Determination of Plasma Electron Temperature in a Pulsed Inductively Coupled Plasma (PICP) device

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Abstract

A Pulsed Inductively Coupled Plasma (PICP) device was built and it was used to generate plasma through electrical pulse discharge process. This research looks at electron temperature of Argon plasma using Optical Emission Spectroscopy (OES) method and comparing with a theoretical model of plasma dynamics. The experimental results show that the electron temperature of 0.6 eV up to 4.0 eV can be obtained under operating pressures of 2, 5 and 10 Pa by varying input stored energy of 1.3, 2.9 and 4.3 kJ respectively. These results correspond to the result calculated based on the dynamics model of plasma. Therefore, it shows that the model can be used to predict other operating parameters for the PICP device which could be useful in other applications such as modification of material and fusion generating reaction.

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1. Introduction

A Pulsed Inductively Coupled Plasma (PICP) device generates plasma by discharging a large current to induce plasma in a chamber that contains operating gas at low pressure. The plasma then moves inward to the centre of the device due to Lorentz’s force. In the past, this type of device has been used in many ways such as radiation source [1] and in modification of materials’ surfaces [2-4].

In this research, electron temperatures of the plasma generated by different conditions were determined based on optical spectroscopy measurement and they were compared with a simulation model. The model
is based on the dynamics of plasma coupled with electrical circuit equation. This will be described in the following section. However, the result presented in this article will demonstrate that PICP can be further modified based on different operating parameters which can help the development of PICP for other useful applications in different fields of interest.

2. Simulation Model

A circuit equation and dynamics model of a typical plasma focus device [5] were adapted to simulate the plasma’s movement in the PICP device. Both circuit and plasma current can be calculated by using a circuit equation [5,6] that is shown as

\[
\frac{dI_c}{dt} = \frac{V_0 - R_c I_c - \frac{1}{2} \frac{I_c dt}{C_0} + \frac{2 \mu \pi}{L} r_p I_p}{L_0 + \frac{\pi \mu}{1} r_c^2 - \frac{\pi \mu}{1} r_p^2}
\]

where \(I_c\) is a circuit current at time \(t\), \(r_c\) and \(r_p\) are the radius of the chamber and the radius position of the plasma current respectively. The dynamic of the plasma is calculated based on different operating conditions such as length of the chamber \(l\), capacitance \(C_0\), and circuit resistance which were 120 cm, 60 \(\mu\)F, and 0.0131 \(\Omega\) respectively. The operating pressure in this investigation was varied to 2 Pa, 5 Pa and 10 Pa under the different voltages, \(V_0\), of 6.8 kV, 8.9 kV and 12 kV respectively. From the circuit equation, both circuit current and plasma current \(I_p\) are related by parameter \(m = I_p/I_c\). The plasma radial position and the shock speed can then be calculated by using these formulas. The dynamics model has two equations that describe a shock front and a piston [5, 6] moving forward to centre of the chamber along its radial axis where the velocity of the shock and the plasma current are given by:

\[
\begin{align*}
\frac{dr_s}{dt} &= \frac{2\gamma}{\gamma + 1} \left( r_p \frac{dr_p}{dt} - r_p \frac{dI_c}{dt} \right) \\
\frac{dr_p}{dt} &= \frac{\gamma r_p^2}{r_p^2 - r_c^2} \left( \frac{r_p}{I_c} \right) - 1
\end{align*}
\]

where \(\mu\), \(\gamma\) and \(\rho_0\) are permeability of free space, specific heat ratio and density respectively. A parameter \(f_m\) that can be found from the shock velocity is the mass swept factor representing the fraction of the plasma swept by the shock front. Both parameters \(m\) and \(f_m\) are adjusted by fitting the current and the position of plasma measured in an experiment. These parameters can be used to estimate the electron temperature of plasma which can be calculated by using an equation such that

\[
T = \frac{M}{R} \frac{\gamma - 1}{(\gamma + 1)^2} \left( 1 + Z_{\text{eff}} \right)
\]

where \(M\) and \(R\) are atomic mass and gas constant respectively. Effective charge \(Z_{\text{eff}}\) can be evaluated by using the relationship between the number density of electron \(N_e\) and density number of ion \(N_i\). The relation is given by \(Z_{\text{eff}} = N_e/N_i\).

3. Experimental setup

A diagram of a PICP device is shown in Fig. 1. The device is made of a quartz tube with 42 cm long and a radius of 5.46 cm. The tube is wrapped around by a single turn conducting coil. Two 30 \(\mu\)F capacitor banks that are connected in parallel are used to store energy of 1.3, 2.9 and 4.3 kJ depending on
their respective charging voltages. The operation of the device is started by varying its operating pressure and charging voltage. When the capacitors bank is discharged, a current flows through the single turn coil that enclosed the chamber and induces plasma by ionizing the gas inside the chamber.

Fig. 1. Schematic diagram of a pulsed inductively coupled plasma system

Three magnetic probes are used to detect the movement of plasma in the chamber where their signals could be used to determine the plasma factors. These factors are used in the modelling described in Section 2. The plasma electron temperature is then determined by the Optical Emission Spectroscopy (OES) method where emitted photons from plasma are measured. The electron temperature deduced is compared with the simulation.

In the experiment, Argon gas was used such that Argon plasma was produced. Argon is a mono-atomic gas therefore its ionization process is the least complicated.

4. Result

A signal shown in Fig. 2 is a normalized current detected by Rogowsky’s coil and the line represents simulated current where the simulation parameters had been adjusted so that the line fits the measured signal. The other plot shows the calculated normalized positions of plasma sheath moving inward to the center of the chamber and a plot of measured plasma sheath positions by three magnetic probes.

Fig. 2. Plots showing a result from the simulation and the experiment under operating pressure and charging voltage of 2 Pa and 6.8 (a) time vs. normalize circuit’s current (b) time vs. positions of plasma current
Plasma factors for different operating conditions are shown in Table 1. These were used to calculate the electron temperature of the plasma by applying both equation (2) and (3) mentioned earlier.

Table 1. Plasma parameters under operating pressure of 2 Pa, 5 Pa and 10 Pa and varying charging voltage of 6.8 kV, 8.9 kV and 12 kV respectively

<table>
<thead>
<tr>
<th>Charging Voltage (kV)</th>
<th>Pressure (Pa)</th>
<th>Parameter: m</th>
<th>Parameter: $f_m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.8</td>
<td>2</td>
<td>0.3</td>
<td>0.424</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.3</td>
<td>0.683</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.3</td>
<td>0.633</td>
</tr>
<tr>
<td>8.9</td>
<td>2</td>
<td>0.2</td>
<td>0.639</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.2</td>
<td>0.639</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.2</td>
<td>0.779</td>
</tr>
<tr>
<td>12</td>
<td>2</td>
<td>0.1</td>
<td>0.638</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.1</td>
<td>0.319</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.1</td>
<td>0.624</td>
</tr>
</tbody>
</table>

The electron temperature of plasma can be determined from Optical Emission Spectroscopy measurement (OES) by detecting the photon emission that is generated from recombination of different ions species. A signal of the photon emission is shown in Fig. 3. Noting that the photon emission signal obtained here is a time integrated signal which means it includes all photon emission from plasma current since the start of compression until the end of the process. Evolution of temperature with time can be plotted by using simulation model which is shown in Fig. 5.

Table 2. Electron temperature of plasma from spectroscopy measurement and simulation

<table>
<thead>
<tr>
<th>Charging Voltage (kV)</th>
<th>Operating Pressure (Pa)</th>
<th>Electron temperature of plasma (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Spectroscopy</td>
</tr>
<tr>
<td>6.83</td>
<td>2</td>
<td>0.89</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>1.49</td>
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<td>0.87</td>
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<td>8.94</td>
<td>2</td>
<td>1.61</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>1.36</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>1.22</td>
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<td>12</td>
<td>2</td>
<td>3.9</td>
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<tr>
<td></td>
<td>5</td>
<td>2.33</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>0.6</td>
</tr>
</tbody>
</table>
The relationship of electron temperature, pressure and operating voltage is shown in Fig. 4. The plasma electron temperature decreases when operating pressure increase. The temperature also increases when the charging voltage increases.

![Bar charts showing electron temperatures of plasma at different operating pressures and discharging voltages](image)

Fig. 4. Bar charts show electron temperatures of plasma at different operating pressures and discharging voltages (a) determined by spectroscopy measurement and (b) determined by simulation model

5. Discussion

From the result, it was found that the trends obtained from the simulation do agree with experimental results. This means the plasma induced in PICP can be represented by the movement of plasma current radially inwards by the Lorentz’ force which is driven by damped electrical current discharge in a typical LCR circuit. However, this experiment does not look at the pinching of the plasma when it reached centre of the chamber. It was also found that when plasma produced by PICP device had radial velocity of $2.5 \times 10^5$ m/s it also had electron temperature of up to 3.90 eV. The operating condition to obtain this velocity is 2 Pa operating pressure and 12 kV charging voltage.

From the simulation, similar electron temperature of 4.28 eV was obtained when plasma operating parameters are 2 Pa operating pressure and 12 kV charging voltage. The different can be accounted for the fact that the temperature from the spectroscopy measurement is an average temperature over the whole discharging process. The temperature from Fig. 5 covers the range from 0.025 eV up to 4.28 eV. By taking into account all variables in measuring process of OES, it is possible to say that the proposed simulation model can be used to predict the trend of the plasma electron temperature in other operating conditions.
Further investigation is required for other non mono-atomic gas, as well as, to see how plasma electron temperature will change when the plasma pinches at the centre of the chamber. Once this is known then it will be possible to set an operating condition that will produce sufficient discharging energy that would require by hydrogen plasma in order to obtain a fusion reaction from this pinching process.
Acknowledgements

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Reference