Electric Field Effect on Electric Probe Operating in Plasma Focus Device

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Abstract. Plasma Focus Device (PFD) has been investigated by many researchers because of its capability as a source of radiation including ions in many applications. However, the investigation and characterization of plasma, ions and radiation are difficult and challenging due to the short pulse duration and harsh electrical environment during the operation of the device. Many researchers used electric probe to measure ions generated by the device and found that high energy ions can be generated by PFD. This work investigates the sensitivity of electric probe to variation of strong electric field produced by 2.3 kJ PFD. The results obtained by simulation are compared with actual experimental results. The results show that, the electric field generated in the PFD can severely affect signal of the electric probe that is operated without proper grounding around the probe as it induces sufficient current within the probe. This can lead to misinterpretation of ion signal or photoelectric signal detected from PFD especially during the focusing phase.

Keywords: Plasma focus, Electric field, Electric probe

I. INTRODUCTION

Plasma Focus Device (PFD) can be used as a low-cost source of radiations and charged particles \cite{1, 2}. These are produced throughout the dynamics phases of plasma in a PFD. The dynamics of plasma can be described in four phases namely; breakdown phase, axial phase, radial phase and focusing phase. PFD has been used in many field of applications such as surface modification \cite{3, 4} as well as for fusion reaction \cite{5}. Researchers have been trying to characterize charged particles which are emitted from the PFD. Many species of ions are detected and characterized by using an electric probe \cite{6, 7}. Rashed et al. \cite{8} characterized argon ion by using Faraday cup detector and BPX 65 to detect ions and x-ray radiation from a PFD device. The research reported energy of argon and nitrogen ions operated under operating gas pressure of 0.8 mbar and 1.4 mbar which are 107.5 keV and 155.45 keV respectively. However, in our previous work where three ion probes were used to measure argon ions produced by 2.3 kJ United Nation University and International Centre for Theoretical Physics
(UNU/ICTP) PFD [9], the ion probe signals showed a peak at focusing phase and a broader signal at a later time. The broader signal represents slower group of argon ions where the average energy was determined to be 0.357 keV. However, the peak ion signals at or very close to the peak voltage at the focusing phase could not be claimed that they were signal of very fast ions emission as the peak signal from all three electric probes that were placed at different distant happened at the same time. It is also interesting to note that some other researcher found that electric field that are generated by a high voltage (HV) source could affect the signal of electric probe. For example, R. L. Stenzel [10] measured electric field in the plasma that the frequency of apply voltage source is between 0 to 20 MHz. The probe can also detected electric field from the transmission line.

The studies of electric field effect had also been done by using COMSOL Multiphysics software (COMSOL). For example, A. Yulianto [11] studied electric field intensity in human body by using COMSOL to simulate electric field distribution in a medium which was a human head. B. A. Rachedi et al. [12] used COMSOL to simulate electric field generated in the vicinity of High Voltage (HV) power transmission lines, and the results found were comparable with the International Commission on Non Ionizing Radiation Protection (ICNIRP) field guidelines.

In this work, we attempt to show how much the electric field generated within a PFD affect the performance of an electric probe used within the device. COMSOL was used to simulate the electric field in PFD and the current induced in an electric probe. The results were then compared with signals obtained experimentally. The experimental setup, measurement method and the simulation model are presented in the next section.

II. EXPERIMENTAL SETUP AND SIMULATION

The setup for electric field simulation is based on UNU/ICTP PFD design. This PFD is a Mather type PFD consisting of a single anode which is surrounded by six cathodes. The radius of the anode and the length of the anode is 0.95 cm and 16.0 cm respectively. The distance from center of the cathode to the center of the anode is 3.2 cm. Argon gas was used as the operating gas. The PFD is normally operated under the optimum focusing operating pressure of 1 mbar. The operating voltage that charges a 30 μF Maxwell capacitor bank is 12.5 kV. The discharge is controlled by an opening switch spark gap. The equivalent discharge circuit of the system is shown in Fig.1.

![Figure 1](image)
In the experiment, the electric probe used is made from a solid coaxial cable which consists of copper wire and copper sleeve with electrical insulator in between. Three electric probes were connected as setup shown in Fig. 2. The probes were connected with a bias circuit as shown in Fig. 2a. The electric probes were placed in positions directly above the anode as shown in Fig. 2b. The copper wire was biased to a small negative potential such that it attracts the positive ions. However, they can be sensitive to electromagnetic pulse and high energy photon due to photoelectric effect. These effects were minimized by having cross section area of the copper wire that is very small and using the copper sleeve as shielding. The electric probe signals were recorded by a 4-channel fast sampling oscilloscope (Tektronik TDS 3034) via differentiating circuits. The common voltage signal of the PFD obtained is shown in Fig. 3a. This was used as a trigger signal for all the electric probes. Typical signal of the electric probes at different positions are shown in Fig. 3b, 3c and 3d.

![Bias circuit](image1)

**FIGURE 2.** Diagram showing (a) bias circuit connected to an electric probe and (b) the setup of electric probes [9].

![Signal plots](image2)

**FIGURE 3.** Plots showing (a) voltage signal across electrodes, (b) signal from 1st electric probe, (c) signal from 2nd electric probe and (d) signal from 3rd electric probe.
The electric field in the PDF was simulated by using finite element method. It can be determined by Maxwell’s equation and charge conservation. These equations are

\[ \nabla \cdot \vec{E} = 0, \quad \vec{E} = -\nabla V \]  
\[ \nabla \cdot \vec{j} = 0, \quad \vec{j} = \sigma \vec{E} + \varepsilon \frac{\partial \vec{E}}{\partial t} + \vec{f} \]  

where \( \vec{E} \) is electric field, \( V \) is electric potential, \( \vec{j} \) is total current density, \( \sigma \) is a conductivity of the medium, \( \varepsilon \) is a permittivity of medium and \( \vec{f} \) is free current density. The finite element was done by using COMSOL program.

For this simulation, the current discharge function \( I(t) \) from the LRC circuit shown in Fig. 1 was used to calculate the change in electric field during the axial phase through to the radial phase. This corresponds to an experiment where the PFD was operated with argon gas at 1.0 mbar. The current discharge function \( I(t) \) and the voltage function \( V(t) \) was determined by fitting with actual experimental data as shown in Fig. 4a and Fig. 4b respectively. The fitting function of the voltage and current can be represented by:

\[ V(t) = V_0 e^{-rt} \cos(\omega t - \Phi) + V_1 \exp\left(-\frac{t-t_0}{\sigma_1}\right) \]  
\[ I(t) = I_0 e^{-rt} \sin(\omega t) \left(1 - \tanh\left(\frac{t-t_0}{\sigma}\right)\right) \]

where \( I_0 = 200 \text{ kA}, V_0 = 4.5 \text{ kV}, V_1 = 6.1 \text{ kV}, r = 100 \text{ kHz}, \omega = 200,000 \pi \frac{\text{rad}}{s}, t_0 = 3.5 \mu s, \sigma = 10 \mu s, \sigma_1 = 500 \text{ ns}, \Phi = \frac{\pi}{2.4} \).

\[ \text{FIGURE 4. Graph showing (a) current function fitted with the experiment under operating pressure of 1 mbar and (b) voltage function across electrode fitted with the experiment under operating pressure 1 mbar.} \]

Since PFD can be considered to be symmetrical through z-axis, therefore only a pair of anode and a cathode is sufficiently for evaluation. Both the electric field and potential in PFD space that vary with time can be presented as diagrams shown in Fig. 5.
FIGURE 5. Diagrams showing electric field (line) and electric potential (color) generated by the finite element simulation during the axial phase, focusing phase, and post focusing phase.

However, when considering the electric probes placed at positions as shown in Fig. 2, the electric probe placed at 22 cm causes breakdown in symmetry of electric field. This can be seen in the diagrams presented in Fig. 6 for both bias and non-bias electric probe cases.

FIGURE 6. Diagram showing effect on electric field from (a) non-bias electric probe and (b) -36 V bias electric probe.

III. RESULTS AND DISCUSSION

From the simulation results, the magnitude of electric field at different probe positions at different time are shown in Table 1. Fig. 7 shows plots of this variation where it can be seen that the magnitude of the electric field is inversely dependent to the distant of the electric probe from the anode. At 3.5 µs, the electric field obtained from the simulation is the maximum due to the maximum voltage across electrode because of the pinching effect of plasma during the focusing phase. This result corresponds to the signals detected by the electric probes where decrease in magnitude of electric probe signals was observed for the electric probe that is placed further distance away from the anode. Also the maximum signals were observed during the focusing
phase for all three probes. The results magnetic field obtained by simulation correspond to the results obtained experimentally by electric probes.

**TABLE 1.** Table showing magnitude of electric field varying with time and position.

<table>
<thead>
<tr>
<th>Electric Probe Position (cm)</th>
<th>Time (µs)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>3.5</th>
<th>4</th>
<th>5</th>
<th>7</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>3.5</td>
<td>4</td>
<td>5</td>
<td>7</td>
<td>9</td>
<td>7</td>
</tr>
<tr>
<td>22</td>
<td></td>
<td>114</td>
<td>167</td>
<td>151</td>
<td>74,100</td>
<td>9,900</td>
<td>6,470</td>
<td>20,400</td>
<td>6,010</td>
<td>3,920</td>
</tr>
<tr>
<td>30</td>
<td></td>
<td>6</td>
<td>9.27</td>
<td>8.39</td>
<td>4,060</td>
<td>542</td>
<td>354</td>
<td>112</td>
<td>329</td>
<td>215</td>
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<tr>
<td>48</td>
<td></td>
<td>0.314</td>
<td>0.460</td>
<td>0.416</td>
<td>201</td>
<td>26.8</td>
<td>17.5</td>
<td>55.3</td>
<td>16.3</td>
<td>10.6</td>
</tr>
</tbody>
</table>

**FIGURE 7.** Graph showing magnitude of electric field varying with time at 22 cm, 30 cm and 48 cm respectively.

In this simulation, in order to understand the effect of biasing the electric probe on the signal obtained, the electric field and the electric current that vary with time for both bias and no bias on the electric probe at 22 cm were plotted and are shown in Fig. 8 and Fig. 9 respectively. It can be seen that the magnitude of electric field on the surface of the non-bias electric probe shown in Fig. 8a and -36V bias electric probe shown in the Fig. 8b are different. The negative bias causes constant electric field on the surface of the probe as expected. It is interesting to note that the magnitude of electric field observed at the time of focusing from both cases differs much less than during other phases where the negative bias voltage at the tip of the probe causes the increase in magnitude of electric field of more than twenty times.

From the equation that represent the electric current density of the electric probe which is \( \sigma \vec{E} \), Fig. 9a, show the variation of the electric current density flow into the non-bias electric probe, which is the x-direction according to Fig. 6, with time. It can be seen that value of current density changes from positive to negative value. The result corresponds to the direction of the electric field during different dynamic phases of PFD as shown in the Fig. 5. The direction of the electric field flow out from the anode into the electric probe before and just after focusing and then the opposite after 4.7 µs. In contrast with the negative bias electric probe shown in Fig. 9b, the electric current density remains positive. However, the magnitude of the electric current density at the time of focusing differs much less than during other phases in comparison with the non-bias electric probe case.

Now considering the displacement current density which is induced by the change in electric field with time, \( \varepsilon_0 \frac{d\vec{E}}{dt} \), Fig. 10, shows variation obtained by calculation of displacement current density in the direction of the electric probe with time. It can be seen that the peak value of the

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displacement current density is much higher than that of the electric current density shown in Fig. 9. For the combine effect which can be shown by plots in Fig. 11, the total current density for both case of bias and non-bias electric probe have similar values as the displacement current density shown in this Figure. Fig. 10 and Fig. 11 also show that biasing of electric probe only cause minimal effect to the total current density because the total current density is very large in comparison at the focusing period where effect of $\frac{d\vec{E}}{dt}$ dominate. At the focusing period, the voltage at the anode abruptly changes as shown in Fig. 4b.

By examining closely at the focusing period, the normalized voltage and normalized displacement current between 3.3 µs - 3.7 µs were plotted and shown in Fig. 12. The peak of the displacement current signal swing from positive to negative value according to the gradient of the voltage signal that changed abruptly as voltage across electrode increased rapidly before the plasma pinched, and dropped suddenly once the pinch broke down.

For the simulation, the voltage across electrode was assumed to be single peak that represents a single focusing event. However, in experimental it is possible to have multiple peaks as shown in Fig. 3a, the electric probes signal shown in Fig. 3 correspond to that voltage signal. It can also be seen that electric probe signals obtained were less from the probe that were placed further away from the anode which correspond to the simulation result shown in Fig. 7. The wider peak of the electric probe signal obtained from the experiment in Fig. 3b, Fig. 3c, and Fig. 3d can be explained by the effect of the averaging of the signal and the differentiating circuit that is connected to the copper wire. The circuit differentiate the change in current from the electric field effect which produced multiple peaks and then averaged which resulting in wider peaks as seen from the experimental result.

This investigation confirms that the change in electric field in a PFD do affect the signal obtained by the electric probe that is place near enough to the anode whether it is biased or not biased. The electric field produces a peak corresponding to the voltage peak produced at focusing phase. This result also confirm that the peak signal from the electric probe is unlikely to be from very high energy ions produced at focusing phase as claimed by some research work because the peak signal of the electric probes placed at different distances and placed on a different axis all happened at the same time. This result corresponds to the electric field effect found by this investigation. This also support our finding in previous work on argon ions produced by UNU/ICTP PFD [9] where only ions with lower energy (less than 1 keV) were detected by the electric probes.
FIGURE 8. Plot showing magnitude of electric field a) on the surface of non-bias electric probe and of b) on the surface of -36 bias on electric probe.

FIGURE 9. Plot showing magnitude electric current density a) on the surface of non-bias electric probe and of b) on the surface of -36 bias on electric probe.

FIGURE 10. Plot showing displacement current density in x–axis, a) on the surface of non-bias electric probe and of b) on the surface of -36 bias on electric probe.

FIGURE 11. Plot showing total current density in x–axis a) on the surface of non-bias electric probe and of b) on the surface of -36 bias on electric probe.
IV. CONCLUSION

It has been shown that electric field produced during the operation of a PFD, especially at the time of focusing can greatly affect the signal obtained by electric probe that is operating near the anode. COMSOL Multiphysics can be used to simulate electric field generated in UNU/ICTP PFD. Voltage and current function used for the simulation can be obtained by fitting the functions with actual experimental measurement. It was found that at the time of focusing, the magnitude of electric field at 22 cm, 30 cm, and 48 cm were 74,100 mV/m, 4,060 mV/m and 201 mV/m respectively. The effect of the abrupt change in the electric field, \( \frac{dE}{dt} \), dominate the signal or the total current density of the electric probe as it produces relatively large displacement current as show by the simulation. The current signal increases rapidly before pinching of the plasma where the voltage across the electrode maximizes and then reduces rapidly as the voltage decreases. It was also found that, the magnitude of electric field reduces at a position which is further away from the anode. This result corresponds to the signal obtained experimentally of electric probes that were placed at three different positions.

Finally, this investigation has shown that the electric field causes peak signal in electric probe that corresponds to the voltage peak at focusing phase. Especially, when it is placed near the electrode. This confirms the suggestion that the peak signal obtained by electric probe during the focusing phase of PFD is unlikely to be coming from detection of very high energy ions.

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