Magnetic system of the heavy ion cyclotron for track membranes production

Yuri G. Alenitsky,
Nikolai L. Zaplatin,
Leonid M. Onischenko,
Eugene V. Samsonov,
Alexander F. Chesnov

Abstract A heavy ion fixed energy cyclotron based on a conventional magnet with a pole diameter of 1.6 m is designed and constructed in JINR. Ions with A/Z = 5 are accelerated up to the energy E = 2.4 MeV/nucleon. The isochronous magnetic field is formed by four pairs of sector shims. The beam phase shift in formed field is less than $\pm15°$RF, and the first harmonic of magnetic field is less than 3 G for all radii of the beam acceleration. Power consumption of magnet is 25 kW. The ECR source with an intensity of 3.5×10^{12} ions/s is used as an ion source. The extracted beam ($\sim10^{11}$ ions/s) is intended for the track membrane production.

Key words cyclotron • magnetic system • sector shim • heavy ions beam

Yu. G. Alenitsky✉, N. L. Zaplatin, L. M. Onischenko,
E. V. Samsonov, A. F. Chesnov
Dzhelepov Laboratory of Nuclear Problems,
Joint Institute for Nuclear Research,
6 Joliot-Curie Str., 141980, Dubna, Russia,
Tel.: +7/ 096 21 62344, Fax: +7/ 096 21 66666,
e-mail: alen@nusun.jinr.ru

Introduction

An isochronous cyclotron for accelerating heavy ions with A/Z = 5 up to the energy 2.4 MeV/nucleon is designed and constructed at the Joint Institute for Nuclear Research at Dubna. The magnetic field of this cyclotron is formed by means of H-shape yoke, main coils and poles, 1.6 m in diameter. The gap between the poles is 100 mm. The four pairs of sector shims are installed in this gap symmetrically up and down to produce axial focusing. The gap between the shims is 40 mm. The choice of main parameters of the magnet and forming of the isochronous field are described.

Main parameters of the cyclotron magnetic system

Analytical formulas assuming a uniform magnetization of the magnet element were used for preliminary choice of the magnet structure. A 2D computer simulation based on a mesh technique was used to check this choice. To find the final form of the sector shims, the magnetic model on a scale 1:2.5 was constructed [1].

The main parameters of magnetic system are given in the Table 1 and the plane view is shown in Fig. 1.

The H-shape electromagnet is used for cyclotron. Poles and yokes of the magnet have axial holes for an axial injection. Four pairs of sector shims are placed on the poles to produce axial focusing. At the same time, an increase in their angular size with radius is used to form the isochronous magnetic field.

For magnetic field measurement a measuring system was designed and constructed, which consists of:
1. A mechanical system which produces both azimuthal (by a step motor) and radial (manually) the Hall probe moving.

Table 1. Cyclotron magnetic system parameters.

Parameter	Size
Overall dimensions of yoke (mm^3)	$3700 \times 2000 \times 1650$
Diameter of poles (mm)	1600
Gap between poles (mm)	100
Diameter of an axial hole (mm)	
in horizontal yokes	250
in poles	100
in the central insertions	20
Weight of iron (T)	83
Angular size of sectors (degree)	30–41.8
Height of sector shims (mm)	30
Angular size of valley shims (degree)	0–5.9
Height of valley shims (mm)	2–4
Gap between coils (mm)	200
Cross sections of the coil (mm)	260×200
Cross section of the coil on copper (mm)	220×160
Ampere – turns of a winding (kA)	~95
Cross section of the conductor, copper (mm)	18.5×18.5
Number of turns	
in pancake	22
in the coil (4 pancake)	88
in a winding (2 coils)	176
Current (A)	524
Current density (A/mm^2)	2.84
Resistance of a winding (Ohm)	0.078
Voltage on a winding (V)	50
Power consumption (kW)	25
Weight of copper (t)	2.4

2. A PC with programs for measuring the system control and for preliminary computing of measurement results.
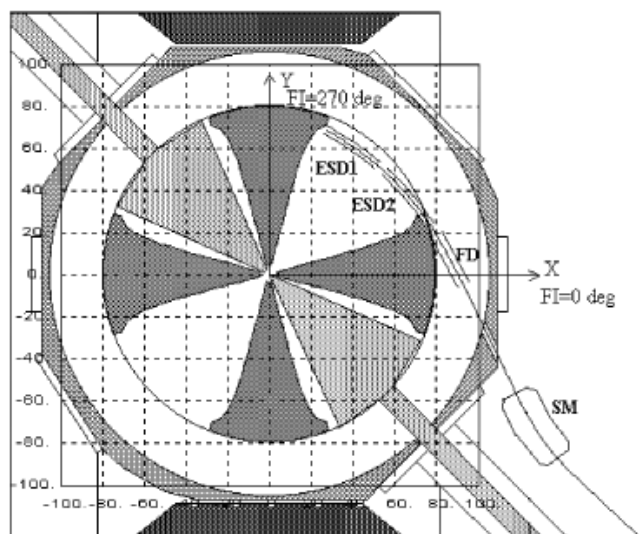
Fig. 1. A plane view of cyclotron magnetic system with four sector shims, two dees, system of extraction and bending magnet (SM).

The axial betatron frequency Q_z is equal to (0.05–0.4) inside the radial range (0.05–0.75) m, while the radial betatron frequency Q_r changes from 1.0 to 1.01. Closeness of Q_r to unity requires to form a average magnetic field with high accuracy and establishes an upper limit for the first harmonic as small as 3 G. Two opposite valleys are used for the dees, one for the electrostatic deflectors and the second for the NMR probe to control the exact value of the magnetic field.

During the magnet production all measures were taken to fabricate the gap between poles ($h = 100$ mm) and the gaps between all four pairs of sector shims ($h = 40$ mm) with the accuracy $\Delta h < 0.05$ mm. To guarantee this requirement all planes of the yoke parts and of poles, which come into contact with each other, were polished. In spite of these efforts, the gaps between the sectors were found (after installing the magnet on the place) to exceed the nominal size of 40 mm by (0.06–0.13) mm. Then, stainless steel inserts of proper size 40.1 ± 0.001 were fabricated and installed between each pair of sectors at radii 780–800 mm where they do not cross the beam path.

Formation of cyclotron magnetic field

The proper dependence of the average magnetic field on radius is created, basically, by increasing the angular extent of sector shims $\alpha = 30$–41.8°. In addition, the valley shims are provided for exact shimming of the average field and for correction of the first harmonic. The external borders of the valley shims (designed and chosen) are shown in Fig. 2.

Sector shims, whoby form was chosen by modelling, were fabricated (Fig. 3) by a factory with high accuracy. The result of measuring the magnetic field without valley shims is shown in Fig. 4 (curve 1). It is evident that the magnetic field in the range of $R = 660$–740 mm is higher than needed even without the valley shims. Hence, the only possible decision was to extract some part of steel from the sector shims. To find experimentally the proper quantity of steel which has to be extracted, some of steel bolts which
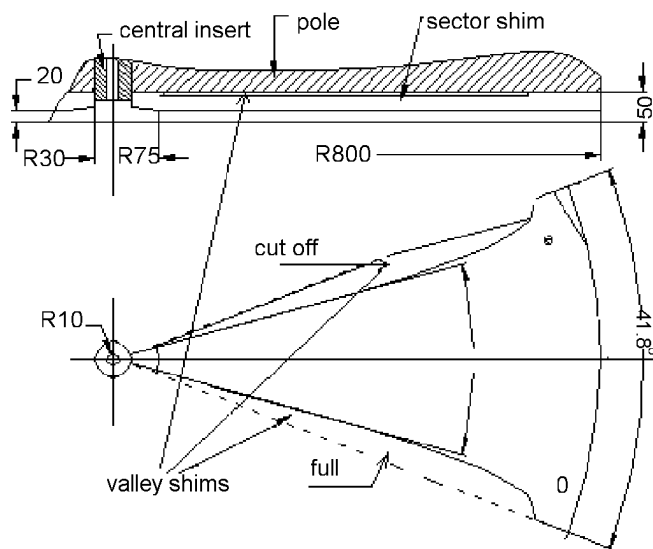

Fig. 2. Pole with sector and valley shims: up – cross section; down – plane view.

Fig. 3. In foreground – bottom pole with vacuum chamber, on the left – top pole with cover of vacuum chamber.

fix the sector shims to the pole at a radius of 710 mm were changed by stainless steel bolts. Using the results of these experiments it was decided to make in each sector shim two 21 mm holes placed at the 740 mm radius at an angle of 17°, symmetrically to the axe of the sector shims (Fig. 2).

The obtained average field with such holes is shown in Fig. 5 (curve B19). This field is lower than needed one and, therefore, the valley shims were used to form the needed field. The average field produced by the valley shims of different size is shown in Fig. 6. The final average magnetic field formed with the valley shims is shown in Fig. 5 (curve B21). The corresponding beam phase shift does not exceed $\sim \pm 15°$RF Fig. 5 (curve dFi).
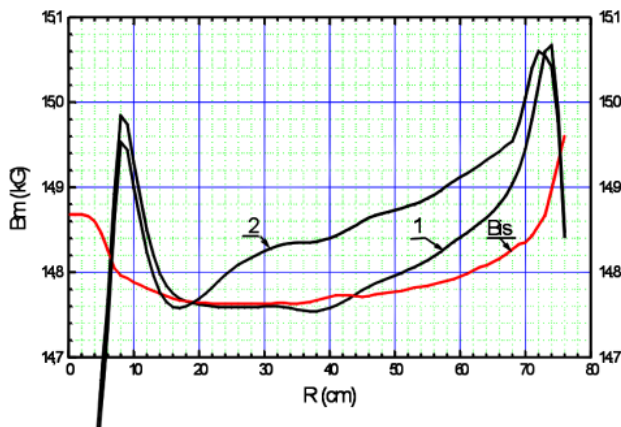

Fig. 4. Average magnetic field: Bis – designed; 1 – measured without valley shims; 2 – measured with full valley shims.
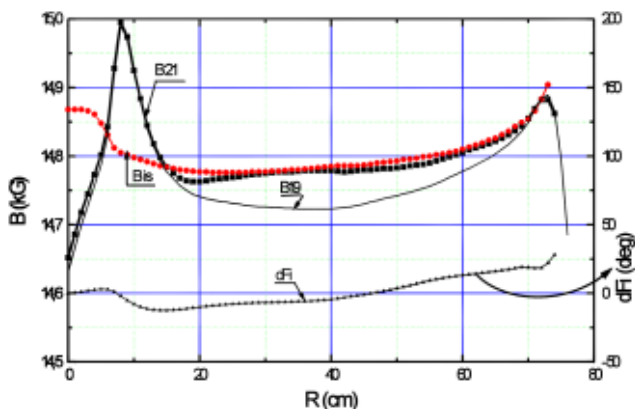

Fig. 5. Average magnetic field (AMF): Bis – designed; B19 – AMF without valley shims; B21 – final AMF, after shimming; dFi – calculated beam phase shift.
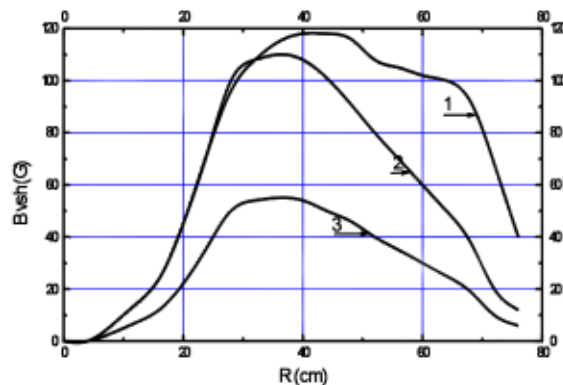

Fig. 6. Average magnetic field of valley shims: 1 – full; 2 – cut off; 3 – cut off and thin.
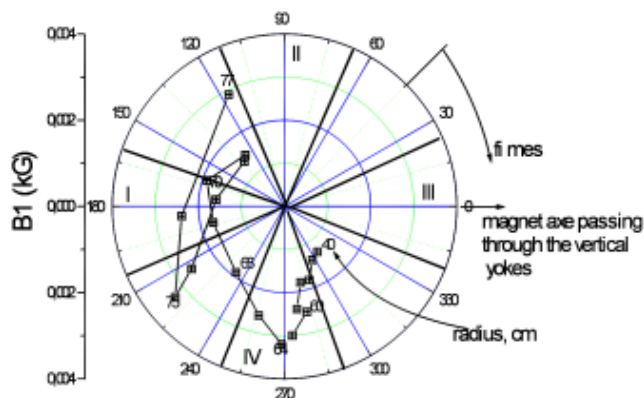

Fig. 7. Amplitude and phase of the first harmonic of a magnetic field.

The first harmonic B1 of the magnetic field was found less than 5 G just after installation of the magnet. This good result can be explained by the high accuracy of fabrication and assembling of the magnet. Rather small changes of valley shims have allowed to decrease B1 < 3 G. Amplitude and phase of the first harmonic for different radii are shown in Fig. 7. For radii $R < 40$ cm B1 is less than 2 G.

Conclusion

The analytical formulas, the 2D computer simulation and the modelling of the magnet element were used for preliminary choice of the magnet structure. For exact isochronous magnetic field forming, the valley shims were used. The small value B1 – the first harmonic is as a result of the high accuracy of fabrication of the ferromagnetic elements. As a result, the high accuracy of isochronous magnetic field in this cyclotron was exceeded.

In August 2002, the beam $^{40}Ar^{8+}$ of the ions was accelerated up to the final radius, beam loses during acceleration being in significant [2].

References

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