CORRECTION OF VERTICAL SHIFTING OF EXTRACTED BEAM AT THE TEST OPERATION OF DC-110 CYCLOTRON

I.A. Ivanenko, B.N. Gikal, N.Yu. Kazarinov, I.V. Kalagin, V.I. Mironov, E.V. Samsonov,
FLNR, JINR, 141980 Dubna, Russia

Abstract

The specialized heavy ion cyclotron DC-110 has been designed and created by the Flerov Laboratory of Nuclear Reactions of Joint Institute for Nuclear Research for scientifically industrial complex "BETA" placed in Dubna (Russia) [1]. DC-110 cyclotron is intended for accelerating the intense Ar, Kr, Xe ion beams with fixed energy of 2.5 MeV/nucleon. The commissioning of DC-110 cyclotron has been carried out at the end of 2012. The project parameters of the ion beams have been achieved.

During commissioning of cyclotron, the vertical displacement of the beam at the last orbits and at the extraction channel was revealed. The calculations and experiments have shown that the reason of this displacement is the radial component of magnetic field at the median plane of the cyclotron, which appears because of asymmetry of the magnet yoke. Correction of the vertical displacement of the beam has been achieved by creating an asymmetry of current distribution in the main coil of the cyclotron electromagnet.

EXPERIMENTAL TESTING OF THE EXTRACTED BEAM POSITION AND DIMENSION

Commissioning of the DC-110 cyclotron has been done at the end of 2012. During the experimental testing of the cyclotron, the extracted beam position and dimension was analyzed. The beam tracks on the constructed elements of extraction system has shown that the beam at the last orbits and during the extraction has a vertical displacement. The extraction system consist of electrostatic deflector and passive magnetic channel. At the Fig. 1 the beam track at the deflector entrance, R=894 mm, has 3 mm of vertical displacement above median plane.

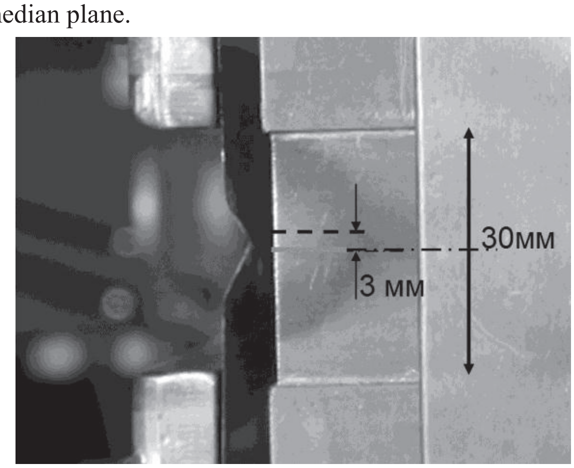

Figure 1: The beam track at the deflector entrance.

At the magnetic channel exit the beam track already has shown 5 mm of vertical displacement. At the distance of 1.1 meter after magnetic channel, in the extracted beam transport line, the luminophore probe is placed. The beam track at the probe has shown 16 mm of vertical displacement and aperture losses, Fig. 2.

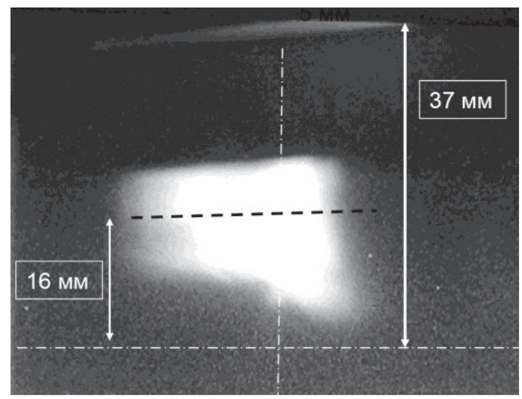

Figure 2: The beam track at the luminophore probe.

ESTIMATION OF MAGNET AXIAL ASYMMETRY INFLUENCE ON BEAM DYNAMIC AT EXTRACTION AREA

The main reason of the vertical displacement of the beam at the last orbits and at the extraction channel is the radial component of magnetic field, Br, on the median plane of the cyclotron. Br component appears because of vertical asymmetry of the magnet yoke.

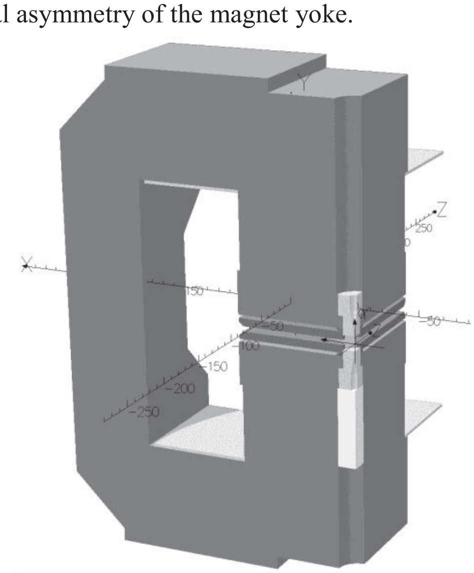

Figure 3: The model of asymmetric yoke of DC-110 cyclotron magnet.

At the case of DC-110 cyclotron, the reason of this asymmetry was the difference of the upper and lower axial holes in the yoke. The upper hole is used for axial injection system. The lower hole not used and was closed with iron in the magnet pole to prevent the vacuum losses.

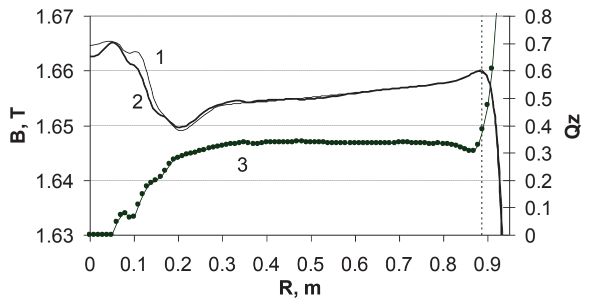

Figure 4: 1, 2 – measured and calculated magnetic fields; 3 – vertical betatron oscillations .

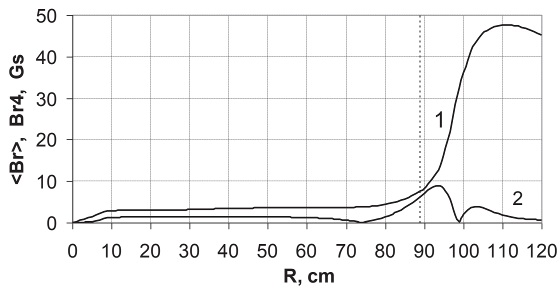

Figure 5: 1 – average value of radial component Br; 2 – fourth harmonic of radial component B4r.

To estimate the influence of Br component on the beam behavior, the 3D calculation of the magnetic field at the asymmetric yoke of cyclotron magnet carried out with code TOSCA. At the Fig. 3 the model of a quarter of DC-110 magnet is shown. The results of calculations and measurements of average magnetic field, <B>, are compared at the Fig. 4 and show the accuracy of field formation better then 0.2% at the main region of acceleration and no more then 0.5% at the cyclotron centre. DC-110 cyclotron has 4 - sectors magnetic structure, and the axial asymmetry of the magnet leads to appearing of radial component of magnetic field and their even harmonics. The average value of Br component and its fourth B4r harmonic, Fig. 5, leads to axial shifting of the beam and can be estimated with equations [2]:

$$\Delta Z(B_r) = \frac{rB_r}{B_z Q_z^2} \quad (1)$$

$$\Delta Z(B_{4r}) = \frac{rB_{4r}B_{4z}}{B_z^2 Q_z^2 (N^2 - (1+n))} \quad (2)$$

At the extraction radius Rext = 0.894 m, the average magnetic field Bz = 1.66T and beam vertical betatron oscillation Qz = 0,38. According to Eqs. 1 – 2, the radial component Br = 7.7Gs leads to the beam vertical displacement $\Delta Z \approx 2.8$ mm. The fourth harmonic of radial component B4r = 7Gs give a small vertical displacement $\Delta Z \approx 0.06$ mm and can be neglected. This estimations give a good coincidence with the experimental beam position at the deflector entrance. When the beam passes through the passive magnetic channel, the vertical displacement increases because the magnetic field gradient, and can be estimated by equation:

$$\Delta Z' = \frac{GL}{B\rho}\Delta Z_0 \quad (3)$$

If the beam vertical displacement before channel $\Delta Z \approx$ 2.8 mm, the magnetic field gradient G ≈ 7 T/m, the effective length of magnetic channel L = 0,47 m and Bρ = 1.66T*0.9 m, then at the channel exit the beam has the vertical angle $\Delta Z' \approx 0.006$rad. At the distance S = 1.1 m between channel and luminofore probe, the beam gain the total vertical displacement $\Delta Z_L \approx 10$ mm. The results of experiment and estimation are compared at the Table 1.

Table 1: The Vertical Shifting of the Beam

Margin	ΔZ, R=894 mm	ΔZ_L, Luminofore
Estimation	Up, 2.8 mm	Up, 10 mm
Experiment	Up, 3 mm	Up, 16 mm

NUMERICAL AND EXPERIMENTAL COMPENSATION OF THE BEAM VERTICAL SHIFTING

One of the possible way to compensate the beam vertical displacement is to add asymmetry to the magnet main coil. The main coil of DC-110 cyclotron consist of upper and lower sub-coils with 6 sections at each. The sections has a consecutive connection and can be tuned off or shunted separately. The nominal current of the main coil I=1000A. The three cases of main coil asymmetry are considered.

- 1 case, the closest to median plane section of lower sub-coil were turned off.
- 2 case, the closest to median plane section of lower sub-coil was shunted.
- 3 case, the farthest to median plane section of lower sub-coil was shunted.

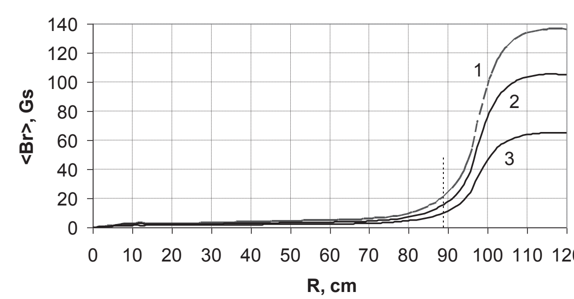

Figure 6: The radial component Br of the magnetic field for 1, 2 and 3 cases of magnet main coil asymmetry.

ISBN 978-3-95450-128-1

To see a "pure" effect of main coil asymmetry, the magnetic field calculations were carried out with the axial symmetry of magnet yoke. The shunted sections have the experimentally measured residual current I=200A. The corresponding Br components were used to estimate the beam vertical displacement, Fig. 6 and Table 2. The estimations have shown the method of main coil asymmetry is enough for compensation the beam vertical displacement.

Table 2: The Estimation of Br Component and Beam Vertical Displacement for Cases of Main Coil Asymmetry

Case of asymmetry	Br, R=894 mm	ΔZ, R=894 mm	ΔZ_L, Luminofore
1	21 Gs	7.8 mm	27 mm
2	15.7 Gs	5.8 mm	20 mm
3	10 Gs	3.7 mm	13 mm

The presented cases of magnet main coil asymmetry were repeated in commissioning of DC-110 cyclotron. The beam vertical position at the deflector entrance were measured at the case with initial, symmetric main coil and at the cases of shunting of main coil sections. The case with turned off section was not considered. The results of these measuring are presented at the Fig. 6 and Table 3.

Table 3: The Measuring of Beam Vertical Position at the Deflector Entrance for Cases of Main Coil Asymmetry

Case of asymmetry	ΔZ, R=894 mm actual position	ΔZ, R=894 mm relative position
No coil asymmetry	Up, 3 mm	0 mm
1	Not measured	-
2	Down, 3 mm	Down, 6 mm
3	0 mm	Down, 3 mm

At the table 3 the "actual position" column presents the actual displacement of the beam as at the Fig. 7. The "relative position" column shows the effect of coil asymmetry and is in good agreement with estimations.

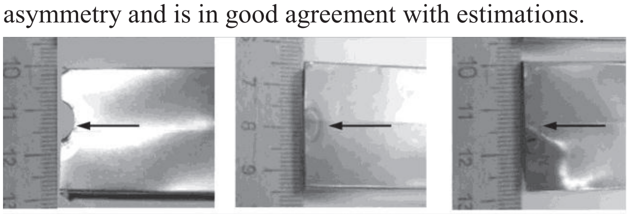

Figure 7: The beam track at the deflector for initial case with symmetric coil and for cases of shunting of sections.

The results of measuring of the beam vertical position at the luminofore probe for 1, 2 and 3 cases of magnet main coil asymmetry are presented at Fig. 8. According this picture the 1 case, when the closest to median plane section of the lower sub-coil is turned off, displace the beam to the median plane of the extraction channel. The signals of profile probes show that the further motion of the beam along extraction channel, up to the target, lies at the median plane. This case was taken as a working variant.

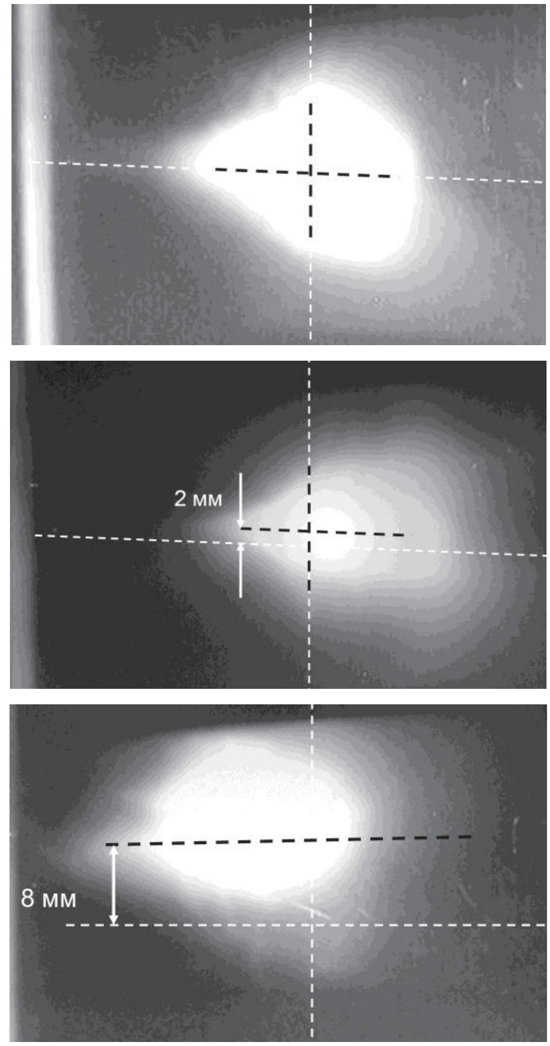

Figure 8: The beam track at the luminofore probe for 1, 2 and 3 cases of magnet main coil asymmetry.

CONCLUSION

During DC-110 cyclotron commissioning the beam project parameters were achieved. The vertical displacement of the extracted beam was successfully compensated by turning off one section of the magnet main coil.

REFERENCES

[1] B.N.Gikal, et al., "The project of DC110 heavy ion cyclotron for industrial application and applied research in the nanotechnology field", Particles and Nuclei, Letters 2010, Vol. 7, No. 7 (163), pp. 891–896.

[2] N.L.Zaplatin, et al., "The definition and correction of the magnetic field median plane of "Phazotron, JINR", JINR report, P9-82-925, Dubna, 1982.