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BEAM DYNAMICS SIMULATIONS IN THE DUBNA SC230 SUPERCONDUCTING CYCLOTRON FOR PROTON THERAPY

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Abstract

We present results of the beam dynamics simulation for the compact isochronous superconducting cyclotron SC230. We have performed beam tracking starting from the ion source. The extraction system scheme and results of beam extraction simulations are presented. The codes and methods used for beam tracking are briefly described.

INTRODUCTION

Physical design of the compact superconducting cyclotron SC230 (91.5MHz) has been performed. The cyclotron will deliver a beam of protons accelerated up to 230 MeV for proton therapy and medico-biological research. We have performed simulations of magnetic and accelerating systems of the SC230 cyclotron and specified the main parameters of the accelerator [1].

As a result, we will have a design with:

- Minimum engineering efforts and challenges;
- Low power consumption;
- High quality of the beam;
- Reasonable size;
- Reliability and stable operation;
- Moderate conservativeness and reduced risks.

EQUILIBRIUM ORBIT ANALYSIS

A number of beam dynamics simulations were performed during the design of the cyclotron.

They are listed below:

equilibrium orbit analysis to reach proper isochronism and focusing,

beam dynamics simulation in the center region, during acceleration and extraction to check correctness of the model.

During the magnet simulations the following design goals were achieved:

Isochronous field in the whole accelerating range;

Last orbit of the circulating particle was kept close to the edge of the pole (at 10-15 mm);

The stray fields were kept at an acceptable level;

Dangerous resonances were avoided.

Isochronism of the average field was reached via a change of the sector's width. Azimuthal width of the sector changes along the radius from 25 degrees at the center to 40 at the extraction zone.

Magnetic field was carefully shaped. Deviation of average field from isochronous curve in main acceleration region is not more than ±5 Gs (see Fig. 1).

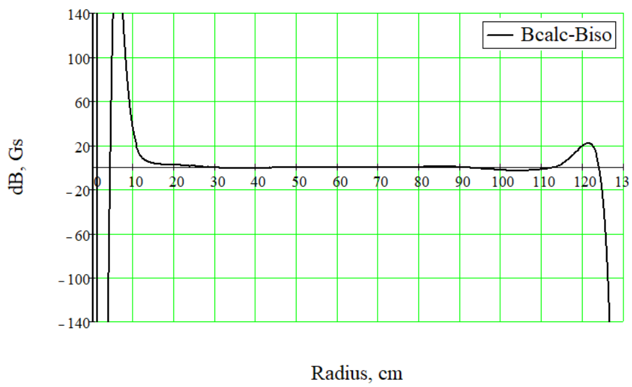

Figure 1: Difference between average magnetic field and isochronous curve.

Betatron tunes calculated with CYCLOPS-like code [2] are presented in Fig. 2. To improve performance of the code, the map is accessed via Matlab's griddedInterpolant class. The equations of motion are solved via an ODE solver (ode45 of MATLAB R2018a) employing the fourth-order RungeKutta algorithm. Our implementation allows simultaneous calculation of a large number of particles, which improves performance due to lower number of loops and more efficient use of RAM memory.

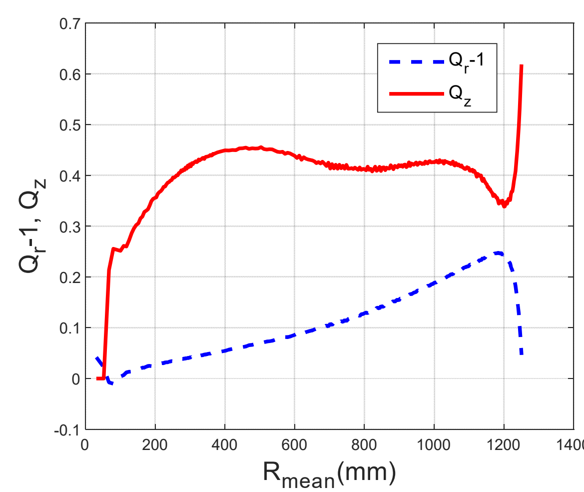

Figure 2: Vertical and radial betatron tunes in SC230.

We would like to point out that all graphs from simulation results appear to be quite smooth, even though they were obtained using a field map with a rather low number of mesh cells (about 4 millions), which was created from the computer model of the magnet calculated in CST studio.

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ACCELERATION

The beam has been accelerated with the 3D magnetic and 3D RF electric field maps where the amplitudes of betatron oscillations were up to Ar=2 mm, z=3mm (Fig. 3). There were no losses of particles at any radius after center region. No influence of any resonance was observed. The accelerated particles successfully reach the edges of the sectors of the cyclotron which are cut along the trajectory and have a chamfer that helps with providing necessary increase of the field.

Acceleration takes about 600 turns beginning from energy 100 keV to 233MeV. The accelerating voltage along radius for different gaps can be seen in Fig. 4.

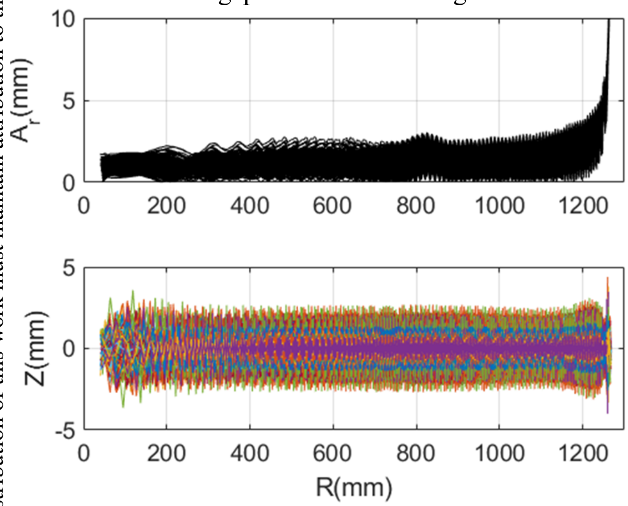

Figure 3: Amplitudes of radial oscillations and vertical motion of the beam.

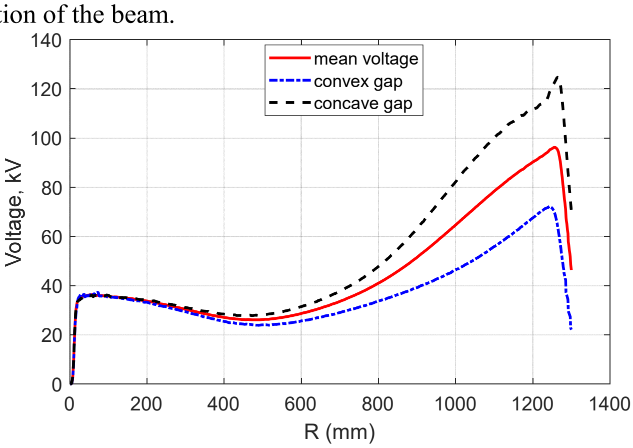

Figure 4: Accelerating voltage along radius.

Simulations in the accelerating region were performed by two different codes based on equations of motion with different independent variables (azimuth angle in Matlab code [2], time - in SNOP code [3]). No resonance effects were observed in both simulations.

CENTRAL REGION

Central plug was optimized in order to provide sufficient axial focusing of the beam in the central region. The value of the resulting field bump in the center is ~150 Gs. This field bump shifts the average RF phase of the beam after central region to achieve optimal energy gain (Fig. 5).

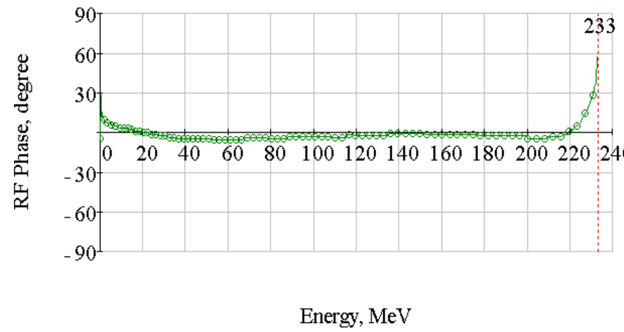

Figure 5: RF phase shift of a reference ion.

Axial hole in the plug is square-shaped (Fig. 6) this is convenient for the internal ion source and allows minimizing the zone without axial focusing by magnetic field.

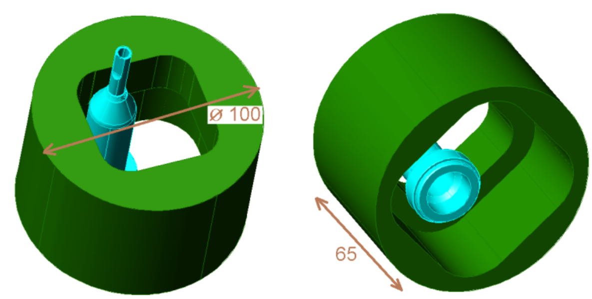

Figure 6: Location of the ion source in the central plug.

Dimensions of the plug: diameter 100 mm, height 65 mm, distance from median plane is 35 mm.

The ion source is shifted from the cyclotron center by 15.8 mm. We plan to use 4 accelerating RF cavities, operating on the 4th harmonic mode. All four RF cavities will be connected in the center.

The central region design affects the beam characteristics in acceleration and extraction stages. Good central region configuration should provide high axial beam quality and precise centering of the beam. On initial turns the width of the accelerating gaps is 3.6 mm, which prevents spark discharge at the peak dee voltage of 50 kV. Axial aperture of the dees increases from 5 mm at first turns to 20 mm in main accelerating zone. Axial distance between the dees and the central plug is 27 mm. The central region structure is shown in Fig. 7.

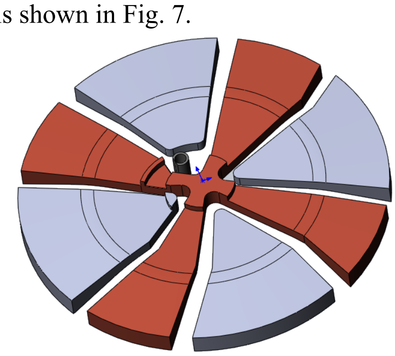

Figure 7: Central region structure.

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To improve the quality of the beam the central region has a phase selection slit, so that only particles with phases within certain ranges are accelerated. Two modes of phase selection were studied – 8-degrees and 12-degrees ranges. It was established that the first mode can provide final beam current within the project requirements (>500 nA). In the second mode the extracted beam intensity can exceed 1 μA. RF acceptance of the central region without phase slits is ~50 RF degrees, and beam transmission through the central region is 25%. Axial size of the beam at initial turns is about 5 mm. The central region provides acceptable beam centering (Fig. 8).

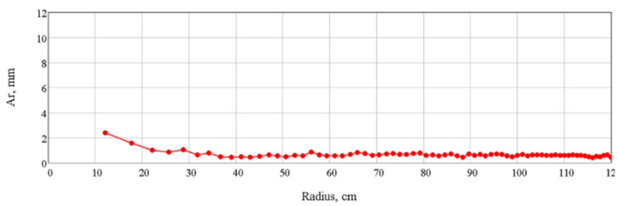

Figure 8: Amplitudes of radial betatron oscillations of the reference particle.

Good radial beam quality will provide a high beam extraction efficiency.

EXTRACTION

Accelerating system consisting of four dees imposes some constraints on the extraction system structure. For example, the extraction elements cannot be positioned in the valleys. Beam deflection can be implemented by means of one electrostatic deflector (ESD), two passive magnetic channels (MC1, MC2) and a single compensator of the first channel (C_MC1) as shown in Fig. 9.

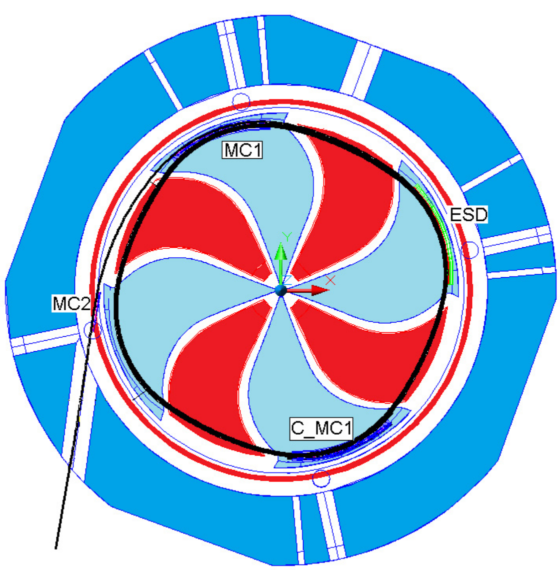

Figure 9: Extraction system of SC230: ESD –electrostatic deflector, MC1 – first magnetic channel, MC2 – second magnetic channel, C_MC1 – compensator of the first harmonic induced by the magnetic channels.

A main requirement for the ESD is a moderate magnitude of the electric field strength. So, the system is designed in order to have a field strength of 100 kV/cm at the deflector. The septum thickness of the ESD is 0.1 mm with a 6 mm gap between the electrodes. Height of the deflector is 50 mm that allows its placing in the axial gap between the sectors. Every magnetic channel consists of septum (thickness ~4 mm) and anti-septum. This structure provides not only field drop that helps deflecting of the beam, but also creates a positive transverse gradient of the field, which focuses the beam in the radial direction. The length of the first channel is 820 mm. Central field -0.18 T, field gradient 0.13 T/m. Distance between deflected and circulating beam is about 20 mm. The length of the second channel is smaller - 300 mm. Central field -0.19 T, field gradient 0.25 T/m. Distance between deflected and circulating beam is about 110 mm.

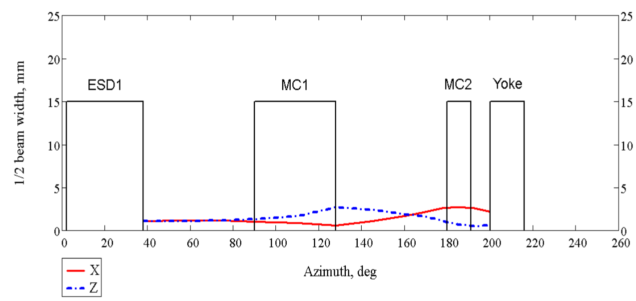

Figure 10: Beam envelopes during extraction (2σ).

Beam envelopes during extraction are smaller than 3 mm in both transversal directions (Fig. 10).

CONCLUSION

Beam dynamics analysis in the SC230 cyclotron were performed in 3D magnetic and accelerating field from the ion source to exit of the cyclotron.

The beam transmission efficiency through the central region, extraction efficiency, and quality of the final beam are in compliance with requirements. According to our simulations we can expect 75% beam extraction efficiency with more than 500 nA extracted beam current.

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