BEAM STUDIES OF INJECTION TO EXTRACTION SYSTEM FOR JAERI AVF CYCLOTRON

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ABSTRACT

The JAERI AVF cyclotron has distinctive features as a multi-particle, variable-energy cyclotron. Harmonic numbers of 1, 2 and 3 are available for acceleration in a wide range of energy. Beam studies have been carried out to study beam behavior in the cyclotron. Isochronous fields has been generated easily by phase measurements and cross-checked by phase measurements for small amounts of positive and negative changes of rf frequency. The relation between an electric field of a deflector and $mv^2/2q$ is surveyed for several ions accelerated in practical operation.

1. INTRODUCTION

The JAERI AVF cyclotron[1,2](K-number=110) is of the model 930 of Sumitomo Heavy Industries, Ltd. The cyclotron is basically the same model as the CYCLONE (Université Catholique de Louvain). The original design of an rf cavity, an inflector and the deflector was modified in order to make allowance for accelerating 90 MeV protons. A movable-panel type resonator originally proposed was replaced by a $\lambda/4$ coaxial type resonator[3] with a movable shorting plate for generating a maximum acceleration voltage of 60 kV. Maximum currents of circular trimming coils were also modified for generating isochronous field for 90 MeV protons. An phase probe was additionally installed for measuring relative beam phases.

In general orbit analysis using ideal isochronous field is carried out in designing the cyclotron. Beam behavior in practical operation, however, is less understood because the actual magnetic field doesn't always correspond to the ideal isochronous field. Some beam diagnostics probes in an acceleration region provide us with rough information on the beam behavior. More precise analysis of beam dynamics is required for understanding the beam behavior and operating the cyclotron. We are now developing an operation assist system[4] for easy and reliable operation of the cyclotron. The system is expected to be a base system for automatic operation in future. The system consists of a knowledge-based expert system and a beam trajectory simulation system. The results of the orbit analysis are utilized for developing the system.

In this work the orbit studies are focused on beam characteristics in a central region, generation of the isochronous field and the correlation of the electric field with mv^2/q and the entrance position of the deflector. Validity of the orbit calculation depends on reproducibility of the actual magnetic field. The calculated field is composed by using measured field maps. Accuracy of the field reconstruction is around 1×10^{-3} for main coil currents between 150 A and 550 A, and is better than 1×10^{-3} above 585 A. The circular trimming coil field is strongly dependent on the base field in the former current region. Measured maps of the trimming coil field are not sufficient for composing an actual magnetic field in the region. Beam studies of the central region to the extraction region were carried out for 70 MeV protons in order to reliably analyze the beam analysis, since the main coil current is 552.59 A. Calculated beam phase shifts for 70 MeV protons correspond to measured ones.

2. CENTRAL REGION

A schematic drawing of the central to the extraction regions is shown in Fig. 1. An inflector of the spiral type and a puller are designed for each harmonic mode. Two sets of phase slits are installed in the central region for defining beam phases. Both of the slits are movable and have enough stroke to define the beam phases for the first turn. Trajectories of central particles simulated by a computer code for 70 MeV protons with injection phases of 0°, ±10°, ±20° and ±30° are shown in Fig. 2. Without the phase defining slits, the central particles within an injection phase of ±30° can reach the entrance of the deflector. Turn numbers for the central particles with injection phases of −20° and −30° are, however, more than those with the other phases by 100∼200 turns. Figure 3 shows trajectories of the particles lying in orthogonal positions on the phase ellipse of which the area is 4 mm×50 mrad×π with injection phases of 0°, +15° and −15°.

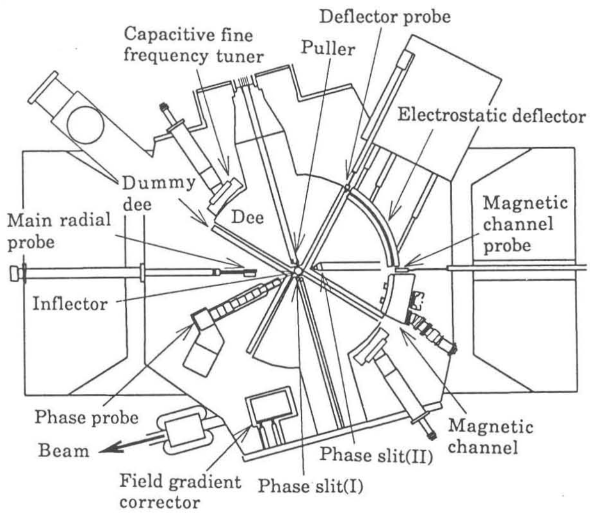

Fig. 1. Layout of the injection to extraction system of the JAERI AVF cyclotron.

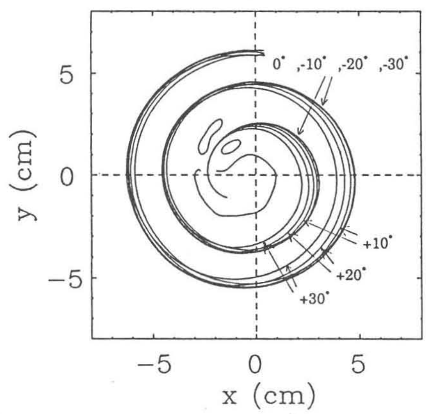

Fig. 2. Central trajectories of 70 MeV protons with injection phases of 0°, ±10°, ±20° and ±30°.

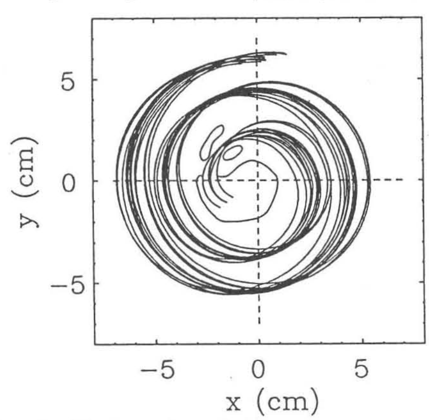

Fig. 3. Trajectories of the particles lying in orthogonal positions on the phase ellipse whose area is 4 mm×50 mrad×π with injection phases of 0°, +15° and −15°.

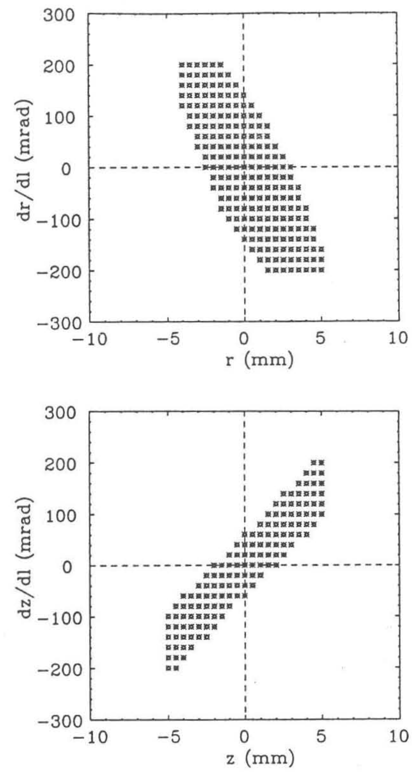

Fig. 4. Horizontal and vertical acceptances of the cyclotron for the injection phases of 0°.

The beams are horizontally focussed at the slit (I) position. An effective phase acceptance for the slit (I) gap of 6 mm is ±15°.

Horizontal and vertical acceptances of the cyclotron for the injection phases of 0° are shown in Fig. 4. The acceptances in both directions are more than 300π mm·mrad, which covers injection beam emittances[5)] of 100π to 200π mm·mrad in horizontal direction and 100π mm·mrad in vertical direction. The calculated acceptances are defined as follows; horizontal and vertical deviations of particles are within the distance of ±10mm from the central particle up to a radius of 25 cm where the isochronous field starts.

3. GENERATION OF ISOCHRONOUS FIELDS

An acceleration dee voltage for the cyclotron is determined by a constant orbit method. A standard condition of the constant orbit method is 90 MeV protons for the harmonic number h=1 with a dee voltage of 60 kV, 460 MeV $^{40}Ar^{13+}$ for h=2 with 34 kV and 175 MeV $^{40}Ar^{8+}$ for h=3 with 34 kV. The beam phase is quite sensitive to field perturbation because turn number amounts to 550 for h=1, 265 for h=2 and 210 for h=3. If a base field level increases or decreases equally by $\Delta B/B=1\times10^{-4}$ from the isochronous field, the beam phase drifts away by 20° in the extraction region. Thus careful fine tuning of the coil currents is required for generating the isochronous field for each ion and energy.

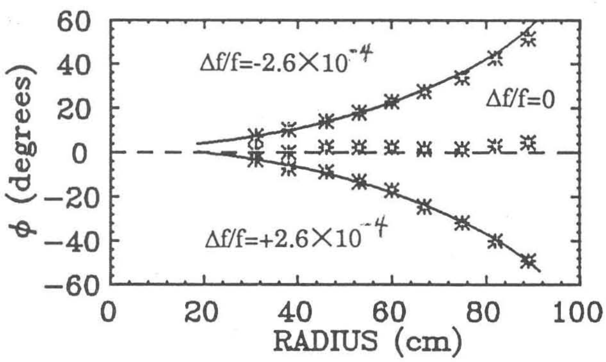

Fig. 5. Phase drifts for 45 MeV protons due to the positive and negative radio-frequency change of $\Delta f/f = \pm 2.6 \times 10^{-4}$. Measured and calculated phases are indicated by stars and solid lines, respectively.

Main coil and circular-trimming-coil currents for generating the isochronous field are calculated by using an optimization code based on measured field maps. Relative phases of beam particles are measured by the phase probe consisting of ten pairs of rectangular pickup electrodes. The electrodes are installed in radial direction as shown in Fig. 1. The electrodes are made of 2.5 mm thick oxygen free copper. The electrodes are radially 58 mm long and azimuthally 40 mm wide for the inner threes, 60 mm for the middle fours and 93 mm for the outer threes. Relative phase differences from the pickup signal of the second electrode are detected by a digital storage oscilloscope. The length of signal cables of the phase probe was made uniform within a variation of 4 mm, so that an error due to the variation is within 0.02 nsec. Current corrections of each circular trimming coil are made by a least-squares fitting code for deducing the currents so as to minimize the field deviation from the isochronous field. The phase deviations can be finally reduced within $\pm 5°$ after a few iterative corrections.

The pickup signal of the phase probe is produced by the particles passing through the electrode covering a radial range of 58 mm. The phase corresponds to the radially averaged phase. The isochronous field was cross-checked by small amounts of radio-frequency shifts of $\Delta f/f = 2 \times 10^{-4}$ to 5×10^{-4} in order to reduce ambiguity of the phase measurement due to the wide sensitive area. If the isochronous field is generated ideally, the same amount of positive and negative rf shifts should result in the same amount of negative and positive phase drifts. The rf shifts are equivalent to a small change of a base field level. It is difficult to estimate exactly the change of the base field for fine tuning of the coil currents due to magnetic hysteresis. On the contrary, the radio-frequency can be set precisely at a resolution of 10 Hz. Phase drifts caused by the rf change of 2.6×10^{-4} for 45 MeV protons are shown in Fig. 5. Phase drifts are calculated on the assumption that the isochronous field starts at a radius of 20 cm and no central field bump is concerned. The measured phases are consistent with the calculated ones. The calculated phases for an initial rf phase shift of 2° are fitted well with the measured ones. The cause of the shift is under investigation. The fields generated in practical operation were found to agree with the ideal isochronous fields within 1 gauss.

4. ELECTRIC FIELD OF DEFLECTOR

Extraction system consists of an electrostatic deflector, a magnetic channel and a field gradient corrector. Analysis of beam behavior in the extraction region is much more complicated because the magnetic field remarkably varies in the radial direction. Electric field distribution of the deflector is not simple due to a complex change of a mechanical gap depending on the positions of septum and high voltage electrodes. Furthermore it is hard to define particle condition at the entrance of the deflector owing to the difficulty of orbit computation up to extraction.

The electric field of the deflector is represented by equivalent field reduction[6]:

$$\Delta B = \frac{\varepsilon}{300 \times \beta}, \tag{1}$$

where ΔB is in kG, ε is the electric field of the deflector in kV/cm and β is v/c. The electric field is given by:

$$\varepsilon = \frac{10^3}{c\rho_0} \times \frac{mv^2}{q} \times \frac{\Delta B}{B_0} \tag{2}$$

at around the entrance of the deflector, where B_0 is magnetic field averaged azimuthally at a curvature of ρ_0 at the entrance of the deflector. If the field reduction ratio $\Delta B/B_0$ and the curvature are approximately constant, the electric field is proportional to mv^2/q. Dependence of the electric field at the entrance of the deflector on mv^2/q obtained in practical operation is shown in Fig. 6 and Table 1. The electric fields are approximately proportional to mv^2/q. The electric fields are not corrected for positional dependence of the deflector on the magnetic field. The dashed line represents the calculated electric field obtained by a linear fitting for the ions. There is the upper limit of the electric field in actual use in the cyclotron. The maximum electric field is required for extracting 90 MeV protons. The entrance of the deflector for 90 MeV protons should be located at outer position in order to reduce the electric field. Actually the position for 90 MeV protons is outer than that for the other ions. We have extracted 90 MeV protons with the electric field of 140 kV/cm which is 70% of the predicted ones.

Dependence of the electric field on the entrance position of the deflector for 70 MeV protons by preliminary analysis is shown in Fig. 7. The electric fields are obtained by averaging the field at the entrance, mid and exit positions. The calculated electric fields are determined as follows; 1) Positions and momentums at the

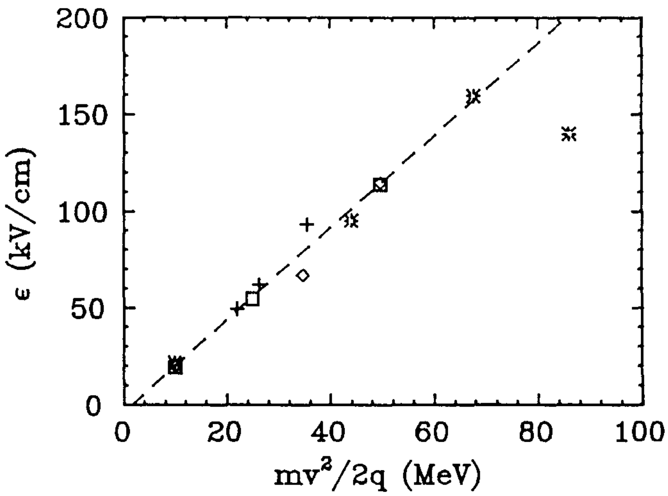

Fig. 6. Dependence of the electric field at the entrance of the deflector on mv^2/q obtained in practical operation. The measured electric fields are indicated by stars for 10 MeV, 45 MeV, 70 MeV and 90 MeV protons, diamonds for 10 MeV, 35 MeV, and 50 MeV deuterons, squares for 20 MeV, 50 MeV and 100 MeV $^4He^{2+}$ and crosses for 175 MeV $^{40}Ar^{8+}$, 460 MeV $^{40}Ar^{13+}$ and 520 MeV $^{84}Kr^{20+}$. The electric fields obtained by a linear fitting for all but 90 MeV protons are represented by a dashed line.

entrance of the deflector are obtained by tracing a central particle from the exit of the inflector. 2) The gap and position of the electrodes are fixed to the actual ones. 3) The electric fields are determined so that the particle should reach the center position of the exit gap. The position dependence of the calculated electric field is consistent with the actual dependence. The calculated fields are, however, higher by around 5% than the actual ones. Precise analysis for the position dependence of the electric field is required.

5. SUMMARY

Beam studies for study of beam behavior in the central and extraction regions have been carried out for the JAERI AVF cyclotron. The cyclotron has more phase acceptance than that of the injection beams. Isochronous fields were generated in practical operation with an accuracy of 1 gauss by using the phase probe. Generation of the isochronous field is cross-checked by small changes of rf of $\Delta f/f = 2 \times 10^{-4}$ to 5×10^{-4}. The phase probe is quite useful for generation of the isochronous field. The actual electric fields of the deflector are approximately proportional to mv^2/q except for 90 MeV protons. Dependence of the field on the entrance position of the deflector was surveyed by the computer code.

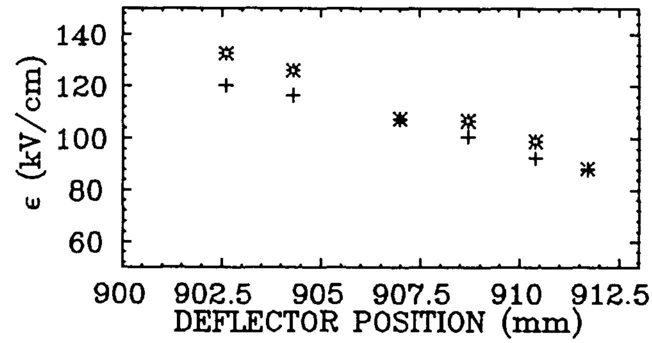

Fig. 7. Dependence of the mean electric field on the entrance position of the deflector for 70 MeV protons by preliminary analysis. The actual and calculated fields are indicated by crosses and stars, respectively.

Table 1. Dependence of the electric field at the entrance of the deflector on mv^2/q obtained in practical operation.

ε(kV/cm)	ion	$mv^2/2$(MeV)	q	B(kG)	h
19	He	20	2	5	2
20	D	10	1	7	2
21	H	10	1	5	2
49	Ar	175	8	16	3
54	He	50	2	11	2
62	Kr	520	20	16	2
67	D	35	1	13	2
93	Ar	460	13	16	2
95	H	45	1	11	1
114	He	100	2	16	1
115	D	50	1	16	1
140	H	90	1	15	1
160	H	70	1	13	1

6. REFERENCES

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