, a M.N. Nasratabdi, a,1 O.-H. Chin b and K.K. Jayapalan b

aDepartment of Nuclear Engineering, Faculty of Advanced Sciences & Technologies, University of Isfahan, Hezar Jerib Street, 81746-73441, Isfahan, Iran
bPlasma Technology Research Centre, Department of Physics, University of Malaya, 50603 Kuala Lumpur, Malaysia

E-mail: mnnasrabadi@ast.ui.ac.ir

ABSTRACT: This research aims to design and build a planar inductive coupled RF plasma source device which is the driver of the simulator project (ISTAPHM) of the interactions between ICRF Antenna and Plasma on tokamak by using the AMPICP model. For this purpose, a theoretical derivation of the distribution of the RF magnetic field in the plasma-filled reactor chamber is presented. An experimental investigation of the field distributions is described and Langmuir measurements are developed numerically. A comparison of theory and experiment provides an evaluation of plasma parameters in the planar ICP reactor. The objective of this study is to characterize the plasma produced by the source alone. We present the results of the first analysis of the plasma characteristics (plasma density, electron temperature, electron-ion collision frequency, particle fluxes and their velocities, stochastic frequency, skin depth and electron energy distribution functions) as function of the operating parameters (injected power, neutral pressure and magnetic field) as measured with fixed and movable Langmuir probes. The plasma is currently produced only by the planar ICP. The exact goal of these experiments is that the produced plasma by external source can exist as a plasma representative of the edge of tokamaks.

KEYWORDS: Plasma diagnostics - probes; Plasma generation (laser-produced, RF, x ray-produced)

1Corresponding author.
1 Introduction

Operation of the Ion Cyclotron Resonant Frequency (ICRF) antenna on tokamaks revealed spurious effect like sputtering, hot spots and loss of powers due to the interaction of the electromagnetic field with the plasma sheath and the creation of a rectified DC voltage. Several theoretical tools have been developed to analyze these effects on ICRF antenna [1–4]. Ion Sheath Test Arrangement (ISTA) is dedicated to investigate the interactions between an ICRF antenna and plasma considering plasma temperature, density and magnetic configuration which represent the plasma edge of a magnetic confinement fusion machine. This system is composed of an external plasma source and a main vessel, in which a dedicated single strap ICRF antenna is installed. The ICRF antenna is located on the main vessel and contains two main coils which provide a static magnetic field up to 0.2 T and an external RF plasma source which creates a plasma with a density around $10^{18}$ m$^{-3}$ using argon and $10^{17}$ m$^{-3}$ using helium with temperature between 5 and 10 eV. This plasma source is designed to reach helicon discharge mode with an array of four magnetic coils which produce a magnetic field of 0.1 T in order to reach a high density and uniform radial profile along the cross section [3–7]. In this work, an external plasma source that consists of a planar plasma source connected to a glass tube, four magnetic coils (operated at 1 kA) and a right-handed helical antenna is used. Also, a planar inductively coupled RF plasma source is studied as theoretical and experimental investigations. The output plasma from the external plasma source is magnetized and powered by a helical antenna up to 3 kW at 13.56 MHz. This external plasma source is presented in figure 1. Planar part of Plasma source consists of a cylindrical vessel where the planar antenna is attached with. External plasma source is designed to get high densities and uniform radial profiles along the cross-section. The composed system of a planar ICP and a main vessel for the ICRF-plasma interactions is named ISTAPHM (the Ion Sheath Test Arrangement with External Plasma Source which is designed to reach Helicon Mode).
There are three antennas in ISTAPHM: Planar antenna, Right-handed helical antenna and ICRF antenna which work independently. So, it is possible that RF frequencies match at all ion cyclotron frequencies which are used in ICRF devices. The plasma can generate in the various frequency externally with two antennas (planar antenna and right-handed helical antenna) that should allow us to reach the helicon transition. The external plasma source operates to reach plasma conditions relevant for a tokamak edge by reaching the helicon mode [8]. RF sheaths generated in front of ICRF antenna can induce deleterious effects like impurity generation, hot spots and sputtering. ISTAPHM allows for dedicated experiments and measurements on RF sheaths. Since the plasma which is produced by external source consists a numerous of moving electrical charges, it is subject to collective interactions which indicate typical resonance effects. Therefore, coupling of high power (high frequency) waves to the plasma by ICRF antenna appears to be an effective method for simulation of heating mechanism in tokamaks. The most favorable application of such a mechanism is that electromagnetic coupling via waves having the ion cyclotron frequency $\omega_{ci}$ or the harmonics $2\omega_{ci}$ or $3\omega_{ci}$. These waves are made by ICRF antenna in ISTAPHM. The ion motion can thus be resonantly enhanced to high kinetic energies. The irradiation by those high frequency waves is usually performed in ISTAPHM at the frequency $\omega_{ci}$, or the harmonics $2\omega_{ci}$, or $3\omega_{ci}$ (30–100 MHz depending on the magnetic field strength) by ICRF antenna. The absorption of the irradiated electromagnetic energy increases with higher ion temperature and can be managed most effectively.
by minimizing the distance between the onset/cutoff location of the wave of ICRF antenna and the plasma edge. The purpose of ISTAPHM project is to investigate the coupling between ICRF (Ion Cyclotron Range of Frequency) antennas and a plasma representative of the edge of tokamaks. It provides a better accessibility for the instrumentation than tokamaks while being representative of the neighboring region of the wave emitter.

2 Theoretical investigation of a planar ICP source

It is assumed that there are a large number of turns in the planar coil. Therefore, the current in the planar induction coil can be approximated by a 2-D disc constant density, azimuthal surface current, $K_\theta$ (A/M). It must be noted that in this work, the cylindrical coordinate system is employed (figure 2). It is assumed that the conducting bottom plate of chamber is at $z = 0$; the bottom of the fused silica window is at $z = L$; also, it is assumed the induction coil disk is located at $z = L + D$.

![Figure 2. Schematic diagram of the planar inductive coupled RF plasma device.](image)

It is assumed that the plasma is composed of immobile ions and cold electrons and that the appropriate Ohm’s law is:

$$E = \frac{m_e}{n_e e^2} \frac{\partial J}{\partial t} + \frac{m_e v}{n_e e^2} J$$  \hspace{1cm} (2.1)

Since we are dealing with a steady state situation, one can assume time dependence for $E$, $B$ and $J$ as:

$$E(r, \theta, z, t) = E(r, \theta, z) e^{i\omega t}, \quad B(r, \theta, z, t) = B(r, \theta, z) e^{i\omega t}, \quad J(r, \theta, z, t) = J(r, \theta, z) e^{i\omega t}$$

which can be rewritten as:

$$J = \frac{\varepsilon_0 \omega^2 n_e}{\nu + i\omega} E$$  \hspace{1cm} (2.2)
Eqs. (2.1) and (2.2) are true if the fields varying in time as $e^{i\omega t}$. Here, $\omega_{pe}^2$ is the electron plasma frequency given by $\omega_{pe}^2 = n_e e^2/\varepsilon_0 m_e$. At first, it was assumed that $n_e$ and $\nu$ have constant values throughout the volume of the reactor chamber.

2.1 Effects of collisions

Collisions can be taken into account in a straightforward manner, simply by including the frictional damping term in the momentum equation [9–11]. The time-harmonic momentum equation for plasmas becomes:

$$i\omega m_e n_e u_e = e n_e E - m_e n_e \nu u_e$$

$$i\omega m_e \left(1 - i\frac{\nu}{\omega}\right) u_e = e E$$

$$u_e = \frac{e E}{i\omega m_e \left(1 - i\frac{\nu}{\omega}\right)}$$

(2.3)

where $\nu$ is the effective electron collision frequency and $u_e$ is the velocity of electron in plasma. The current density $J$ can be written as:

$$J = -n_e e u_e = -\frac{n_e e^2}{i\omega m_e \left(1 - i\frac{\nu}{\omega}\right)} E = -\frac{\varepsilon_0 \omega_{pe}^2}{i\omega \left(1 - i\frac{\nu}{\omega}\right)} E = \sigma P E$$

where the complex plasma conductivity, $\sigma_p$ is defined as:

$$\sigma_p = -\frac{\varepsilon_0 \omega_{pe}^2}{i\omega \left(1 - i\frac{\nu}{\omega}\right)}$$

(2.4)

The power absorbed by the discharge is defined as:

$$P_{abs} = \frac{1}{2} \text{Re}(J \times E^*)$$

(2.5)

Eq. (2.5) establishes the link between $P_{abs}$ and the RF fields. Using the time averaged power, $P_{abs}$ can be shown as:

$$P_{abs} = \frac{1}{2} \frac{\nu}{\omega^2 + \nu^2} \varepsilon_0 \omega_{pe}^2 E^2 = \frac{1}{2} \frac{\nu}{\omega^2 + \nu^2} \frac{e^2 n_e}{m_e} E^2$$

(2.6)

Therefore, when electrons undergo collisions, the randomization of their phase coherence of motion allows for a transfer of energy to the heavy particles. Because this type of heating occurs when collisions are present, which is inherent to the fact that the plasma has a non-zero resistivity, it is called collisional heating or ohmic heating by analogy with ohmic resistances.

2.2 Maxwell’s equations and boundary condition

It is assumed that the excitation frequency in the ICP reactor is low. Therefore, the plasma wavelength is long compared to the dimensions of the reactor’s chamber [9–11]. Hence one can ignore the displacement current in Maxwell’s equations and use the following simplified set:

$$\nabla \times E = -\frac{\partial B}{\partial t} = i\omega B$$

$$\nabla \times B = \mu_0 J$$

(2.7)

(2.8)

(2.9)
Then,
\[ \nabla \times \nabla \times E = i \omega \mu_0 J \] (2.10)

Based on eq. (2.4), eq. (2.10) can now be rewritten as:
\[ \nabla \times \nabla \times E = \frac{\mu_0 \varepsilon_0 \omega^2}{c^2} E = \frac{\omega_p^2}{(1 - i \frac{\omega}{\omega_p})} E = a^2 E \] (2.11)

where \( a^2 = \frac{\omega_p^2}{c^2 \left[ 1 - i \frac{\omega}{\omega_p} \right]} \).

The cylindrical symmetry of the problem dictates that the induced fields have only the following components:
\[ E \equiv \{0, E_\theta, 0\}; \quad B \equiv \{B_r, 0, B_z\}; \quad J \equiv \{0, j_\theta, 0\}; \]

Then, eqs. (2.8) and (2.11) yield the following three scalar equations for \( E_\theta, B_r \) and \( B_z \):
\[ \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial E_\theta}{\partial r} \right) + \frac{\partial^2 E_\theta}{\partial z^2} = \alpha^2 E_\theta \] (2.12)
\[ -i \omega B_r = -\frac{\partial E_\theta}{\partial z} \] (2.13)
\[ -i \omega B_z = -\frac{1}{r} \frac{\partial (r E_\theta)}{\partial r} \] (2.14)

Solving eq. (2.12) for \( E_\theta \) using separation of variables method, \( E_\theta(r, z) = R(r)Z(z) \), and then substituting \( E_\theta \), into eqs. (2.13) and (2.14) results in the following equations:
\[ r^2 \frac{d^2 R}{dr^2} + r \frac{dR}{dr} + (\lambda^2 r^2 - 1)R = 0 \] (2.15)
\[ \frac{d^2 Z}{dz^2} = k^2 Z \] (2.16)

where \( k^2 = [\lambda^2 + a^2] \). Here, \( \lambda \) is a separation constant. It is assumed that the vessel is made of a perfect conductor so that the tangential electric and the normal magnetic fields are equal to zero on the vessel walls. It is assumed that there are a large number of turns in the planar coil. So, there is only azimuthal surface current, \( K_\theta \) (A/M). \( K_\theta \) is related to the RF current in the coil, I, by the relation:
\[ K_\theta = \frac{NI}{a} \] (2.17)

where \( N \) is the number of coil’s turns and \( a \), is the radius of the RF coil. With these assumptions, the boundary conditions are:

- At \( z = L + D \) (i.e. at the bottom of planar coil disc surface):
\[ B_r = \frac{\mu_0 K_\theta}{2} \] (2.18)

Then eq. (2.13) leads to:
\[ \left. \frac{\partial E_\theta(r, z)}{\partial z} \right|_{z=L+D} = \frac{i \omega \mu_0 K_\theta}{2} \] (2.19)
• Using boundary conditions for the tangential electric field and the normal magnetic field between the fused silica window and the plasma, that is, at \( z = L \):

\[
E_\theta(r, L) = E_\theta(r, L_+)
\]

(2.20)

and

\[
B_z(r, L) = B_z(r, L_+)
\]

(2.21)

Using eqs. (2.14) and (2.21), we will have:

\[
\frac{1}{r} \frac{\partial}{\partial r} \left(r E_\theta \right) \bigg|_{z=L_-} = \frac{1}{r} \frac{\partial}{\partial r} \left(r E_\theta \right) \bigg|_{z=L_+}
\]

(2.22)

• At \( r = a \) and \( z = 0 \), the tangential electric and the normal magnetic fields are equal to zero. That is:

\[
E_\theta(a, z) = 0 \quad \text{and} \quad E_\theta(r, 0) = 0
\]

(2.23)

Solving eqs. (2.15) and (2.16), one obtains the following physically realistic solutions:

\[
R(r) = A_1 J_1(\lambda r)
\]

(2.24)

\[
Z(z) = B_1 \sinh(kz) \quad \text{for } z < L
\]

\[
E_\theta(r, z) = A \sinh(kz) J_1(\lambda r)
\]

and

\[
R(r) = A_2 J_1(\lambda r)
\]

\[
Z(z) = B_2 \exp(\lambda z) + C_2 \exp(-\lambda z) \quad \text{for } L < z < L + D
\]

\[
E_\theta(r, z) = [B \exp(\lambda z) + C \exp(-\lambda z)] J_1(\lambda r)
\]

(2.25)

Using eq. (2.23), \( E_\theta(a, z) = 0 \), and \( J_1(x) = 0 \), hence \( \lambda_n a = \mu_n \) where \( \mu_n \) are the Bessel one order roots. Therefore, the eigenvalues of the eq. (2.12) are given by the following formula:

\[
\lambda_n = \frac{\mu_n}{a}
\]

\[
k_n = \sqrt{\alpha^2 + \lambda_n^2}
\]

(2.26)

and the eigen functions are:

\[
E_{\theta n}(r, z) = A_n \sinh(k_n z) J_1(\lambda_n r)
\]

(2.27)

Using equations (2.26) and (2.27), the solution for equation (2.12) is led to:

\[
E_\theta(r, z) = \begin{cases}
\sum_{n=1}^{\infty} A_n \sinh(k_n z) J_1(\lambda_n r) & \text{for } 0 \leq z \leq L \\
\sum_{n=1}^{\infty} B_n \exp(-\lambda_n z) + C_n \exp(\lambda_n z) J_1(\lambda_n r) & \text{for } L < z \leq L + D
\end{cases}
\]

(2.28)
From eqs. (2.13), (2.14) and (2.28), the following expressions for \( B_r \) and \( B_z \) are obtained:

\[
B_r(z, z) = \left\{ \begin{array}{ll}
-\frac{i}{\omega} \sum_{n=1}^{\infty} A_n k_n \cos(k_n z) J_1(\lambda_n r) & \text{for } 0 \leq z \leq L \\
-\frac{i}{\omega} \sum_{n=1}^{\infty} k_n \left[ -B_n \exp(-\lambda_n z) + C_n \exp(\lambda_n z) \right] J_1(\lambda_n r) & \text{for } L < z \leq L + D
\end{array} \right.
\]  

(2.29)

\[
B_z(r, z) = \left\{ \begin{array}{ll}
\frac{i}{\omega} \sum_{n=1}^{\infty} A_n k_n \sin(k_n z) J_0(\lambda_n r) & \text{for } 0 \leq z \leq L \\
\frac{i}{\omega} \sum_{n=1}^{\infty} k_n \left[ -B_n \exp(-\lambda_n z) + C_n \exp(\lambda_n z) \right] J_0(\lambda_n r) & \text{for } L < z \leq L + D
\end{array} \right.
\]  

(2.30)

Then,

\[
\left. \frac{\partial E_\theta}{\partial z} \right|_{z=L+D} = \sum_{n=1}^{\infty} \lambda_n \left[ -B_n e^{-\lambda_n(L+D)} + C_n e^{\lambda_n(L+D)} \right] J_1(\lambda_n r) = -i \frac{\omega \mu_0 K_\theta}{2}
\]

(2.31)

Using the identity:

\[
\int_0^a r J_1^2(\lambda_n r) dr = \frac{a^2}{2} \left[ J_1^2(\lambda_n a) + \left( 1 - \frac{1}{\lambda_n^2 a^2} \right) J_1^2(\lambda_n a) \right]
\]

(2.32)

and the orthogonality of Bessel functions:

\[
\lambda_n \left[ -B_n e^{-\lambda_n(L+D)} + C_n e^{\lambda_n(L+D)} \right] \frac{a^2}{2} J_1^2(\lambda_n a) = -i \frac{\omega}{2} \mu_0 K_\theta \int_0^a r J_1(\lambda_n r) dr
\]

(2.33)

Assuming \( \nu_n = B_n e^{-\lambda_n(L+D)} + C_n e^{\lambda_n(L+D)} \), then, eq. (2.33) reduces to:

\[
\nu_n = -i \frac{\omega}{2} \mu_0 K_\theta \int_0^a r J_1(\lambda_n r) dr
\]

(2.34)

The application of the boundary conditions given by eqs. (2.20) and (2.23), together with the definition of \( \nu_n \), lead to the following coupled set of simultaneous equations which can be solved for \( A_n, B_n \) and \( C_n \):

\[
\begin{align*}
B_n e^{-\lambda_n L} + C_n e^{\lambda_n L} &= A_n \sinh(k_n L) \\
-\lambda_n [B_n e^{-\lambda_n L} - C_n e^{\lambda_n L}] &= k_n A_n \cosh(k_n L) \\
-B_n e^{-\lambda_n(L+D)} + C_n e^{\lambda_n(L+D)} &= \nu_n
\end{align*}
\]

(2.35)

The results are:

\[
A_n = \frac{\nu_n \lambda_n}{\lambda_n \sinh(\lambda_n D) \sinh(k_n L) - k_n \cosh(k_n L) \cosh(\lambda_n D)}
\]

\[
B_n = \frac{A_n}{2 \lambda_n} e^{\lambda_n L} \left[ \lambda_n \sinh(k_n L) - k_n \cosh(k_n L) \right]
\]  

(2.36)

\[
C_n = \frac{A_n}{2 \lambda_n} e^{-\lambda_n L} \left[ \lambda_n \sinh(k_n L) + k_n \cosh(k_n L) \right]
\]

These values can be substituted into eqs. (2.28), (2.29) and (2.30) to obtain the electric and magnetic field components in the range of \( 0 \leq r \leq a \) and \( 0 \leq z \leq L + D \) inside the inductively coupled RF plasma source. The mentioned equations together with boundary conditions describe the dynamics of the plasma and predict the simulated outputs and variables of the plasma. This work
simultaneously enables us to use a method for designing of AMPICP (Analytic Model of Planar Inductive Couple Plasma) and can be used approximately to describe plasma and electromagnetic fields behavior in a planar inductive coupled RF plasma source device. This research aims to design and build a planar inductive coupled RF plasma source device by using the AMPICP model. The results of AMPICP model for the predicted $E_{\text{max}}$, $J_{\text{max}}$, $B_{\text{max}}$ and maximum magnetic pressure in the planar ICP and various radii are indicated in figure 3 and table 1. The AMPICP code is written by Matlab programming language.

One of the advantages of simulation for designing is that, the designer can select criteria such as radius. Figure 3 and table 1 show the maxima of induced magnetic field, electric field, current density and magnetic pressure versus chamber and planar coil radii. Using simulation to extract the design parameters, the maxima of induced and deposited electromagnetic power and magnetic pressure, are the main criteria for choosing geometric dimensions. These criteria provide high density required for ICRF vessel.

Table 1. Predicted $E_{\text{max}}$, $J_{\text{max}}$, $B_{\text{max}}$ and Magnetic pressure as functions of chamber radius in the planar ICP Reactor (Reactor Height = 20 cm, Reactor-Coil Spacing = 2 cm, Planar Coil Radius = 4.2 cm, $f = 13.56 \text{MHz}$, $N_e = 8 \times 10^{17} \text{m}^{-3}$, $\omega = 2\pi f$, $\nu = 40\omega$).

<table>
<thead>
<tr>
<th>Chamber Radius (cm)</th>
<th>$E_{\text{max}}$ (V.m$^{-1}$)</th>
<th>$J_{\text{max}}$ (A.m$^{-2}$)</th>
<th>$B_{\text{max}}$ (T)</th>
<th>Maximum Magnetic Energy Density ($\frac{\mu^2}{2\nu}$) (J. m$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2</td>
<td>0.0145</td>
<td>0.0960</td>
<td>2.6916 x 10$^{-8}$</td>
<td>2.8826 x 10$^{-10}$</td>
</tr>
<tr>
<td>8</td>
<td>234.5992</td>
<td>1.5487 x 10$^3$</td>
<td>2.7565 x 10$^{-4}$</td>
<td>0.0302</td>
</tr>
<tr>
<td>9</td>
<td>731.8883</td>
<td>4.8317 x 10$^4$</td>
<td>9.7580 x 10$^{-4}$</td>
<td>0.3789</td>
</tr>
<tr>
<td>10</td>
<td>2.4550 x 10$^3$</td>
<td>1.6207 x 10$^4$</td>
<td>0.0081</td>
<td>26.1581</td>
</tr>
<tr>
<td>11</td>
<td>2.4629 x 10$^3$</td>
<td>1.6260 x 10$^4$</td>
<td>0.0082</td>
<td>26.6801</td>
</tr>
<tr>
<td>12</td>
<td>2.4676 x 10$^3$</td>
<td>1.6290 x 10$^4$</td>
<td>0.0083</td>
<td>27.6446</td>
</tr>
<tr>
<td>13</td>
<td>2.4715 x 10$^3$</td>
<td>1.6316 x 10$^4$</td>
<td>0.0082</td>
<td>26.5247</td>
</tr>
<tr>
<td>14</td>
<td>2.4735 x 10$^3$</td>
<td>1.6329 x 10$^4$</td>
<td>0.0082</td>
<td>26.8112</td>
</tr>
<tr>
<td>14.5</td>
<td>2.4738 x 10$^3$</td>
<td>1.6331 x 10$^4$</td>
<td>0.0083</td>
<td>27.6315</td>
</tr>
<tr>
<td>15</td>
<td>2.4751 x 10$^3$</td>
<td>1.6340 x 10$^4$</td>
<td>0.0081</td>
<td>26.3710</td>
</tr>
<tr>
<td>16</td>
<td>2.4758 x 10$^3$</td>
<td>1.6344 x 10$^4$</td>
<td>0.0082</td>
<td>26.6894</td>
</tr>
<tr>
<td>17</td>
<td>2.4767 x 10$^3$</td>
<td>1.6350 x 10$^4$</td>
<td>0.0081</td>
<td>26.2360</td>
</tr>
<tr>
<td>18</td>
<td>2.4768 x 10$^3$</td>
<td>1.6351 x 10$^4$</td>
<td>0.0082</td>
<td>26.5493</td>
</tr>
<tr>
<td>20</td>
<td>2.4774 x 10$^3$</td>
<td>1.6355 x 10$^4$</td>
<td>0.0078</td>
<td>24.2807</td>
</tr>
<tr>
<td>22</td>
<td>2.4773 x 10$^3$</td>
<td>1.6354 x 10$^4$</td>
<td>0.0077</td>
<td>23.5000</td>
</tr>
<tr>
<td>24</td>
<td>2.4798 x 10$^3$</td>
<td>1.6371 x 10$^4$</td>
<td>0.0077</td>
<td>23.7052</td>
</tr>
<tr>
<td>26</td>
<td>2.4785 x 10$^3$</td>
<td>1.6362 x 10$^4$</td>
<td>0.0074</td>
<td>21.6797</td>
</tr>
<tr>
<td>28</td>
<td>2.4760 x 10$^3$</td>
<td>1.6346 x 10$^4$</td>
<td>0.0072</td>
<td>20.5291</td>
</tr>
<tr>
<td>30</td>
<td>2.4764 x 10$^3$</td>
<td>1.6348 x 10$^4$</td>
<td>0.0072</td>
<td>20.8469</td>
</tr>
</tbody>
</table>
Figure 3. Predicted $E_{\text{max}}$, $J_{\text{max}}$, $B_{\text{max}}$ and Magnetic pressure as functions of chamber radius in the planar ICP Reactor (Reactor Height = 20 cm, Reactor-Coil Spacing = 2 cm, Planar Coil Radius = 4.2 cm, $f = 13.56$ MHz, $\omega = 2\pi f$, $N_e = 8 \times 10^{17}$ m$^{-3}$, $\nu = 40\omega$).
The ability to select various parameters such as geometrical dimension is considered as one of the advantages of simulation in designing a planar RF source. The maxima of induced magnetic field, electric field, current density and magnetic pressure versus chamber radius are shown in figure 3 and table 1. As can be seen from figure 3, the optimum radius in order to have the best deposition RF power is 12 cm, but it is possible to increase it up to 20 cm. This issue is confirmed in the constructed devices [9, 10].

Figure 4 shows predicted maximum absolute magnetic field as a function of N-turns in the planar ICP source. Absolute magnetic field required for planar coil in the ISTAPHM system is 0.1 T. Simulation results of external plasma source for the main driver of ISTAPHM system reveal that the number of turns in a planar ICP should be 74. This value is obtained from interpolation between predicted data.

2.3 Methodology of drawing magnetic field lines

The distribution of the magnetic field lines within the chamber of the plasma reactor is visualized by drawing the field lines. Two approaches are described for drawing the magnetic field lines. In the first approach, the magnetic field lines are produced by solving the following differential equations together with eqs. (2.28), (2.29) and (2.30). Since the tangential magnetic field line at a given point is a vector with the same direction as \( B \) at that point, the following equations are governed for the trajectory of the field lines:

\[
B_z (r, z, t) = |B_z (r, z)| \cos(\phi_{B_z} + \omega t)
\]

\[
B_r (r, z, t) = |B_r (r, z)| \cos(\phi_{B_r} + \omega t)
\]

\[
|B (r, z, t)| = \sqrt{B^2_r + B^2_z}
\]

(2.37)
\[ \frac{dr}{ds} = \frac{B_r(r, z, t)}{|B(r, z, t)|} \]
\[ \frac{dz}{ds} = \frac{B_z(r, z, t)}{|B(r, z, t)|} \]

Here, \( s \) is the distance along the field lines from a given starting point. \( |B_r(r, z)| \) and \( |B_z(r, z)| \) are the amplitudes of \( B_r \) and \( B_z \). Also, \( \phi_{B_r} \) and \( \phi_{B_z} \) are the phases of \( B_r \) and \( B_z \) \( |(r, z)| \) with respect to current in the induction coil. In general, the solution of the above set of eqs. (2.37) is a function of time and, therefore, at any time there is a different magnetic pattern within the reactor chamber.

However, for the situation in which the chamber is evacuated, the pattern of the field lines remains fixed; it is only the magnitude of the field which varies, i.e., for this case, \( \phi_{B_r} \) and \( \phi_{B_z} \approx 0 \) [12]. In practice, a starting point is chosen and the set of eqs. (2.37) are solved using an Adams-Moulton Predictor-Corrector Method (AMPCM) [13]. This procedure is repeated for the desired number of field lines. In the second approach, since the plasma reactor has cylindrical symmetry \( (\partial / \partial \theta \equiv 0) \), the magnetic field lines can be visualized by drawing the contours of the scalar quantity, \( r A_\theta \), where \( A_\theta \) is the \( \theta \)-component of the vector potential \( (A_\theta = \frac{1}{r} \int_0^r r B_z(r, z) dr) \) for a cylindrically symmetric situation). The following argument shows that the above prescription holds in terms of the vector potential:

\[ \mathbf{B} = \nabla \times \mathbf{A} \]
\[ \mathbf{B} = \hat{e}_r \left( -\frac{\partial A_\theta}{\partial r} \right) + \hat{e}_z \frac{1}{r} \frac{\partial}{\partial r} (r A_\theta) \tag{2.38} \]

For a cylindrically symmetric situation, we will have:

\[ \nabla (r A_\theta) = \hat{e}_r \frac{\partial}{\partial r} (r A_\theta) + \hat{e}_z \frac{\partial}{\partial z} (r A_\theta) \tag{2.39} \]

It is straightforward to show that the scalar product of \( \mathbf{B} \) and \( \nabla (r A_\theta) \) is identical to zero and hence, the contours of equal values of the scalar quantity, \( r A_\theta \) depict the magnetic field lines [14]. Figures 5 and 6 show the theoretically derived patterns of absolute magnetic field and magnetic field contours within the reactor chamber when it is filled uniformly with two different densities: \( n_e = 8.9930 \times 10^{14} \text{ m}^{-3} \) and \( n_e = 8 \times 10^{17} \text{ m}^{-3} \). Using first approach, theoretical expressions for \( B_r \) and \( B_z \) existing in AMPICP model have been taken into account for drawing magnetic lines.

It can be seen from figure 6 that the magnetic field contours are dependent on densities as the AMPICP model predicts. The density of magnetic field lines indicates the local strength of the magnetic field. Since power is transferred from the planar coil and dissipated in the plasma, the magnetic field propagates into the plasma; the magnetic pattern is not the same as a standing wave as in the case for the evacuated reactor chamber with infinitely conducting walls (figures 5 and 6). The direction of the field is managed by the direction of the induced current rings that are generated in the plasma, and the direction of the induced current in the plasma directly under the fused silica window changes twice with RF period as shown in figures 5 and 6. Magnetic field lines of a given color are associated with a ring of induced current of a given sense. As time is going pass, these distinct rings of induced current, together with their associated magnetic fields move down the reactor chamber.
Figure 5. Predicted Magnetic field distribution for a planar ICP Reactor (Reactor Height = 20 cm, Reactor-Coil Spacing = 2 cm, Planar Coil Radius = 4.2 cm, Chamber Radius = 14.5 cm, f = 13.56 MHz, ω = 2π f, ν = 40ω, the wall conductivity (σ = ∞)).

Figure 6. Predicted magnetic field lines for a planar ICP Reactor at different densities (Reactor Height = 20 cm, Reactor-Coil Spacing = 2 cm, Planar Coil Radius = 4.2 cm), Chamber Radius = 14.5 cm, f = 13.56 MHz, ω = 2π f, ν = 40ω, wall conductivity (σ = ∞).
3 Results and discussion

The Langmuir probe is one of the most versatile diagnostics available for measuring the main plasma parameters. The probe is capable of determining, locally within the discharge, such parameters as electron temperature, electron density, ion density, the plasma potential, the floating potential and the electron energy distribution function (EEDF). The Langmuir probe, in its simplest form consists of a thin cylindrical wire which is immersed in the plasma. When the probe is biased with reference to the plasma chamber it draws a current from the plasma. As the bias voltage on the probe is changed the current that is drawn from the plasma also changes. The relationship between the probe bias voltage and the current drawn is the key to the Langmuir probe as a diagnostic tool. One of the problems that may be considered when using Langmuir probes is that besides their physical presence in the plasma, they also cause an electrical disturbance in the discharge when they measure current. The Langmuir potential is strongly negatively biased with respect to the plasma potential $V_p$. Even highly energetic electrons are repelled and only ions are collected by the probe. An ion sheath develops in front of the tip. At $V = V_F$, the fluxes of electrons and ions are equal and the probe is at the floating potential ($I_{tot} = 0$). When the applied voltage varies from the floating potential $V_F$ to the plasma potential $V_p$, it becomes gradually insufficient to repel at first energetic electrons and then electrons with decreasing energies. The current recorded in this region is a mixed contribution of ion and electron currents. Above the plasma potential, the low energy ions are repelled and only electrons are collected. An electron sheath in this time surrounds the probe tip [15]. Experimental and predicted I-V curves are presented for three characteristic regions A, B and C in figure 7 and table 2. The predicted results in table 2 are obtained based on fitting.

![Figure 7](image-url) Predicted Langmuir probe I-V characteristic depicting the three regions of collection in the planar ICP Reactor (Reactor Height = 20 cm, Reactor-Coil Spacing = 2 cm, Planar Coil Radius = 4.2 cm, $f = 13.56$ MHz): the ion saturation region [A], the retarding region [B] and the electron saturation region [C].
Table 2. Characteristics of the mixed gases argon (10 sccm) and oxygen (5 sccm) at $P = 0.170 \text{ mbar}$.

<table>
<thead>
<tr>
<th>$V_F (\text{V})$</th>
<th>$I(V_F) (\text{A})$</th>
<th>$V_P (\text{V})$</th>
<th>$I(V_P) (\text{A})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>Predicted</td>
<td>Experimental</td>
<td>Predicted</td>
</tr>
<tr>
<td>0.3195</td>
<td>0.2</td>
<td>1.8963$\times 10^{-5}$</td>
<td>0</td>
</tr>
<tr>
<td>27.3426</td>
<td>23</td>
<td>3.2267$\times 10^{-4}$</td>
<td>2.8$\times 10^{-4}$</td>
</tr>
</tbody>
</table>

3.1 Measurement of plasma parameters based on numerical method using Langmuir probe characteristics

For non-collided thick sheath plasma, the OML Laframboise theory can be employed [15]. The data handling system of our Langmuir probe offers this type of analysis. In the first step, the plasma potential is calculated as the crossing point of the second derivative of $I(V)$ with zero. It is supposed that this crossing point is the most accurate technique to determine the exact inflection point where the electron saturation starts. It could be pointed out that the beginning of the saturation region is however sometimes extremely difficult to distinguish from the retardation region. The floating potential is found at the point where $I_{tot} = 0$. The electron temperature is calculated by taking into account the current measured at the plasma potential and dividing it by the integral of the $I-V$ curve from $V_F$ to $V_P$, as follow [16]:

$$I(V_p)\int_{V_F}^{V_P} I(V) dV = \frac{1}{k_B T_e}$$

(3.1)

Once the electron temperature is determined, the electron density is calculated according to:

$$n_e = \frac{I(V_p)}{A_P} \left( \frac{2\pi m_e}{e^2 k_B T_e} \right)^{1/2}$$

(3.2)

where $A_P$ is the collecting area of the probe. Replacing $k_B T_e$ by eq. (3.1) results:

$$n_e = \left( \frac{2\pi m_e}{e^2} \right)^{1/2} \frac{I^2(V_p)}{A_P^2} \left( \frac{1}{\int_{V_F}^{V_P} I(V) dV} \right)^{1/2}$$

(3.3)

In the absence of any damping due to collisions of the electrons with ions or other electrons, oscillatory motion of charged particles would continue permanently. Using eq. (2.13), plasma frequency versus Langmuir probe characteristic output is computed as bellow:

$$\omega_{pe} = \left( \frac{n_e e^2}{m_e e_0} \right)^{1/2}$$

(3.4)

For the plasma conditions used in quasi-neutral case, the ion and electron densities are related as $n_e = \sum Z_i n_i$ that $Z_i$ is the atomic number of ion. However, strong electrostatic interactions still exist between charged species. Each charged particle represents a perturbation for the other surrounding particles and these latter tend to screen the Coulomb potential of the charged particle to maintain quasi-neutrality. The characteristic distance at which this screening occurs is the Debye length:

$$\lambda_{De} = \left( \frac{e_0 k_B T_e}{n_e e^2} \right)^{1/2}$$

(3.5)
where the units of $\lambda_{De}$, $n_e$ and $T_e$ are cm, cm$^{-3}$ and eV, respectively. In low pressure inductively coupled plasmas, the collisional processes which most likely happen are elastic electron-neutral collisions, ion-neutral collisions, neutral-neutral collisions and the electron-ion collisions. The electron-ion collision frequency is obtained from the Miyamoto and Fitzpatrick expressions [17, 18]:

$$
\nu_{ei} = \frac{n_e e^4 L n \Lambda}{4 \pi \varepsilon_0^2 m_e^{0.5} (eT_e)^{3/2}}
$$

(3.6a)

$$
\nu_{ei} = 0.1093 \left( \frac{n_e}{T_e^{3/2}} \right) L n \Lambda
$$

(3.6b)

In eq. (3.6b), the units of $\nu_{ei}$, $T_e$ and $n_e$ are s, eV and cm$^{-3}$, respectively. $\ln \Lambda$ is the well-known Coulomb logarithm given by:

$$
\ln \Lambda = 23 - \ln \left( \frac{n_e^{1/2} (k_B T_e)^{-3/2}}{10^2} \right)
$$

(3.7)

Also, using eqs. (3.1), (3.3) and (3.8), the electron-ion collision frequency finds a characteristic relation versus Langmuir probe characteristic output as follow:

$$
\nu_{ei} = \left( \frac{e^3}{2 \sqrt{2 \pi \varepsilon_0^2}} \right) \frac{I^2(V_P)}{A_p} \left( \frac{1}{\int_{V_P}^{V} \frac{1}{I(V) dV}} \right)^2 \left( 23 - \ln \left( \frac{2 \pi m_e}{e^2 \times 10^8} \frac{I^2(V_P)}{A_p} \left( \frac{1}{\int_{V_P}^{V} \frac{1}{I(V) dV}} \right)^{1/4} \right) \right)
$$

(3.9)

Charged particles flux and their average thermal velocities are other important parameters to be considered. When an insulated surface is placed in plasma, electrons and ions will reach the surface. Then particle fluxes and their velocities are needed. Another important issue about these parameter applications is in fusion instruments such as thing that ISTAPHM and IECF [19].

$$
\phi_{0e} = \frac{1}{4} n_e \vec{v}_e \quad \text{that} \quad \vec{v}_e = \sqrt{\frac{8 k_B T_e}{\pi m_e}}
$$

$$
\phi_{0i} = \frac{1}{4} n_i \vec{v}_i \quad \text{that} \quad \vec{v}_i = \sqrt{\frac{8 k_B T_i}{\pi m_i}}
$$

(3.10)

where $m_e$ and $m_i$ refer to electron and ion masses, respectively. The quantities $\vec{v}_e$ and $\vec{v}_i$ represent the thermal velocities of electron and ion. When ions are considered to be cold ($T_i = 0$ K), using eqs. (3.1) and (3.3), the thermal velocity and flux of electrons can be written as:

$$
\vec{v}_e = \sqrt{\frac{8}{\pi m_e} \int_{V_P}^{V} \frac{I(V) dV}{I(V_P)}}
$$

$$
\phi_{0e} = \frac{I(V_P)}{e A_p}
$$

(3.11)
The total effective momentum transfer electron collision frequency consists of the electron-neutral collision frequency \( \nu_{en} \) to which the stochastic collision frequency \( \nu_{st} \) and the electron-ion collision frequency are added. A comparison of various collision frequencies can give information on the predominant heating mechanism. For example, at low pressures, where collisions are reduced, the stochastic frequency is expected to be an important part of the total effective collision frequency, whereas at high pressure, where collisions are important, the momentum transfer electron-neutral frequency is expected to be the largest part. At intermediate pressures, both may play a role.

The stochastic frequency, \( \nu_{st} \), has been defined by Vahedi et al. [20] by equating the collisionless power (at low pressure where almost all the energy is deposited in the electrons through the collisionless named as anomalous heating mechanism), to an effective collisional heating power. The calculated \( \nu_{st} \) is given by:

\[
\nu_{st} \approx \frac{1}{4} \frac{\bar{v}_e}{\delta_a} \quad (3.12)
\]

\[
\delta_a = \frac{c}{\omega_{pe}} \left( \frac{\omega_{pe} \bar{v}_e}{2c \omega} \right)^{1/3} \quad (3.13)
\]

where \( \bar{v}_e \) is the electron thermal velocity defined in eq. (2.21) and \( \delta_a \) is the skin depth. The electrical field is confined to a certain skin depth close to the quartz plate. This confined electric field is predicted by the AMPICP model as shown in figure 8. Using eqs. (3.3), (3.4) and (3.11), the skin depth, \( \delta_a \) and the stochastic frequency relations based on Langmuir probe characteristic output are obtained as follow:

\[
\delta_a = \left( \frac{\varepsilon_0^2 c^4 A_p^2}{\omega \pi e^2 I^4(V_p)} \left( \int_{V_F}^{V_p} I(V) \ dV \right)^2 \right)^{1/6} \quad (3.14a)
\]

\[
\nu_{st} \approx \left( \frac{\varepsilon_0^2 c^4}{4 \omega e^2 m_e^3 \pi^4} \frac{A_p^2}{I^4(V_p)} \left( \int_{V_F}^{V_p} I(V) \ dV \right)^5 \right)^{1/6} \quad (3.14b)
\]

Finally, the electron-ion collision term is expressed in the generalized Ohm’s law by Inan Gołkowski [21]:

\[
S_{ei} = \eta e^2 n_e^2 (u_i - u_e) \quad (3.15)
\]

It may be noted that the constant of proportionality \( \eta \) was known as the specific resistivity of the plasma. Alternatively, the loss of momentum due to collisions can be expressed in terms of the collision frequency (i.e., the number of collisions per second), \( \nu_{ei} \) as follow by:

\[
S_{ei} = m_e n_e \nu_{ei} (u_i - u_e) \quad (3.16)
\]

which implicitly assumes that the electrons lose all of their relative momentum in collisions with heavier ions. The comparison of eqs. (2.25) and (2.26) indicates that

\[
\eta = \frac{m_e \nu}{e^2 n_e} \quad (3.17)
\]

The eq. (3.17) is valid for weakly ionized or fully ionized plasmas in inductively coupled plasmas, provided that the appropriate collision frequency is used. In other words, for weakly ionized plasmas
we can replace $\nu$ with the electron-neutral collision frequency $\nu_{en}$, while for fully ionized plasmas $\nu$ is equal to the electron-ion collision frequency $\nu_{ei}$. For fully ionized plasma eq. (3.7) can be used to write an expression for the specific resistivity:

$$\eta = \frac{m_0^{0.5} e^2 \ln \Lambda}{4\pi \varepsilon_0^2 (eT_e)^{3/2}}$$

(3.18)

Also for fully ionized plasma, using eqs. (3.1) and (3.9), the specific resistivity may be replaced by a new relation consisting Langmuir probe output characteristic as bellow:

$$\eta = \frac{m_0^{0.5} e^2}{4\pi \varepsilon_0^2} \left( \frac{\int_{V_F}^{V_P} I(V) dV}{\int_{V_F}^{V_P} I(V) dV} \right)^{3/2} \left( 23 - \ln \left( \frac{2\pi m_e}{e^2 \times 10^8} \right) \right) \left( \frac{I^3(V_p)}{A_p^2 \int_{V_F}^{V_P} I(V) dV} \right)^{1/4}$$

(3.19)

Eqs. (3.1), (3.3), (3.4), (3.6a), (3.6b), (3.8), (3.9), (3.11), (3.17), (3.18) and (3.19) are functions of $\int_{V_F}^{V_P} I(V)dV$. In all of them, algorithm of composite trapezoidal rule is used for computing numerical integration $\int_{V_F}^{V_P} I(V)dV$ in the interval of $(V_F, V_P)$. Figure 9 and table 3 show that the plasma potential $V_P$ is reduced by increasing the amount of oxygen but the changes of floating voltage is almost constant.

Tables 4 and 5 summarize the experimental results that are computed by eqs. (3.1), (3.3), (3.4), (3.6a), (3.6b), (3.8), (3.9), (3.11), (3.17), (3.18) and (3.19). These tables show the effects of increasing oxygen gas pressure and decreasing argon gas pressure on temperature, electron density,
Figure 9. Predicted Langmuir probe I-V characteristic depicting the three regions of collection in the planar ICP Reactor: the ion saturation region [A], the retarding region [B] and the electron saturation region [C] in the planar ICP Reactor (Reactor Height = 20 cm, Reactor-Coil Spacing = 2 cm, Planar Coil Radius = 4.2 cm, f = 13.56 MHz).

Table 3. Characteristics of the mixed gases Argon and oxygen for a planar ICP Reactor (Reactor Height = 20 cm, Reactor-Coil Spacing = 2 cm, Planar Coil Radius = 4.2 cm, Chamber Radius = 14.5 cm, f = 13.56 MHz).

<table>
<thead>
<tr>
<th>Langmuir Probe Output</th>
<th>$V_F$ (V)</th>
<th>$I(V_F)$ (A)</th>
<th>$V_P$ (V)</th>
<th>$I(V_P)$ (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 sccm Argon, 5 sccm Oxygen, P = 0.170 mbar</td>
<td>0.3195</td>
<td>1.8963×10$^{-5}$</td>
<td>27.3426</td>
<td>3.2267×10$^{-4}$</td>
</tr>
<tr>
<td>7.5 sccm Argon, 7.5 sccm Oxygen, P = 0.177 mbar</td>
<td>0.7716</td>
<td>2.8013×10$^{-5}$</td>
<td>16.8070</td>
<td>3.2234×10$^{-4}$</td>
</tr>
<tr>
<td>5 sccm Argon, 10 sccm Oxygen, P = 0.187 mbar</td>
<td>0.3281</td>
<td>6.1598×10$^{-5}$</td>
<td>10.9587</td>
<td>3.4229×10$^{-4}$</td>
</tr>
</tbody>
</table>

Debye length and electron flux. In table 5, it is assumed that plasma in ICP reactor is fully ionized. So the computed specific resistivity is a lower bound of specific resistivity. It is possible that degree of ionization is limited in the ICP reactor but degree of ionization can be increased by selecting suitable power of RF generator.

Figure 10 shows predicted electron velocity distribution for the case in which the reactor chamber is uniformly filled with plasma. It is assumed that $n_e = 8.9930 \times 10^{14}$ m$^{-3}$. The maximum velocity in this predicted electron velocity distribution is $V_{\text{max}} = 3.6326 \times 10^3$ m/s. The results show good agreement between measured and calculated data. Hereby our calculated results are justified.
Table 4. Experimental Values of Plasma Parameters of the mixed gases Argon and oxygen for a planar ICP Reactor (Reactor Height = 20 cm, Reactor-Coil Spacing = 2 cm, Planar Coil Radius = 4.2 cm, Chamber Radius = 14.5 cm, f = 13.56 MHz, $A_p = 4.76 \times 10^{-6} \text{m}^2$).

<table>
<thead>
<tr>
<th>Experimental Data</th>
<th>$k_B T_e$ (eV)</th>
<th>$n_e$ (cm$^{-3}$)</th>
<th>$\lambda$ (cm)</th>
<th>$\ln \Lambda$</th>
<th>$\bar{\nu}_e$ (cm/s)</th>
<th>$\phi_{0e}$ (1/(cm$^2$ s))</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 sccm Argon, 5 sccm Oxygen, P = 0.170 mbar</td>
<td>16.8353</td>
<td>8.9930×10$^8$</td>
<td>0.1017</td>
<td>14.6241</td>
<td>2.7455×10$^8$</td>
<td>4.2367×10$^{16}$</td>
</tr>
<tr>
<td>7.5 sccm Argon, 7.5 sccm Oxygen, P = 0.177 mbar</td>
<td>11.3245</td>
<td>1.3356×10$^9$</td>
<td>0.0684</td>
<td>13.8315</td>
<td>2.2517×10$^8$</td>
<td>4.2324×10$^{16}$</td>
</tr>
<tr>
<td>5 sccm Argon, 10 sccm Oxygen, P = 0.187 mbar</td>
<td>7.7239</td>
<td>2.0793×10$^9$</td>
<td>0.0453</td>
<td>13.0362</td>
<td>1.8596×10$^8$</td>
<td>4.4943×10$^{16}$</td>
</tr>
</tbody>
</table>

Table 5. Experimental Values of Plasma Parameters of the mixed gases Argon and oxygen for a planar ICP Reactor (Reactor Height = 20 cm, Reactor-Coil Spacing = 2 cm, Planar Coil Radius = 4.2 cm, Chamber Radius = 14.5 cm, f = 13.56 MHz, $A_p = 4.76 \times 10^{-6} \text{m}^2$).

<table>
<thead>
<tr>
<th>Experimental Data</th>
<th>$\omega_{pe}$ (s$^{-1}$)</th>
<th>$\nu_{ei}$ (s$^{-1}$)</th>
<th>$\nu_{st}$ (s$^{-1}$)</th>
<th>$\delta a$ (m)</th>
<th>Specific resistivity for fully ionized plasma (Ω.m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 sccm Argon, 5 sccm Oxygen, P = 0.170 mbar</td>
<td>1.6915×10$^9$</td>
<td>2.0810×10$^7$</td>
<td>8.6129×10$^6$</td>
<td>0.0797</td>
<td>0.8225</td>
</tr>
<tr>
<td>7.5 sccm Argon, 7.5 sccm Oxygen, P = 0.177 mbar</td>
<td>2.0614×10$^9$</td>
<td>5.2983×10$^7$</td>
<td>8.6100×10$^6$</td>
<td>0.0654</td>
<td>1.4102</td>
</tr>
<tr>
<td>5 sccm Argon, 10 sccm Oxygen, P = 0.187 mbar</td>
<td>2.5721×10$^9$</td>
<td>1.3802×10$^8$</td>
<td>8.7841×10$^6$</td>
<td>0.0529</td>
<td>2.3595</td>
</tr>
</tbody>
</table>

3.2 Electron energy distribution function

Electron Energy Distribution Function (EEDFs), $f(\xi)$, charged particles flux and their average thermal velocities provide information on the energy available for excitation or ionization of the discharge gas. For potentials lower than the plasma potential, the probe acts as an energy analyzer for the electrons at energies $\xi = e(V_p - V)$, $V \leq V_p$. The smart probe software offers the possibility of obtaining the EEDF’s from the measured I-V curves. In general, one prefers to work with the Electron Energy Probability Functions (EEPFs), $g(\xi)$, as their representation in a semi-logarithmic plot as a function of the energy $\xi$ in a straight line for a Maxwellian distribution [14, 21, 22]. The EEDFs and the EEPFs are deduced from one another according to:

$$f(\xi) = \xi^{1/2} g(\xi)$$

Inductively coupled plasmas are not fully Maxwellian and their EEDF is best described by a so-called Druyvesteyn distribution. The function $g(\xi)$ can then be written as:

$$g(\xi) = 0.5648 \ n_e \left( \frac{1}{k_B T_e} \right)^{3/2} \ exp \left[ -0.243 \left( \frac{\xi}{k_B T} \right)^2 \right]$$

[3.21]
Figure 10. Predicted Electron Velocity Distribution for the case in which the reactor chamber is uniformly filled with plasma in a planar ICP Reactor (Reactor Height = 20 cm, Reactor-Coil Spacing = 2 cm, Planar Coil Radius = 4.2 cm, Chamber Radius = 14.5 cm, $f = 13.56$ MHz, $\omega = 2\pi f$, $\nu = 40 \omega$).

Using eqs. (3.1) and (3.3), then eqs. (3.21) and (3.20) reduce to:

$$g(\xi) = 0.5648 \frac{\sqrt{2\pi m_e}}{e} \frac{l^3(V_p)}{A_P} \left( \frac{1}{\int_{V_F}^{V_p} I(V) dV} \right)^2 \exp \left[-0.243 \left( \frac{I(V_p)}{\int_{V_F}^{V_p} I(V) dV} \xi \right)^2 \right]$$  \hspace{1cm} (3.22)

$$f(\xi) = 0.5648 \frac{\sqrt{2\pi m_e}}{e} \xi \frac{l^3(V_p)}{A_P} \left( \frac{1}{\int_{V_F}^{V_p} I(V) dV} \right)^2 \exp \left[-0.243 \left( \frac{I(V_p)}{\int_{V_F}^{V_p} I(V) dV} \xi \right)^2 \right]$$  \hspace{1cm} (3.23)

The electron density $n_{eg}$ and mean energy of the electrons $\langle \xi_g \rangle$ can be respectively deduced by integration of the measured EEPFs as follow:

$$n_{eg} = \int_0^{\infty} g(\xi) d\xi$$  \hspace{1cm} (3.24)

$$\langle \xi_g \rangle = \frac{\int_0^{\infty} \xi g(\xi) d\xi}{\int_0^{\infty} g(\xi) d\xi}$$  \hspace{1cm} (3.25)
Based on the mean electron energy $\langle \xi_g \rangle$, the effective electron temperature, $T_{\text{eff}}$ is calculated as follow:

$$k_B T_{\text{eff}} = \frac{2}{3} \langle \xi_g \rangle$$  \hspace{1cm} (3.26)

The composite trapezoidal rule is numerically applied for determination of EEPF, EEDF, $\int_0^\infty g(\xi)d\xi$ and $\int_0^\infty \xi g(\xi)d\xi$ in eqs. (3.22) and (3.23).

![Graphs showing EEPF and EEDF](image)

**Figure 11.** Experimental EEPF and EEDF of the mixed gases Argon and oxygen for a planar ICP Reactor (Reactor Height = 20 cm, Reactor-Coil Spacing = 2 cm, Planar Coil Radius = 4.2 cm, Chamber Radius = 14.5 cm, $f$ = 13.56 MHz).

As figure 11 and table 6 show, EEPFs are almost the same above 60 eV for three cases. The difference between Langmuir probe and EEPF results show that the existing plasma is not at equilibrium.
Table 6. Experimental Values of Plasma Parameters of the mixed gases Argon and oxygen for a planar ICP Reactor (Reactor Height = 20 cm, Reactor-Coil Spacing = 2 cm, Planar Coil Radius = 4.2 cm, Chamber Radius = 14.5 cm, f = 13.56 MHz).

<table>
<thead>
<tr>
<th>Outputs of Probability Functions and Langmuir probe</th>
<th>( n_e ) (cm(^{-3}))</th>
<th>( k_B T_e ) (eV)</th>
<th>( n_{eg} ) (cm(^{-3}))</th>
<th>( &lt;\xi g &gt; ) (eV)</th>
<th>( k_B T_{ef} ) (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 sccm Argon, 5 sccm Oxygen, P = 0.170 mbar</td>
<td>( 8.993\times10^8 )</td>
<td>16.8353</td>
<td>( 4.892\times10^8 )</td>
<td>16.5203</td>
<td>11.0135</td>
</tr>
<tr>
<td>7.5 sccm Argon, 7.5 sccm Oxygen, P = 0.177 mbar</td>
<td>( 1.335\times10^9 )</td>
<td>11.3245</td>
<td>( 5.471\times10^8 )</td>
<td>9.5544</td>
<td>6.3696</td>
</tr>
<tr>
<td>5 sccm Argon, 10 sccm Oxygen, P = 0.187 mbar</td>
<td>( 2.079\times10^9 )</td>
<td>7.7239</td>
<td>( 2.558\times10^8 )</td>
<td>7.7152</td>
<td>5.1435</td>
</tr>
</tbody>
</table>

4 Conclusion

ISTAPHM project is a simulator which enables us to predict the operations in the antenna region on tokamaks and operates with plasma conditions at the edge of tokamak plasmas. The first step in the ISTAPHM project focuses on finding a design method for a plasma source like planar ICP, predicting electromagnetic fields effects in the plasma source by AMPICP model. The Langmuir theory was developed by a numerical analysis and a few computational relations. Then the plasma source parameters were experimentally measured using these developed results. To optimize the plasma source performance for ISTAPHM project we are going to get more flexibility in the range of densities by using higher powers, and to operate with helium plasmas in the next works.

References


