STUDY OF THE BEAM EXTRACTION FROM SUPERCONDUCTING CYCLOTRON SC200

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Abstract

According to the agreement between the Institute of Plasma Physics of the Chinese Academy of Sciences (ASIPP) in Hefei, China, and the Joint Institute for Nuclear Research (JINR), in Dubna, Russia, the project of superconducting isochronous cyclotron for proton therapy SC200 is under development at both sites. The cyclotron will provide acceleration of protons up to 200 MeV with maximum beam current of ~1 μA.

Extraction system of the beam consists of electrostatic deflector and two passive magnetic channels. Electric field strength in deflector does not exceed 170 kV/cm, gradients of magnetic field in channels are in a range of 2-4 kG/cm. Both channels focus the beam in horizontal plane. Axial focusing of the beam is provided by edge magnetic field of the cyclotron.

Results of the beam tracking inside extraction system are presented. Efficiency of the beam extraction was estimated for different amplitudes of the betatron oscillations in the accelerated beam.

WORKING DIAGRAM OF CYCLOTRON

Different 3D codes have been used [1] in order to find acceptable geometry of the cyclotron magnetic system. Main purpose was to provide the working diagram without crossing of the most dangerous resonances such as $2Q_z=1$ and Q_r-$Q_z=1$. Many of the magnetic field maps computed by the different codes had large nonlinearities especially at edge region where a sector gap was rather small (<2 cm). These nonlinearities led to a waving of the betatron tunes and multiple crossing of the resonances. The most linear field map was obtained by the CST code [2].Figure 1 shows the working diagram of the cyclotron calculated on the base of this map. To get this diagram, the average magnetic field of the map was substituted by isochronous one. Resulting field map that correspond to presented diagram was applied for simulation of the beam acceleration up to deflector entrance.

One can see that the working point crosses the resonance Q_r-$Q_z=1$ at the very end of acceleration. This condition forced us to locate the deflector before full crossing of the resonance and implement extraction of the beam. The results are discussed below. The possibility that avoids crossing of this resonance is expected by means of special correctors during real shaping of the magnetic field.

Simulation of the beam acceleration shows that crossing of the $3Q_r=4$structural resonance is not dangerous. Increase in the radial amplitudes is acceptable.

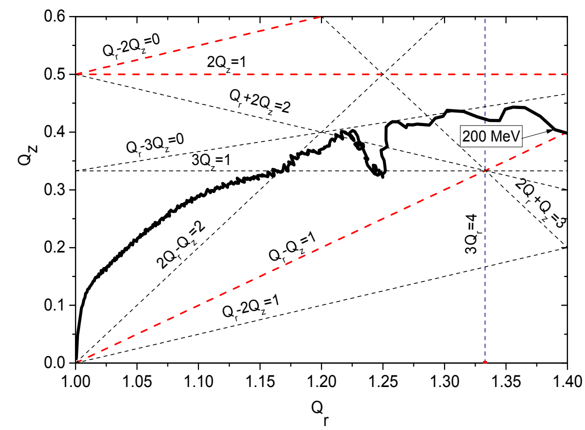

Figure 1: Working diagram of the SC200 cyclotron.

BEAM PARAMETERS AT DEFLECTOR ENTRANCE

There are two different ways to enlarge radial gain enhancement at deflector entrance, resonance and not resonance. The 1-st one was used in VARIAN C250 cyclotron [3], the 2-nd one in IBA C235 [4]. And the 2-nd will be applied in our cyclotron. In this scheme of extraction, the radial gain enhancement is mainly provided by radial betatron motion at Q_r~1.2-1.3. If amplitude of incoherent radial oscillations in accelerated beam comprises 3-5 mm then the radial width of the beam at deflector entrance is of about 2-3 mm. Not more than 10% of this value is provided by energy gain per turn, and the main part is connected with betatron motion.

In order to get the beam parameters at deflector, a bunch of 1000 protons was accelerated from the energy of 80 MeV. Initial parameters of protons were matched with the cyclotron acceptance at this energy for different amplitudes of radial oscillations in the range of 2-5 mm. Amplitude of axial oscillations was equal to 2.5 mm.

Different types of proton losses were estimated:

- axial, due to impact of the Q_r-$Q_z=1$coupling resonance;
- on a tip of septum, assuming 0.1 mm its thickness;
- on external side of the septum looking on the accelerated beam.

Different septum thickness along its length has been studied, constant 0.1 mm or linear increased up to 1-2 mm.

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Axial profile of the beam in energy range of 80-200 MeV is presented in Fig. 2. Sum losses of the beam before its tracking inside the extraction system are shown in Fig. 3.

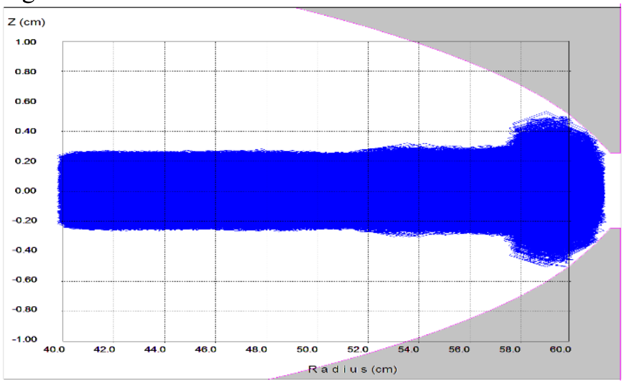

Figure 2: Axial profile of the beam in energy range 80-200 MeV. Spiral sectors are marked by grey color.

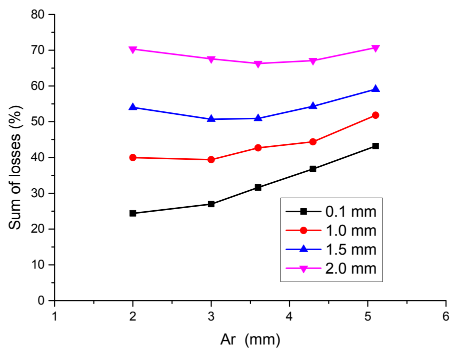

Figure 3: Sum of proton losses (axial+tip of septum+external side of septum) for different final septum thickness versus amplitude of radial oscillations.

Sum of losses does not exceed 40% even for the beam with 5 mm radial oscillations if septum has constant thickness 0.1 mm. Linear increase of septum thickness leads to essential increase of the losses on external septum side.

Parameters of protons at entrance of deflector are shown in Fig. 4 for the beam with 3 mm radial oscillations. Average energy of the beam comprises 203.6 MeV, energy spread ±0.8 MeV.

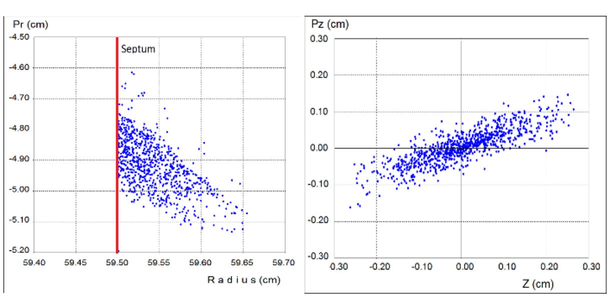

Figure 4: Position of protons on planes (r, P_r) and (z, P_z)at deflector entrance.

TRACKING IN EXTRACTION SYSTEM

The beam is extracted by means of electrostatic deflector and two passive magnetic channels. First part of extraction system is shown in Fig. 5. It consists of electrostatic deflector and passive magnetic channel 1 (MC1). The channel MC1 is subdivided into 4 parts with different cross-sections and field gradients. Channel MC1 is followed by second channel MC2 located inside the magnet yoke. Both channels focus the beam in horizontal plane, axial focusing is provided by edge magnetic field of the cyclotron.

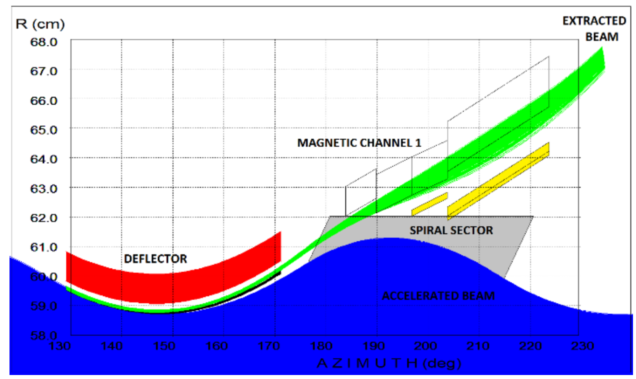

Figure 5: First part of the extraction system. Final thickness of the septum is 1 mm. Electric field in deflector is 160 kV/cm.

Proton losses were estimated during tracking of the beam inside the deflector with aperture 3 mm. Main part of these losses was detected on septum surface, losses on high voltage electrode appeared if amplitude of radial oscillations was greater than 4 mm. Sum of losses inside the deflector is presented in Fig. 6.

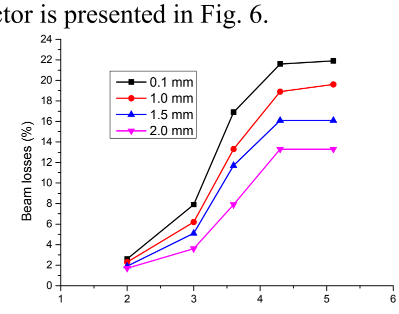

Figure 6: Sum of proton losses inside deflector (septum+high voltage electrode) for different final septum thickness versus amplitude of radial oscillations.

To estimate overall efficiency of extraction, the losses of accelerated beam (Fig. 3) were added to the losses inside deflector (Fig. 6). Resulting efficiency of extraction is shown in Fig. 7. No losses were detected inside both magnetic channels.

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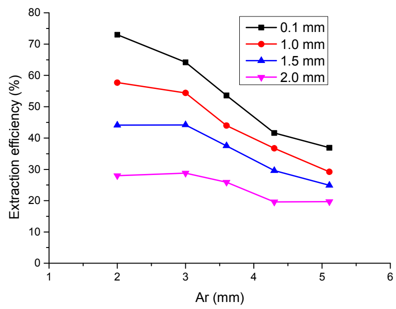

Figure 7: Resulting efficiency of the beam extraction for different final septum thickness (0.1-2.0) mm versus amplitude of radial oscillations.

Plan view of the extraction system together with trajectories of protons is presented in Fig. 8. RMS envelopes of the beam are shown in Fig. 9. Reference point for the beam extraction was defined at radius of 160 cm. Phase portraits of the beam in reference point are shown in Fig. 10. Estimated emittance of the beam is a range of about 5-10 π mm·mrad

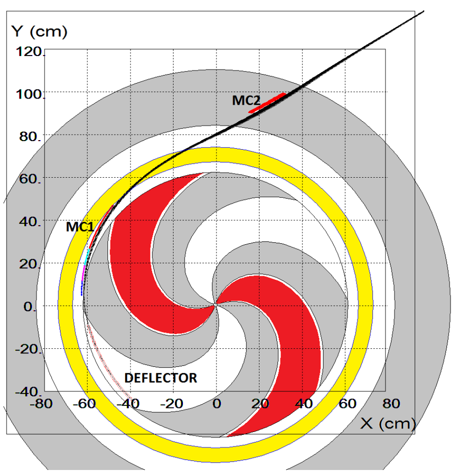

Figure 8: Schematic plan view of extraction system with proton trajectories.

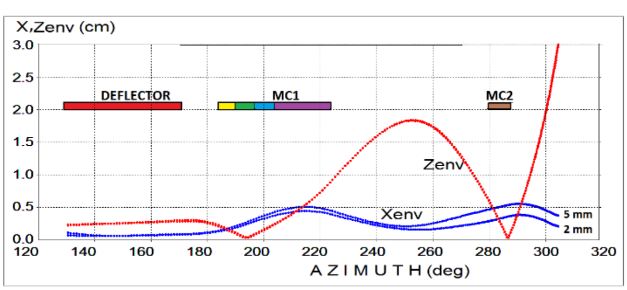

Figure 9: RMS envelopes (2σ) in extraction system. Horizontal envelopes plotted for two amplitudes of radial oscillations 2 and 5 mm.

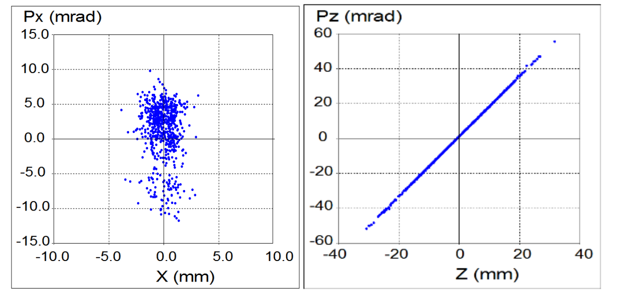

Figure 10: Phase portraits of the beam in reference point (r=160 cm).

PASSIVE MAGNETIC CHANNELS

The SC200 extraction system uses 2 magnetic channels. The first magnetic channel (MC1) is in strong magnetic field within 2.2~3.4 T. The second one (MC2) is in cyclotron yoke hole where is the magnetic field of ~1 T. These fields are much enough to magnetize the channels iron bars. So, for both channels the passive design is used. The MC1 is placed rather close to the sectors edge. Due to this fact the two initial parts of the channel have the 2 bars design, and two output ones have 3 bars system. The MC2 design has 3 iron bars. 3D design view of the MC1 is shown in Fig.11.

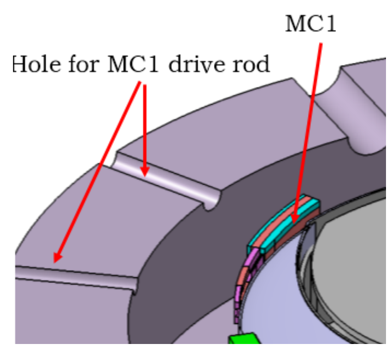

Figure 11: 3D design sketch of the MC1.

The channels magnetic field simulation was performed by 2D POISSON code. As an example, the design of MC1' 4-th part and its magnetic field parameters are shown in Fig. 12. Channel MC2 has similar geometry.

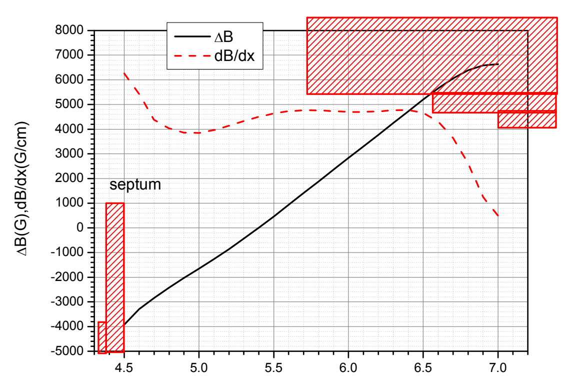

Figure 12: Cross section of 4-th part of MC1 and its field response and gradient.

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CONCLUSIONS

Acceptable extraction efficiency ~50-60% is attained for the SC200 cyclotron if septum has the increasing thickness from 0.1 mm up to not more than 1 mm and the accelerated beam has the amplitude of radial oscillations up to 3.5 mm. Enlarged final septum thickness up to 2 mm leads to essential decrease of the extraction efficiency. The static voltage of 50 kV is applied on the deflector with the 3 mm aperture.

Two passive magnetic channels are used only to focus the beam in horizontal plane, and the axial focusing is provided by edge magnetic field of the cyclotron.

SC200 physical design will be ended within this year. And the magnetic field tuning plans to be kicked off next year.

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