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BEAM DYNAMICS STUDY IN THE C235 CYCLOTRON FOR PROTON THERAPY

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Study of the beam dynamics in the C235 cyclotron dedicated to the proton therapy is presented. Results of the computer simulations of the particle motion in the measured magnetic field are given. Study of the resonance influence on the acceleration process was carried out. The corresponding tolerances on the magnetic field imperfections and transverse beam parameters were defined using these simulations.

Представлены результаты изучения динамики пучка в циклотроне C235, предназначенном для протонной терапии. Описаны методы компьютерного моделирования движения частиц в измеренном магнитном поле. Особое внимание уделялось влиянию резонансов, пересекаемых в процессе ускорения. Определены допуски на возмущения магнитного поля и поперечные размеры пучка, позволяющие ускорить частицы без потерь.

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INTRODUCTION

IBA (Belgium) has designed and equipped over half of the clinical-based particle therapy facilities in the world. Cyclotrons, energy selection systems, gantries and other related equipment were installed in: the National Cancer Center, Kashiwa, Japan; The Wan Jie Proton Therapy Center, Zibo, China; The Massachusetts General Hospital, Boston, USA; The National Cancer Center, Seoul, Korea; The Sino-Japanese Friendship Hospital, Beijing, China; The Florida Proton Therapy Institute, Jacksonville, USA. Having sold, installed and operated of number of C235 cyclotrons all over the world, IBA continuously works on improving cyclotron characteristics.

1. CYCLOTRON MAIN PARAMETERS

The C235 machine (see Fig. 1) is intended for protons acceleration up to 235 MeV. The accelerator for the 235 MeV proton beam delivery in all these facilities is the C235 compact cyclotron with spiral sectors and dees and an elliptical gap decreasing from the center to the final radii.

The extracted beam current is about 10–50 μA. Characteristics of the cyclotron are presented in Table 1.

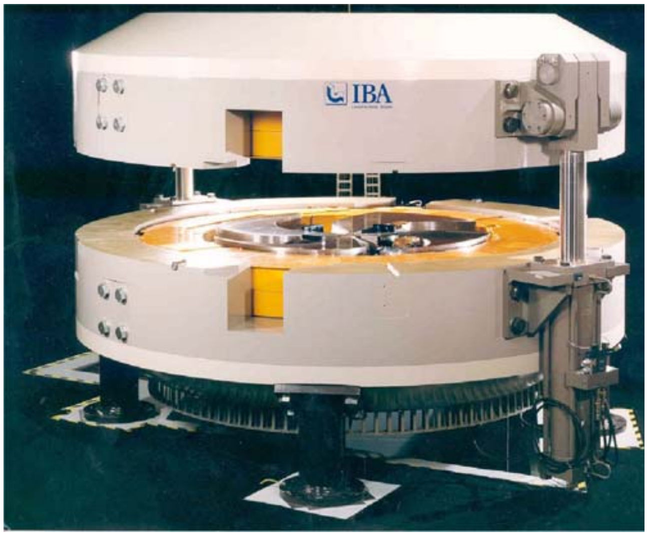

Fig. 1. The C235 cyclotron main view

Table 1. **Main parameters of C235**

Energy of the accelerated protons, MeV	235
Average magnetic field, T: in the center at the extraction radii	 1.7 2.15
Extraction radius, m	1.08
Magnetic field at the extraction radius, T: in the hill in the valley	 3.09 0.98
Gap of the magnetic system, cm: in the valley in the hill	 60 9.6–0.9
Number of sectors	4
Coil current*turns number, kA	525
Power of the magnet coil, kW	190
Weight of the magnet, t	210
Number of dees	2
Accelerating voltage, kV: in the center at the extraction radius	 55 150
Frequencies of betatron oscillations Q_r/Q_z	1–1.37/0–0.28

The magnetic system has an elliptic gap decreasing from 9.6 cm at the center to 0.9 cm at the final radii. The vertical aperture of dees is 2 cm. The internal ion source is located in the very center of the cyclotron and has a vertical input into the machine.

The measured average magnetic field and its high harmonics of the cyclotron are shown in Figs. 2 and 3.

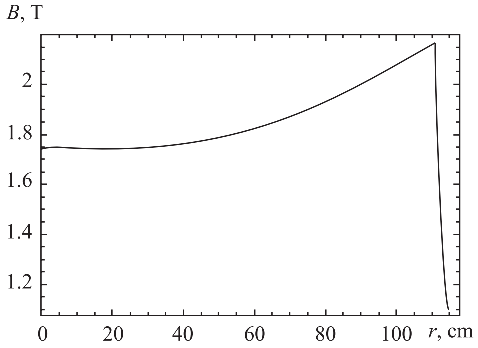

Fig. 2. Average field of the C235 (P06) cyclotron

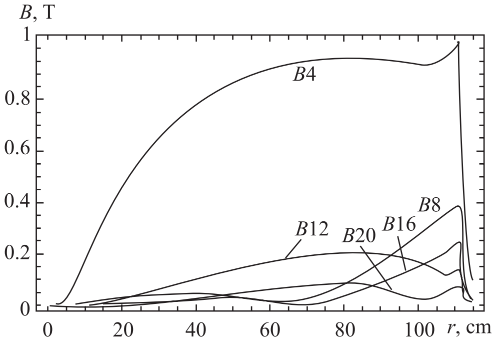

Fig. 3. High harmonics of the magnetic field of the C235 (P06) cyclotron

Working point diagram of the cyclotron is presented in Fig. 4 (Q_r and Q_z frequencies of betatron oscillations). Last point in the graph corresponds to the energy of 233.7 MeV, energy step is 0.4 MeV.

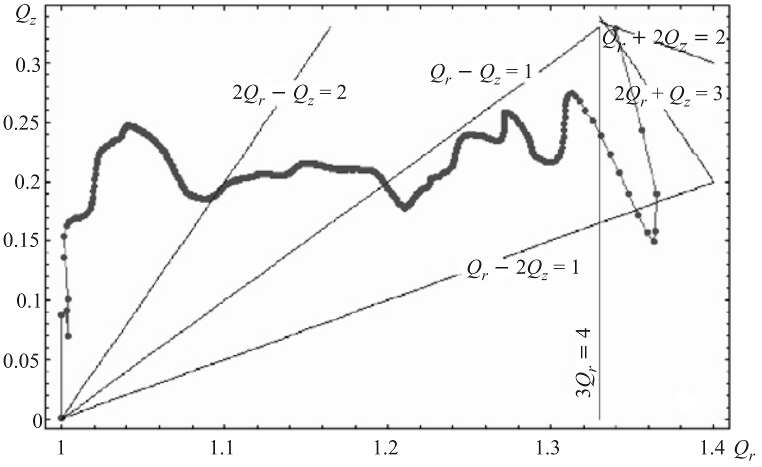

Fig. 4. Working point diagram of the cyclotron

The internal resonance $4Q_r = 4$ and the resonance of errors $Q_r = 1$ are crossed by the working point at the center radii ($\sim 5-17$ cm). Coupling resonance of the 3rd order $2Q_r - Q_z = 2$ exists at the 63–64 cm radii, $Q_r - Q_z = 1$ — at the 90–92 cm. Internal resonance $3Q_r = 4$ is crossed at the 107 cm radius. The last two resonances of the 3rd order $Q_r - 2Q_z = 1$, $2Q_r + Q_z = 3$ and $Q_r + 2Q_z = 2$ are crossed at the 109 cm radius.

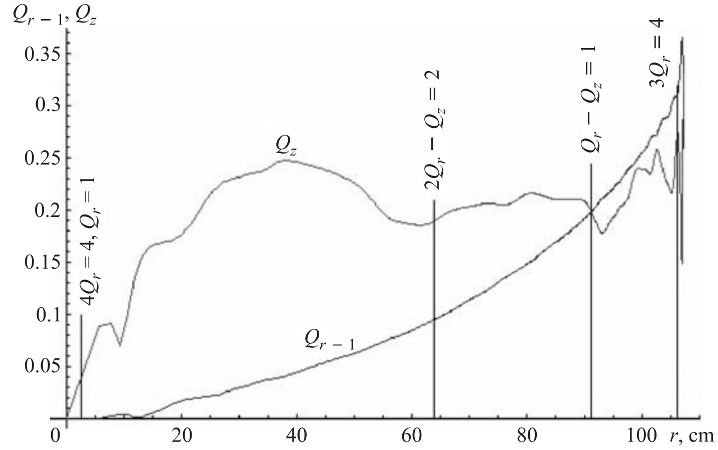

Fig. 5. Betatron frequencies of the C235 (P06) cyclotron

Important to note that in this cyclotron the accelerated beam is extracted before crossing the last three resonances. The betatron frequencies are presented in Fig. 5.

2. STUDY OF THE RESONANCES CROSSING DURING THE ACCELERATION

2.1. $4Q_r = 4$ **Resonance.** $4Q_r = 4$ is the internal resonance of the 4th order which is excited by the nonlinearities of the main harmonic of the magnetic field ($B4$). Amplitude of this harmonic is presented in Fig. 6. It is possible to see that $B4$ has a nonlinear growth in the resonance region. Radial betatron frequency in the center of the cyclotron is shown in Fig. 7. This resonance is crossed three times in the range of radii 4–17 cm.

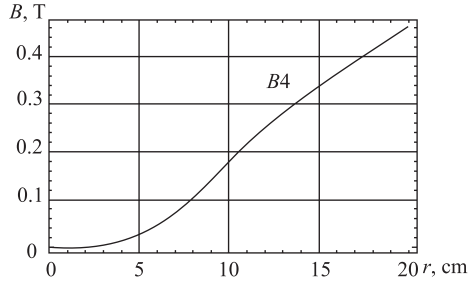

Fig. 6. Amplitude of the 4th harmonic of the magnetic field

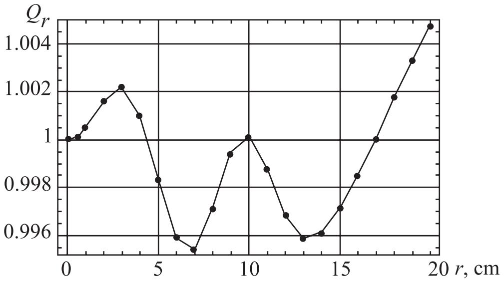

Fig. 7. Radial betatron frequency in the resonance region

A bunch of 1000 particles normally distributed at radial phase plane with amplitudes of free radial oscillations (A_r) up to ~ 2 mm and matched with the cyclotron parameters was generated at ~ 4 cm radius and then accelerated up to ~ 30 cm radius. Accelerating voltage in the center of the cyclotron is supposed to be equal to 60 kV. Calculations show that the radial motion of the bunch is stable during the acceleration through the resonance region. Positions of the bunch on radial phase plane are shown in Fig. 8.

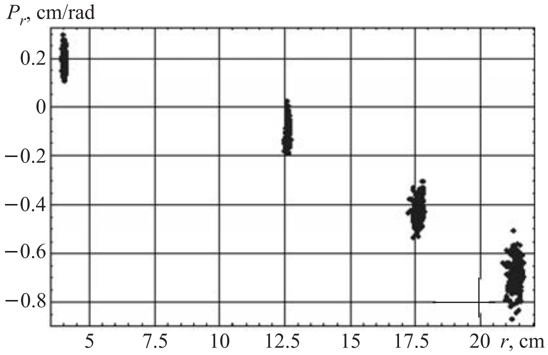

Fig. 8. Positions of the accelerated bunch on radial phase plane (distance between the points is 10 turns)

Calculations show that the radial emittance of the bunch is quite stable during the acceleration through the resonance region as well as amplitudes of free radial oscillations.

Hence, internal resonance $4Q_r = 4$ is not dangerous in this cyclotron and has almost no influence on the radial motion of the beam during the acceleration.

2.2. $Q_r = 1$ **Resonance.** The driving term of this resonance is the amplitude of the 1st harmonic of the magnetic field imperfections in the centre of cyclotron. Radial displacement of the equilibrium orbit is the result of this resonance.

Starting bunch with emittance $\varepsilon_r = 15\pi$ mm · mrad and A_r up to ~ 2 mm was used for the resonance investigation. Amplitude of the 1st harmonic used in simulations had linear

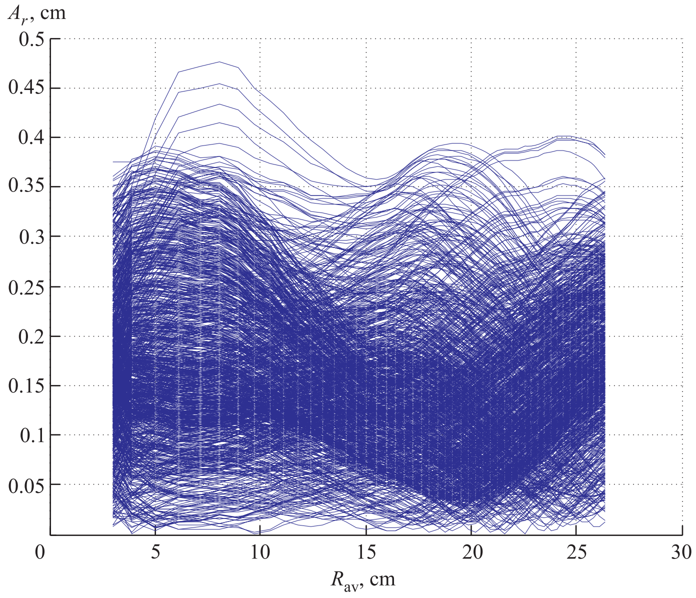

Fig. 9. Amplitudes of radial oscillations of the protons in the cyclotron center (without 1st harmonic)

and constant dependence along radius. Maximal value of the amplitude was on radius 6 cm and it was equal to 2 and 5 G (Figs. 10 and 11).

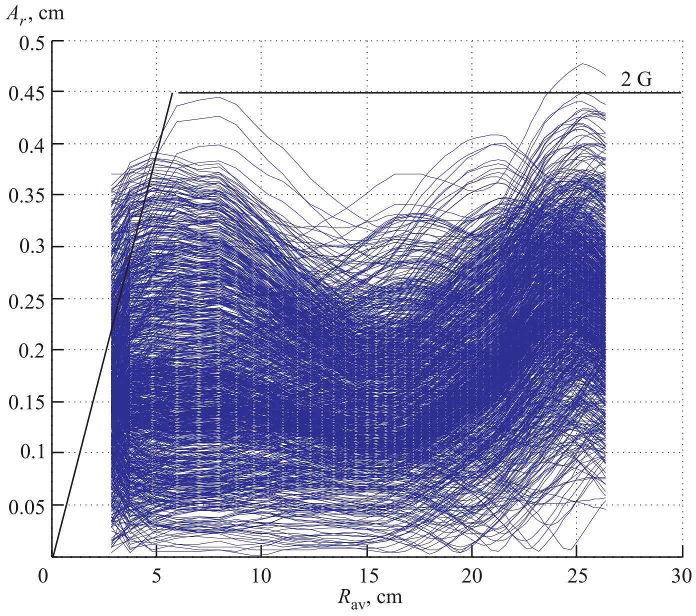

Fig. 10. Amplitudes of radial oscillations of the protons in the cyclotron center (1st harmonic of the magnetic field 2 G)

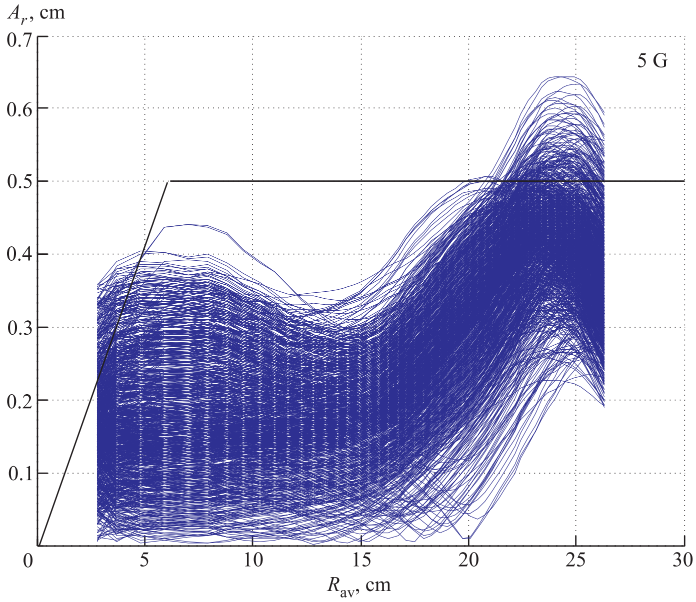

Fig. 11. Amplitudes of radial oscillations of the protons in the cyclotron center (1st harmonic of the magnetic field 5 G)

The results of simulations of the beam acceleration in the centre of cyclotron are shown in Figs. 9, 10 and 11.

The 1st harmonic with amplitude up to 2–3 G leads to 0.5–1 mm radial amplitudes increase. In order to see resonance effect more clearly, we increased the 1st harmonic amplitude to 5 G (see Fig. 11). Two times radial amplitudes increasing was observed in this case.

Hence, it is possible to conclude that $Q_r = 1$ is the dangerous resonance. The restriction to the amplitude of the 1st harmonic of the magnetic field in the center region of the cyclotron is 3 G. This condition was satisfied in the C235 (P06) machine.

2.3. $2Q_r - Q_z = 2$ **Resonance.** The 2nd harmonic of the radial component of the magnetic field imperfection is the driving term of this resonance. It was added in the vicinity of the resonance. Influence of the 2nd harmonic of the axial and azimuthal components of the magnetic field imperfections was calculated too.

Resonance radius is ~ 63 cm. The bunch of 200 particles was generated at radius ~ 52 cm and then accelerated through the resonance region in order to study influence of the resonance on the transverse size of the beam. Maximum of harmonic amplitude was located at the resonance radius — 63 cm. In all computations in the range 60–66 cm of radii the nonlinear (parabolic) dependences of the amplitude of harmonic vs radius were used.

There were no noticeable changes in amplitudes of radial oscillations and axial motion of the bunch after the resonance crossing if B_{2z} less than 200 G was used in simulations.

Only if B_{2z} more than 200 G was used, it was observed a noticeable increase of the amplitudes of the radial betatron motion after the bunch passing the resonance.

Simulations have shown that the second harmonic of the radial component of the magnetic field error leads to an increase in the beam axial size after passing the resonance zone. Radial amplitudes of the betatron motion remain at their initial values. The beam axial size increasing was detected when we used B_{2r} more than 150 G in the maximum of the field imperfections.

Calculations showed that for B_{2r} less than 150 G there are no noticeable changes in the amplitudes of betatron motion.

We did not detect any changes in size of betatron amplitudes after crossing of the resonance region at presence of the second harmonic of the azimuthal magnetic field imperfections with amplitude up to 500 G. Hence, influence of the magnetic field imperfections in the region of the resonance $2Q_r - Q_z = 2$ is unnoticeable if $B_{2z} < 200$ G, $B_{2r} < 150$ G and $B_{2\phi} < 500$ G. In these calculations we used imperfections located at 60–66 cm range of radii, so the corresponding tolerances to the harmonics nonlinearities ($d^2B_{2z,2r,2\phi}/dr^2$) are equal to 40, 20 and 100 G/cm^2.

The 2nd harmonic of the radial field imperfections leads to the most significant effect on the beam motion after passing this resonance. Resonance is not dangerous.

2.4. $Q_r - Q_z = 1$ **Resonance.** This is the linear coupling resonance of the 2nd order. The first harmonic midplane asymmetry (harmonic of the radial component of the magnetic field) excites this resonance. Nonsymmetric distribution of the iron in the poles or nonsymmetric field generated by main coils (tilted coils) could be cause of such a distortion.

The same bunch as in the previous case (see section above) was used for study the influence of this resonance on the transverse beam size during the acceleration. The 1st harmonic of the radial component of the magnetic field (B_{1r}) was added into main field map and simulation of the bunch acceleration through the resonance region was carried out. The results are presented in Fig. 12.

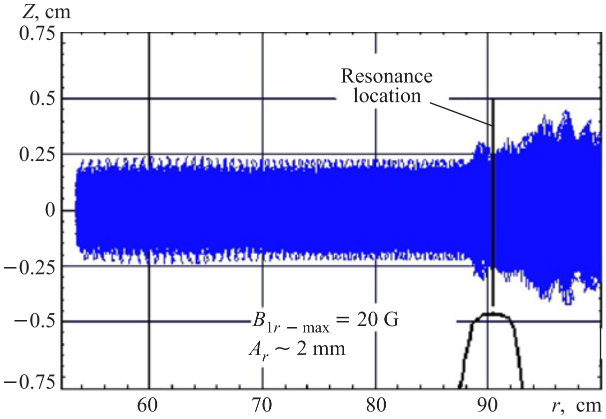

Fig. 12. Vertical motion of the beam in the vicinity of the $Q_r - Q_z = 1$ resonance. Z coordinates of each particle are given four times per turn

It is possible to see that in presence of B_{1r} (with amplitude 20 G in the maximum) the beam increases vertical size from 4 up to 8 mm. It is not acceptable because of the small vertical aperture of the magnetic system at the final radii. This result was obtained for the beam with $A_r \sim 2$ mm (the additional calculations show that for the beam with A_r more than 2 mm the influence of the resonance is stronger).

Therefore, $Q_r - Q_z = 1$ is a dangerous resonance. It is possible to formulate the tolerance to the value of the 1st harmonic of the radial component of the magnetic field in the resonance region. For beam with $A_r \sim 2$ mm B_{1r} must be less than 5–7 G (in this case the beam size increase will be less than 20%).

2.5. $3Q_r = 4$ **Resonance.** The resonance $3Q_r = 4$ is internal nonlinear resonance of the third order, which is excited by the nonlinearities of the fourth harmonic of the magnetic field. The average radius of the orbit of ion at the moment of the resonance crossing is equal to 107.4 cm, corresponding energy — 229 MeV.

The derivatives along a radius of the amplitude and phase of this harmonic are shown in Figs. 13 and 14. One can see that amplitude and phase of the 4th harmonic have considerable nonlinearity at the resonance radius ($\sim$ 107 cm).

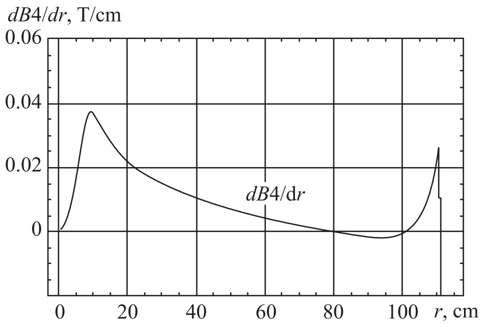

Fig. 13. The derivative of the amplitude of the 4th harmonic of the magnetic field

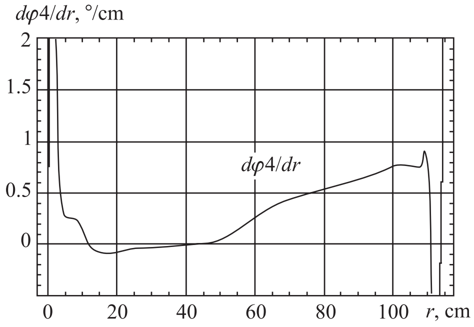

Fig. 14. The derivative of the phase of the 4th harmonic of the magnetic field

It is difficult to estimate the influence of this resonance on the beam motion in this cyclotron because of the large amplitudes of the radial betatron oscillations ($\sim 10{-}12$ mm) of the beam at the final radii (due to essential — up to $\sim$ 80 G — 1st harmonic of the magnetic field). Also, the beam is extracted just after the resonance crossing. The results of this resonance study in the static (without acceleration) regime are shown in Fig. 15.

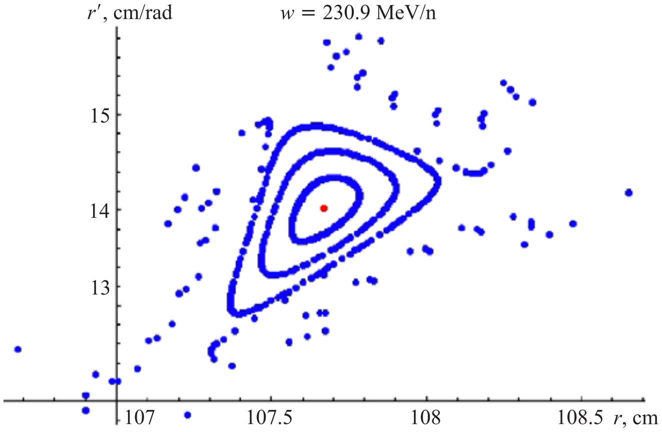

Fig. 15. Motion of the protons with $A_r = 1$, 2, 3 and 3.5 mm on the (r, P_r) phase plane in the static regime. Distance between points is one turn. In the center there is a position of the equilibrium orbit with average radius equal to radius of the resonance ($\sim$ 107 cm)

It is possible to see that the motion becomes unstable when the amplitude of free radial oscillation of the particle is more than 3 mm.

Figure 16 demonstrates the crossing of the resonance in the dynamic regime.

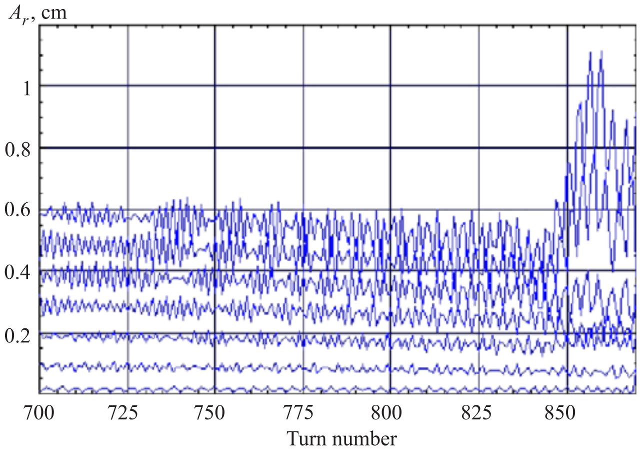

Fig. 16. Crossing of the $3Q_r = 4$ resonance for protons with $A_r = 0.1$, 1, 2, 3, 4, 5 and 6 mm

It is possible to see increase of the free radial amplitudes of the protons with $A_r > 3$ mm due to the resonance action.

This resonance is dangerous. It is preferable to decrease the nonlinearity of the amplitude and phase of the fourth harmonic of the magnetic field in the resonance vicinity to decrease force of the resonance.

CONCLUSIONS

Beam dynamics in the C235 cyclotron study was carried out. All resonances up to the 4th order crossed by the beam during the acceleration were investigated. Measured magnetic field

Table 2. **Main results of the resonances study in the C235 cyclotron**

Resonance	Radius, cm	Driving term	Action of the resonance	Tolerances to the magnetic field imperfections, G	Level of danger
$4Q_r = 4$	4–17	Amplitude of the 4th harmonic B_{4z}, phase of the 4th harmonic f_{4z}	Insignificant influence on the radial motion		Not dangerous
$Q_r = 1$	4–17	Amplitude of the 1st harmonic B_{1z}	Increase of the amplitudes of free radial oscillations of protons in the beam	$B_{1z} < 3$	Dangerous
$2Q_r - Q_z = 2$	63	Nonlinearity of the 2nd harmonic of the radial and axial component of the magnetic field B_{2r}, B_{2z}	Increase of the vertical size of the beam	$B_{2z} < 200$, $B_{2r} < 150$	Not dangerous
$Q_r - Q_z = 1$	91	The 1st harmonic of the radial component of the magnetic field B_{1r}	Increase of the vertical size of the beam	$B_{1r} <$ 5–7	Dangerous
$3Q_r = 4$	107	Amplitude of the 4th harmonic B_{4z}, phase of the 4th harmonic f_{4z}	Increase of the amplitudes of free radial oscillations of protons in the beam beginning from $A_r \sim 3$ mm		Dangerous

map for P06 machine was used in these calculations. It is possible to conclude that $Q_r = 1$, $Q_r - Q_z = 1$ and $3Q_r = 4$ resonances have a strong influence on the beam motion in this cyclotron. The tolerances on low harmonics of the different components of the magnetic field were formulated (see Table 2) basing on these calculations.

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