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# Ion beam preliminary testing of DECY-13 cyclotron at the central region using dc extraction voltage

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**Abstract**. The subsystem devices of the DECY-13 cyclotron have been installed except the RF-dee device, so a final ion beam testing has not been tested for cyclically accelerated ion beam or ion beam commissioning. An initial or preliminary test of the ion beam has been performed, for preparing the final beam test. The preliminary test was carried out by measuring ion beam current in the central region of the cyclotron. The extraction of the ion beam from ion source is done by pulling the ion beam using a DC voltage of a puller mounted on a center part of the dee. The test was carried out by observing the effect of the magnitude of the cathode voltage, magnetic field and the puller voltage on the beam current that caught in a beam probe placed at a distance of 3 mm from the puller. The results of the ion beam test show that the degree of influence from the strongest is successively from the components of puller voltage, cathode voltage and magnetic field. The obtained largest ion beam current was 126 µA at the parameters of 0.86 T magnetic field, cathode voltage of 1200 V, 50 mA cathode current, 5 sccm gas flow rate, final vacuum of $8 \times 10^{-6}$ Torr and puller voltage of 2 kV. These results indicate that the initial ion beam current output qualifies for the steps toward the final test.

## 1. Introduction

Installation the DECY-13 cyclotron is now up to the stage where the magnet has been installed and integrated into the vacuum chamber, the Penning-type ion source also has been set in the cyclotron vacuum chamber. The cyclotron will accelerate $H^-$ ion beam until 13 MeV energy. The ion beam then extracted to be proton beam directed a target by using a carbon foil stripper. The vacuum chamber has been tested and a pressure is obtained by a vacuum of 7-8 $\times 10^{-6}$ Torr after a gas flow of 5 sccm, and this pressure already qualifies for ion source testing [1]. According to the measurements, the magnetic field in the central region is 1.275 T [2]. Previously, the ion source has been tested in an ion source testing device located out of the cyclotron, and the resulted ion beam current was 35 µA using 8 kV extraction voltage [3]. The ion source also has already been tested the ability of the vacuum, the movement mechanism to adjust the position of the head and is equipped with a hydrogen gas supply device. A center part of dee with a puller on it has also been set in the central region, and the puller is connected to a DC voltage supply.

A final testing of the ion beam *i.e.* testing by measuring ion beam in the target will be carried out when the RF-dee device is already installed in the cyclotron vacuum chamber. In order to prepare the final test an initial testing *i.e*. testing the ion beam in the central region of the cyclotron has been performed. The status of the DECY-13 Cyclotron where the devices have already been available as mentioned above is possible to test the ion beam production in the central region. This testing is called for preliminary testing of ion beam in the cyclotron central region using DC voltage. The testing consists of observing ion beam current related to the influences of the internal performance and the beam extraction efficiency.

The internal performance of the ion source is influenced by the power of ion source cathode *i.e.* voltage and current supply in the cathode, and gas pressure that depends on gas flow rate and cyclotron magnetic field. The extraction efficiency is determined by electrical optics between the ion source head and puller, which in this case is dominantly influenced by the puller voltage. In short, the production of the ion from ion source is influenced by cathode voltage, puller voltage, gas flow rate, and intensity the magnetic field [4]. Minimizing the parameters, in this experiments was limited to observe the influence of the cathode voltage, the magnetic field and the puller voltage. In this case the gas flow rate and the extraction gap (the distance ion source and the puller) were in constant value.

The cathode voltage determines the ion production in the ionization chamber, and the cathode normally. The cathode is normally powered by a -2 kV 2 A pulsed/DC power supply [5], and for the experiment purpose a DC power supply of 2.5 kV 3 A has been prepared. The performance of the Penning ion source in a cyclotron is strongly associated with the cyclotron magnetic field, in this case, the magnetic field used to confine the plasma in the ionization chamber of ion source so that the ionization process occurs be multiplied if compared with no magnetic field. Optimum operation of a Penning ion source of the cyclotron generally occurs in a magnetic field of several kilogauss [5-7]. A 1.25 Tesla magnetic field of the cyclotron is enabled for this purpose, though perhaps that based on the references mentioned above, the magnetic of the DECY-13 cyclotron is in the out of the optimum area. The results of the experiment in this paper will answer it. The puller voltage extracts out the ion beam from the ion source towards an ion collector for measuring ion beam current. The DC voltage could not exceed 2 kV, above the value, the corona on the extractor will occur and the collected negative charge signal increases to several mA quickly [6]. It is prepared a DC power supply that adequate for the puller voltage.

In this paper will be presented the results of an experiment of the characteristics of the ion source under the influence of some operating parameters that are mentioned above. The parameters in the experiments have not been set to the actual value as in the actual operation later. The results of the experiment will be able to predict the ability of ion sources in producing the ion beam current at the operating level during the actual operation of the cyclotron.

## 2. Experimental method

### *2.1 Experiment device*

The experimental device consists of an ion source, a cyclotron magnet, a central part of dee which installed a puller and beam current probe. The schematic of the experimental device focused in the central region of the cyclotron is shown in Figure 1.

The ion source is also equipped with a hydrogen gas supply component, completed by a smooth flow rate regulator and a monitoring gas flow rate. The magnetic field of the cyclotron magnet in a perpendicular direction to the drawing and can be varied up to 1.8 T. Ion beam extraction from the ion source is ruled by a puller mounted on a central part of the dee. The results of ion beam extraction were measured by using a movable beam probe connected to a microampere. The extractor and the beam should have the same potential, but they are insulated from each other [5]. This arrangement is to protect any ionization of the gas occurring between the puller and beam probe tip. The beam probe tip also emits electrons when the ions impact on it. However, given the strong magnetic field, they will probably not be able to escape from beam probe tip, so the beam intensity measurement will be fine [8].

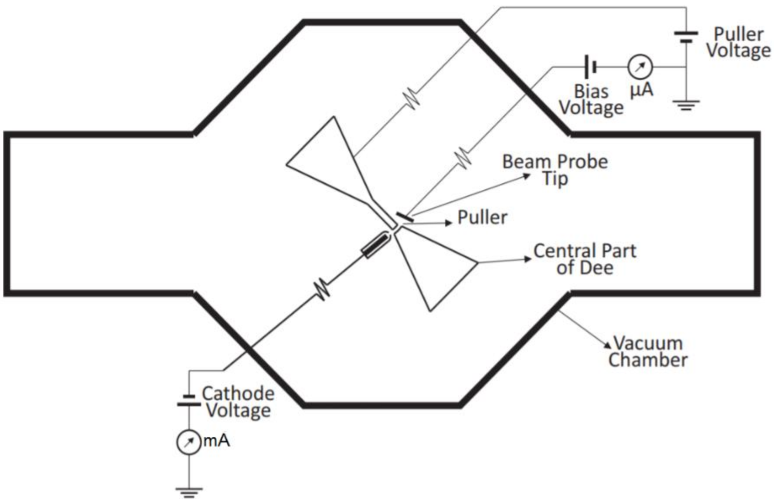


**Figure 1.** Schematic of the experimental device.

The radial position of extraction point or anode slit of ion source from the central region point is also fixed in advanced and determined by a formula:

$$r = \frac{1}{B}\sqrt{\frac{mV}{q}} \quad (1)$$

where $B$ is the magnetic field of cyclotron in the central region, $q$ is the charge of H- ions, $m$ is ion mass of $H^-$ and $V$ is the effective voltage of puller or dee (*i.e.* peak voltage divided by 1.4). By using equation (1) and by applying $B$ =1.25 T, $m$ = 1.67×10-27 kg, $V$ = 28 kV and $q = 1.6 \times 10^{-19}$ C, we obtained the radial position is 0.02 m = 2 cm. This radial position will be applied to determine an optimum value of the distance between anode slit and puller or extraction gap.

The optimization on the extraction gap has been carried out by using a program of Scilab 5.2.1 on the 2 cm radius from the center point of the central region. This program employed a Runge-Kutta numerical algorithm. This method was also performed in Korea for a cyclotron design by using the pwheel program [9]. The distance has varied in between 3 mm and 7 mm, and as a result that the best position of the ion source head in the 2 cm radius is at 4 mm to the puller [10]. This gap is not so much different to other common experiments [11-13].

*2.2 Experiment procedure*

The first and foremost precondition is a pressure in the vacuum chamber to approximate a pressure of 1-3 × 10-6 Torr and a hydrogen gas flow rate is set at 5 cc/min. The experiment is started with observing the influence of magnetic field to ionization intensity in the ion source (*i.e.* the measured cathode current) in the varying of cathode voltage. From these results, then will be determined the feasible value or value area of the cathode voltage and the magnetic field. By using these feasible values then the influence of the cathode voltage, the magnetic field and the puller voltage on the ion beam current will be observed.

*2.2.1. Observation of the influences of the magnetic field and the cathode voltage on the intensity of ionization.* The intensity of ionization is indicated by the intensity of the cathode current. In this observation the puller voltage remains 0 V, the cathode voltage as a parameter with the values of 700 V to 1500 V; the value of the magnetic field is varied and cathode currents are measured for each value of the cathode voltage. The magnetic field strengths approximately of 0.2 to 1.3 T are preferred. These experiments will result two things. First, the influence of the cathode voltage and the magnetic field against the ionization intensity will be characterized. Secondly, the best values or feasible values of the cathode voltage and the magnetic field on resulting the intensity of ionization will be determined.

*2.2.2. Observation of influence of the cathode voltage on the ion beam current*. This experiment and subsequent experiments are carried out by measuring the ion beam caught in the ion beam collector. This observation will explain whether the effect of the cathode voltage on the ionization intensity will has same effect on the extracted ion beam current. By using feasible value range of the cathode voltage and the optimum value of the magnetic field those are resulted in the observation 1 above, that effect will be observed.

2*.2.3. Observation of influence of the magnetic field on the ion beam current.* The best value of magnetic field with regard to the cathode voltage and the optimum value of extraction gap will be applied to observe the influence of the puller voltage on the ion beam current. Similar to the observation 2 above, this observation will explain whether the effect of the magnetic field on the ionization intensity will has same effect on the extracted ion beam current. The puller voltages of 0 to 3 kV have been applied to pull the ion beam from the ion source.

*2.2.4. Observation of influence of the puller voltage on the ion beam current*. All results of above experiments above will be referenced in this experiment i.e. the best or feasible values of the cathode voltage and the magnetic field.

## 3. Results and discussion

*3.1. The influence of magnetic field and the cathode voltage on the intensity of ionization*
The measurement data of cathode current as an effect of magnetic field on the variation of the cathode voltage are shown in the Figure 2.

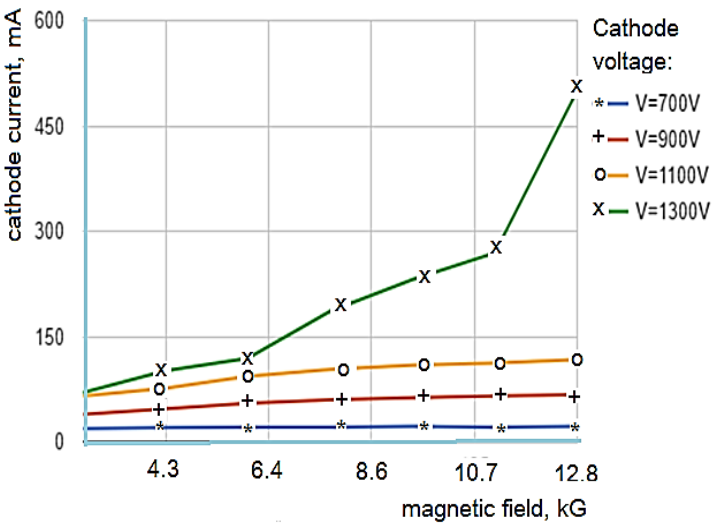


**Figure 2.** The influence of the magnetic field on the cathode current.

In this experiment, it is obtained that the cathode current increases sharply on the cathode voltage of 1300 V, but in this experiment did not set up a cathode voltage more than 1300 V because the cathode current was not stable and even at 1500 V the current meter was burnt. It is shown clearly that feasible operation of the cathode voltage to get high an ionization is beyond 1300V, and the magnetic field is higher than 4 kG. In this feasible range of the cathode voltage, the influence of the magnetic field is not very sharp.

### *3.2. The influence of the cathode voltage on the ion beam current*

The data in Figure 2 shows that at around 6 kG or 0.6 T, the increase of the cathode voltage results in a significant increase of the cathode current. An expected logical result is that it will also result in a significant increase of ionization intensity in the ionization chamber and then result in a significant increase of the ion beam current. The results that are shown in the following Figure 3 will confirm that expectation. The voltage was limited to 1200 V because on 1300 V the voltage source was not stable caused by instability in plasma.

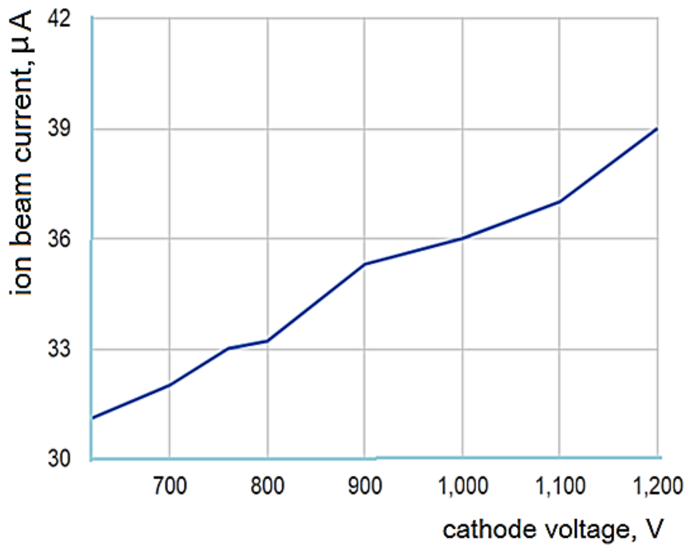


**Figure 3.** Influence of the cathode voltage on the ion beam current.

In Figure 2, the ratio of the cathode currents in the cathode voltages of 1100 V and 700 V is about 4; but in Figure 3 the comparison of the ion beam currents in the same cathode voltage range is only about 1.2. It means that the increase of ion beam current is not as strong as the increase of the cathode current or it means that increase of the ionization intensity is not effect linearly to the ion beam current. This phenomenon can be explained that due to $H^-$ ions are formed by low energy electron in the plasma [14], while the increase of the cathode voltage will raise the electron energy and then raise the ionization intensity but not so much raise the low energy electron in the plasma.

### *3.3. Influence of the magnetic field on the ion beam current*

Observation of influence of the magnetic field on the beam current was done on the cathode was 1200 V 50 mA, hydrogen gas flow rate was 5 sccm and the final vacuum was $8\times10^{-6}$ Torr. The result is showed in Figure 4.

The ion beam current can start being observed at the magnetic field of 0.4 T and increasing slowly along with the rise of the magnetic field. The magnetic field of DECY-13 Cyclotron will be set at 1.25 T, and from the numerical data obtained, the beam current value can be extrapolated as 135-140. In general, however, the change of the ion beam current is not so high with increasing of the magnetic field. This result also accordance with the experiment by Long *et al.* [6], which no significant influence of the magnetic field on the ion beam current when experiment is done at several kilogauss.

### *3.4. Influence of the puller voltage on the ion beam current*

The experiment was prepared on a relatively flat area of magnetic field in accordance with the curve in Figure 4 and in this case a 0.8 T was applied. The cathode was set at the maximum safe value, which in this case, was 1200 V, and this voltage resulted in a 50 mA cathode current. The puller voltage was varied and the ion beam current was measured. The result of relationship of both as shown in Figure 5.

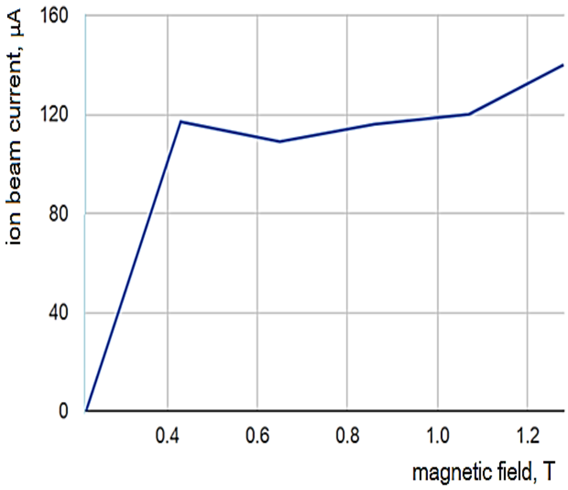


**Figure 4.** Influence of the magnetic field on the ion beam current.

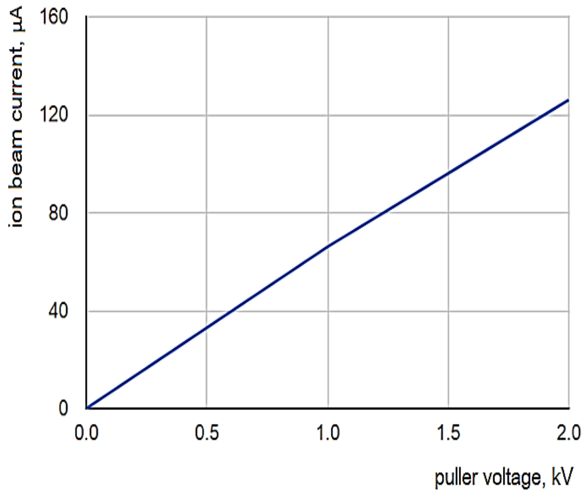


**Figure 5.** Relationship between the puller voltage and the ion beam current.

The observation was limited to 2 kV puller voltage because at a voltage of 2.5 kV the beam current rose to a very large value. This is in accordance with the experiment carried out by Long *et al.*, that above the 2 kV voltage the ion beam increases to several mA quickly caused by a corona occurring on the puller [6]. Normally, the curve of ion beam current versus puller voltage is proportional to the power of 3/2 [15, 16], but the curve in Figure 5 shows a linear relationship. It can be understood because the voltage is still in low value so it is not yet apparent a curve of power 3/2. A numeric data that is applied to make the curve above show that a maximum ion beam current is 126 μA.

The designation in Figure 3, Figure 4 and Figure 5 show that the puller voltage is most instrumental in influencing the ion beam current, then the cathode voltage and the magnetic field in the last rank. It means that the stability of the voltage source will be most noticed, and in the future when the cyclotron will be tested by the dee voltage, the stability of the RF system must be guaranteed. Although the cathode voltage and the magnetic field have a lower ranking, they must be also be noticed well because both of them have an important role in the plasma formation in the ion source.

These results have not yet figured a final performance of the ion beam current in the cyclotron central region. A stability of operation parameters has not been observed that perhaps can influence to the ion beam performance. In the next experiment will be studied more in depth and more detail regarding the stability problem, and efforts to overcome the stability problem will be done. However, the results of these experiments can indicate an existence of a function of the DECY-13 cyclotron components, especially its function in resulting the internal ion beam current.

As far as the authors know, another testing of ion beam current in the cyclotron central region using DC voltage is not yet carried out. The experiment of Long *et al.* that attained 200 μA using 2 kV puller voltage and the magnetic field of several kilogauss, was carried out in the bench testing out of the cyclotron [6]. The experiment of Jung *et al.* from SKKUY-9 Compact Cyclotron (Korea) obtained an $H^-$ ion beam of 98 μA at a radius position of 1 MeV energy [17], it means that they have been using a RF dee voltage. Compared to those two experiments, the ion beam current of 126 μA on this experiment seems lower. Efforts will be made to increase the beam current, one of them is looking for an optimum value of the gas flow rate but still maintaining the vacuum on feasible value.

## 4. Conclusion

The preliminary testing of the ion beam for preparing a final test in DECY-13 Cyclotron has been carried out. The testing was carried out in the central region of the cyclotron using DC voltage extraction of the puller. The results of the experiment show an existence of a function of the DECY-13 cyclotron components. The obtained highest value of the $H^-$ ion beam current is 126 μA using 2 kV puller voltage, and efforts are still needed to increase this current by optimizing operation parameters.

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**References**

[1] Abdessalam F W Abdelrahman M M Soliman B A and Basal N I 2013 *Phys. Rev. & Resear. Int.* **3(4)** 427
[2] Taufik T Hermanto A Anggraita P and Santosa S 2014 *Atom Indonesia* **40** 70
[3] Silakhuddin S Santosa S 2015 *Atom Indonesia* **43** 139
[4] Wang Z Yang P Dong *et al*. 2012 *Rev. Sci. Instrum*. **83** 063302-1
[5] Yang Z Long J D Dong P *et al* 2012. *Chinese Phys. C (HEP & NP)* **36** 100-1003
[6] Long J Yang Z Dong P *et al.* 2013 *Nucl. Sci. Tech*. **24** 040201-3
[7] Yeon J H Kim H S Gad K M *et al.* 2013 *Proc. of Cyclotrons* 197
[8] Obradors D Ahedo M B Arce P *et al.* 2017 *Proc. of IPAC* Copenhagen Denmark
[9] Anggraita P Mulyani E and Kudus I A 2015 *Atom Indonesia* **41** 146
[10] Silakhuddin S Kudus I A 2017 *Atom Indonesia* **432** 85
[11] Oliver C Abramian P Ahedo B Arce P 2013 *et al. Proc. of Cyclotrons* Vancouver BC Canada
[12] Minervini J V 2012 *Technical Report Publishing of Defense Threat Reduction Agency USA*
[13] Mu X J Ghergherehchi M Yeon Y H *et al.* 2014 *Chinees Phys.* C **38** 127004-5
[14] Korenev S 2013 *Proc. of Cyclotrons* Vancouver BC Canada
[15] Eisa M E M Conradie J L and Cellier P J 2013 *World J. of Nuclear Sci. and Tech.* **3** 85
[16] Faircloth D Lawrie S Gabor C Letchford A *et al*. 2012 *Rev. Sci. Instrum*. **83** 02A701-2
[17] Jung S Y Kim H W and Ghergherehchi M 2014 *J. of Instrum.* **9** T04005-11