DESIGN STUDIES OF A COMPACT SUPERCONDUCTING CYCLOTRON FOR PROTON THERAPY

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Abstract

The ASIPP (Hefei, China)-JINR (Dubna, Russia) collaboration is developing a superconducting cyclotron SC200 for proton therapy. The cyclotron will provide acceleration of protons up to 200MeV with maximum beam current of 1 µA. In 2015 Institute of Plasma Physics, Chinese Academy of Sciences, ASIPP, (Hefei, China) and Joint Institute for nuclear research, JINR (Dubna, Russia) started collaboration to develop a superconducting cyclotron for proton therapy. The first prototype of SC200, tuned and tested in Dubna, will remain at JINR and will be used for further research and development of cancer therapy by protons. The results of testing will be used by ASIPP for a serial SC200 manufacturing.

The 200 MeV final energy has been chosen for this accelerator based on statistics for China for necessary depth of treatment and experience of work of the medical department in Laboratory of Nuclear problems on the base of JINR Phasotron. Mean magnetic field will be in the range of 2.9T-3.5T (center-extraction).

The results of conceptual design study of a 200 MeV superconducting isochronous cyclotron are presented. Computer modeling results for the magnetic, accelerating and extracting systems are given. Simulations of the beam dynamics are also presented.

INTRODUCTION

SC200 is an isochronous superconducting compact cyclotron. Superconducting coils will be enclosed in cryostat, all other parts are warm. Internal ion source of PIG type will be used. It is a fixed field, fixed RF frequency and fixed 200 MeV extracted energy proton cyclotron. Extraction will be organized with an electrostatic deflector and magnetic channels. Currently for proton acceleration we are planning to use 2 accelerating RF cavities, operating on the 4-th harmonic mode.

SUPERCONDUCTING (SC) MAGNET SYSTEM OF CYCLOTRON SC-200

Preliminary conceptual designs of SC magnet and cryogenic system are finished. Main parameters are presented in Table 1.

Figure 1: View of the SC200 Cyclotron.

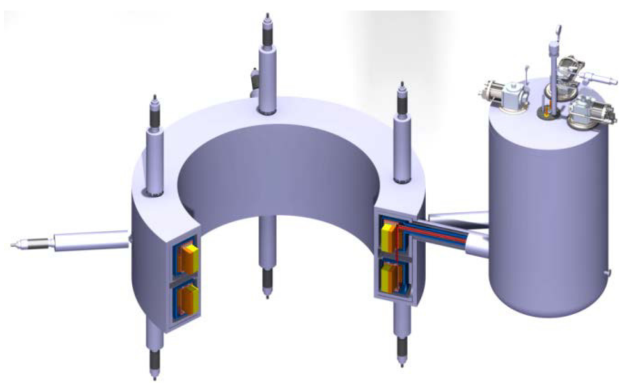

Figure 2: View of the SC coil and cryogenic system.

Table 1: The Parameters of Refrigerator

Cooling method	immersion
GM refrigerator	3
50K thermal shield	3*45W @50K
Thermal coupling with magnet	Thermal siphon

The simulation and design of the SC-200 magnetic system is based on its main characteristics:

- Four-fold symmetry and spiral sectors
- Deep-valley concept with RF cavities placed in the valleys
- Pole diameter less than 150 cm.

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- Average field ($R_{extraction}$) ~ 3.5 T.
- Magnetic induction inside yoke less 2-2.3 Tesla.
- Magnet (yoke) weight less 30 tons
  During the magnet simulation the following design goals should be achieved:
- Optimization of the magnet sizes.
- Realization of the vertical focusing (Qz) at the extraction region as close to 0.4 as possible (to decrease the vertical beam size and minimize the median plane effects).
- Keeping optimal value of the spiral angle of the sectors (minimize total sectors phase angle change).
- Average magnetic field shaping by variation of the sectors azimuth width and by pole profiling.
- Minimization iron weight, keeping the stray field at an acceptable level.
- Avoiding dangerous resonances.
- Optimal solution for SC coil design.
- Realisation of optimal design of electrostatic and magnetic elements for the extraction channels.

The magnet modelling has been performed in 2D POISSON code and 3D ANSOFT MAXWELL one. VECTOR FIELDS TOSCA software [1] will be used for future optimization of the magnet design.

The sectors of the computer model have the edge radius 62 cm. The average line of the sector is the Archimedes spiral φ=R(cm)/25. The vertical sectors gap is described by the ellipsis with semi axis of 3/62 cm and cut at the edge at the distance of 0.75 cm from median plane. The magnet's main parameters are presented in the Table 2.

Table 2: Parameters of the Magnet System of the SC200 Cyclotron

Magnet type	Compact, SC coil, warm yoke
Pole diameter ,m	1.24
Magnet diameter, m	2.2
Magnet height, m	1.22
Hill gap, m	0.06-0.015
Valley gap, m	0.6
Yoke material	St.1010
Yoke weight, t	25
Extraction radius, m	0.6
Average magnetic field ($R_o/R_{extr.}$),T	2.9/3.5
Excitation current (1 coil), A*turns	1 000 000
Excitation current density, A/mm^2	70
Magnetic field in the coil (max), T	4.5
Cryostat and coils weight, t	5
Total magnet weight, t	30

Profiling of the pole shape and vertical profile of the sectors was used to shape the required isochronous magnetic field. The magnet's computer model after realization of these steps is shown in Fig.3.

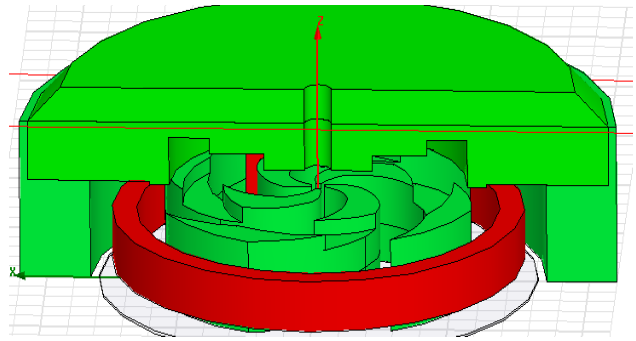

Figure 3: Computer model of the magnet with profiling its geometry.

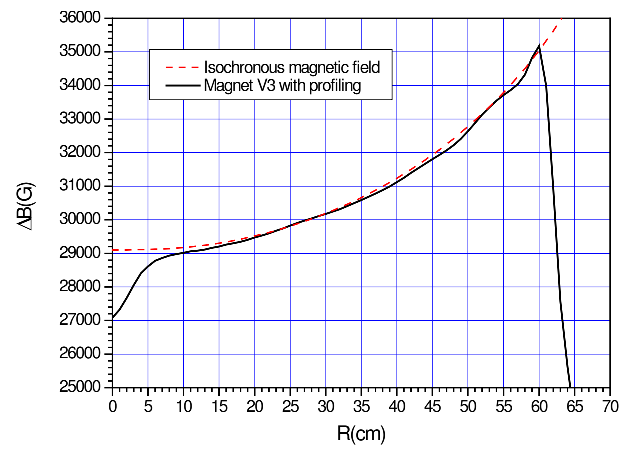

Figure 4: Magnetic field for the model with profiling pole and sectors.

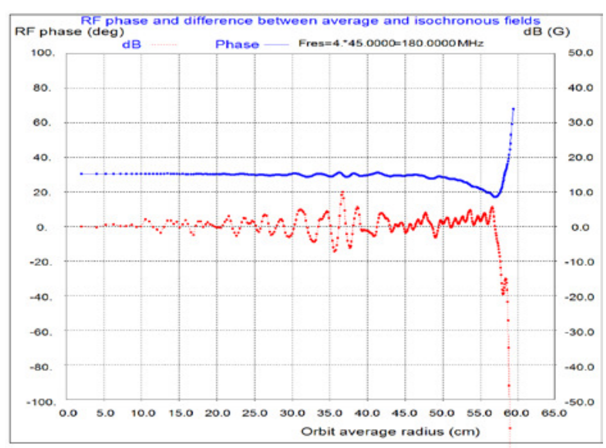

Figure 5: RF phase of the central proton during acceleration and difference between used average field and exact isochronous field.

The difference between fields was calculated using a deviation of proton orbital frequency from the resonance value 45 MHz. Starting phase 30ºRF was assumed in order to provide the beam axial focusing in central region of the cyclotron. The code PHASCOL [2] was used for particle dynamics simulation.

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ACCELERATION SYSTEM

Magnetic field modelling and beam dynamics have determined orbital frequency of the ions equal to about 45 MHz. To operate on 4-th harmonic, the RF system has to achieve frequency of 180 MHz. We are planning to use two normal conducting RF cavities for ion beam acceleration in the SC200 cyclotron.

The geometry of the RF cavity is restricted by the size of the valley of the magnet. We have fitted the double gap delta cavity inside the valley of the magnet. Azimuth extension of the cavity (between middles of accelerating gaps) is 45 degrees. We have chosen the accelerating gap to be equal to 7 degrees, and not less than 5mm in the center, where 7 degrees is less than 5mm to avoid the sparking.

Main parameters of the RF system are presented in Table 3.

Table 3: Parameters of Accelerating System

RF cavities	warm
Number of cavities	2
Operating frequency, MHz	180
Harmonic number	4^{th}
Radial dimension, m	0.62
Vertical dimension, m	0.6
Number of stems	3

As the first step of our simulations we have used COMSOL Multiphysics RF module [3] to simulate the cavity. In the future in order to improve the accuracy of simulations and to avoid possible numerical errors we will use several software packages such as CST Microwave studio [4] and ANSYS [5]. To check if the 180 MHz frequency can be achieved with such geometry of the valley we have decided to build a model with 3 stems (see Fig.6). Similar cavity design [6] was proposed for the project of the superconducting cyclotron C400 [7] for hadron therapy.

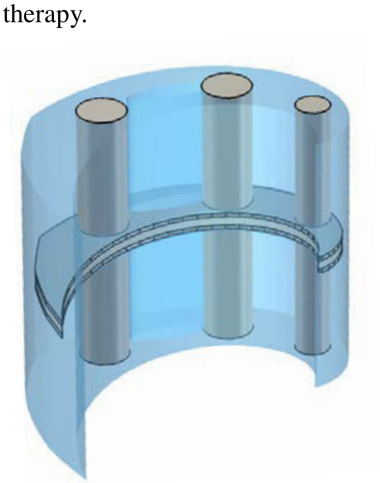

Figure 6: View or the RF cavity computer model.

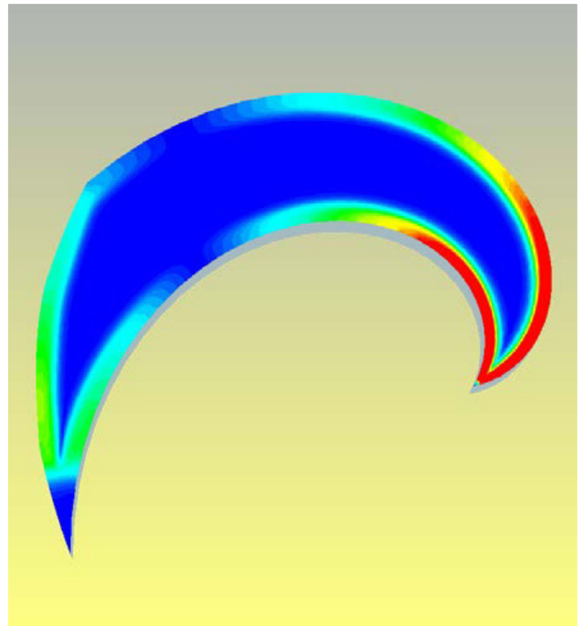

Figure 7: Electric field distribution in the median plane.

Frequency of the cavity with 3 stems reaches 186 Mhz. However the work still has to be done to optimize the field distribution, to optimize number of stems, their sizes, shapes and positions.

CONCLUSION

The work on design of the proton superconducting cyclotron SC200 continues. Manufacturing of SC200 systems and elements will be done during the 2017. Assembling, tuning and testing SC200 should be finished in 2018.

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