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THE RESULTS OF MAGNETIC FIELD FORMATION AND COMMISSIONING OF HEAVY-ION ISOCHRONOUS CYCLOTRON DC280

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Abstract

The DC280 cyclotron is the new accelerator of FLNR Super Heavy Elements Factory. It was commissioned in the beginner of 2019. DC280 is intended for production of high intensity, up to 10 pmkA, beams of heavy ions with mass to charge ratio A/Z = 4 - 7. The wide range of accelerated ions from Helium to Uranium and smooth variation of extracted beam energy in the range W = 4 to 8 MeV/nucl. are provided by varying of the level of main magnetic field from 0.64 T to 1.32 T. The DC280 magnetic field was formed in a good conformity with results of computer modelling. In spite of the commissioning of cyclotron still is in progress, the first experiments gave the intensity 1.35 pmkA of $84Kr^{14+}$ and 10 pmkA of $12C^{2+}$. At the present work the results of calculations, magnetic field measurements and first experiments are presented.

INTRODUCTION

The main feature of new DC280 cyclotron is a wide range of operational modes and a high intensity of accelerated beams [1].

The cyclotron can accelerate heavy ions from Helium to Uranium with mass to charge ratio of A/Z = 4 – 7. The extracted energy of the beams can be smoothly varied in the range of W = 4 – 8 MeV/nucl. by changing of main magnetic field level and shape. The main challenge of DC280 magnetic system formation is covering all possible operational modes with minimal power consumption. According to the working diagram, Fig. 1, the magnetic field level should be varied in the wide range from 0.64 T to 1.32 T. In parallel, the isochronous radial growth of average magnetic field should be varied from 30 Gs to 100 Gs. For that, the 11 radial and 4 pairs of harmonic correcting coils are utilized and provide the needed operational correction.

DC280 is a compact type cyclotron. It has H-shape main magnet with 4-meter pole diameter, Table 1. Four pairs of straight, 45-degrees sectors form the variation of magnetic field, that keeps betatron frequencies in the ranges $1.005 < Q_r < 1.02$ and $0.2 < Q_z < 0.3$. The isochronous magnetic field is formed by variation of sectors height from the pole side. The sectors surfaces from median plane side stay flat. It decreases the sensitivity of replay function and, as a result, decreases the requirement to accuracy of sector shaping. DC280 magnet was manufactured and assembled with designed accuracy. Table 1 presents some important parameters with accuracies that were measured after assembling.

For DC280 magnetic field formation the original magnetometer was created. As a result of mapping and final formation, the magnetic field was formed in a good agreement with results of computer modelling. The first harmonic amplitude was decreased to about 1 Gs.

The first experiments have shown the efficiency of beam transmission from the inner radiuses until deflector has reached up to 90%.

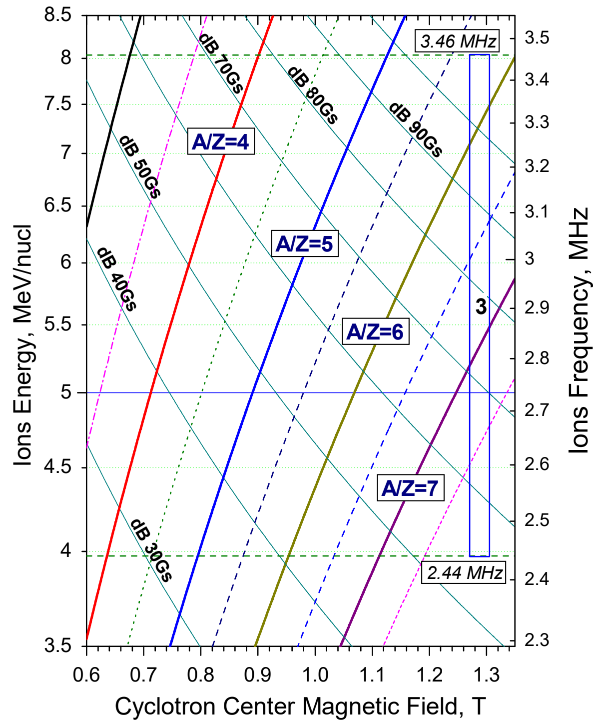

Figure 1: DC-280 Working diagram.

Table 1: Main Parameters of DC-280 Cyclotron Magnet

Parameter	Value
Main magnet size, mm	8760x4080x4840
Pole, mm	4000
Pole to pole gap, mm	500, accuracy ±0.2
Sector to sector gap, mm	208, accuracy ±0.17
Poles axis centering, mm	accuracy 0.53
Sector angular extent (spirality)	45° (0°)
Main magnet power, kWt	280
Correcting coils power, kWt	18

MAPPING SYSTEM

For final magnetic field formation, the DC280 mapping system was created [2]. The mapping system is based on 14 Hall probes and measures the magnetic field in a polar coordinate system with accuracy 10^{-4}. The Hall probes are placed on the plank with radial distance of 160 mm one to another. The plank is moved radially with a step of 10 mm

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or 20 mm in a range of 160 mm. The maximal radius of mapping is 160 mm x 14 = 2240 mm. All Hall probes were calibrated at the special test magnet in the range of 0.1 T – 2.9 T with NMR magnetometer. The possible errors between calibration functions of the neighbour probes are controlled by extra radial step of the plank, when previous probe is placed on the start position of the next probe. The usage of 14 probes decreases a time of mapping: the mapping of full, 360° azimuth range with 1° azimuthal and 10 mm radial steps takes about 7 hours. The 90° range mapping with 2° and 20 mm steps takes about 1 hour. The mechanisms of radial and azimuthal motions are equipped with pneumatic engines, Fig. 2. The standard poly-urethane toothed belt is placed around bottom pole and provides discreet azimuthal steps with a high accuracy.

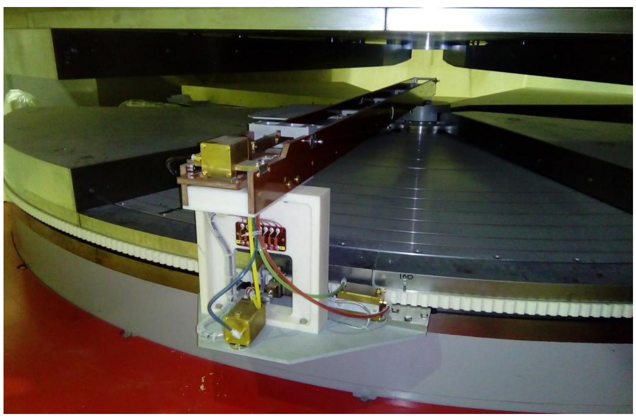

Figure 2: DC280 magnetometer with toothed belt.

RESULTS OF MAPPING

DC280 magnetic field measurements took about 3 months. During the mapping the database of main magnetic fields and additional fields of correcting coils was collected at different levels in the range 0.6 T to 1.32 T.

The time, required for magnetic field stabilization at a first turning on was measured. It takes about 40 minutes to reach the magnetic field stability of 10^{-4}, Fig. 3. The changing of the magnetic field level between different operational modes, including turning on of the correcting coils, are progressed faster and takes less than 10 minutes.

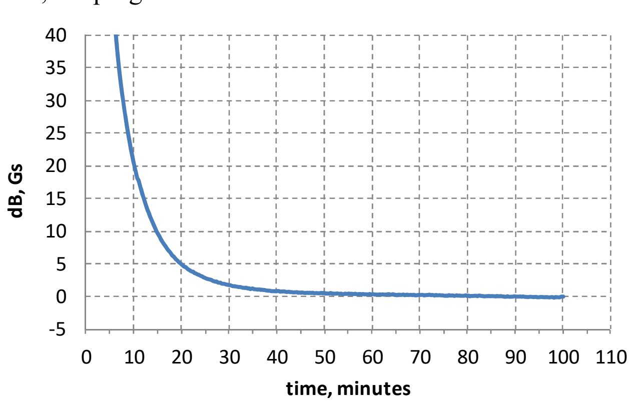

Figure 3: The time of magnetic field stabilization.

Figure 4 presents the signal from Hall probe, positioned at the cyclotron centre during the azimuthal motion of the magnetometer plank. It demonstrates good centring of the magnetometer and the low level of probe noises, not more than $2x10^{-5}$.

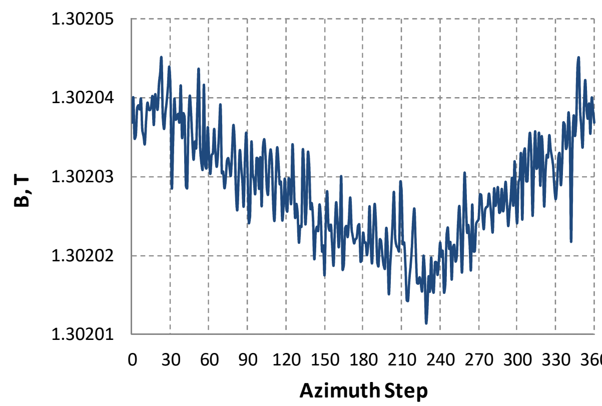

Figure 4: Signal from Hall probe at cyclotron centre.

To correct magnetic field, the sectors are equipped with removable shims. The shims have the shape of 10 mm width plates and are placed at edges of sectors. The shims could be easily removed and machined.

The results of the magnetic field measurements have shown a good coincidence with results of the numerical simulations, Fig. 5. At this case, correction of the average magnetic field by means of shaping of the sector shims was not required.

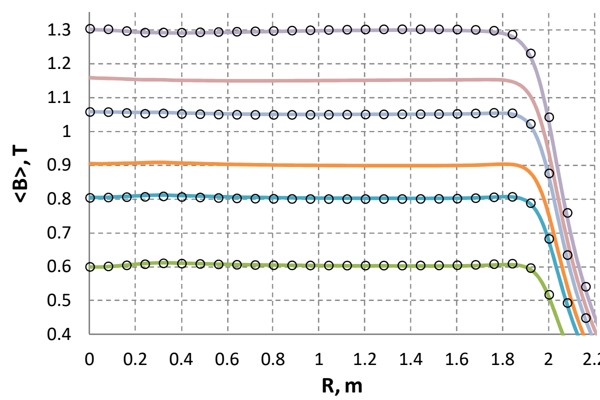

Figure 5: The calculation of the average magnetic field (circles) and the results of the measurements (line).

During DC280 magnetic field measurements, decreasing of pole to pole gap under magnetic field forces was investigated. For the magnetic field of 1 T the poles converging was not uniform azimuthally and varied from 0 to 0.2 mm.

The not uniform converging of the poles as well as finite accuracy of the manufacturing and assemblage leads to asymmetry of cyclotron magnetic system and cause the first harmonic of the magnetic field. The results of magnetic field measurements have shown the presence of the first harmonic with amplitude up to 10 Gs, Fig. 6.

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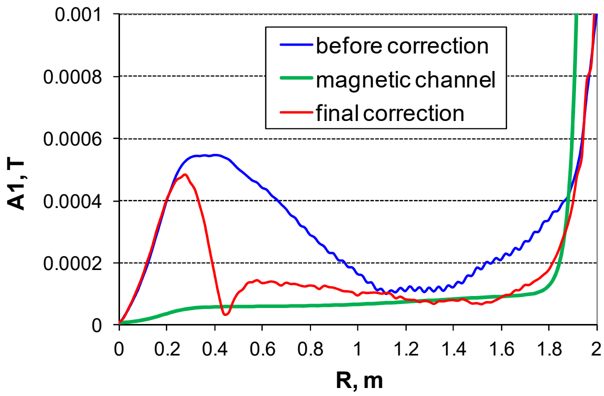

Figure 6: The amplitudes of first harmonic before and after correction and caused by magnetic channel installation.

DC280 magnet is equipped with focusing magnetic channel as a part of cyclotron extraction system. The channel is placed after electrostatic deflector at the radiuses 1900 mm – 2100 mm. Magnetic channel restricted the magnetometer motion. For field correction, the calculation results of the channel contribution to the first harmonic were used. Because a high distance between DC280 sectors is 208 mm and between the poles is 500 mm, the magnetic channel produces first harmonic with amplitude about 1 Gs up to extraction radius, Fig 6. Analysis of combination of measured first harmonic without magnetic channel and calculated first harmonic, produced by magnetic channel, gave the final shapes of sectors shims to compensate the total first harmonic. The final measurements shown that first harmonic was decreased to 1 – 2 Gs. Because sector shims have a technological restriction, the first harmonic could not be corrected on inner radiuses 0 – 400 mm and stays with permissible amplitude about 5 Gs at the centre.

RESULTS OF COMMISSIONING

In the first half-part of 2019 the beams of $84Kr^{14+}$, $12C^{2+}$ and $40Ar^{7+}$ were accelerated to energy 5.9 MeV/nucl. The intensities of extracted beams from cyclotron were 1.35, 6 and 10 pmkA respectively.

For $84Kr^{14+}$ beam the efficiency of injection into cyclotron was 14% without buncher, and 62% with buncher. Efficiency of acceleration inside cyclotron, with losses on residual gases as 10%, was 85%. Efficiency of beam extraction to the ion transport channel was 89%. The total efficiency from injection line to transport channel was about 42%.

For $12C^{2+}$ beam the efficiency of injection into cyclotron was 11.5% without buncher, and 54% with buncher. Efficiency of acceleration to the extraction radius was 83% and efficiency of extraction was 64%.

Figure 7 displays the experimental dependence of relative current of $84Kr^{14+}$ beam on magnetic field level for different radiuses of acceleration. The figure demonstrates that DC280 magnetic system forms the operational magnetic field in a good coincidence to isochronous. It is confirmed by a good transmission factor of acceleration. Because the presented results were received at the first experiments during cyclotron commissioning, the increasing of beam transmission factor at following experiments is expected.

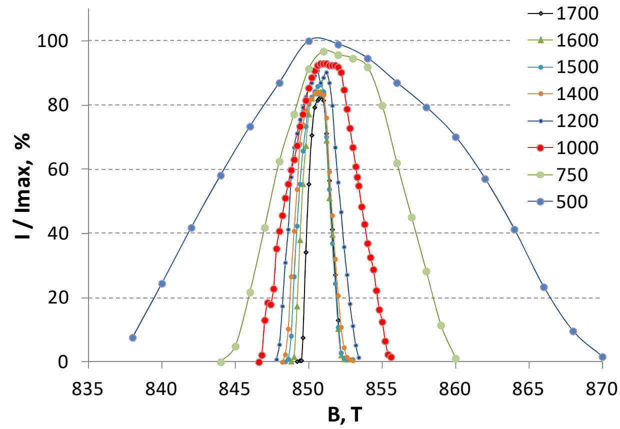

Figure 7: The dependence of relative current of $84Kr^{14+}$ beam on magnetic field level at different radiuses.

CONCLUSION

DC280 cyclotron was commissioned in the beginning of 2019. Despite the cyclotron is still in the progress of adjusting, the first experiments have shown a good efficiency of beam acceleration. In particular, it demonstrates that cyclotron magnetic system forms the operational magnetic field in a good coincidence to isochronous. To reach planned intensities of ion beams with middle atomic masses (A~50) up to 10 pmkA, the more operational time, improvement of vacuum conditions in the cyclotron chamber, adjustment of flat-top and usage of magnetic field database for programmer optimization of the operational modes parameters are needed.

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