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RADIOBIOLOGY, ECOLOGY AND NUCLEAR MEDICINE

Magnetic System of a Superconducting Separated-Sector Cyclotron for Hadron Therapy

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Abstract—The development of a cyclotron magnetic system based on superconducting sector magnets is discussed. The cyclotron is conceived as a booster accelerator of a source of $^{12}C^{6+}$ ions with energy of 400 MeV/nucleon for the purposes of hadron therapy. The results of preliminary investigations aimed at developing such a facility have been reported in our previous papers. In this paper, we consider various configurations of the booster's magnetic system for various field levels. We also analyze the effects of the positions and shapes of superconducting coils on the magnetic field and select the optimum configuration for the cyclotron's magnetic system.

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1. INTRODUCTION

The development of accelerators for generating carbon beams with energies of 400–450 MeV/nucleon is an urgent problem. Until now, synchrotrons were largely used as sources of charged particles for the purposes of hadron therapy [1–3]. On the other hand, isochronous cyclotrons broadly used for the proton therapy may offer a viable alternative to synchrotrons. The designs of existing compact superconducting cyclotrons have a number of advantages but suffer from significant drawbacks [4]. More promising for the purposes of hadron therapy is the facility based on sequential cyclotrons with a superconducting separated-sector cyclotron as a booster [5]. Preliminary design studies of an accelerator complex for generating a beam of $^{12}C^{6+}$ ions with energy of 400 MeV/nucleon are reported in [6]. The development of a superconducting sector magnet for this facility is considered in this paper. The magnetic field is simulated using the Opera3D three-dimensional package.

2. SUPERCONDUCTING SEPARATED-SECTOR MAGNET

A number of conditions must be met when designing a facility based on a superconducting sector magnet. First, the accelerator should be small and light, and therefore should operate with a maximum magnetic field. Secondly, for the injector to be acceptably small and constructively simple, the injection energy corresponding to the beam's first-orbit rigidity in the cyclotron should be moderate. Thirdly, the magnetic-system design should be amenable to practical realization, i.e., the superconducting-coil parameters such as the current density and the induced ponderomotive forces should meet the practical limitations. Additionally, the intersector space should be sufficiently large for installing the elements of the accelerating system, the beam-injection system, etc. [7]. Yet another experimental problem is that the system should maintain an isochronous magnetic field and the accelerating beam should cross a minimum number of dangerous resonances. Accelerator schemes with different numbers of sector magnets and different magnetic-field levels are investigated. We start with a maximum level of the azimuth-averaged magnetic field corresponding to the cyclotron unit value of 3 T. In what follows, this parameter is briefly referred to as the field level. In the process of system optimization towards reaching a realistic design of the magnet, the field level is reduced.

3. MAGNETIC STRUCTURES WITH FIELD LEVELS OF 2–3 T

The initial magnetic structure, designed for a field level of 3 T, included four sectors in order to maximize the magnetic-field flutter. However, since the flutter shows a significant variation with radius (see Fig. 1), the frequency of betatron oscillations Qz diminishes from 2.2 at the start of acceleration to 0.8 at the final radius and, as a consequence, the working point crosses several dangerous resonances, including those at Qz = 2, 2Qz = 3, and Qz = 1. Besides, the isochronous field at the injection radius diminishes from 3 to 2.4 T owing to the flutter correction.

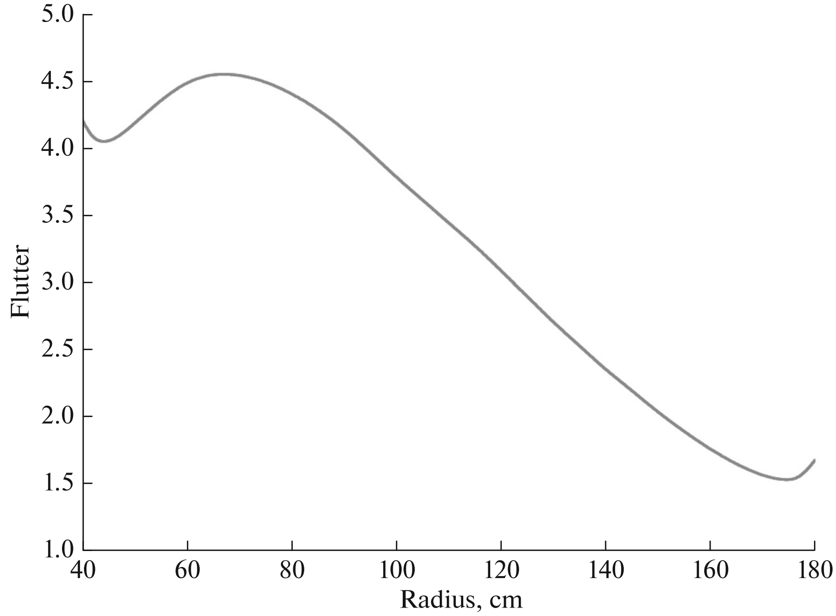

Fig. 1. Radial dependence of the magnetic-field flutter in the cyclotron with a field level ~3 T.

In order to suppress the significant Qz variation with the radius, a spatial variation of the field was induced by modifying the magnetic structure with the 30° maximum spiral angle at the final radius (see Fig. 2), whereby the Qz variation with radius was reduced by a factor of 1.5 (see Fig. 3). The major parameters of this regime are quoted in Table 1. This reduction of the axial-frequency variation is still insufficient for rendering the beam transversally stable in the process of acceleration. Moreover, the maximum field in the sector-magnet gap reaches 10 T and the engineering current density in the superconducting coil reaches 170 A/mm^2, significantly exceeding the quench limit for transition of the superconductor to the resistive state. The current density cannot be reduced by increasing the cross section of the coil, since no extra space is available because of the cryostat that has to be deployed in the same area. These technical problems imply that the field level should be reduced.

Later, we returned to the simpler radial-sector shape of the coils and tried out the following modifications of the magnetic system:

1. Bending the coil in the axial direction at the 3-T field level.

2. Positioning the planes of the upper and lower coils at a relative angle of ~8° at the magnetic-field level of 3 T.

3. Increasing the number of sectors to six at the 3-T field level.

4. Adding a central circular coil and reducing the field level down to 2.5 T.

5. Reducing the field level to 2 T.

These modifications resulted in reducing the current density in the superconducting coil to an accept-

Table 1. Major parameters of the cyclotron with a field level of 3T and a spiral angle of 30°

Parameter	Value
Ion type	$^{12}C^{6+}$
Number of sectors	4
Mean magnetic field: injection/extraction	2.4/4.5 T
Energy: injection/extraction	30/400 MeV/nucl.
Radius: injection/extraction	40/160 cm
Air gap between sectors	14–140 mm
Dimensions: diameter × height	4.7 × 1.5 m
Total weight (sector magnets)	120 t

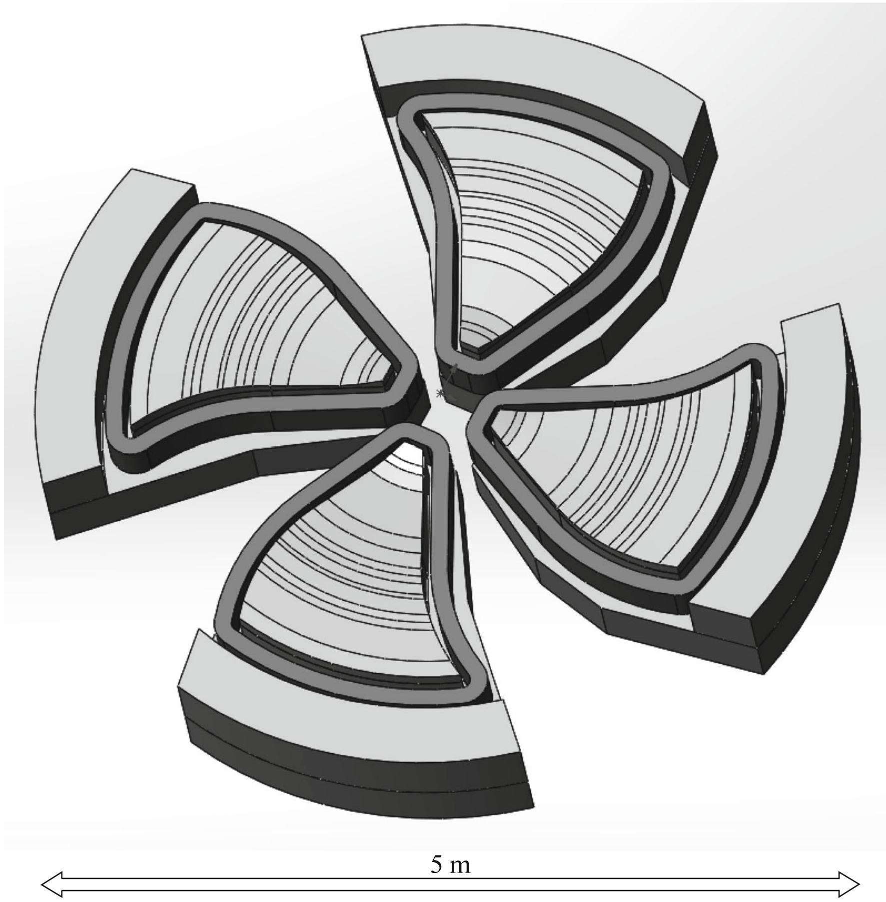

Fig. 2. Magnetic structure of the booster with a field level of 3 T and a spiral angle of 30°.

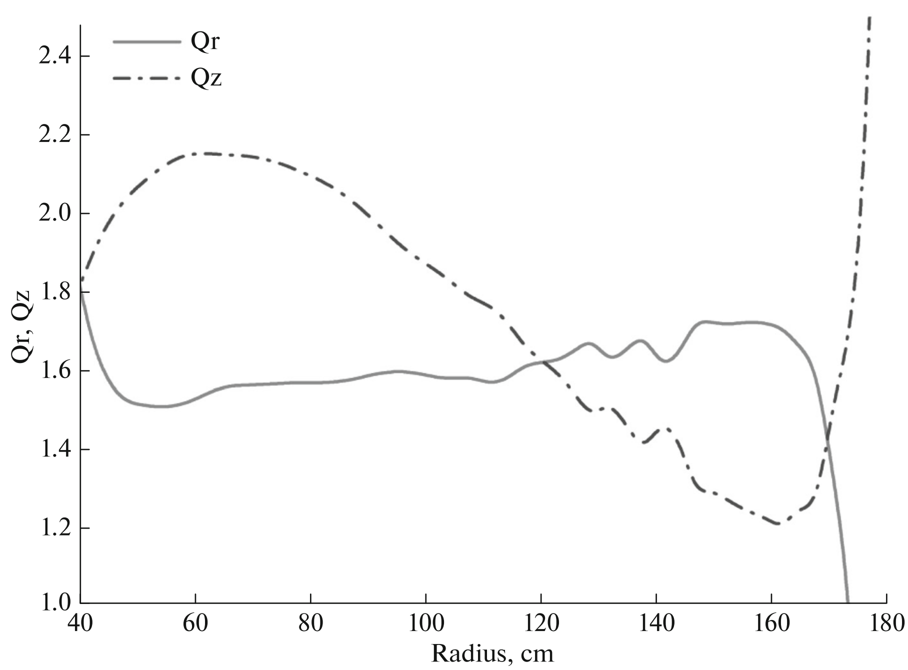

Fig. 3. Frequencies of particle free oscillations for the cyclotron with a field level of 3 T and a spiral angle of 30°.

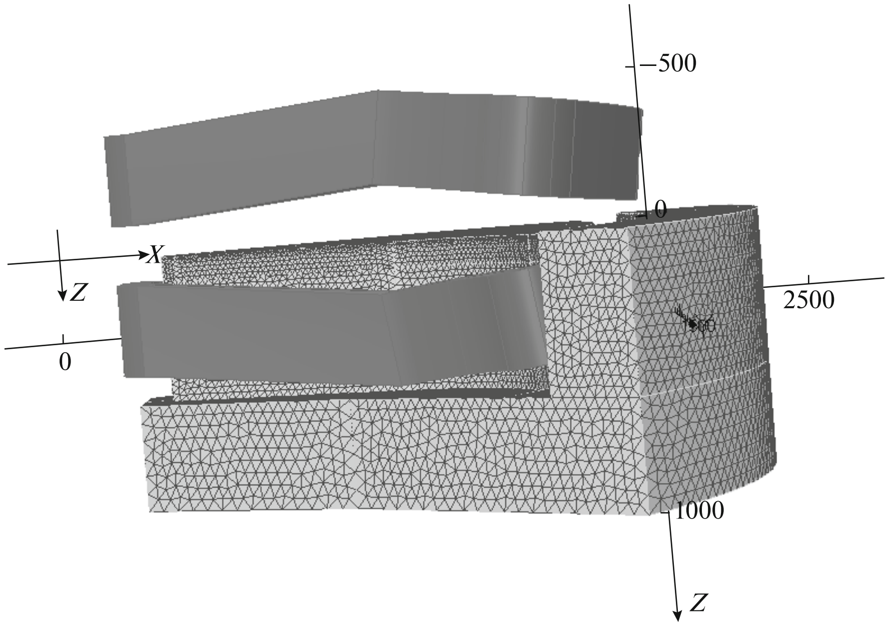

Fig. 4. Superconducting coil with a bend in the axial direction for the cyclotron with a field level of 2.5 T.

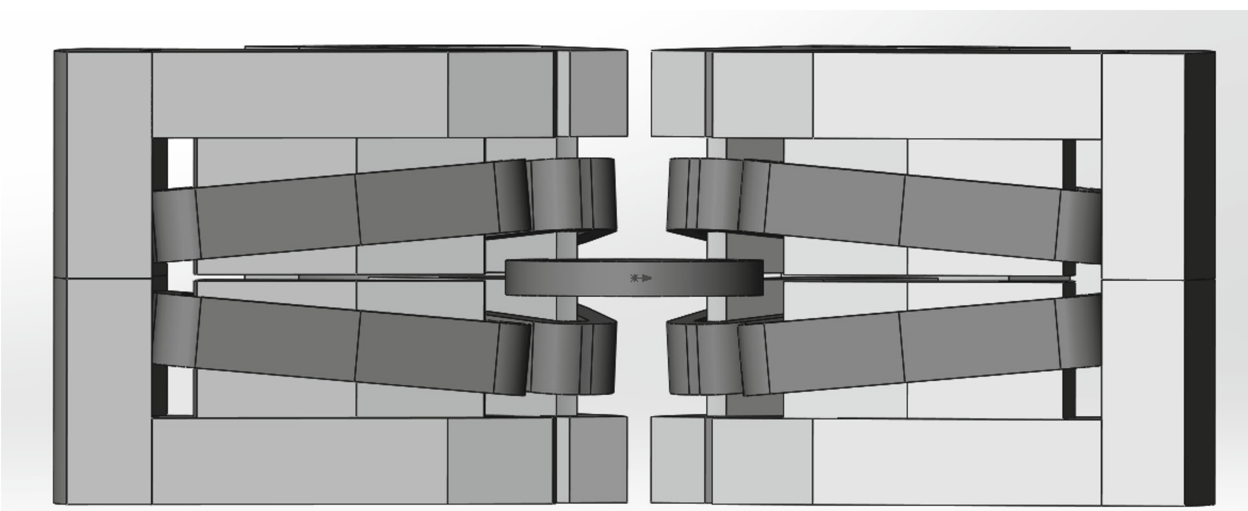

Fig. 5. Magnetic structure with a central coil for the cyclotron with a field level of 2 T.

able value of 65 A/mm^2. On the other hand, we were still unable to reduce the frequency of axial oscillations to an acceptable level. The effects of the aforementioned modifications may be qualitatively explained as follows:

1. Bending the coil in the axial direction (see Fig. 4) effectively reduces the magnetic-field flutter and, correspondingly, the Qz frequency in the region of the maximum axial gap between the coils.

2. The nonzero opening angle between the coils also results in reducing the flutter at intermediate radii in the beam-acceleration range. However, the field level in this region is thereby effectively reduced.

3. Increasing the number of sectors results in changing the flutter over the full range of the radius and, as a consequence, in shifting Qz.

4. Deploying the central circular coil (see Fig. 5) is aimed at compensating the field-level reduction due to the increase of axial distance between the coils towards smaller radii.

The arrangement with six sectors, a field level of 2 T, and an internal circular coil (see Fig. 6) allows one to push the current density in the coils down to an acceptable level. However, the working point is in the vicinity of the dangerous Qz = 1 (4Qz = 4) resonance in the region of final radii, where the number of turns

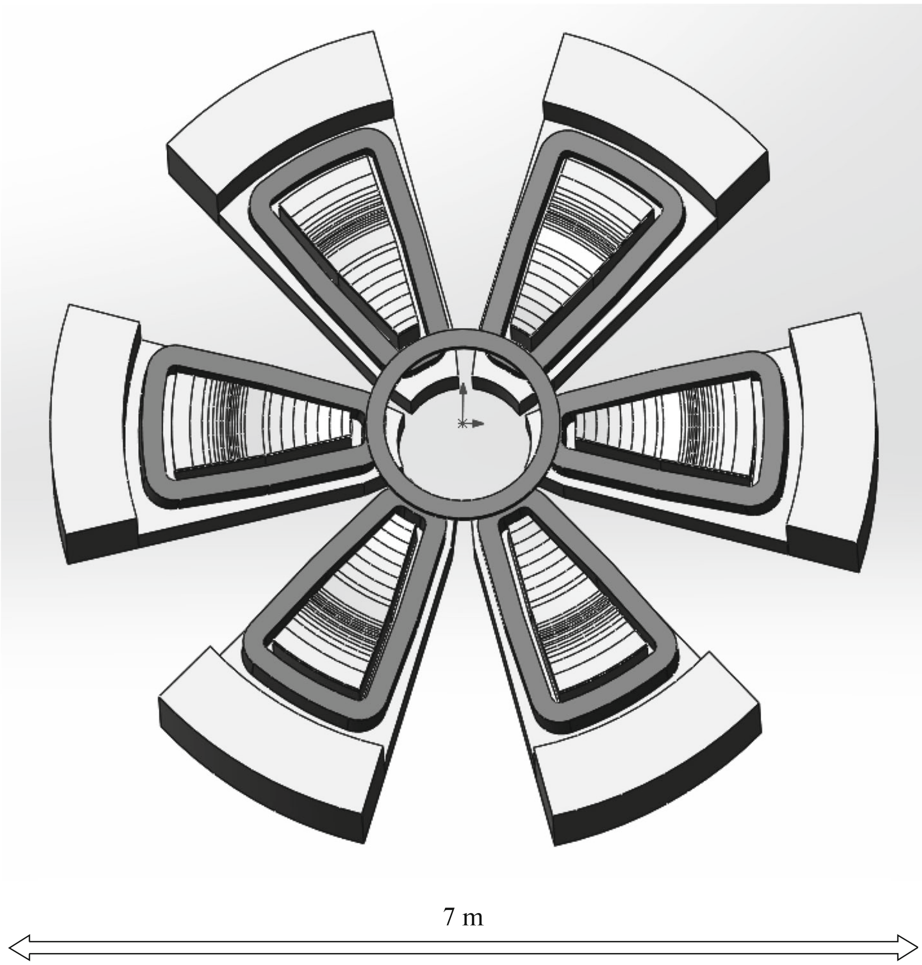

Fig. 6. Six-sector magnetic structure with a central coil and a field level of 2 T. The planes of sector coils form an angle of 8°.

is large (see Fig. 7). Apart from that, constructing such a structure with an additional central coil may create practical problems. Indeed, the net weight of the magnets with coils reaches 300 t and the machine diameter is 6.8 m. The maximum field in the sector-magnet gap reaches 8.5 T.

4. MAGNETIC STRUCTURE WITH A FIELD LEVEL OF 1.6 T

The inadequate magnetic field at intermediate radii of the acceleration range may be compensated by enlarging the azimuthal sizes of the sectors, whereby the central coil may be excluded from the magnetic system. However, the intersector space must be sufficient for deploying the coil cryostat (50–70 mm) and the RF system, and the minimum axial distance between the coils should not be below 120 mm. These conditions imply that the field level has to be reduced to 1.6 T. As a result, an ion with energy of 400 MeV/nucleon is extracted from a radius increased to 280 cm, and the external diameter of the cyclotron reaches 8 m (see Fig. 8). The required reduction of the magnetic-field flutter at intermediate radii is reached with the coil convex shape in this region, which also helps reduce the ponderomotive forces in the coil. The magnetic induction in the coil cross section reached 7.2 T. Maximum magnetic field reaches 7 T in the sector-magnet gap, 2.7 T in the yoke, and 8 T in the pole tips. Major parameters of the discussed accelerator structure are quoted in Table 2. The yoke of each sector has external dimensions of $3.1 \times 2.0 \times 2.2$ m^3. The sector weight is ~52 t. Current density in the superconducting coil with a transverse cross section of 170×330 mm^2 amounts to 62 A/mm^2. The planes of sector coils form an angle of 8°. The radial dependence of the mean magnetic field is rendered isochronous by axial profiling of the pole and its tips; see Fig. 9, 10.

By varying the azimuthal size of the sector and the position of the coil, as is permitted by the extra intersector space, one may form a magnetic-field map so that the flutter increases with radius and the variation of the Qz frequency is reduced to a minimum (Figs. 11, 12, respectively). The frequency is shifted over the full range of the radius by varying the coil azimuthal size.

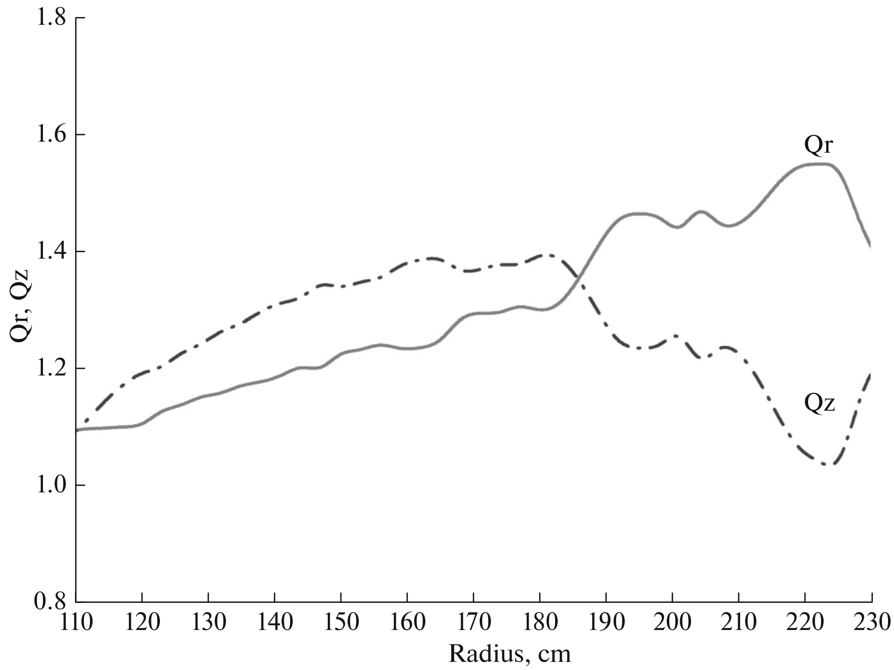

Fig. 7. Frequencies of particle free oscillations for the magnetic structure shown in Fig. 6.

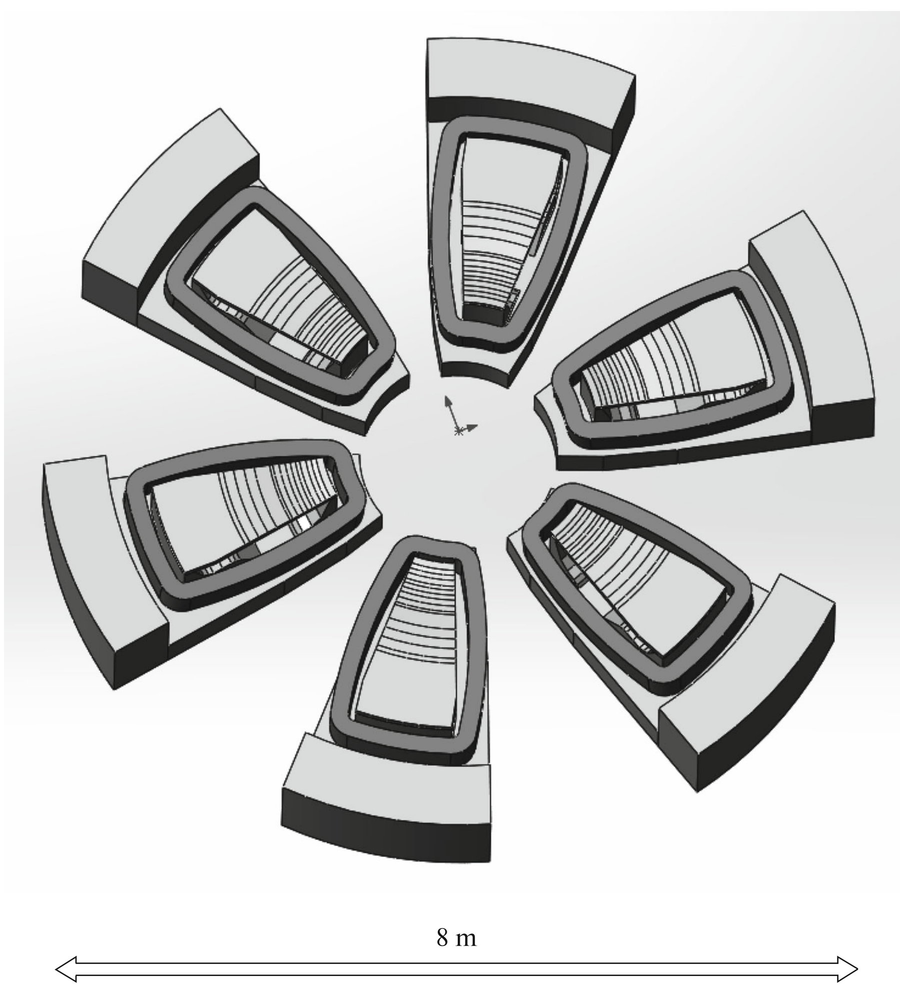

Fig. 8. Magnetic system of the booster cyclotron with a field level of 1.6 T.

Table 2. Major parameters of the cyclotron with a field level of 1.6 T

Parameter	Value
Ion type	$^{12}C^{6+}$
Number of sectors	6
RF frequency	73.56 MHz
RF harmonic	6
Mean magnetic field: injection/extraction	1.64/2.11 T
Maximum magnetic field: injection/extraction	4.22/6.40 T
Energy: injection/extraction	70/400 MeV/nucl.
Radius: injection/extraction	143/278 cm
Sector's azimuthal size	40°–30°
Air gap between sectors	88–135 mm
Dimensions: diameter × height	8 × 2.2 m
Total weight (sector magnets)	310 tons

Thereby, the working point may be kept away from the dangerous resonances associated with the axial frequency of betatron oscillations (Qz = 1, 2Qz = 3, Qr – Qz = 0). Unfortunately, we are still unable to avoid the crossing of the 2Qz – Qr = 1 and 2Qr – Qz = 2 resonances, whose negative effects will be investigated in the future.

Using the field-isochronization algorithm described in [6], the RF phase of the beam is kept within ±30° of the optimum value. The magnetic induction along the sector's center line varies within ±2 mT of the required value; see Fig. 13. The RF phase of the beam is computed using the analytical form of beam energy gain. The latter is obtained assuming that accelerating gaps with 200-kV amplitudes of the RF field are placed in three valleys of each orbit. For a particle crossing the accelerating gap, the energy increase is computed taking into account its RF phase. The number of turns for a centrally injected particle amounts to 1240.

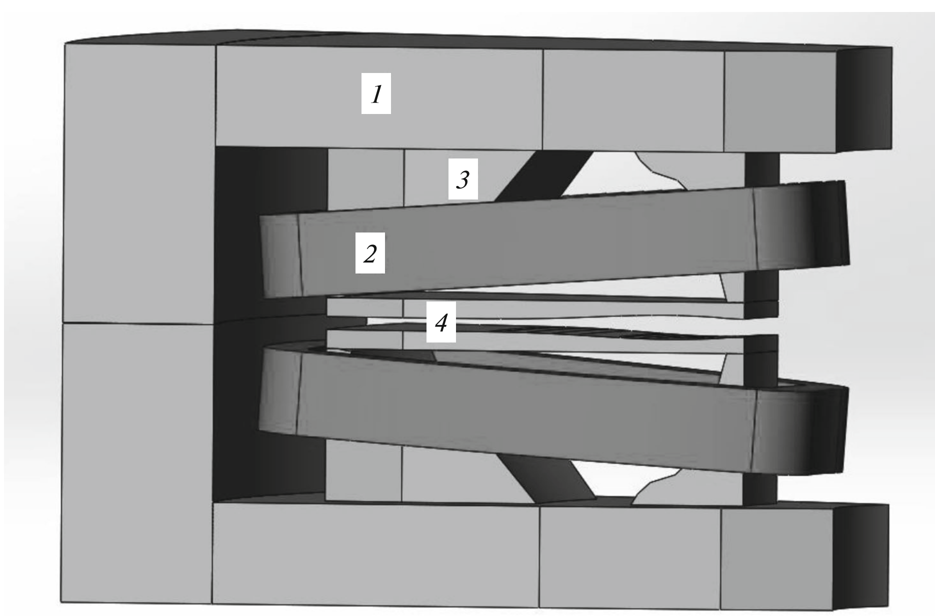

Fig. 9. Scheme of a sector magnet of the cyclotron with a field level of 1.6 T, showing the yoke (*1*), the superconducting coil (*2*), the pole (*3*), and the pole tip (*4*).

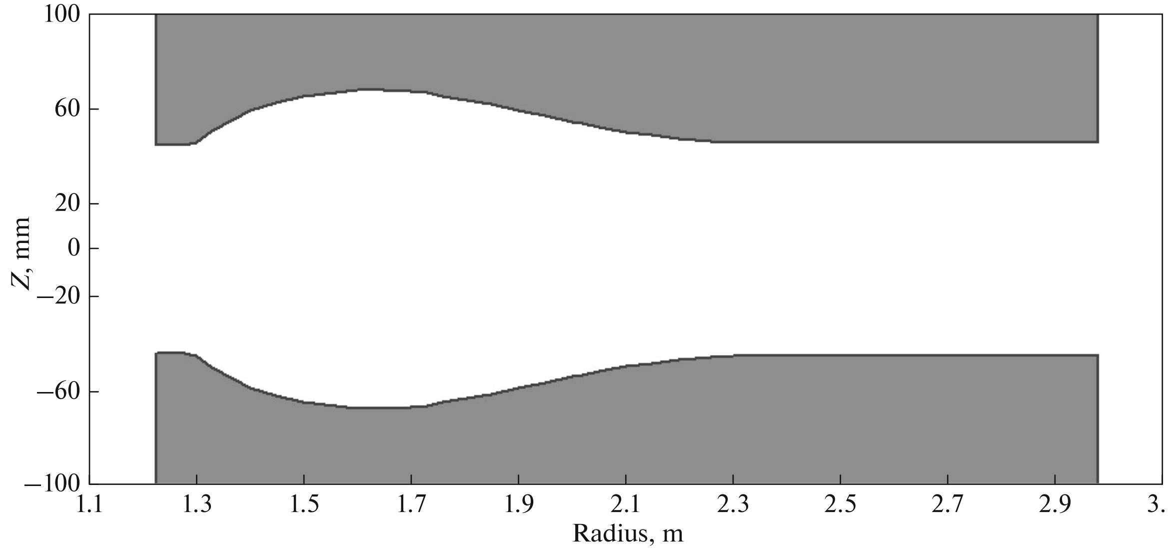

Fig. 10. Axial profiling of the pole tip.

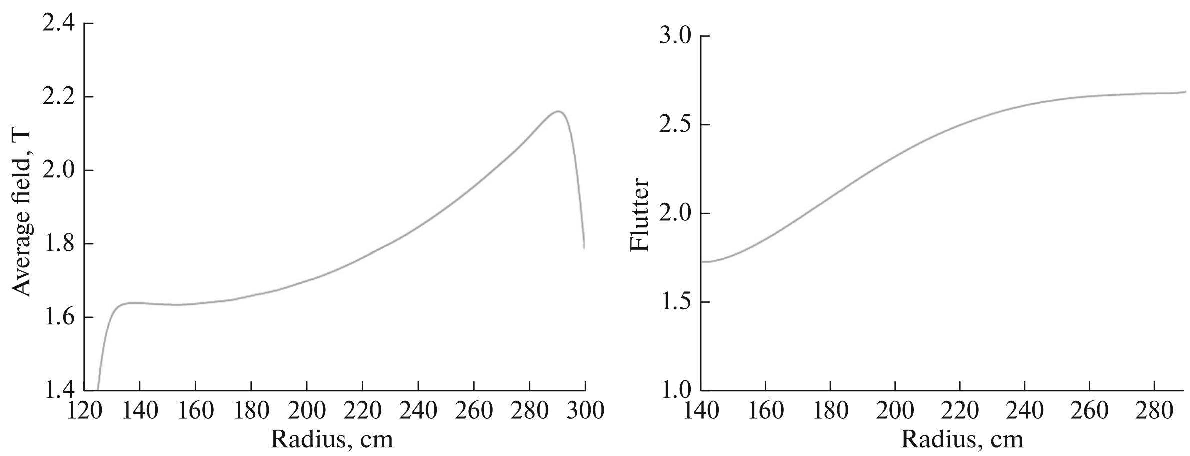

Fig. 11. Azimuth-averaged magnetic field (on the left) and flutter (on the right) for the cyclotron with a field level of 1.6 T.

5. STRUCTURAL ELEMENTS OF BEAM INJECTION INTO THE BOOSTER CYCLOTRON

For the considered cyclotron, the injection energy was selected as 70 MeV/nucleon [6]. The beam-injection system (Fig. 14) comprises four magnetic channels shown in Fig. 15 and an electrostatic deflector. The values of central fields in the four channels are selected as 1.2, 1.4, 1.4, and 0.8 T, respectively. The fourth magnetic channel features a coil that crosses the median plane and separates the circulating beam from the injected one (the septum). The strength of the deflector's electric field is selected as 80–90 kV/cm and may be slightly tuned towards centering the injected beam.

Transverse defocusing of the beam by the main field may be compensated for using channel structures with increasing or decreasing magnetic fields. In the beam-injection region, the axial distance between the walls of the cryostats of the sector-magnet coils, ~ 400 mm, is sufficient for deploying the magnetic channels there. Apart from that, in the zone where the third magnetic channel is deployed, the distance between the sector-magnet poles is sufficiently large for deploying this channel between the poles. This does not create any problems with forming the required isochronous field, since the dominant contribution to the cyclotron field is provided by the superconducting coils. The magnetic-induction vector in the valley is opposite those in the sectors. Its value is maximum at intermediate radii, where it reaches

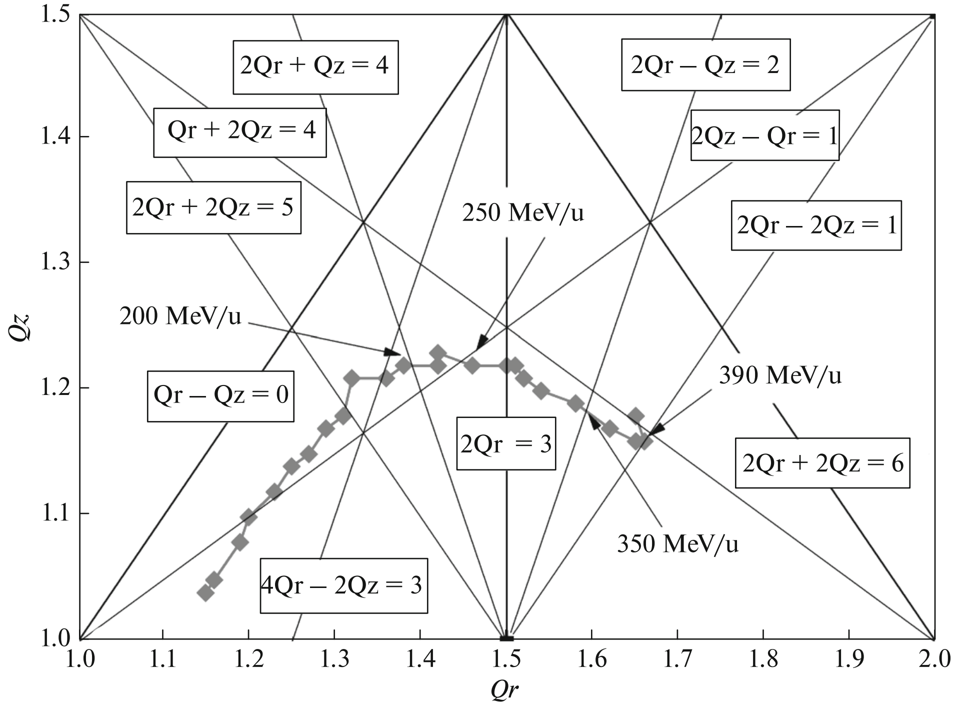

Fig. 12. Operation diagram for the cyclotron with a field level of 1.6 T.

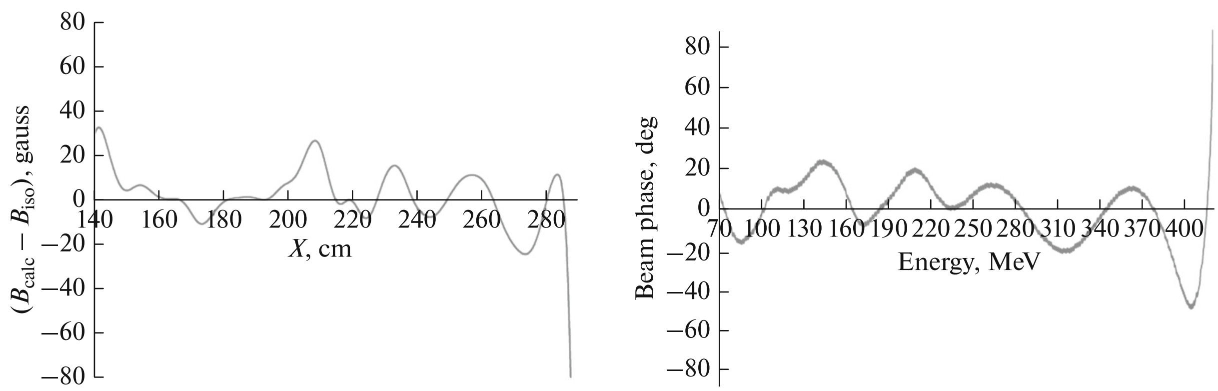

Fig. 13. On the left: for the field on the central axis of the sector magnet, the deviation from the nominal value required isochronizing the magnetic-field map. On the right: RF phase of the beam.

~1.4 T; see Fig. 16. The induction is also high in the beam-injection zone near the initial orbit (~1.2 T).

The beam trajectory in the valley is not straight. When propagating through the valley, the beam successively travels in the increasing and decreasing magnetic fields, which provide alternating focusing. For efficient injection, the beam angular spread must be minimum when entering the valley. The beam-particle dynamics are analyzed assuming the following beam characteristics at the valley entrance point near the final radius: transverse emittance of 2 $\pi \cdot$ mm $\cdot$ mrad, transverse size of 5 mm, and zero for the Twiss parameter α. This results in an angular spread below ±1 mrad. At the entrance of the electrostatic deflector, the internal orbits are separated by ~4 mm. The particle loss on the deflector septum, whose thickness increases from 0.2 to 0.5 mm along its length, is on a level of ~15%. The transverse size of the beam injected into the booster does not exceed ±6 mm. Upon passing through the deflector, the beam size proves to be acceptably small (±4 mm). Thus, with a deflector aperture of ~10 mm, particle losses in the deflector are small. We may conclude that the proposed elements of the beam-injection system meet the requirements dictated by particle dynamics.

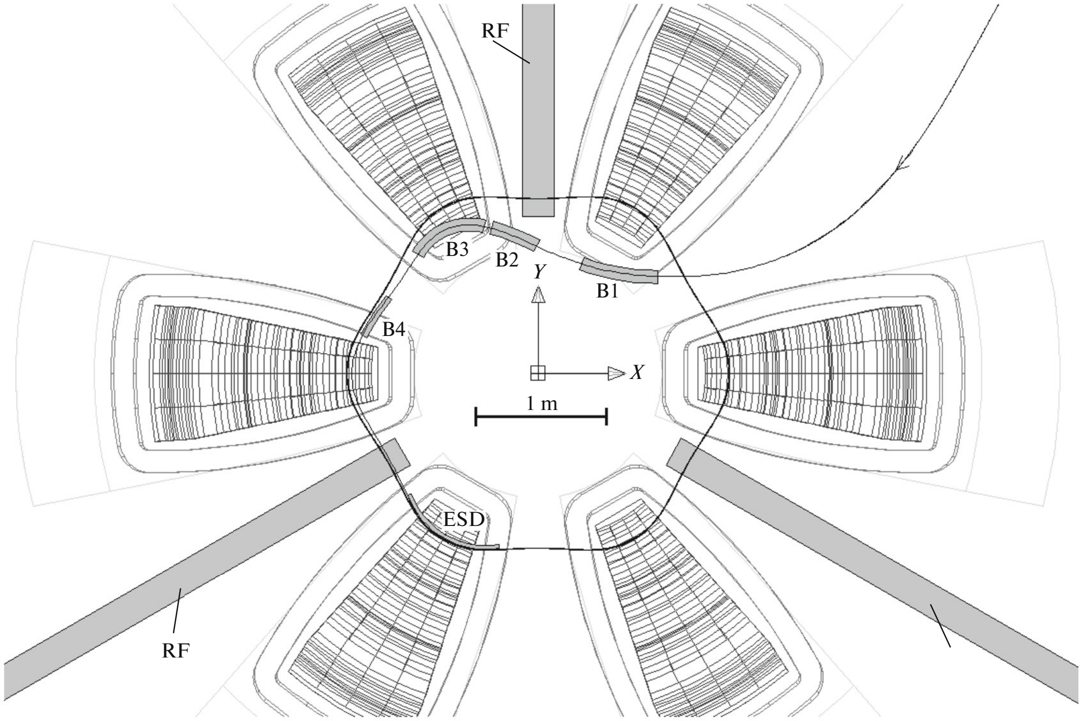

Fig. 14. Beam injection into the booster cyclotron.

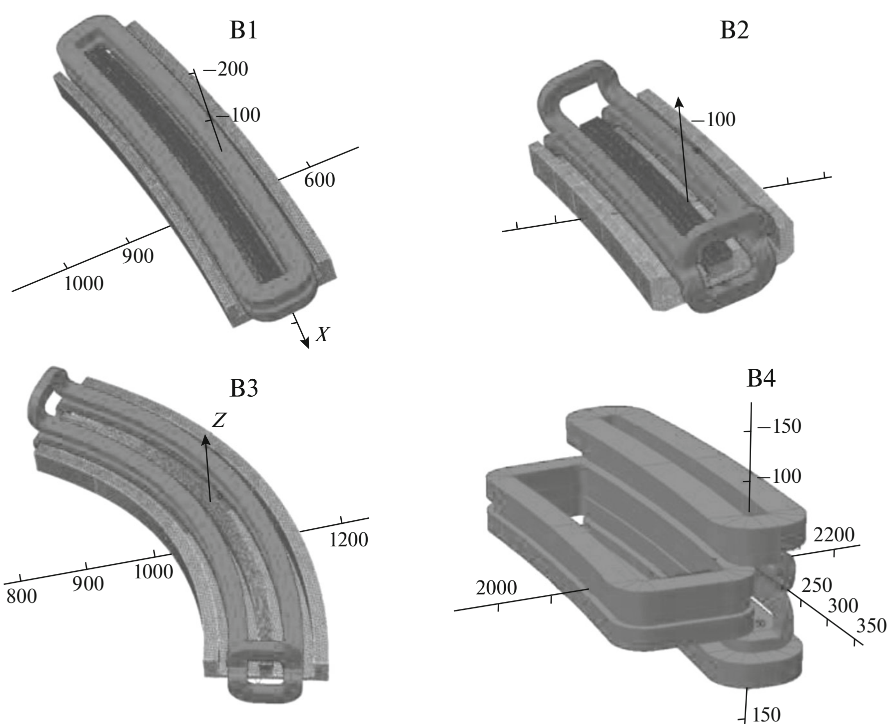

Fig. 15. Magnetic channels of the beam-injection system.

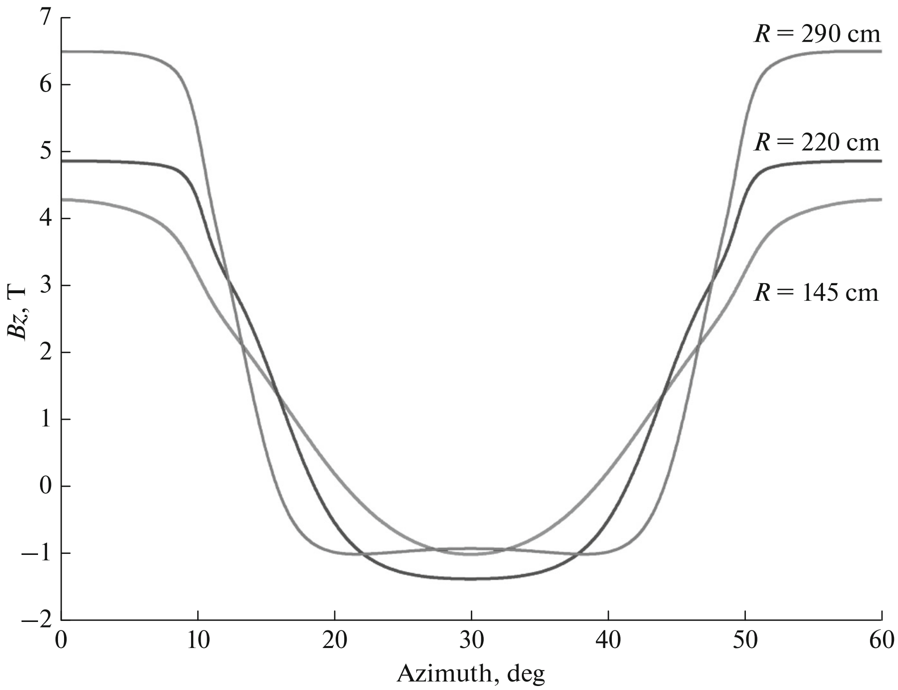

Fig. 16. Azimuthal distributions of the magnetic field for different radii.

6. CONCLUSIONS

A preliminary design of the superconducting sector magnet and of the beam-injection system for a booster cyclotron aimed at accelerating carbon ions to 400 MeV/nucleon is proposed. The required map of isochronous magnetic field is obtained with a maximum magnetic field of ~6.4 T in the sector-magnet median plane at the extraction radius. The magnet features a radial gradient of the magnetic field created by inclining the superconducting coils. In the future, we foresee constructing a mechanical model of the magnet which may help develop methods of compensation for the large electromagnetic stress forces arising in the discussed structure. The designed elements of the beam-injection system satisfy the requirements dictated by the beam-particle dynamics.

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