Design of SC230 - the new cyclotron for proton therapy

ASIPP

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Abstract

SC230 a 230 MeV superconducting cyclotron designed in JINR. It is intended to be developed as a joint project with ASIPP. The cyclotron is designed for proton therapy and biomedical research. This presentation focuses on the results of the conceptual design of the accelerator. In the process of physical design, simulations of the magnetic and RF systems were carried out, the main characteristics of the accelerator were established. Magnetic field was isochronized with sufficient precision, as well as yoke mechanical stress simulation was performed. Beam tracking was conducted to determine whether the quality of the extracted beam is in accordance with project requirements.

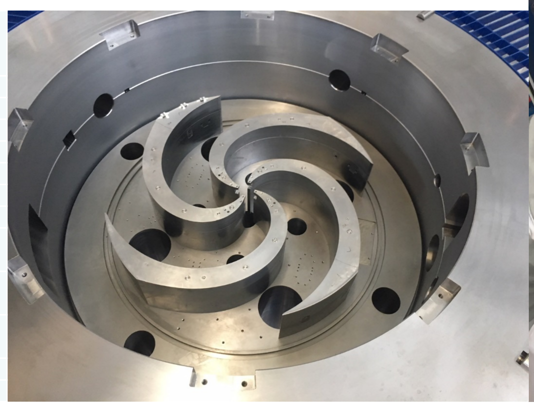
Introduction

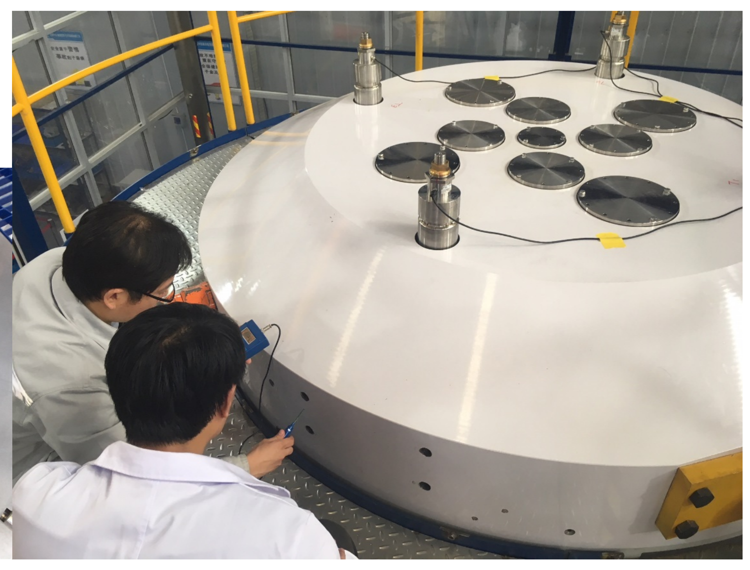
The 660-MeV proton accelerator (Phasotron) operates at the JINR's Medico-Technical Complex for 70 years. It is outdated and worn out. Replacement - a new isochronous cyclotron SC230 will be used for further medico-biological research and for patient treatment.

Since 2016 the SC200 superconducting cyclotron has been jointly developed by JINR and ASIPP (Hefei, China) [1]. The production of the cyclotron faced a lot of engineering challenges due to high magnetic field of the accelerator. Therefore in SC230 project we decide to rethink some design decisions after careful analysis of SC200, other projects and operating cyclotrons for proton therapy.

SC200 Cyclotron

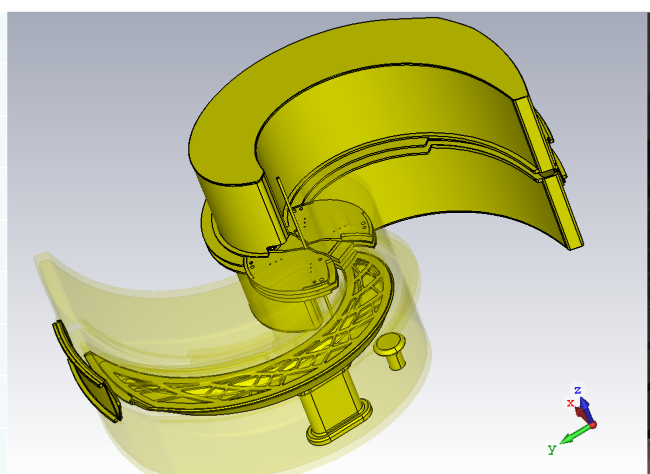
Magnet type	Compact, SC coil, warm yoke
Pole diameter (m)	1.22
Magnet diameter (m)	2.5
Magnet height (m)	1.7
Hill gap, max/min (m)	0.04-0.01
Valley gap, max/min (m)	0.3
Yoke material	St.1010
Extraction radius (m)	0.6
Average magnetic field ($R_o/R_{extr.}$) (T)	3.0/3.6
Excitation current (1 coil) (A*turns)	750 000
Magnetic field in the coil (T) max.	4.5
Cryostat and coils weight (t)	5
Total magnet weight (t)	55

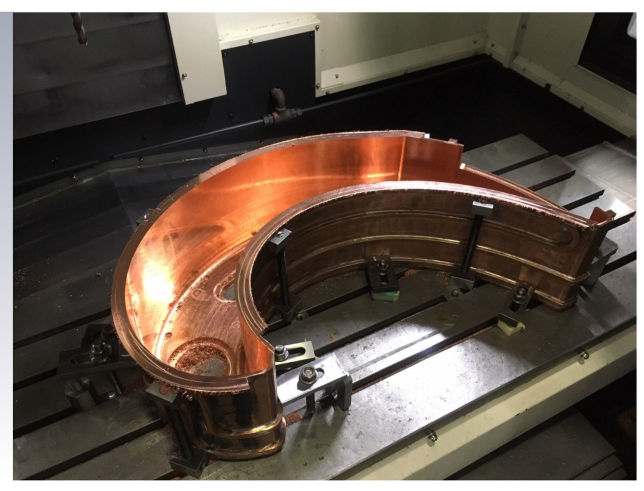




SC200 is an isochronous superconducting compact cyclotron. Superconducting coils is enclosed in cryostat, all other parts are warm. Internal ion source of PIG type is used. It is a fixed field, fixed RF frequency and fixed 200 MeV extracted energy proton cyclotron. Extraction is organized with an electrostatic deflector and magnetic channels. For proton acceleration we use 2 accelerating RF cavities, operating on the 2nd harmonic mode [2]. The estimate total weight is about 60 tons and extraction radius is 60 cm. Average magnetic field is up to 3.5 T and the particle revolution frequency is about 45 MHz.

RF cavities	warm
Number of cavities	2
Operating frequency, MHz	90
Harmonic number	2nd
Radial extension of the cavity, m	0.63
Radial extension of the dee, m	0.61
Number of stems	1
Diameter of the stem, m	0.09
Radial position of the stem, m	0.398

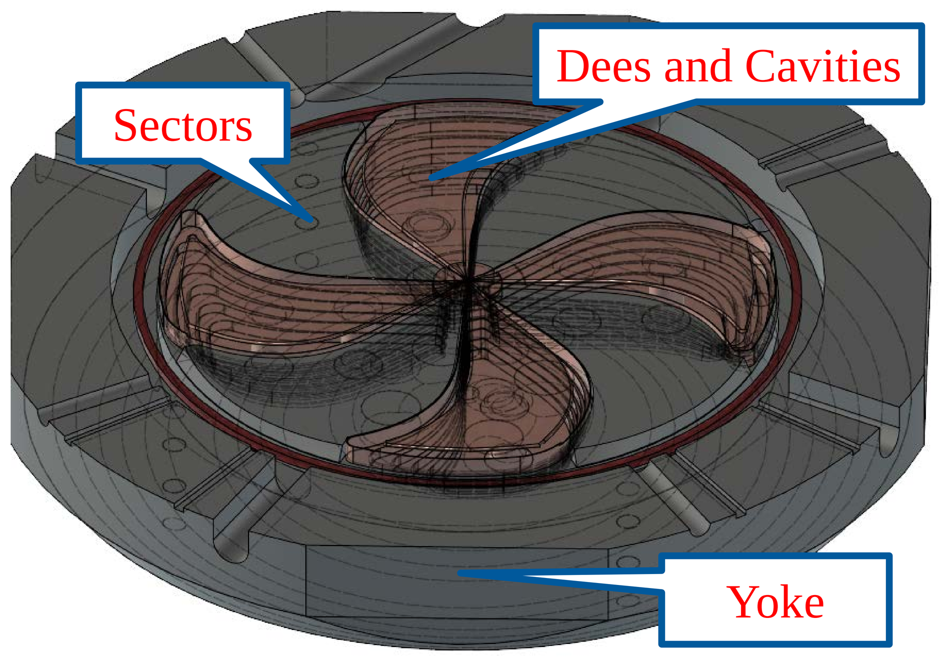




The proton beam with energy 200 MeV can irradiate all of the tumor localizations with a maximum depth of 25 cm. SC200 cyclotron will also be used for eye melanoma treatment at energies 60-70 MeV after degrading beam energy.

SC230 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



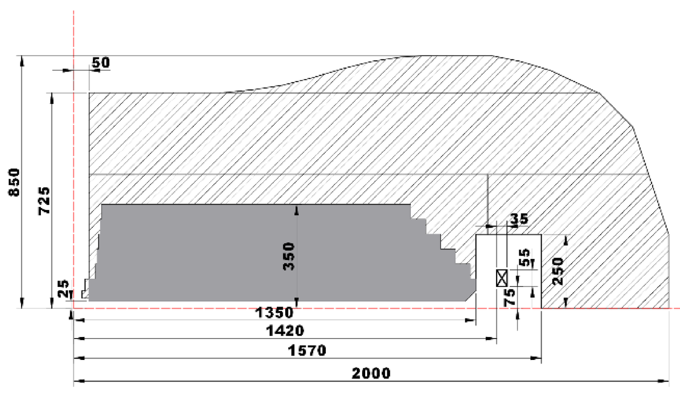
Conceptual design of the SC230

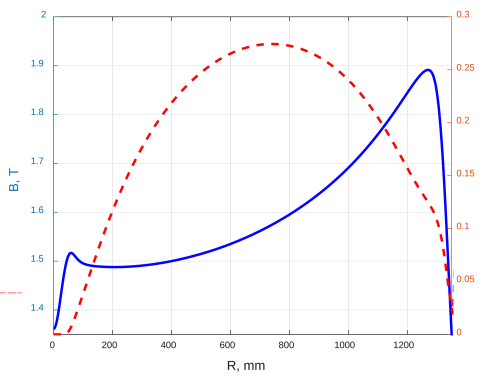
Our design combines advantages of both successful accelerators: low magnetic field and fourth harmonic (IBA C235 cyclotron [3]), four accelerating cavities and superconducting coils (Varian PROSCAN [4]).

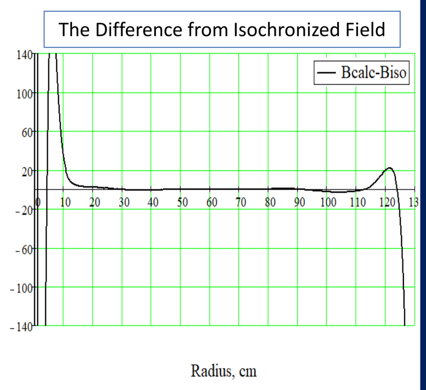
We increased the pole in order to decrease mean magnetic field to ~1.5 T in the center. Corresponding frequency for this value is 91.5 MHz, as in SC200. It is possible to use both superconducting and resistive coil. We plan to use NbTi; however, we are researching the possibility of using high-temperature superconductor [5].

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.







Magnet design

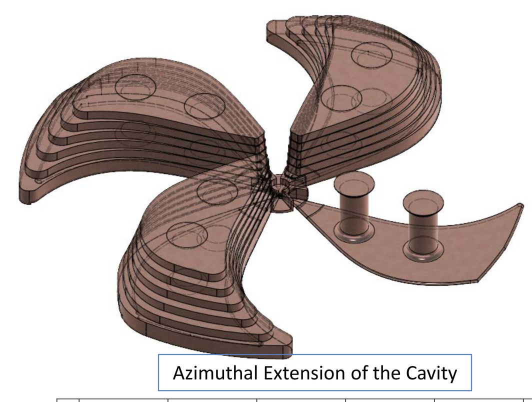
The dimensions of the yoke were chosen to restrict the magnetic stray field in the range of 200-300G just outside accelerator, providing full saturation of the iron poles and yoke.

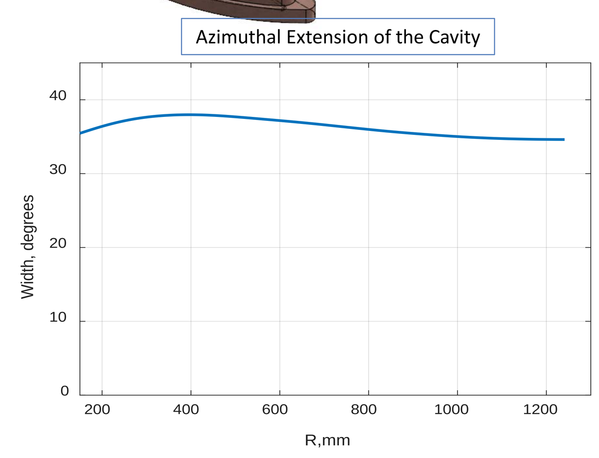
Frequency, MHz	91.5
Harmonic number	4
Number of cavities	4
Power losses, kW (total)	43
Q-factor	13800
Voltage center/extraction, kV	35/95

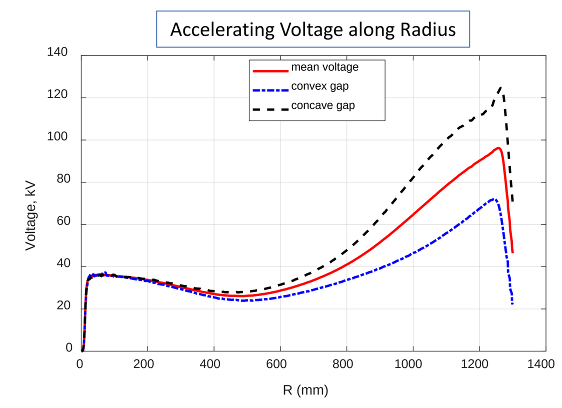
Accelerating system design

We design 4 accelerating RF cavities connected in the center, working on approximately 91.5 MHz, operating on the 4th harmonic mode. Cavities can be equipped with an inductive coupling loop and will be adjusted by capacitance trimmers like in SC200 [2]. Suitable accelerating frequency and voltage along radius were achieved.

Assuming the wall material is copper with a conductivity σ = 5.8 *107 1/(Ωm), the quality factor is calculated to be ~13800 and power losses of all cavities are: for storage energy 1 joule, voltage in the center/extraction 35-95 kV, thermal losses are 43 kW.







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.

References

[1] G.Karamysheva, et al., Present Status of the SC202 Superconducting Cyclotron Project, VIIIth Interna-tional Particle Accelerator Conference (IPAC 2017), Copenhagen, Denmark, THPVA120.

[2] Gen Chen et al., Research and development of RF System for SC200 Cyclotron, 9th International Parti-cle Accelerator Conference, IPAC18, Vancouver, BC, Canada.

[3] J. Schippers, R. Dölling, J. Duppich, G. Goitein, M. Jermann, A. Mezger et al., "The SC cyclotron and beam lines of PSI's new proton therapy facility PROSCAN", Nucl. Instr. and Meth., vol.B(261), p.773, 2007.

[4] K. Kamakura, Design of a High Temperature Super-conducting Magnet for Next Generation Cyclotrons, Doctoral Dissertation, 2019, Japan, http://www.rcnp.osaka-u.ac.jp/~keita/phd_progress/phd_progress.pdf

[5] D. Vandeplasche et al., Extracted beams from IBA's C235, Proceedings Particle Accelerator Conference, 1997, V.1.

Codes used: CST (https://www.cst.com), Autodesk (https://www.autodesk.com/products/fusion-360/overview) , MATLAB.