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JINR PROJECTS OF CYCLOTRON FOR PROTON THERAPY

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Abstract

The physical design of the compact superconducting cyclotron SC230 (91.5 MHz) has been performed. The cyclotron can deliver up to 230 MeV beam for proton therapy and medical and biological research. As the cyclotron will have a relatively small magnet field, it is possible to use both superconducting and resistive coil. Besides a superconducting cyclotron we simulate design of the cyclotron with a conventional copper water-cooled coil.

INTRODUCTION

Since 2016 the project of 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.

Recent developments of superconducting cyclotrons for proton therapy, such as SC200, Pronova [2], Sumitomo 230 MeV [3] share similar parameters that define the structure of the cyclotron. All projects are four-sector cyclotrons with ~3 T central field. Such parameters were chosen in pursuit of compact dimensions. None of those cyclotrons are yet in operation. It was, therefore, decided to rethink some design decisions after careful analysis of SC200, other projects and operating cyclotrons for proton therapy.

There are two most successful accelerators in the proton therapy: Varian Proscan [4], design proposal by H. Blosser et al. in 1993, and C235 (IBA Belgian) [5]. Both cyclotrons have much smaller central field, 2.4 and 1.7 T. First of all, we increased the pole of the cyclotron in order to decrease mean magnetic field to about 1.5 T in the center. Corresponding RF frequency for this value of the magnetic field is about 90 MHz at 4th harmonics operation mode. 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. Earlier [6] we reported design of the SC230 cyclotron with superconducting coil. Its parameters are recapitulated in Table 1.

Table 1: Parameters of the Cyclotron SC230

Parameter	Value
Magnet type	Compact, SC coil, warm yoke
Ion source	PIG
Final energy, MeV	230
Pole radius, mm	1350
Mean mag. field (center), T	1.5
Dimensions (height×diameter), m	1.7 × 4
Weight, tonnes	130
Hill/Valley gap, mm	50/700
A·Turn number	170 000
RF frequency, MHz	91.5
Harmonic number	4
Number of RF cavities	4
Voltage, center/extraction kV	35/90
RF power, kW	40
Number of turns	600
Beam intensity, μA	1.0
Extraction type	ESD

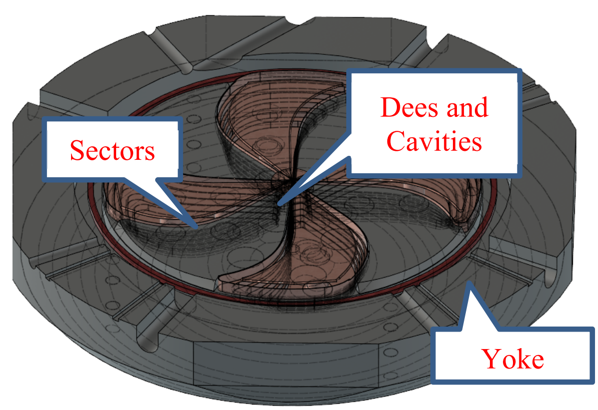

Figure 1: Layout of the cyclotron's 3D computer model (magnet and accelerating system).

SC-230 CYCLOTRON

Computer Simulations of the Magnet

Simulations were performed in CST studio [7] in the parametrized model of the magnet (see Fig. 1) created in Autodesk Fusion 360. The dimensions of the yoke (see 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. Average magnetic field and flutter from CST simulation are presented in Fig. 3.

Betatron tunes calculated with CYCLOPS-like code are presented in Fig. 4.

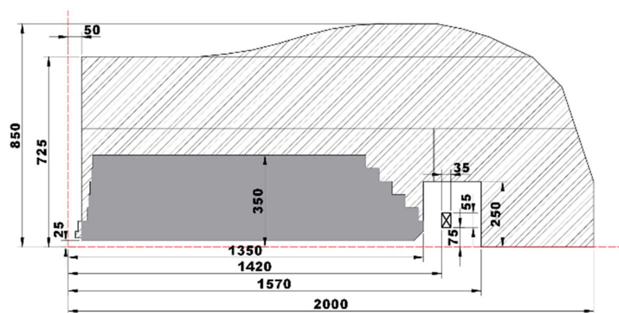

Figure 2: SC230 magnet yoke and SC coil general dimensions.

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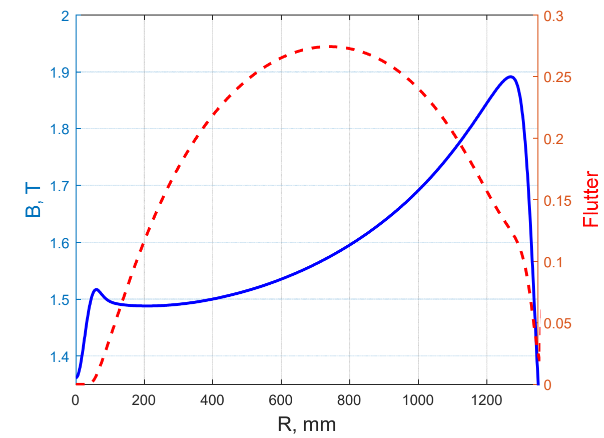

Figure 3: Average magnetic field and flutter along the radius.

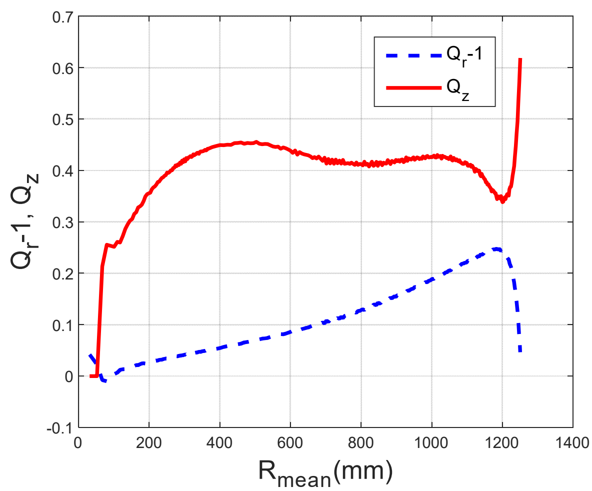

Figure 4: Vertical and radial betatron tunes in SC230.

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. 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].

Computer Model

The characteristic parameters of the half-wavelength coaxial resonant cavity with two stems have been obtained from simulation. The RF cavity resonator solution for the SC230 cyclotron can be seen in Fig. 5.

Azimuthal extension of the cavity (between middles of accelerating gaps) is about 40 degrees. 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. Suitable accelerating frequency and voltage along radius were achieved.

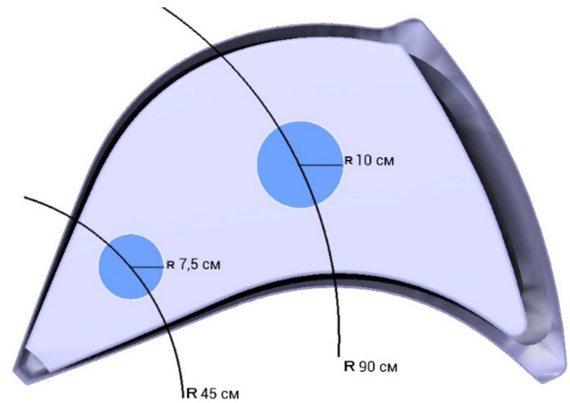

Figure 5: View of the model of the cavity.

Power Losses

Power dissipation in the model was calculated assuming the wall material is copper with a conductivity $\sigma = 5.8\text{x}10^7\ (\Omega\text{m})^{-1}$. 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.

Extraction from this cyclotron will be performed by electrostatic deflector. The height of the deflector is 50 mm, which makes it possible to place it in an axial gap between the sectors. The ESD voltage, required for extraction is just 100 kV/cm.

A CYCLOTRON FOR PROTON THERAPY RC240.

Magnet System

We simulate a cyclotron similar to the SC230 cyclotron, but with some changes optimizing the accelerator design with resistive coils (RC).

Relying on modern computing capabilities it is possible to design a cyclotron with resistive coils with sizes smaller than the leader of the proton therapy market C235 (IBA).

To have more compact design of the cyclotron with resistive coil the vertical gap between sectors needs to be as small as possible. In the proposed design the gap between the sectors is 15 mm, which resulted in a low current value in the coil, and the weight of the magnet was about 140 tonnes. It is important that the gap between sectors is constant, compared to IBA C235 design with elliptic gap, that decreases towards the extraction down to 9 mm. It is much easier and cheaper to manufacture and easier to control during installation. The diameter of RC240 is below 4 m, in order to simplify the logistics of the magnet. It is important for the cyclotron that needs to be delivered to the hospitals in different location to be fairly simple for the transportation. Therefore, each element of yoke is below 30 tonnes.

Table 2 displays the main RC240 parameters. Figure 6 shows the magnetic flux through the median plane.

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Table 2: Parameters of the Cyclotron RC240

Parameter	Value
Magnet type	resistive
Ion source	PIG
Final energy, MeV	240
Pole radius, mm	1350
Mean magnetic field (center), T	1.45
Dimensions (height×diameter), m	1.62 × 3.95
Weight, tonnes	140
Hill/Valley field, T	1.8/0.4
Hill/Valley gap, mm	15/700
A·Turn number	120 000
Magnet power consumption, kW	140
RF frequency, MHz	89
Harmonic number	4
Number of RF cavities	2
Voltage center/extraction, kV	50-110
RF power, kW	50
Turn number	800
Beam intensity, μA	1.0
Extraction type	ESD

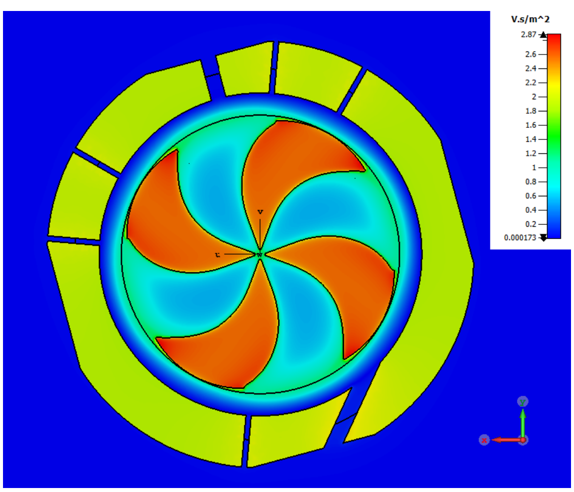

Figure 6: Magnet flux through median plane.

The number of A·Turn is 120000 and therefore it's power consumption is rather small 140 kW.

The average magnetic field and flutter from CST simulation is presented in Fig. 7.

The RC240 needs 2 times less A-turns in the coils compared to IBA C235, so we are able to use a much smaller coil cross-section. The RC240 coil is only 272x170 mm^2, and IBA C235 coil is about 600 x 500 mm^2. So even having much smaller field and bigger sectors radius, thanks to much smaller coil the overall size and weight of the RC240 is much smaller and it consumes less power.

Results of simulations of the magnetic field were exported to Matlab to be analysed with CYCLOPS-like code. Orbital frequency shows rather good isochronism of the field (see Fig. 8).

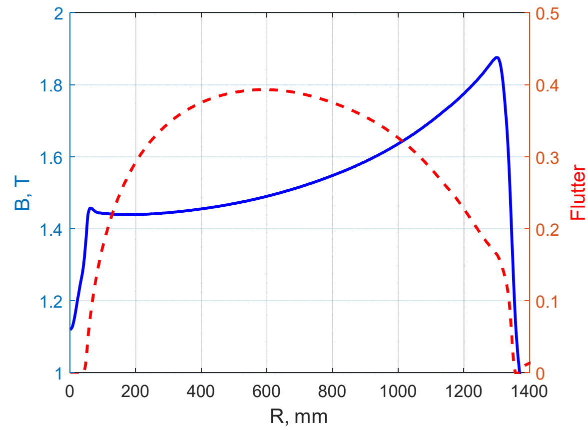

Figure 7: Average magnetic field and flutter along the radius.

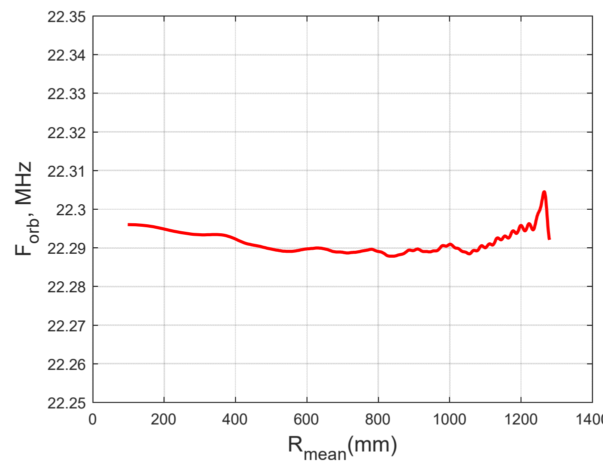

Figure 8: Orbital frequency.

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Results of simulations of the magnetic field were exported to Matlab to be analysed with CYCLOPS-like code.

Figure 9 shows that working point does not cross dangerous resonances. This cyclotron has different path of the working point. In both IBA C235 and Varian as well as in projects with 3 T magnetic field (SC200, Sumitomo and Pronova) Q_z (vertical tune) stays below 0.5. In case of the RC240 the flutter is too high, so we immediately “jump” over Qz = 0.5 and stay over the Qr = 2Qz resonance. Particle tracking in realistic 3D electric and magnetic fields have been performed in order to prove that such unconventional path is indeed ok.

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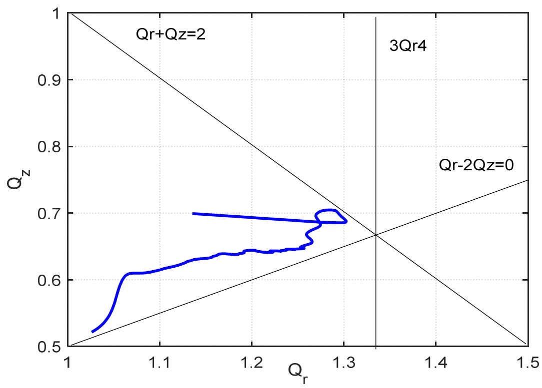

Figure 9: Working diagram.

Accelerating System

Two RF cavities are located at the opposite valleys of the magnet. Accelerating RF cavities will operate at 89 MHz (acceleration on the 4th harmonic mode). Space in the valley is enough to place cavities with azimuth extension about 40 degrees.

The characteristic parameters of the half-wavelength coaxial resonant cavity with two stems have been obtained from simulation in CST studio. Quality factor of the cavity is about 14000.

RF cavities will be connected in the center, can be equipped with an inductive coupling loop and will be adjusted by capacitance trimmers.

Extraction from this cyclotron will be performed by ESD placed in empty valley. The ESD voltage, required for extraction is about 100 kV/cm.

As a result, we have a design of both options of cyclotron with:

- Low power consumption.
- High quality of the beam.
- Minimum engineering efforts and challenges.
- Reasonable size and weight.

CONCLUSION

We chose a low level of the magnetic field in the cyclotron and found out that dimensions of the cyclotron can be reasonable. Low magnetic field will provide efficient extraction with electrostatic deflector. The superconducting option is lighter, consumes less power, has bigger gap between poles, however superconducting coil is more expensive to build and to run. Both options are great candidates for JINR to be used for medical research program.

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