# Dynamics of ions generated by 2.3 kJ UNU/ICTP plasma focus device

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**Abstract**. UNU/ICTP Plasma Focus Device has been used as an ions source in many applications. In this paper, the full dynamic range of argon ions produced by the Plasma Focus Device from its initial phase through to beyond the focusing phase of the plasma is shown experimentally. The average speed of the ions is determined by measuring time taken for ions to reach different positions using magnetic probes and ion probes. Also, by adapting a well-established computational model that represents the dynamics of plasma in such device, it is also possible to determine the speed of these ions up to the point where the movement of the plasma sheath under the Lorentz force is completed. However, it was found that the speed determined by the computational model is higher in comparison with the values obtained experimentally at all different operating pressures. The ions' speed found for operating pressure of 0.5 mbar, 1.0 mbar, 1.5 mbar and 2.0 mbar were 5.16 ± 0.04 cm/μs, 4.24 ± 0.04 cm/μs, 3.81 ± 0.03cm/μs and 3.16 ± 0.04 cm/μs respectively. These correspond to the ion energy of 551.38 ± 8.55 eV, 372.29 ± 7.02 eV, 300.61 ± 4.73 eV and 206.79 ± 5.24 eV.

## 1. Introduction

More than two decades, many small Mather type plasma focus devices (PFD) had been developed and used as ion beam source in many applications [1-4], especially in area of material science. Researchers have tried to characterize ions that are generated by the device. Technique such as time-of-fight (ToF) had been used by Bhuyan et al. [5] to measure energy flux of methane ion beam generated from PFD. It was found that species of carbon $C^{+4}$ and $C^{+5}$ had energy about 200-400 keV and 400 – 600 keV respectively. Thomson parabolas spectrometer was used to determine ion species, such as $N^{+1}$, $N^{+2}$ and $N^{+3}$, produced by PFD operated at low operating pressure by H. Kelly et al. [6] and C S Wong et al. [7]. It was found that the species had energy more than 170 keV and 225 ± 66 keV respectively. In other research, ions from a lighter molecule such as hydrogen could have energy of 0.15 MeV to 2 MeV when operated at a pressure of 2.3 torr [8]. Hoon Heo et.al [9] had studied correlations between argon ion beam and x-rays produced in a PFD. Similar investigation to this work presented here had been done by Rashed et al. [10]. They investigated ions emission and x-ray emission of heavier molecule produced by 2.2 kJ UNU/ICTP PFD with operating gas pressure of 0.8 mbar and 1.4 mbar and found that the energy of argon ions and nitrogen ions were 107.5 keV and 155.46 keV respectively.

In this research, we attempt to show the plasma dynamics of all phases that happen in a PFD by investigating the change in speed of plasma and the speed of ions in the axial direction with time. The investigation is done from the axial phase through to the focusing phase and beyond the focussing phase where the ions are no longer moving with the influence of the Lorentz force. These experimental results are expected to correspond with the result obtained by well-established computational model developed by S. Lee [11] that represents the dynamics of plasma in such device. However, computational model has limitation of being able to represent the plasma dynamics only up to the focussing phase. Thus, the experimental results obtained will provide better insight to how energy of ions changes throughout all the phases and beyond that have not yet been determined by the calculation. The experimental setup, measurement methods and the computation model are described in the following section.

## 2. Experiment and Simulation

A United Nation University and International Centre for Theoretical Physics Plasma Focus Device (UNU/ICTP-PFD) shown in Figure 1 was used in this experiment. It is a Mather type PFD consisting of six cathodes surrounding a single anode. The diameter of the anode and the length of the anode is 0.95 cm and 16.0 cm respectively. The distance from center of the anode to the cathode is 3.2 cm. The PFD was operated with pure argon gas under operating pressure of 0.5 mbar, 1 mbar, 1.5 mbar and 2.0 mbar. The power source of the PFD is a Maxwell 30 μF capacitor that was charged to 12.5 kV. The discharge was controlled by a spark gap switch.

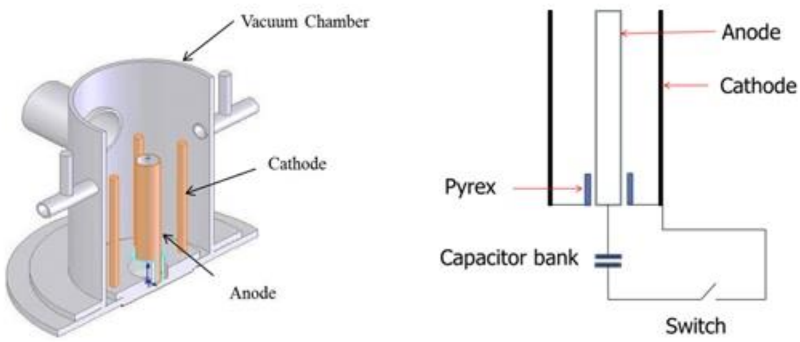



**Figure 1.** Diagram and drawing of UNU/ICTP PF device.

### *2.1. PFD Simulation*

The PFD dynamics model based on S. Lee [10] was used to simulate the movement of plasma in a PFD. The model assumes that a plasma sheath is formed and it is accelerated by induced magnetic pressure. The motion of the plasma sheath is considered in four phases namely breakdown phase, axial phase, redial phase and focussing phase as shown in Figure 2(a). In this work, length of the anode, radius of the anode, distance from the center of the anode to a cathode, capacitance of the capacitor bank and the input voltage of a typical UNU/ICTP PFD mentioned before were used as key parameters for the calculation.

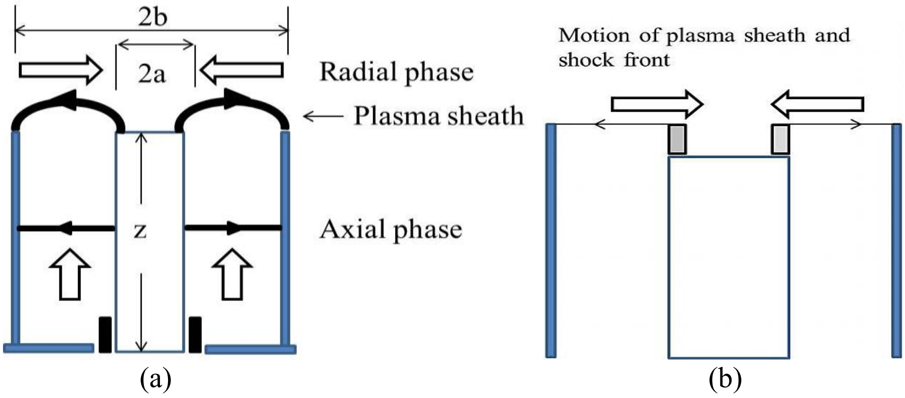



**Figure 2.** Diagram (a) showing the dynamics of plasma sheath both axial and radial phase (b) showing the front view of plasma sheath's motion in the radial direction.

In the axial phase, the movement of the plasma sheath is described by an equation of motion and circuit's equation, these equations can be shown as

$$\frac{d^2z}{dt^2} = \frac{\frac{fc^2}{fm}\frac{\mu \ln\frac{b}{a}}{4\pi^2\rho_o\left(\frac{b^2}{a^2}-1\right)}\left(\frac{I}{a}\right)^2-\left(\frac{dz}{dt}\right)^2}{z}, \text{ and } \frac{dI}{dt} = \frac{V_o-\frac{\int Idt}{C_o}-\frac{Ifc\mu}{2\pi}\left(\ln\left(\frac{b}{a}\right)\right)\frac{dz}{dt}}{L_0+\frac{fc\mu}{2\pi}\left(\ln\left(\frac{b}{a}\right)\right)}$$

where $t$ is time, $z$ is position of plasma along anode axis, $z_o$ is length of the anode, $a$ is radius of the anode, $b$ is distance from the center of the anode to cathodes, $\rho_o$ is mass density of gas in a plasma focus device, $L_o$ is inductance of the circuit, $C_o$ is capacitance of a capacitor bank, $V_o$ is a input voltage to a PF device, $\mu$ is magnetic permeability in vacuum, $f_c$ is a current factor and $f_m$ is a mass factor. Both current factor and mass factor were found by fitting calculated values of the current $I$ with the actual current measured from experiment by a Rogowski coil. In this phase, the speed of plasma changes as the plasma sheath moves by the Lorentz's force.

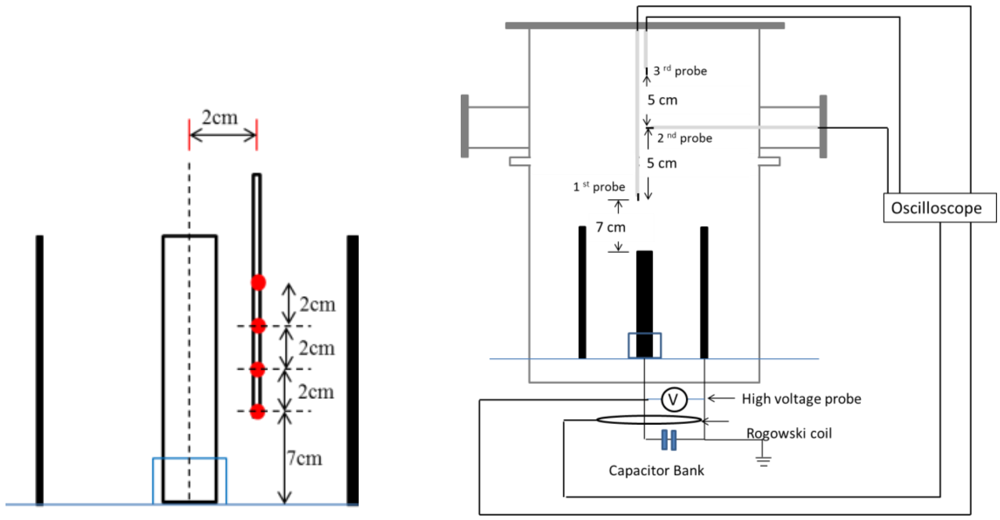
Once the plasma sheath reaches the end of the anode, it enters the radial phase where the sheath continues to expand along the z axis but also moves radially inward to the center of the anode. The plasma sheath drives gas molecules and compresses it forming a "slug" behind a shock front. This slug moves rapidly to the center of the anode as shown in Figure. 2(b). When the shock front moves to the center of the anode, it is reflected back while the plasma sheath is still moving inward. The shock front and the plasma sheath thus collide and ending the radial phase.

In this work, the speed of the plasma sheath was calculated by the model throughout plasma dynamics process from the axial phase through to the radial phase. However, it will be shown that the movement of ion are mainly contributed from the axial phase.

### *2.2. Experimental Setup and Measurement*

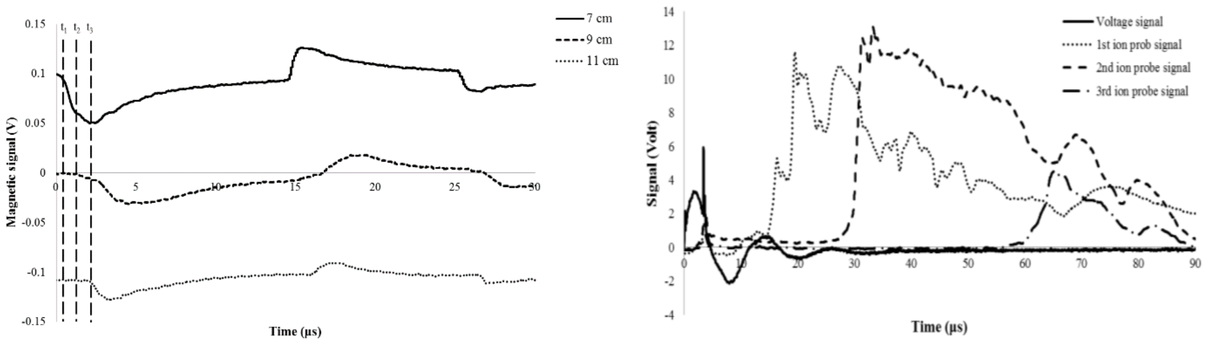
For measurement of the speed of the plasma sheath and ion emitted, magnetic probes and ion probes were used respectively. They were placed at different positions along the axial direction as shown in Figure 3(a). The magnetic probes measure the speed of the plasma sheath during the axial phase. They are small solenoid multi-turn coil that were placed evenly apart. The signal from the probe generated by the induce current when plasma sheath is moving pass the coil. The signals were recorded by 4 channels fast sampling oscilloscope via integrating circuits.

The ions released after the focusing phase, usually refer to as "ion beam" and/or "plasma jet" can be detected directly by ion probes. Three solid coaxial wires were used as ion probes in this experiment. They were placed in positions directly above the anode as shown in Figure 3(b). The wires were biased to a small negative potential in order to collect only positive ions. However, they are also sensitive to electromagnetic pulse and high energy photon because of the photoelectric effect. These effects are being minimized by small cross section area of the wire and shielding. The signals were recorded by 4 channels fast sampling oscilloscope via differentiating circuits. The voltage signal of the PF device was used as a trigger signal and were recorded at the same time as both the magnetic probes and the ion probes. Typical signals of the probes are shown in Figure 4.




(a) (b)

**Figure 3.** Diagram showing (a) the setup of magnetic probes in a PF device and (b) the setup of ion probes.

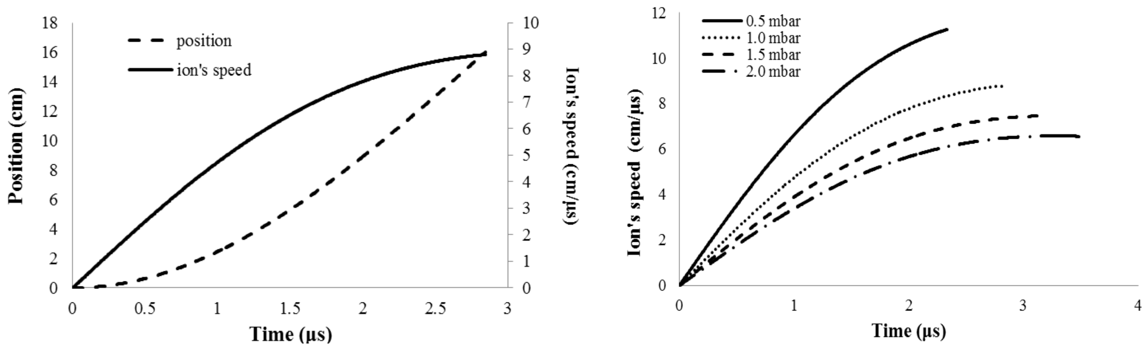



(a) (b)

**Figure 4.** Graph showing (a) signals from magnetics probes and (b) signals from voltage detector and ion probes of PF device operating with argon gas at 1 mbar.

## 3. Results and Discussion

From the calculation based on S. Lee model, the change in position with time of the plasma sheath, which assume to be at the same speed as ions, along the axial direction is shown in Figure 5(a). It can be seen that the speed of the plasma sheath initially increase and then reduce towards end of the anode which one can deduce that the driving Lorentz force in the axial direction also reduces toward the end of the axial phase. Similarly Figure 5(b) shows the calculated speed of ions obtained when the PFD was operated with different pressures. The speed of ions at the end of axial phase reduces as the pressure increases as expected. This is due to the increase in plasma density.

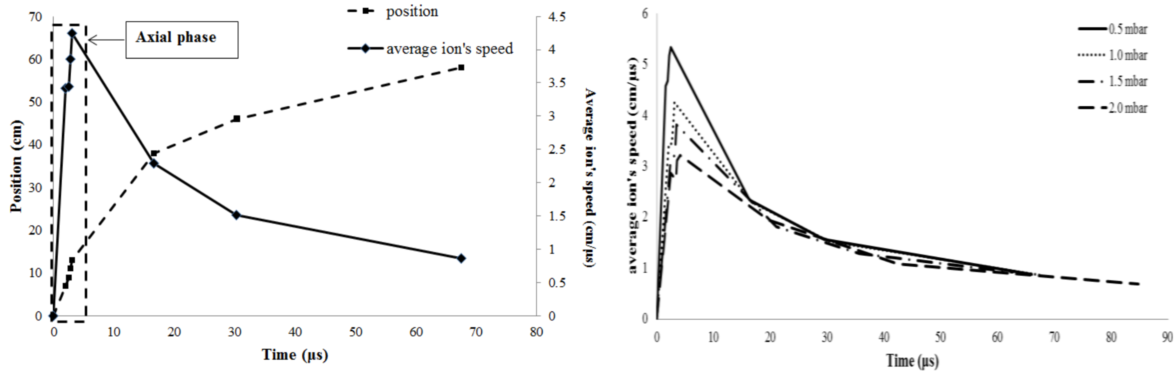



(a) (b)

**Figure 5.** Graph showing (a) positions of ion and average ion's speed obtained from PF device operating with argon gas at 1 mbar and (b) showing calculated ion's speed for various operating pressure.

From the magnetic probe and the ion probes measurement, the position of ions and average ion's speed can be plotted and shown in the Figure 6(a). It can be seen that the maximum speed of ions is reached at the end of the axial phase and then the speed of ions, that were released, reduces exponentially due to collision process. Ions with very high energy or "ion beam" like have not been detected. The measurement result shows that no ion has gained speed after the axial phase has completed. It can be seen in Figure 6(b) that similar results were obtained for various operating pressures and that the speed of ions decreases when the operating pressure increases. This behavior can be explained also by the collisional process of particles as the number density of particles depends directly with the operating gas pressure. The experimental results correspond in term of time taken to reach the end of the axial phase for each different operating pressure with the result obtained by the calculation. However, it can be seen from Figure 7 that the values of the speed of ions obtained by extrapolation of both magnetic probes measurement and the ion probes measurement at various PFD operating gas pressure are lower than the calculated value from the model. This can be explained by the lack of data between the transition of the phases and that, in reality, the Lorentz force changes direction during this transition which may contribute to the reduction of the speed in the axial direction. A more detail simulation can be done by finite element method to obtained more accurate result during the transition period in the future.

Table 1 shows comparison of the maximum speed of argon ion obtained from the calculation and the experiment where corresponding ion energies were calculated for each operating argon gas pressure. It is interesting to note that the argon ion energies obtained are much lower than that reported by Rashed et.al [10]. Figure 8 shows magnification in the period of time at focussing phase. It can be seen that the signal registered by all three ion probes at different distances occur at the same time, therefore the signals measured cannot be from ions but rather from the electromagnetic pulse or the photoelectric effect from high energy photons emitted during the focussing phase. The signal can be misinterpreted if only one single ion probe or detector is used with the time-of-flight technique for determination of ion energy.




(a) (b)

**Figure 6.** Plot showing (a) measured positions of ion and average ion's speed obtained from PF device operating with argon gas at 1 mbar and (b) showing measured ion's speed for various operating pressure.

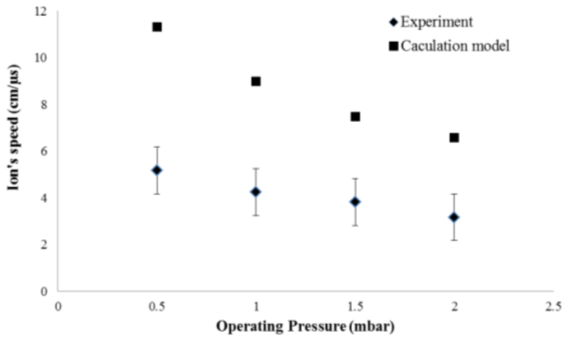



**Figure 7.** Plot showing comparison of ion's speed obtained from experiment and calculation from the model.

**Table 1**. Table showing comparison between results obtained by computation and experiment.

| Operating pressure (mbar) | Computation | | Experiment | |
|---|---|---|---|---|
| | Max. ion's speed (cm/µs) | Max. ion's Energy (eV) | Max. ion's speed (cm/µs) | Max ion's Energy (eV) |
| 0.5 | 11.3 | 2,646.12 | 5.16 ± 0.04 | 551.38 ± 8.55 |
| 1.0 | 8.97 | 1,667.39 | 4.24 ± 0.04 | 372.29 ± 7.02 |
| 1.5 | 7.46 | 1,153.26 | 3.81 ± 0.03 | 300.61 ± 4.73 |
| 2.0 | 6.56 | 891.78 | 3.16 ± 0.04 | 206.79 ± 5.24 |

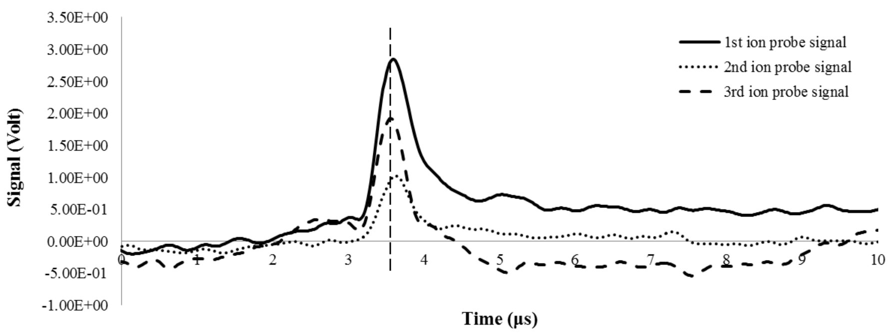



**Figure 8.** Graph showing signals from ion probes at the time of focussing phase.

## 4. Conclusion

The dynamics of argon plasma generated by 2.3 kJ UNU/ICTP PFD had been investigated in terms of the speed of ions from the axial phase through to beyond the focussing phase by experimental measurement for various operating gas pressure. The experimental results were compared with well-established S. Lee model calculation. It was found that at operating gas pressure between 0.5 mbar to 2.0 mbar, the maximum speed of ion reached were between 5.16 ± 0.04 cm/μs and 3.16 ± 0.04 cm/μs toward the end of the axial phase where the Lorentz force starting to change in magnitude and direction. After that, the ions are released without any driven force and losing it speed and energy through collision process. No sign of high energy "ion beam" like were detected with this PFD configuration and operating conditions. The maximum ion energy obtained were 551.38 ± 8.55 eV, 372.29 ± 7.02 eV, 300.61 ± 4.73 eV and 206.79 ± 5.24 eV for operating gas pressure of 0.5 mbar, 1.0 mbar, 1.5 mbar and 2.0 mbar respectively. The experimental results correspond well with calculation based on S. Lee model.

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## Acknowledgement

The authors would like to extend their great appreciation to Prof. Chiow San Wong for his valuable advice. The appreciation also goes to Asian African Association for Plasma Training (AAAPT) for its support in initiating the plasma focus research in this laboratory, and to the Plasma Technology and Nuclear Fusion Research Unit, Chulalongkorn University and Chulalongkorn University for their financial support.