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MODELING OF THE MAGNETIC SYSTEM OF THE CYCLOTRON OF MULTICHARGED IONS

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Abstract

This paper presents the results of the calculation of the magnetic system of the cyclotron for accelerating of multicharged ions developed at NIIEFA JSC. The cyclotron complex is designed to generate ions with a mass-to-charge ratio in the range A/Z= 3÷7, accelerate them to energies in the range of 7.5-15 MeV per nucleon. The cyclotron electromagnet has a four-sector structure, with a pole diameter of 4 m. Radial coils placed on the poles under the sectors are designed to adjust the magnetic field for providing isochronous acceleration conditions for different ions. A group of azimuthal coils designed to correct the first harmonic of the magnetic field and to center the orbits of the accelerated ion, as well as to adjust the position of the axial symmetry plane of the magnetic field is located on the sectors. The required magnetic field topology for ion acceleration was formed in the induction range of 1.29-1.6 T. Calculations were performed for the 1/8 part of the electromagnet. A mode was chosen in which the dependence of induction on the radius, which provides isochronism, is realized due to the shape of "iron". For this mode with an induction in the center of 1.44 T, the shape of side plates, plugs, and sector chamfers was determined. The currents in radial coils and the main dynamic characteristics of the cyclotron magnetic field for ion acceleration in the energy control range were calculated using the obtained magnetic field maps.

INTRODUCTION

According to the design data, the cyclotron of multicharged ions is designed to accelerate ions having a mass-to-charge ratio A/Z=3÷7 (C_{12}^{+3}, O_{16}^{+4}, O_{18}^{+3}, Ne_{20}^{+5}, Si_{28}^{+6}, Ar_{40}^{+10}, Fe_{56}^{+14}, Kr_{84}^{+18}, Ag_{107}^{+22}, Xe_{136}^{+28}, Bi_{209}^{+43}). The electromagnet of the cyclotron will provide the isochronous motion of a wide range of ions in the process of acceleration to energy regulated in the range of 7.5 - 15 MeV/nucleon [1]. Taking into account the significant dimensions of the electromagnet, the H-shaped version of the magnetic circuit with a four-sector magnetic structure was chosen. The diameter of the pole of the electromagnet is 4 m. The air gaps in the "hill" and in the "valley" are 80 mm and 370 mm, respectively. This structure makes it possible to place resonators in the valleys of the electromagnet with the horizontal placement of rods and tanks. The electromagnet is equipped with a set of correcting coils.

Correcting coils are designed for: adjusting the shape of the distribution of the magnetic field over the radius to ensure isochronous conditions for the acceleration of specific ions; adjusting the position of the plane of symmetry of the magnetic field; correcting the first harmonic of the magnetic field and centering the orbits of the accelerated ions.

MAGNETIC SYSTEM OF THE CYCLOTRON

The magnetic field for the cyclotron of multicharged ions was simulated using the Ansys Maxwell software package [2, 3]. Magnet type is H-shaped. The structure of the magnetic field is four-sector, the angular length of the sectors is 51^0. The formation of the magnetic field was carried out by changing the shape of the boundaries of the sector side plates and correcting coils. As a result of numerical simulation, the magnetic circuit of the multicharged ion cyclotron and the shape of the sector side plates was determined, provided the required ion acceleration mode for A/Z = 4.66. 3D calculation model of 1/8 part of the magnet is shown in Fig. 1.

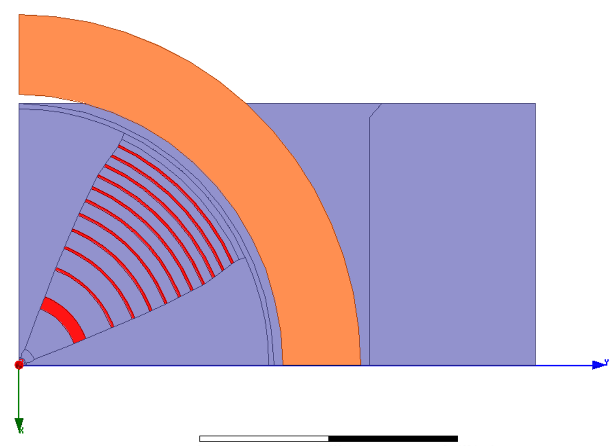

Figure 1: 3D calculation model of 1/8 part of the magnet.

The required maximum of the magnetic field rigidity at the final orbit (Rf.o. = 1.8 m) should reach 2.73 T·m [1].

During the magnetic field formation in the center, there were difficulties due to the effects of the saturation of steel and the complex shape of the surface of the sectors. As a result of numerical modeling, the shape of the sector side plates and the cyclotron central plug was determined, providing an isochronous mode of acceleration for particles with A/Z = 4.66.

Figure 2 shows the calculated magnetic fields for ions with A/Z=3÷7.

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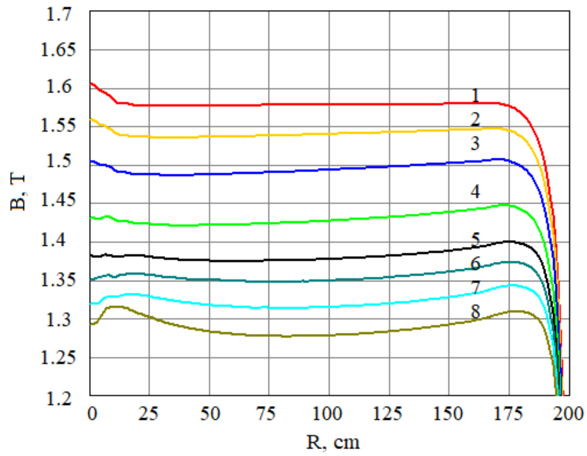

Figure 2: Radial distribution of the average magnetic field for different excitation level of the main coils (1 - 700, 2 - 640, 3 - 570, 4 - 480, 5 - 420, 6 - 390, 7 - 360, 8 - 330 kA·turn).

When changing the energy and/or the type of particles having a different A/Z ratio, it is necessary to adjust the currents in the radial coils. These coils in the amount of 11 pairs are placed in the grooves of the aluminum / or stainless steel disk, which is located between the pole of the cyclotron and the sectors. Additionally, 2 sets of coils are provided for correcting the first harmonic of azimuthal inhomogeneities. This low power correction coils will be housed in vacuum-tight housings (aluminum or stainless steel) located on the sectors. 3D calculation model of 1/2 electromagnet with azimuthal coil housing is shown in Fig. 3. The housing bodies of the correcting coils are water cooled.

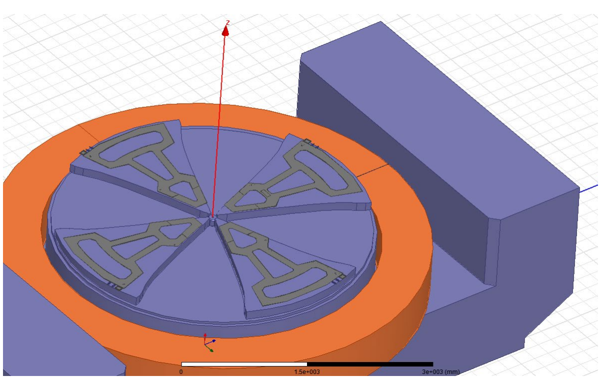

Figure 3: 3D calculation model of 1/2 electromagnet with azimuth coil housings.

Calculations of the correcting coil fields for various levels of the cyclotron magnet excitation have been performed. The radial distribution of the fields of the radial correcting coils at the maximum level of induction in the center of 1.6 T (700 kA·turn) is shown in Fig. 4.

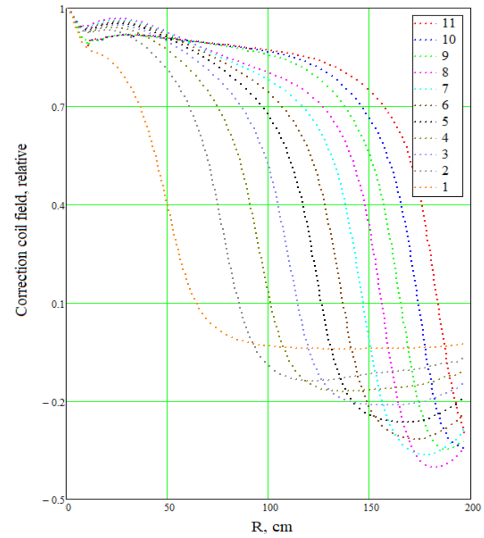

Figure 4: The radial distribution of the radial coil fields at the maximum level of induction in the center 1,6 T (700 kA·turn).

The currents in the correcting coils were determined. The maximum power consumption of the correcting coils will be no more than 20 kW.

Harmonic analysis of the obtained magnetic field was made, and the frequencies of betatron oscillations were calculated for the required set of ions. Figure 5 shows the movement of the operating point of the heaviest accelerated particle (Bi_{209}^{+43}) in the phase diagram.

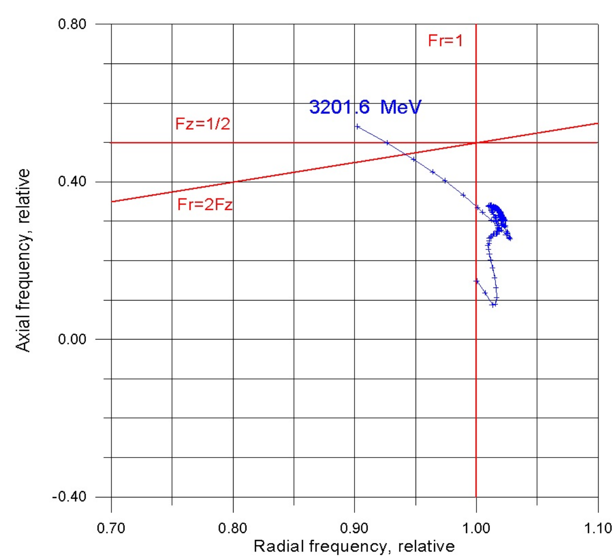

Figure 5: Phase diagram of Bi_{209}^{+43} acceleration at the level of 700 kA·turn.

The calculated phase motion in the resulting magnetic field for the maximum mode of the cyclotron, corresponding to the induction in the center of 1.6 T, is shown in Fig. 6.

The main characteristics of the cyclotron electromagnet are listed in Table 1.

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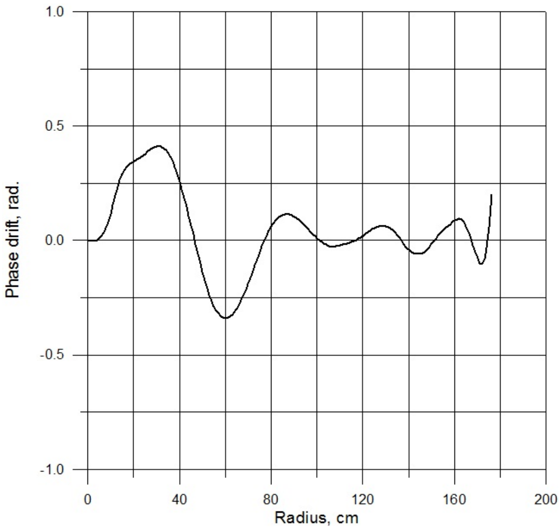

Figure 6: Calculated phase motion in the resultant magnetic field at the level of 700 kA·turn.

Table 1: Main Characteristics of Multicharged Ion Cyclotron Electromagnet

Magnetic core (steel 10)	H-shaped
Outside dimensions of the electromagnet, m	8,1×5,36×4,3
Pole diameter, m	4
Number of sectors per pole	4
Gap "valley"/ "hill", mm	370/80
Sector angular extent, maximum, degrees	51
Induction in the center, range, T	1,29 – 1,6
Main coil power supply, kW, not more	262
Mass of the electromagnet (steel/copper), t	870/72
Number of pairs of radial coils	11
Number of pairs of azimuthal coils	8
Total power consumption of the correcting coils, kW, not more	20

It is worth noting that the technical solutions adopted at the preliminary design stage will allow the acceleration of light ions to energies higher than 15 MeV/nucleon in the cyclotron of multicharged ions. However, the maximum energy of the light ions will be limited by both the parameters of the correcting coils and the required potential of the electrostatic deflector.

CONCLUSION

Thus, an electromagnet of the cyclotron of multicharged ions designed to accelerate ions with the ratio A/Z = 3÷7 to energy regulated in the range of 7.5-15 MeV/nucleon has been developed. As a result of numerical simulation, the parameters of the magnetic system of the multicharged ion cyclotron were determined. Correcting coils have been developed to ensure the isochronous operation of the cyclotron for different types of ions. The power consumption at the maximum excitation current is 262 kW. Each main coil consists of sections, the design of which protects the conductor from damage during transportation, movement, and installation in its working position. The mass of the electromagnet (Fe/Cu) is 870/72 tons, respectively. The formed magnetic field for accelerating ions with A/Z = 3÷7 meets the requirements for the stability of particle motion. Phase diagrams are obtained for the resulting magnetic fields formed for acceleration of ions in the required energy range.

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