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COMMISSIONING OF A 70 MEV PROTON CYCLOTRON SYSTEM OF IBS AND A PLAN FOR ITS UTILIZATION*

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Abstract

A 70 MeV H^- cyclotron system is installed at the Institute for Basic Science (IBS) to be used as a proton driver for ISOL system. The first internal beam was accelerated in May 2022 and utilized to highly isochronize the magnetic field. In June, 40 MeV and 70 MeV beams were extracted from the cyclotron and beam emittance was measured. Acceptance tests were carried out with a temporary beam line installed to measure the beam profiles at the location of ISOL target. A beam position monitor built in-house was used to measure beam off-center and currents. Along with successfully performing a high-power beam test at 50 kW for six hours, commissioning was completed in the end of 2022. We now plan to utilize this newly established facility also for the productions of neutrons and medical isotopes.

INTRODUCTION

A 70 MeV H^- cyclotron system is installed in Shindong campus of IBS as part of rare isotope science project (RISP), which ended in 2022 [1]. An isotope separator on line (ISOL) system utilizing proton beams has been constructed to produce rare isotope beams for precision measurements of isotope properties and so forth [2]. Figure 1 shows the layout of the facility and the cyclotron is a commercial product of IBA, Belgium [3].

The injection line of the cyclotron was tested in May, 2002 measuring a maximum current of 10 mA at the exit of ion source. Then a current of 800 μA was measured at the radial probe placed in the center region, which was needed to deliver a 50-kW beam at 70 MeV to beam dump. An RF buncher operating at 61 MHz enhances the longitudinal phase acceptance in the center. Beam commissioning was completed by Oct. 2022 after delivering beams to cave A for beam profile formations at the target location using a wobbler and to cave B for the maximum power test.

The ISOL system has been tested from early 2023 using a beam current of 1 μA at 70 MeV. To protect the cyclotron system from possible molecular backflow and sudden leakage of radioisotopes by an accident of target damage, a cryopanel system and fast closing valve are installed in the beam line and recently tested. No vacuum leakage is detected by residual gas analyser (RGA) for a beam power of less than 100 W.

Since cave B is not occupied, it can be used for other applications such as neutron production. Using different targets, various energy spectra of neutrons can be generated. We plan to compute the spectra using PHITS [4] and measurements will follow to validate the production system.

Figure 1 shows the layout of the facility. Two caves are prepared for ISOL, but only cave A is equipped with the modules. Beam line commissioning was performed using proton beams at 40 MeV and 70 MeV checking the beam centering and measuring beam properties.

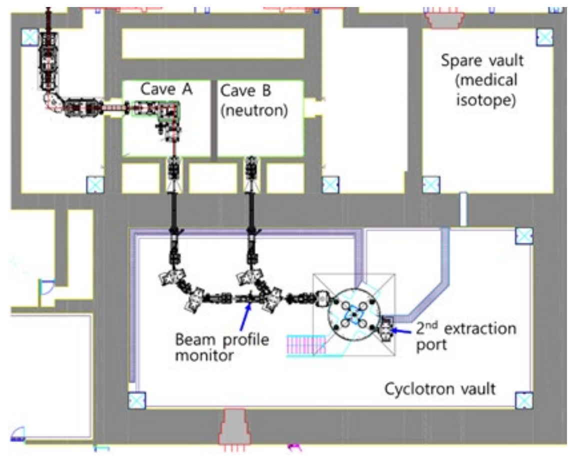

Figure 1: Layout of the the cyclotron facility.

A spare vault shown in Fig. 1 can be used to accommodate target systems for medical isotope production if a new beam line is added to enable 2nd extraction port. Proton beams in the energy range of 30-70 MeV can be used to produce medical isotope generators such as ^{68}Ge and theranostics isotopes such as ^{67}Cu and ^{47}Sc [5].

BEAM COMMISSIONING

The cyclotron and beam lines were commissioned with beam measurements. In the process, the cyclotron magnetic field was highly isochronized using Smith-Garren method [6], which allowed stable beam operation during commissioning. We also measured transverse emittances.

We built a beam position monitor (BPM), which has four pick-up electrodes [7]. It was temporarily installed in the beam line of cave A during commissioning to monitor the beam position and the current. The readout of beam position was calibrated using a moving wire carrying 61 MHz rf signals with an accuracy of 0.1 mm. The voltage signals are processed by Libera Spark HL™ [8] before being displayed on PC. We calibrated the reading of beam currents using current measurements at the beam dump.

Commissioning of the Cyclotron

The ion source is a multi-cup H^- source and can produce a maximum current of 10 mA with a maximum bias voltage

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of 30 kV. The current of 10 mA was measured by Faraday cup at the outlet of the source and the injection line was commissioned by measuring a current of over 800 μA at a radius of 12 cm using a radial probe. An RF buncher in the injection line increases transmission efficiency from the source to the center region to be over 20 % at a current of 20 μA, but the efficiency becomes well below 10 % at 800 μA.

The cyclotron magnet was isochronized at the factory by machining iron shims on the edges of the hills thereby reducing integrated phase error expressed as below:

$$\emptyset(E_f) = \int_0^{E_f} \frac{2\pi h}{f_{rf}} \frac{\Delta f(E)}{\Delta E_n cos\emptyset(E)} dE\ , \quad (1)$$

where Δf is rotation frequency error and ΔE_n is energy gain per turn. It was accepted when a phase slip of less than ±10° is achieved. As soon as a beam is accelerated in the cyclotron, Smith-Garren method was used to highly isochronize the magnetic field. The beam currents were measured at different radii up to a radius of 1090 mm as a function of main coil current. Layers of 0.5 mm and 1 mm thick iron shims were attached on the sides of each hill keeping the four-fold cylindrical and median plane symmetries. Each local shim actually affects entire cyclotron field and it took more than ten iterations for completion. A margin in the main coil current obtained is around 0.2 A at nominal operation current of 154.7 A.

Commissioning of the Beam line

We measured transverse emittances of cyclotron beam by varying the strengths of two quadrupoles and using a beam profile monitor located in the beam line as indicated in Fig. 1. The profile monitor is equipped with ϕ0.5 mm thick scanning tungsten wires. Assuming Gaussian distribution, rms emittances measured were 4.3 and 7.3 π mm·mrad on the x and y planes at a beam current of 25 μA. They are expected to be larger at higher currents. We plan to investigate the beam properties at high currents later.

A temporary beam line was installed in cave A during commissioning as shown in Fig. 2, in which beam diagnostics, 4-jaw collimator and beam dump are shown. The collimator can handle up to around 15 kW and the beam dump up to 50 kW.

Figure 3 shows BPM measurements versus time in initial high-current tests. A noticeable result is that the beam center moves away from the beam pipe center when the current increases. In addition, beam positions fluctuated more evidently during high-current operation presumably due to space charge effects in the injection line. This positional instability can affect the beam profiles at the ISOL target assembly and resultant variation of thermal stresses could damage the target. The target is composed of thin slices to enhance evaporation of isotopes of interest produced by nuclear reactions [9] and is fragile.

To match with ISOL target sizes, two different beam diameters of 2 cm and 5 cm were tested. The larger size target can take a higher beam power for higher yields of aimed isotopes but is more fragile. The beam focusing of upstream quadrupoles was controlled for the case of ϕ2 cm as shown in Fig. 4 while the wobbling magnet operating at 60 Hz AC was used to shape the beam for ϕ5 cm.

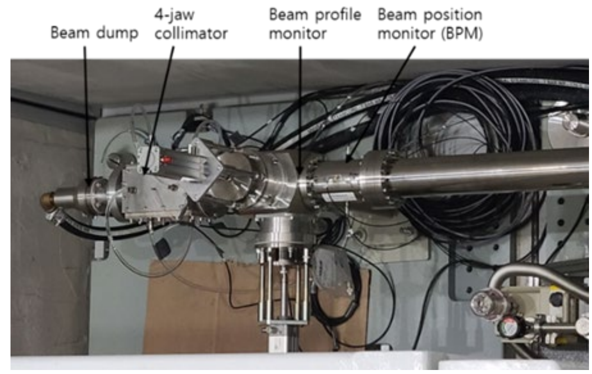

Figure 2: A temporary beam line installed in cave A with beam diagnostic tools for commissioning.

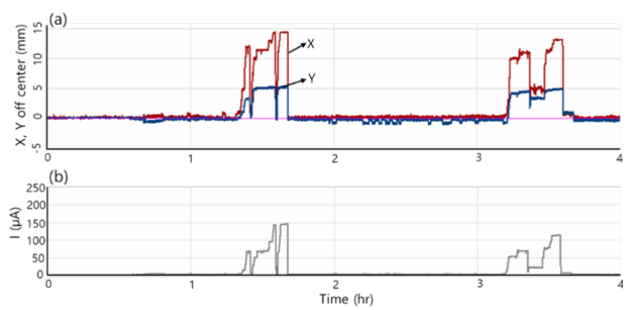

Figure 3: (a) Beam off-center in x-y directions, (b) beam currents measured by BPM.

The maximum beam current test was carried out in cave B for a power of 50 kW at 70 MeV for six hours. It was the final beam test in terms of commissioning and in consideration of high radioactivity produced during the test.

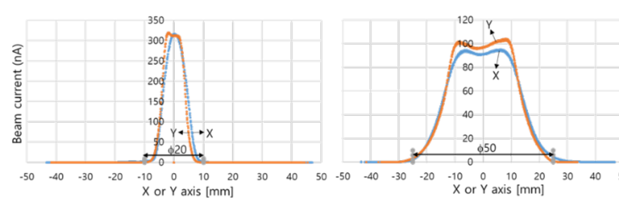

Figure 4: Beam current distributions in x-y directions for two diameters of 2 cm (left) and 5 cm (right) measured by the beam profile monitor in cave A.

PREPARATION FOR ISOL OPERATION

The beam line to ISOL target is equipped with components to protect the cyclotron if target vacuum is broken. In fact, the target assemble is not hermetically sealed as it operates as high as at 2000 °C so that molecular backflow of radioactive materials can occur during normal operation. Figure 5 shows a cyropanel and fast closing valve system. The former can capture back flowing gases and the latter is to isolate cyclotron vacuum in the event of target damage. The cyclotron utilizes six cryopumps, so the

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leakage of radioactive particles in vacuum can heavily contaminate the cyclotron if the vacuum is not quickly isolated.

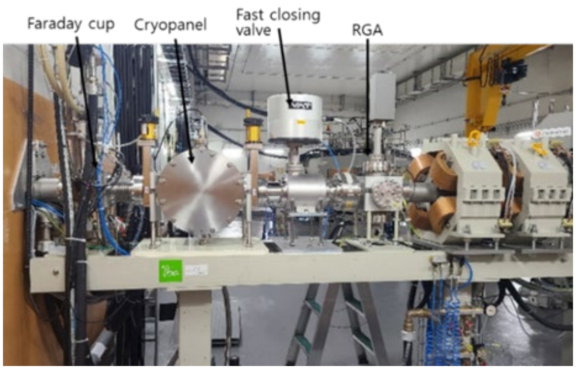

Figure 5: The beam line to cave A showing components to protect the cyclotron during ISOL operation.

Figure 6 shows a sectional view of the cryopanel, which is cooled by a two-stage cryocooler. The cooler has cooling capacities of 90 W at 77 K and 10 W at 20 K on 1st and 2nd stages, respectively. The beam passes through the panel attached to the 2nd stage. The cool-down was tested and temperatures were measured during the beam test at a beam current of 1 μA as shown in Fig. 6, which indicated no temperature change in the cryopanel. Vacuum level of the beam line became better than 1×10^{-6} mbar allowing a high sensitivity for RGA. Residual gas spectra did not change at a beam power of 70 W.

A fast-closing valve (VAT Series 75.0) is installed to quickly react vacuum losses during ISOL operation. The flap valve is closed within 15 ms when emergency signal is delivered to the control module. A cold cathode vacuum gauge is used as the main sensor and vacuum criteria for valve actuation need to be studied. The speed of gas flow can be several hundred meters per sec [10], so complete blockage of the flow is not feasible.

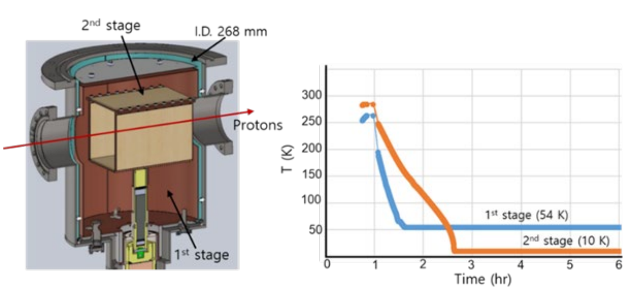

Figure 6: (a) Sectional view of the cryopanel system, (b) temperatures at two stages vs. time.

PLAN FOR NEUTRON AND MEDICAL ISOTOPE PRODUCTIONS

The facility currently has a single beam line connected to the ISOL system in cave A and the beam line ends by beam dump in cave B. We plan to use cave B and a spare vault for neutron and medical isotope productions, respectively [11]. Figure 7 shows the beam line in cave B, where the vacuum window of beam dump made of Ti sustained the beam power of 50 kW during commissioning. Thus we plan to use the same type of window for neutron production. The production target can be placed in separate vacuum also allowing frequent exchange to study neutron spectra of different targets [12, 13].

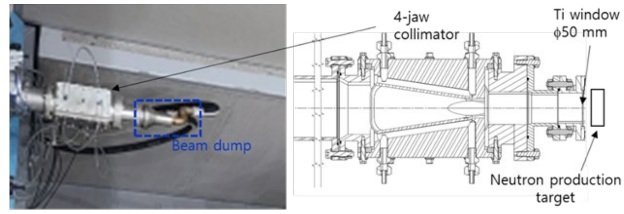

Figure 7: The end of beam line in cave B. The location of neutron production target is indicated.

Figure 8 shows a plan view of the beam line extended from 2nd extraction port of the cyclotron. A minimum number of beam line components is included in the current design. Two target stations are preferred to produce various isotopes such as ^{68}Ge, ^{67}Cu and ^{47}Sc. Automatic handling of the targets using a robot arm attached to overhead crane has been considered along with installing three hot cells to process different medical isotopes.

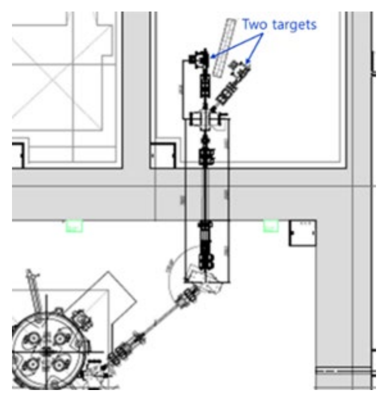

Figure 8: Beam line extension from 2nd extraction port of the cyclotron for medical isotope production.

SUMMARY

The proton cyclotron system of IBS was successfully commissioned at two energies of 40 MeV and 70 MeV and up to a beam power of 50 kW. Beam profile formations were tested for two sizes of ϕ2 cm and ϕ5 cm of ISOL target. The wobbling magnet can produce differing beam profiles in view of minimizing thermal stresses on the target. The cryopanel system installed in the beam line aims to adsorb backflow gases on the cold surface at 10 K. The system was tested when a target made of SiC was irradiated at a current of 1μA at 70 MeV. Molecular backflow was not observed at a low beam power of 70 W. So higher power tests in the future will tell more clearly about the backflow. A minor modification of the beam line in cave B will allow installing a neutron production target. In addition, we look into a beam line design for medical isotope production. It seems feasible to construct a medical isotope facility with the building partly modified.

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