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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.

An isochronous cyclotron cannot compete with synchrocyclotrons in dimensions and weight, but a cyclotron accelerates a quasi-continuous beam, therefore, it is the most promising accelerator for the application of a new method of radiation therapy - flash.

The MSC230 cyclotron [3] can produce a 230 MeV proton beam for therapy and biomedical research. Table 1 shows the main parameters of the MSC230 cyclotron. We plan to get about 10 μA of beam current in our cyclotron to study the efficiency of the flash method.

Figure 1 shows the interior of the magnetic and accelerating systems of the cyclotron.

Table 1: MSC230 Cyclotron Main Parameters

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, (2σ)	
Radial	8
Vertical	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	40/100
Extraction	
Extraction radius, m	1.08
Extraction system	ESD+2MC

Figure 1: View of the MSC230 cyclotron model.

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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.

The simulation in CST studio of the MSC230 magnetic system (see working diagram in Fig. 2) 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.

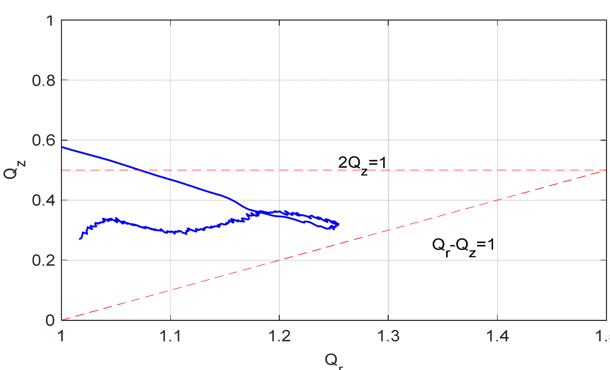

Figure 2: Working diagram.

The size of the vertical gap between the sectors is constant along the radius and is 50 mm, which is sufficient to accommodate the electrostatic deflector. To ensure the growth of the mean field in the extraction zone, we set the shape of the chamfer of the sector edge not around a circle centered at the geometric center of the cyclotron, but along the shape of the trajectory of the accelerated particles, which differs from the circle the more, the higher the flutter of the magnetic field. Another feature that serves this purpose is the "double sector" - part of the sector has a smaller vertical gap between the sectors, while maintaining enough space for the deflector (see Fig. 3).

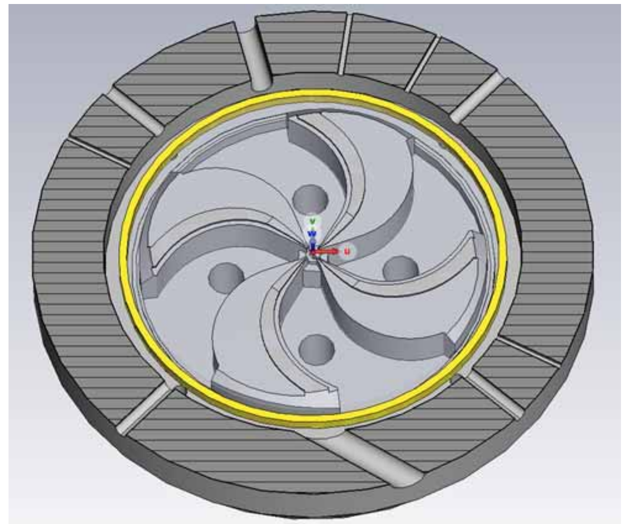

Figure 3: Magnet of the cyclotron MSC230.

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. 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 (see Fig. 4). Suitable accelerating frequency and voltage along radius were achieved.

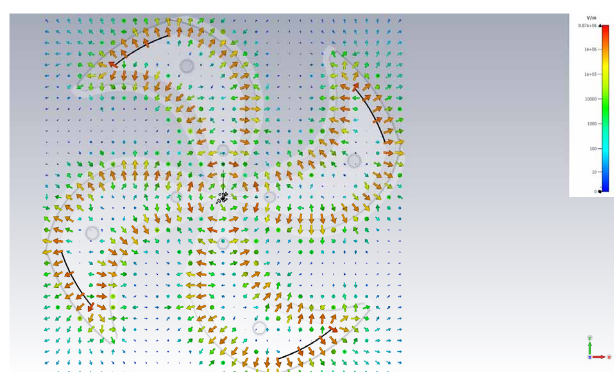

Figure 4: Electric field distribution.

CENTER REGION

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, a collimator 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 coefficient were improved (see Ref. [4]).

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Comsol was used to simulate particle trajectories in the center (see Fig. 5). Comsol has the possibility to account for losses of accelerated particles on the accelerator walls. Blue circles show particles at the end of the tracking (it is assumed that when colliding with elements of the cyclotron structure the particles stop, which allows to see the place of loss of particles.

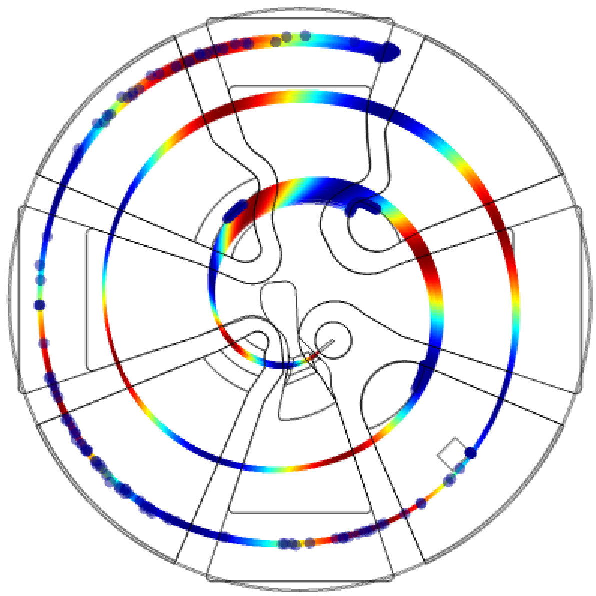

Figure 5: Beam trajectories in the optimized center (Comsol). Color indicates oscillation phase of the accelerating system.

EXTRACTION SYSTEM

The low magnetic field together with the high acceleration rate due to 4 resonators and the fourth harmonic mode will allow efficient extraction by means of an electrostatic deflector (ESD), located between the sectors, and 2 passive focusing magnetic channels (MC1 and MC2) [5]. 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 (Fig. 6).

The calculated horizontal emittance at the accelerator's exit is about 8π·mm·mrad, whereas the vertical one is about 2π·mm·mrad.

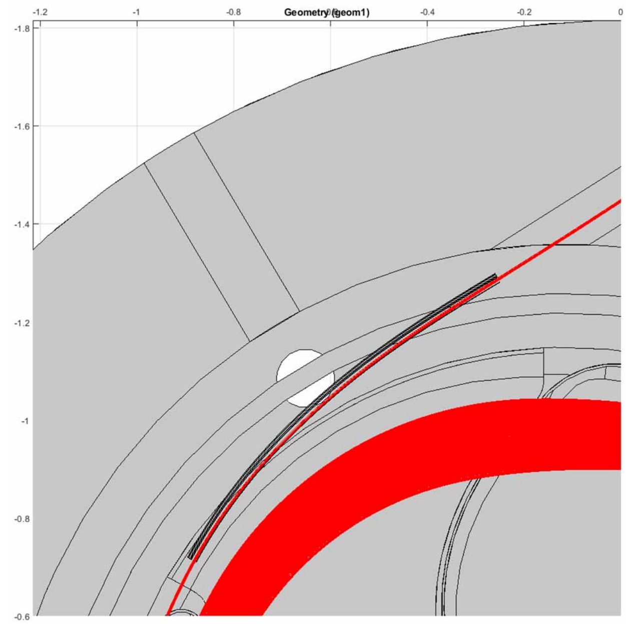

Figure 6: The beam tracing in the cyclotron structure.

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. On this basis, coupled with MTC's experience of treatment by the method of conformal therapy, opens up the possibility of equipment modernization. This is necessary for precise control and delivery of a high dose rate for studies of the FLASH therapy method.

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

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