ISOCHRONOUS FIELDS FOR RIKEN RING CYCLOTRON

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Summary

Measurement of magnetic field of the sector magnet was made, and the procedure to produce the isochronous field by use of the data was examined. Results of the measurement as well as the details of the procedure are described.

1. Introduction

The RIKEN ring cyclotron is a multi-particle and variable-energy machine and can accelerate ions ranging from proton to uranium in a wide range of energies. Considerably different distributions of isochronous fields are required for different masses and energies of accelerated particles. In our cyclotron twenty-nine pairs of trim coils are wound on the pole surface of the sector magnet to meet the above requirement.

In the actual operation, the final tuning of the magnetic field will be done with the help of twenty pairs of phase probes that are installed in the valley region of the cyclotron. To make such an operation easy, extensive data, used to obtain the isochronous field as close to the ideal one as possible, have been taken for the sector magnet. In this paper the results of the measurement and the procedure to produce the isochronous field in our cyclotron will be presented.

2. Magnetic field of the sector magnet

Main part of the measurement of magnetic field of the sector magnet was performed in 1985. (At that time the vacuum chamber had not been installed.) In the summer of 1986, after the installation of the vacuum chamber, the measurement was made again only along the center line of the sector magnet.

2-1. Excitation procedure

During the first stage of the measurement, the procedure to excite the sector magnet was studied in order to obtain a reproducible and fast-stabilizing field distribution. From the examination of various modes of procedures, it was found that the best procedure is the following: firstly, the magnet is excited by use of all the main and trim coil power supplies up to the maximum field level, and then it is de-excited before reaching the required field level. The former process is essential to obtain reproducible distribution and the latter is necessary to stabilize the distribution as quickly as possible. Figure 1 shows the time chart of this procedure. Reproducibility of the field distribution along the sector-center line was found to be better than 5×10^{-4}. In particular, the reproducibility becomes as good as 1×10^{-4} at a time when the field conditions just before the excitation are similar to each other. The time required to reach a stable field level is about 1.5 h for higher excitation levels and 3 h for the lowest.

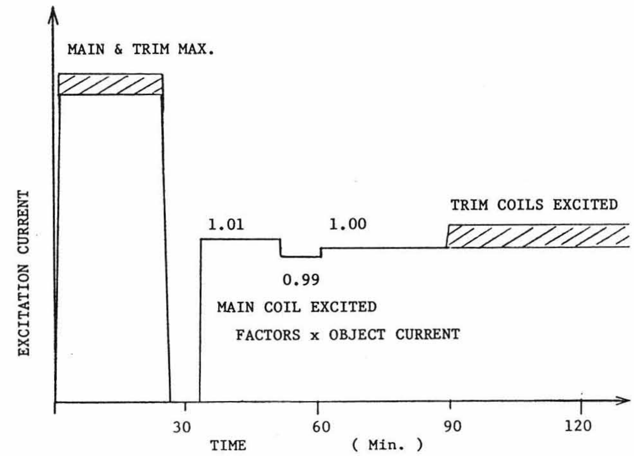

Fig. 1. Time chart for exciting the sector magnet.

2-2. Base and trim coil field distributions

Base and trim coil fields were measured along the sector-center line at an interval of 10 mm for seven levels of main coil currents (300, 520, 640, 710, 800, 940 and 1050 A). These main coil currents correspond to the base fields of 6, 10, 12, 13, 14, 15 and 15.5 kG (maximum), respectively.

The measurement of base fields was made for four sector magnets. The base field distributions at the seven levels for the N-sector magnet are given in Fig.2. Difference of the base field distributions among

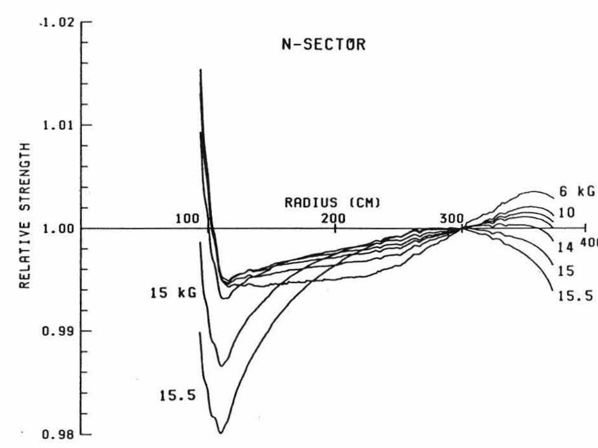

Fig. 2. Base field distributions along the center line of the N-sector magnet at seven levels of main coil currents.

four sector magnets was 5×10^{-3} at the maximum. This value is small enough compared with a value of 2.5×10^{-2} up to which the power supply can adjust independently the field levels of the four sector magnets. The differences among the four sector magnets at 800 A (14 kG) are given in Fig. 3. Steep rises of the distributions in the injection region in Figs. 2 and are due to the iron shims that are placed beneath the trim coils. They were placed in order to help the required currents of trim coils in that region being reduced. Their thicknesses were determined using the field data taken in 1985, and they are 1, 0.5, and 2 mm for the regions covered with the trim coils No.1-3, No.4 and about half of the coil No.5, respectively.

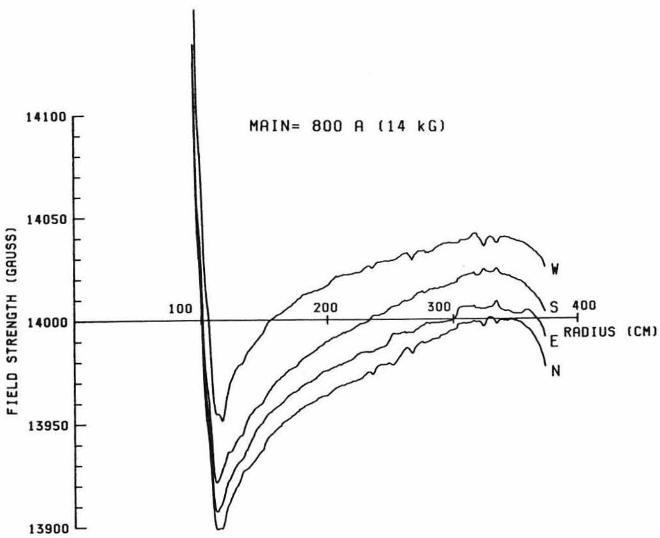

Fig. 3. Differences of the base field distributions among four sector magnets at 800 A (14 kG).

The measurement of trim coil fields was performed for one sector magnet only (the S-sector magnet). Three levels of currents were fed for each trim coil to obtain a non-linearity of the effectiveness of the trim coil field. For the first cycle, every coil was excited coil by coil by one-third of the maximum current of its power supply and the field distribution was measured at each step. In the same way, for the second cycle two-thirds of its maximum current was fed to each coil and, for the last cycle its maximum current. It is noted that the current once fed to a coil never be switched off again throughout the above procedure. This is because we found, in a preliminary measurement, that the data taken in such a way that the current was switched off after each step of measurement gave a poor prediction for an isochronous field distribution. The poor prediction comes from the hysteresis of trim coil fields. The measurement at each step was started 10 to 15 min after excitation of a trim coil. Figures 4 a) and b) show examples of trim coil field distributions. These were taken at base fields of 6 kG and 15.5 kG (maximum field level), respectively, for the first cycle of the measurement. It is noted that the return leads of the coils from No.1 to No.7 are wound around the nose of the pole and the other around its back.

After the last cycle of the measurement of trim coil fields was finished, the distributions along the sector-center line were measured for four sector magnets. Differences of the total effectiveness of the trim coils thus obtained between the S-sector magnet and others are helpful for estimating the required trim coil currents of the sector magnets other than the S-sector magnet.

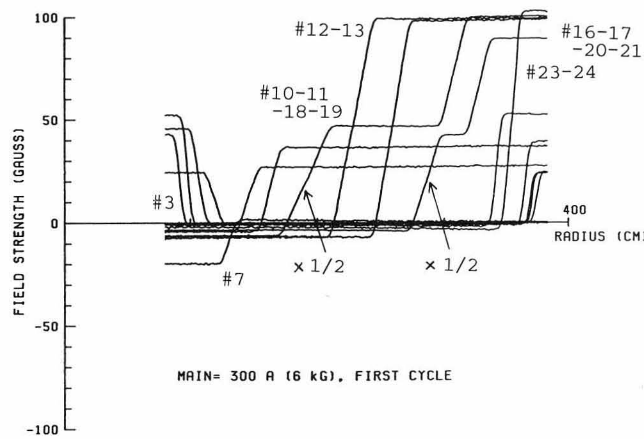

Fig. 4 a). Trim coil field distributions along the sector-center line at 300 A (6 kG). To each trim coil a third of its power supplie's maximum current, about 150 A, is fed in this case.

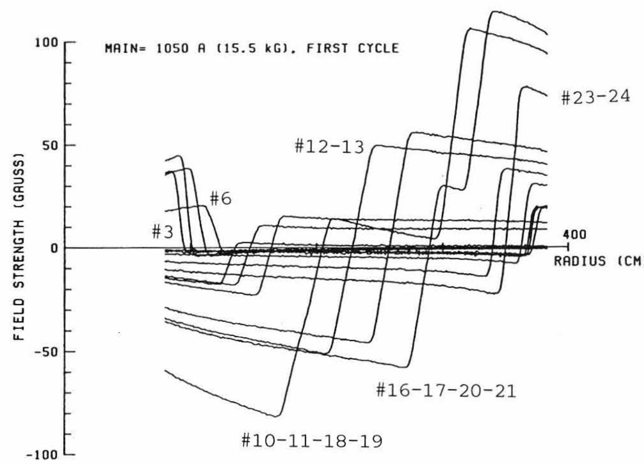

Fig. 4 b). Same as Fig. 4 a) but at 1050 A (15.5 kG; maximum field level).

2-3. Field map

To obtain the required isochronous field distribution along the sector-center line, we have adopted a method similar to that used at GANIL.[1] In this method, equilibrium orbits are calculated and the ratios between the field strength and the radius averaged along the orbits ($\overline{B}$ and $\overline{R}$) and those at the sector-center line (B_{ax} and R_{ax}),

$$K_b = B_{ax}/\overline{B}, \quad K_r = R_{ax}/\overline{R}, \qquad (1)$$

are obtained.

Map data of the field distributions are then indispensable for that purpose. Measurement of the field map was carried out under two situations. One is the situation in which no injection and extraction elements are present inside or around the sector magnets (unperturbed field) and the other the situation in which the injection elements are present (perturbed field). In the measurement of perturbed fields, no extraction elements were set because otherwise the map data could not be taken owing to their disturbances to the measuring apparatus. There was, however, no problem because perturbations caused by these elements had been found to be negligible from another measurement.

Unperturbed fields were measured only for the S-sector magnet at the seven field levels. Not only the base field distribution but also the field distributions when the trim coils were excited were measured for each level. The latter measurement is necessary because in our case the field rise of an isochronous field is rather high for some kinds of ions and, therefore, the azimuthal distribution is expected to change largely according to the trim coil currents. Every trim coil was excited to half the maximum and the maximum of its power supply. Thus a total of 21 map data were taken for unperturbed field distributions. The azimuthal range of the map was 90° (from valley to valley) with intervals of 0.25°, 0.5°, 1° and 2° according to the sharpness of the azimuthal distribution. The radial interval was 20 mm over the whole region. The number of the mesh points was 15,765. It took about 4.5 h for each measurement.

Perturbed field distributions were measured for four sector magnets. Each injection element was excited corresponding to the main coil current during the measurement, and the trim coils were not excited at all. The radial interval was taken to be 35 mm in order to reduce the measuring time. The time taken for each measurement was 2.5 h. Perturbations due to the injection elements were observed, more or less, in all the sector magnets.[2] Among them the largest one is the perturbation due to the injection bending magnet (BM1). These perturbations themselves, however, were not compensated because from the computer simulation harmonic fields produced by them were found to be harmless for the motion of an accelerated beam.

3. Isochronous field

By use of the above data, an isochronous field distribution along the center line of each sector magnet can be calculated and the optimum currents of main and trim coils to produce it can be obtained.

The procedure to obtain K_b and K_r values in eq. (1) for each sector magnet for perturbed fields (actual fields) is as follows: at first, equilibrium orbits and average field strengths along these orbits are calculated in the unperturbed field for the three cases of trim coil currents with zero, their half maximum and maximum. Then, the effects of the injection elements on K_b values are calculated by taking the difference of field strengths between the perturbed field and the unperturbed field with the trim coil currents equal to zero. At that time these two field distributions are normalized to each other at the sector-center line. It was assumed that the above effects do not depend on the trim coil currents. K_b values for perturbed fields are thus obtained. (K_r values were assumed to be the same as those for unperturbed fields.) These K_b and K_r values are calculated for each sector magnet for a number of combinations: seven excitation levels of main coil currents of 300, 520, 640, 710, 800, 940 and 1050 A repeated with three cases of all the trim coil currents at zero, their half the maximum and the maximum power levels. Figure 5 shows K_b and K_r values for the S-sector magnet for seven levels of main coil currents with the trim coil currents being zero. Their dependence on the excitation level of the trim coils at a main coil current of 800 A is shown in Fig. 6. The

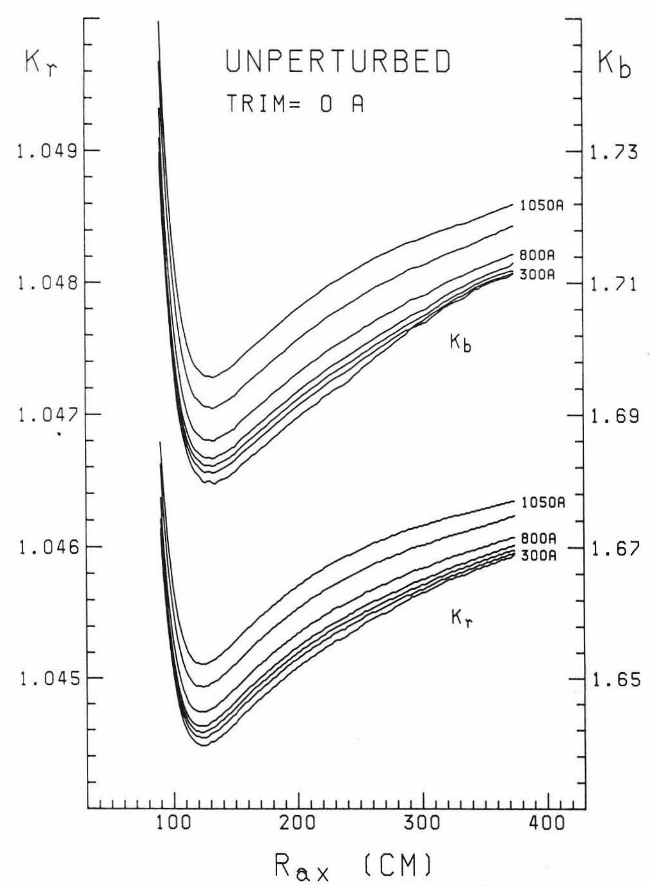

Fig. 5. K_b and K_r values for the unperturbed fields for seven levels of main coil currents. Trim coil currents are zero.

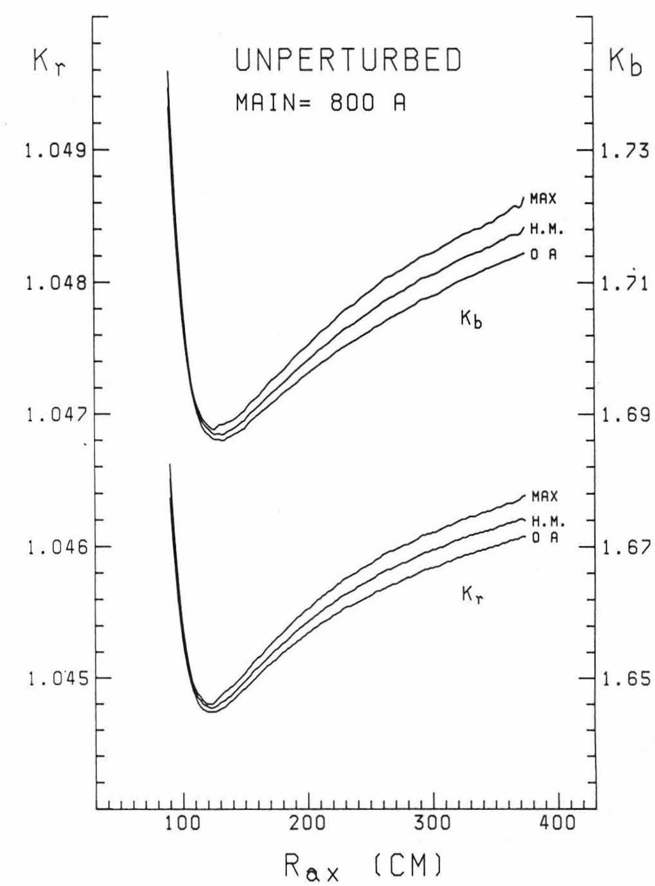

Fig. 6. Dependence of K_b and K_r values on the excitation level of the trim coils. Main coil current is 800 A.

rise of the distributions in the injection region results from that the effective sector angle in that region is small as compared to other regions because both sides of the nose part of the sector magnet have been cut away in order to keep a wider space between magnets for inserting the rf resonators. In Fig. 7 is shown the comparison among the required distributions of the isochronous field of 21 MeV/u Ar ion (10.5 kG - 11.0 kG), which is expected to be the first ion to be accelerated, along the sector-center lines that are calculated for the four sector magnets. The rises of the distributions in the injection region for the E- and S-sector magnets show that higher currents are necessary for the trim coils in that region of these sector magnets in order to compensate the perturbations due to the BM1.

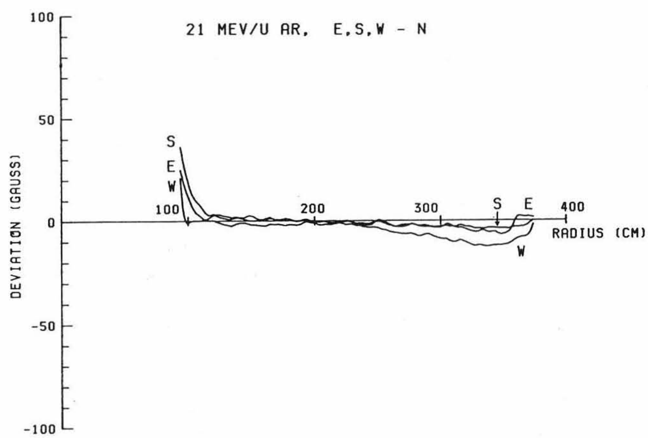

Fig. 7. Comparison among the required distributions of the isochronous field of 21 MeV/u Ar ion along the sector-center lines that are calculated for the four sector magnets. Differences from the distribution for the N-sector magnet are shown.

The distribution along the sector-center line required for an isochronous field of accelerated ion is obtained by the interpolation using the above data base. The next step for producing the isochronous field is to calculate main and trim coil currents. Their optimum currents are automatically searched with the computer program code. It is noted that there are no data of trim coil fields for sector magnets other than the S-sector magnet. Therefore, the required distributions along the sector-center line for these sector magnets are modified by taking account of the differences of the total effectiveness of all the trim coils among four sector magnets as mentioned in sect. 2-2. In a similar way, in addition to the above modification, the effect of the vacuum chamber made of stainless steel and that of the iron shims on the trim coil fields are also taken into account for the calculation of the required isochronous field distribution. This is necessary because the field distributions of each coil were measured when the vacuum chamber and the iron shims had not been installed. Calculations of the fitting were done for several kinds of typical ions. They confirmed that the sector magnet system can produce an isochronous field of any kind of accelerated ion. Figure 8 shows the result of the fitting for the isochronous field distribution of 21 MeV/u Ar ion for the S-sector magnet. The currents thus obtained were actually fed to the main and trim coils, and the field map was measured for each sector magnet. In Fig. 9 is shown the deviation between the expected isochronous field distribution and the measured one along the sector-center line of the S-sector magnet.

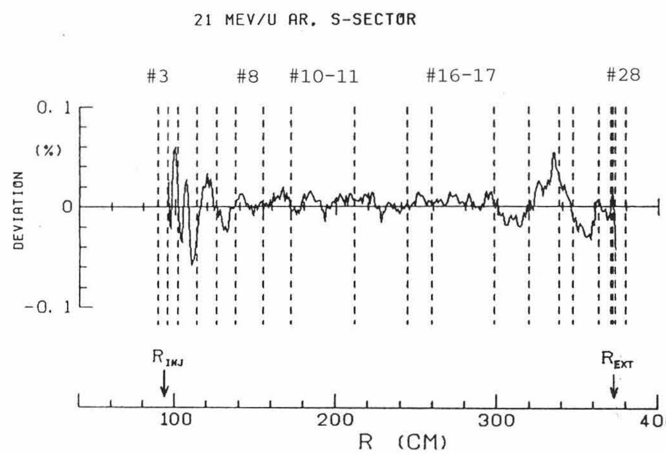

Fig. 8. Fitting for the isochronous field distribution of 21 MeV/u Ar ion. Calculation was done for the S-sector magnet. Dashed lines show the boundaries of the trim coils.

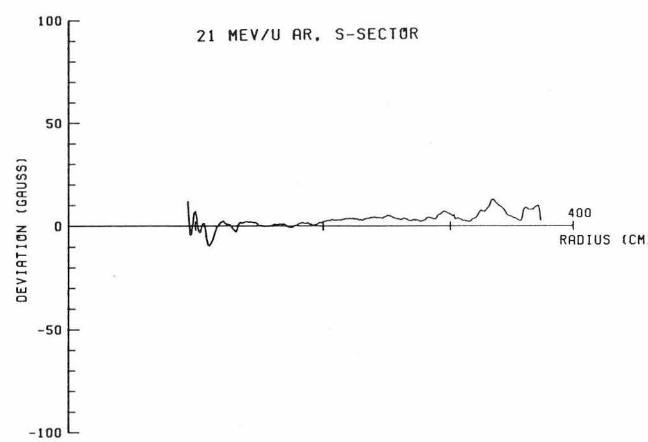

Fig. 9. Deviation between the expected isochronous field distribution of 21 MeV/u Ar ion and the measured one. Comparison was made for the S-sector magnet.

4. Conclusion

Magnetic fields of the sector magnet were measured. From the extensive data the K_b and K_r values have been obtained for the four sector magnets at various combinations of levels of main and trim coil currents. These extensive data base are used to produce an isochronous field of any kind of accelerated ion. It is concluded from the measurement and the computer simulation that only slight adjustment of the field will be necessary in the actual operation to accelerate a beam successfully.

References

1. M.Barre et al., Proc. of the 9th Int. Conf. on Cyclotrons and their Applications, Caen, (1981) 371.
2. Y.Yano et al., 'Beam Injection and Extraction System of RIKEN Ring Cyclotron', this conference.