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Simulations of the impact of small details on the magnetic field distribution for the compact superconducting cyclotron SC200 commissioning

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Abstract. Modern packages for the design and simulation of cyclotron magnet systems, such as Tosca, CST Studio, Comsol, etc., combined with recent hardware of high performance, allow us to simulate and estimate even a subtle impact on the magnetic field distribution caused by small details and other systems of the accelerator. Such reckoning provides the data to perform and simulate the refinement of the magnet called the 'shimming'. That means a significant part of the commissioning stage could be done in 'virtual reality'. This could substantially decrease the duration of the shimming procedure of the real magnet and the amount of the material wasted on it, eventually this results in a field of high-precision which could be compared to real one.

1 Introduction

It is planned to manufacture two cyclotrons in China: one will operate in Hefei cyclotron medical center, the other will replace Phasotron in Medico-technical center JINR Dubna and will be used to treat cancer with protons [1].

3D magnet simulation is the most important part when it comes to the development of an isochronous superconducting cyclotron as it defines the particle motion in the accelerator. Also, the accuracy of the calculation has been increased and the numerical error is now lower than 0.1 Gauss in most of the final simulations [2]. This accuracy, of course, cannot be achieved in the production, however, when the accuracy of the model is much lower than the accuracy of the manufacturing, it becomes possible to simulate tolerances and errors, and the major weak spots, this would help on the production stage.

2 Small Details of Manufactured Model

Due to physical limitations and the necessity of engineering restrictions, the model put into production significantly differs from a simulated one. Ambition to achieve several contradictory goals:

-Smooth and isochronous magnetic field distribution
-An easy way to disassemble and shimm the sectors
-Solid attachment against strong magnetic fields

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resulted into 2-partition sector design with a plenty of screws covered with plugs. Accidental mistake called ‘Zig-Zag’ in the process of the smoothing was made.

2.1 About Modelling and Simulation

The key to achieve high precision of a simulation is the proper model partitioning. One has to create a lot of different phantom shapes around the object and area that need most of the attention. And when you compare results from different models with and without that object all shapes should be present on both.

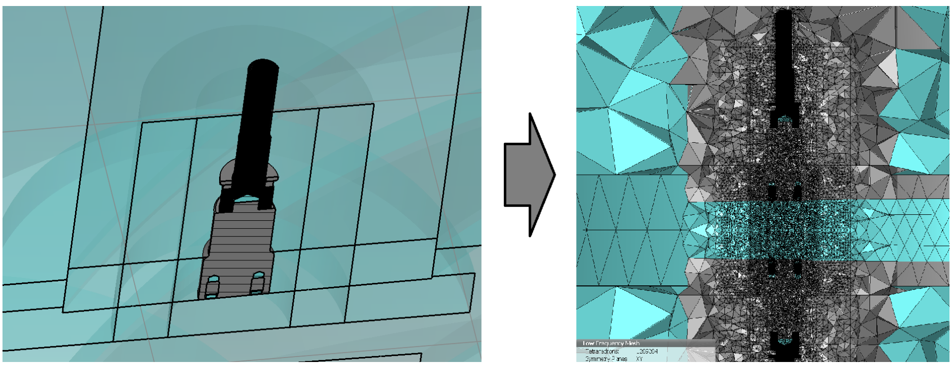


Figure 1. The model partitioning resulted into elements concentrated into screw area.

As an example, due to the right model partitioning, roughly 75% of the 1.3M mesh elements were concentrated into the screw, its surroundings and median plane below it (Fig. 1.). Combined with right comparison it allowed us to extract maps with precision of around 0.1 Gs in the right places (Fig. 3, right.) and estimate the difference in the mean field with the precision of 0.5 Gs. And all of it was done by a rather poor solver order (2nd) and accuracy (10^{-6}).

2.2 The ‘Zig-Zag’ Flaw

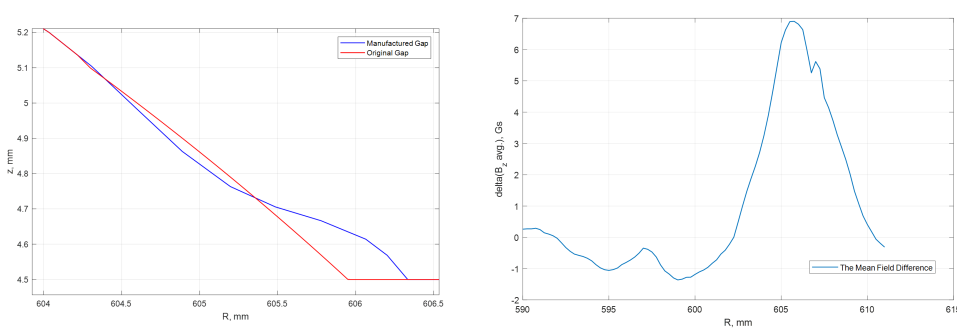


Figure 2. Left: The designed geometry of the gap compared to the manufactured one. Right: The amount of the reduction of the mean field versus the radius.

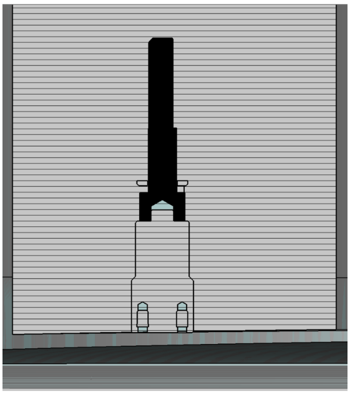
'Zig-Zag' is about 300 microns deviation in the gap curve (Fig. 2, left.). Two separate models with especially neat geometry in the Zig-Zag region were made, simulated, and the results were compared.

Apart from the great deviation in the mean field (Fig. 2, right.), its maximum was displaced on 500 microns. It has an influence on the extraction trajectory and needs to be corrected. Possible solutions could be cutting the gap and increasing the field, or leaving it as it is and compensating it with azimuthal spirality shimming.

2.3 The Impact of a Screw

Every sector consists of two parts: A and BCD, combined between themselves and the yoke by screws of medium carbon steel-1045 covered with plugs of sector's steel-1010 to avoid field distortions. Sectors were manufactured with 2 degrees azimuthal reserve for the following shimming. All parts were produced and then measured along the numerous amounts of lines and points, deviation from the manufactured model didn't exceed 50 microns.

Measured BH-curve of steel-1045 was brought to the proper shape, i.e. the faulty part was replaced and extended until 7 T by a physically realistic one, and then the curve was smoothed for a better processing by CST studio. A plug and a screw from the middle of the sector from the manufactured model were inserted into the simulated model (Fig. 3, left.). The plug turned out to be extruded on about 500 microns, so 3 models were created: without a plug, with a plug, with the cut plug for no extrusion to be. The models were simulated, the results were processed.



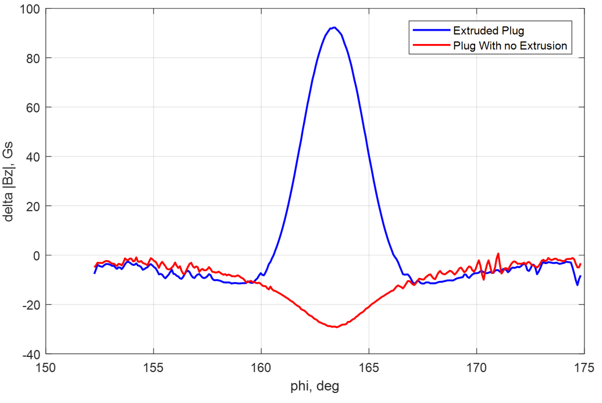


Figure 3. Left: Cross-section of the screw inserted into a sector, covered with the plug. Right: The impact of the screw on the magnetic field distribution versus angle, on the radius that crosses its center.

The Cartesian maps were extracted in order to assess the maximum positive deviation for the extruded plug (MPos) and the maximum negative deviation for the cut plug (MNeg), so that MPos=95.7 Gs, MNeg=-29 Gs (Fig. 3, right.). Cylindrical maps were also extracted and evaluated to estimate the impact on the mean field. The deviation of mean field floats around 2 Gs in both cases, but in the case of the cut plug, the impact is much smoother and much more monotonous.

3 Magnetic Corrections

RF system produces a significant alternating magnetic field, this field ‘slows down’ the phase of the beam (Fig. 4, left.) and needs to be taken into consideration.

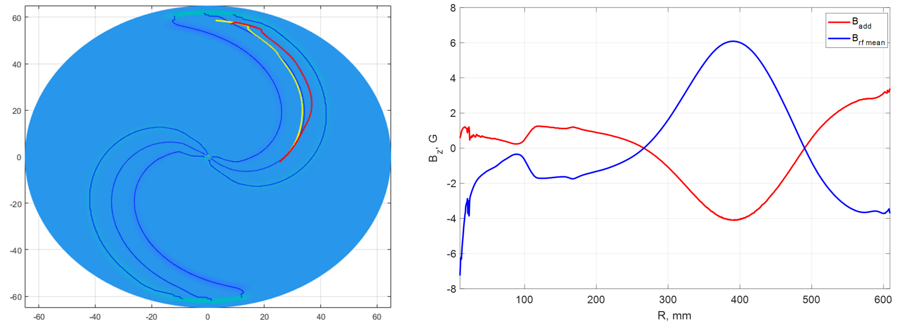


Figure 4. Left: Beam phase delay, red line shows the influence of the RF system, yellow - phase without influence. Right: Mean value of B_{rf} field (blue line) and additional field versus radius.

Because of the action of the magnetic field of the accelerating cavity the mean field, isochronous on equilibrium orbits, should be increased by B_{add} [3] to compensate action of the B_{rf} (Fig. 4, right.). For ideal isochronous magnetic field distribution the value of the compensation field can be estimated from the simple formula:

$$B_{add} = -B_{rfmean} * cos(\theta_{cav})$$

θ_{cav} - azimuthal extension between the maximums of the accelerating field distribution. Firstly, simulations were performed for the central particle in field map from the model of the Hefei cyclotron, isochronized only in the end for simulation of the extraction (Fig. 5.). So even for the mean field not completely isochronized ($phase \pm 10° RF$) compensation by simplified approach gives a rather good result ($\Delta\phi = 5° RF$).

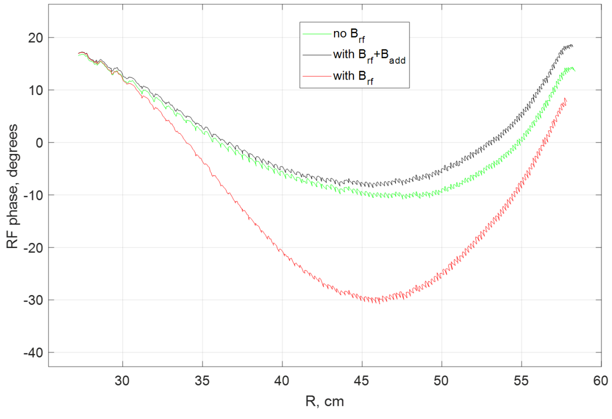


Figure 5. Phase motion of the central particle: neglecting B_{RF} (green line), taking into account RF magnetic field (red line) and with B_{RF}+compensation (black line) for Hefei cyclotron.

Compensation of the RF magnetic field should be done. The isochronous field should be increased at R=40 cm by 4 G and decrease at R=60 cm by 3 G according to the Fig. 4 and for the designed voltage 70 kV at R=7 cm.

4 Conclusion

The ‘Zig-Zag’ produces a significant effect on the mean field and needs to be dealt with. The impact of screws was assessed, improvement - to cut the plug, was found. The compensational mean field for the RF-system impact was derived.

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