# CALCULATION AND MEASUREMENTS OF THE MAGNETIC FIELD OF IM90 BENDING MAGNET OF CYCLOTRON DC280 AXIAL INJECTION SYSTEM

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*Abstract*

Nowadays a project of a high-intensity cyclotron of heavy ions DC-280, is realized in Flerov Laboratory of Nuclear Reactions of Joint Institute for Nuclear Research. The cyclotron must provide a middle-mass ion beam intensity (A-50) up to 10 µA/particle for solvation of super-heavy elements synthesis. In a channel of axial injection of the cyclotron, the IM90 magnet is used for beam separation with required ratio of mass to charge A/Z.

The results of calculations of electromagnetic field of IM90 magnet are presented at this paper. 3-D model of the electromagnetic field was created and the corresponding calculations were realized. A calculation of the effective length of the magnet and it comparison with the data of magnet measurements were carried out.


## INTRODUCTION

The swivel magnet IM90 is used for the analysis of the beam spectrum in the high axial injection system (Figure 1).

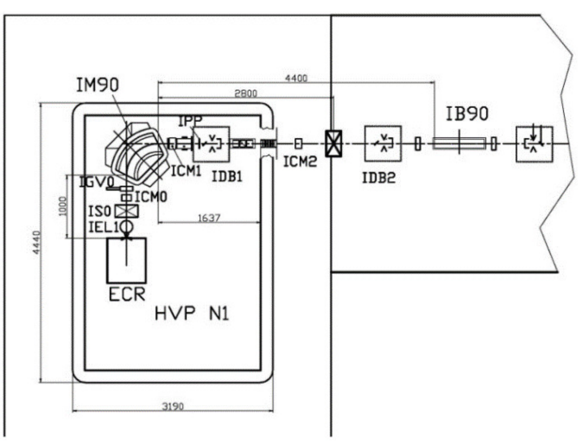


Figure 1: The scheme of the axial injection channel (view from above). Where: ECR- the ion sources; IM90 is the analysing magnet; IB90 is the bender; IS0, IS1, IS2, IS3 are the focusing solenoids; IEL1, IEL2 are the Einzel lenses; IAT is the accelerating tube; ICM0÷ICM3 are the steering magnets; IPP is the pepper-pot; ICP is the beam chopper; IDB1÷IDB3 are the diagnostic boxes; IBN is the polyharmonic buncher [1,2].

The ion beam will be extracted from ECR with the energy of 25 keV/Z. After extraction the ion beam will be focused by the IEL1 Einzel lens and by the IS0 solenoid to the IM90 analysing magnet input. The ion charge spectrum will be analyzed by means of magnetic field variation in the IM90 and by the IS0 with measuring the ion current by Faraday cup (FC) in the IDB1 diagnostic box.

The manufactured IM90 magnet is structurally differ from the computer model and the Technical Tasks 2012-2013. (Figure 2).

In according to the terminology of the technical specification, the magnet is made as a "closed" screen, but with expanded beams and magnet stands up to the screens. At the same time, the outer overall dimensions did not change, because they were determined by the location of screens. Screens are necessary to reduce the extent of the magnetic field of the magnet. The maximum calculated induction of the magnetic field is 0.14 T in the gap. It provides the analysis of the charge spectrum for all types of accelerated ions. The requirement to the analyzing magnet IM90, which is located on the high-voltage platform, is minimum possible energy consumption. As a result, the magnet is designed with excitation coils, which have indirect water cooling and work at medium current density of not more than 2.5 A / $mm^2$. The main characteristics of the magnet are shown in Table 1.

The resolution of the magnet allows to analyze all types of beams accelerating in the cyclotron DC-280.

Table 1: Main Parameters of IM90 Magnet

| | |
|---|---|
| Magnetic field induction, T | 0,14±1% |
| Gap, mm | 110 |
| Active pole length, mm | 785,4 |
| Inhomogeneity of magnetic induction in the zone ±65 mm | $\pm 1x10^{-4}$ |
| Operating voltage of coil, V | 76,8±2,5% |
| Cooling of coil - water | Distilled water |
| Water pressure difference, $kG/cm^2$ | 4,0±5% |
| Total cooling water flow , l/min | 3 |
| Nominal power supply, kW | 1,41±2,5% |
| Total weight of magnet, kg | 2326 |

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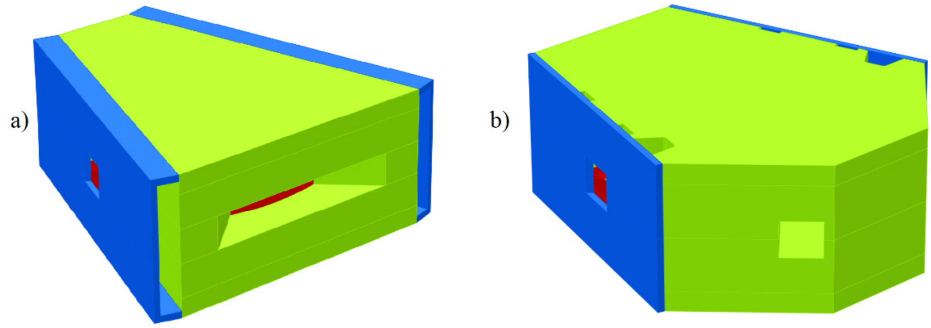


Figure 2: Model of the magnet: old model (terms of reference 2012-2013); b) new model (Complies with to the real product).

The design is based on three-dimensional calculation of the magnet field carried out by using OPERA 3D program code [3].

## CALCULATION RESULTS

The reference orbit of the magnet and magnetic field distribution at this orbit are shown in Fig. 3 and 4 [4].

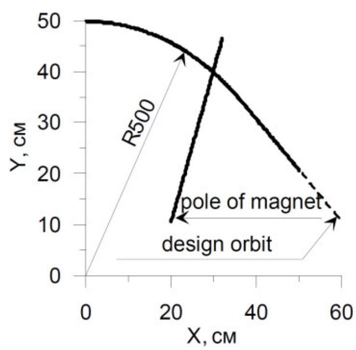


Figure 3: Reference orbit of IM90 magnet.

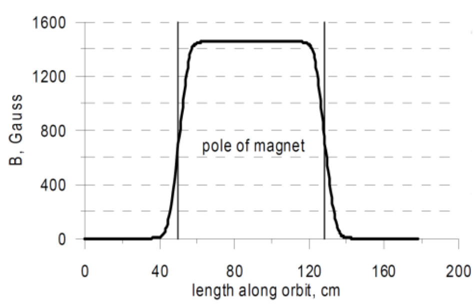


Figure 4: Bz field along reference orbit of IM90 magnet.

By definition, the effective length is calculated as:

$$L_{eff} = \int_{-\infty}^{+\infty} \frac{B(S)}{B(0)} dS$$

The effective length corresponding to an ideal equilibrium orbit (R=50 cm.) in a magnet:

$$L_{eff} = \frac{\pi}{2} \cdot R = \frac{\pi}{2} \cdot 50 = 78.5398 \text{ см.}$$

The result of the effective length calculation is shown in table 2.

Calculated paths in computer model are constructed in accordance with the radii of measurements [5].

Comparisons of measurements (Rи) and calculations (R) are presented in figures 5-7.

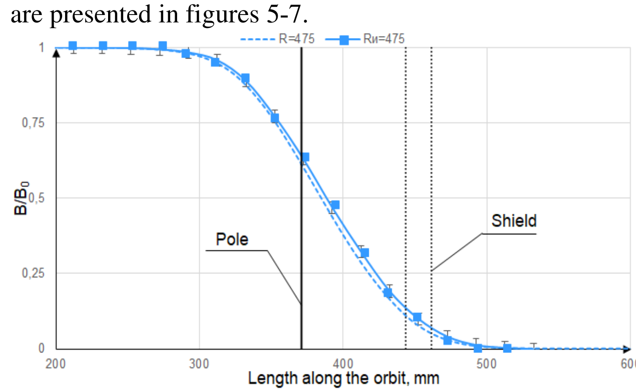


Figure 5: The ratio of the edge field to one in the center of magnet computed at the internal trajectory.

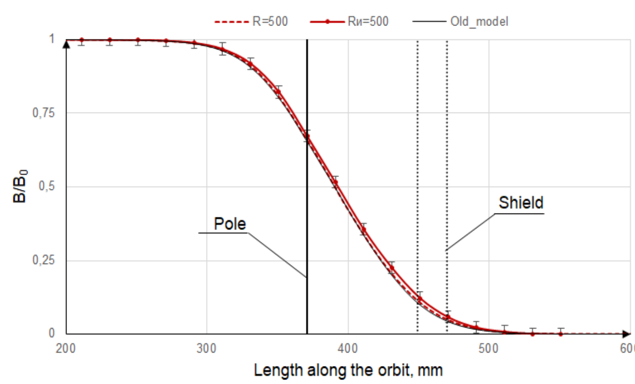


Figure 6: The ratio of the edge field to one in the center of magnet computed at the central trajectory.

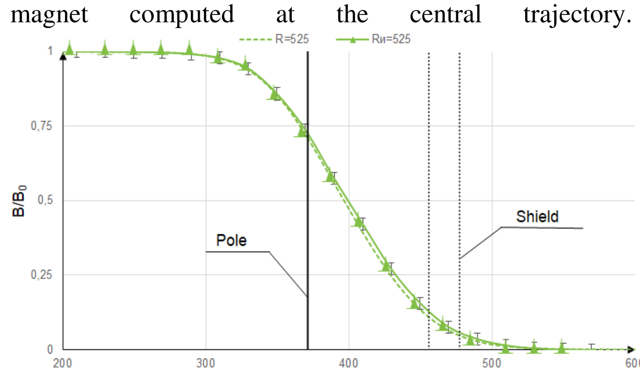


Figure 7: The ratio of the edge field to field in the center of magnet computed at the external trajectory.



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Table 2: The Effective Length

| | $L_{eff}$, см |
|---|---|
| Analytical | 78.53982 |
| Old model (fig.2 a) | 78.23309 |
| New model (fig.2 b) | 78.39816 |
| Measurements [5] | 79.51902 |

## MEASUREMENTS

The magnetic measurements were carried out by the Hall detector (GALISS / TESLAMETER, MODEL S080), which was alternately set first to the azimuth part of trajectory, and then to the linear part (Fig. 8). The magnetization curve of the magnet (that is dependence of the magnetic field induction in the center of the magnet on winding current) was measured (Fig. 9). Table 3 shows the magnetic field values obtained in the measurements and calculations at different current levels. The relative error greater at low field levels and less at high. The calculation was carried out for steel 10.

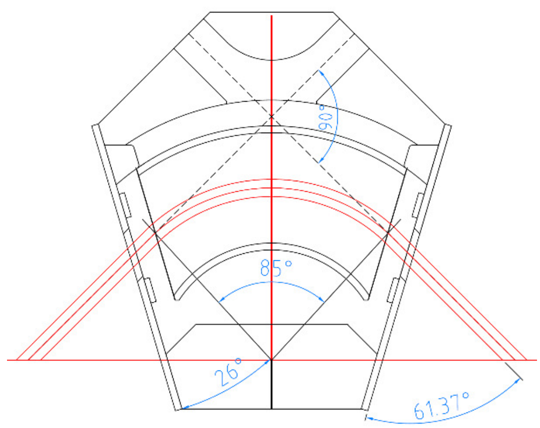


Figure 8: Trajectories of measurements and calculations.

Table 3: Magnetization Curve

| | Measurements | Calculation | Ratio error |
|---|---|---|---|
| I, A | B, kG | B, kG | % |
| 0 | 0 | 0 | 0 |
| 3.1 | 0.254 | 0.243813 | 4.178117 |
| 5.2 | 0.422 | 0.410219 | 2.871881 |
| 8.3 | 0.679 | 0.656853 | 3.371730 |
| 12.7 | 1.034 | 1.007755 | 2.604304 |
| 15.7 | 1.283 | 1.247207 | 2.869852 |
| 20.1 | 1.638 | 1.598372 | 2.479273 |
| 23.2 | 1.889 | 1.845599 | 2.351605 |
| 25.8 | 2.094 | 2.052820 | 2.006031 |

The calculated magnetization curve is approximated by a polynomial of the second order with a sufficient degree of accuracy (Fig. 10, 11):

$$y = B_1 \cdot x + B_2 \cdot x^2$$

Polynomial coefficients: $B_1$=0.07903, $B_2$=2.21523·$10^{-5}$.

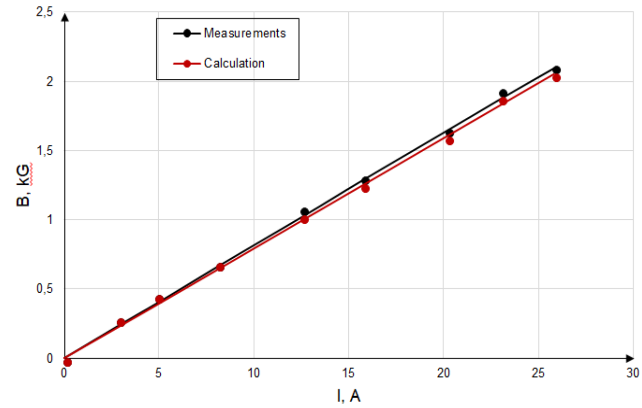


Figure 9: Magnetization curve.

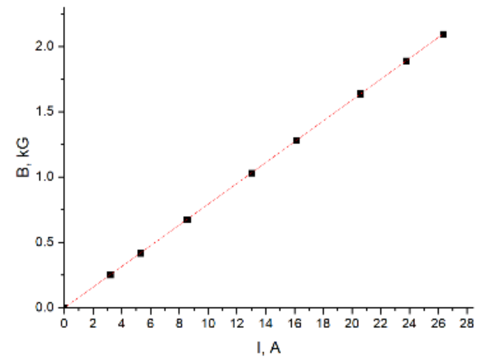


Figure 10: Graph of approximation of the calculated magnetization curve.

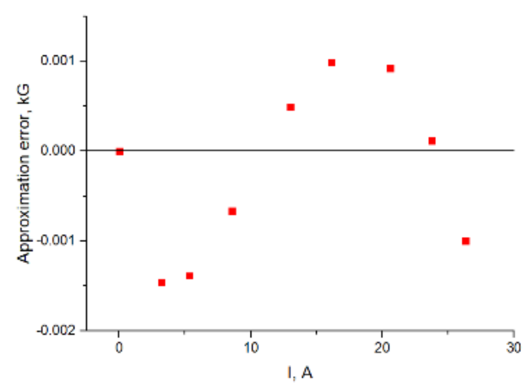


Figure 11: Approximation error.

## CONCLUSION

It has constructed 3D model and calculated Magnetic Field of Swivel Magnet IM90 for Axial Injection System of Cyclotron DC280.

Calculations showed that the change in the design of the magnet did not have a significant effect in the calculated value of the effective length (Leff = 78.39816 cm). Inaccuracy of measurements was estimated at 1%: errors related to the positioning of the Hall detector; measurement error of magnetometer; temporary instability of measurements.

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