DEVELOPMENT OF A NEW ACTIVE-TYPE GRADIENT CORRECTOR FOR AN AVF CYCLOTRON

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Abstract

A new type of a gradient corrector with active coils has been developed for beam focusing and bending in the extraction region of the RCNP AVF cyclotron. The gradient corrector is of quadrupole type consisting of a pair of a C-type iron yoke separated each other. A sixteen-turn hollow conductor was coiled around each side yoke, and the two iron dipoles generate a linear field gradient independently. A field gradient up to 9 T/m are available under excitation of a cyclotron main coil for focusing a heavy ion beam with magnetic rigidity up to 1.6 T-m. The position of the gradient corrector is variable within +/-20 mm from a beam extraction axis. Production of the designed field gradient was verified by a field measurement using a Hall-element under excitation of the main coil. We have succeeded in focusing an extracted beam at an object point of the MEBT optics by a combination of the gradient corrector and a quadrupole triplet. Correction of an extracted beam orbit was also demonstrated by optimizing the coil current and position of the gradient corrector.

INTRODUCTION

At the RCNP cyclotron facility the project for improving proton beam intensity and quality is in progress [1]. The cyclotrons will be upgraded to give intense proton beam more than 10 μA with little beam loss on the way from the AVF cyclotron to a target. In the extraction region of the AVF cyclotron, mismatching of the extracted beam trajectories to the MEBT system and insufficient beam focusing in the extraction region caused beam loss and activation of the extraction components.

A horizontal beam spread in the extraction region, caused by a steep fall of a main coil field is compensated by a field gradient corrector placed on the way to a medium energy beam transport (MEBT) system before extraction. A field gradient more than a few T/m is needed to focus the extracted beam, and the required gradient value depends on the magnetic rigidity Bρ of the beam. In a conventional AVF cyclotron, a typical field gradient corrector was of passive type, which has dipole iron pieces whose pole shape was optimised to form a linear field gradient for generating horizontal focusing force using the fringing magnetic field of a main magnet in the extraction region. If the position of the gradient corrector was fixed, the field gradient was uniquely determined by the excitation level of the main magnet. The focal distance of the gradient corrector was not always optimum for each Bρ of particles. The field gradient was tuneable in the limited conditions that the position of the pole tips is changeable.

Gradient correctors of active type were developed by IBA for a small self-extracting 14 MeV H^+ cyclotron using a permanent magnet [2] and by JAEA for the JAEA K110 AVF cyclotron using active coils [3]. The gradient correctors were quite useful for beam focussing and well-matching between the cyclotron extraction axis and the MEBT line. However, fine tuning of the field gradient including non-linear components was difficult.

A new type of a field gradient corrector was developed for the RCNP AVF cyclotron. It consists of a set of quadrupole with active coils and generates a tuneable independent field gradient on both sides of the poles. This paper describes the design and performance of the new gradient corrector of active type.

BEAM OPTICS FOR MATCHING THE EXTRACTED BEAM WITH MEBT

The extraction system of the RCNP AVF cyclotron consists of an electrostatic deflector with a span angle of 120 degrees, a magnetic channel with coils above and below the iron channel to compensate the first harmonic components in the acceleration region, a magnetic shielding iron channel for generating zero-field just before extraction of the cyclotron. The layout of the extraction system is shown in Fig. 1. The magnetic shielding channel was followed by a deflection magnet and a quadrupole triplet lens for adjusting the extracted particle trajectories to the MEBT line and forming a doubly-focussed object for MEBT optics. Beam loss occurred downstream of the magnetic shielding channel because of non-existence of horizontal focussing elements. Thus we decided that the magnetic shielding channel was

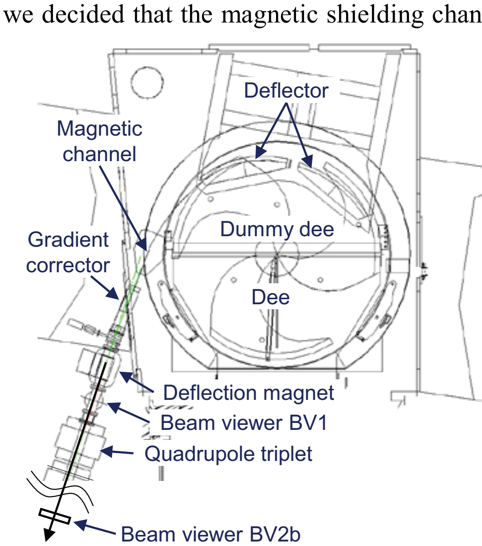

Figure 1: Layout of the RCNP AVF cyclotron.

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replaced by the gradient corrector of active type to improve the beam transmission of the extraction system.

A typical emittance of ion beams extracted from the AVF cyclotron was several to 20 π mm-mrad, which depends on the quality and intensity of beams. We assumed that a transversal beam emittance at the entrance of the magnetic channel was 20 π mm-mrad, and horizontal and vertical beam spreads were ±15 mm and ±5mm, respectively. In practical operation, the object size of MEBT optics was within several mm. Examples of the beam optics from the magnetic channel to the beam viewer BV2b, which is the object position of the MEBT optics, are shown in Fig. 2. The horizontal beta function β_x of the beam optics without excitation of the gradient corrector increased to 30 m at the quadrupole triplet, which caused activation of a beam duct around there. The maximum β_x was reduced to 10 m by excitation of the active gradient corrector. In this calculation, we assumed that the magnetic field inside of the magnetic channel was zero, and a virtual quadrupole lens for horizontal defocussing was placed in the region between the magnetic channel and the gradient corrector. The field gradient of the virtual Q-lens was estimated from the

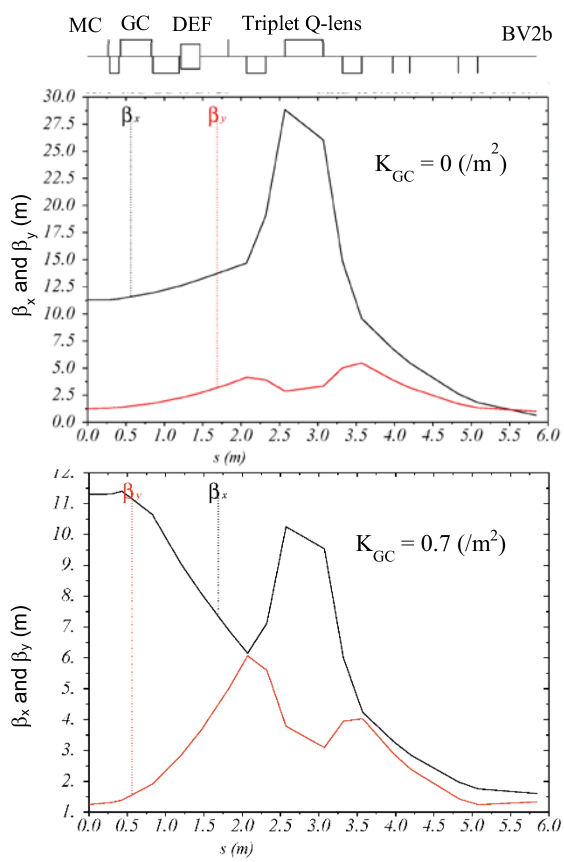

Figure 2: Examples of beta functions of the beam optics from the magnetic channel to the beam viewer BV2b. The upper figure shows the beam optics without excitation of the gradient corrector coils. The lower one shows modified beam optics for excitation of the gradient corrector at K = 0.7 /m^2.

magnetic field distribution of the cyclotron magnet in the extraction region. The combination of the gradient corrector and the triplet Q-lens allowed us to minimize the transversal beam spread.

DESIGN OF THE GRADIENT CORRECTOR OF ACTIVE TYPE

In principle, the iron pieces of the gradient corrector collect the fringing field of the cyclotron magnet. The shape of the pole gap and the position of the iron poles contribute to production of the linear field gradient. The new gradient corrector has a set of quadrupole similar to a normal quadrupole lens used in a beam transport line. The pole face of the gradient collector doesn't have an exact hyperbolic shape due to the non-linear external field distribution in the extraction region.

In order to produce transversally-reversed field gradient for focusing a beam traveling in the falling-slope region of the cyclotron fringing field, the pole pieces were separated into right and left parts, and upper and lower poles were combined by an iron return yoke on each side. An active coil fabricated from a sixteen-turn hollow conductor were mounted on each return yoke. The two coils were independently excited. The coil on the cyclotron center side weakens the strong cyclotron fringing field and the coil on the far side increases the weakened field. A linear field gradient was guaranteed in the region within ±20 mm from the center axis of the gradient corrector by optimizing the shape of the iron pole faces. The calculation model for the three-dimensional magnetic field distribution is shown in Fig. 3.

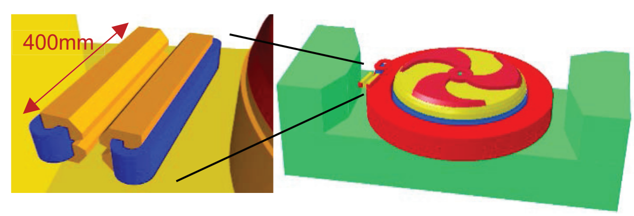

Figure 3: Three dimensional model of the gradient corrector for magnetic field calculation.

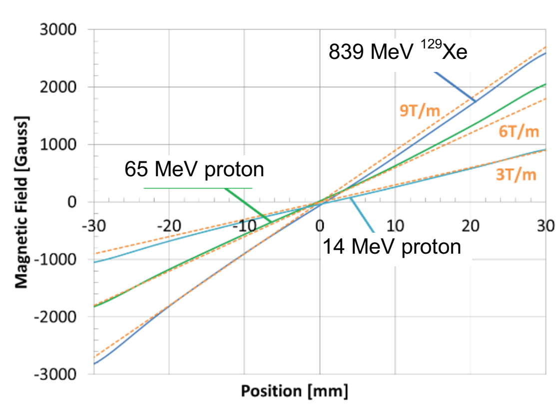

Figure 4: Horizontal field gradient of the gradient corrector for 14 and 65 MeV protons and 839 MeV ^{129}Xe, obtained by a three-dimensional magnetic field analysis code.

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The maximum field gradient required for matching the extracted beam to the MEBT system was estimated for three magnetic rigidity conditions; 3 T/m for 14 MeV proton with Bρ of 0.54 Tm, 6 T/m for 65 MeV proton with Bρ of 1.18 Tm, 9 T/m for 839 MeV 129Xe with Bρ of 1.64 Tm. The designed field gradient for the three conditions are shown in Fig. 4.

FIELD MAPPING

Before packing the iron poles and coils into a stainless steel vacuum case, we roughly checked the magnetic field distribution in the standalone excitation mode by manually scanning a gauss meter probe in the pole gap region. The inner beam channel wall of the vacuum case, where a beam passes through, was covered with a 2 mm thick tantalum plate for protection of the wall from beam bombardment. A pair of 25 mm thick graphite beam baffle slits was mounted at the entrance and exit of the gradient corrector. The baffle slits were isolated to detect a current of a beam hitting the slits.

After installing the gradient corrector in the extraction region of the RCNP AVF cyclotron, a full-field mapping was carried out with a Hall element (SIEMENS SBV601-S1) mounted on an aluminium holder. The distribution of the vertical magnetic field component was obtained by shifting the Hall element position transversally. The mail coil currents for the field mapping were 259 A for 14 MeV proton, 582 A for 65 MeV proton and 1110 A for 839 MeV 129Xe. The measured field gradient for each excitation condition is listed in Table 1. The field gradients are tuneable by changing two coil currents of the gradient corrector. The rating current and voltage of the power supply for the active coils was 580 A and 8 V, respectively. The power supply has enough specification for optimizing the field gradient.

Table 1: Measured Field Gradient and Magnetic Rigidity of Typical Accelerated Particles

Particle and Energy	Bρ (Tm)	Measured dBz/dx (T/m)	Main coil (A)	GC East (A)	GC West (A)
Proton 14MeV	0.54	1.7	259	48	45
Proton 65MeV	1.18	3.3	582	105	80
129Xe 839MeV	1.64	5.2	1110	260	132

PERFORMANCE OF THE GRADIENT CORRECTOR

We have succeeded in focusing the extracted beam at the object point BV2b by combination of the new active-type gradient corrector and the quadrupole triplet. Comparison of a 65 MeV beam profiles between the former beam optics with the magnetic shielding channel and the new optics using the active-type gradient corrector is shown in Fig. 5. The practical beam profiles were observed by a beam viewer with a fluorescence mesh plate at BV1 and BV2b. The extracted beam was doubly focussed at BV2b to form an object image for the MEBT optics. A large horizontal beam spread and an error of beam alignment were observed at BV1 for the former beam optics, which caused beam loss and activation of beam line components. The horizontal beam spread at BV1 was sufficiently corrected by the gradient corrector and a well-focussed beam spot with a size of a few mm was formed at BV2b. Matching of the extracted beam trajectory to the MEBT axis was demonstrated by shifting the gradient corrector position by around 6 mm to use an off-set region of the field gradient. Performance test of the gradient corrector and beam development to improve beam transmission is in progress.

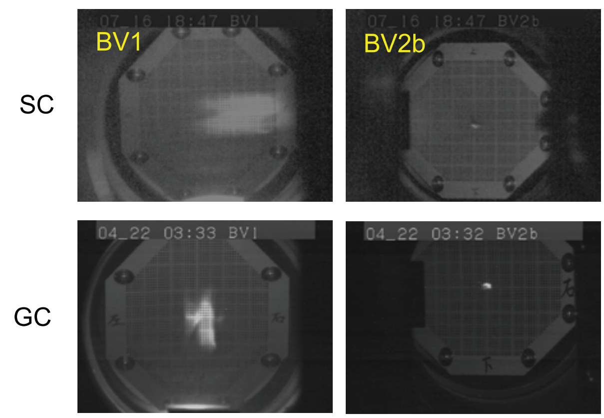

Figure 5: Comparison of 65 MeV proton beam profiles observed at the beam viewer BV1 and BV2b between the former beam optics using the magnetic shielding channel (SC) and the present optics with the gradient corrector (GC).

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