ISBN: 978-3-95450-212-7 ISSN: 2673-5482 doi:10.18429/JACoW-CYCLOTRONS2022-MOP0013

EXPERIMENTAL STUDY OF BEAM ENERGY CONTROL AT THE TIARA AVF CYCLOTRON

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Abstract

The TIARA AVF cyclotron provides a helium (He) beam for producing ^{211}At, as one of its many beam applications. The generation rate of ^{211}At increases with the energy of the He beam. However, contamination of ^{210}Po produced by the radioactive decay of ^{210}At, which is generated by energy above 29 MeV, must be prevented for medical applications. Therefore, the energy of the He beam must be precisely measured and controlled. A time-of-flight beam energy monitor was installed in the direct beamline from the cyclotron to measure the beam energy in real-time. The cyclotron magnetic field and accelerating voltage, which are two potential causes of the beam energy change, were arbitrarily adjusted within a range of around 1%. With this control, the generation rate of ^{211}At and ^{210}At was investigated as the beam energy was varied. The results showed that the cyclotron parameters were easily controlled to the optimum beam energy that increased generation rate of ^{211}At and did not produce ^{210}At.

INTRODUCTION

The azimuthally varying field (AVF) cyclotron with a K number of 110 MeV in an ion beam irradiation facility, Takasaki Ion Accelerators for Advanced Radiation Application (TIARA) provides various ion beams from 10 MeV H^+ to 490 MeV Os^{30+} for experiments in the field of materials and biotechnology research, etc. [1]. To produce RI, light ion beams such as proton and helium (He) are mainly used. Recently, ^{211}At (half-life, 7.2 h) is produced for alpha nuclear medicine therapy research using the He beam accelerated by the TIARA AVF cyclotron. The production of ^{211}At uses the nuclear reaction of ^{209}Bi (α, 2n) ^{211}At. The ^{211}At yield in this nuclear reaction increases up to about 30 MeV in the injection energy of the He beam into the Bi target [2]. On the other hand, the nuclear reaction of ^{209}Bi (α, 3n) ^{210}At produces ^{210}At (half-life, 8.1 h) when the injection energy of the He beam into Bi surpasses 29 MeV. ^{210}At is chemically inseparable from ^{211}At, and radioactive decay produces ^{210}Po (half-life, 138 d), which is highly toxic [3]. Given that ^{210}Po has a longer half-life than that of ^{211}At, this poses the problem of being left as an impurity, such as in the case of drugs manufactured for clinical use. Therefore, for the mass production of ^{211}At, it is necessary to increase the intensity of the injection beam and precisely control the beam energy near the upper limit, wherein ^{210}At is not generated.

A precise bending magnet with beam slits installed in front of and behind it can be used to quantify the energy of the beam accelerated by the TIARA AVF cyclotron. However, this method cannot supply the beam to the RI production equipment installed in the beamline located straight from the cyclotron. Moreover, it was difficult to pass the beam through the slits before and after the magnets in a short time when parameters such as the magnetic field were changed in the cyclotron to fine-tune the beam energy. Therefore, a beam energy and position monitor (BEPM) system [4] was installed on this linear beamline to allow real-time measurements without blocking the beam. A BEPM can measure changes in beam energy due to changes in the cyclotron parameters in real-time. The generation rate of impurity-free ^{211}At can be maximized by controlling the He beam energy near the upper limit, where no ^{210}At is produced, based on the beam energy measurement using the BEPM. Therefore, the beam energy was measured using the BEPM to investigate the relationship between the cyclotron parameters and the beam energy and the variation of the beam energy from experiment to experiment.

In this study, we give an overview of the BEPM and the measurement results of the beam energy for each experiment and describe the beam-energy change measurement results using the Dee voltage and magnetic field used to tune the cyclotron. Additionally, the generation rate results from the measurement of ^{211}At obtained by irradiating the Bi target with the beam energy changed by the cyclotron tuning are described.

BEAM ENERGY MEASUREMENTS

Measurement Method

As shown in Fig. 1, RI production for the TIARA cyclotron is performed in the RI production equipment located at the end of the linear beamline from the cyclotron exit.

A precision-bending magnet (TAM) installed in this beamline deflects the beam to supply other experimental ports and measures the beam energy. However, when the beam energy to be supplied to the RI production system is measured using the TAM, irradiation for RI production cannot be performed for about 1 h because of the excitation and demagnetization of the TAM, beam energy measurement, and further beam transport adjustments. Therefore, a BEPM system was introduced to obtain the beam energy in real-time by measuring the time-of-flight of the beam bunch passing through the two pickup electrodes.

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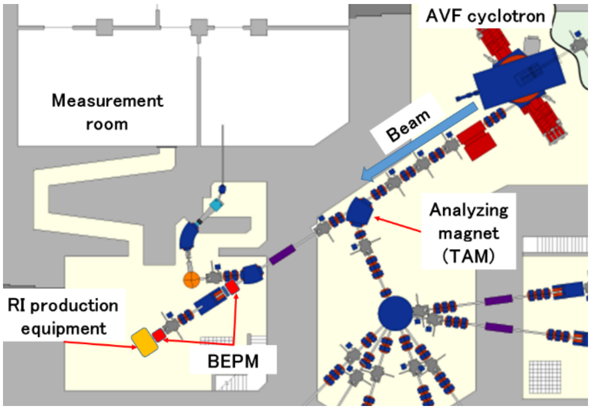

Figure 1: Schematic layout of the TIARA AVF cyclotron and beam transport line for RI production. BEPM electrodes are installed at two locations in the beamline. For applications other than RI production, the beam is deflected by the TAM.

The BEPM pickup electrodes shown in Fig. 2 were installed at two locations in the beamline from the cyclotron to the RI production system. To measure the beam position, the pickup electrodes are divided into four sections. A total of eight signals from the pickup electrodes are each amplified by an amplifier and then transmitted by coaxial cable. In the measurement room, the upstream and downstream signals are switched by switch modules (PXI-2599: NI) and signal processing is performed to digitize them with a digitizer (PXIe-5160: NI). These signal processes are integrated and processed by the LabVIEW development system program installed on the PC, and the respective measurement results are stored. Based on the difference between the voltages measured at the top and bottom of the electrode and the left and right electrodes, the beam position is calculated as the distance from the center. Additionally, the beam energy is calculated from the time difference between the averaged signals of the upstream and downstream pickup electrodes.

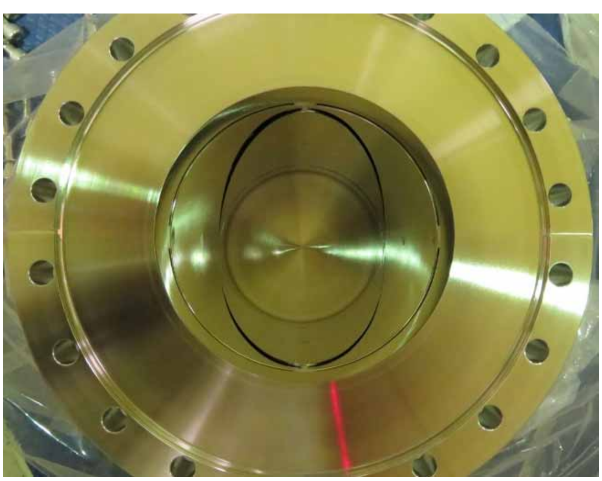

Figure 2: Photograph of the BEPM pickup electrode. The pickup electrodes are divided into four sections: upper, lower, left, and right.

Beam Energy Measurements for Each Experiment

In the production of ^{211}At at the RI production equipment of the TIARA the target Bi plate is fixed to an aluminium (Al) holder. The Al holder used to fix the target is cooled by water and the Bi plate is cooled by the He gas, given that the melting point of Bi is as low as 271.5 °C [5]. A 100 µm thick titanium (Ti) plate is installed to separate the helium gas for cooling from the vacuum in the beamline. The He beam is accelerated to about 50 MeV by the cyclotron, considering the energy lost by passing through the Ti plate and the helium gas. In addition, an Al plate about 0.39 mm thick is inserted in front of the Bi plate to adjust the energy of the He beam on the Bi plate to about 29 MeV. We measured the energy of the 50 MeV He beam using BEPM and TAM for each experiment. The results are shown in Fig. 3.

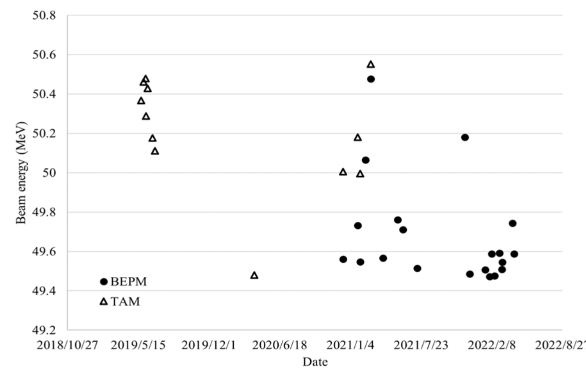

Figure 3: Distribution of the measured beam energy by the BEPM and the TAM for each experiment.

Both measurement methods show that the energy of the He beam often varies daily around 50 MeV. Energy measurement using TAM cannot be performed every time because of the time required for excitation, demagnetization, and adjustment. Therefore, there were few opportunities to measure beam energy with both measurement methods on the same day. When both methods were used on the same day, the results of energy measurements using the TAM were always higher than those using the BEPM, but the magnitude of the measured energy change was the same. This is because the angle of the injection beam into the TAM cannot be restricted, and the beam with an angle of injection into the TAM was deflected. Therefore, the energy measurement using TAM has the disadvantage of being time consuming and lacking in accuracy. On the other hand, the BEPM, which can monitor the beam energy in real-time, showed that the beam energy fluctuation during the same day after the adjustment at the start of the cyclotron operation was less than about 0.1%. Therefore, slight differences in the magnetic field, etc. at the start-up of the cyclotron for each experiment and the accompanying adjustment caused changes in the beam energy. As a result of investigating the adjusted cyclotron parameters for the cause of this energy change, it was found that there is a difference between the acceleration voltage and the

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excitation current of the harmonic coils. Therefore, we controlled the change in beam energy caused by these parameters and measured the beam energy using the BEPM.

BEAM ENERGY CONTROL WITH CYCLOTRON PARAMETERS

Dee Voltage

When the Dee voltage is increased, the beam orbit in the cyclotron moves outward as the energy gain increases. In this case, if the beam can pass through the deflector electrodes or other extraction equipment, the beam with increased energy can be extracted. Figure 4 shows the measured beam energy and relative position at the upstream BEPM for each Dee voltage.

The positive relative position of the beam at the BEPM is to the right of the beam's direction of travel, while the negative direction is to the left. Given that the beam orbit in the TIARA AVF cyclotron rotates clockwise as viewed from above, if the energy of the accelerated beam is lower than expected, the rotation radius of the beam is reduced and the deflected beam to the right is extracted from the cyclotron. Conversely, if the beam energy is higher, the deflected beam to the left is extracted from the cyclotron. The energy of the extracted beam increased by 0.15 keV and the relative position of the beam changed by 15 mm in the negative direction by increasing the Dee voltage from 31 kV to 32.5 kV. The range of change in the Dee voltage is limited by the acceptance of the beam by the extraction device, and large changes in the Dee voltage cause the beam to collide with the extraction device, resulting in a loss. This requires additional orbit correction by steering magnets or other means to irradiate the target. Therefore, although the Dee voltage can vary the beam energy, it is difficult to produce a large difference in beam energy by the Dee voltage alone because of the large changes in beam intensity and orbit.

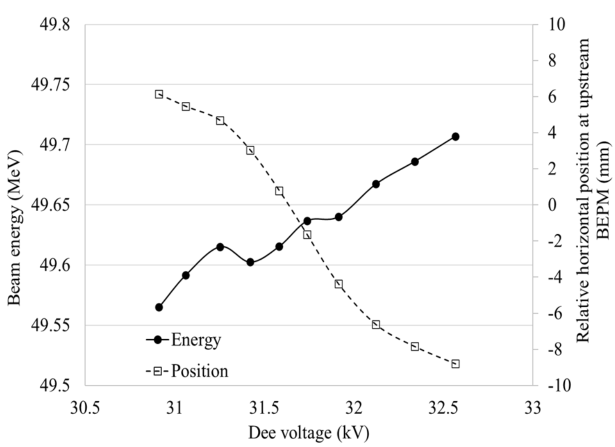

Figure 4: Correlations between the Dee voltage and relative horizontal position of the beam and between the Dee voltage and beam energy. The left and right vertical axes show the beam energy and relative horizontal beam position as line and dashed line graphs, respectively.

Harmonic Coils in the Central and Extraction Regions

In the center and extraction regions, two pairs of coils, known as harmonic coils, are installed in the valley sections of the upper and lower magnetic poles and are excited with opposite polarity to one another. The harmonic coils in the central region (CR) are mainly used for centering the injected ion orbit. The harmonic coils in the extraction region (ER) are used for modifying the beam orbit, such as enlarging the turn separation for beam extraction. The change in beam energy concerning the excitation current of one set of harmonic coils in the CR and the ER was measured using the BEPM. The beam energy changes with the excitation current of the harmonic coils, as shown in Fig. 5. The beam energy change by the harmonic coils in the CR and the ER was about 0.4 MeV and 0.7 MeV, respectively. The width of the change in the excitation current of the harmonic coils in the ER was narrower and more sensitive than those in the CR. Furthermore, the extracted beam current decreased rapidly with changes in the excitation current of the harmonic coils in the ER. On the contrary, the extracted beam current was almost unaffected by changes in the excitation current of the harmonic coils in the CR. Therefore, the beam energy can be controlled by using the harmonic coils in the ER for coarse adjustment and the harmonic coils in the CR, wherein the beam current fluctuation is small, for fine adjustment.

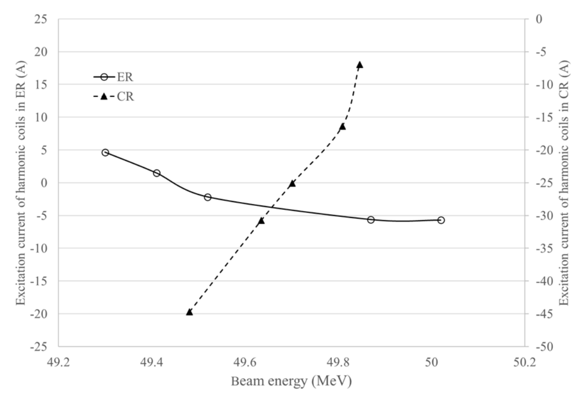

Figure 5: Relations between the beam energy and excitation currents of the harmonic coils in the extraction region (ER) and the central region (CR). The left and right vertical axes show the excitation currents of the harmonic coils in the ER and the CR as line and dashed line graphs, respectively.

GENERATION RATE OF ASTATINE BY BEAM ENERGY CONTROL

To confirm the change in beam energy by adjusting the cyclotron parameters, the production rates of ^{211}At and ^{210}At were measured by irradiating the Bi target with the He beam of different energies. The Dee voltage and the excitation current of one set of harmonic coils in the CR were used as parameters for the energy change of the He beam. Figure 6 shows the results of nuclide identification and quantitative analysis of irradiated Bi using a Ge

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semiconductor detector. The energy of the He beam is reduced to nearly 29 MeV between the BEPM and the Bi target by the 0.1 mm Ti foil, He gas layer of 1.2 kgf/cm^2, and 0.39 mm Al foil. The results show that the generation rate of ^{211}At increases as the energy of the He beam is increased by adjusting the parameters of the cyclotron. ^{210}At was measured above about 49.7 MeV of the He beam energy, and its generation rate increased with energy. Therefore, we found that the optimum beam energy to produce ^{211}At in our irradiation equipment is about 49.6 MeV.

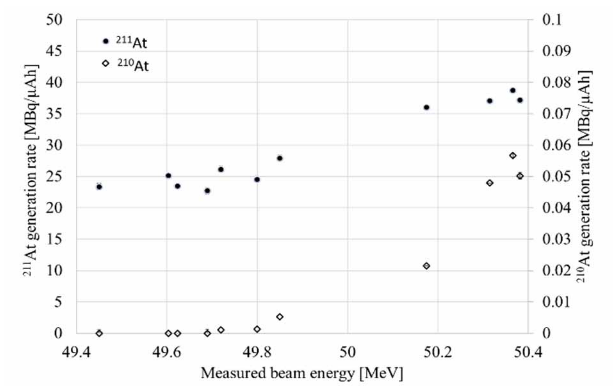

Figure 6: Relations between the beam energy and measured generation rates of ^{211}At and ^{210}At. The left and right vertical axes show the generation rates of ^{211}At and ^{210}At, respectively.

CONCLUSION

The TIARA AVF cyclotron allows precise control of the beam's energy by changing the Dee voltage and the excitation current of the harmonic coil. Changes in the beam energy due to these parameters can be measured in real-time using the BEPM. The change in beam energy with the Dee voltage ranged up to 0.3 MeV but was accompanied by a decrease in the extracted beam current and a change in the beam orbit. The beam energy could be changed by the excitation current of the harmonic coil in the ER in the range of about 0.7 MeV. However, the adjustable range of the excitation current was narrow, and the extracted beam current was reduced significantly.

The beam energy can be changed by the excitation current of the harmonic coil in the CR in the range of 0.4 MeV, and the change in the extracted beam current is small. The optimum beam energy for ^{211}At production in the current RI production system is 49.6 MeV, based on the relationship between the He beam energy and the production rates of ^{211}At and ^{210}At by the Dee voltage and the excitation current of the harmonic coil in the CR. In this study, using excitation current of one set of the harmonic coil in the CR was optimal for controlling the beam energy. We plan to search for the optimal parameters with less variation in the extracted beam current and beam position and a wider range of beam energy changes because they are the effects of limited parameters.

ACKNOWLEDGEMENTS

This work was supported by the JSPS KAKENHI Grant Numbers JP 20K08014.

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