MODELING AND FORMING THE MAGNETIC FIELD OF THE HEAVY ION CYCLOTRON

Yu.G.Alenitsky, A.F.Chesnov, S.A.Kostromin, L.M.Onischenko, E.V.Samsonov, N.L.Zaplatin
Dzhelepov Laboratory of Nuclear Problem, Joint Institute for Nuclear Research, 141980, Str.Joliot-Curie, 6, Dubna, Russia, fax:+7-09621-66666
E-mail alen@nusun.jinr.ru

The heavy ion cyclotron was designed and constructed in the Dzhelepov Laboratory of Nuclear Problem, Joint Institute for Nuclear Research. Ions with A/Z~5 were accelerated up to the energy E=2.4 MeV/nucleon. The ECR source with an intensity of $3.5\cdot10^{12}$ ions/sec is used as an ion source. The extracted beam of $\sim10^{11}$ ions/sec is intended for the track membrane production. The magnetic field of this cyclotron is formed in the compact magnet with the pole diameter 1.6 m by means of four pairs of sector shims installed symmetrically up and down. The gaps are 100 mm, and 40 mm between the poles and shims, respectively. The proper dependence of the isochronous magnetic field on the radius is created, basically, by increasing the angular extension of sector shims inside the range α = 30º...41.8º. Power consumption of an electromagnet is 25 kW.

PACS: 29.20.Hm.

1. INTRODUCTION

The heavy ion fixed energy cyclotron based on the compact magnet with the pole diameter 1.6 m was designed and constructed in JINR. The ions with A/Z=5 were accelerated up to the energy E=2.4 MeV/nucleon for track membrane production. The isochronous magnet field is formed by means of the fore pair of sector shims. The beam phase shift in the formed field is less then ± 10º of RF, and the first magnetic field harmonic is less then 3 G in all the radii of the beam acceleration. Power consumption of the magnet is 25 kW. The analytical formulas assuming a uniform magnetization of the magnet elements were used for the preliminary choice of the magnet structure. The 2D computer simulation based on a mesh technique (FEMM) was used to check this choice. To find the final form of the sector shims the magnetic model with scale 1:2.5 was constructed. The 3D computer simulation based on RADIA code was made to determine an influence of some parts of the magnet on the field structure. The choice of main parameters of the magnet and the modeling and forming the isochronous field are described below.

2. CHOICE OF THE BASIC PARAMETERS OF THE MAGNETIC SYSTEM

Analytical formulas assuming a uniform magnetization of the magnet elements were used for the preliminary choice of the magnet structure [1]. A 2D computer simulation based on a mesh technique was used [2] to check this choice. To find the final form of the sector shims the magnetic model on a scale 1:2.5 was constructed [3]. The 3D computer simulation based on the RADIA code [4] was carried out to determine an influence of some parts of the magnet on the field structure.

The H-shape electromagnet is used for cyclotron. Four pairs of sector shims are placed on the poles to provide axial focusing. At the same time, an increase in their angular size with the radius from α=30˚ in center to α=41.8˚ at the last radii is used to form the isochronous magnetic field. Poles and yokes of the magnet have axial holes for the axial injection. The main parameters of magnetic system are given in the Table and the view of computing model is shown in Fig.1.

The basic parameters of the cyclotron magnetic system

Overall dimensions of yoke	(mm^3)	3700x2000 x1650
Diameter of poles	(mm)	1600
Gap between poles	(mm)	100
Weight of iron	(t)	83
Height of sectors	(mm)	30
Gap between coils	(mm)	200
Section of the coil	(mm)	260 x 200
Section of the coil on copper	(mm)	220 x 160
Ampere – turns of the coil	(kA)	~95
Cross section of the conductor	(mm)	18.5x18.5
Coil current	(A)	524
Voltage on the coil	(V)	50
Power consumption	(kW)	25
Weight of copper	(t)	2.4

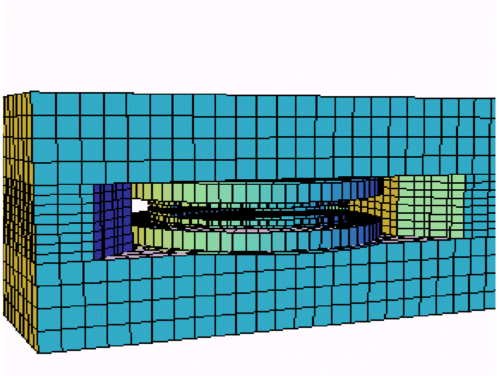

Fig.1. Main view of 3D computing model

The sector shims whose form was chosen for modeling (Figs.2,3) were fabricated (Fig.4) at the factory with a high accuracy. The valley shims applied to exact creation of the isochronous field and for correction of the first harmonic of the cyclotron magnetic field are also shown in Figs.2,3.

In the coil case of the cyclotron magnet's internal cylinder and ring inverted to the horizontal yoke are made of steel to provide a growing average field in the gap of the magnet. A quarter of the magnet pole with sector and valley shims and steel elements of the coil case are shown in Fig.2.

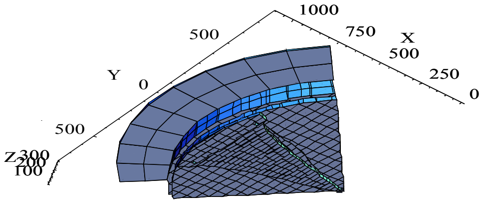

Fig.2. 3D computing model of ¼ pole, one sector and valley shims and the ferromagnetic parts of the coil case

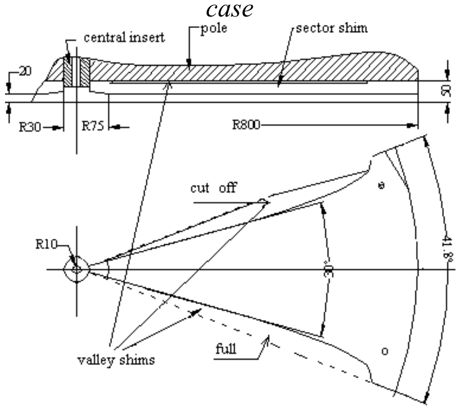

Fig.3. Pole with sector and valley shims up cross section; down-plane view

Fig.4. In foreground-bottom pole with the vacuum chamber, on the left-top pole with the cover of the vacuum chamber

An influence of steel elements of coil cases computed by the 3D code Radia on a magnetic field is shown in Fig.5. The curve dB represents a difference between the calculated average magnetic field with steel elements and without them. It is seen, that these constructive elements of the coil case create a magnetic field smoothly growing on a radius up to 300 G. The difference between the calculated dB and experimental field was found less than 10 G.

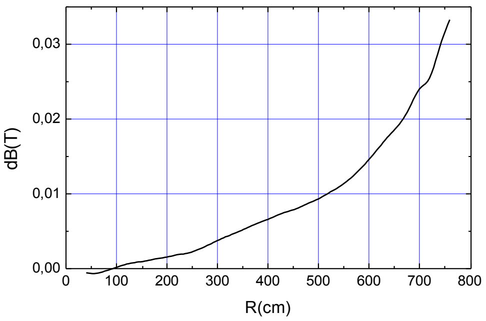

Fig.5. Magnetic field of the coils case steel elements computed by the 3D code Radia

To measure the magnetic field we have designed and constructed a measuring system comprising:

1. Mechanical system that provides both azimuthal (by step motor) and radial (manually) moving of the Hall probe.
2. PC with the codes for control of the measuring system and for preliminary computing of the measurement results.

The axial betatron frequency Q_z is equal (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 Q_r to unity requires to form the average magnetic field with a high accuracy and establishes the upper limit 3G for the first harmonic of imperfections.

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=40мм) with an accuracy $\Delta h<0.05$ mm To guarantee this requirement all planes of the yoke parts and poles that come into contact with each other were polished. In spite of these efforts the gaps between sectors were found (after installing the magnet on the place) exceeding the nominal size of 40 mm by 0.06...0.13 mm. Then stainless steel inserts of proper size 40.1±0.01 mm were fabricated and installed between each pair of sectors at radii 780–800 mm where they do not cross the beam path.

3. FORMING OF CYCLOTRON MAGNETIC FIELD

The proper dependence of the average magnetic field on radius is created, basically, by increasing the angular extent of the sector shims. In addition the valley shims are placed for exact shimming of the average field and for correction of the first harmonic. The external borders of the valley shims are shown in Fig.3. This is unique place for the valley shims arrangement, because two opposite valleys are used for the dees.

The result of measuring the magnetic field without valley shims is shown in Fig.6 (curve 1). It is evident that the magnetic field in the range of R=660...740 mm is higher then needed one 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 fix the sector shims to the pole at a radius of 710 mm were changed by stainless steel ones. Using the results of these experiments it was decided to make in each sector shim two 21 mm holes placed at the radius 740 mm at the angle 17° symmetrically to the sector shims axe (Fig.3).

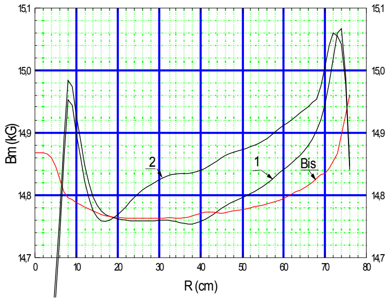

Fig.6. Average magnetic field: Bis-(required); 1-first measurement;2-measurement with valley shims

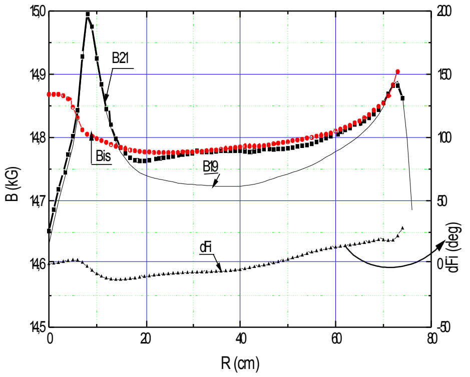

Fig.7. Average magnetic field: Bis-designed; B19-without valley shims; B21-final after shimming; dFi-calculated beam phase shift

The obtained average field with such holes is shown in Fig.7 (curve B19). This field is lower than needed one and therefore the valley shims were used to form the needed field. The final average magnetic field formed with the valley shims is shown in Fig.7 (curve B21). The corresponding beam phase shift does not exceed ~±10° RF (Fig.7, curve dFi).

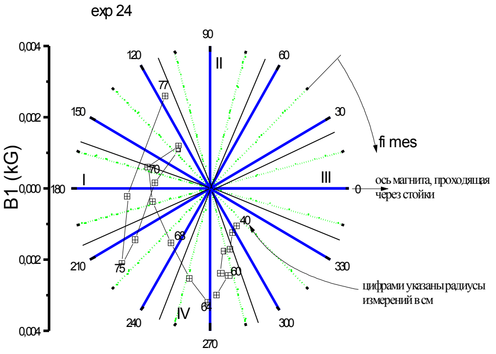

Fig.8. Amplitude and phase of the first harmonic of a magnetic field

The first harmonic B1 of the magnetic field was found less then 5 G just after installation of the magnet.

This good result is explained by a high accuracy of fabrication and assembling the magnet. Rather small changes of valley shims have allowed to decrease B1<3G. The amplitude and the phase of the first harmonic for the different radii are shown in Fig.8. For radii R<40 cm B1 is less than 2 G.

4. CONCLUSIONS

The analytical formulas, the 2D computer simulation and the modeling of the magnet element were used for the preliminary choice of the magnet structure. For exact approach to the isochronous field the valley shims were used. The small value of the first harmonic is the result of a high accuracy of fabrication of the ferromagnetic elements.

In August 2002 the beam of ions 40Ar^{8+} was accelerated up to final radius, beam losses during acceleration were not significant [5].

REFERENCES

1. V.I. Danilov. Forming the magnetic field for the accelerators with space variation, *Dissertation,* Dubna, 1959, (in Russian)
2. *httm://femm.berlios.de/index.html*
3. Yu.G.Alenitsky *et al* Modeling of the magnetic system of isochronous cyclotron CYTRECK // *Communications of JINR, P9-2002-185, Dubna,* 2002, *(in Russian)*
4. *www.Srf.fr.machine.groups.insertion.devices.Codes /Radia/RadiaTitle.html*
5. *http://trackpore.com/*

МОДЕЛИРОВАНИЕ И ФОРМИРОВАНИЕ МАГНИТНОГО ПОЛЯ ЦИКЛОТРОНА ТЯЖЕЛЫХ ИОНОВ

Ю.Г. Аленицкий, Н.Л. Заплатин, С.А. Костромин, Л.М. Онищенко, Е.В. Самсонов, А.Ф. Чеснов

Циклотрон для ускорения тяжелых ионов спроектирован и изготовлен в Лаборатории Ядерных Проблем им. В.П. Джелепова ОИЯИ. Основные параметры магнитной системы циклотрона получены на основании расчетов по аналитическим формулам, при условии равномерного намагничивания объёма ферромагнетика, а также по двухмерной программе с использованием сеточной методики (FEMM). Для выбора формы секторных шимм была изготовлена модель магнитной системы в масштабе 1:2,5. Приведены основные параметры магнитной системы и результаты моделирования и формирования магнитного поля циклотрона.

МОДЕЛЮВАННЯ І ФОРМУВАННЯ МАГНІТНОГО ПОЛЯ ЦИКЛОТРОНА ВАЖКИХ ІОНІВ

Ю.Г. Аленицький, Н.Л. Заплатин, С.А. Костромин, Л.М. Онищенко, Є.В. Самсонов, А.Ф. Чеснов

Циклотрон для прискорення важких іонів спроектований і виготовлений у Лабораторії Ядерних Проблем ім. В.П. Джелепова ОІЯД. Основні параметри магнітної системи циклотрона отримані на підставі розрахунків по аналітичних формулах, за умови рівномірного намагнічування об'єму ферромагнетика, а також по двомірній програмі з використанням сіткової методики (FEMM). Для вибору форми секторних шимм була виготовлена модель магнітної системи в масштабі 1:2,5. Приведено основні параметри магнітної системи і результати моделювання і формування магнітного поля циклотрона.