THE METHOD AND RESULTS OF FORMATION OF THE DC-60 CYCLOTRON MAGNETIC FIELD

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Abstract

The complex method and results of the DC-60 isochronous cyclotron magnetic field formation are presented. The method integrates the analytical, numerical and experimental approaches. The problems of the magnetic yoke optimization with taking into account the steel magnetic properties and deformation under the action of the magnetic forces are considered. The special attention is given to the problem of compensation of the passive magnetic channel influence. The measurements have shown what the magnetic field is formed in a good conformity with the computer simulation data. The results of the calculations and the final measurements of the magnetic field are presented.

INTRODUCTION

The isochronous cyclotron DC-60 is developed and created in Laboratory of nuclear reactions (FLNR, JINR, Dubna). The cyclotron is intended for applied and fundamental research with the accelerated beams of heavy ions from Carbon to Xenon of the energies from 0.34 to 1.77 MeV/nucleon [1]. The magnetic structure of the cyclotron allows to carry out the smooth adjustment of the beam energy over the range ± 25 % from nominal by means of variation of the average magnetic field level at the range from 1.25 T till 1.65 T.

Table 1: Main parameters of the DC-60 cyclotron

Main size of the magnet, [mm]	4000×1680×2300
Weight of the magnet [t]	103.5
Maximal power, [kWt]	≈ 45
Diameter of the pole, [mm]	1620
Distance between the poles, [mm]	176
Number of the sectors pairs	4
Sector angular extent (spirality)	52^o (0^o)
Sector height, [mm]	51.5
Distance between the sectors (magnet aperture), [mm]	33
Distance between the sector and pole (for correcting coils), [mm]	20
Number of radial coils	6
Number of azimuthal coils	4

The cyclotron magnet has "H" – shape yoke. At the working area of the magnet the four pairs of sectors form the isochronous magnetic field with the necessary focusing action. The betatron frequencies lies on the range $1.01<Q_r<1.02$ and $0.3<Q_z<0.4$.

FORMATION OF THE DC-60 CYCLOTRON MAGNETIC FIELD

Formation of the magnetic structure of the DC-60 cyclotron was carried out at the three stages [2].

At the first stage the preliminary choice of parameters of the DC-60 cyclotron magnetic structure was carried out. This choice is based on the analytical dependencies of the main cyclotron magnet parameters, obtained during the calculations and experiments at creation of FLNR cyclotrons, such as U200, U400, U400M, IC100, DC-72, U400P. These dependencies are presented at the analytical form [3] and have used to define the basic sizes and characteristics of the DC-60 cyclotron magnet.

At the second stage the computer simulation of the DC-60 cyclotron magnetic field is carried out. Simulation is carried out on the basis of 3D computer model with the help of the program complex КОМРОТ [4].

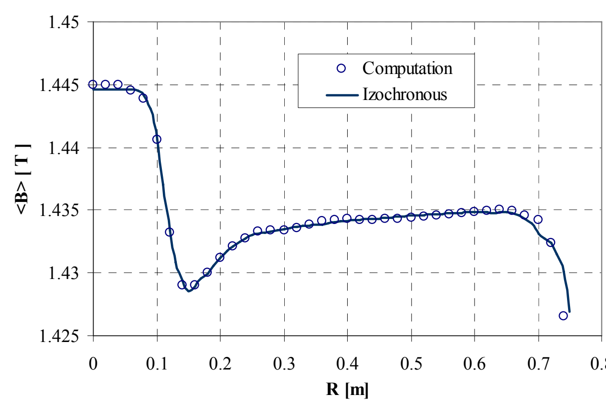

Figure 1: The isochronous magnetic field and the result of numerical formation.

As the result of simulation the straight line sectors with the flat surface are used. The sectors are placed on the magnet pole with the radial displacement with 25.6 mm from the centre of magnet. The form and position of the sectors creates the sector structure with variable azimuthal extension and allows:

- to form the isochronous magnetic field at the level 1.43T for acceleration mode of ions with A/Z=7 (see Fig. 1). The isochronous magnetic field is formed only by means of the magnet iron. Accuracy of numerical formation of the magnetic field is better than $3x10^{-4}$.

- to form the average magnetic field with almost a flat radial distribution at the range 1.25T – 1.65T. At this range the maximal average field radial growth no more then 70Gs (see Fig. 2).
- to simplify the sectors manufacturing and shimming.

6 radial and 4 azimuthal correcting coils are used for adjustment of the operating modes of the DC-60 cyclotron. The formed magnetic structure has allowed to use the low-power system of correcting coils with the maximum total power consumption no more then 400Watt per pole.

At the numerical simulation it was taken into account:

- The measured magnetic properties of the steel of the magnet yoke;
- The deformation of the magnet elements under the action of the magnetic forces;
- The influence of the passive magnetic channel (the element of the beam extraction system) upon the magnetic field.

The calculation of the magnet elements deformation under the action of the magnetic forces was carried out with the maximum level of the average magnetic field 1.65T. The distance between the magnet poles decreases on 0.2 - 0.3 mm in dependence on the efforts of the magnet fixture tightening [5]. These leads to increasing of the average magnetic field level on about 15Gs. The results of the calculation were taken into account during the magnetic field formation. The experiment has shown that the distance between magnet poles decreases on about 0.3 mm at the action of the magnetic field 1.65T.

The installation of the passive magnetic channel of the extraction system leads to:

- changing of the radial distribution of the average magnetic field;
- generation of the first harmonic of the magnetic field azimuthal distribution.

The calculation of the magnetic field with the passive magnetic channel is curried out on the computer model with 1/2 geometry of the cyclotron magnet (360^{o} on the azimuth). The calculation has shown, that the average magnetic field is changed from +5Gs in the centre of cyclotron to -18Gs at the extraction radius under the action of the passive magnetic channel. At the same time the first harmonic of the magnetic field appear with the amplitude from 0Gs in the centre of the cyclotron up to 45Gs at the extraction radius. The compensation of the passive magnetic channel influence was carried out by means of the sector shims.

At the third, experimental stage of the DC-60 cyclotron magnetic structure formation the magnetic field measurements are carried out by means of the automatic magnetometer. The magnetometer contains 8 Hall probes placed on the azimuthally moved rod. Additional, monitor Hall probe supervises the time dependence of the magnetic field during the measurements. The azimuthal range of the measurements 90^{o} or 360^{o} with the step 1^{o} or 2^{o}. The radial range of the measurements from 0 mm to 1120 mm with the step 10 mm or 20 mm. The 8 Hall probes allows to reducing the time of the measurements. One measurement takes a time from 45 minutes (azimuthal range 90^{o}, steps 2^{o} and 20 mm) till 6 hours (azimuthal range 360^{o}, steps 1^{o} and 10 mm).

The results of the magnetic field measurements have shown a good coincidence with results of the numerical simulation (see Fig. 2). At this case, the correction of the average magnetic field by means of the sector shims was not required. The deviation of the radial distribution of the measured average magnetic field from the calculation results does not exceed 10 Gs for the main acceleration area and 100 Gs in the cyclotron centre, Fig. 3.

The finite accuracy of the manufacture and assemblage of the magnet cause the first harmonic of the magnetic field. The measurements, carried out without magnetic channel installation, have shown the presence of that kind of the first harmonic with amplitude no more then 10Gs.

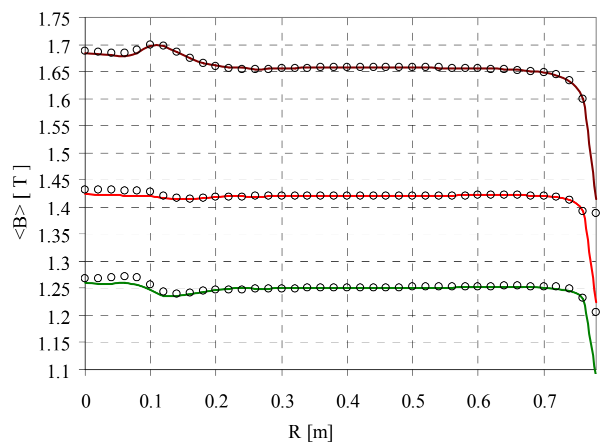

Figure 2: The calculation form of the average magnetic field (circles) and the results of the measurements (line)

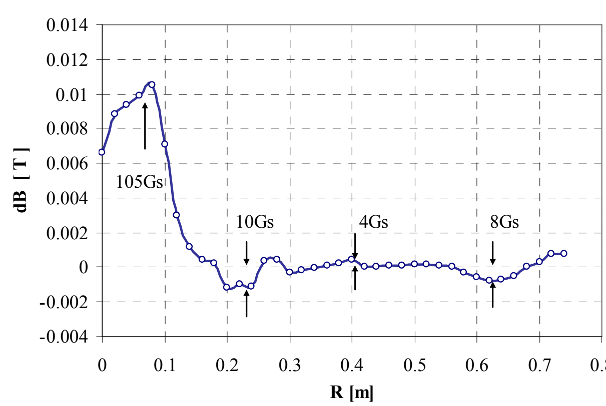

Figure 3: The deviation of the measured average magnetic field from the calculation results, 1.43T

The complex correction of the DC-60 cyclotron magnetic field is curried out. The complex correction includes:

- the correction of the average magnetic field errors, caused by the installation of the magnetic channel.

- the compensation of the first harmonic, caused by finite accuracy of the magnet manufacture and assemblage;
- the compensation of the first harmonic, caused by the installation of the magnetic channel.

In the frame of the complex correction the total first harmonic is calculated. The total first harmonic is the sum of the first harmonics, caused by finite accuracy of the magnet manufacture and assemblage and by the installation of the magnetic channel. From these calculations the necessary form and position of the sector shims are defined.

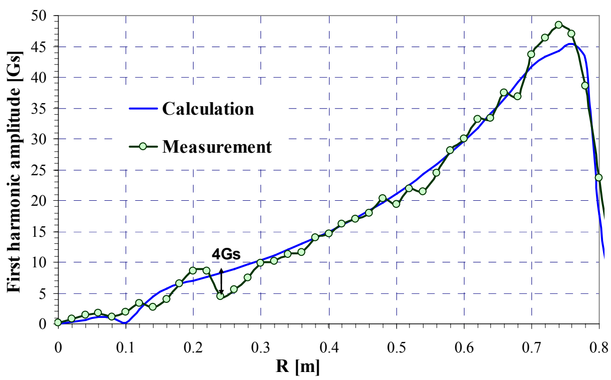

Figure 4: The calculation and measured form of the first harmonic amplitude at the case of the sector shims installation, but without the magnetic channel.

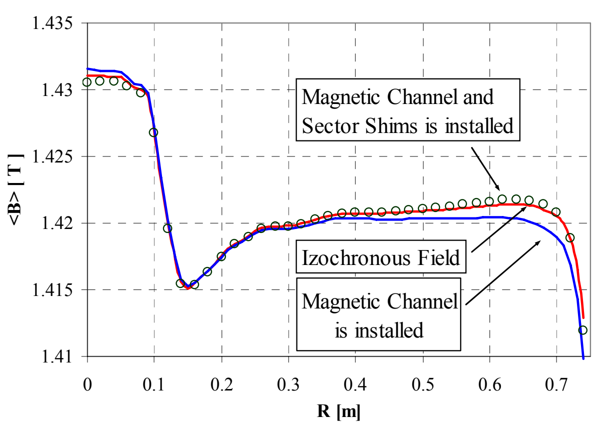

Figure 5: The form of the average magnetic field at the case of: isochronous distribution; with installation magnetic channel only; with installation both magnetic channel and sector shims.

The installation of the magnetic channel on the DC-60 cyclotron magnet prevents the movement of the magnetometer rod. To check-up the results of the complex correction the measurements of the magnetic field are curried out without installation of the magnetic channel, but with the sector shims.

At this case the measured first harmonic should have the same amplitude as the amplitude of the first harmonic caused by the magnetic channel installation (see Fig. 4), but with the opposite direction of the phase.

As a result of the complex correction the amplitude of the rest first harmonic does not exceed 4Gs that is sufficient for a normal operation of the cyclotron.

The installation of the sector shims has allowed to correct the average magnetic field distortion, induced of the magnetic channel. The maximum deviation of the resulted average magnetic field from the isochronous no more then 4Gs, (see Fig. 5). So, the installation of the sector shims produce the complex correction both the total first harmonic and the average magnetic field.

CONCLUSION

The magnetic field of the DC-60 cyclotron is formed in a good conformity with the computer simulation data. In 2006 the DC-60 cyclotron is assembled and put into operation at Interdisciplinary Scientific-Research Complex (ISRC), Astana, Kazakhstan. The experiments on acceleration of the beams of nitrogen, argon, krypton ions ($^{14}N^{2+}$, $^{40}Ar^{4+}$, $^{40}Ar^{5+}$, $^{40}Ar^{7+}$, $^{84}Kr^{12+}$) were curried out at the various levels of the magnetic field 1.25T - 1.65T as well as for fourth and sixth RF harmonics operation modes. The formed magnetic field has allowed to carry out acceleration of the ion beams with efficiency up to 95 % from internal radius (R=120 mm) to extraction radius of the cyclotron (R =690 mm).

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