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ФИЗИКА И ТЕХНИКА УСКОРИТЕЛЕЙ

NUMERICAL SIMULATION OF ION ACCELERATION AND EXTRACTION IN CYCLOTRON DC-110

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At the Flerov Laboratory of Nuclear Reactions of JINR, in the framework of the project BETA, a cyclotron complex for a wide range of applied research in nanotechnology (track membranes, surface modification, etc.) is being created. The complex includes a dedicated heavy-ion cyclotron DC-110, which yields intense beams of accelerated ions Ar, Kr and Xe with a fixed energy of 2.5 MeV/A. The cyclotron is equipped with external injection on the base of ECR ion source, a spiral inflector and the system of ion extraction consisting of an electrostatic deflector and a passive magnetic channel.

The results of calculations of the beam dynamics in measured magnetic field from the exit of the spiral inflector to the correcting magnet located outside the accelerator vacuum chamber are presented. It is shown that the design parameters of ion beams at the entrance of the correcting magnet will be obtained using a false channel, which is a copy of the passive channel, located on the opposite side of the magnetic system. Extraction efficiency of ions will reach 75%.

В Лаборатории ядерных реакций им. Г. Н. Флерова ОИЯИ в рамках проекта «Бета» создается циклотронный комплекс для широкой области прикладных исследований в нанотехнологиях (трековые мембраны, модификация поверхности и т. д.). Комплекс включает циклотрон тяжелых ионов ДЦ-110, производящий интенсивные пучки ускоренных ионов Ar, Kr и Xe с фиксированной энергией 2,5 МэВ/нуклон. Циклотрон оборудован внешней инжекцией, спиральным инфлектором и системой вывода ионов, включающей электростатический дефлектор и пассивный магнитный канал.

Представлены результаты расчетов динамики пучка в измеренном магнитном поле от выхода спирального инфлектора до корректирующего магнита, расположенного вне вакуумной камеры ускорителя. Показано, что проектные параметры пучков ионов на входе корректирующего магнита будут получены при использовании фальшканала, являющегося копией пассивного магнитного канала и расположенного на противоположной стороне магнитной структуры. Эффективность вывода пучков ионов достигает 75 %.

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INTRODUCTION

The project of an accelerating complex for the production of track membranes on the base of the specialized cyclotron of heavy ions DC-110 is being developed at FLNR JINR for the scientific and industrial center BETA [1]. The cyclotron will make it possible to generate intensive beams of the accelerated ions of $^{40}Ar^{6+}$, $^{86}Kr^{13+}$ and $^{132}Xe^{20+}$ with the fixed energy 2.5 MeV/A, which will ensure the production of track membranes on the basis of polymer films with thickness to 30 μm. The accelerated ions have the close mass to charge ratios 6.667, 6.615 and 6.6. Therefore, the fine adjustment of regime with a change in the accelerated particle, caused by a difference in the mass to charge ratio, can be executed due to the operational frequency control of resonance system in the small range in the fixed magnetic field. The intensity of beam, which is required in the process of irradiating the film, is given in Table 1.

Table 1. **Basic parameters of cyclotron operating conditions**

Accelerated ions	$^{40}Ar^{6+}$	$^{86}Kr^{13+}$	$^{132}Xe^{20+}$
Mass to charge ratio A/Z	6.667	6.615	6.6
Energy of ions, MeV/A	2.50	2.50	2.50
Harmonic number	2	2	2
Frequency of accelerating voltage, MHz	7.7	7.7	7.7
Intensity of extracted beam, μA	6 (1 pμA)	13 (1 pμA)	10 (0.5 pμA)

For obtaining the intensity indicated, first of all for xenon, on the cyclotron there will be installed ECR ion source, which works at a frequency of 18 GHz, the effective system of injection and bunching of beam is created. The use of coils for the correction of average field is not planned on the cyclotron; isochronous magnetic field is shaped only with the geometry of sectors and shims.

Beam extraction from the cyclotron is achieved with the aid of the electrostatic deflector. Along the trajectory of the extracted beam the passive magnetic channel is used, which ensures the necessary beam focusing at the entrance into the ion line, where the correcting magnet is located. Magnetic channel has the iron masses which affect the distribution of magnetic field in the acceleration region of beam. One of the tasks with shaping of magnetic field is a compensation of this influence with the aid of the shims. As calculations showed, the installation of the false channel for symmetrically working channel makes possible the more correct compensation for this influence, to avoid the growth of the radial oscillations of beam, which ensures achievement of design energy of beam and high coefficient of beam extraction from the cyclotron.

MAGNETIC FIELD OF CYCLOTRON

The electromagnet of the cyclotron DC-110 is created on the base of the magnet SP-72, it has H-descriptive form and pole of diameter 2 m. Coils for the correction of average magnetic field are not used in the cyclotron DC-110. For an improvement of the accelerated beam orbits centering, two pairs of the azimuthal correcting coils between the sectors on radii 280–520 mm are installed.

In working magnet gap four pairs of sectors without the spiralization are placed. Each sector is equipped with the lateral detachable shims, which make it possible to introduce the necessary correction of field with final shaping of the isochronous conditions for acceleration. The comparison of the measured average magnetic field and its isochronous value is shown in Fig. 1. The fluctuation of field deviation in the limits to 25 G up to a radius of 25 cm does not exert a substantial influence on the phase motion calculated analytically (Fig. 2), on the strength of the fact that the ions rapidly leave a central region. The maximum phase drift of ion does not exceed 3° HF.

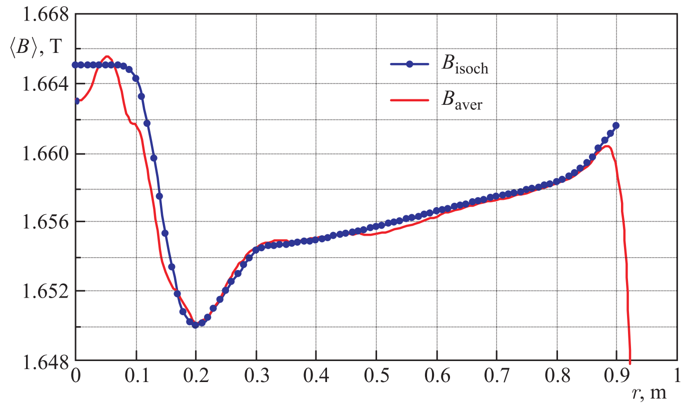

Fig. 1. Comparison of measured average field $B_{\rm aver}$ and isochronous field $B_{\rm isoch}$

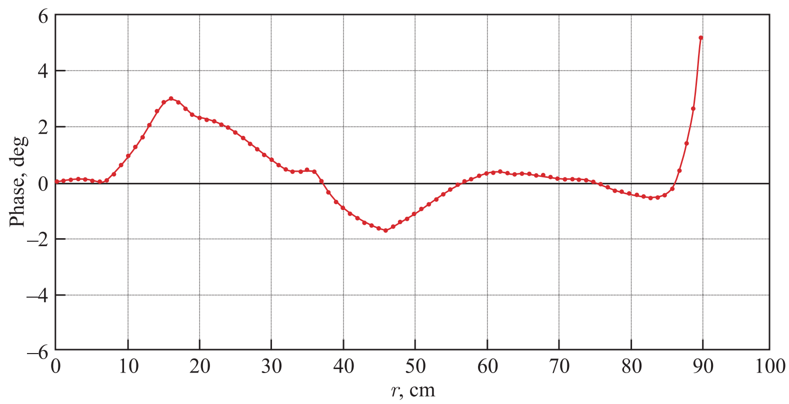

Fig. 2. Phase drift of central ion

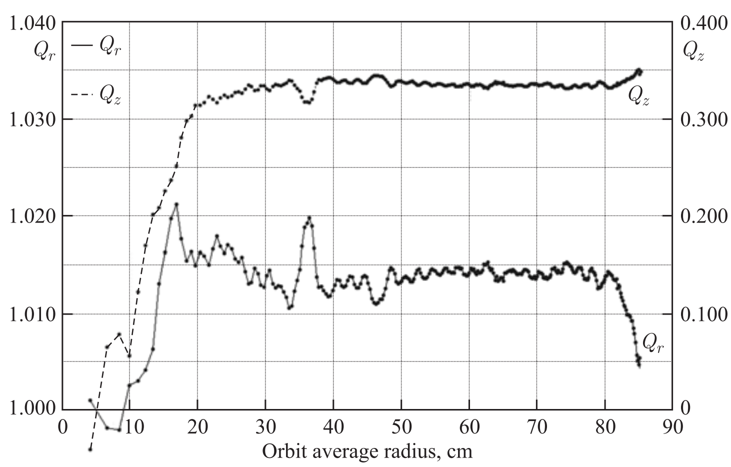

Fig. 3. Frequency of free oscillations Q_r and Q_z versus average radius of the orbit

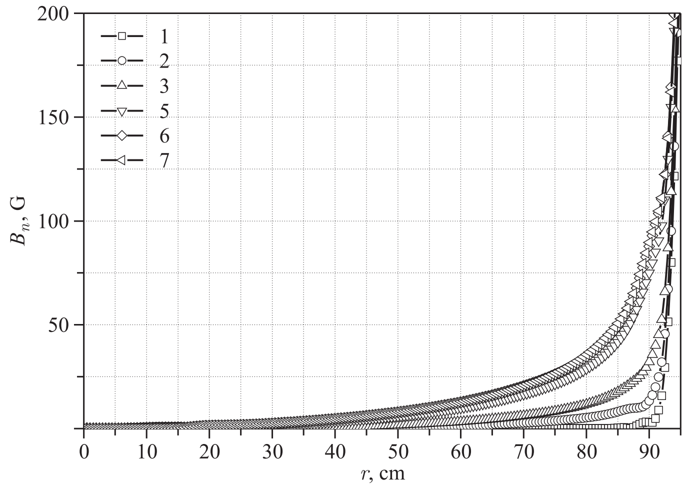

Fig. 4. Harmonic amplitudes of imperfections in calculated field without false channel. If false channel is installed, then the odd harmonics will disappear while the even ones will be doubled

The values of the free betatron frequencies for the measured field (Fig. 3) are located far from the dangerous resonance values.

In the system of ion extraction the passive magnetic channel is present, which leads to the harmonics of perturbation in the region of the accelerated beam, that reach several ten gausses (Fig. 4). The most dangerous odd harmonics 1, 3, 5, 7 lead to the strong distortion of the accelerated orbits. The suppression of odd harmonics was provided by means of the azimuthally symmetrical installation of the false channel. A double increase in this case of the second harmonic does not render, as will be shown below, an essential negative influence on the beam.

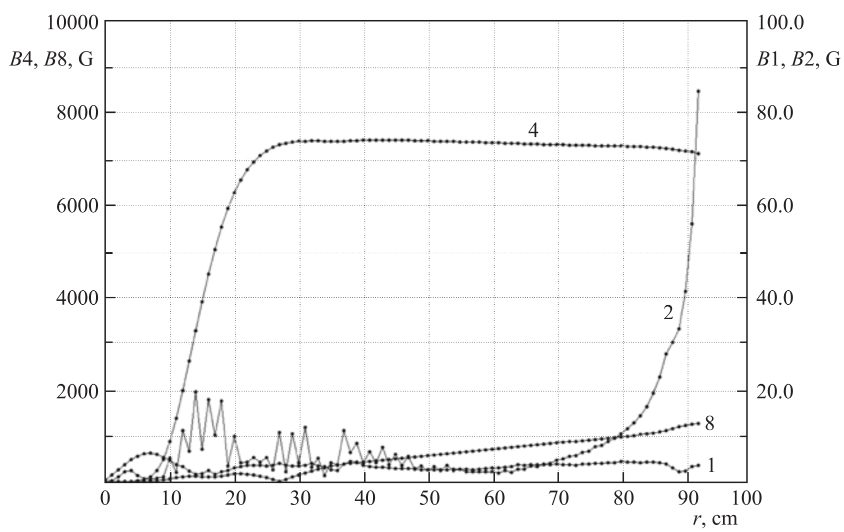

Fig. 5. Measured harmonics of magnetic field versus radius

The amplitude of the leading 4th harmonic of the measured magnetic field, and also the main harmonics of imperfection with the installed false channel are depicted in Fig. 5. The amplitude of the 1st harmonic in full range of radii does not exceed 5 G, while the amplitude of the 2nd one smoothly grows to 100 G to a radius of extraction. The influence of these perturbations of magnetic field on the dynamics of beam will be shown below.

BEAM ACCELERATION

The bend of beam with the energy 3 keV/A from the line of axial injection into the median plane of cyclotron is ensured by the electrostatic inflector, whose parameters are given in Table 2, and the first two turns of ions are shown in Fig. 6.

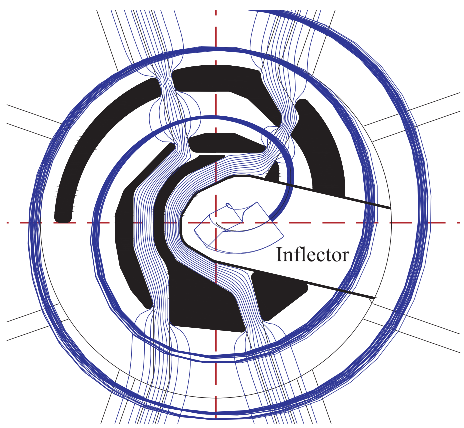

Fig. 6. Outline sketch of DC-110 central region and the test trajectories of the $^{86}Kr^{13+}$ ions during the first two turns

Table 2. **Parameters of spiral inflector for ^{86}Kr^{13+} acceleration mode**

A/Z	6.61
Magnetic field in the center, kG	16.7
Injection energy, keV/Z	20
Voltage on electrodes, kV	± 6.9
Magnetic radius, cm	3.13
Electric radius, cm	3.5
Gap between potential plates, cm	1.2
Width of electrodes, cm	2.4

For the series calculations of acceleration 2500 $^{86}Kr^{13+}$ ions were taken after $3/4$ turn after inflector. The phase width of bunch was equal to 30° RF, the transverse emittances of the beam were $\sim 100\,\pi$ mm · mrad. To describe accelerating field, 3D field map was used during the first turn, while analytical presentation [2] which considered the geometric dimensions of the accelerating gaps has been applied after the first turn. The amplitude of RF voltage was equal to 50 kV. The complete equations of ion motion in electromagnetic field of cyclotron were integrated. The position of bunch on the plane (r, z) during ~ 120 turns of acceleration is shown in Fig. 7. Insignificant axial losses of the ions ($< 1\%$) were fixed only during the first turns and then the axial size of beam did not exceed 26 mm. The result of calculated phase motion of ions coincides with the analytical estimation presented in Fig. 2. The result of the numerical simulation for the differential probe signal (lamellas thickness 2 mm) is given in Fig. 8. Rapid changes in the signal amplitude on radii 45, 65 and 80 cm appear as a result of the coherent radial oscillations beats during the acceleration.

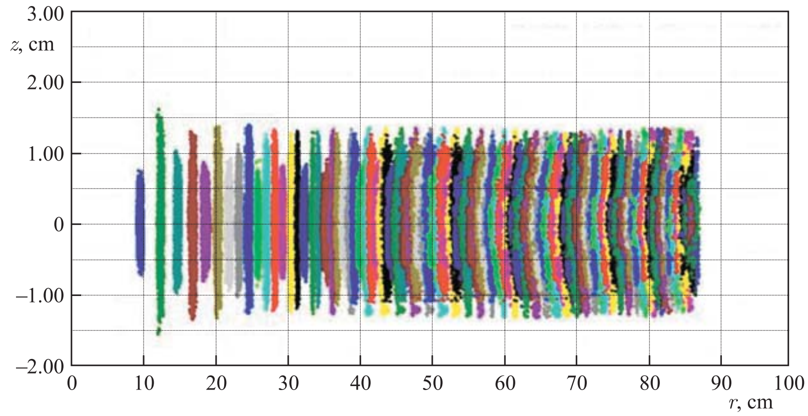

Fig. 7. Position of accelerated ions on the plane (r, z) with step one turn

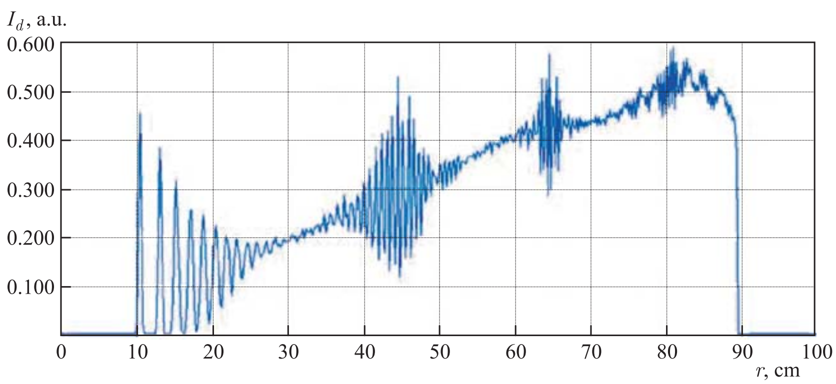

Fig. 8. Result of numerical simulation for differential probe signal. Lamellas thickness is 2 mm

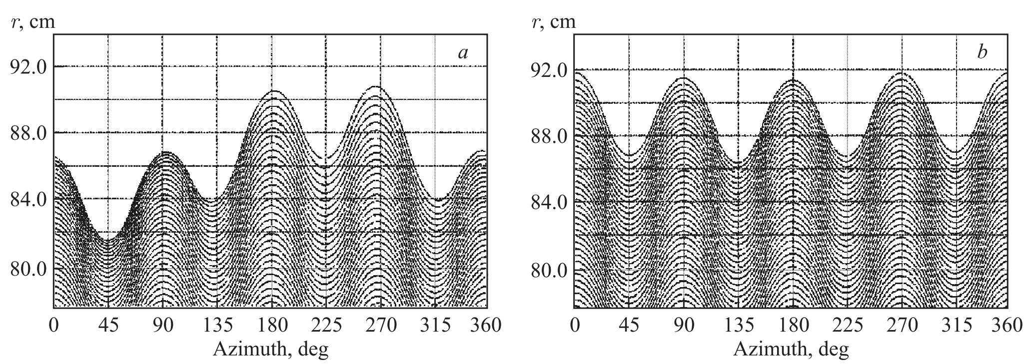

Fig. 9. Comparison of the central ion final trajectories: *a*) in the magnetic system there is no false channel, *b*) magnetic system with the false channel

It is possible to see in Fig. 9 the comparison of the final orbits of the bunch central ion in the simulated magnetic field with the false channel and without it. If the false channel is absent, then a maximum radius of orbit on the azimuth of the entrance into the deflector 118°

is equal to 84.0 cm; in this case the energy of ion is equal to 2.28 MeV/A. Upon further acceleration, this ion is scattered in the fringe field because of the large radial oscillations. In the presence of false channel, the ion reaches a design radius of 88 cm at the entrance into the deflector and its energy is close to a design value of 2.5 MeV/A.

The 1st and 2nd harmonics of the magnetic field perturbations render an essential influence on the radial motion of the beam in DC-110. The amplitude of the 1st harmonic is determined by inaccuracies in production and assembling of the cyclotron magnet. The amplitude of the 2nd harmonic almost completely depends on the presence of false channel in the magnetic system.

The nature of the action of these harmonics on the beam dynamics is various. The amplitude of the 1st harmonic noticeably affects the coherent radial oscillations of beam, since betatron frequency Q_r in the entire acceleration region is close to 1.

The gradient of an increase in the amplitude of the 2nd harmonic dB_2/dr is the driving term of the parametric resonance $2Q_r = 2$. In principle, this resonance can lead to an increase in the free radial incoherent oscillations of ions and to radial emittance growth as well. Effective force of this resonance depends on the specific conditions: the value of gradient; how far the working point is located from the resonance; the duration of the resonance action.

The amplitude of the 2nd harmonic after the installation of false channel is visible in Fig. 5, where the results of the measurements for DC-110 magnetic field are represented. In the region of the final radii of acceleration the amplitude reaches 100 G, and its gradient is up to 50 G/cm. To study the influence of these disturbances on the beam dynamics, the calculations of 200 ions acceleration at various compositions of the field perturbations were done:

a — there are no perturbations of magnetic field;

b — there is 1st harmonic;

c — there is 2nd harmonic;

d — there are 1st and 2nd harmonics;

e — there are 1st and 2nd harmonics and harmonic coils are switched on.

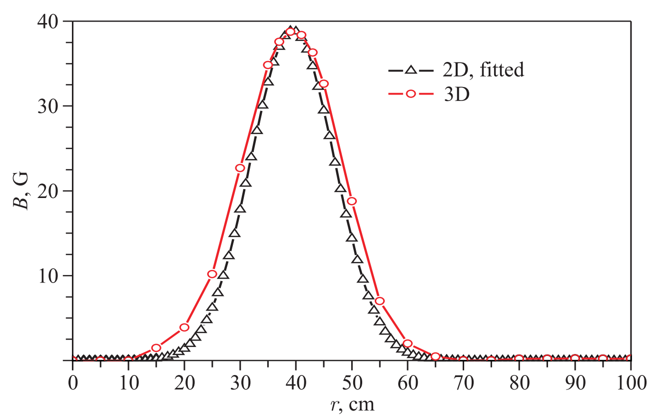

Fig. 10. Calculated by 2D and 3D simulations, an amplitude of the 1st harmonic B_1 created by harmonic coils

For an increase in the energy of extracted beam it is necessary to decrease the amplitude of the beam coherent motion with the approach to the deflector. The variation of the amplitude and phase of the 1st harmonic created by harmonic windings was carried out for

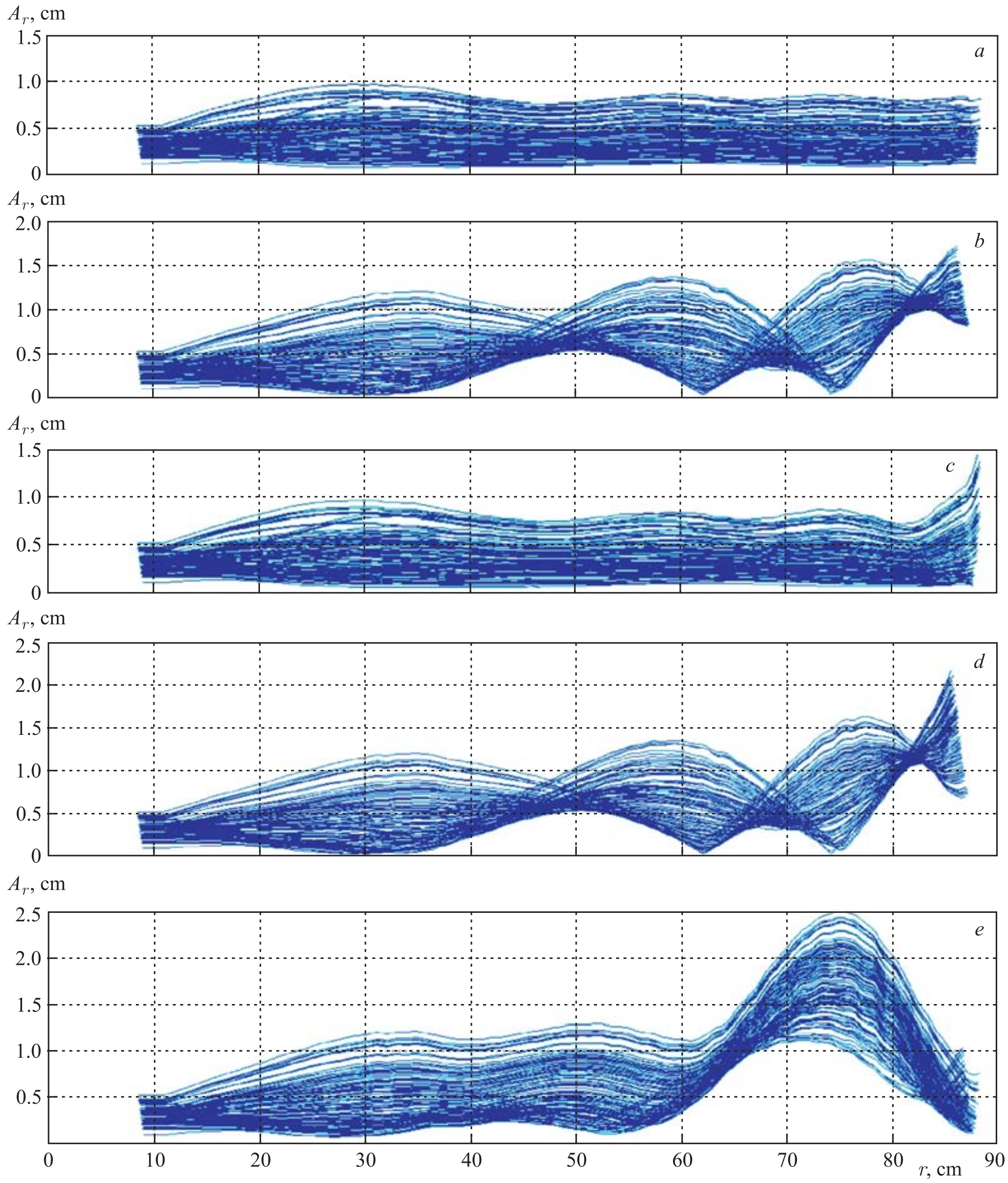

Fig. 11. Amplitudes of the radial oscillations for 200 ions depending on the average radius of orbits. *a*) No perturbations of magnetic field; *b*) 1st harmonic is in the field; *c*) 2nd harmonic is in the field; *d*) 1st and 2nd harmonics are in the field; *e*) 1st and 2nd harmonics are in the field and harmonic windings are also switched on

this purpose. Calculated radial distribution of the 1st harmonic, obtained during the two- and three-dimensional simulations, is shown in Fig. 10. To find optimum condition, during calculations of acceleration this radial distribution was multiplied by the coefficient in the limits of 0.1–0.3, and the phase of the harmonic, created by coils, revolved in the range 0–360° with a step of 45°.

As a result of a series of calculations, it was established that the optimum value of coefficient is equal to 0.15 (amplitude of harmonic in the maximum on a radius of 40 cm equals 5.7 G), and the phase of the harmonic, created by coils, must be equal to 90° counting from horizontal axis (see Fig. 12). The results of the calculations of the amplitudes of oscillations are represented in Fig. 11, from which it follows that

— in the absence of disturbances the amplitude of radial oscillations is not more than 8 mm;

— 1st harmonic leads to the coherent amplitude of 10 mm at the end of the acceleration;

— 2nd harmonic produces an increase in the incoherent oscillations from 8 to 14 mm at the end of the acceleration;

— the use of harmonic windings can ensure the reduction of the maximum amplitude of the radial oscillations at the end of the acceleration from 22 to 10 mm.

BEAM EXTRACTION

A schematic view of the system of beam extraction is shown in Fig. 12. It consists of the electrostatic deflector (Fig. 13) and the magnetic channel (Fig. 14). The beam is extracted to the center of the correcting magnet with the coordinates $r = 184$ cm, $\varphi = 261°$, this is so-called fixed point. The electrostatic deflector with the strength of electric field of ~ 60 kV/cm is arranged in the valley of magnet and has the azimuthal extent of $118-152° = 34°$ (~ 520 mm). Two vertically flat electrodes of the deflector (septum and potential plate) have a radius of curvature of ~ 1945 mm. The distance between the plates is 9 mm. The magnetic channel focuses the beam in the horizontal plane, it is located in the sector which follows the deflector, and has azimuthal extent $174-201° = 27°$ (~ 470 mm). Inside the horizontal working aperture of the channel $\Delta x = 20$ mm the gradient of magnetic field $\sim 27-28$ T/m is created. The radius of the channel entrance (middle of aperture) is 955 mm, the radius of its exit is 1010 mm.

The calculations of the beam extraction into the fixed point were done taking into account the harmonic coils response in magnetic field. Parameters of the 1st harmonic which must ensure the coils were determined above. The radial position of the entrance of the septum was equal to 880 mm, and exit to 902 mm. The aperture of the deflector was considered equal to 9 mm. During the calculation of the beam radial enhancement to the entrance of the deflector, the losses of ions on the front face of the septum and on its side looking on the circulating beam (below it is called external side) were determined. The magnitude of losses on the front face proved to be not more than 12%. In this calculation it was assumed that the thickness of the septum was equal to 0.5 mm. Losses of ions on the external side of the septum did not exceed 0.5%. Figure 15 shows the parameters of 2150 ions on the different planes, which correspond to the azimuth of the

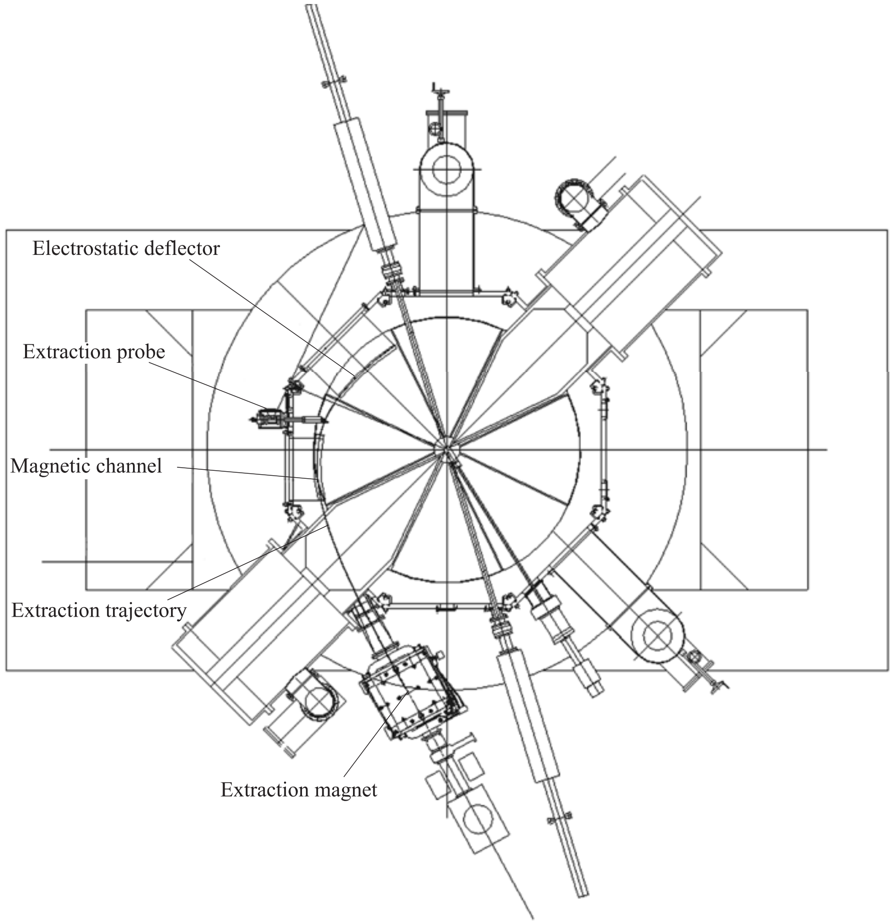

Fig. 12. Plan view of cyclotron with the system of extraction

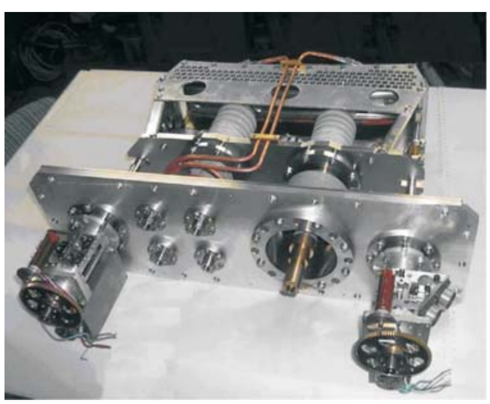

Fig. 13. Electrostatic deflector

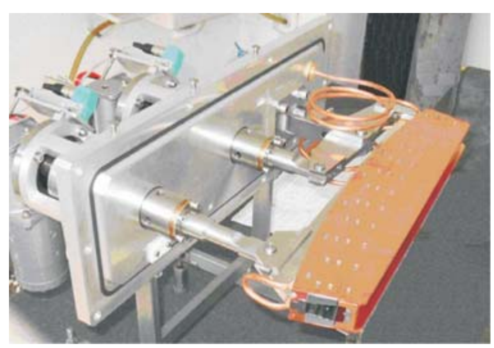

Fig. 14. Passive magnetic channel

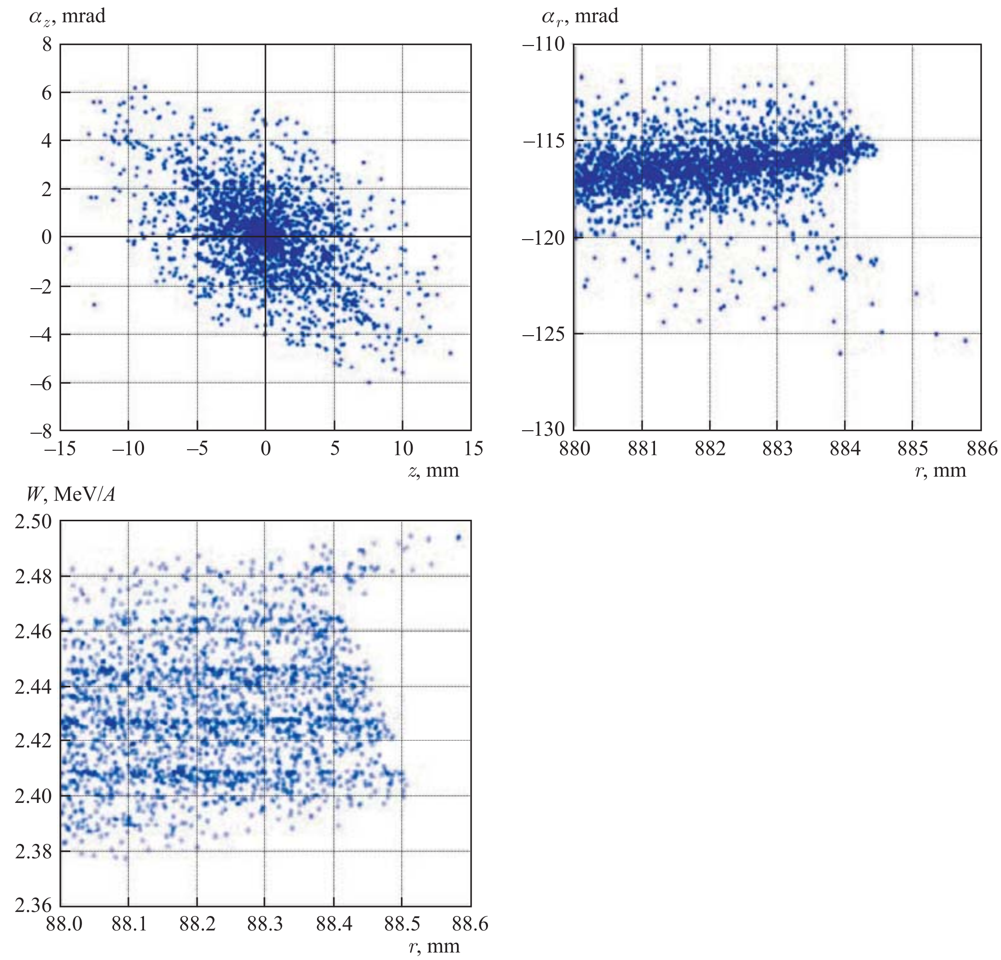

Fig. 15. Parameters of 2150 ions at the entrance of the deflector

entrance into the deflector. In this figure z is a deviation of ion from a middle plane, α_z, α_r are angles between an ion trajectory and middle plane and circle, respectively. RMS values of the beam emittances are $\varepsilon_r = 7\ \pi\,\mathrm{mm}\cdot\mathrm{mrad}$, $\varepsilon_z = 23\ \pi\,\mathrm{mm}\cdot\mathrm{mrad}$, energy spread $\Delta W/W = \pm 2\%$.

Ion losses on the septum inside the deflector were analyzed during the beam extraction simulation. They proved to be within the limits of 13%. The losses were negligible on the high-voltage plate, and inside the magnetic channel they were absent. The trajectories of ions in the deflector and in the magnetic channel are shown in Fig. 16.

To get the beam in the fixed point, a displacement of the magnetic channel entrance was required in outside direction by 9.2 mm in comparison with its design position. The exit of channel was fixed in the design position. The obtained accuracy of the central ion entry into the fixed point is better than 1 mm. An angle of the beam path into the fixed

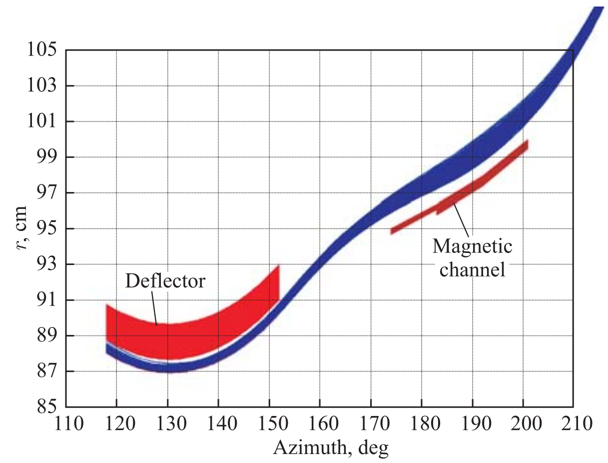

Fig. 16. Trajectories of extracted ions inside the deflector and magnetic channel

Table 3. **Characteristics of the extraction system**

Losses on front face of septum, %	11.7
Losses on external side of septum, %	0.5
Losses on internal side of septum, %	12.9
Sum of losses, %	25.1
Extraction efficiency, %	74.9
Voltage on deflector, kV	45.8
Aperture of deflector, mm	9.0
Aperture of magnetic channel, mm	
horizontal	25
vertical	15

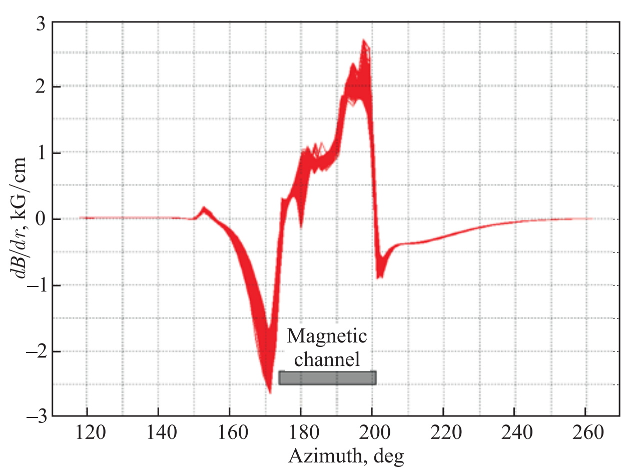

Fig. 17. Radial gradient of magnetic field on the trajectories of ions during extraction. Horizontally defocusing gradient of fringe field on the azimuths 155–175° is changed by focusing one in the aperture of the magnetic channel 175–200°

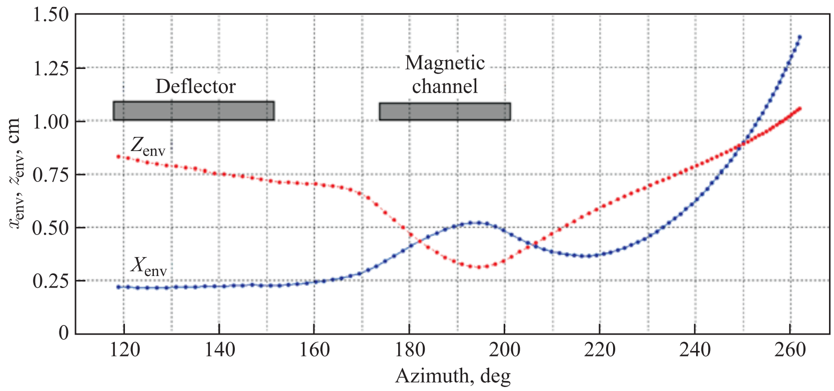

Fig. 18. RMS values (2σ) of the beam envelopes

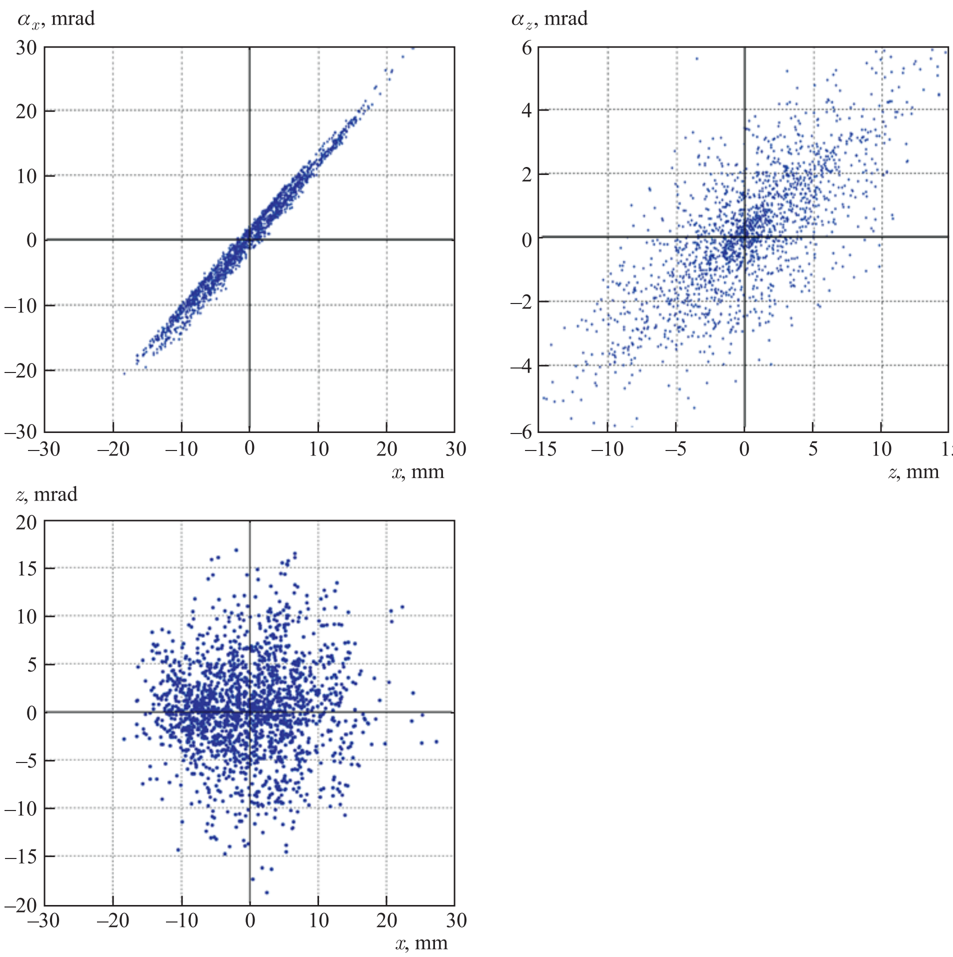

Fig. 19. Beam parameters on different planes which correspond to the position of the fixed point

point coincides with the design value with accuracy 0.5°. The basic results of calculations according to the extraction system are assembled in Table 3, and additionally illustrated in Figs. 17–19.

CONCLUSIONS

The formed magnetic field of DC-110 ensures the acceleration of ions with the phase drift within the limits ±3° HF.

The use of a false channel in the structure of magnetic system makes it possible to achieve energy of extracted beam close to the design value 2.5 MeV/A.

The best parameters of the extraction system of the cyclotron are realized using the harmonic windings located on the mean radii of acceleration 25–55 cm.

The extraction efficiency is 75%, all losses of ions occur on the septum of the deflector.

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