# PROJECT OF JINR SUPERCONDUCTING SYNCHROTRON FOR HADRON THERAPY

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## *Abstract*

The project of the medical carbon synchrotron at maximal ion energy of 400 MeV/n was developed in JINR. The project goal is accumulation of the superconducting technology at construction of the carbon synchrotron with a circumference of 65 m on basis of the Nuclotron type magnet elements. For injection of the carbon ions it is proposed to use IH linac of $C^{4+}$ at energy 4 MeV/n. The superconducting gantry is developed for patient treatment at a weight of 150 t.

## INTRODUCTION

Today, the cancer is the second highest cause of death in developed countries. Its treatment still presents a real challenge. Protons and carbon ions allow depositing the radiation dose more precisely in a cancer tumor, reducing greatly the amount of dose received by healthy tissue surrounding the tumor with respect to electrons. But in addition to the ballistic accuracy of protons, the carbon ion beams have an extra advantage in radiation therapy: they have a different biological interaction with cells and are very effective even against some type of cancerous cells which resist to usual radiations. That is why the last years have seen increasing interest in particle therapy based on $^{12}C^{6+}$ ions. A project of the medical superconducting synchrotron dedicated for the carbon therapy has been designed in JINR.

The basis of this medical accelerator is the superconducting JINR synchrotron – Nuclotron [1,2] (Fig.1).

Figure. 1: JINR superconducting synchrotron- Nuclotron.

The Nuclotron type straight dipole magnets [2] (Fig.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 at a weight of 150 t.

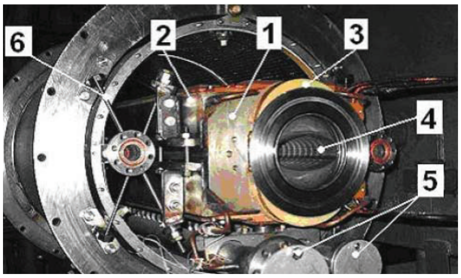

Figure. 2: The Nuclotron type dipole magnets

## INJECTION

The superconducting electron string ion source [3] is planed to use for $^{12}C^{4+}$ injection in the carbon linac. Additionally this source can applied for formation of primary radioactive carbon ion beams $^{11}C^{4+}$ in ISOLDE scheme. The intensive primary radioactive $^{11}C^{4+}$ ion beams can be used simultaneously for cancer treatment and on-line PET. The compact IH linac [4] (Table 1) will applied 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.

Table 1. Parameters of carbon IH linac.

| Parameters | RFQ | IH-DTL |
|---|---|---|
| Injection energy, MeV/u | 0.01 | 0.61 |
| Extraction energy, MeV/u | 0.61 | 4 |
| Operation frequency, MHz | 200 | 200 |
| Charge-mass ratio | 1/3 | 1/3 |
| Cavity length, m | 2.5 | 3.4 |
| Cavity outer diameter, m | 0.42 | 0.44 |
| Power, kW | 120 | 360 |
| Normalized 90% emittance, π·mm·mrad | 0.85 | 1.1 |
| Normalized 90% longitudinal emittance, π·ns·keV/n | 1 | 1.2 |
| Energy spread,% | | ±0.4 |
| Maximal beam current, eμA | 392 | 390 |

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## CARBON SYNCHROTRON

The FODO structure (Fig.3) is more preferable for injection and extraction schemes and corrections of the closed orbit distortions. The basic parameters of the carbon synchrotron are given in Table 2. The synchrotron magnetic system (Table 3) 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.

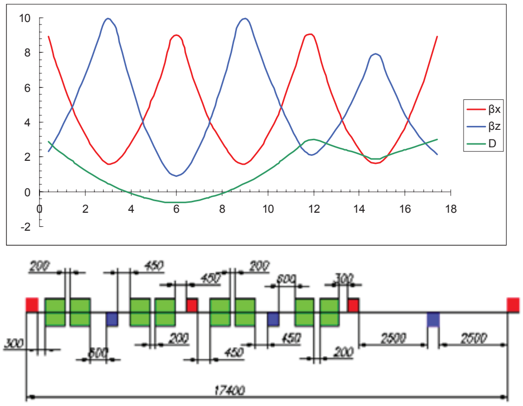

Figure 3: Synchrotron super period characteristics.

Table 2. Basic parameters of carbon synchrotron.

| | |
|---|---|
| Injection/maximal energy | 4,2/400 MeV/u |
| Maximal/ injection magnetic rigidity | 6,36/0.59 T·m |
| Circumference | 69,6 м |
| Column limit of intensity at injection | $6{\cdot}10^9$ p/cycle |
| Betatron tune shift | 0,02 |
| 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 | (170 – 400) MeV/u |
| Extraction efficiency | 96% |
| Critical energy | 3.1 GeV/u |

The multiturn injection (Fig.4) is realized at fulfilling of the horizontal acceptance during 10-15 ion turns. The stored beam intensity is equal to $10^{10}$ ions $C^{6+}$ 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 (Fig.5). The extraction time is varied from 0.5 s to 10 s. The intensity of extracted beam is equal to $10^9$ 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 |

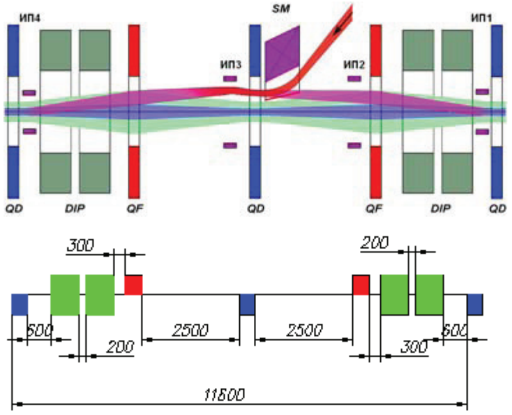

Figure 4: Multiturn injection scheme, orbit and beam envelope: red – injected beam, violet – deflected beam, blue – circulated beam after first injection, green - circulated beam.

Table 4 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 | $\pm 10^{-3}$ |
| Relative maximal momentum spread | $\pm 2{\times}10^{-3}$ |

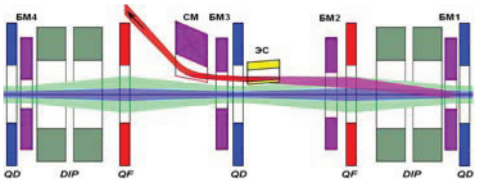

Figure 5: Scheme of slow beam extraction.

## BEAM DELIVERY SYSTEM

The beam delivery system (Fig.6) 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.

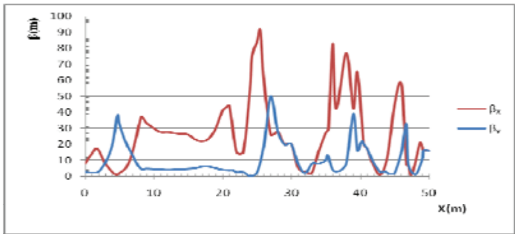

Figure 6: Beta-functions of beam delivery system.

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 is 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 JINR-IBA collaboration develops superconducting cyclotron C400 and carbon gantry (Table 4) in frame work of Archade project [5,6]. This gantry is planed to use in JINR carbon synchrotron complex. The gantry provides rotation around the patient on an angle 0-$180^0$. The positioner also rotates together with patient on an angle $180^0$-$360^0$. The main gantry superconducting dipole magnet has aperture 20×20 cm at magnetic field homogeneity of $10^{-4}$. The magnetic field rate corresponds to 1 T/min. The magnet is cooled by 4 He-free criocoolers. The distance from dipole magnet exit to isocenter corresponds 2 m.

Table 4. Superconducting carbon gantry

| Gantry | |
|---|---|
| Weight, t | 156 |
| Diameter, m | 9.2 |
| Length, m | 12,7 |
| Scanning area in isocenter, cm | 20×20 |
| Gantry rotation angle, degree | 180 |
| Positioner rotation angle, degree | 180 |
| Main dipole magnet | |
| Magnetic field, T | 3.2 |
| Bending radius, m | 2 |
| Weight, t | 28 |

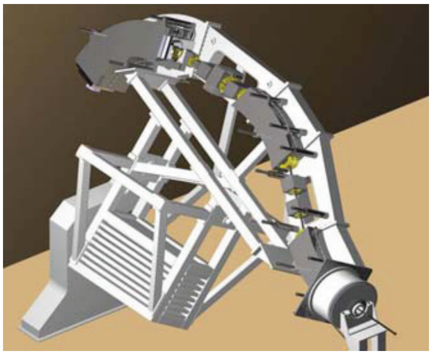

Figure 7: Superconducting carbon gantry.

## REFERENCES

[1] A.D. Kovalenko UPhN, v.177, №8, (2007) 914.

[2] A.A. Smirnov, A.D. Kovalenko, Nuclear Particle Letters, v.1, №6 (2004) 11.

[3] E.D. Donets et al., Review of Scientific Instruments, v71, N2, part II, (2000) 896.

[4] K.Noda et al., Radiation Res. 48 suppll. (2007) A43.

[5] Y. Jongen et al., HIAT09, D9 (2009).

[6] Y. Jongen, Design of a K=1600 SC cyclotron for Carbon therapy, ECPM, Nice (2006).