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RECONSTRUCTION OF U400M CYCLOTRON: UPGRADE OF U400M CYCLOTRON MAGNETIC STRUCTURE

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Abstract

U400M isochronous cyclotron was created on the base of U300 classic cyclotron and is under operation at FLNR, JINR since 1996. At present time, the cyclotron electromagnet with 4-meter pole diameter needs a reconstruction that includes a replacement of magnet main coil, corrections of the magnetic field at the central region and at the extraction radius. For measurements and shimming of cyclotron magnetic field the automatic mapping system, based on 14 Hall probes, will be created.

INTRODUCTION

U400M cyclotron has two extraction beam lines, for light ions with A/Z 2.286 – 5 and energy 80 – 20 MeV/nucl., and for heavy ions with A/Z 5 – 9 and energy 20 – 6 MeV/nucl. [1]. Operating modes of U400M cyclotron are presented at the diagram, (see Fig. 1).

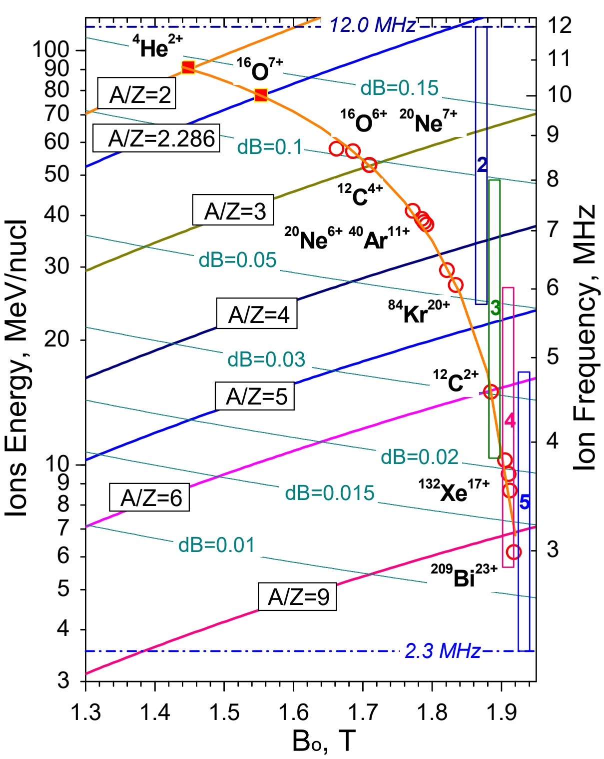

Figure 1: The operation modes diagram of U400M.

At the diagram the A/Z lines presents the isochronous acceleration modes, dB lines – corresponding radial magnetic field growth from cyclotron centre till extraction radius 1.8 m. Cyclotron acceleration system uses from 2 till 5 RF harmonic modes. Because restricted efficiency of trim coils, it is possible to form operation modes in a narrow range around orange line. The typical operating modes are presented by circles. The operation modes with A/Z<2.6, presented by squares, can not be realized because magnetic field distortion at the highest radius R>1.76 m.

U400M cyclotron has H-shape magnet with 4 meter pole diameter. Main parameters of magnet are presented in Table 1. Four pairs of 42° sectors with 40° spirality form the isochronous field. The range of operation magnetic field levels are from 1.5 T till 1.92 T.

Table 1: Main Parameters of U400M Cyclotron Magnet

Magnet size, m	11x4.2x7.46
Diameter of the pole, m	4
Gap between poles, m	0.5
Gap between sectors, m	0.1
Number of sector pairs	4
Sector angular extent	42°
Sector spirality	40°
Number of trim coils	15
Max field, T	1.92

For operational optimization of the magnetic field the 15 trim coils are used. Maximal power consumption of magnet is about 650 kWt.

MAIN COIL RECONSTRUCTION

The first step of U400M magnet reconstruction includes a replacement of magnet old coil to a new one. Because the new coil has smaller radius and transverse size, and will be placed closer to magnet median plane, the radial growth of average magnetic field will change and will not coincide with isochronous operating field, (see Fig. 2).

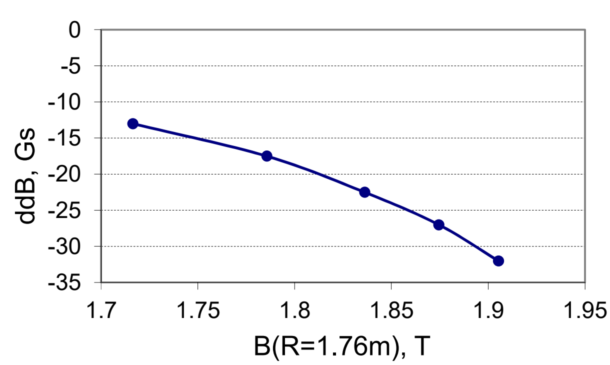

Figure 2: The change of magnetic field radial growth because of main coil reconstruction.

The simplest way to compensate it is to decrease the magnetic field level of cyclotron operating modes. At this

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case, on the one side, the radial raising of average magnetic field is increased and, on the over side, the radial raising of isochronous field is decreased. The radial raising of real and isochronous fields will coincide at compromise point at a lower level of magnetic field, position 2 in Fig. 3.

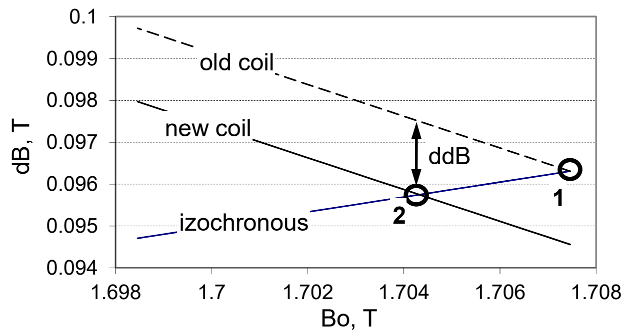

Figure 3: Changing of magnetic field level for operation mode A/Z = 3 with new coil.

In Fig. 3 the lines “old coil” and “new coil” present the dependence of radial raising of magnetic field on its level with corresponding coils. And the line ”isochronous” presents the isochronous radial raising of magnetic field for A/Z = 3 ion beam acceleration operation mode.

The experience of U400M operation have shown that the beam, extracted from cyclotron, needs the vertical correction. For that, the additional, Br - coil will be installed near the new main coil. This small coil will generate up to 10 Gs of Br component of magnetic field at the area of extraction radius. It is enougth for producing of 10 mm beam vertical displacement on the length 2.3 m of the beam extraction line. The additional coil consists of two one-section sub coils with 16 turns of 15x15, ∅8.5 mm conductor in each. The total power consumption of Br-coil is about 12 kWt.

MAGNETIC FIELD OPTIMIZATION

U400M magnetic field was formed in 1996, (see Fig. 4). The field has some discrepancy with isochronous form at the central region and at the area of extraction radius that leads to phase shifting of the beam during acceleration.

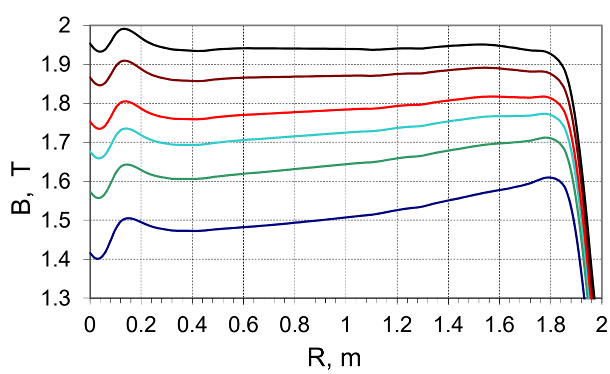

Figure 4: U400M magnetic field at operative levels.

To fix this problem the magnetic field measuremant and magnetic structure optimization are planned at the beginning of 2022.

At the highest levels, the downturn of the field at the area of extraction radius is observed. It decrease the effective extraction radius and restrict the final energy of the beam.

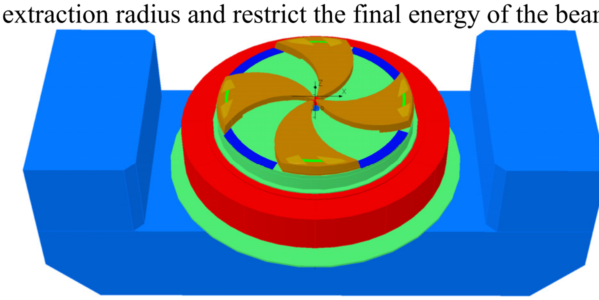

Figure 5: Computer model of U400M magnet with additional valley shims and machining of sector shims.

The preliminary 3D calculations where carried out to optimise the magnetic field, (see Fig. 5). Two steps of shimming of magnet are proposed.

First of all, the additional valley shims will be placed at the poles between sectors.Valley shims has radiuses from 1.8 to 1.995 meters and height 16 mm. The shim height is restricted by elements of RF system. In Fig. 5, the valley shims are marked by blue color.

The adding of valley shims leads to two parallel effects, (see Fig. 6):

- Raising of the real magnetic field.
- Raising of the isochronous field.
- Because the valley shims place far from magnet median plane, this effect have a wide radial range.

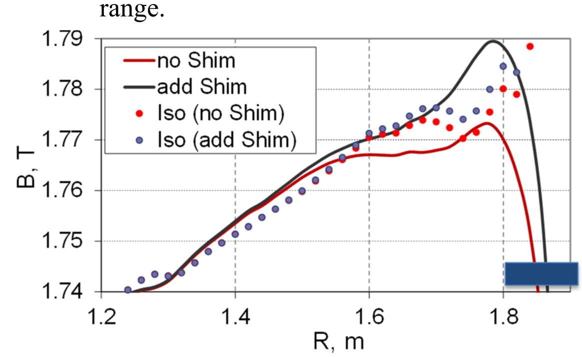

Figure 6: Magnetic fields at the area of extraction radius with and without valley shims, are shown by lines. Circles present corresponding isochronous fields. Blue rectangle shows the radial position of the valley shim.

The shape of isochronous field is received from Gordon’s procedure and strongly dependent on azimuthal variation of the real magnetic field [2]. Both effects give increasing of the effective extraction radius by about 10 mm. Another positive effect of the valley shim is the decreasing of the flatter jump at the sector outer radius. That shifts the possible crossing of resonaces Qr = 1 and Qz = 0.5 behind the extraction radius.

Nevertheless, the difference between isochronous and real magnetic fields at the radiuses 1.7 – 1.8 meters, after valley shims instalation, leads to the beam phase shifting at the last orbits. To correct it, the next step of magnetic field optimisation will be realised.

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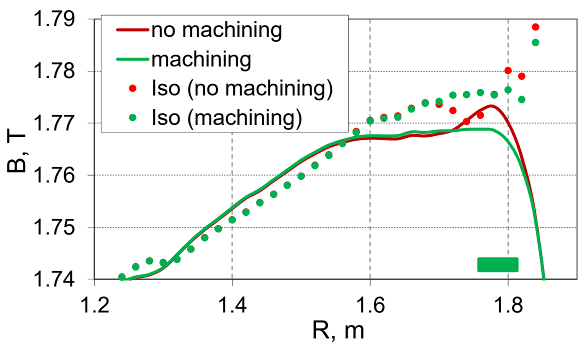

Figure 7: Magnetic fields at the area of extraction radius with and without shim machining, are shown by lines. Circles present corresponding isochronous fields. Green rectangle shows radial position of sector shim machining.

Each sector has a removable shim, placed along the central line at the top side of the sector. The removable sector shims will be machined at the radii from 1.75 till 1.81 meters by removing metal on a deep of 2.6 mm. In Fig. 5, the machining of the shims at the top side of sector is marked by green color. The machining of the sector shims leads to two counter effects (see Fig. 7):

- Lowering of the real magnetic field.
- Raising of the isochronous field.

Because the area of shim places close to magnet median plane, this effects are localised in a thin radial range.

This two counter effects compensate the difference between real and isochronous magnetic field that arises after valley shim adding, and decrease the beam phase machining shifting at the last orbits.

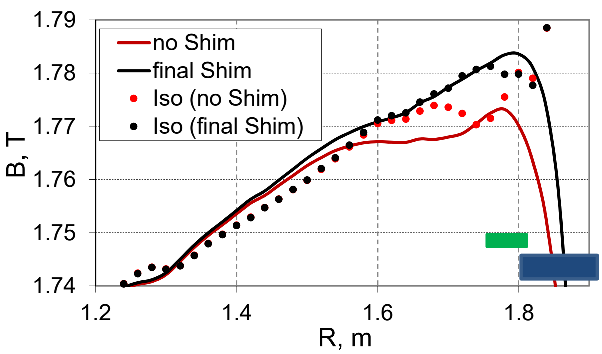

Figure 8: Magnetic field with and without final shimming, are shown by lines. Circles represent corresponding isochronous fields. Green and blue rectangles show sector and valley shims radial position.

The final shimming will include both adding of valley shims and machining of sector shims. As a result of the shimming, the real magnetic field will approach to the isochronous form at the area of extraction radius, (see Fig. 8) that increase effective extraction radius by about 10 mm and improve beam phase shifting at the last orbits.

The additional task of magnetic field mapping is a investigation of the presence and possibility of compensation of 1st harmonic of the field.

MAPPING SYSTEM

For measurements and shimming of U400M cyclotron magnetic field during reconstruction, the automatic mapping system will be created [3]. The feature of U400M mapping system is a usage of 14 Hall probes. Probes are placed on a magnetometer radial bar. The distance between the probes is 160 mm. Bar produces 8 radial steps by 20 mm each. The total radius of mapping 8x20x14 = 2240 mm. At the end of radial motion of the bar, each previous probe is stand at the initial position of the next probe. So the control of repeatability of measurements between the probes is carried out.

Azimuthal range of mapping could be 90° or 360° with step 1° or 2°. Total time of mapping varies from about 40 minutes till 8 hours in dependence on value of radial and azimuthal steps.

CONCLUSION

At present time, U400M cyclotron is under reconstruction. The reconstruction consist of two main tasks, a replacement of magnet coil and optimization of the magnetic field. The new coil will have smaller cross section and will be placed closer to magnet median plane. With new coil the real magnetic field will change and deviate from isochronous operating field. This discrepancy would be corrected by small shifting of field level until real and isochronous field radial growths will coincided again. Additional, Br - coil will be placed near the new main coil to produce the beam vertical correcting before extraction.

The optimization of the magnetic field consists of shimming of magnetic structure at the central region and at the area of extraction radius. The adding of valley shims and machining of sector shims increase the effective extraction radius by about 10 mm and compensate the beam phase shifting at the last orbits. To provide cyclotron reconstruction, the automatic mapping system will be created. The usage of 14 Hall probes extremely decrease mapping time. According the plans the reconstruction will complete till the middle of 2022.

REFERENCES

[1] I. V. Kalagin *et al.*, “Status of JINR FLNR cyclotrons”, in *Proc. 14th Int. Conf. on Heavy Ion Accelerator Technology (HIAT'18)*, Lanzhou, China, Oct. 2018, pp. 23-27. doi:10.18429/JACoW-HIAT2018-MOOXA01

[2] M. Gordon, “Calculation of Isochronous Fields for Sector-Focused Cyclotrons”, *Particle Accelerators*, vol. 13, pp. 67–84, 1983.

[3] I. A. Ivanenko, V. V. Aleinikov, G. N. Ivanov, and V. V. Konstantinov, “Measuring System for FLNR Cyclotrons Magnetic Field Formation”, in *Proc. 25th Russian Particle Accelerator Conf. (RuPAC'16)*, Saint Petersburg, Russia, Nov. 2016, pp. 544-546. doi:10.18429/JACoW-RUPAC2016-THPSC004