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COMPARISONS AND SIMULATIONS OF SUPERCONDUCTING DIPOLE MAGNETS FOR JINR ION GANTRY

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Abstract

A medical complex for carbon ion therapy has been developed in the JINR based on the own technology of the superconducting ion synchrotron - Nuclotron. One important feature of this project is related to the application of superconducting gantry. In the project, two schemes of superconducting gantries have been considered. In the first scheme, the last gantry element is supposed to be represented by a superconducting magnet with a scan region in it of 20 × 20 cm. In the second scheme the gantry consists of two 67.5° and one 90^0 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. The comparison and simulation of superconducting dipole magnet for JINR carbon ion gantry is under discussion.

JINR SUPERCONDACTING COMPLEX FOR CARBON ION THERAPY

A medical complex for therapy with carbon ions has been developed in the JINR based on the technology of the Nuclotron (JINR superconducting synchrotron) (Fig.1) [1]. The perimeter of the superconducting synchrotron in this complex is 70 m. The magnetic system of the synchrotron consists of four superperiods, each including eight dipole magnets, four focusing lenses, four defocusing lenses, and multipolar correctors 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.

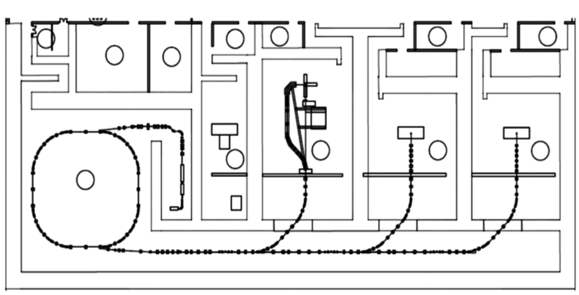

Figure 1: Layout of JINR accelerating equipment based on superconducting synchrotron for center of ion therapy.

One important feature of this project is related to the application of superconducting gantry. In the projects, two schemes of superconducting gantries have been considered.

In the first scheme [1], the last element is supposed to be represented by a superconducting magnet with a scan region in it of 20×20 cm. This magnet has the following parameters: the field is 3.2 T, relative homogeneity of the field is 2×10^{-4}, the rate of the increase in the field is 1 T/min, the turning radius is 2 m, the weight is 28 t, and stored energy is 8.5 MJ. The distance between the output of the wide aperture magnet and isocenter is 2 m. The gantry, in this case, weighs 156 t, its diameter is 9.2 m, and length is 12.7 m. When using a wide aperture magnet, two scanning dipole magnets are installed first, making possible to implement the scheme of active scanning with an effectiveness of beam formation of about 90%.

In the gantry scheme [2] discussed below, superconducting magnets of low aperture (about 120 mm) are used. The gantry consists of two 67.5° and one 90^0 bending sections, each including similar dipole magnets with bending angle 22.5^0 (Table 1).

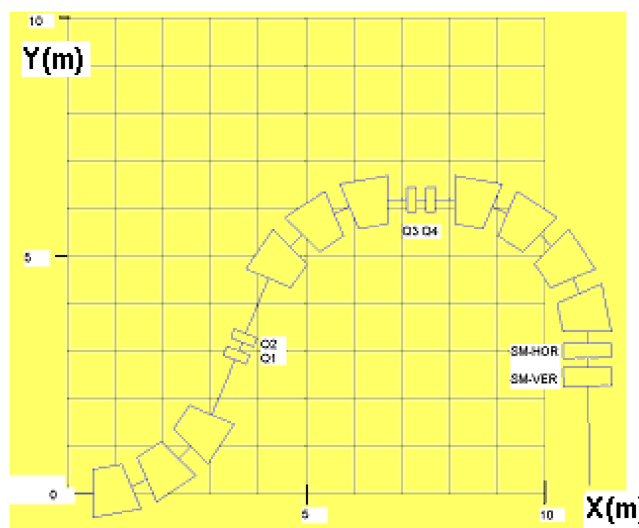

Figure 2: Layout of the JINR superconducting carbon ion gantry.

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

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to 0.8T. The vertical scanning magnet (SM-VER) is placed 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.

The beam has following parameters at gantry entrance: carbon ion energy - 430 MeV/u, vertical and horizontal emittance - 6 π mm×mrad, vertical and horizontal sizes - ±4 mm, ion energy spread - 0.1–1 %. Dipole magnets with working aperture of ± 3cm provide beam transportation at ion energy spread of 1%.

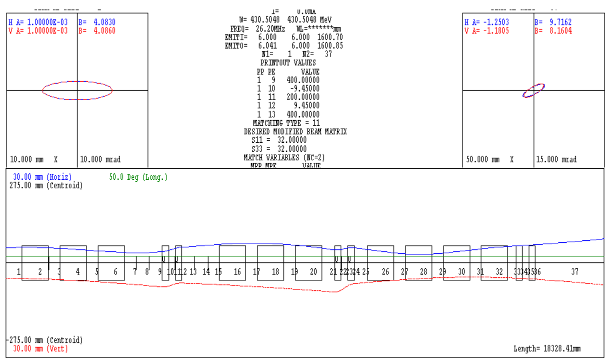

Figure 3: Beam transportation through gantry magnet system at energy spread of 0.1%.

After the last magnet, the system of beam formation is installed. It includes a vertically scanning magnet, scattering foil, 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. It also makes possible to simplify the beam transportation channel and to get rid of its two sections: sections of alignment of vertical and horizontal emittances (it is implemented using scattering foil in the nozzle) and a section of matching. The limitations of the system are a large diameter of gantry truss (it is larger by 4.2m than for the first scheme) and efficiency of beam formation twice as little as that of the first scheme.

SUPERCONDUCTING DIPOLE MAGNETS

The parameters of gantry dipole magnet are given in Table 1. The dipole magnet has cosψ current distribution. Coil divided on 12 sectors with fixed number of turns in each sector. The external vacuum chamber is constructed from iron steel. Superconducting dipole magnets are cooled by circulated He gas high impurity through Sumitomo cryocooler head.

The 3D simulation of magnetic field was performed by OPERA (Fig.4). The maximum magnetic field corresponds to 3.2T. The distribution of magnetic field along transverse coordinate is given in Fig.5.

Table 1: 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
Rms beam sizes (1σ), σ_y/σ_x, mm	6/3
Horizontal homogeneity of magnetic field, mm	±16
Homogeneity of magnetic field	$\pm 2.2 \times 10^{-4}$
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

To provide high quality of the magnetic field integral the following construction improvements (Fig.6) of magnetic coils were introduced: the coils 1-7 were displaced on 1.5 mm from middle plane at right magnet side; the coils 1-2 were shifted to magnet center on 10 mm at left magnet side. The displacement of these coils to center reduces diameter of vacuum chamber to 40 mm.

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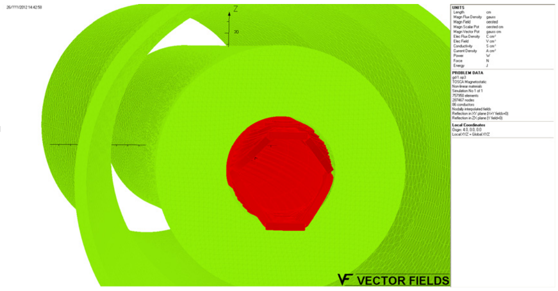

Figure 4: 3D model of dipole magnet in OPERA simulations.

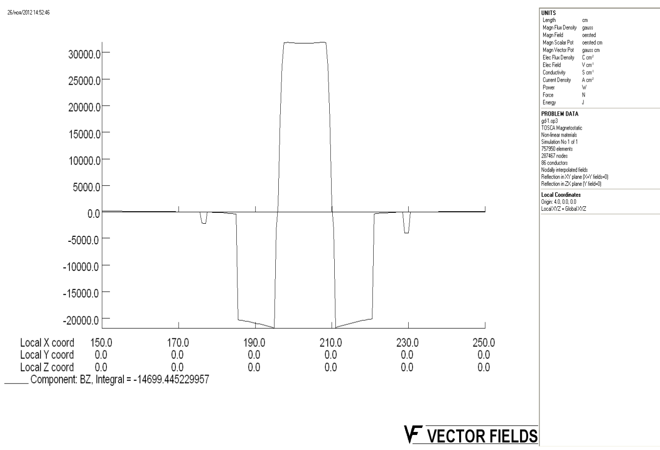

Figure 5: Distribution of magnetic field along transverse coordinate.

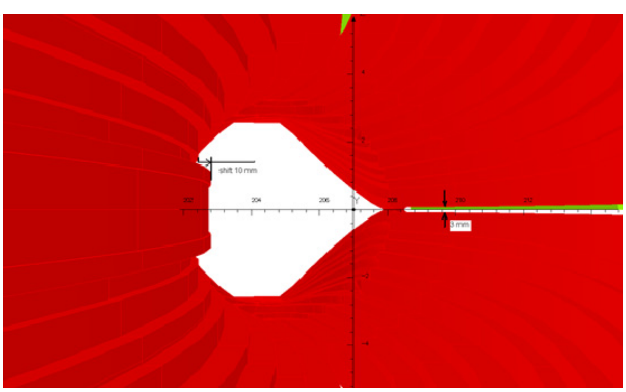

Figure 6: Modified coil geometry of dipole magnet.

Homogeneity of magnetic field 2×10^{-4} is performed in the magnet aperture of R~10 mm (Fig.7). Relative deviation of the magnetic field integral is equal to ±1.4 10^{-4} (Fig.8) at transverse aperture of $\Delta X=\pm3$ cm. So, the errors of magnetic field $\delta B/B \cong 2\times10^{-4}$ lead to 10% beam position displacement at dipole magnet exit.

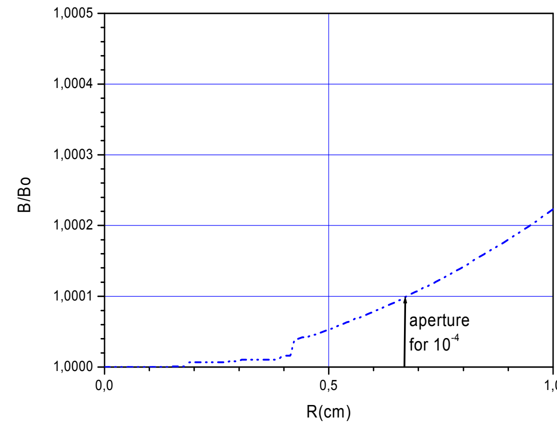

Figure 7: Dependence of magnetic field on transverse coordinate.

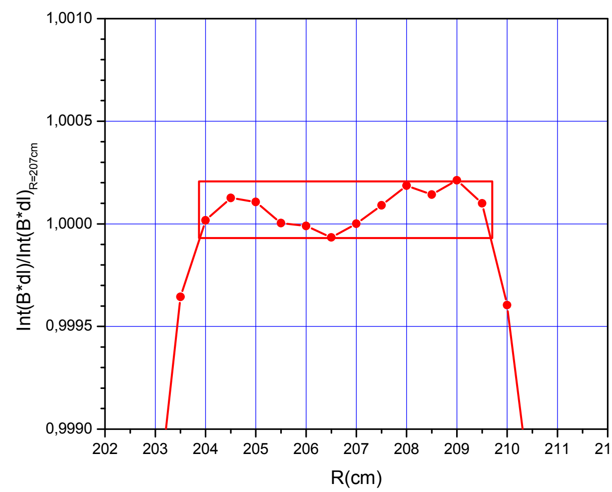

Figure 8: Uniformity of magnetic field integral in the dipole magnet.

The dipole magnet together with dipole component has quadrupole component at maximal gradient: k=1/B×dB/dr = 0.0036 (1/m2) and sextupole one at maximal gradient k' =1/BR×d2B/dr2=1.1 (1/m3). However values of these components are small and they do not influent on beam size at its transportation in gantry magnetic system (Fig.3).

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.

REFERENCES

[1] E.M. Syresin et al, Particle and Nuclei Letters, v. 8, No. 4, 202 (2012).
[2] S.V. Kostromin, E.Syresin, Physics of Particles and Nuclei Letters, v. 10, No. 7, 833 (2013).