Analytical formulation of relationship between ionization current and extracted ion beam current in a Penning ion source

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ABSTRACT

A study on the performance of the Penning-type internal ion source of the DECY-13 cyclotron has been conducted to evaluate the relationship between cathode current and extracted ion beam current, as well as the stability of the extracted beam. The DECY-13 cyclotron, developed at the Research Center of Accelerator Technology, BRIN, is designed to produce 13 MeV protons for radioisotope production. In the experiment, the cathode current was varied between 200–400 mA, while the magnetic field and extraction voltage at 1.25 T and 3 kV, respectively. The results indicate a clear power-law dependence between cathode current (I_c) and extracted beam current (I_{ext}), expressed as $I_{ext} = 343.8\, I_c^{1.42}$. This relationship suggests that ionization efficiency increases sharply with cathode current. Stability tests at 400 mA cathode current showed that the extracted beam current remained stable at ~70 μA over 45 minutes, with only minor fluctuations. These findings demonstrate that cathode current is an effective parameter for controlling extracted beam current. The results contribute to a better understanding of ion source behavior in cyclotron systems and provide a foundation for further optimization of Penning ion sources for radioisotope production.

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1. INTRODUCTION

A cyclotron-type particle accelerator device has been installed at the Research Center of Accelerator Technology, Research Organization of Nuclear Technology, National Research and Innovation Agency of Indonesia (BRIN). The device is the result of design development carried out by researchers, engineers, and functional personnel at the BRIN nuclear facility. The cyclotron, designated as DECY-13, Design of Experimental Cyclotron in Yogyakarta, derives its name from the fact that the produced protons possess an energy of 13 MeV. The purpose of the construction of the cyclotron is for experimental facilities in the production of radioisotopes used for diagnosis with the positron emission tomography (PET) technique.

The proton produced comes from a Penning-type internal ion source that produces negative hydrogen ions (H^-), then accelerated by the RF dee system to an energy of 13 MeV. At the end of acceleration, the ion is passed into a carbon foil, and a stripping process occurs in which two electrons of the H^- ion are released, and the ions are converted into protons. The proton beam is then bombarded at the target in the context of a radioisotope production experiment [1].

Penning ion sources have the advantages of a simple structure and convenient operation, and are widely used in many compact accelerators such as cyclotrons [2], and an extremely compact and easily changeable ion source which could be installed in the central region of compact medical cyclotrons [3]. For the operation of a cyclotron, the performance of the ion source, which is the "heart" of the cyclotron, needs to be studied. The performance of the ion source consists of output factors and factors that influence the output. Output factors include the value of the extracted ion beam current [4], ion composition [5], and stability [4]. The output factors that are easy to measure are the magnitude of the extracted ion beam current and its stability. Factors that influence the output value are generally the cathode voltage, which is affected by the cathode current, the ionized gas flow rate, and the magnetic field intensity [6]–[9]. The gas flow rate and magnetic field intensity are usually set at fixed values. Therefore, what will be studied through this experiment is the relationship between variations in the cathode current and the ion beam current. The operating time factor on the beam current stability will also be observed. The data obtained from these relationships are then processed to obtain analytical formulations.

Many reference search results have been obtained regarding the observation of the characteristics of the relationship between the input and output variables of ion sources through ionization process experiments reported by the authors through different experiments [6], [10]–[13]. For the extraction process, Yang *et al.* [12] have observed the relationship between the gas flow rate and the extraction voltage to the extracted beam current. Vybin has conducted experiments on the relationship between the geometry of the extraction components and the extracted ion beam current [14]. Then, Xu *et al.* [15] have conducted experiments on the relationship between the cathode voltage and the beam current. Murtaza *et al.* [16] have conducted an experiment on the relationship between the gas flow rate and the extraction voltage to the extracted beam current. Analytical formulations for ionization and extraction processes based on theoretical predictions have been proposed by Lobov *et al.* [17]. Collectively, these studies demonstrate that the performance of ion sources has been extensively characterized through experimental and theoretical investigations of ionization and extraction processes. However, the problem is that there is no prior experimental observation of the relationship between the cathode current and the extracted beam current. And also, none of the observers has made an analytical formulation based on experimental data of the relationship.

This paper discusses the results of the observation of the relationship and presents its analytical formulation. This is where the contribution of this study lies in the analytical formulation based on experimental data in the form of a power-law formulation that will enrich the study of the performance of Penning ion sources for cyclotrons. This represents a novelty compared to previous studies of the relationship between cathode and extracted ion beam currents. As an additional enrichment of the study, the stability of the extracted ion current values as a function of time will be observed. This experimental study is expected to facilitate improvements in the performance of Penning-type ion sources used in cyclotron systems. Although this study uses the ion source on the DECY-13 cyclotron as its object, it can also be applied to other cyclotron facilities with similar systems, and this has been proven by its application to the ion source of the Eclipse cyclotron at Dharmais Hospital. A stability analysis of the extracted ion beam current is also presented.

The important significance of the results of this study is that it can support the process of optimizing operations in medical cyclotron facilities. On a national scale, this research program supports the national research program managed by the Indonesian National Research and Innovation Agency. The program, called Accelerator Technology for Medicine and Industry, aims to develop and utilize particle accelerator technology to support strategic medical and industrial applications.

2. METHOD

2.1. Experimental device

The main components of the cyclotron are the ion source, magnets, vacuum tank and dee. In the DECY-13 cyclotron, a Penning-type ion source supplies a beam of H^- ions into a cyclic accelerator system, namely a magnet and a dee device. The vacuum tank is operated up to several orders of magnitude times 10^{-6} Torr. An illustration of the ion source placement in the cyclotron system is shown in Figure 1.

Penning ion sources operate with hot or cold cathodes to generate high-voltage plasma discharges and low gas pressures. Their construction configuration consists of two plate-shaped cathodes, a cylindrical or ring-shaped anode, and a cathode housing. The ionization process diagram in a Penning ion source is shown in Figure 2 [18] (with modification).

A voltage difference of several kV is applied between the cathode and anode to cause electron discharge from the cathode to the anode. Electrons released from the cathode are attracted to the anode, but most do not attach to the anode but drift within the cylindrical or anode ring chamber towards the other cathode. This other cathode repels the electrons back towards the anode, and this continues so that the electrons oscillate within the anode chamber. The oscillatory motion of the electrons will form a plasma due to the collision of molecules and gas atoms introduced into the anode chamber. An axial magnetic field is applied to the anode chamber, which will create a spiral motion of the electron oscillations and this increases the ionization rate within the anode chamber [19], [20].

The cathode current, which is symbolized on the meter Ⓘ in Figure 2, comes from the components [2], [21]–[23]:

a) Primary electron current generated directly from thermionic emission at the cathode; this current trigger initial ionization.
b) Secondary electron current generated when positive ions strike the cathode.
c) Positive ion current impacting the cathode.

In the case of hydrogen gas supplied into the ionization chamber from an ion source, H^+ ions and H^- ions will be formed. H^+ ions are formed due to ionization due to electron collisions. Meanwhile, the formation of negative hydrogen ions H^- occurs due to the process of attaching electrons with lower energy to the H atom. The formation of other negative hydrogen ions H^- comes from the process of high-energy electrons that excite the energy of H_2 molecules then excited H_2 is dissociated by low electrons and H^- ions are formed. The H^- ions are then extracted out by a positive polar extraction voltage [20]. The ions are captured by the collector, and the current is measured with a current meter.

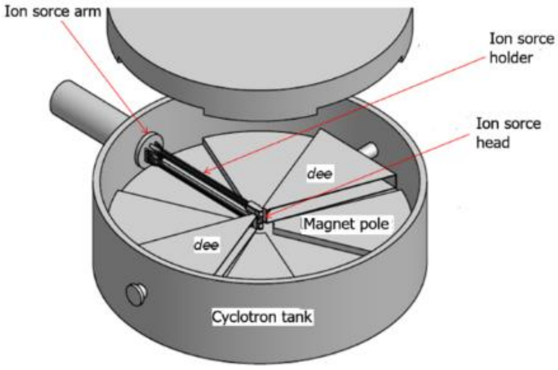

Figure 1. Schematic of a cyclotron showing the placement of its ion source

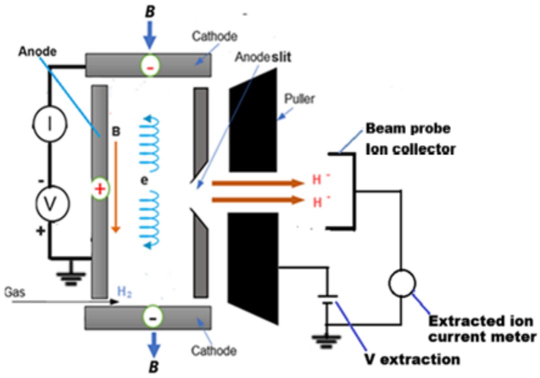

Figure 2. Scheme of Penning ion source and extraction device, which is used to observe the effect of operating parameters on the extracted ion current

2.2. Experiment setup

Experimental measurements were carried out within the cyclotron vacuum chamber to evaluate the performance of the ion source and the stability of the extracted ion beam output. Furthermore, the influence of the cathode current and other operating parameters on the extracted ion beam current was systematically investigated to determine its effect on beam performance and operational consistency. The configuration of the observation components used in these measurements is illustrated in Figure 3, which depicts the arrangement of instruments employed for data acquisition and analysis. The operating parameters of the Penning-type ion source are shown in Table 1.

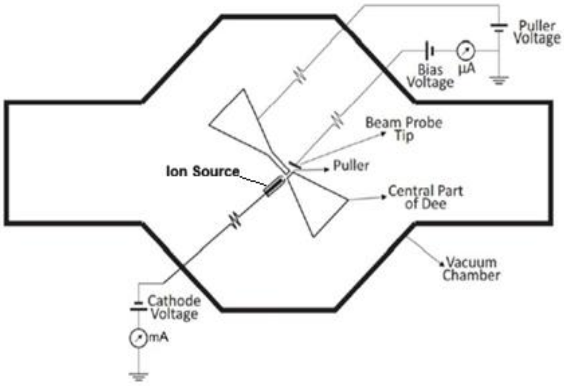

Figure 3. Scheme of beam extraction experiment, as a more realistic depiction of the scheme in Figure 2

The gas flow rate determines the number of molecules ionized, thus affecting the ionization intensity. The magnetic field and cathode current determine the path length of the ionizing electrons and the number of ionizing electrons, both of which determine the ionization intensity and ultimately affect the ion current extracted from the ionization chamber. The extraction voltage draws the ions from the ionization chamber, thus significantly determining the extracted ion current.

Table 1. Operating parameters of Penning ion source

No	Parameter	Type	Notation	Unit
1.	Gas flowrate	Input	Q	Sccm
2.	Extraction voltage	Input	V_{ext}	kV
3.	Magnetic field	Input	B	T
4.	Cathode current	Input	I_c	mA
5.	Extracted ion current	Output	I_{ext}	μA

2.2.1. Observation on variations of extraction voltage and magnetic field on ion source performance

The effect of variations in operating quantities on the output performance of the ion source also needs to be observed. This is important to ensure that the ion source's operational performance is suitable for the primary observation, namely, the relationship between the cathode current and the extracted ion current. Variations in extraction voltage were observed for their effect on the extracted ion beam current using a gas flow rate of 7 sccm, a magnetic field of 1.25 T, and a cathode current of 200 mA. Variations in magnetic field were observed for their effect on the cathode current using a gas flow rate of 9 sccm.

2.2.2. Observations on the stability of the extraction ion beam current

When observing the output characteristics of a system, it is important to first observe the stability of the output. Therefore, observing the relationship between the cathode current and the extracted ion beam current will be preceded by observing the stability characteristics of the extracted beam current as a function of time. These preliminary observations will be carried out at a cathode current of 400 mA, a gas flow rate of 7 sccm, a magnetic field of 1.25 T, and a source-puller gap of 3 mm. Observations with variations in the extraction voltage are carried out in the range of 0 to 3 kV, and stability observations over a time range of up to 45 minutes.

2.2.3. Observation on the effect of cathode current on the extracted beam current

In this step, the gas flow rate was set at 7 sccm, the extraction voltage from the puller was 2.5 kV, and the magnetic field from the cyclotron was 1.27 T. The cathode current was varied from 200 to 400 mA, and the extracted ion beam current was observed on the beam probe. The observation data were then presented in the form of a relationship between the extracted ion current as a function of the variation in the cathode current magnitude. Furthermore, the data were analyzed by presenting them in a curve, and the analytical formulation of the relationship between the two quantities was presented.

The formulation is based on processing experimental data on the relationship between the cathode current (I_c) and the extracted ion beam current (I_{ext}). Experimental observations show that changes I_c have significant effect on I_{ext} and that I_{ext} is zero when I_c is zero, then the relationship between the two quantities can be assumed to follow a simple mathematical equation, as (1).

$$y = b \times x^a \tag{1}$$

Where y represents I_{ext} and x represents I_c, and b and a are both constants that can be positive or negative. The next step is linearization by modifying the equation to (2).

$$\ln(y) = a\ln(x) + ln(b) \tag{2}$$

The (2) is a linear function with the independent variable being ln*(x)* and the dependent variable being ln*(y)*. If there are n data sets of a relationship between x and y, the constants a and ln *(b)* can be determined with the help of linear regression as presented in (3) and (4) [24], [25]:

$$a = \frac{n(\sum \ln(x)\ln(y)) - (\sum \ln(x))(\sum \ln(y))}{n(\sum ln(x)^2) - (\sum ln(x))^2} \tag{3}$$

and

$$\ln(b) = \frac{(\sum \ln(y) - a\sum \ln(x)}{n} \tag{4}$$

The analytical formulation of the regression results will be measured for their level of agreement with the measured data. The value used to assess this is the coefficient of determination, symbolized by R^2. Based on (2), the value of R^2 is as (5).

$$R^2 = 1 - \frac{\sum(Y_i' - \hat{Y}_i')^2}{\sum(Y_i' - \bar{Y}_i')^2} \quad (5)$$

With $Y_i' = \ln(y_i)$, is the value of log transformation ; $\hat{Y}_i' = \ln(\hat{y}_i) = \ln(b) + a\ln(x_i)$, is the value of model prediction and $\bar{Y}_i'$ is an average of all Y_i'. The value of R^2 in the range of $0 \leq R^2 \leq 1$, and its value is interpreted as the proportional reduction in total variation associated with the use of variable x. Therefore, the greater the R^2, the greater the reduction in total variation in y [26].

2.2.4. Validation of analytical formulation results

The analytical formulation results obtained in subsection 2.2.3 were then validated against observations at the Penning-type ion source of the 11 MeV Eclipse cyclotron at Dharmais Hospital, Jakarta. The observations at the Eclipse cyclotron ion source used a much higher extraction voltage of approximately 14.5 kV. This validation process will also define the validity range of the analytical formulation generated in subsection 2.2.3.

3. RESULTS AND DISCUSSION

3.1. Variations of extraction voltage and magnetic field on ion source performance

The observation results of the relationship between the variation of the extraction voltage and the extracted ion beam current are shown in the curve of Figure 4. It can be seen in the figure that the curve does not fully follow the Child-Langmuir law, namely, the relationship between the two is in the form of a power of 3/2, but approaches a linear form or a power of 1. This can be caused by the fact that at low extraction voltage and low extraction current, the ions do not start from zero potential but from a plasma meniscus whose shape depends on the extraction current. If the voltage is increased, the shape of the meniscus changes so that the power function of the voltage will increase towards the value of 3/2. However, these observation results are sufficient to provide confidence in the existence of an extracted ion current, which is then used to observe the relationship between the cathode current and the extracted ion beam current.

The effect of variation of the magnetic field on the cathode current is shown in Figure 5. The results indicate that the variation of the magnetic field at the operational magnetic field value of the DECY-13 cyclotron, which is around 1.2 T, has no effect on the cathode current value. This provides a strong suspicion that the variation of the magnetic field in this range also has no effect on the characteristics of the extracted ion current.

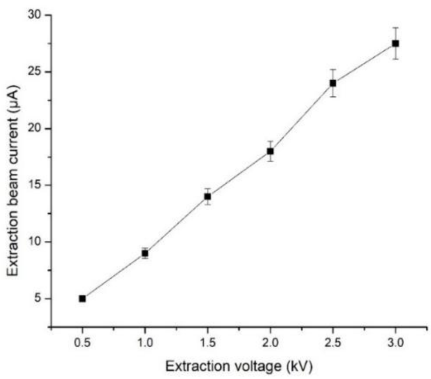

Figure 4. Effect of variation of extraction voltage on extracted ion beam current

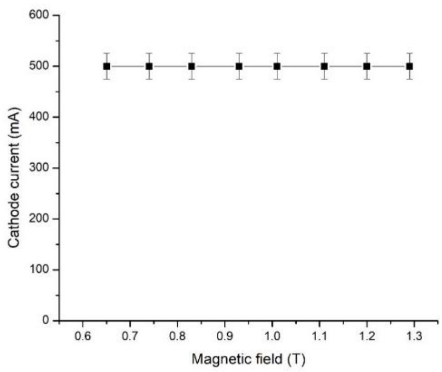

Figure 5. Effect of magnetic field on cathode current

3.2. Stability of extracted ion beam current

The experimental results in observing the stability of the extracted ion beam current are shown in Figure 6. The results show that the stability can be categorized into three phases. The first phase, in the first 30 minutes, is the stable phase where the current is constant at 70 µA, suggesting that the ion source operates in a stable regime without significant fluctuation. This indicates good discharge stability and consistent extraction efficiency. Then in the 35th minute, a small decrease to 68 µA may reflect minor instabilities in the plasma, cathode heating effects, or slight variations in chamber conditions (e.g., pressure, temperature, and power supply). Finally, at the 40th minute is the recovery phase, where the rise to 72 μA indicates the source returns to stable operation, with a slight improvement over the initial value. This could be due to better plasma equilibrium after longer operation (conditioning effect of the cathode or chamber walls). Overall, the stability shows minimal variation (only ±2 μA from the baseline of 70 μA), indicating that the ion source maintains good long-term stability over the 45-minute period.

A brief overview of the trade-offs in the performance test results of this ion source can be summarized as follows. The ability to generate an extracted ion current of up to 300 microamperes can be achieved with an high stability. The stability value is calculated using the formula: $stability = \left(1 - \frac{\sigma}{x_{ave}}\right) \times 100\%$ with $\boldsymbol{\sigma}$ is deviation standard. Using numerical data of Figure 6, the calculated stability coefficient value is 98.3% or the variation coefficient is 1.7%. This value indicates a balance between the magnitude of the ion current and the stability level. Given the complexity of the design for increasing the ion beam current, this will be a future design development.

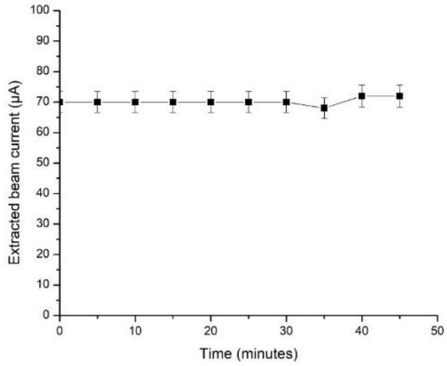

Figure 6. Stability of extracted ion beam current shows stable operation with only ±2 μA variation, confirming reliability

3.3. Effect of cathode current on extracted beam current

Experimental data on the relationship between cathode current and extracted ion beam current are shown in Table 2. If the values in Table 2 are denoted as *x* for the cathode current and *y* for the extracted beam current, and processed using (1) to (4), the following results are obtained:

$$a = \frac{n(\sum \ln(x)\ln(y)) - (\sum \ln(x))(\sum \ln(y))}{n(\sum ln(x)^2) - (\sum ln(x))^2}$$
$$= \frac{5(-24.79) - (-6.17)(20.43}{5(7.91) - 6.17^2}$$
$$\frac{-123.95 + 126.053}{39.55 - 38.07} = \frac{2.1}{1.48} = 1.42$$
$$\ln(b) = \frac{(\sum \ln(y) - a\sum \ln(x)}{n} = \frac{20.43 - 1.42(-6.17)}{5} = 5.84$$
$$b = e^{5.84} = 343.8$$

According to the calculation result of *a* and *b* values above, (1) will be (5).

$$y = 343.8x^{1.42} \tag{5}$$

Then, the relationship between the cathode current and extracted beam current is as (6).

$$I_{ext}(extracted\ ion\ current, \mu A) = 343.8 \times (I_c)^{1.42}(cathode\ current, \mu A) \tag{6}$$

The measurement data and analytical data are shown in Table 3 and in Figure 7.

The curves show that increasing cathode current generally increases extracted ion current, but the effect is strongest in the 200–300 mA range. Beyond ~350 mA, saturation tendencies appear, suggesting the system's maximum ion extraction capacity is being approached at 2.5 kV extraction voltage. Future optimization could involve testing at higher extraction voltages or adjusting gas pressure to see if the saturation points shift.

Table 2. The experimental data on the relationship between cathode current and extracted ion beam current

No	Cathode current (x), A	Extracted beam current (y), μA	ln(x)	$\ln(x)^2$	ln (y)	ln(x)ln(y)
1.	0.20	30	-1.61	2.59	3.40	-5.47
2.	0.25	55	-1.39	1.93	4.01	-5.57
3.	0.30	75	-1.20	1.44	4.32	-5.18
4.	0.35	75	-1.05	1.10	4.32	-4.54
5.	0.40	80	-0.92	0.85	4.38	-4.03
Σ			-6.17	7.91	20.43	-24.79

Table 3. The experimental data on the relationship between cathode current and extracted ion beam current

No	Cathode current A	Measured extracted beam current, μA	Analytical extracted beam, μA
1.	0	0	0
2.	0.20	30	35
3.	0.25	55	48
4.	0.30	75	62
5.	0.35	75	77
6.	0.40	80	94

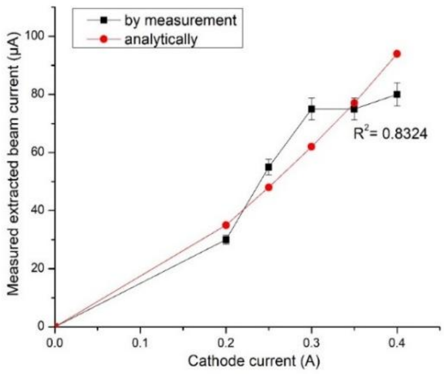

Figure 7. The extracted beam current as a function of the cathode current, at 2.5 kV puller voltage, 1.25 T magnetic field, and 7 sccm gas flow rate

The experimental investigation into the relationship between cathode current and extracted ion beam current reveals a clear power-law dependence. Based on the regression analysis, the best-fit correlation was found to be $I_{ext}(extracted\ ion\ current, \mu A) = 343.8 \times (I_c)^{1.42}(cathode\ current, \mu A)$, indicating a superlinear relationship where the beam current grows more rapidly than the cathode current in the lower current regime. This suggests that ionization efficiency within the discharge chamber benefits disproportionately from increases in cathode current, at least until saturation effects dominate. The results presented in this study directly address the research gap identified in the introduction. While no prior experimental observations or analytical formulations of the relationship between the cathode current and the extracted beam current had been reported.

The comparison between experimental and analytical results (Table 2) demonstrates good agreement in the 0.2–0.35 A cathode current range, with deviations appearing as the cathode current approaches 0.4 A. The experimental data indicate a tendency toward saturation around 75–80 μA of extracted ion current, whereas the analytical model continues to predict higher values (93.4 μA at the cathode current of 0.4 A). This discrepancy highlights the limitation of the fitted model when extrapolated beyond the optimal operating window. Physically, the saturation behavior may be attributed to space-charge effects, limited ionization cross-section under the fixed 2.5 kV extraction voltage, or constraints imposed by the plasma density and confinement at 1.25 T magnetic field strength.

An important strength of this study is the quantitative comparison between measured data and analytical predictions, allowing for evaluation of model validity across a range of operating parameters. The regression method using logarithmic linearization was appropriate and yielded interpretable scaling coefficients. From a practical perspective, the results imply that cathode current is an effective control parameter for optimizing extracted beam intensity, but only within a bounded operational range. The evidence of saturation suggests diminishing returns for cathode current values exceeding ~350 mA. Overall, the findings provide valuable insight into cathode–beam current dynamics in ion sources, and the derived power-law relation may serve as a useful predictive tool for beam current tuning, albeit with caution near the saturation regime.

In the extraction process in this experiment, because the puller voltage is positive, only negative ions are extracted from the plasma chamber. The ion species that may be formed are e, H^- and H_2^-. Because the mass of the electron is very small compared to the mass of the H ion, it will be deflected by the high-intensity magnetic field before reaching the current collector. The negative ion of H_2 can indeed be formed, but in an unstable condition and has a very short lifetime (10^{-10} to 10^{-8} seconds). This is because the H_2^- ion has two original electrons and one additional electron, and this additional electron has the property of breaking bonds, which makes the ion system unstable and disintegrates. In other words, the negative ions of H_2 are very rarely formed in the ionization process of hydrogen gas. In addition, this ion source is designed to produce H^- ions for use in the cyclotron. In the central region components of the cyclotron, a beam guide mechanism has been implemented to filter other ions, ensuring that only H^- are extracted.

3.4. Results of validation

The analytical formula has been tested on data from the ion source at the Dharmais cyclotron. The results show that for beam currents up to 350 µA (see Figure 8), the formula is still quite suitable for application. However, for beam currents above this value, the actual measured values are lower than the analytical formula values. This can occur due to the space charge effect on denser or higher ion beams.

3.5. Practical relevance

These results will impact more effective radioisotope production methods using cyclotrons. In this case, the radioisotope produced will be largely determined by the extracted beam current applied to the radioisotope production target. By understanding the relationship between the extracted ion current and the main input parameter, the cathode current, it will be easier to determine the required extracted ion current.

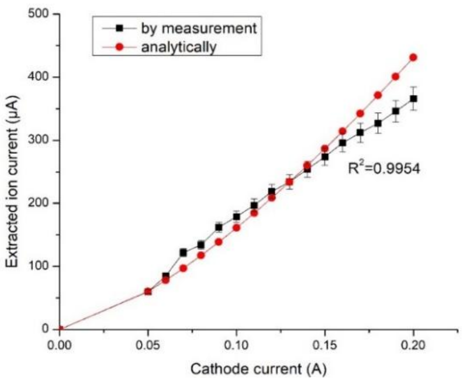

Figure 8. The relationship between the cathode current and the extracted ion current from the measurement results and the analytical formulation results at the Eclipse 11 MeV cyclotron ion source

4. CONCLUSION

This study experimentally established and validated a power-law relationship between cathode current and extracted ion beam current in a Penning ion source. Experimental observations of the effect of variations in extraction voltage indicate that extraction voltage (V_{ext}) is the dominant factor influencing the extracted ion beam current I_{ext}. The curve pattern of the relationship between the two quantities is produced as $I_{ext} \sim V_{ext}{}^{3/2}$ which is commonly found in ion sources. Meanwhile, variations in the magnetic field over the operational range of the DECY-13 cyclotron have a negligible effect on ion source performance. The extracted ion current remains largely stable at around 70 µA for 45 minutes of operation with only minor fluctuations, which has a stability of 98.3%. The brief dip at 35 minutes and subsequent recovery suggest minor transient effects rather than significant degradation. This demonstrates that the ion source is reliable for continuous operation, and any variations observed stay within acceptable limits for experimental stability. The study establishes a power-law relationship between cathode current (I_c) and extracted ion beam current (I_{ext}) and expressed as $I_{ext} = 343.8\, I_c^{1.42}$, confirming that increases in cathode current enhance ionization efficiency up to a saturation threshold. The analytical formula demonstrates good agreement with experimental data from the Dharmais cyclotron ion source for up to 350 µA of ion beam current. Beyond 350 µA, deviations occur as the measured beam currents become lower than the predicted values, likely due to space charge effects that become significant at higher ion beam densities. To extend the applicability of the analytical model, future work should examine a wider range of extraction voltages and gas pressures, as well as incorporate plasma diagnostics to better understand the mechanisms underlying the observed saturation.

The results of this study underline the practical usefulness of cathode current as a tuning parameter. These findings contribute to a deeper understanding of beam extraction behavior and offer a foundation for further refinement of ion source performance models. The relationship between the cathode current, also called the discharge current, that influence on the extracted ion beam current on the Penning ion source here include the cathode current, also called the discharge current. Practically, the results of this research will support effective efforts in the use of cyclotrons for the production of radioisotopes.

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AUTHOR CONTRIBUTIONS STATEMENT

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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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