Effect of gas flow rate on ionizing power characteristics of penning type ion source

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ABSTRACT

An experimental observation on the effect of hydrogen gas flow rate value on ionization power characteristics of penning type ion source has been conducted. The experiments were conducted in the range of gas flow rate values between 3 and 8 sccm, which is a range of discharge that is generally used in cyclotron operations. The characteristic of ionization power is the change in power which is determined from the cathode voltage and cathode current that occurs when the gas flow rate is varied. The fixed operating parameter is the magnetic field at a value of 1.29 T. The characteristic data is presented in graphs and analyzed theoretically. The experiment was conducted at the DECY-13 cyclotron. The results of the analysis show that the effect of increasing the gas flow rate does not significantly affect the characteristics of ionization power. However, further analysis shows that the increase in gas flow rate will have a significant effect on the increase in ion formation rate in the ionization chamber due to a significant increase in the increase in gas pressure in the chamber. The benefit of the results of this study is as an initial capital to increase ion productivity from ion sources.

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1. INTRODUCTION

The ion source is the initial component of the ion beam generation process in a particle accelerator including a cyclotron. One of the types of the ion source that has been widely used in many applications is penning type ion source [1], [2]. This type of ion source is used in in the DECY-13 cyclotron to produces negative hydrogen ion (H^-) beams to be fed into the cyclotron system for the acceleration process [3]. The H-ion beam in the ion source comes from the ionization process of hydrogen gas injected into the ion source. Penning type ion sources are commonly used in cyclotrons, especially for internal ion sources [4]-[8]. This Penning-type ion source also was known to produce a high intensity beam of ions especially using hydrogen gas [9].

The main components of the penning type ion source are a thick chip as the cathode and a hollow cylinder as the anode. A high electrical voltage is applied to the cathode, which is about -2 kV against the grounded anode [10]-[12]. With the voltage difference between the cathode and anode, electrons will escape from the cathode surface and will ionize the gas molecules/atoms in the anode chamber [13], [14]. A magnetic field in the axial direction is presented in the cylindrical cavity of the anode which makes the electrons move in a spiral manner so as to increase the intensity of ionization [15], [16]. Basically, the ionization process in the penning type ion source is influenced by several parameters, namely cathode voltage, puller voltage, gas flow rate, and magnetic field intensity [17]. The penning type ion source in the cyclotron is operated at a maximum cathode voltage of up to approximately 3 kV and a cathode current of about 1 A, so the power used is about 3 kW.

The flow rate of the gas injected into the ion source will affect the gas pressure value in the ionization chamber, further affecting the density of gas atoms/molecules in the chamber, and ultimately affecting the ionization density. Ionization density is also affected by electron energy and ionizing electron current. Electron energy depends on the cathode voltage value, and electron current depends on the cathode current. The multiplication of the cathode current by the cathode voltage is what is meant by ionizing power in this research report.

Several experiments have been conducted on the effect of gas flow rate on ionization characteristics. For example, Long *et al.* [18] observed the effect of changing the gas flow rate on the light intensity in the ionization chamber at a cathode current of 1.34 A. Yang *et al.* [19] observed the effect of changing the gas flow rate value on the cathode voltage at a specific cathode current of 1.29 A. Calvo *et al.* [4] observed the effect of changes in cathode current on cathode voltage for various gas rate values and observed the effect of changes in gas rate on cathode voltage for various cathode current values of several hundred mA. Of the several experiments that have been mentioned, what has not been done is the effect of gas flow rate on the characteristics of ionizing power and its effect on the ionization rate.

Although several experiments have investigated the correlation between gas flow and operational quantities in penning ion sources, there is a lack of research addressing the correlation between gas flow rate and ionizing power. Another lack of research that addresses the role of gas flow rate on ionization intensity rate in ion source plasmas. There are still two problems that remain unanswered. The first problem is how the gas flow rate affects the ionizing power, and the second problem is the role of the gas flow rate on the ionization intensity. The aim of this experimental study is to address two gaps in prior research and provide solutions to these problems.

This paper presents experimental results and an analysis of the effect of gas flow rate on the ionizing power characteristics. These findings are novel, as no previous work has explored this specific area. Additionally, we will investigate the ionization density rate, or ionization productivity, of the ion source, which will further contribute to the originality of this study. This research is important to do because by recognizing the characteristics of the ion source power, methods can be formulated to increase the quantity and quality of the ion source output.

2. METHOD

2.1. Experimental device

2.1.1. Penning type ion source

As a device that becomes the object in this study is a penning type ion source is used in the DECY-13 cyclotron. The ionization process in ion sources generally occurs due to attraction by a high electric field discharge or due to collisions by electrons that have kinetic energy that exceeds the binding energy of electrons in the atom. In penning type ion sources where the ionization process is due to electron collisions, the minimum energy to release these electrons is called ionization energy. For atoms or molecules in gas, the ionization energy is 13.6 eV for H atoms [20] and 15.4 eV for H2 molecules [21].

The main device of the ion source consists of a head and holder, where the head contains the ionization chamber while the holder serves as a support for the head as well as a place to attach the cooling water channel, cathode voltage channel, and gas supply channel. The schematic of the penning ion source is shown in Figure 1. This ion source device is installed internally in the cyclotron tank, so except for the cathode voltage source, cathode current meter, and gas supply components, all other components are in the cyclotron vacuum chamber.

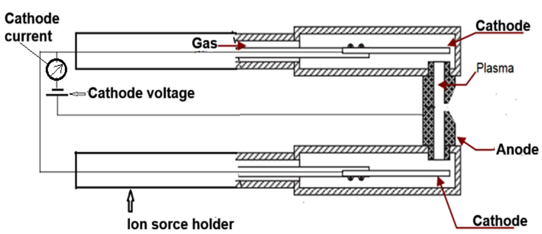

Figure 1. Schematic of penning type ion source

2.1.2. Ion source power supply

The ionization process that occurs in the penning type ion source is played by the ionizing current after the achievement of a high voltage between the cathode and anode that allows the discharge of electrons from the cathode. The high voltage ranges from 1700-1800 V, which is a voltage value at which plasma discharge usually occurs for tantalum cathodes [22]-[24]. So, the largest ionizing current comes from the current of electrons escaping from the cathode or called cathode current. The specifications of the power supply are capable of producing a high voltage at the cathode of at least 1700 V and a cathode current that is generally in the hundreds of mA to 2 A. In this case, the cathode current is the value that is controlled or regulated while the cathode voltage is the value resulting from the cathode current setting.

A power supply to supply the cathode current used in this experiment is the Shekonic model WWL-LDG linear high voltage CV CC DC power supply. The power supply has a maximum capacity of 3 kV 2.5 A. Because for this ion source experiment a current control is needed, which means changing the CV mode to CC mode by reducing the load resistance (R load) in this case the resistance in the ion source plasma chamber, this is in accordance with the basic principle of CC mode is R load < (Vout/Iout). These conditions are achieved by creating a high ionizing current in the ion source plasma which can occur in strong ionization in the ion source, and based on experimental experience it occurs after the cathode voltage (Vout) is above 1700 V. In order to achieve that voltage, a resistor of 1 kohm is added to the power supply output. The schematic of the power supply is shown in Figure 2.

Figure 2 shows a power supply system used to supply voltage and current to the ion source. This circuit consists of several main blocks, starting from a transformer to adjust the required voltage, a rectifier circuit consisting of a bridge diode to convert AC voltage to DC voltage up to a maximum value of 3 kV. After going through the rectification process, this DC voltage is then filtered using a combination of capacitors and resistors to make it more stable and reduce voltage ripple.

Furthermore, this system is controlled by a controller which consists of a comparator circuit, switch, and feedback mechanism. The comparator compares the feedback voltage (Vfb) with the reference voltage (Vref) to ensure that the voltage or current provided is in accordance with requirements. The switch in the controller allows the system to work in two modes, namely CV mode and CC mode. CV voltage mode is active when the output voltage is stable and the current will follow the voltage, while current mode or CC is used if current stability has been met and the voltage will adjust the load.

In addition, there is a shunt resistor (R_{shunt}) which one of its functions is used to measure the current flowing to the load, where the voltage produced by this resistor is used as feedback in current control. At the end of the system, there is a R_{plasma} component that represents the plasma resistance in the ion source or load, and a 1 kΩ resistor used as a current limiter and as a safety. The entire system aims to provide stable and controlled power to the ion source, which is used in the application of the ionization process in the ion source.

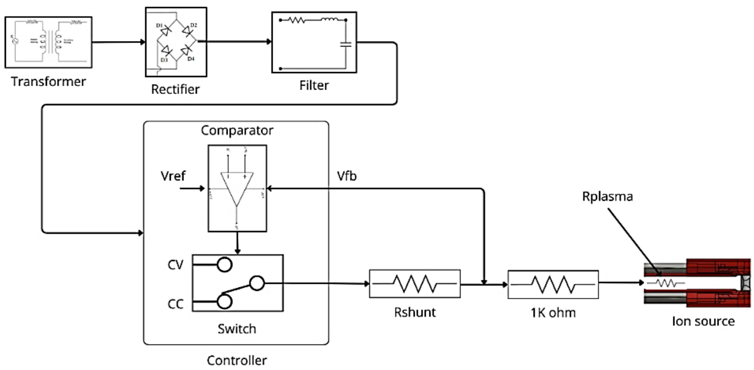

Figure 2. The CC power supply schematic for ion source

2.2. Experiment setup

The schematic of the experimental setup is illustrated in Figure 3. The regulated input quantity is the gas flow rate, which is monitored using a gas flow meter. The actual output quantity is the ionization density of the plasma formation; however, since this measurement is challenging to obtain, we represent it with the ionizing power. Two quantities that correspond to the ionizing power are the cathode voltage, measured by the cathode voltage meter, and the cathode current, measured by the cathode current meter. The ionizing power of the ion source plasma is calculated by multiplying the voltage and the cathode current.

This experiment requires the following conditions:

i) The vacuum of the cyclotron tank is greater than 3×10^{-6} Torr
ii) The magnet is set at a generation current of 280,000 ppm which is equivalent to a magnetic field of 1.25 T at the center point of the cyclotron where the ion source head is located.
iii) The hydrogen gas flow rate can be flowed up to 8 sccm and it is observed that the vacuum changes to no less than 3×10^{-5} Torr

iv) The ion source power source can operate up to a minimum cathode voltage of 2 kV and can operate in control current mode.

After achieving operation in control current mode at cathode current values up to hundreds of mA, observations were made on the effect of gas flow rate on electrical power characteristics in two conditions, namely:

i) Observation of the effect of variations in gas flow rate on the power characteristics of the ion source, namely the multiplication of current with cathode voltage. The value of gas flow rate variation is between 3 to 8 sccm and each gas flow rate value is observed for various cathode current values between 0.1 A to 1 A.

ii) A cross-over test was then performed by observing the characteristics of the change in cathode voltage over the gas flow rate variations between 3 to 8 sccm for a specific cathode current value to be selected. Observations of changes in cathode current were not made because the operating mode was control current.

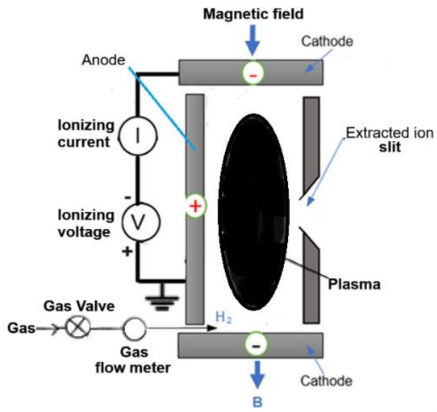

Figure 3. Experimental setup scheme

2.3. Analysis procedure

The analysis will focus on the effects of variations in gas flow rate on the power characteristics of the ion source. We will examine how these characteristics appear and explore their theoretical understanding. Finally, we will study how these characteristics impact the rate of ionization density generated by the ion source.

3. RESULTS AND DISCUSSION

3.1. Characteristics of ionizing power

The results of the experiments conducted have observed the relationship between the gas flow rate and the power characteristics of the ion source as shown in Figure 4. From the curves in Figure 4, it appears that the gas flow rate does not have a noticeable effect on the ionizing power. Furthermore, it will be explored why this can happen, so as cross-examination data, the results of the cathode voltage characteristics of the gas flow rate variation from 3 to 8 sccm are presented in Figure 5.

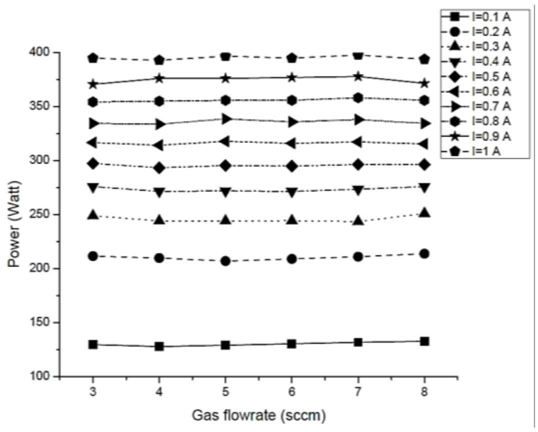

Figure 4. Effect of gas flow rate variation on cathode power

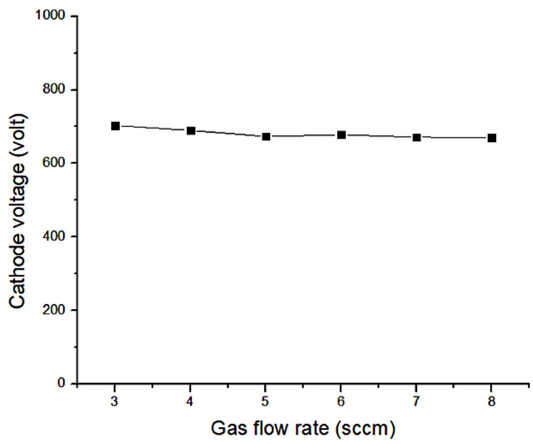

Figure 5. Effect of gas flow rate on cathode voltage

From Figure 5, it can be seen that there is almost no change in the voltage value when the gas flow rate is varied. This means that the absence of the effect of gas flow rate variation on ionizing power, as shown in Figure 4, is due to the absence of its effect on the cathode voltage. However, since the performance of the ion source is basically measured based on the output in generating the ion beam, the effects of these characteristics on the ionization intensity rate will be analyzed as described below.

3.2. Implications for ionization intensity rate

To study the implications for ionization intensity, the following analysis is used. In a penning ionization gauge (PIG) ion source, where ionization is formed due to electron collisions, the number of atoms or molecules ionized depends on the parameters: i) Electron current density (amperes per m^2), $I_{e;}$ ii) Effective volume of ionization, v; iii) Number of moles of gas per unit volume of ionization chamber, n_a; and iv) Ionization cross section, σ_i.

The ion formation rate I_i in the ionization chamber [25].

$$I_i = J_e\, v\, n_a\, \sigma_i \tag{1}$$

For penning ion sources, J_e can be taken from the discharge current density between the cathode and anode or the so-called cathode current. is the part of the volume in which the gas atoms are ionized, which is not necessarily equal to the volume of the ionization chamber. The ionization chamber referred to here is the space of the anode cavity. Assuming the hydrogen gas in the ionization chamber is an ideal gas, the value of n_a can be calculated from (2).

$$n_a = \frac{p}{kT} \tag{2}$$

Where p is the gas pressure, k the Boltzmann constant = 1.38×10^{-23} J/K and T the plasma temperature in ^{o}K.

By combining the curve in Figure 5 where there is almost no change in cathode voltage V which means there is no change in ionization cross section value σ_i, because σ_i depends on V, with (1), it can be temporarily said that the variation of the gas flow rate does not affect the ionization intensity.

Based on (2), the value of atoms/molecules per unit volume of ionization space n_a increases when the pressure p rises. This results in the rate of ion formation in the ionization chamber rising, based on (1), resulting in the electrical conductivity value of the plasma rising. Because the electric current is made constant, the increase in conductivity has the effect of decreasing the voltage between the cathode and anode.

The effect on ion productivity can be discussed as follows. Ion productivity depends on the value of the ion formation rate I_i. In (1) the value of I_i is influenced by the value of the variable magnitude of the electron current density J_e played by the cathode current, the number of atoms or molecules per unit volume n_a, and the ionization cross section σ_i. In this case the value of σ_i is considered to be a very small change in the range of changes in the value of the cathode voltage V_k (proportional to the energy of the impactor electrons) that occurred in this experiment which is only in the range of 640 to 670 V [26], [27]. Since the value of J_e in this experiment is set constant, it is only the value of n_a that will be the quantity that needs to be reviewed in its influence on the value of I_i. The latter requires an analysis of the relationship between the gas injection rate and the gas pressure in the ionization chamber. For this purpose, it can be analyzed using the CFD simulation program presented in the following discussion.

The simulation using the CFD program presents data on the relationship between the hydrogen gas flow rate and the pressure in the ionization chamber of the ion source. The parameters in the simulation were the same as the parameters in the discussed ion source here. Referring to the simulation data that has been carried out by the author, the processing of the simulation results is presented in Table 1.

Table 1. Relationship between gas flow rate and pressure in the ionization chamber

No	Gas flowrate (sccm)	Gas pressure $\times10^{-5}$(Torr)	No	Gas flowrate (sccm)	Gas pressure $\times10^{-5}$(Torr)
1.	3	5.17	4.	6	8.73
2.	4	6.14	5.	7	10.39
3.	5	7.25	6.	8	12.32

From the data, it can be seen that increasing the gas rate gives a significant increase in gas pressure in the ionization chamber. Referring to (2), the increase in gas pressure will linearly increase the value of the number of gas moles per unit volume, n_a and ultimately, based on (1) will also increase the value of the ion formation rate I_i in the ionization chamber significantly. By comparing the pattern of gas pressure increase, it is quantitatively predicted that increasing gas from 3 sccm to 5 sccm will increase the ion formation rate by 1.4 times and to 2.4 times for an increase to 8 sccm. So, the increase in gas flow rate plays an important role in increasing ion productivity. Of course, there is a certain limit value of the permitted gas flow rate so as not to have a detrimental effect on reducing the vacuum in the cyclotron accelerator chamber. The operating vacuum level of a cyclotron is in the range of several 10^{-6} Torr, which can be experimentally determined as the maximum value of the gas flow rate.

3.3. Invention results

Based on the results are presented above, two key findings from this research can be summarized as follows: i) Changes in the gas flow rate, ranging from 3 sccm to 8 sccm, do not affect the characteristics of ionization power; and ii) Although the characteristics of ionization power remain unchanged, theoretical analysis indicates a significant increase in ionization intensity due to the higher gas flow rate. The rate of ionization intensity due to the increase in gas flow rate.

4. CONCLUSION

The effect of variation in the rate of hydrogen gas injected into the ionization chamber does not appear to have any significant changes in the ionizing power value. However, there is a tendency to decrease the voltage with an increase in the gas injection rate based on the theoretical analysis of the theoretical formula due to the conductivity value that rises. Since the cathode current value is made constant, the increase in conductivity value causes a decrease in the cathode voltage value. However, the decrease in voltage value does not significantly affect the rate of ion formation in the ionization chamber. Based on further analysis, the effect of increasing the gas flow rate will have a significant effect on the rate of the ionization intensity rate due to the effect of a significant increase in gas pressure from an increase in the gas flow rate.

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AUTHOR CONTRIBUTIONS STATEMENT

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Dwi Satya Palupi	✓					✓				✓		✓		
Taufik	✓	✓				✓				✓				
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Fajar Sidik Permana		✓			✓		✓		✓					
Suharni		✓				✓			✓				✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

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.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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