JINR SUPERCONDUCTING SYNCHROTRON FOR HADRON THERAPY

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Abstract

The medical carbon synchrotron at maximal ion energy of 400 MeV/u was developed in JINR. The project goal is accumulation of the superconducting technology at construction of the carbon synchrotron with a circumference of 69.6 m on basis of the Nuclotron type magnet elements. For injection of the carbon ions it is proposed to use IH linac of C4+ at energy 4 MeV/n. The superconducting gantry is developed for patient treatment. The gantry consists of two 67.5° and one 900 bending sections, each including two similar dipole magnets of a low aperture (about 120 mm). Such gantries are intended for multiple raster scanning with a wide carbon beam and the technique of layer wise irradiation with a spread out Bragg peak of several mm.

INTRODUCTION

Hadron therapy with beams of heavy nuclear particles (protons and carbon ions) is the most efficient radiation oncology treatment. Hadron therapy in Russia can offer substantial advantages for treatment to 50000 patients per year. Carbon ion therapy is particularly efficient for patients with radioresistant tumors. A project of the medical superconducting synchrotron dedicated for the carbon therapy has been designed in JINR (Fig.1).

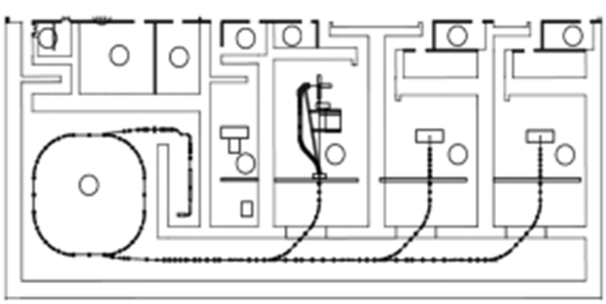

Figure 1: Layout of JINR accelerating equipment based on superconducting synchrotron for center of ion therapy.

The perimeter of the superconducting synchrotron in this complex is 70 m. The magnetic system of the synchrotron consists of four superperiods. The distribution of carbon ions with energy from140 MeV/u to 400 MeV/u from synchrotron into three medical booths is implemented in the transport channel.

The basis of this medical accelerator is the superconducting JINR synchrotron – Nuclotron [1,2]. The Nuclotron type straight dipole magnets [2] were adopted for the optic of the medical synchrotron and beam delivery system. The superconducting magnets permit to reduce the accelerator electrical consumption, the size and weight of the accelerator. Especially the superconducting technology is important at design of the carbon gantry. A superconducting gantry was developed for tumor treatment.

INJECTION

The superconducting electron string ion source [3] is planed to use for $^{12}C^{4+}$ injection in the carbon linac. The compact IH linac [4] will apply as synchrotron injector.

The injection channel consists from two sections: the discharge section, where accelerated in IH linac ions C^{4+} are discharged to ions C^{6+}, and the section of injection of ions C^{6+} in the synchrotron.

CARBON SYNCHROTRON

The basic parameters of the carbon synchrotron [5] are given in Table 1. The FODO structure (Fig.2) is more preferable for injection and extraction schemes and corrections of the closed orbit distortions. The synchrotron magnetic system (Table 2) consists of 4 superperiods, which involves 8 straight dipole magnets, 8 quadrupole lenses and multipole correctors. The maximum magnetic field in dipole magnets corresponds to 1.8 T. The beam and the synchrotron structure dynamic characteristics are given in Table 3.

Table 1: Basic Parameters of Carbon Synchrotron

Injection/maximal energy	4/400 MeV/u
Injection magnetic rigidity/ maximal	0.59/ 6.36T·m
Circumference	69.6 м
Column limit of intensity at injection	10^{10} p/cycle
Betatron tune shift	0.03
Revolution time at injection	2.37 μs
Number of turns at injection	20
Injection efficiency	50 %
Time of synchrotron acceleration	0.5 s
Slow extraction time	(0.5 -10) s
Energy of extracted beam	(140 – 400) MeV/u
Extraction efficiency	96%
Critical energy	3.1 GeV/u

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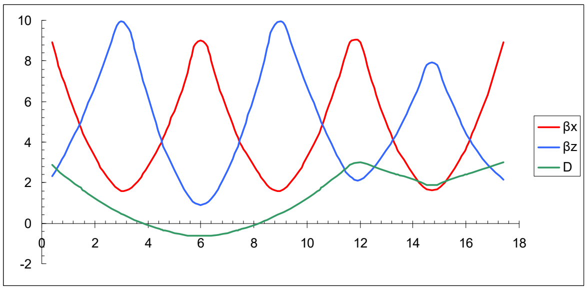

Figure 2: Synchrotron super period characteristics.

The multiturn injection is realized at fulfilling of the horizontal acceptance during 20 ion turns. The stored beam intensity is equal to 1010 ions C6+ per pulse. The working point corresponds to betatron tunes $Q_{x,z} \approx 3.25$. Nonlinear 3 order resonance $3Q_x=10$ is used for slow beam extraction. The extraction time is varied from 0.5 s to 10 s. The intensity of extracted beam is equal to 109 pps.

Table 2: Structure and Magnetic Elements

Number of superperiods/FODO periods	4/12
Number of dipole magnets/ quadrupole lenses	32/24
Magnetic field at injection/maximal field	0.17/1.8 T
Rate of magnetic field	3.26 T/s
Maximal/injection gradients in F lenses	8.5/0.8 T/m
Maximal/injection gradients in D lenses	–7.5/–0.7 T/m
Curvature radius in dipole magnets	3.53 m
Sagitta in dipole magnets	8.7 mm

Table 3: Beam and Synchrotron Structure Dynamic Characteristics

Betatron tunes	3.25
Chromaticity $\Delta Q_x/(\Delta p/p)$	-3.1
$\Delta Q_z/(\Delta p/p)$	-3.2
Parameter of orbit compaction	0.053
COD, mm	3
Horizontal/Vertical acceptance, π·mm·mrad	180/70
Emittance of injected beam, π·mm·mrad	10
Emittances of accelerated beam $\varepsilon_x/\varepsilon_z$, π·mm·mrad	20/1.5
Emittance of extracted beam $\varepsilon_x/\varepsilon_z$, π·mm·mrad	0.5/1.5
Relative momentum spread	$\pm 10^{-3}$

BEAM DELIVERY SYSTEM

The beam delivery system (Fig.3) consists of following sections: the extraction section; the foil section provided equal beam emittances in both transverse planes; the accommodation section; the section for beam delivery in the cabin; the section of beam transportation between the medical cabins; the isocentric gantry; the channel with fixed beam position cabin. The beam delivery system should provide the fixed transverse beam sizes in the gantry isocenter. These sizes do not depend on the gantry rotation angle, the extracted ion energy, emittance of the extracted carbon ion beam.

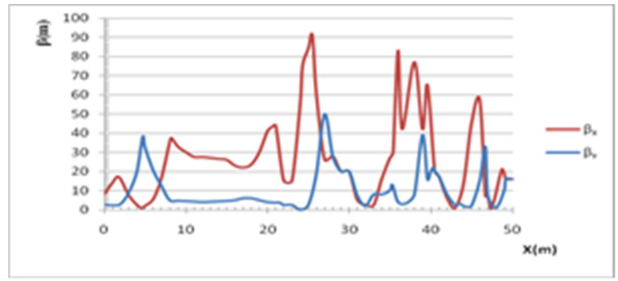

Figure 3: Beta-functions of beam delivery system.

The extracted carbon beam has non symmetric horizontal and vertical emittances, the vertical emittance is few times larger horizontal one. A special scattering foil is installed in the beam delivery system to provide both equal horizontal and vertical beam emittances. The accommodation section is used to provide same optical beam characteristic in the vertical and horizontal directions at exit. It accommodates the beam optic to the gantry for any its rotation angles. The section for beam delivery in cabin consists of the chopper, the achromatic bend and 2 triplets. The chopper involves 4 dipole magnets. The beam is pick-upped by an absorber trap, when dipoles switch off. The beam is transported in the channel when magnets switch on. The section of beam transportation between cabins has the horizontal betatron phase shift 2π and vertical one π. The optic of the isocentric gantry is achromatic at beam transportation to the tumor target. The gantry optic provides equal horizontal and vertical beta functions and zero alpha-function on the tumor target. The parameters of gantry optic are adjusted to obtain the equal vertical and horizontal beta and alpha functions at the gantry entrance at variation of extracted beam emittances and sizes.

SUPERCONDUCTING CARBON GANTRY

The superconducting magnets of low aperture (about 120 mm) are used in the gantry [6]. The gantry consists of two 67.5° and one 90^0 bending sections (Fig.4), each including similar dipole magnets with bending angle 22.5^0.

The total gantry size corresponds to 10.5×6.5 м. Two duplets of quadruple lenses (Q1-Q2), (Q3-Q4) are placed between dipole magnets. The quadruple lenses have the effective length of 2 m and gradients Q1-Q2 – 9.5 T/m, Q3-Q4 – 10.5 - 13.5 T/m.

Two scan magnets are placed at the end of gantry magnetic system with scanning area ±10cm at isocenter. The horizontal scanning magnet (SM-HOR) is situated on a distance of 2.7m from isocenter, the magnet length corresponds to 0.3m, the maximal magnetic field is equal to 0.8T. The vertical scanning magnet (SM-VER) is placed

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on a distance of 2.1 m from isocenter, its maximal field is equal to 0.8 T and length is of 0.4 m.

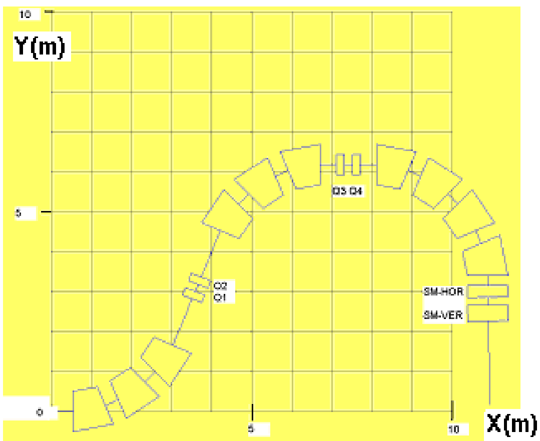

Figure 4: Layout of the JINR superconducting carbon ion gantry.

The beam has following parameters at gantry entrance: carbon ion energy 400 MeV/u, vertical and horizontal sizes of 4 mm, ion energy spread 0.1–1 %. Dipole magnets with working aperture of ± 3cm provide beam transportation at ion energy spread of 1%.

After the last magnet, the system of beam formation is installed. It includes a vertically scanning magnet, comb filter, wedge like filter of variable thickness, and a monitor of beam position. As a result, the distance from isocenter to output edge of the last dipole magnet is about 3.5 m.

Such gantries are intended for multiple raster scanning with a wide carbon beam and the technique of layer wise irradiation with a spread out Bragg peak of several mm. The efficiency of beam formation for such gantry is about 40%. The advantage of this gantry system is a simpler technology of manufacturing of superconducting dipole magnets with a small aperture and weight. The weight of all dipole magnets is about 10–15 t. The limitations of the system are a large diameter of gantry truss and 40% efficiency of beam.

The parameters of gantry dipole magnet are given in Table 4. Superconducting dipole magnets are cooled by circulated He gas high impurity through Sumitomo cryocooler head. The maximum magnetic field corresponds to 3.2T. The iron yoke weight is equal to 500 kg, and weight of cooled mass is about 650 kg. Two cryogenic coolers are installed at each dipole magnet.

Homogeneity of magnetic field 2×10-4 is performed in the magnet aperture of R~10 mm. Tthe errors of magnetic field $\delta B/B \cong 2\times10^{-4}$ lead to 10% beam position displacement at dipole magnet exit. Relative deviation of the magnetic field integral is equal to ±1.4 10-4 at transverse aperture of $\Delta X=\pm3$ cm.

Table 4: Parameters of Superconducting Dipole Magnets of Gantry

Magnet parameters	Value
Number of dipole magnets	8
Magnet type, current distribution	cosψ
Number of winding sectors	10
Total number of turns (per pole)	2841
Operating current, A	220
Magnetic field, T	3.2
Magnetic field rigidity, T m	6.63
Turning radius, m	2.07
Turning angle, °	22.5
Horizontal homogeneity of magnetic field, mm	±16
Homogeneity of magnetic field	$\pm2.2\times10^{-4}$
Homogeneities of field integral	10^{-3}
Internal and external radii of winding, mm	61/72
Internal and external radii of yoke, mm	78/178
Diameter of internal warm vacuum chamber of beam, mm	40
Radius of external vacuum chamber of magnet, mm	258/273

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