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O. Karamyshev, G. Karamysheva, S. Gurskiy,
V. Malinin, D. Popov, G. Shirkov, S. Shirkov,
V. Smirnov, S. Vorozhtsov

CONCEPTUAL DESIGN OF THE SC230 SUPERCONDUCTING CYCLOTRON FOR PROTON THERAPY

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Карамышев О. В. и др. E9-2019-2
Концептуальный проект сверхпроводящего циклотрона SC230 для протонной терапии

Выполнен физический проект компактного сверхпроводящего циклотрона SC230. Циклотрон предназначен для ускорения пучка до энергии 230 МэВ для протонной терапии и медико-биологических исследований. Проведено моделирование магнитной и ускоряющей систем циклотрона SC230, и определены основные параметры ускорителя. Представлены возможная схема системы вывода и предварительные результаты моделирования динамики пучка. Коротко описаны программы и методы, используемые для расчета движения пучка.

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Karamyshev O. et al. E9-2019-2
Conceptual Design of the SC230 Superconducting Cyclotron for Proton Therapy

Physical design of the compact superconducting cyclotron SC230 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. Possible schema of the extraction system and preliminary results of beam dynamics simulations are presented. Codes and methods used for the beam tracking are shortly described.

The investigation has been performed at the Dzhelepov Laboratory of Nuclear Problems, JINR.

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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The initial operation of the accelerator took place in 1949 and now it is outdated and worn out.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 the 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 due to high magnetic field of the accelerator. Therefore, we decided 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 synchrotrons which are useful for single room solutions. An isochronous cyclotron cannot compete with synchrocyclotrons in dimensions and weight, Mevion S250 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 230 MeV, share similar parameters that define the structure of the cyclotron. All projects are 4-sector cyclotrons with $\sim$ 3 T central field. Such parameters were chosen in pursuit of compact dimensions. None of those cyclotrons is 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, Belgium) [4] (see Table 1). Both cyclotrons have much smaller central field, 2.4 and 1.7 T.

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 1.7 T in the center.

As the cyclotron will have a relatively small magnetic field, it is possible to use both superconducting and resistive coil. Both solutions have their pros and

Table 1. Comparison of parameters of cyclotrons for proton therapy

Parameter	Cyclotron			
	Mevion S250	Varian PROSCAN	IBA C235	SC230
Yoke diameter, m	1.8	3.1	4.34	3.7
Height, m	1	1.6	2.1	1.7
B_0, T	8.9	2.4	1.7	1.7
Coil	Nb_3Sn	NbTi	Resistive	NbTi or HTS?
Weight, tonne	20	90	210	98
Beam time structure	Pulsed	CW	CW	CW
Extraction energy, MeV	250	250	235	230

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 250 kA $\cdot$ 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 250 kA $\cdot$ turns, is about 0.6×0.5 m in cross-section, and superconducting coil with cryostat would be less than 0.25×0.25 m. Our simulations show that a similar design to IBA C235 with superconducting coil instead of copper coil would reduce the yoke weight from 210 down to about 100 tonnes and would make the cyclotron much more compact.

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 50–60 A/mm^2; however, those coils operate at 4 T and more, the SC230 coil will operate at 2.5 T field in coil, and that can theoretically give us an order of magnitude greater possible current density and reduce the coil size down to 10 cm^2 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 current density moderate and it should not exceed 70 A/mm^2.

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 1 km. According to our calculations, we would need about 5 km of wire. We are researching the possibility of using HTS because HTS materials

Table 2. 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	500

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 (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 (running costs should be low);
- High quality of the beam (regarded as the main feature);
- Reasonable size;
- Reliability and stable operation;
- Moderate conservativeness and reduced risks.

SC230 is an isochronous superconducting compact cyclotron. Superconducting coils will be enclosed in a cryostat, all other parts are warm. Internal ion source of PIG type with hot cathode will be used. It is a fixed field, fixed RF frequency and fixed 230 MeV extracted energy proton cyclotron. Extraction can be organized with an electrostatic deflector and magnetic channels. For proton acceleration we are planning to use four accelerating RF cavities (one shortened), operating on the 4th harmonic mode (Table 2). Average magnetic field of the cyclotron is up to 2.2 T and the particle revolution frequency is about 26.7 MHz.

1. THE MAGNET SYSTEM OF THE SC230 CYCLOTRON

Simulations were performed in CST studio [6] in the parametrized model of the magnet (see Fig. 1) created in Autodesk Fusion 360 [7]. Changing parameters automatically changes the computer model. In addition, sector geometry can be replaced by importing from Matlab. Final cross check will be done with Tosca code.

The dimensions of the yoke (see Table 3 and Fig. 2) were chosen to restrict the magnetic stray field in the range of 200–300 G just outside accelerator, providing full saturation of the iron poles and yoke.

Results of simulations of the magnetic field are exported to Matlab to be analysed with CYCLOPS-like code or to perform particle tracking in 3D field

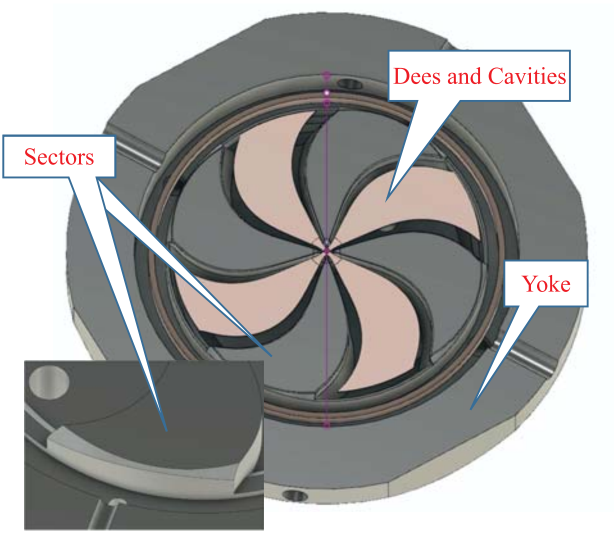

Fig. 1. Layout of the cyclotron's 3D computer model (magnet and accelerating system)

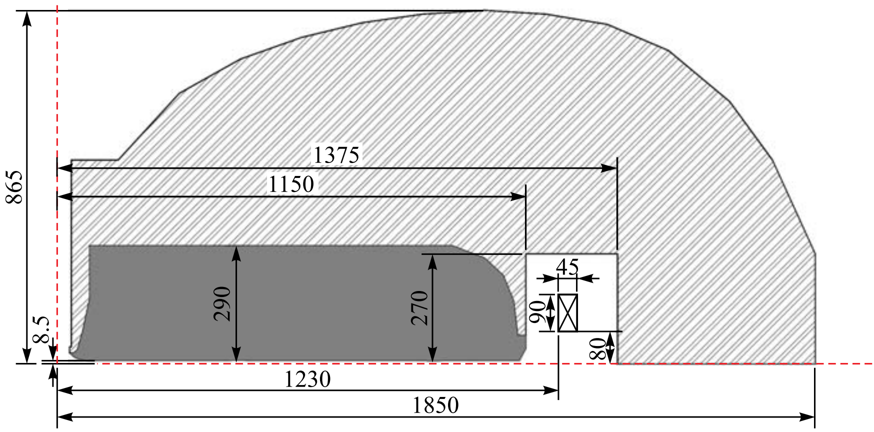

Fig. 2. SC230 magnet yoke and SC coil general dimensions (in mm)

maps by codes integrating a system of differential equations of motion written in Matlab.

During the magnet simulations the following design goals were achieved:

- Isochronous field in the whole acceleration range;
- Last orbit of the circulating particle was kept close to pole edge of 7–10 mm;

Table 3. Magnet parameters

Yoke material	St.1010
Average magnetic field ($R_0/R_{\rm extr}$), T	1.7/2.2
Extraction radius, m	1.07
Pole diameter, m	2.3
Magnet diameter, m	3.7
Magnet height, m	1.7
Hill gap, mm	17
Maximum valley gap, m	0.58
Number of ampere · turns (1 coil)	250 000
Maximum magnetic field in the coil, T	2.5
Cryostat and coils weight, tonne	5
Magnet weight, tonne	98

- 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 changed along the radius from center to extraction from 25° to 40°.

Orbital frequencies of the final average field (Fig. 3) and flutter (Fig. 4) are presented in Fig. 5. From Fig. 5 we can estimate that the difference between the mean field and the isochronous field is about 10–20 G in acceleration region. We would like to notice that all results were obtained with a rather low number of mesh cells (about 4 millions).

Betatron tunes calculated for a sample set of energies with CYCLOPS-like code are presented in Fig. 6.

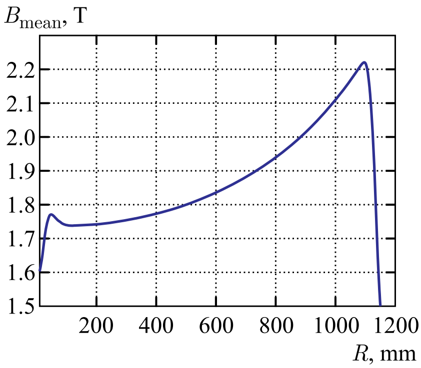

Fig. 3. Average magnetic field along the radius

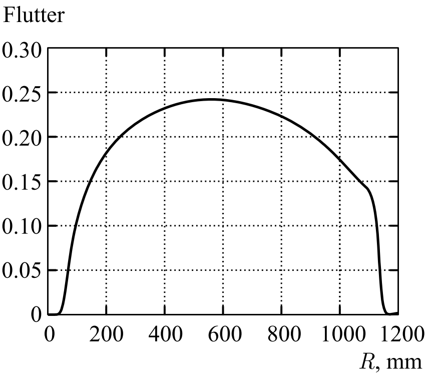

Fig. 4. Flutter along the radius

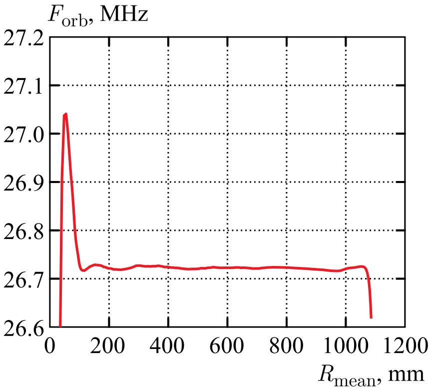

Fig. 5. Orbital frequency against mean radius

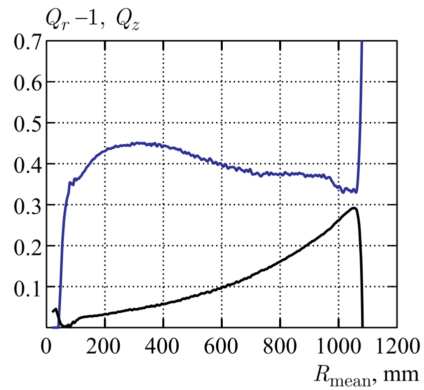

Fig. 6. Vertical and radial betatron tunes in SC230

2. 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 four accelerating RF cavities, operating on the 4th harmonic mode. The 4th harmonic is a natural choice for a cyclotron with four sectors, providing high acceleration rate. All the four RF cavities will be connected in the center and will be working at approximately 107 MHz frequency (see Table 4). The cavities will be equipped with an inductive coupling loop and will be adjusted by capacitance trimmers like in SC200 [8].

The characteristic parameters of the half-wavelength coaxial resonant cavity with a single stem have been obtained from simulation in CST studio. The RF cavity resonator solution for the SC230 cyclotron can be seen in Fig. 7. Azimuthal

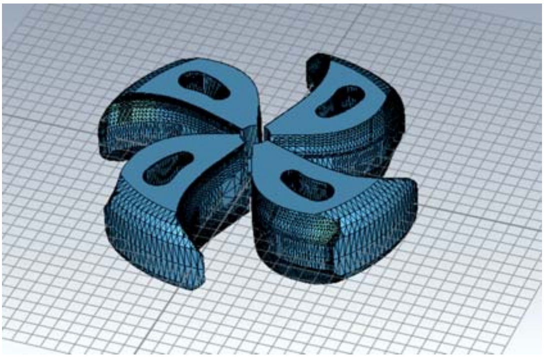

Fig. 7. Overview of 3D model of the RF system

Table 4. Parameters of the accelerating system

Frequency, MHz	107
Harmonic number	4
Number of cavities	4
Total power losses, kW	50
Q factor	15000
Center/extraction voltage, kV	40/120

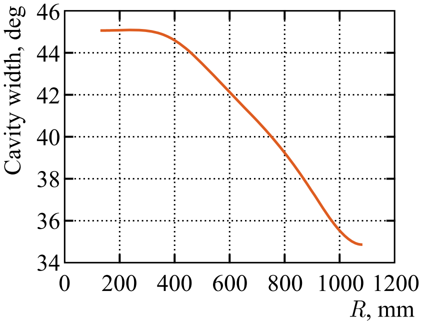

Fig. 8. Azimuthal extension of the cavity (between the middles of acceleration gaps)

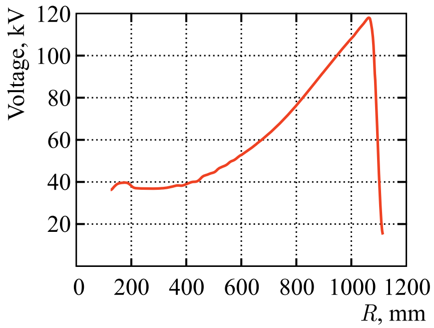

Fig. 9. Mean accelerating voltage along radius

extension of the cavity against radius is presented in Fig. 8. Suitable accelerating frequency and voltage along radius were achieved. The calculation results of accelerating voltage are presented in Fig.9.

2.1. Power Losses. Power dissipation in the model was calculated assuming the wall material is copper with a conductivity $\sigma = 5.8 \cdot 10^7$ 1/($\Omega \cdot$ m). The quality factor was about 15000, and for storage energy 0.25 J the power losses of a single cavity were about 12 kW and voltage in the center/extraction was 40/120 kV.

The whole system has a calculated power dissipation of about 50 kW. Overall power and cooling requirements of the RF system are rather small.

3. BEAM DYNAMICS STUDIES

3.1. Center Region. In order to have efficient center region, we create vertical focusing by azimuthal variation and a bump in the magnetic field. The bump value is about 190 G. After the radius $R = 40$ mm, magnetic focusing induced by the bump occurs. The magnetic field variation starts at a small radius of $R = 50$ mm and helps with the vertical focusing.

Figure 3 demonstrates the magnetic field bump in the very center of the cyclotron, and Fig. 6 shows vertical betatron frequency Q_z. For the radius less than 4 cm, vertical focusing is provided for lagging particles by electric accelerating field.

Internal PIG proton source with hot cathode will be used in our cyclotron and will provide a current of at least 50 μA [9]. We plan to use a rather small voltage of about 40–50 kV in the center to avoid sparking. Accurate 3D model of the source and the central region is not finished yet, but it is clear that the center region will be standard.

3.2. Acceleration Region. Isochronism of the model is good enough to check the possibility of acceleration, but will be better at the last stage after we finally fix the design of the cryostat and of the superconducting coils. The beam has been accelerated in the 3D magnetic and 3D RF electric field maps with amplitudes of betatron oscillations of up to 3 mm. There were no losses of particles in any radius after the center region. No influence of any resonance was observed. We succeed in acceleration up to the very edge of the sectors of the cyclotron (see Fig. 10) which are cut along the trajectory and have a chamfer which helps with providing necessary increase of the field (see Fig. 1, left). Acceleration takes about 500 turns.

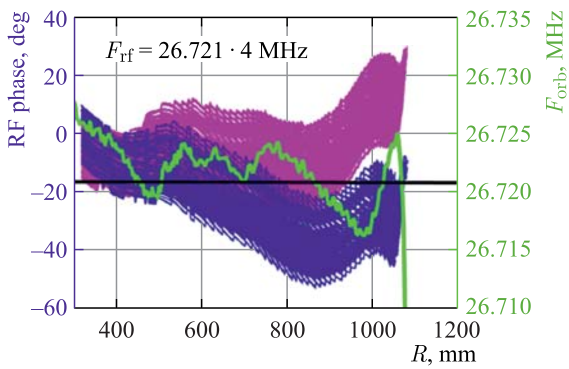

Fig. 10. Phase motion of the beam (blue line — in the convex gap, magenta — in the concave gap of the cavities)

3.3. Extraction. Simulations show that the extraction can be carried out by a deflector with 130–150 kV/cm electric field (in the valley), and we will need to use two magnetic channels MC1 and MC2 focusing the beam in the horizontal plane. The deflector can be placed in the valley with shortened cavity. MC1 should be placed close to the sector just after the electrostatic deflector at an azimuth of 95° and MC2 at an azimuth of 140° (see Fig. 11) to conserve beam quality and achieve horizontal focusing. Focusing of the beam in the vertical plane is provided by a drop of edge magnetic field. The collimator and quadrupoles can be used to match the beam parameters with requirements imposed by a transport system after exit from the cyclotron.

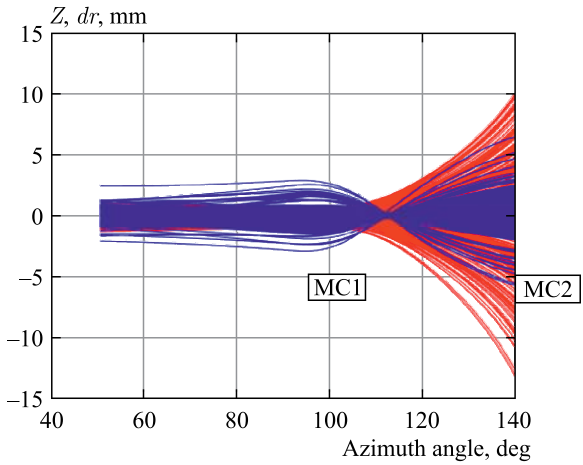

Fig. 11. Beam path through the ES deflector (50°–90°). Red lines — horizontal, blue lines — vertical motion. Suitable positions for gradient correctors are marked by MC1, MC2

Radial increase of the orbit due to acceleration is about 2 mm for the chosen magnetic field of the cyclotron and energy gain. We are examining the possibility of using a magnetostatic element with thickness of about 1 mm. In this case we will lose 20–50% of the beam, but we will avoid using an electrostatic deflector which is not very reliable device and needs maintenance.

CONCLUSIONS

We chose a low level of the magnetic field in the cyclotron and found out that dimensions of the cyclotron do not increase significantly if we use superconducting coils. Our cyclotron has about the same weight as Varian PROSCAN, which has the field level about one a half times greater than ours. The design of the cryostat and of SC coils is not finished yet, but it is rather moderate now and maybe finally their dimensions will be decreased.

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 four cavities and fourth harmonic of acceleration will provide 2 mm radial increase of the orbit due to acceleration. As a result, we can have efficient extraction with electrostatic deflector or we can apply a magnetostatic element.

High acceleration rate reduces tolerances to isochronism. The simplicity of shimming the iron is a great advantage not only for our cyclotron, but also for mass production. Computer simulation of the main systems of the SC230 cyclotron and beam dynamics has been performed. The technical design of the cyclotron can be finished in 2019.

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Издательский отдел Объединенного института ядерных исследований
141980, г. Дубна, Московская обл., ул. Жолио-Кюри, 6.
E-mail: publish@jinr.ru
www.jinr.ru/publish/