STUDY ON ENERGY UPGRADE AND BEAM TRANSMISSION EFFICIENCIES FOR RIKEN K-70 AVF CYCLOTRON

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Abstract

The central region of the RIKEN AVF cyclotron was modified in order to increase the beam energy of protons and M/Q = 2 ions, and acceleration tests were performed. Before the modification, we investigated the injection acceptance in the modified structure of the central region. In the acceleration tests, the energy of protons was successfully increased from 14 MeV to 30 MeV in the acceleration harmonics 1 (H = 1) operation. On the other hand, in the conventional acceleration harmonics 2 (H = 2) operation, the transmission efficiencies were lower than those before the modification.

INTRODUCTION

The RIKEN AVF cyclotron [1] was commissioned in 1989 and is used as a stand-alone machine and an injector for the RIKEN ring cyclotron. Its K-value is 70 MeV, and the maximum extraction energies to date are 14 MeV for protons and 12.5 MeV/u for M/Q= 2 ions. This cyclotron has been operated jointly by RIKEN and the Center for Nuclear Study, the University of Tokyo. The operation time was 2900 h in 2014, and the information regarding its operation is described in Ref. 2.

Figure 1 shows the acceleration performance of the AVF cyclotron. The maximum magnetic field is 1.76 T. The RF frequency ranges 12–24 MHz and the nominal dee voltage is 50 kV. Until 2009, the operational region had been limited to the yellow area, but in order to increase the beam energies to meet the demands from users for nuclear physics and radioisotope production, the modification of the central region of the cyclotron was designed by Vorozhtsov et al. [3] and was executed in the summer of 2009. As a result, the operational region has been expanded to the blue area in Fig. 1, while the extraction energies have increased to 12 MeV/u from 9 MeV/u for M/Q = 2 ions. After this modification, in order to further increase the extraction energy (to 30 MeV for protons), they also designed another structure with a smaller RF shield by changing the support structure of the inflector. Figure 2 shows the superimposed plan views of the central region. One is for the existing structure (S1) modified in 2009, and the other is for the tested structure (S2), in which the RF shield was made smaller. The region accelerated in the structure S2 is expanded to the green area in Fig. 2. Using the structure S1 or S2, light ions such as protons can be accelerated in the acceleration harmonics 1 (H = 1). The displacement between H = 1 and 2 in the blue and green areas is caused by an acceleration phase-shift from the peak of the dee voltage for H = 1 acceleration. In the H = 1 operation, protons can be

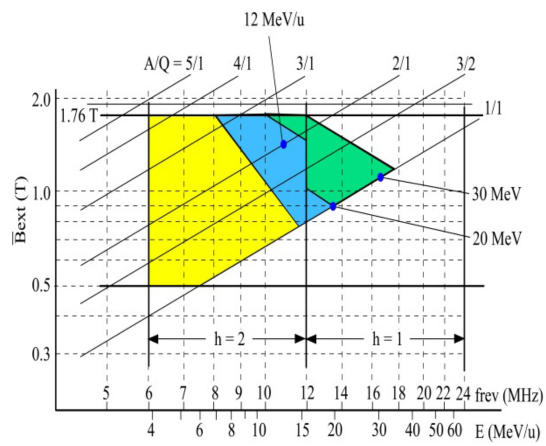

Figure 1: Acceleration performance of the AVF cyclotron. The yellow, blue, and green areas correspond to the original (before 2009), existing, and currently-tested geometries, respectively.

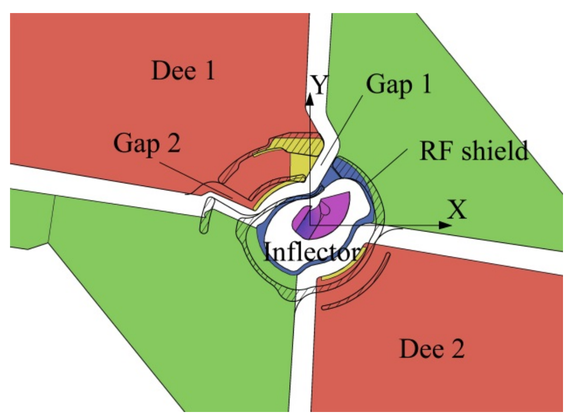

Figure 2: Existing and tested geometries of the central region. The shaded area indicates the existing geometry.

accelerated up to 20 MeV for S1 and 30 MeV for S2. An acceleration test of 20 MeV protons was executed in the existing S1 structure in July 2016. Moreover, in August, we changed the central region from the existing structure S1 to the structure S2, and performed the acceleration tests. In the tests, in addition to the acceleration of 20 and 30 MeV protons, the H = 2 acceleration test was also performed to check whether the transmission efficiencies through the cyclotron deteriorated.

TRACKING SIMULATION

Before modifying the central region with the structure S2 and performing tests, we re-studied the influence on shows a computer model used for the calculation of the the injection acceptance by tracking calculations. Figure 3

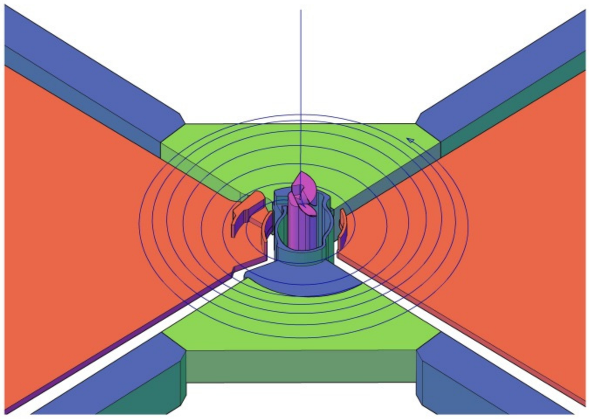

Figure 3: Computer model for electric field calculations. The model shows the lower side from the median plane, except for the inflector.

shows a computer model used for the calculation of the electric fields. The electric and magnetic fields were calculated by using Opera-3d [4]. The RF fields were treated statically and also calculated with Opera-3d. The enhancement of the magnetic field in the central region (bump) was set to be approximately 1.5% inside the radius of 150 mm. The starting point of the particles in the tracking calculation was defined at 200 mm above the median plane, and the acceptances were evaluated at this point. The space charge effect was not considered in our calculations.

Acceptance for Lateral Direction

Figure 4 shows the acceptance of 12 MeV/u deuterons calculated for S1 and S2. The *x* and *y* axes lie along the magnetic yoke of the cyclotron, as shown in Fig. 2. The acceptance is defined as a distribution in the phase space of the particles accelerated beyond a radius of 150 mm. The dee voltage is 45 kV in these calculations. The phase angles to the RF fields of all particles are set to be constant at the starting point. However, those at the first acceleration gap spread to widths of approximately 25° and 57° in the *x* and *y* directions because of the difference in the orbit lengths in the inflector.

Figure 5 shows the acceptance sizes calculated for 12 MeV/u deuterons as a function of phase angle for the dee voltage of 45 kV. The phase angle is defined as the RF phase when the particle injected along the central axis passes the center of the first acceleration gap. In the case of Fig. 4, the phase angle of the central particle was 4°. As the acceptance of the inflector was 550π mmmrad, the rest of the particles were lost before accelerating to a radius of 150 mm: more than 90% of them are lost on the upper and lower surfaces of the dee electrodes with an inner height of 24 mm. It was found that the acceptance for S1 is almost the same or slightly larger than that for S2.

Figure 6 shows the dee-voltage dependence of the acceptance sizes calculated for 30 MeV protons and 12 MeV/u deuterons. In this case, protons are accelerated in S2 in H = 1 operation, and deuterons in S1 in H = 2. The phase angles of the central particle in the center of the first acceleration gap were approximately 4° for all cases. This figure indicates that it is possible to accelerate protons at 30 MeV with the same dee voltage as, and a larger acceptance size than, that for 12 MeV/u deuterons.

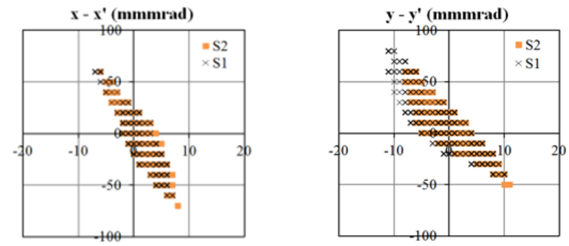

Figure 4: Acceptance shapes for 12 MeV/u deuterons calculated for S1 and S2. See text for the calculation conditions

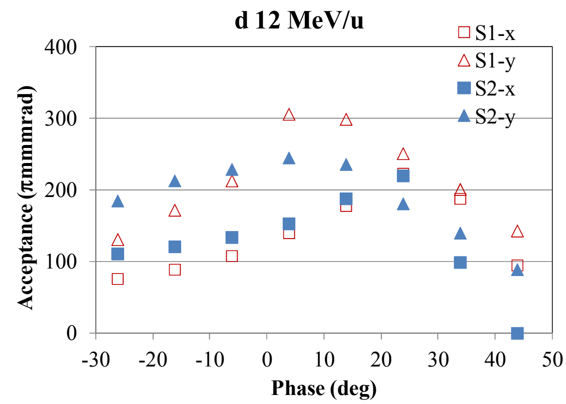

Figure 5: Acceptance sizes of 12 MeV/u deuterons calculated for both S1 and S2 as a function of the phase at the tracking starting point. (See text).

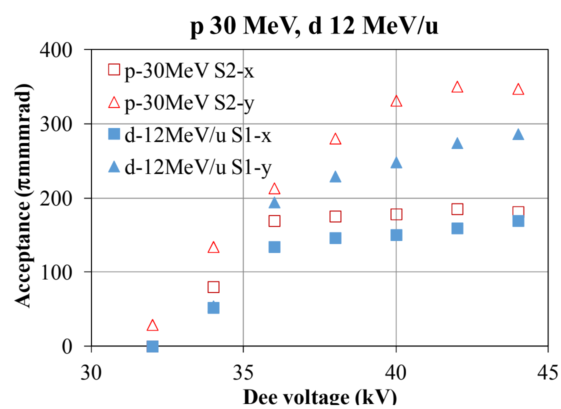

Figure 6: Acceptance sizes for 30 MeV protons and 12 MeV/u deuterons as a function of dee voltage. The acceptances of the protons and deuterons were calculated for S1 and S2, respectively.

Acceptance for Longitudinal Direction

Figure 7 shows the phase distributions of particles at the center of the acceleration gaps, which are injected along the central axis and are accelerated to more than seven turns. Figure 7(a) shows a comparison between S1

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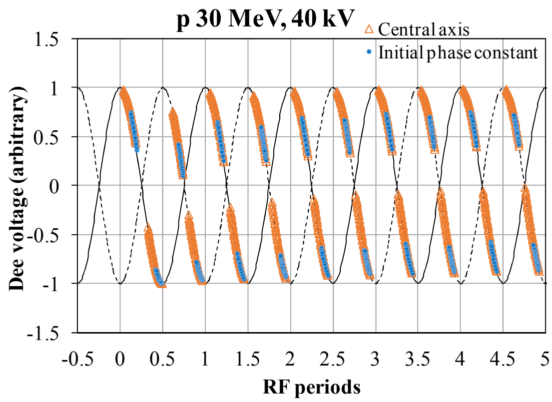
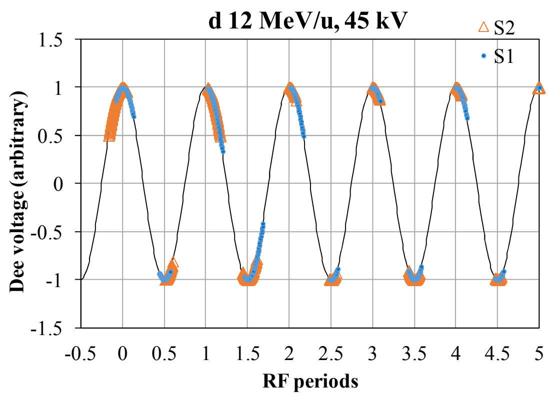


(a)



(b)

Figure 7: Phase distributions at the center of the acceleration gaps of the particles accelerated to more than seven turns. See text for details.

and S2 calculated for 12 MeV/u deuterons at a dee voltage of 45 kV. In case of S1, the particles pass the center of the first and second gaps at the phase of voltage peaks, and the phases are delayed at the third and subsequent gaps. The beams passing acceleration gaps are subjected to focusing and divergence forces in the vertical direction at the entrance and exit of the acceleration gaps, respectively. Therefore, the particles passing the gap at the delayed phase from the peak are subjected to a net focusing force. On the other hand, in case of S2, as the position of the second gap is located further downstream than that in case of S1, the phase at the first gap advances, and the particles are subjected to a net divergence force at the first gap. This is considered to be a cause for the smaller acceptance for S2 than that for S1 at the delayed phase region, as seen in Fig. 5. Figure 7(b) shows the phase distributions for H = 1 acceleration of 30 MeV protons at a dee voltage of 40 kV. The orange triangles correspond to the particles injected along the central axis with all phases, and the blue circles to the particles with a constant phase at the starting point, but with different initial positions and angles in the x-direction. The spreads in phase for the blue circles are due to the differences of orbit length in the inflector.

ACCELERATION TESTS

We modified the central region from S1 to S2 and performed acceleration tests in August 2016. In these tests, we not only tried increasing the energy of proton beams by the H = 1 operation, but also investigated the influence on the transmission efficiencies through the cyclotron in the H = 2 operation. Table 1 gives a summary of the acceleration tests. A total of seven beams were accelerated. As the machine time was restricted to within 36 h, the mean adjustment time for acceleration of one beam was approximately 4 h. In the table, I36 and C01 indicate the positions of Faraday cups located just above the yoke of the cyclotron and 2 m downstream from the exit of the cyclotron. In the H = 1 operation, 20 MeV protons could be accelerated without difficulty, but the beam current for 30 MeV protons was as small as 1.1 μA. This was because the dee voltage was insufficient owing to the deterioration of the RF cavities. On the other hand, the transmission efficiencies (beam current ratio of I36 and C01) in the H = 2 operation were worse than those before the current modification. It was confirmed that the beam currents for 14 MeV protons and 12 MeV/u deuterons can reach 20 μA, which is the limit due to radiation safety. The beam current of $^{22}Ne^{7+}$ was almost the same as before. However, the transmission efficiency for $^{22}Ne^{5+}$, which simulates $^{84}Kr^{20+}$, was approximately 60% of the peak performance to date. The transmission efficiency for Fe beams was only 10%, while its efficiency so far had been larger than 20% or occasionally 30%. In general, the transmission efficiencies in the H = 2 operations in S2 were rather poor compared with those in S1, although the time for machine study was not sufficient. Therefore, we have decided to revert the tested structure to the existing one because the use of this new structure could be at risk of affecting the operations for users' experiments.

Table 1: Summary of Acceleration Test.

Ion	Energy	RF frequency (MHz)	Harmonics	I36 (μA)	C01 (μA)
p	14 MeV	23	2	90	14.3
H_2^+	12 MeV/u	21.25	2	57	9.6
$^{22}Ne^{7+}$	6.0 MeV/u	15.05	2	42	7.5
$^{22}Ne^{5+}$	4.0 MeV/u	12.3	2	12	2
p	20 MeV	13.6	1	76	10
p	30 MeV	16.5	1	116	1.1
$^{56}Fe^{15+}$	5 MeV/u	13.8	2	1.2	0.12

CONCLUSION

We modified the central region of the RIKEN AVF cyclotron in order to increase the beam energy, and performed acceleration tests. In the tracking simulations, the injection acceptance in the modified central region was not very different from that for the existing structure. In the acceleration tests, we successfully increased the beam energy of protons from 14 MeV to 30 MeV. On the other hand, the transmission efficiencies in the H = 2 operations were lower than those before the modification. Hereafter,

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we will analyze the results of the acceleration tests and review the structure of the central region.

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