ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPAK028

BEAM DYNAMICS SIMULATIONS IN THE DUBNA SC202 SUPERCONDUCTING CYCLOTRON FOR HADRON THERAPY

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Abstract

In 2015 the joint project JINR (Dubna, Russia) - ASIPP (Hefei, China) on design and construction of superconducting proton cyclotron SC202 was started. Two cyclotrons are planned to be manufactured in China, according to the Collaboration Agreement between JINR and ASIPP [1]. The first cyclotron will be used for proton therapy in Hefei and the second one will replace the Phasotron in the research and treatment program on proton therapy in Dubna. New schema of extraction system and results of beam acceleration and extraction simulations for Dubna cyclotron are presented.

INTRODUCTION

SC202 is an isochronous superconducting compact cyclotron. Superconducting coils will be enclosed in cryostat, all other parts are warm. Internal ion source of PIG type will be used. For proton acceleration we are planning to use 2 accelerating RF cavities placed in the valleys, operating on the 2nd harmonic mode. RF system will operate at the frequency 91 MHz. Magnet of the cyclotron has four-sector structure. Sectors of the magnet have angular width 22-35 degrees (from center to extraction). Mean magnetic field of the cyclotron will be in the range of 2.9T-3.5T (center-extraction). Vertical gap between the up and down sectors near beam extraction is 10 mm. Pole radius is equal 63 cm. Coil curren-t is 725 000 A*turn. Weight of the magnet is about 55 tons.

BEAM EXTRACTION DESIGN

The particles from SC202 Dubna cyclotron will be extracted with one ESD electrostatic deflector, two magnetic channels MC1 and MC2 (Fig. 1). SC202 Dubna extraction system will be supplied by compensation channels CM1 and CM2 in order to avoid first harmonic of magnetic field which can induce resonances $2Q_z=1$ and $Q_r-Q_z=1$.

The essence of the extraction scheme presented for SC202 Dubna cyclotron consists in the formation of a magnetic field in the extraction region mainly by means of a vertical gap between the sectors. This vertical gap narrows to the extraction area for the circulating beam. Whereas for the extracted beam (after the deflector) the field is formed by an expanding gap (see Fig. 2). As a result, the beam after deflector does not pass through the zone of a strongly falling field, it goes along the sector, slightly deviating (up to 1 cm) from the radius with a minimum vertical gap. Further, passing inside the accelerating cavity, being in a smaller magnetic field of the valley than the circulating beam, the extracted beam approaches the next sector significantly further in radius than in the sector just after the deflector, which allows beam to be extracted without loss of quality using conventional passive magnetic channels.

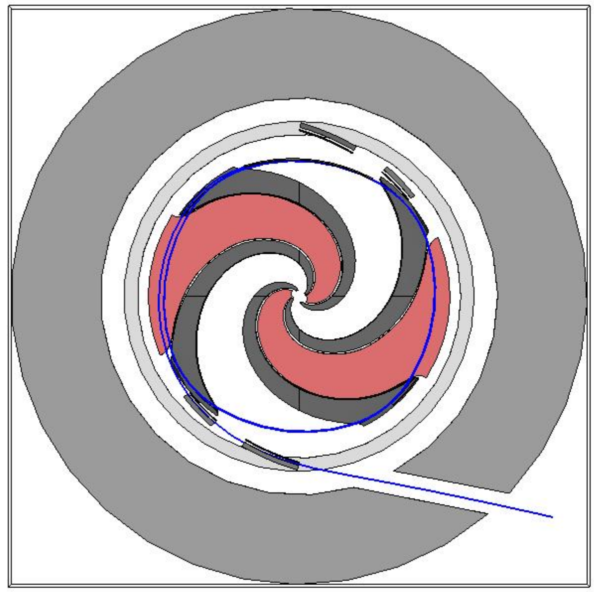

Figure 1: View of the half of the cyclotron with the extraction system. Blue line is the trajectory of the particle. Elements of the extraction schema: ESD – electrostatic deflector, MC1, MC2 – passive magnetic channels, CMC1, CMC2 – compensation magnetic channels.

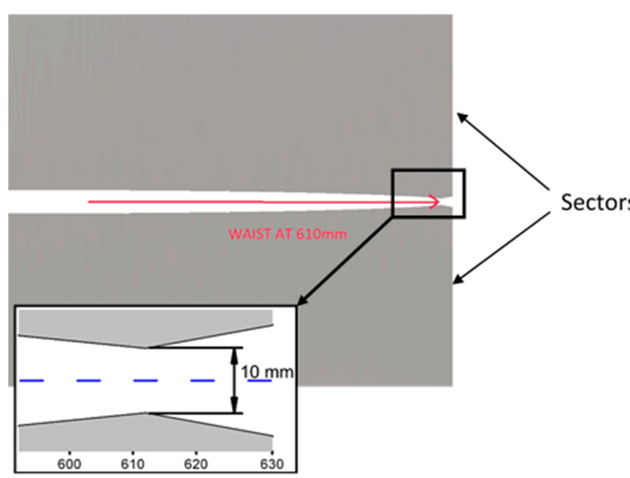

Figure 2: Vertical gap between sectors of magnet.

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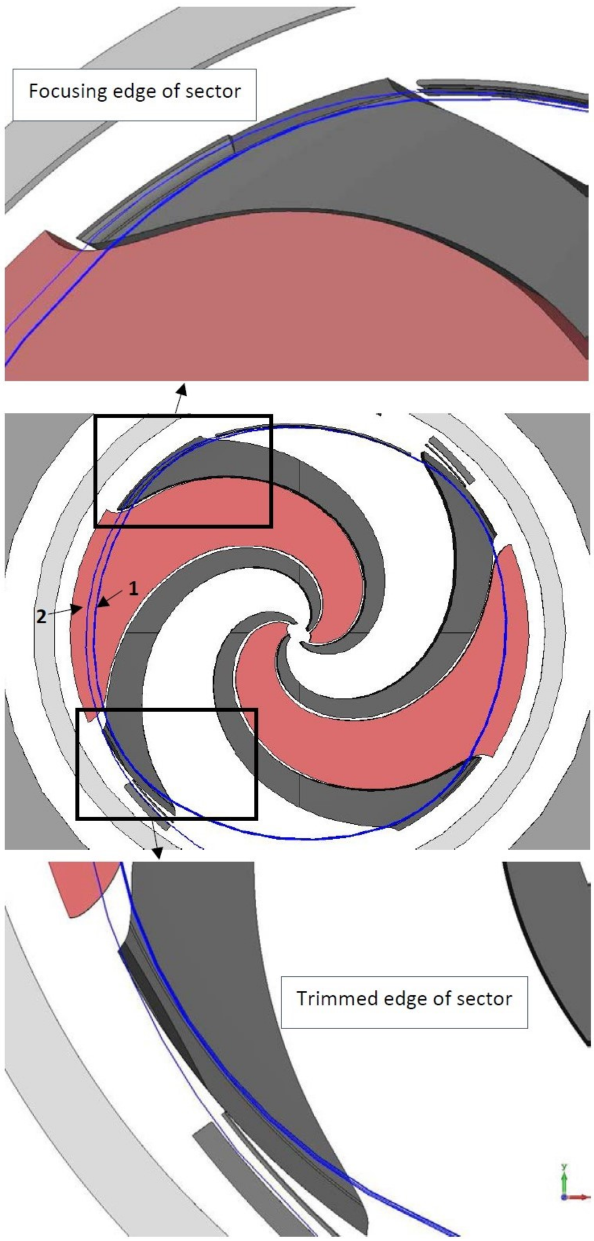

Figure 3: Focusing elements as a part of the sector. Trajectories of circulating (1) and extracted (2) particle.

Distinctive features of our extraction are:

1) A special form of vertical gap between sectors in the output zone. Minimum vertical gap is 10mm at R=610 mm (Fig. 2)
2) The special shape of the sectors for the extracted beam:

a) the increased radial length of sectors up to 630 mm,
b) the first sector in the course of the extracted beam has the form which promotes proper vertical and radial focusing of the beam at the edge of the sector (Fig. 3, up),
c) the second sector along the path is cut along the radius for free passage of the beam (Fig. 3, down).

3) Accelerating cavity with an increased radial extension, allowing the passage of the extracted beam separated by about 1 cm from the circulating beam.
4) Two-fold rotational symmetry of magnetic field distribution

As a result, it is possible to use a deflector with an electric field strength about 150-170 kV/cm. The value of electric field is high but such deflector can be manufactured with the existing technology.

Circulation beam is going up to radius 610 mm, extracted beam goes along first sector at radius about 620mm.

One can see that at the edge of the nearest sector after the deflector has a special form (Fig. 3), providing proper focusing.

COMPUTER MODELLING

The major problem of R&D phase of the SC202 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. We achieve high accuracy in simulations of the magnet together with quick analysis and remodelling possibilities for all parts of model such as a complex form of elliptical gap and sector profile.

This technique helped us to find effective solution for extraction from SC202 Dubna.

As a result we create magnet model with isochronous field and proper focusing of the beam in transverse directions. Average field in the cyclotron is shown in Fig. 4. Field is isochronous up to R=610 mm. One can see slow decrease of the average magnetic field in the extraction zone due to special form of the vertical gap between up and down sectors.

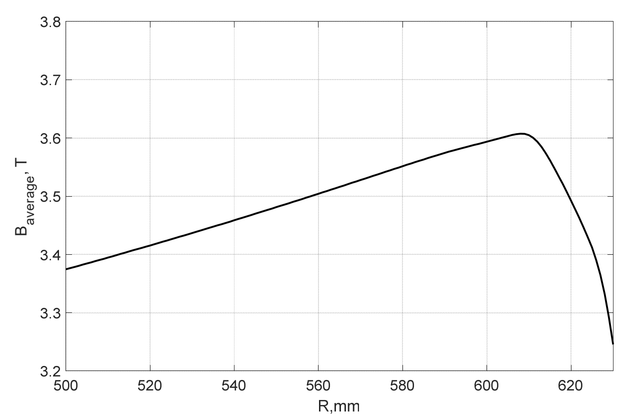

Figure 4: Average magnetic field for SC202 Dubna.

Betatrone frequencies for the designed magnet structure are presented in the working diagram (Fig. 5).

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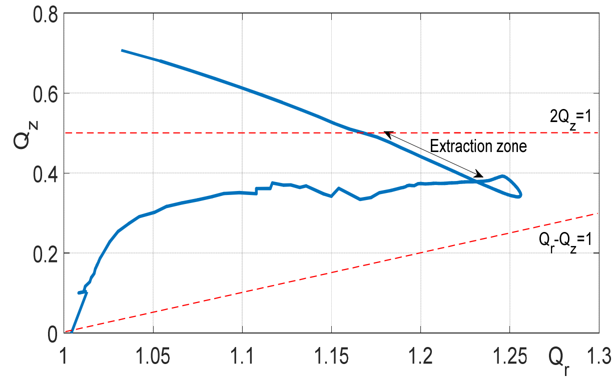

Figure 5: Working diagram.

Red dashed lines in the working diagram show resonances of the second order $2Q_z$=1 and Q_r-Q_z=1. The working point is far from those lines in the whole accelerating region.

The beam tracking was simulated in the 3D field maps obtained from magnet and RF cavity simulations in CST studio. Proton beam consisted of 1000 particles and started its acceleration from the energy 160 MeV. The beam motion was calculated up to a reference point located outside the accelerator at a distance of 25 cm from the yoke of the magnet.

Phase portraits of the beam at the deflector entrance are presented in Fig. 6. Losses on the septum tip is 15 % for the width of septum 0.1 mm.

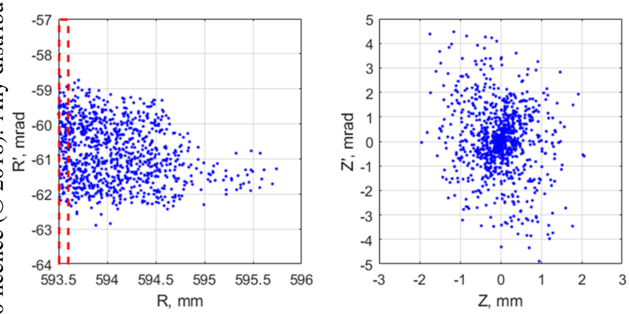

Figure 6: Beam distribution at the deflector entrance. Septum width 0.1mm is marked by red dashed line.

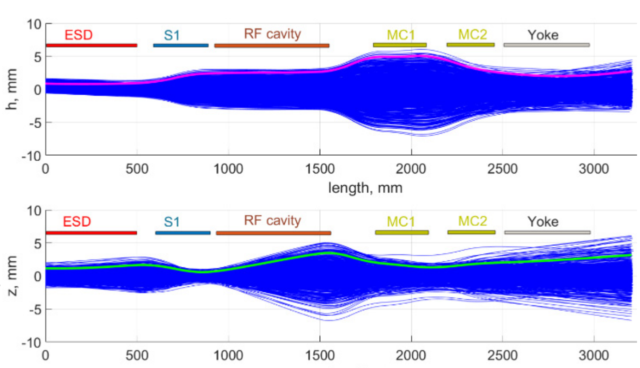

Figure 7: Horizontal and vertical motion of the beam during extraction, thick lines - 2 RMS envelopes.

We formed in the extraction zone a magnetic field ensuring the motion of the output beam with acceptable focusing in transverse directions. We investigated various positions, forms and dimensions of passive magnetic channels to avoid beam losses during passing through the channels and to minimize beam transversal dimensions.

The results of the beam tracing in deflector and after extraction by the deflector are shown in Fig. 7. Beam envelopes (2 RMS) are shown by solid thick lines (red in the upper picture, green in the down one).

Advantages of extraction schema for SC202 Dubna:

- Simplicity inherited from the approach used in C235 cyclotron [2].
- The acceptable tension on the deflector - 150-170 kV / cm.
- Wide range of possible output radii within 3 mm.
- The absence of the first harmonic of the magnetic field in the output zone, and, consequently, less dangerous approach of the operating point to the resonances Q_r-Q_z = 1 and $2Q_z$ = 1 (see Fig. 5), it is easier to form a magnetic field in a real magnet.
- A radially extended sector creates a higher flutter, therefore, a smaller spiral angle of the sectors is required to provide the necessary vertical focusing of the beam, which gives an advantage to the design of resonator and deflector.

CONCLUSION

Proposed extraction scheme allows efficient extraction of the beam from an isochronous superconducting cyclotron with a minimal increase in the transverse beam envelopes. The scheme uses an electrostatic deflector with an acceptable electric field strength followed by two passive magnetic channels. Losses of the beam will be determined mainly by thickness of the septum electrode of the deflector and will not be less than 15 % for 0.1mm septum. This scheme of extraction is suitable for cyclotron with standard for proton therapy energy 230-250 MeV either. It will only be necessary to redesign the shape correspondently to higher energy of the sectors that provides the transverse focusing of the beam.

ACKNOWLEDGEMENTS

Authors are especially grateful to L.Calabretta for fruitful discussions and helpful ideas, which were used in our extraction approach.

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