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CONCEPTUAL DESIGN OF THE SC230 SUPERCONDUCTING CYCLOTRON FOR PROTON THERAPY

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Abstract

Physical design of the compact superconducting cyclotron SC230 (91.5MHz) has been performed. The cyclotron will deliver up to 230 MeV beam 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.

INTRODUCTION

At the Dzhelepov Laboratory of Nuclear Problems, JINR, the Medico-Technical Complex (MTC) was developed on the basis of the 660-MeV proton accelerator (Phasotron), where patients are treated in a regular way using 3D conformal proton beam therapy.

The initial operation of the accelerator took place in 1949 and now it is outdated and worn out. Therefore, it seems currently important to replace Phasotron with a new compact dedicated proton accelerator. A new isochronous cyclotron SC230 will be used for further medico-biological research and for patient treatment.

Since 2016 the SC200 superconducting cyclotron for hadron therapy has been jointly developed by JINR and ASIPP (Hefei, China) [1]. The production of the cyclotron faced a lot of engineering challenges which are mainly aroused due to high magnetic field of the accelerator. Therefore we decide to rethink some design decisions after careful analysis of SC200, other projects and operating cyclotrons for proton therapy.

Modern tendency to reduce size and cost of Ion Beam Radiotherapy leads to the success of superconducting synchrocyclotrons which are useful for single room solutions. An isochronous cyclotron cannot compete with synchrocyclotrons in dimensions and weight, Mevion 250 weighs about 20 tonnes [2], but a cyclotron has a CW beam and therefore high average current sufficient for different applications. The isochronous cyclotron is the best choice for the universal full-scale proton therapy centers.

Most proton therapy centers commissioned worldwide utilise isochronous cyclotrons as the drive accelerator, because they are compact, simple to operate and very reliable. Cyclotrons deliver a continuous output (CW beam) with high beam current and can accurately modulate the proton beam current.

Recent developments of superconducting cyclotrons for proton therapy, such as SC200, Pronova K230, Sumitomo 230MeV, share similar parameters that define the structure of the cyclotron. All projects are 4-sector cyclotrons with ~3T central field. Such parameters were chosen in pursuit of compact dimensions. None of those cyclotrons are yet in operation.

There are two most successful accelerators in the proton therapy: Varian PROSCAN [3], design proposal by H.Blosser et al. in 1993, and C235 (IBA Belgian) [4]. Both cyclotrons have much smaller central field, 2.4 and 1.7 Tesla.

We are not restricted in dimensions of cyclotron; therefore, we decided first of all to increase the pole of the cyclotron in order to decrease mean magnetic field to about 1.5 T in the center (see parameters in Table 1). Corresponding frequency for this value of the magnetic field is 91.5 MHz which was used for SC200 cyclotron design.

As the cyclotron will have a relatively small magnet field, it is possible to use both superconducting and resistive coil. Both solutions have their pros and cons, however for the SC230 we have chosen superconducting coil. Although the resistive coil is cheaper and easier, it consumes more power, it is a source of heat that may affect the cyclotron, and as we need 170kA-turns it would be large, and large resistive coil requires a rather complicated and powerful cooling system. For example, the resistive coil of the IBA C235 cyclotron, which delivers 250kA-turns is about 0.6x0.5m in cross-section, and superconducting coil with cryostat would be less than 0.25x0.25m. Our simulations show that similar design as IBA C235 with superconducting coil instead of copper coil would reduce the yoke weight from 210 tonnes down to about 100 tonnes and would make the cyclotron much more compact. Since in this proposal we reduce RF frequency even more than the frequency in C235, the accelerator weight will be about 130 tonnes.

Additional advantage for superconducting option is operation schedule. There is no necessity to turn of magnet for night time so superconducting cyclotron can be switch on in the mornings just by turning on RF and other systems.

The superconducting technologies are evolving and become more and more affordable, so running cost of the SC coil should decrease; however the same cannot be said about electricity costs, that is why we are focused on low power consumption of the cyclotron.

Low magnetic field is also an advantage for the SC coil design. The magnetic field in the coil is an important value, and critical current strongly depends on it. The usual value of the current density in NbTi coils in superconducting cyclotrons or synchrocyclotrons for proton therapy is 50-60A/mm2; however, those coils operate at 4T and more, the SC230 coil will operate at 2T field in coil, and that can theoretically give us an order of magnitude greater possible current density and reduce the coil size down to 10cm2 and lower. But our focus is on reliability and simplicity and we prefer not to have risks of quench, so we plan to keep the

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current density moderate and it should not exceed 110A/mm2.

We plan to use NbTi for coil manufacture; however, the cyclotron's design makes it possible to use high-temperature superconductor (HTS) materials, which is very promising [5]. So far the liquid nitrogen temperature superconductors were very expensive and coil was manufactured only in short pieces of wire, not exceeding 1km. According to our calculations, we would need about 5km of wire. We are researching the possibility of using HTS because HTS materials provide large margin against quenching, need lower cryocoolers power and have more compact cryostat dimensions.

We propose a design which combines advantages of both successful accelerators: low magnetic field level and fourth harmonic of acceleration (IBA C235 cyclotron), four accelerating cavities and superconducting coils (Varian PROSCAN).

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.

Table 1: Parameters of the Cyclotron

Accelerated particles	protons
Magnet type	Compact, SC coil, warm yoke
Number of sectors	4
Number of RF cavities	4
Ion source	Internal, PIG
Final energy, MeV	230
Number of turns	600

MAGNET SYSTEM OF SC-230 CYCLOTRON

Computer Simulations of the Magnet

Simulations were performed in CST studio [6] in the parametrized model of the magnet (see Fig. 1) created in Autodesk Fusion 360 [7].

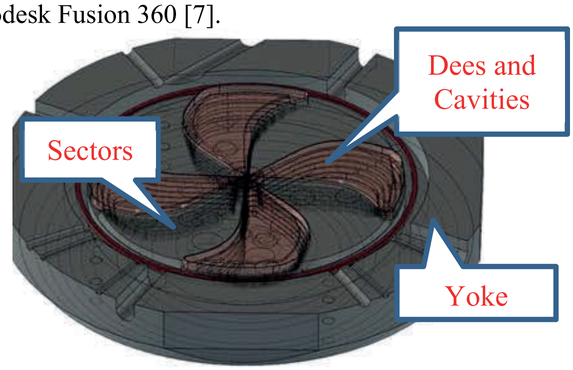

Figure 1: Layout of the cyclotron's 3D computer model (magnet and accelerating system).

Changing parameters automatically changes the computer model. In addition, sector geometry can be replaced by importing from Matlab. Final cross check was performed with Tosca code.

The dimensions of the yoke (see Fig. 2) were chosen to restrict the magnetic stray field in the range of 200-300G just outside accelerator, providing full saturation of the iron poles and yoke. Average magnetic field and flutter from CST simulation are presented in Fig. 3.

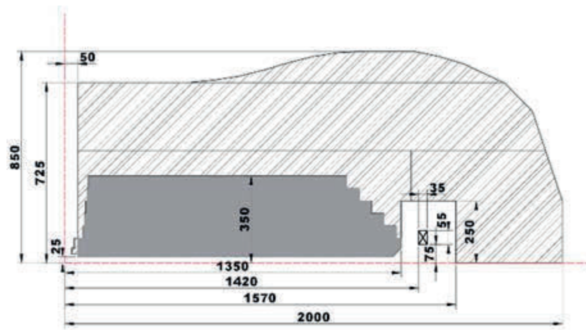

Figure 2: SC230 magnet yoke and SC coil general dimensions.

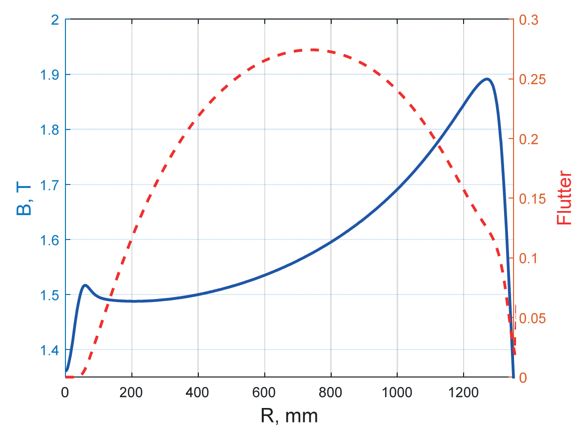

Figure 3: Average magnetic field and flutter along the radius.

ACCELERATING SYSTEM DESIGN

RF cavities are located at the valleys of the magnet, the geometry of the RF cavity is restricted by the size of spiral sectors. For proton acceleration, we are planning to use 4 accelerating RF cavities, operating on the 4th harmonic mode. Main parameters of accelerating system are presented in Table 2. The choice of 4th harmonic is a natural choice for a cyclotron with 4 sector and provides high acceleration rate. All four RF cavities will be connected in the center and will be working on approximately 91.5 MHz frequency. Cavities can be equipped with an inductive coupling loop and will be adjusted by capacitance trimmers like in SC200 [8].

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Table 2: Accelerating System Parameters

Frequency, MHz	91.5
Harmonic number	4
Number of cavities	4
Power losses, kW (total)	43
Q-factor	13800
Voltage center/extraction, kV	35/95

Computer Model

The characteristic parameters of the half-wavelength coaxial resonant cavity with two stems have been obtained from simulation in CST studio. The RF cavity resonator solution for the SC230 cyclotron can be seen in Fig. 4. Azimuthal extension of the cavity (between middles of the gaps) against radius is presented in Fig. 5.

Figure 4: Overview of 3D model of RF system.

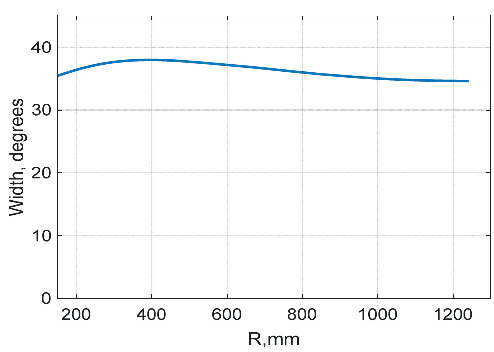

Figure 5: Azimuthal extension of the cavity (between middles of accelerating gaps).

Suitable accelerating frequency and voltage along radius were achieved. The calculation results of acceleration voltage are presented in Fig. 6.

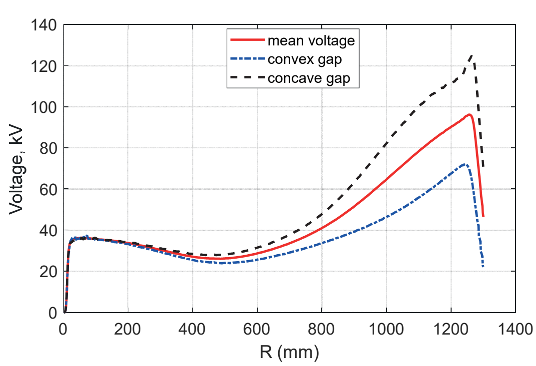

Figure 6: Accelerating voltage along radius.

As the beam will be accelerated in the fourth harmonic mode we believe that the RF magnetic field will not have noticeable effect on the beam.

The value of the accelerating voltage was obtained by integrating the electric field in the median plane of the resonant cavity along the arc of a circle for each gap separately.

Power Losses

Power dissipation in the model was calculated assuming the wall material is copper with a conductivity $\sigma = 5.8 * 10^7$ 1/(Ωm). The quality factor was about 13800 and power losses of all cavities were: for storage energy 1 joule voltage in the center/extraction 35-95 kV, thermal losses are 43 kW.

Overall power and cooling requirements of the RF system are rather small.

CONCLUSION

We chose a low level of the magnetic field in the cyclotron and found out that dimensions of the cyclotron do not increase very much if we use superconducting coils.

Special chamfer on the edge of sector along the particle's trajectory provides isochronism close to the sector edge. Low magnetic field together with high acceleration rate due to 4 cavities and fourth harmonic of acceleration will provide 2-3 mm radial increase of the orbit due to acceleration. As a result we can have efficient extraction with electrostatic deflector.

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