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EXTRACTION SYSTEM OF UPGRADED AVF CYCLOTRON OF RCNP

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Abstract

At the Research Center for Nuclear Physics (RCNP) of Osaka University, the demand for both high-intensity and high-quality beam has been increasing. New injection, acceleration, and extraction system of the AVF cyclotron are under development to meet the demand. Extraction system was designed to increase the extraction efficiency since beam loss at electrodes or apertures makes unacceptable radio activation of apparatus when the beam intensity increased. Simulation study confirmed that 10 MeV protons, 65 MeV protons and 140 MeV $^4He^{2+}$ particles with emittance of 2 mm × 3 mrad can pass through the newly designed extraction system and the existing beam transport line.

INTRODUCTION

The AVF cyclotron of RCNP has been utilized for the purposes of fundamental research in physics, production of nuclear medicine, industrial applications such as soft error measurement, as well as for an injector to the K400 ring cyclotron. To increase beam intensity and beam quality, improvement of the AVF cyclotron described are being carried out as follows.

- To increase energy gain for larger turn separation, a single 180° dee electrode system will be replaced with two 87° dee system.
- Maximum injection voltage will be increased to 50 keV from 15 keV. It makes beam emittance smaller, though the new Low Energy Beam Transport (LEBT) and injection system are required.
- To reduce costs and time of improvement, the pole, the yoke, and the extracting beamline are unchanged.

We will especially report on the extraction system here. Since the yoke and extracting beamline are kept in the current condition, the position of two dees is determined as shown in Fig. 1(b). Because the extracted beam from AVF cyclotron must go to the center in the first bending magnet of beamline, the deflector's position is also determined. The beam which passes through the deflector comes into the dee and exit from dee's base and goes toward the extracting beamline. Such beam passes through the fringe of the cyclotron main magnetic field; whose large field gradient causes horizontally defocus effect. In order to suppress such an effect, we utilized doublet Q like gradient corrector system. One gradient corrector, which is newly developed, focuses horizontally while the other defocuses horizontally. The efficiency of deflector must be increased as much as possible to reduce beam loss that causes activation of apparatus. Although an extraction system of an AVF cyclotron has usually electrostatic deflector and magnetic channel for extracting the beam [1,2]. Such magnetic channels are installed to the hill region after the deflector electrodes and reducing the magnetic field increases the radius of the extracting beam. Since the AVF cyclotron of RCNP has three sectors, the deflector electrode can be installed in the valley region. Therefore, our new design need not to have magnetic channel at the hill region where has high magnetic field. The deflector system has an adjustment system of the position and the gap width, which is changed according to the beam species and energy.

Beam simulation has been performed by utilizing SNOP [3,4] and OPAL [5] codes. The magnetic fields used in these simulations are calculated with OPERA-3d [6] using magnet pole and coil design data. Calculated and measured average field data in the median plane agree within 0.5% in the almost area except central region.

NEW EXTRACTION SYSTEM

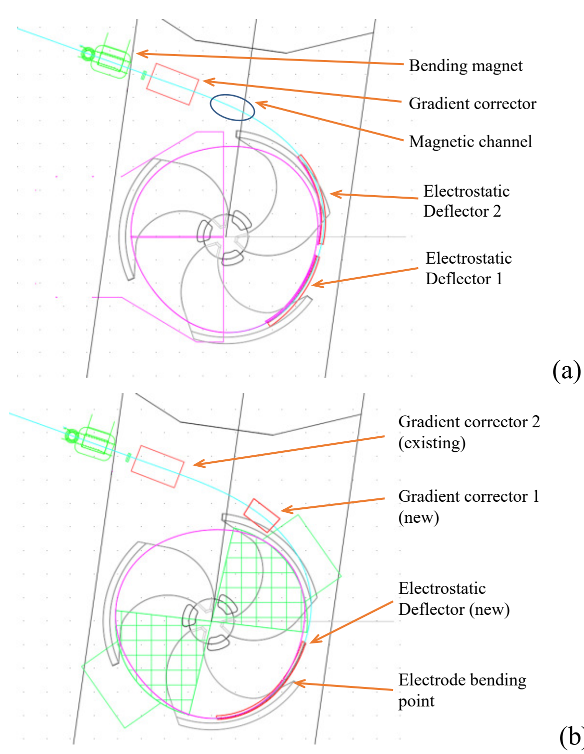

Figure 1: Schematic drawing of a) existing and b) new extraction system of the AVF cyclotron at RCNP.

Existing extraction system of the AVF cyclotron consists of two 60° electrostatic deflectors, passive magnetic channel and gradient corrector (Fig. 1a) [7,8]. We have designed

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new system (Fig. 1b) to maximize the extraction efficiency of 65 MeV proton beam, which is primarily used at RCNP [9]. It also must pass any species and energies used in a variety of experiments. The new deflector has 72° of angle, which is to be installed between two dees and insert probes. To converge the beam, two gradient correctors, one is for horizontal focusing another is for horizontal defocusing are utilized. We do not use magnetic channel because it has to be installed near the outermost beam orbit. It could not avoid collision of the beam particles and then causes radio activation of the apparatus, while longer deflector as described below can bend the beam sufficiently.

TO DETERMINE THE OUTERMOST ORBIT

When particles of the outermost orbit come to the entrance of the deflector electrodes, they go into the extraction orbit. Before calculating the extracting orbit, static equilibrium orbit (SEO) is determined with the use of OPAL code. The isochronous magnetic field is established so as not to cause phase slip, and orbit shape is determined so that the beam came back to the same position and direction after one turn rotation. Then SNOP is used to run the bunch of 2 mm × 3 mrad forward to extracting direction and backward to determine an outermost orbit. By optimizing the valley coils (they make the harmonic magnetic field), beam rotates off center and turn separation at the entrance of deflector becomes larger.

THE ELECTROSTATIC DEFLECTOR

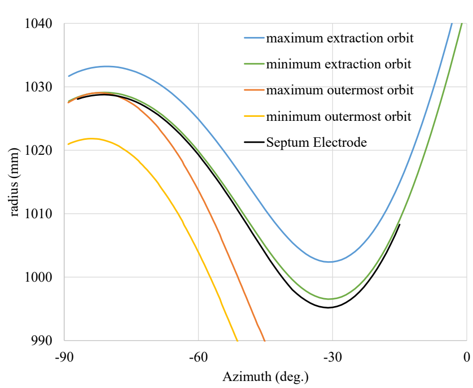

Figure 2: The extraction orbit, the outermost orbit and the position of the septum electrodes in the case of 65 MeV protons in cylindrical coordinates.

Two requirements determined the position and the shape of the deflector electrodes. One is extracted particles in the deflector are properly bent and do not hit to the electrodes, and the other is that particles of outermost orbit do not collide to the electrodes. It should be noted that the outermost orbits are different for the particle species and the extraction energy. The extraction orbit, the outermost orbit and the position of the septum electrodes in the case of 65 MeV protons are shown in Fig. 2. Septum electrodes can be installed between minimum extraction orbit and maximum outermost orbit. Phase space plots of the proton 65 MeV beam in the deflector are shown in Fig. 3. Those figures show 2 mm × 3 mrad beam can pass between the deflector electrodes. Since the entrance of the deflector locates at the hill, the radius of extracting beam orbit decreases from -80° to -30° in azimuth. The septum electrode is divided at the point where the beam enters the valley from the hill to change the shape and electric field distribution.

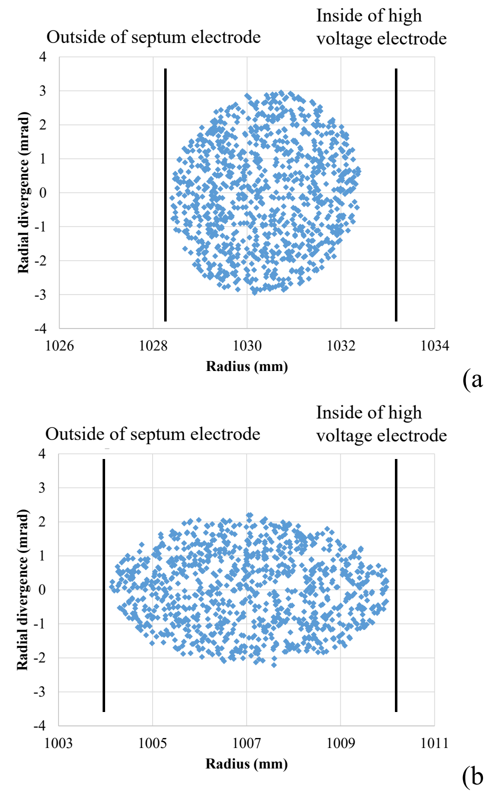

Figure 3: Phase space plot of the proton 65 MeV beam in the deflector. The positions are a) at the entrance and b) at the exit. The positions of the deflector electrodes are also shown.

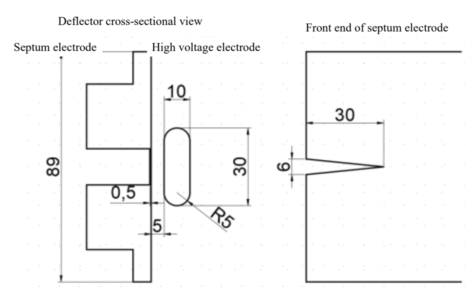

Figure 4: Drawing of the deflector electrodes. All dimensions are in mm. Gap width between septum electrode and high voltage angle is variable from 4 mm to 10 mm.

Design of deflector electrodes is shown in Fig. 4. Septum electrode is 0.5 mm thick, which is the least thickness keeping mechanical strength and which has V-shape cut to spread the heat load by the collision of the beam particles. Although 2 mm × 3 mrad beam can pass the deflector without loss, beam tail or beam tuning incorrection can hit the septum. Maximum 50 kV is applied to the deflector electrode, while septum electrodes are connected to the ground. The whole deflector system is movable in use of motors at 2 points which are at the entrance and the exit. Besides, the

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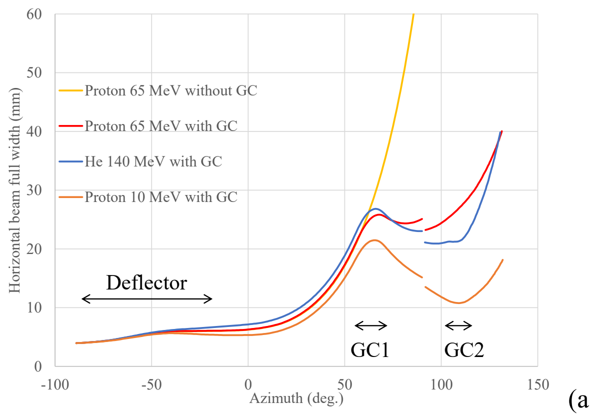
gaps of the two electrodes are adjustable at 3 points which are the entrance, the bending position and the exit. Using these 5 adjustment instruments, the deflector covers the orbital variations by particle species and enables fine-tuning.

BEAM CONVERGENCE WITH GRADIENT CORRECTOR



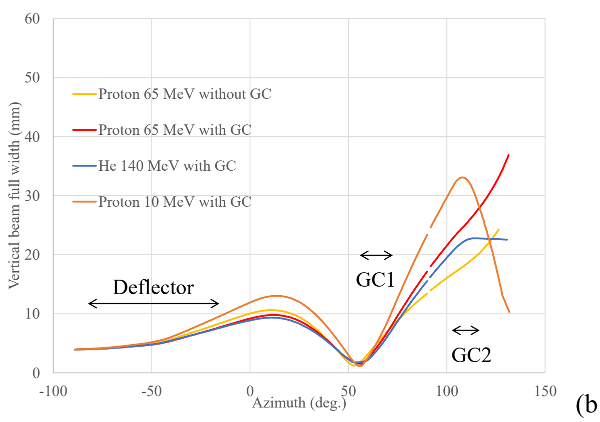


Figure 5: Beam size variation of (a horizontal and (b vertical direction at each azimuth with or without Gradient Corrector (GC) in the case of 65 MeV Protons. There are also shown the beam sizes of 140 MeV $^4He^{2+}$ and 10 MeV protons. Definition of the horizontal direction is the radius of cylindrical coordinates if the azimuth is less than 90° or orthogonal direction to the beamline if the azimuth is more than 90°.

When the beam is extracted from AVF cyclotron, it passes through the fringe field region. Gradient correctors should suppress divergence of the beam caused by such field. Without gradient correctors, the beam width becomes 200 mm, which is larger than the diameter of the beam duct in the bending magnet of the beamline (shown in Fig. 1). Design goal of the extraction system is to make the beam full width smaller than 100 mm in horizontal and 50 mm in vertical. Because gradient corrector has to be pulled out from cyclotron for maintenance, its position has a restriction. We resolve that by setting gradient corrector to the same structure of a dee electrode which also pulled back for maintenance.

To focus and match the beam to the beamline, two gradient correctors with active coil are utilized. Figure 5 shows the horizontal and vertical beam size of the extraction region. The field gradient of new gradient corrector is set to 7.5 T/m (a positive value means the magnetic field is stronger in the outer area) for the horizontal focusing while -2.8 T/m without gradient corrector. Similarly, the field gradient of existing gradient corrector is set to -1.0 T/m for vertical focusing, while -0.3 T/m without gradient corrector.

Beam Orbit Variation by Ion Species and Energy

The orbits of accelerated beams in AVF cyclotron depend on ion species and their energy since particle's Lorentz gamma and the ratio of magnetic fields at the hill and the valley are not constant. The apertures of deflector electrodes and gradient correctors must have a sufficient size and an adjustment range for such orbit distortion. Figure 6 shows the region of beam transit area plotted with a difference from the central orbit of 65 MeV protons for three different beams, 65 MeV protons, 140 MeV $^4He^{2+}$ and 10 MeV protons. In the case of 140 MeV $^4He^{2+}$, iron is nearly saturated by high magnetic field, which makes smaller hill/valley field ratio. Therefore, the orbit approaches to a circle and the deflector electrode can move to have a larger bending angle to follow it.

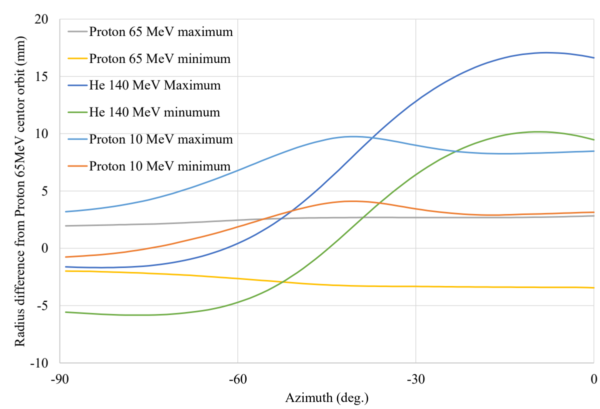


Figure 6: The difference from the central orbit of 65 MeV protons of the maximum or the minimum radius of the orbit of 65 MeV protons, 10 MeV protons and 140 MeV $^4He^{2+}$, respectively.

CONCLUSIONS AND OUTLOOK

New extraction system of the AVF cyclotron for various ion species was designed by a simulation study. It can extract 2 mm × 3 mrad beam of 65 MeV protons in a single turn. Two gradient correctors which work as a doublet Q lens can deliver the beam in the proper size to the existing beamline. The deflector electrode has five position adjustment systems and there is no need for a magnetic channel. Next, we are going to design injection system, which the beam will be accelerated appropriately.

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