PROGRESS IN DESIGN OF MSC230 SUPERCONDUCTING CYCLOTRON FOR PROTON THERAPY

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Abstract

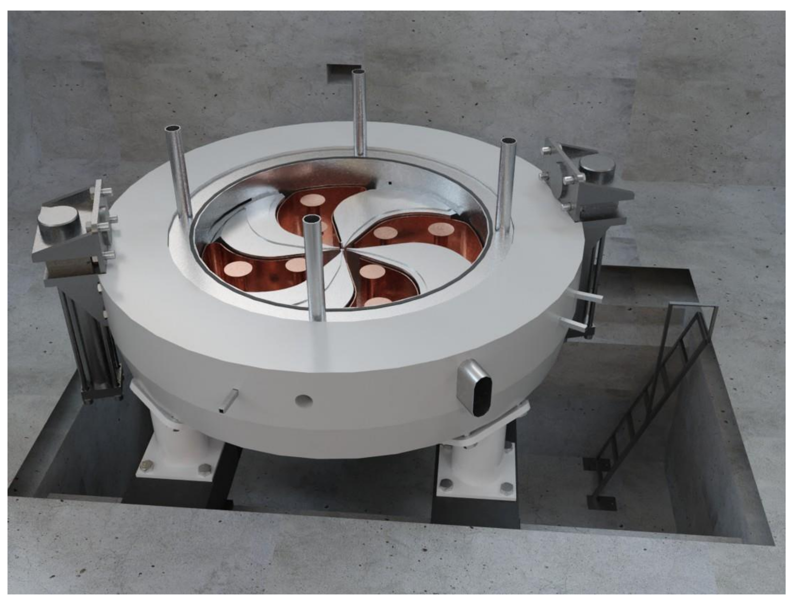
The current status of the MSC230 superconducting cyclotron designed for biomedical research is presented. MSC230 is an isochronous four-sector compact cyclotron with a magnetic field in the center of 1.7 T. Acceleration is performed at the fourth harmonic mode of the accelerating radio-frequency (RF) system consisting of four cavities located in the cyclotron valleys. The accelerator will use an internal Penning type source with a hot cathode. Particular attention is paid to extraction, as it must have a high extraction efficiency.

Introduction

Recent studies of a promising new method, called FLASH [1-2], have shown that it has great potential for expanding the use of proton therapy on tumors that previously could not be treated with protons, at the same time significantly improving the quality of treatment. Compared to radiation therapy at a conventional dose rate (1–7 Gy/min), FLASH irradiation is performed at a dose rate over 50 Gy/s in less than 0.5 seconds. Healthy tissue is better able to withstand FLASH radiation, while the level of damage to the tumor is the same as with conventional treatment.

However, before proton FLASH therapy can be fully implemented in practice, it is necessary to solve several engineering and technical challenges. More particularly, there is a need in an accelerator that provides a high average beam current, which, according to various estimates, is 0.5-100 μA for the entire range of energies used in treatment.

The task of the FLASH research makes relevant the creation of a research and innovation center at JINR equipped with a modern proton accelerator, a beam delivery system and laboratory equipment for biomedical research.



View of the MSC230 cyclotron model

General properties	
Accelerated particles	Protons
Magnet type	SC coils, ‹‹warm›› yoke
Injection	Internal source
Number of turns	500
Beam Parameters	
Energy, MeV	230
The relative error of the proton beam energy, %	0.15
Extracted beam intensity (continuous mode), nA	2-1000
Extracted beam intensity (flash mode), nA	5000-10 000
Emittances of the extracted beam, π*mm*mrad Radial Vertical	 8 2
Magnetic system	
Average magnetic field ($R_o/R_{extr.}$), T	1,7/2,15
Dimensions (height × width), m	1,7 × 3,9
Magnet weight, tonne	~130
Hill/valley gap, mm	50(25)/700
Excitation current (1 coil) , A*turns	270 000
Accelerating system	
Frequency, MHz	106.5
Harmonic number	4
Number of cavities	4
Power losses, kW (total)	60
Voltage center/extraction, kV	40/120
Extraction	
Extraction radius, m	1.08
Extraction system	ESD+2MC

MAGNET SYSTEM

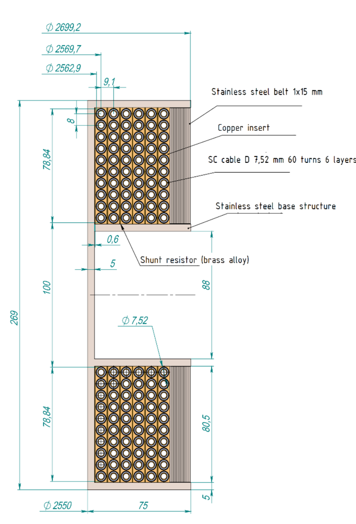
The MSC230 magnet is composed of a superconducting (SC) solenoid and an iron yoke. The technology with the use of a hollow composite SC cable, proposed at JINR and well-proven in the magnets of the Nuclotron synchrotron, was chosen as the basis for the manufacture of the solenoid. JINR has a base for the production of such a cable, which requires only the modernization of the existing equipment.

Work on the superconducting cyclotron system is currently being actively pursued. The MSC230 cyclotron cryogenic system is designed for creating a magnetic field in the cyclotron magnet yoke structure. Its main components are shown in Figure below. The main technical characteristics of the cryogenic system are presented in Table.

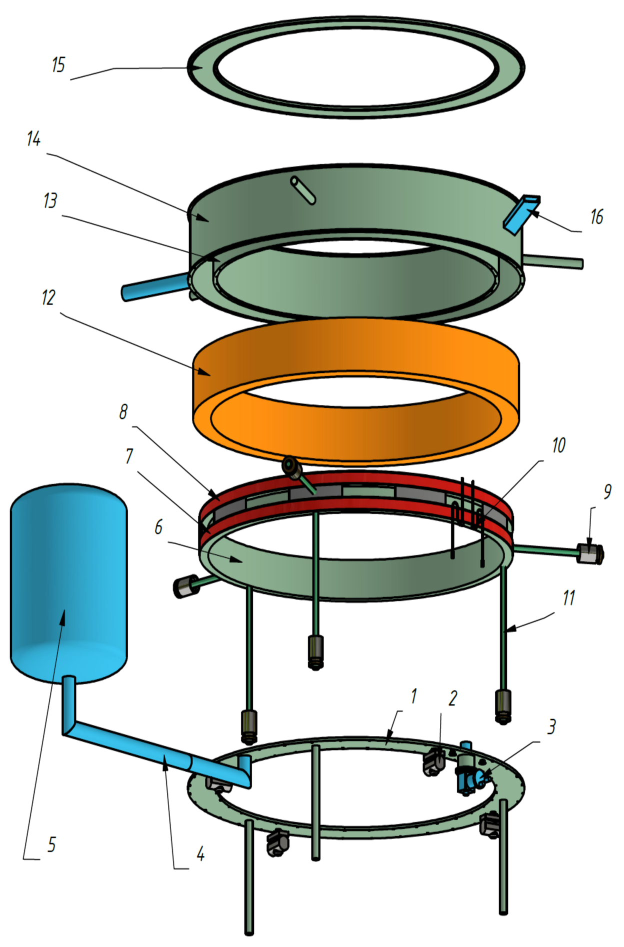
The vacuum vessel (cryostat) is connected to all supply and coolant lines, as well as to the solenoid support system. The vacuum vessel consists of a bottom cover (1), top cover (15), inner (13) and outer (14) cylindrical shells bolted to each other. The distinctive feature of the chosen design concept is detachable top and bottom covers that allow accessing the cryostat internal space for repair and maintenance purposes. The cryostat vacuum space is separated from the cyclotron and the beam output pipe (16) space.

The solenoid structure consisting of the stainless steel base structure (6), two superconducting coils (7,8), and HTSC current leads (10) is placed in the copper heat shield (12) and rests on the support system including three axial (11) and three radial rod supports. Each rod support is equipped with a differential thread adjusting device (9) and an electrical actuator as an option. The heat shield is cooled down to the liquid nitrogen temperature by four cryocoolers (2) and by liquid nitrogen as a standby support system. The current leads are cooled by the cryocooler (3). The solenoid structure cross-sectional view is presented in Figure below.

The refrigerator (5) provides both solenoid and heat shield cooling systems supply with liquid helium and nitrogen. The liquid helium and liquid nitrogen supply pipelines, as well as the return ones, are placed in the vacuum tunnel (4) equipped with an internal heat shield cooled by liquid nitrogen.



Solenoid structure cross-sectional view with dimensions (mm).



Cryogenic system exploded view (see the text description for the numbered parts).

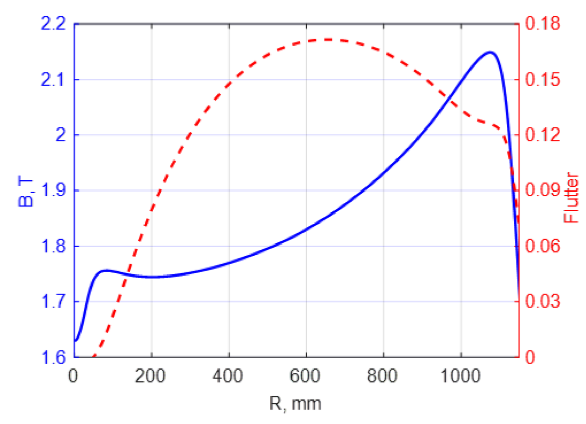
Cryogenic system main technical characteristics

Parameter name	Measure unit	Value
Solenoid inner diameter	m	2.55
Solenoid outer diameter	m	2.70
Number of coils	pcs	2
Distance between coils	m	0.1
Solenoid height	m	0.28
Maximum magnetic field induction in the aperture gap	T	2
SC coil conductor	Cu + Nb-Ti	
Insulating vacuum space pressure	Pa	$\leq 1 \times 10^{-3}$
Operating current	A	500
Interaction force between coils	kN	420
Axial support load	kN	100
Radial support load	kN	50

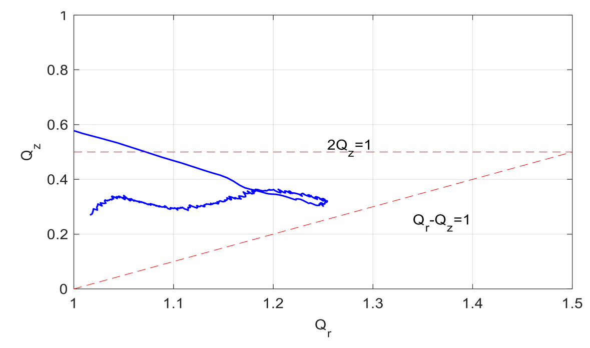
The simulation in CST studio of the MSC230 magnetic system was based on its main characteristics:

- Four-fold symmetry and spiral sectors
- Deep-valley concept with RF cavities placed in the valleys
- Pole radius = 118 cm
- Stray magnetic field in the 200 Gs range near the accelerator

The following mechanical model is proposed:
The disk plate must have a hole for the vacuum o-ring with the cryostat;
2 lifting jacks for yoke opening;
4 numbers of feet;
Technological holes.



Average magnetic field and flutter along the radius.



Working diagram

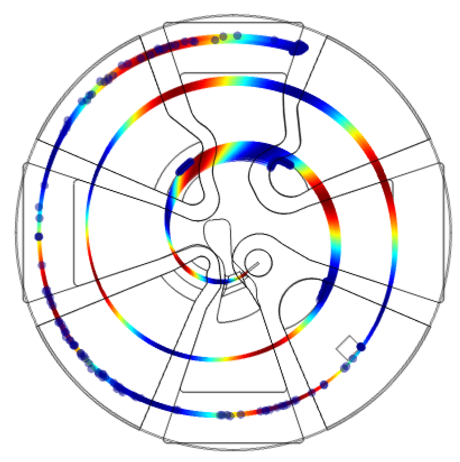
ACCELERATING SYSTEM DESIGN

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 har-monic mode. 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 centre and will be working on approximately 106.5 MHz frequency.

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

Suitable accelerating frequency and voltage along radius were achieved.

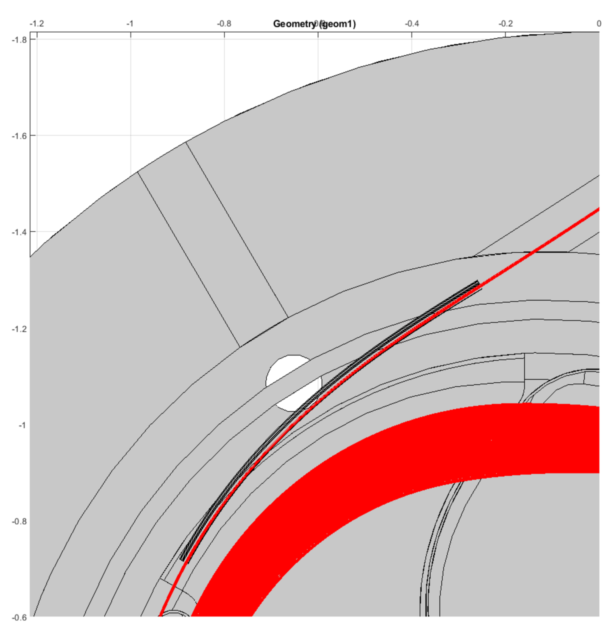
CENTER REGION



Beam trajectories in the optimized center (Comsol). Color indicates RF phase.

To provide vertical focusing, we create a bump (radial gradient) of the magnetic field (80-100 Gauss) .
Magnetic focusing caused by the decreasing magnetic field begins after a radius R = 30 mm.
For R< 30 mm: accelerating electric field provides vertical focusing of lagging particles.
In the central region, two collimators should be placed, limiting the amplitude of vertical oscillations to 2-3 mm.
Form of dee tips in the center region was optimized. Beam quality and transmission were improved see [3] this conference.

EXTRACTION SYSTEM



The beam tracing in the cyclotron structure.

The beam extraction for this machine will be carried out by means of 1 electrostatic deflector (ESD), located between the sectors, and 2 passive focusing magnetic channels (MC1 and MC2). We restricted electric field in deflector by the value of 100 kV/cm.

The beam, after being pulled with the deflector, passes through the accelerating RF-cavities and magnetic channels. Passive magnetic channels are located inside sector's gap, the first one decreases the average magnetic field for 600 Gs and provides gradient of 1000 Gs/cm, the second one only provides a gradient of 1700 Gs/cm.

The beam tracing though the extraction system was performed in 3D magnetic field maps which were calculated taking into account the magnetic channels and the compensating channels.

The calculated horizontal emittance at the accelerator's exit is about 8π mm mrad, whereas the vertical one is about 2π mm mrad. See more [4] this conference.

Conclusion

The cyclotron design includes conservative and proven solutions that reduce risks and simplify engineering challenges. The MSC230 accelerator will be a source of an intense proton beam for the Medical Technical Complex of DLNP, JINR.

The technical design and production of the main cyclotron systems began at Efremov Institute of Electrophysical Apparatus, St.-Petersburg.

References:

[1] A.Patriarca, FLASH Radiation Therapy: Accelerator Aspects, 11th International Particle Accelerator Conference, IPAC 2020, Caen, France.

[2] S. Jolly et al., Technical Challenges for FLASH Proton Therapy, International Conference on Medical Accelerators and Particle Therapy, Seville, Spain 2019.

[3] Malinin V., The design of the center region of MSC230 cyclotron, THBO06, this conference

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