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Research paper

Angular Ion Emission Characteristics of Argon, Helium, and Hydrogen Plasma Focus Discharges Using a Five-Channel Faraday Cup Array

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Abstract

Angular ion emission characteristics are important for understanding ion transport and the spatial distribution of energetic ions generated in dense plasma focus (DPF) devices. In this study, a five-channel Faraday cup array was designed, fabricated, and implemented to investigate the angular ion emission characteristics of argon, helium, and hydrogen plasma focus discharges. The system enables simultaneous measurement of ion signals at five angles relative to the anode axis. Individual calibration of the Faraday cup channels compensated for differences in detector response, and the collected signals were quantified by integrating the ion current pulses. Measurements were performed at different operating pressures and charging voltages of 12 and 14 kV. For all investigated gases, the maximum integrated ion charge was measured along the anode axis, indicating predominantly axial ion emission. The collected ion charge decreased with increasing observation angle, demonstrating the angular dependence of ion emission. The effects of operating pressure and charging voltage varied with the working gas and discharge conditions. Comparison of argon, helium, and hydrogen plasmas revealed gas-dependent differences in collected ion charge, with argon exhibiting the highest values under the selected operating conditions. These differences reflect the combined effects of working gas properties, plasma dynamics, and ion transport. The developed five-channel Faraday cup array provides a practical diagnostic approach for simultaneous angular measurements and comparative investigations of ion emission in plasma focus devices.

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1. Introduction

Dense plasma focus (DPF) devices are compact pulsed plasma sources capable of producing highly transient, high-temperature, and high-density plasmas through the rapid acceleration and compression of a magnetized plasma sheath. Since their introduction, DPF systems have attracted considerable interest due to their ability to generate intense emissions of energetic ions, electrons, X-rays, and neutrons, with potential applications in radiation sources, material processing, ion implantation, and fusion-related studies [1–4]. During the pinch phase, a significant fraction of the electrical energy stored in the capacitor bank is transferred to the plasma, resulting in the formation of energetic particle populations through complex electromagnetic acceleration processes.

The characteristics of energetic ion emission from DPF devices are strongly influenced by the properties of the working gas and discharge conditions. Parameters such as ion mass, charge state distribution, ionization energy, and charge-to-mass ratio (q/m) affect ion acceleration, transport, and emission behavior. Light species such as hydrogen and helium generally exhibit higher velocities due to their larger charge-to-mass ratios, whereas heavier gases such as argon can lead to different ion acceleration mechanisms and momentum transfer processes. Previous studies have shown that ion emission characteristics in plasma focus devices strongly depend on operating parameters, including working gas species, gas pressure, and electrode configuration [1, 5-7]. Therefore, systematic investigation of different working gases is essential for understanding the relationship between plasma composition, discharge conditions, and ion emission characteristics.

Various diagnostic techniques have been developed to investigate energetic ions produced in DPF devices, including Thomson parabola analyzers, track detectors, ion energy analyzers, and Faraday cup systems [8, 9]. Faraday cups are widely used for measuring ion current and collecting electrical charge from charged-particle beams because of their relatively simple design and direct measurement principle [10]. Multi-channel Faraday cup arrays have also been developed for spatially resolved measurements of charged-particle beams, demonstrating the potential of array-based diagnostics for simultaneous measurements at multiple positions [11]. Recent studies have continued to employ Faraday cup diagnostics to characterize ion energy and beam properties in plasma focus devices. For example, nitrogen-ion energies and their penetration into titanium were investigated using Faraday cup measurements and time-of-flight analysis [12]. More recently, fast Faraday cup measurements have been incorporated into comprehensive experimental investigations of plasma dynamics and radiation output in the FAETON-I dense plasma focus device [13]. In parallel, investigations of ion emission in the wider plasma focus chamber have highlighted the complexity of the spatial distribution and possible sources of energetic ions [14]. Together with previous experimental investigations of angular ion emission in plasma focus devices [15, 16], these studies highlight the importance of ion diagnostics for understanding ion acceleration, transport, and spatial emission characteristics.

Although previous studies have investigated the angular distribution of ion emission in dense plasma focus (DPF) devices, including the effects of working gas properties and operating conditions [15–17], further experimental investigations are needed to characterize the angular emission behavior of different gases under comparable conditions. In particular, simultaneous measurements at multiple observation angles can provide a more consistent comparison of the angular distribution than measurements performed sequentially at

individual angles. In addition, differences in detector response should be considered when comparing signals recorded by separate Faraday cup channels. These considerations motivate the development of a calibrated multi-channel Faraday cup system for investigating the angular ion emission characteristics of different working gases in a DPF device. In the present work, the angular ion emission characteristics of a 5-kJ dense plasma focus device are experimentally investigated using a five-channel Faraday cup array. The diagnostic system was designed and fabricated to simultaneously measure ion current signals at different angular positions relative to the anode axis. The Faraday cup channels were individually calibrated, and the integrated ion charge obtained from the ion current pulses was used as a quantitative parameter for evaluating the angular distribution of ion emission. Argon, helium, and hydrogen plasma focus discharges were comparatively studied under different operating pressures and discharge voltages to investigate the influence of working gas properties and discharge conditions on ion emission behavior.

The obtained results provide insight into the relationship between plasma composition, operating parameters, and angular ion transport in compact DPF devices, highlighting the potential of multi-channel Faraday cup diagnostics for spatially resolved investigation of ion emission characteristics.

2. Experimental Setup and Diagnostic System

2.1. Dense Plasma Focus Device

The experiments were carried out using a 5 kJ Mather-type plasma focus (MTPF) device. The discharge system consists of a capacitor bank with a capacitance of 22.4μF, a total circuit inductance of approximately 110nH, and a maximum discharge current of about 144 kA. The experiments were performed at charging voltages of 12 kV. During the discharge, the stored electrical energy is transferred to the coaxial electrode system, generating a high-current plasma sheath that is accelerated along the electrode structure and subsequently compressed during the pinch phase. The electrode assembly consists of a central copper anode surrounded by twelve cylindrical cathode rods symmetrically arranged around the anode. The effective length and radius of the anode are 9.5 cm and 3 cm, respectively. The effective height of the insulator sleeve is 5 cm, while the effective length of the cathode rods is 14.5 cm. This electrode configuration provides the required conditions for plasma sheath formation, axial acceleration, and compression during plasma focus operation. The vacuum system of the device consists of a rotary pump combined with a liquid nitrogen trap, allowing the chamber base pressure to reach approximately 4×10^{-3} Torr. Hydrogen, helium, and argon were used as working gases in the experiments.

The angular ion emission characteristics were investigated using a time-resolved five-channel Faraday cup array. The diagnostic system enabled simultaneous recording of ion current pulses at different observation angles, and the collected ion charge was obtained by integrating the calibrated ion current signals over the complete ion pulse duration.

2.2. Design and Fabrication of the Five-Channel Faraday Cup Array

To characterize the angular ion emission from the plasma focus discharge, a five-channel Faraday cup array was designed and fabricated. The diagnostic system was developed to enable simultaneous measurement of ion current signals at different angular positions, allowing the investigation of angular ion emission characteristics. The Faraday cup array was

installed above the anode with a distance of 75 mm between the anode tip and the detector plane. Five individual collectors were arranged at observation angles of 0°, ±25° and ±50° with respect to the device axis. A schematic representation of the experimental setup of the 5 kJ MTPF device and the arrangement of the five-channel Faraday cup array is shown in Figure 1. Each Faraday cup consists of an external shielding body, an electrically isolated ion collector, and a supporting insulator structure. The outer body was fabricated from stainless steel 304 and electrically connected to ground to reduce electromagnetic interference and improve measurement stability. A copper collector was selected as the ion receiving electrode due to its high electrical conductivity, good thermal properties, and suitable performance for pulsed ion measurements. The collector geometry was designed with a 2 mm entrance aperture and a 12 mm effective depth, resulting in an aspect ratio of approximately 4–6. This configuration provides efficient ion collection while reducing the contribution of particles entering from undesired directions. Electrical isolation between the collector and the grounded outer body was achieved using a PTFE back insulator, ensuring reliable operation under vacuum conditions.

A photograph of the fabricated detector assembly is presented in Figure 2, showing the arrangement of the Faraday cup collectors and their mechanical support structure.

The ion current signals from the five Faraday cup channels were transferred through a dedicated electrical feedthrough to an external acquisition system.

All five signals were simultaneously recorded using a five-channel oscilloscope with a common time reference, allowing direct comparison of ion emission characteristics at different angular positions during the same discharge event. This simultaneous acquisition minimizes shot-to-shot variations and provides reliable data for evaluating the angular distribution of the collected ion charge.

The use of multiple simultaneously operated Faraday cup channels eliminates the need for separate discharges at different observation angles and reduces the uncertainty associated with shot-to-shot variations.

2.3. Faraday Cup Calibration and Integrated Ion Charge Measurement

Prior to the plasma focus experiments, the response of the five-channel Faraday cup array was calibrated to compensate for possible differences in sensitivity among individual detector channels. Since reliable comparison of ion emission at different angular positions requires correction of detector response variations, a calibration procedure was performed for each Faraday cup.

During the calibration process, each Faraday cup was individually installed at the central position (0°) with respect to the device axis, and approximately ten reproducible plasma focus discharges were performed for each detector channel. The reproducibility of the discharges was evaluated based on the similarity of the hard X-ray emission level and the characteristic discharge current behavior. Only discharges with comparable plasma conditions were considered for the calibration procedure.

The ion signal recorded by each Faraday cup channel was converted into the collected ion charge by integrating the complete ion current pulse from the initial rise of the signal to its return to the baseline level:

$$Q_i = \int_{t_1}^{t_2} I_i(t)dt \quad (1)$$

where $I_i(t)$ is the measured ion current and t_1 and t_2 represent the beginning and the end of the ion pulse, respectively. The obtained integrated charge values were used for calibration of the

Faraday cup channels and subsequent evaluation of the angular ion emission characteristics.

The response of each detector channel was normalized with respect to the central Faraday cup (Faraday cup No. 3), which was selected as the reference detector located along the main axis of the plasma focus device. The normalized response of Faraday cup No. 3 was defined as unity, and its calibration coefficient was set to 1. The calibration coefficient of each channel was calculated as the inverse of its normalized response.

Therefore, multiplication of the measured integrated ion charge by the corresponding calibration coefficient compensates for the relative sensitivity differences among the detector channels.

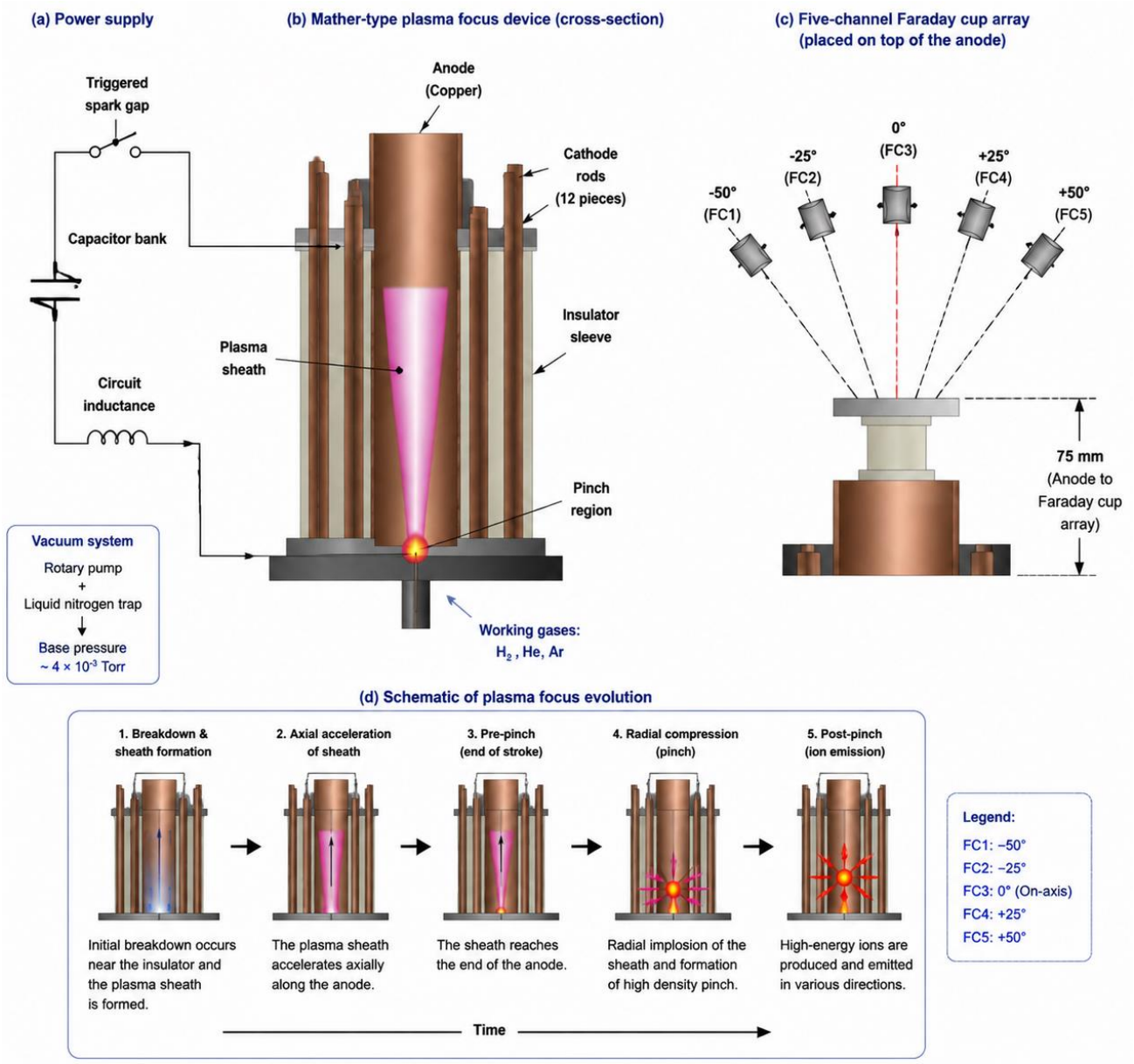


Figure 1. Schematic diagram of the 5 kJ MTPF device and the arrangement of the developed five-channel Faraday cup array. The array was installed above the anode tip at a distance of 75 mm from the anode surface, with five observation angles of 0°, ±25° and ±50° relative to the device axis



Figure 2. Photograph of the fabricated five-channel Faraday cup array showing the arrangement of the collectors and mechanical support structure

The obtained calibration coefficients are listed in Table 1, and the average integrated ion signals measured during the calibration procedure together with their corresponding uncertainties are presented in Figure 3.

During the analysis of experimental measurements, all recorded signals from the Faraday cup channels were corrected using the corresponding calibration coefficients. After calibration, the angular ion emission characteristics were obtained from the corrected integrated ion charge measured simultaneously by the five Faraday cups.

The corrected integrated ion charge at each observation angle was used as a quantitative parameter for comparing the relative ion emission characteristics of argon, helium, and hydrogen plasmas. Since all five detector channels recorded ion signals from the same discharge event during the main experiments, the influence of shot-to-shot fluctuations was minimized, enabling reliable comparison of ion emission behavior at different angular positions.

Table1. Numerical value of the calibration coefficient of Faraday cups

Faraday cup No.	Angle	Calibration coefficient
1	-50°	1.11
2	-25°	0.85
3	0°	1
4	+25°	0.79
5	+50°	1.04

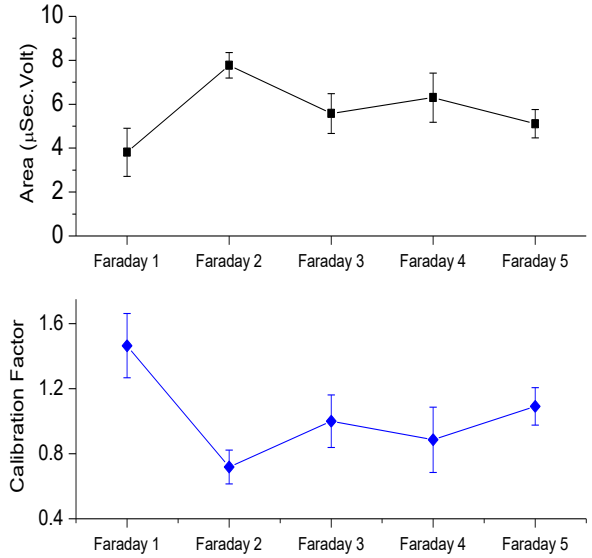


Figure 3. Average integrated ion signals obtained from individual Faraday cup channels during the calibration procedure (upper panel) and the corresponding calibration factors calculated with respect to the central Faraday cup (No. 3) as the reference channel (lower panel)

3. Results and Discussion

3.1. Discharge Current Characteristics and Integrated Ion Signal Processing

The discharge behavior of the plasma focus device was first characterized using the Rogowski coil signal. Figure 4 presents the discharge current waveforms and their corresponding derivatives for argon, helium, and hydrogen plasmas at the selected operating pressures for each working gas. The derivative of the discharge current was calculated to identify characteristic temporal features associated with rapid changes in the discharge evolution, including the current variation during the plasma compression stage. As shown in Figure 4, the discharge current evolution exhibits different characteristics for the investigated working gases, which can be attributed to differences in plasma conductivity, ion mass, and dynamic behavior during the plasma compression and expansion phases. Since the discharge characteristics depend strongly on the working gas species, the pressure conditions were selected separately for each gas to obtain reproducible plasma focus operation.

After characterization of the discharge behavior, ion emission signals were recorded using the five-channel Faraday cup array. Figure 5 presents a representative set of time-resolved output voltage signals recorded simultaneously by the five-channel Faraday cup array for an argon discharge at 12 kV and its selected operating pressure. The Faraday cups were positioned at 0°, ±25° and ±50° with respect to the anode axis, enabling simultaneous detection of ion emission at different observation angles. The different signal amplitudes observed at different angular positions demonstrate the angular dependence of the detected ion emission.

The output voltage signals were converted to ion current using the 50 Ω termination resistance. The collected ion charge for each Faraday cup channel was then obtained by integrating the complete ion current pulse, from the initial rise of the signal to its return to the baseline level, according to the procedure described in Section 2.3. The calibrated integrated ion signals were subsequently used as the quantitative parameter for evaluating the angular ion emission characteristics of argon, helium, and hydrogen plasmas.

3.2. Angular Distribution of Ion Emission

The angular characteristics of ion emission were investigated using the five-channel Faraday cup array.

For each detector channel, the recorded ion current pulse was integrated over its complete duration, from the initial rise of the signal to its return to the baseline level, and the resulting integrated signal value was used as a quantitative parameter for comparing the relative ion emission behavior at different observation angles. The measurements were performed at two charging voltages of 12 and 14 kV.

Each data point represents the average value obtained from five successful discharges in order

to reduce the influence of shot-to-shot variations in plasma focus operation. The effects of operating pressure, discharge voltage, and working gas species on the angular ion emission characteristics were investigated for argon, helium, and hydrogen plasmas.

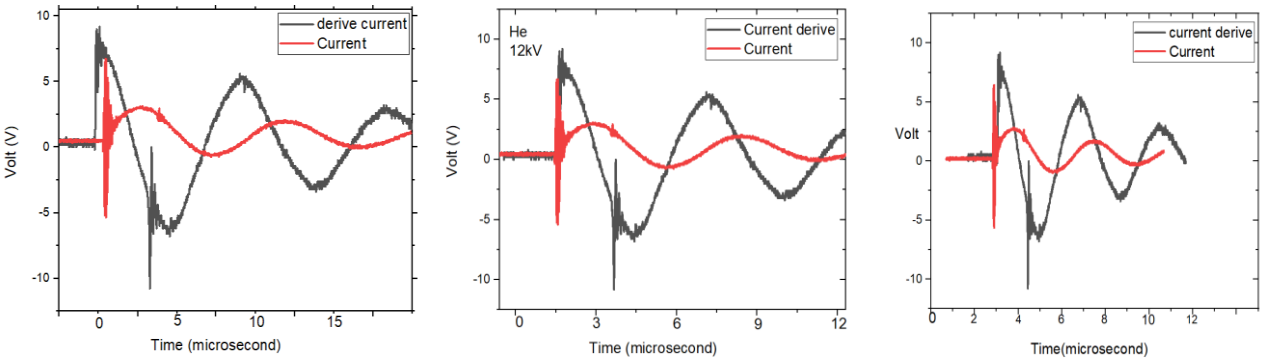


Figure 4. Discharge current waveforms and corresponding derivatives for (a) argon, (b) helium, and (c) hydrogen plasmas obtained at a discharge voltage of 12 kV and at the optimum operating pressure of each working gas

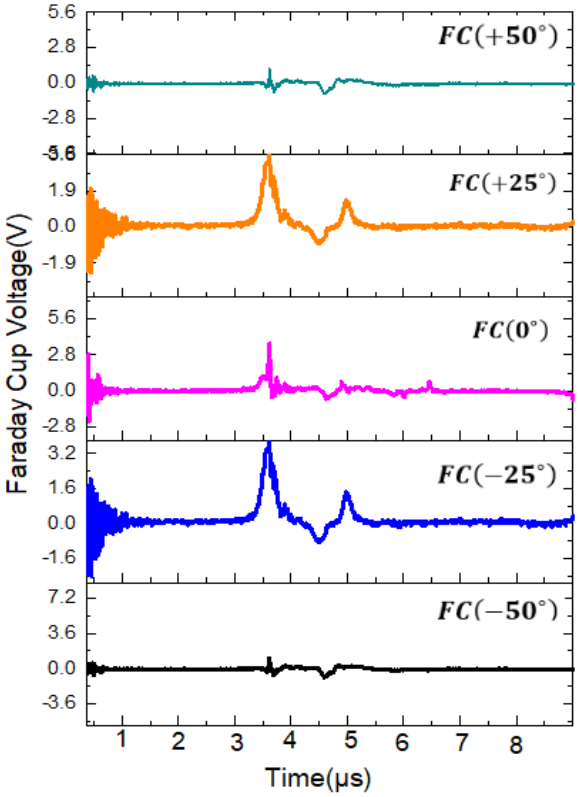


Figure 5. Representative time-resolved output voltage signals recorded simultaneously by the five-channel Faraday cup array for an argon plasma discharge at 12 kV and optimum operating pressure

Figure 6 presents the integrated Faraday cup signal as a function of operating pressure for argon plasma at discharge voltages of 12 and 14 kV. For both voltage conditions, the maximum integrated signal is observed at the central Faraday cup (0◦), indicating that the majority of the detected ion emission is concentrated along the anode axis. With increasing observation angle from the axis, the integrated signal decreases gradually, demonstrating the angular divergence of the emitted ions from the plasma focus region. The comparable signal levels at positive and negative observation angles indicate an approximately symmetric ion emission pattern around the device axis. At 12 kV, the integrated Faraday cup signal shows a relatively similar angular behavior over the investigated pressure range, with the highest values generally occurring near the lower and intermediate pressure conditions. Increasing the discharge voltage to 14 kV results in an enhancement of the integrated signal, particularly at the axial position. This increase can be attributed to the higher energy deposition and stronger plasma acceleration dynamics under the higher charging voltage. However, the overall angular distribution profile remains nearly unchanged, suggesting that increasing the discharge voltage mainly affects the magnitude of ion emission rather than significantly altering the angular spread of the emitted ions. The angular distribution of the integrated Faraday cup signal

for helium plasma is shown in Figure 7. Similar to the argon plasma, helium ion emission exhibits a maximum value at the central observation angle (0°) followed by a gradual decrease toward larger angles. This behavior confirms that helium ions are also predominantly emitted along the anode axis, while a smaller fraction of the detected ions reaches off-axis positions due to plasma expansion and ion transport processes. Increasing the discharge voltage from 12 to 14 kV enhances the integrated signal at all observation angles, with the most pronounced increase occurring along the axis. The preservation of the angular distribution profile at both voltages indicates that the higher discharge voltage increases the overall ion emission magnitude without significantly modifying the angular divergence. Compared with argon, the higher integrated signal observed for helium under the investigated conditions can be related to differences in ion production, ionization processes, and plasma expansion dynamics. However, the measured integrated signal represents the electrical response of the Faraday cup and is influenced by both the number of emitted ions and their charge states. Figure 8 presents the angular distribution of the integrated Faraday cup signal for hydrogen plasma at 12 and 14 kV. Hydrogen plasma also exhibits an axial-peaked emission pattern, with the maximum signal detected at 0° and a gradual reduction at larger observation angles. This similarity among the three working gases indicates that the dominant axial ion emission behavior is a general characteristic of the investigated plasma focus operation. The increase in discharge voltage leads to a clear enhancement of the integrated Faraday cup signal over the entire angular range. Nevertheless, the relative difference between the axial and off-axis signals remains comparable at both voltages, suggesting that the higher discharge voltage primarily increases the amount of detected ion emission rather than significantly changing the angular distribution. A comparison of the integrated Faraday cup signals obtained for argon, helium, and hydrogen plasmas reveals clear differences in the magnitude of the detected ion emission. In general, helium and hydrogen plasmas exhibit higher integrated signals compared with argon, particularly at the central observation angle. These differences can be associated with the distinct plasma formation and expansion characteristics of the working gases, including ionization behavior, ion mass, and transport dynamics. It should be noted that the integrated Faraday cup signal represents the time-integrated electrical response of the detector, which is related to the collected ion charge but does not directly provide the absolute ion number. Therefore, the observed differences among the gases are affected by both the emitted ion population and the charge-state distribution. The influence of operating pressure and discharge voltage on the integrated Faraday cup signal can also be observed from the measured distributions. For a fixed discharge voltage, higher integrated signals are generally obtained at lower operating pressures, which can be attributed to the lower probability of ion-neutral collisions during ion transport from the plasma region to the Faraday cups. Increasing the discharge voltage from 12 to 14 kV enhances the detected ion emission for all investigated gases, indicating stronger ion generation and acceleration under higher discharge energy conditions. For argon plasma, the integrated Faraday cup signal at the axial position (0°) at 14 kV reaches approximately 2.5 times the value measured at 12 kV under the investigated conditions.

Furthermore, the higher discharge voltage results in a wider pressure range with relatively stable ion emission. For argon plasma, the maximum integrated signal is observed near 0.8 Torr at both voltages, while a relatively stable emission region appears in the pressure range of approximately 1.4–1.8 Torr at 12 kV and approximately 1–2 Torr at 14 kV.

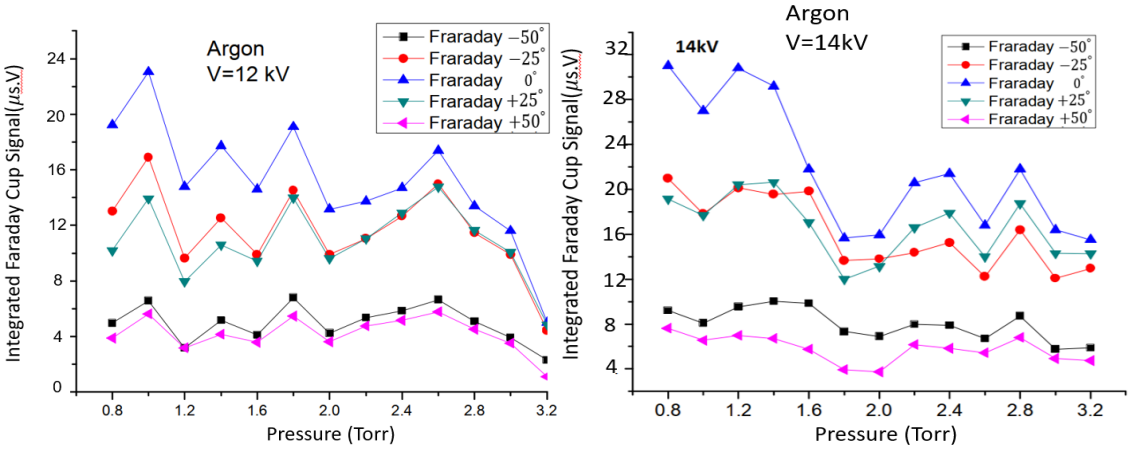


Figure 6. Collected ion charge measured by the Faraday cup array as a function of operating pressure at different observation angles for argon plasma at discharge voltages of (a) 12 kV and (b) 14 kV. Each data point represents the average value obtained from five successful discharges

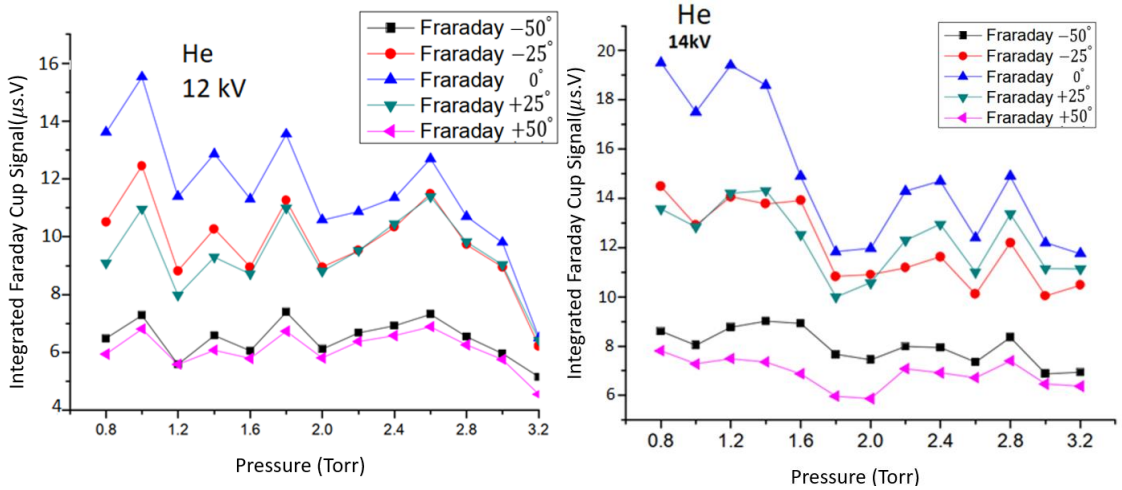


Figure 7. Collected ion charge measured by the Faraday cup array as a function of operating pressure at different observation angles for helium plasma at discharge voltages of (a) 12 kV and (b) 14 kV. Each data point represents the average value obtained from five successful discharges

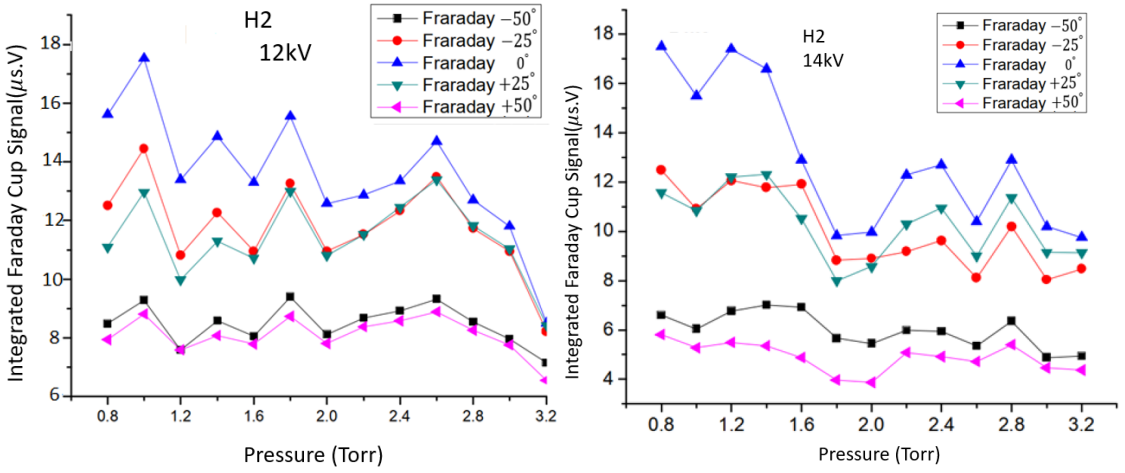


Figure 8. Collected ion charge measured by the Faraday cup array as a function of operating pressure at different observation angles for hydrogen plasma at discharge voltages of (a) 12 kV and (b) 14 kV. Each data point represents the average value obtained from five successful discharges

3.3. Comparison of Ion Emission Characteristics for Different Working Gases

To provide a direct comparison of the ion emission characteristics of different working gases, the integrated ion charge obtained from the central Faraday cup (0°) was evaluated for argon, helium, and hydrogen plasmas at their respective optimum operating pressures, as shown in Figure 9. The optimum pressure for each working gas was selected based on the maximum value of the integrated ion charge obtained at the central observation angle. This approach enables comparison of the ion emission response of different gases under their most favorable discharge conditions.

The results demonstrate that the working gas species has a significant influence on the magnitude of the integrated ion charge. Among the investigated gases, argon plasma exhibits the highest integrated ion charge, whereas helium and hydrogen plasmas show lower values under the selected operating conditions. The higher collected ion charge observed for argon can be associated with the combined effects of plasma generation efficiency, ion production mechanisms, charge-state distribution, and ion transport behavior. Although argon has a higher atomic mass compared with helium and hydrogen, its plasma formation and ionization characteristics can lead to a larger collected electrical response under the investigated discharge conditions.

The comparison between 12 and 14 kV discharges indicates that the effect of increasing the discharge voltage depends on the working gas species. In general, the higher charging voltage enhances the integrated ion charge by increasing the energy coupled to the plasma and modifying the acceleration dynamics of the ions. However, the magnitude of this enhancement is not identical for all gases due to differences in plasma evolution, ionization processes, and discharge stability. It should be emphasized that the integrated ion charge measured by the Faraday cup represents the collected electrical charge associated with the emitted ion population and does not directly correspond to the absolute number of emitted ions. Therefore, the observed differences among argon, helium, and hydrogen plasmas are influenced by both the number of emitted ions and their charge-state distribution. Nevertheless, the results confirm that the developed five-channel Faraday cup array provides an effective diagnostic tool for comparative investigation of gas-dependent ion emission characteristics in plasma focus devices.

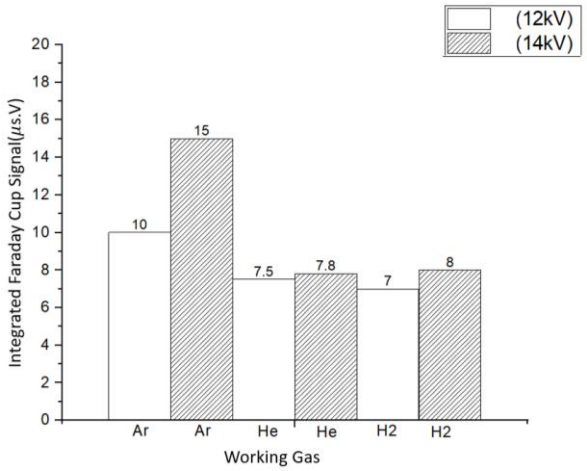


Figure 9. Comparison of the calibrated integrated Faraday cup signals collected by the central Faraday cup (0°) for argon, helium, and hydrogen plasmas at their selected operating pressures for discharge voltages of 12 and 14 kV

4. Conclusion

In this work, a five-channel Faraday cup array was designed, fabricated, calibrated, and employed to investigate the angular ion emission characteristics of a 5-kJ plasma focus device operated with argon, helium, and hydrogen working gases. The developed diagnostic system enabled simultaneous measurement of ion signals at different observation angles, and the calibrated integrated Faraday cup signals obtained from the ion current pulses were used as a quantitative parameter for evaluating the angular ion emission behavior.

The angular measurements demonstrated that, for all investigated gases, the maximum integrated Faraday cup signal was obtained at the central observation angle (0◦), indicating that the ion emission is predominantly concentrated along the anode axis. The gradual decrease of the integrated signal at larger observation angles reflects the angular divergence of the emitted ion population during plasma expansion and transport. The similar behavior observed at positive and negative angles confirms an approximately symmetric ion emission pattern around the device axis.

The results showed that operating pressure and discharge voltage significantly affect the detected ion emission. Lower operating pressures generally resulted in higher integrated Faraday cup signals due to the reduced probability of ion-neutral collisions during ion transport from the plasma region to the detector. Increasing the discharge voltage from 12 to 14 kV enhanced the ion emission response; however, the magnitude of this enhancement depended on the working gas species and discharge conditions, indicating the influence of plasma formation dynamics and ion acceleration processes.

The comparison of argon, helium, and hydrogen plasmas revealed clear gas-dependent differences in the integrated ion charge. Under the selected operating conditions, argon plasma exhibited the highest collected ion charge, while helium and hydrogen showed lower values. These differences are attributed to the combined effects of ion production mechanisms, plasma expansion behavior, charge-state distribution, and ion transport properties of different working gases. Since the Faraday cup measurement represents the electrical charge collected from the emitted ions rather than the absolute number of ions, the observed variations reflect the combined influence of ion population and charge states.

Overall, the developed five-channel Faraday cup array provides a reliable diagnostic approach for spatially resolved investigation of angular ion emission characteristics in plasma focus devices. The obtained results demonstrate the importance of working gas properties and discharge parameters in controlling ion emission behavior and provide useful information for optimization of compact plasma focus ion sources.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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