COMPUTER MODELLING OF THE SC202 SUPERCONDUCTING CYCLOTRON FOR HADRON THERAPY

O. Karamyshev†, G. Karamysheva, V. Malinin, N. Morozov, D. Popov, E. Samsonov, G. Shirkov, S. Shirkov, (JINR, Dubna, Russia)

Y.Bi, G.Chen, K.Ding, Y. Song, (ASIPP, Hefei, China)

Abstract

The SC202 superconducting cyclotron for hadron therapy is under development by collaboration between ASIPP (Hefei, China) and JINR (Dubna, Russia). The accelerator will provide 200 MeV proton beam with maximum current of 1mA in 2017-2018. We have performed simulations of all systems of the SC202 and designed the magnet, acceleration system and extraction elements.

INTRODUCTION

The SC202 project started in September 2016 as a continuation of the SC200 project [1-2] that has been under development since end of 2015. The cyclotron must deliver 200MeV for proton therapy by end of 2017. The final energy has been chosen to satisfy the needs of the treatment centre of DLNP JINR. The SC200 has been completed in 2016, however the project has been considered very risky and it was decided to lower the manufacturing risks by starting the SC202 project. Biggest concerns were low vertical gap between sectors (5mm), very high stray field of magnet due to light yoke and very tight central region. In SC202 the vertical gap has been increased to 9mm, yoke size was increased and sectors became narrow to allow good acceleration rate with 2 RF resonators operating on 2^{nd} harmonic. SC202 overview is presented in Fig.1.

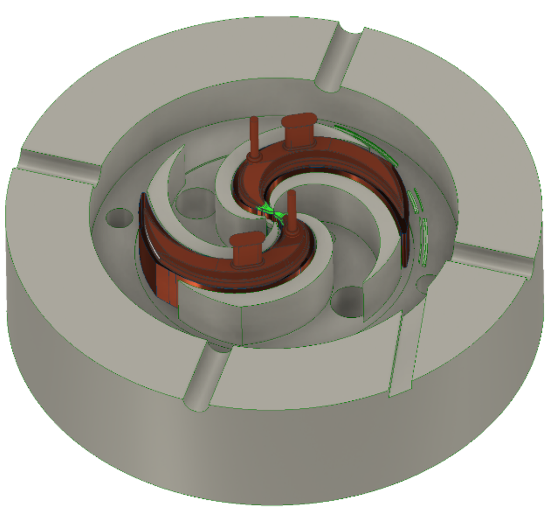

Figure 1: SC202 overview.

MAGNET MODELLING

3D magnet simulations is the most difficult part when it comes to isochronous superconducting cyclotron development as it defines the particle motion in the accelerator. The major problem of R&D phase of the SC200 project was that 3D simulations of magnet were very time-consuming and it was difficult to achieve acceptable accuracy of the simulated field. In order to fix this issue a technique that uses CAD software together with CST studio and quick analysis of the magnet field map in MATLAB has been developed. This technique allowed us to increase the amount of simulated magnet geometries to over 5000 in 4 months. Such fine tuning allowed us optimise the magnet in very short time. Also the accuracy of the simulations has been increased and the numerical error is lower than 0.1 Gauss. This accuracy, of course, cannot be achieved in production, however when accuracy of the model is much lower than accuracy of manufacturing, it becomes possible to simulate tolerances and errors and the major weak spots that would help on the production stage.

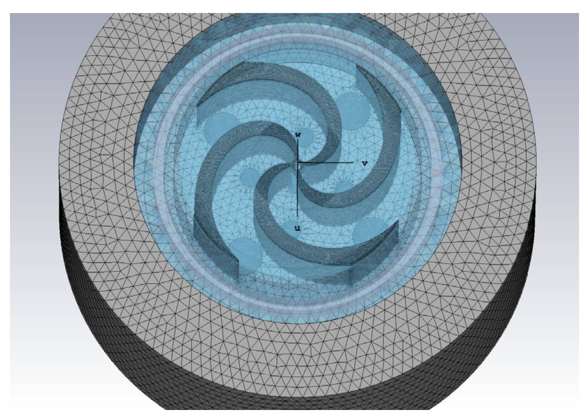

Figure 2: SC202 meshed model with mesh optimised for higher accuracy in central region.

In order to optimise computer time we have optimised meshing (see Fig.2) to achieve necessary accuracy (see Fig.3) in the specific areas of interest by reducing mesh cell dimensions in those areas together with increasing mesh size in out-of-interest areas to reduce overall mesh cell amount.

† email address olegkar@icloud.com

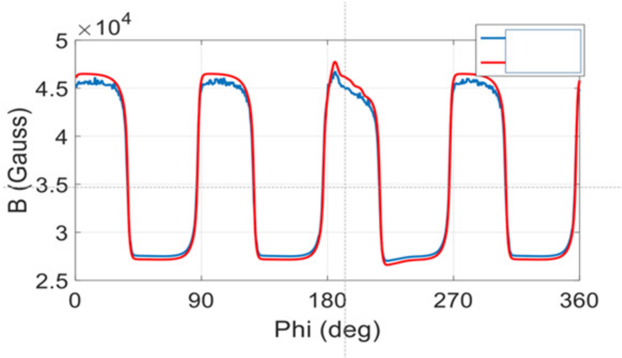

Figure 3: Magnetic field in median plane along the azimuth in extraction region calculated with and without mesh optimisation.

MAGNET FIELD ANALISYS

Traditionally, CYCLOPS-alike procedures are used to perform the betatron frequencies calculations. Developed over 30 years ago, it remains one of the most useful tools in cyclotron design work. However, when it comes to design of superconducting cyclotron with high magnetic field and high non-linear gradients 3D particle tracking in 3D magnet field maps are required to ensure that results of simulations are trust-worthy.

In our design we aim to avoid all dangerous resonances such as $2Q_z=1$ and Q_r-$Q_z=1$. Also, it is desirable not to cross $3Q_r=4$ resonance. We have successfully avoided those resonances, however, due to high spiral angle and increasing azimuthal length of sectors non-linear resonances could be dangerous. 3D particle tracking ensures us that there is no such problem, however in order to study non-linear resonances and define the conditions of their appearance we have performed simulations with 2D field map in median plane used to perform particle tracking. This is a traditional method and it is widely used in cyclotron physics. In the median plane of the cyclotron only vertical component exists (due to symmetry) and other components of the magnetic field can be calculated by:

$$B_r = z\frac{\delta B}{\delta r} - z^3 f_3,$$

$$rB_\varphi = z\frac{\delta B}{\delta \varphi} - z^3 g_3,$$

$$B_z = B - z^2 f_2 + z^4 f_4,$$

where:

$$f_2(r,\varphi) = \frac{1}{2}\left(\frac{\delta^2 B}{\delta r^2} + \frac{1}{r}\frac{\delta B}{\delta r} + \frac{1}{r^2}\frac{\delta^2 B}{\delta \varphi^2}\right),$$

$$f_3(r,\varphi) = \frac{1}{6}\left(\frac{\delta^3 B}{\delta r^3} + \frac{1}{r}\frac{\delta^2 B}{\delta r^2} - \frac{1}{r^2}\frac{\delta B}{\delta r} + \frac{1}{r^2}\frac{\delta^3 B}{\delta r \delta \varphi^2} - \frac{2}{r^3}\frac{\delta^2 B}{\delta \varphi^2}\right),$$

$$g_3(r,\varphi) = \frac{1}{6}\left(\frac{\delta^3 B}{\delta r^2 \delta \varphi} + \frac{1}{r}\frac{\delta^2 B}{\delta r \delta \varphi} + \frac{1}{r^2}\frac{\delta^3 B}{\delta \varphi^3}\right),$$

$$f_4(r,\varphi) = \frac{1}{24}\left(\frac{\delta^4 B}{\delta r^4} + \frac{1}{r^4}\frac{\delta^4 B}{\delta \varphi^4} + \frac{2}{r^2}\frac{\delta^4 B}{\delta r^2 \delta \varphi^2} + \frac{2}{r}\frac{\delta^3 B}{\delta r^3} - \frac{2}{r^3}\frac{\delta^3 B}{\delta r \delta \varphi^2} - \frac{1}{r^2}\frac{\delta^2 B}{\delta r^2} + \frac{4}{r^4}\frac{\delta^2 B}{\delta \varphi^2} + \frac{1}{r^3}\frac{\delta B}{\delta r}\right)$$

The formulas are presented for cylindrical coordinate system, which is most suitable for cyclotron. It is important to be able to calculate all derivatives for correct beam dynamics simulations during research and development and, especially on commissioning stage, when real magnetic field will be measured only on median plane. The biggest problem of these calculation is that the derivatives (see Fig.4) must be taken using the measured or calculated field map, which already contains error. Special mathematical algorithms were developed in order to obtain smooth and realistic derivatives of magnetic field on median plane.

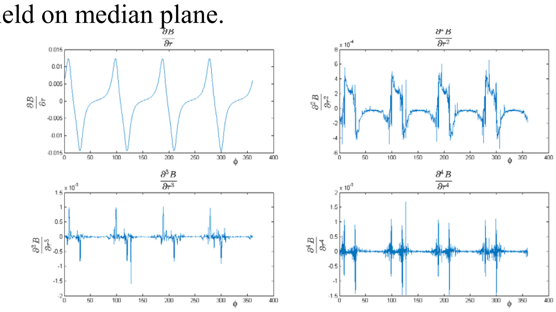

Figure 4: Derivatives of magnetic field in median plane taken without smoothing algorithms.

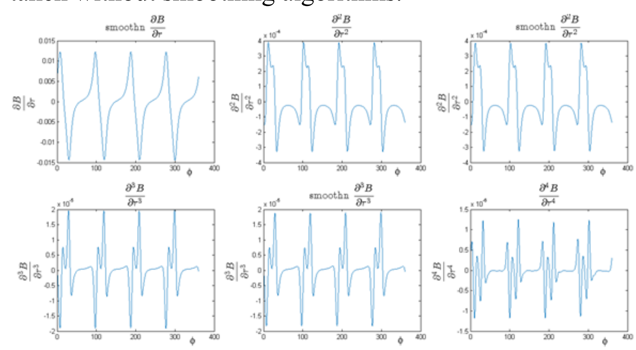

Figure 5: Derivatives of magnetic field in median plane taken with smoothing algorithms.

Such results (Fig.5) were obtained by combining fitting of the field map by spline surface together with smoothing algorithms.

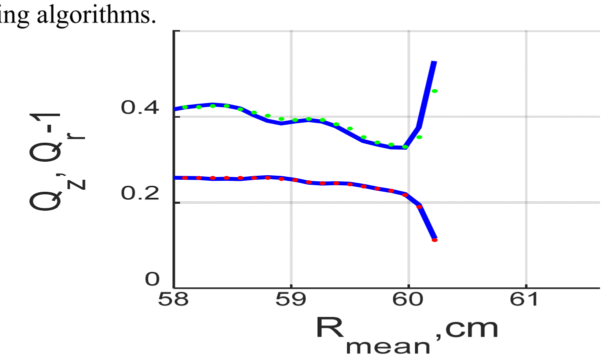

Figure 6: Difference between 3D and 2D betatron frequencies calculations. Dots – 3D tracking. Solid line – Cyclops-alike procedure.

Betatron frequencies were calculated by both 3D tracking and CYCLOPS-alike procedure that uses 2D map in median plane. Difference in the extraction area is shown on Fig 6.

ISBN 978-3-95450-182-3

RF SYSTEM AND CENTRAL REGION SIMULATIONS

RF system of SC202 is convectional for cyclotrons of such kind. Two RF cavities operating on 2nd harmonic.

Operation on 2nd harmonic together with 4-sector magnet structure requires narrow sectors to achieve good acceleration rate. RF cavity is shown in Fig 7, voltage distribution in Fig.8.

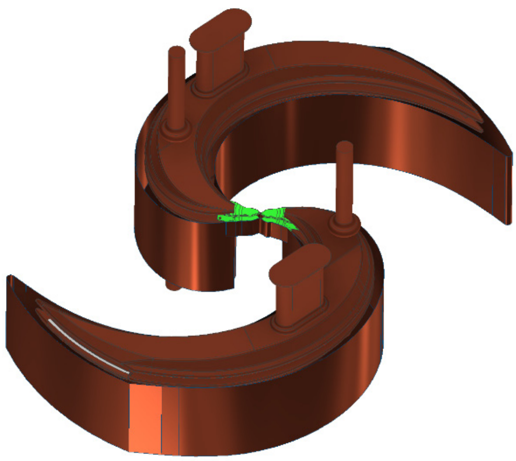

Figure 7: RF cavity overview.

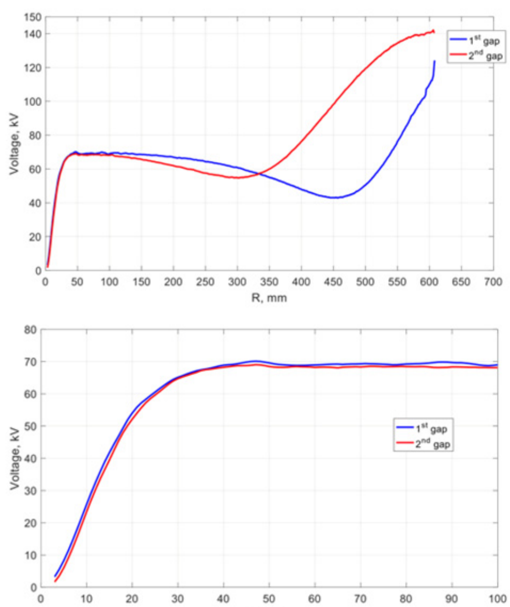

Figure 8: RF voltage along radius.

Both electric and magnetic fields of RF cavity from 3D simulations were used in particle tracking from the ion source to the extraction point of the SC202. High accuracy of the simulations are required in order to perform such tracking. Results of beam dynamics simulations in SC202 cyclotron are presented in Fig 9.

Central region of SC202 design was a challenging task due to its tight scale. We have decided that centration of the beam will be achieved by shaping of the Dee tips and vertical and radial dimensions will be limited in central region by placing diaphragms on 2nd and 3rd turns. No correction coils will be installed, as there is no space. That requires careful and accurate simulations of the central region and well-designed Dee tips (Fig.10).

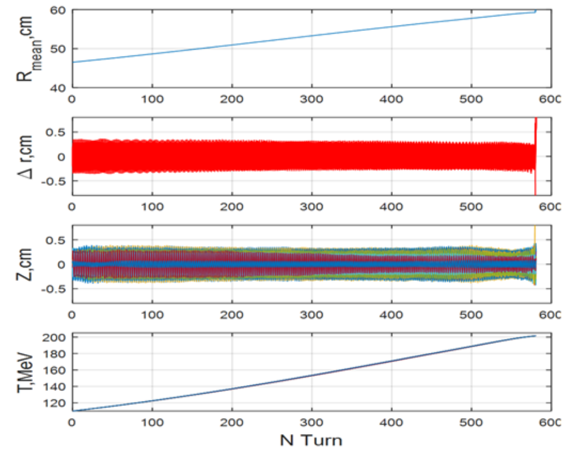

Figure 9: Particle tracking in main accelerating region until extraction in 3D electric and magnetic fields.

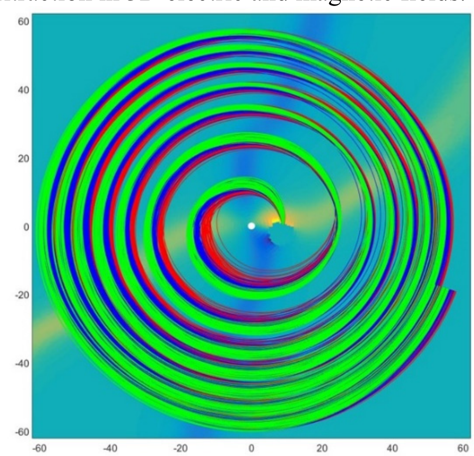

Figure 10: Beam dynamics in central region.

CONCLUSION

Accurate and fast modelling of the magnet and other systems of SC202 allowed us to complete design of SC202 in just 4 month. Magnetic field has been simulated with accuracy of 0.1-0.25 Gauss, and isochronous field is better than 3 Gauss/cm, which allowed us to do fully realistic beam dynamics simulation from ion source to the extraction. High accuracy and high efficiency of simulations will help on commissioning stage during shimming of the magnet. Techniques that were developed will be used in future accelerators and in further studies for SC202 project.

REFERENCES

[1] Karamysheva G.A. et al., “Compact Superconducting Cyclotron SC200 for proton therapy”, in proc. Cyclotrons and Their Applications 2016, Sept. 2016, Zürich, Switzerland.

[2] Morozov N.A. et al., “Computer Modelling of Magnet for SC200 Superconducting Cyclotron”, in proc. Cyclotrons and Their Applications 2016, Sept. 2016, Zürich, Switzerland.