JINR SUPERCONDUCTING SYNCHROTRON FOR HADRON THERAPY

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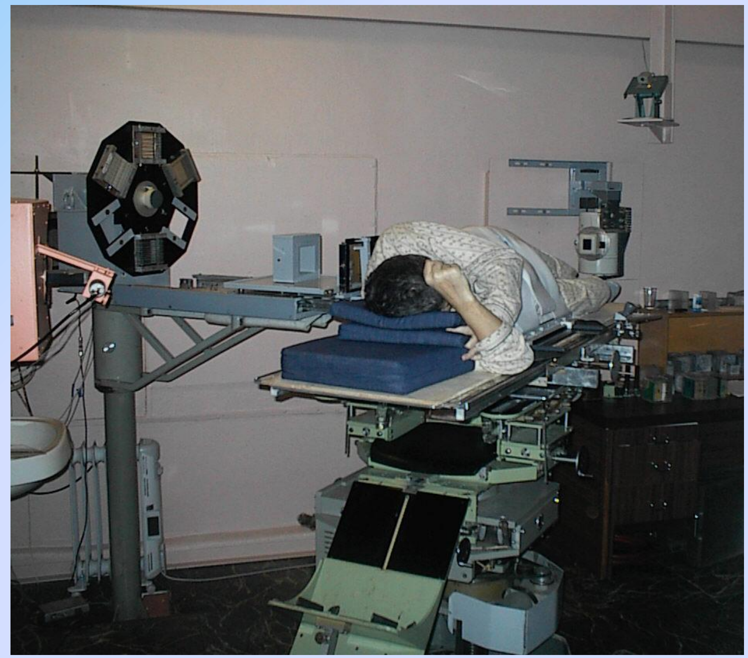
The medical carbon synchrotron at maximal ion energy of 400 MeV/n was developed in JINR. The project goal is accumulation of the superconducting technology at construction of the carbon synchrotron with a circumference of 69.6 m on basis of the Nuclotron type magnets of JINR acting superconducting synchrotron. 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. The gantry consists of two 67.5° and one 90° 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.

JINR activity in hadron therapy

Development of technology of proton therapy
Construction of accelerator for proton therapy
Development of medical carbon ion accelerators

Technology of proton therapy

Synchrocyclotron applied for proton treatment



3D conformal proton beam treatment realized in JINR.

Tumors treated in JINR in 2000-2014

Meningiomas	179
Chordomas, chordosarkomas	37
Gliomas	65
Lymphoma	1
Acoustic Neurinomas	20
Astrocytomas	48
Paragangliomas	6
Pituitary Adenomas	26
AVMs	78
Brain and other metastasis	77
Other head and neck tumors	286
Melanomas	19
Skin diseases	69
Carcinoma metastasis of the lung	8
Breast cancer	52
Brain cancer	11
Prostate Adenomas	1
Sarcomas	17
Other	41
Total	1041

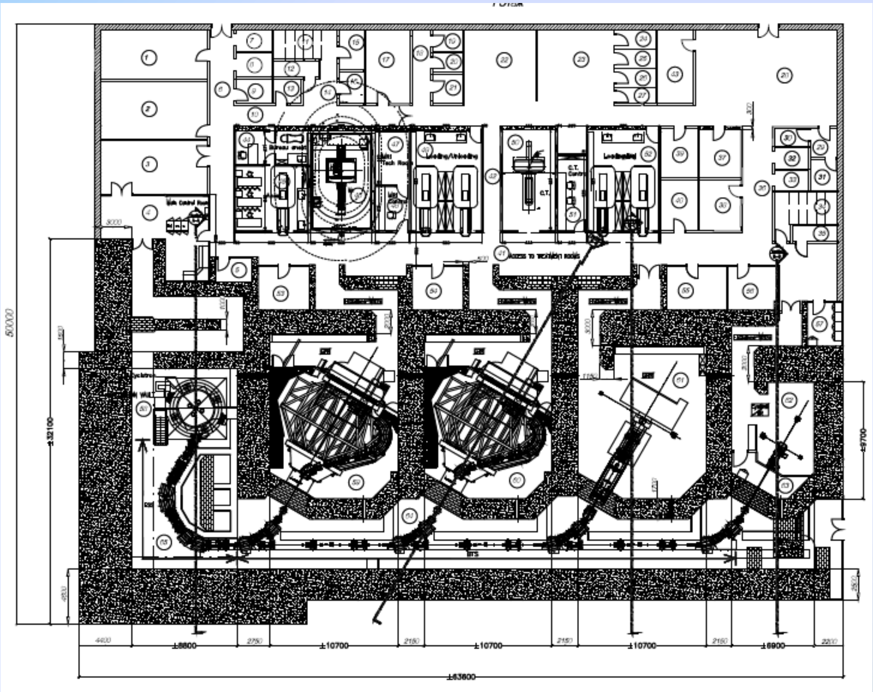
Federal high-technology center of medical radiology, Dimitrovgrad, Uljanovsk reg.

Center involves:
Center of proton therapy
PET center

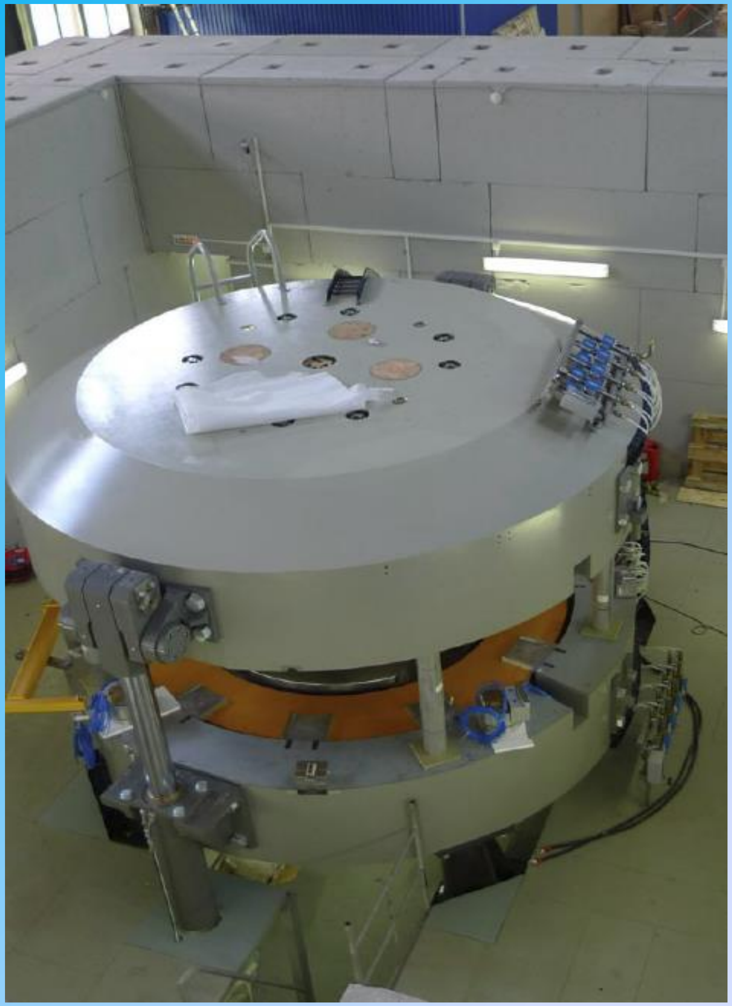
Project of proton therapy center was developed in collaboration between Federal Medico-Biological Agency and Joint Institute for Nuclear Research

Proton therapy center consists of two medical cabins with gantry, cabin with fixed beam position, cabin for eye treatment and system of preliminary positioning Patlog

JINR-IBA developed and constructed joint cyclotron C235-V3 for center of proton therapy in Dimitrovgrad.



Production of C235-V3 cyclotron by JINR-IBA



Cyclotron C235-V3 for proton therapy in JINR vault applied for beam tests

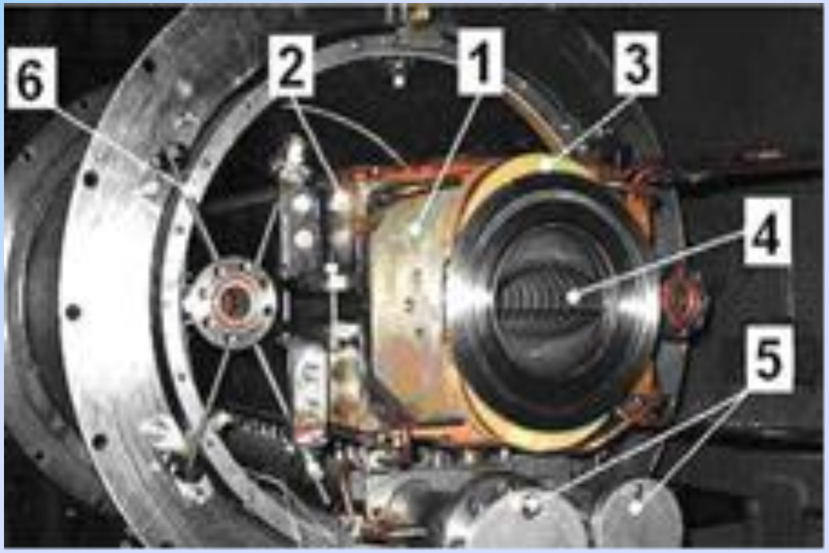
Parameter	C235	C235-V3
Optimization of magnetic field at central region	no	yes
Extracted beam current, uA	0.3	1
Vertical beam size at radius 20 cm was reduced	18mm	8 mm
Beam losses were reduced at proton acceleration	50%	25%
Beam losses at extraction were reduced	50%	25%
Reduction of radiation dose of cyclotron elements caused by of beam current losses		Radiation dose of cyclotron elements were reduced by several times

JINR Superconducting synchrotron-Nuclotron

The basis of medical accelerator for carbon ion therapy is the superconducting JINR synchrotron – Nuclotron

JINR superconducting synchrotron-Nuclotron.

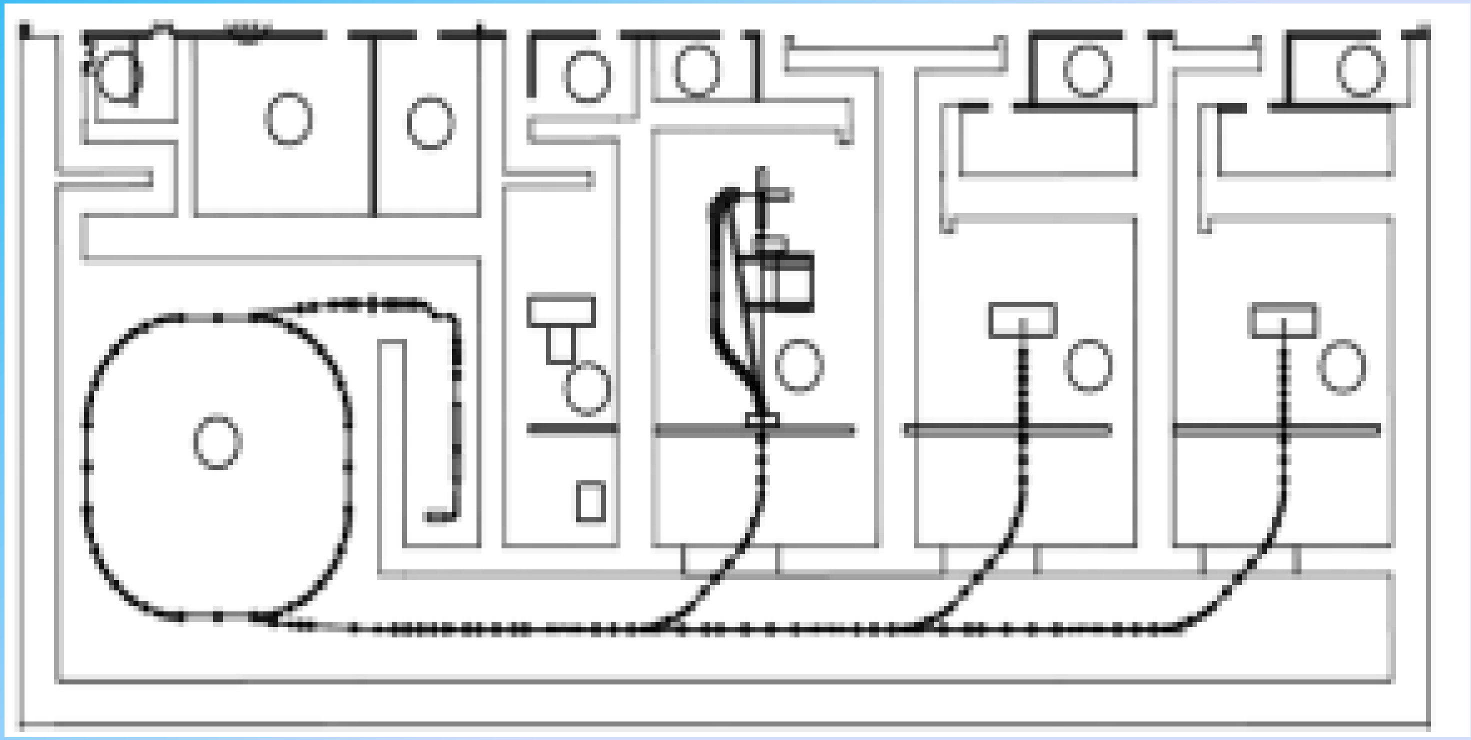
Maximum particle energy, 6 GeV/n
Perimeter, 251.5 m
Max. magnetic field, 1.8 T
Temperature, 4.5 K



The Nuclotron type fast cycling 3.6T/s dipole magnets with circulating two phase helium flow in superconducting cable

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.

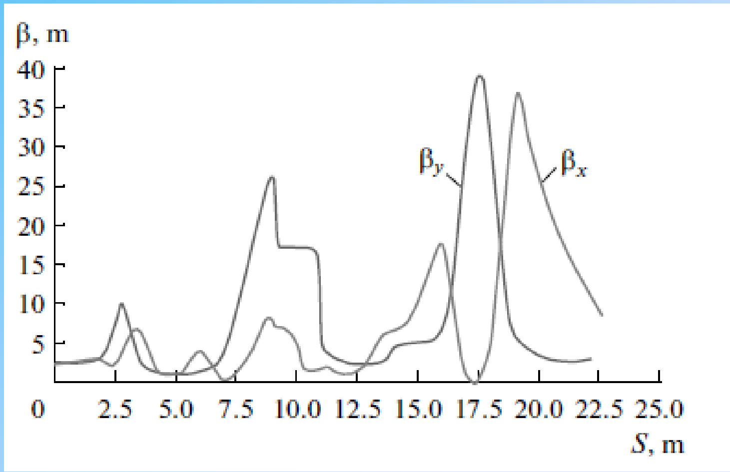
Medical complex for carbon ion therapy



1.Injection:
Electron string ion source
IH-linac
Injection channel consists of striping section and the section of injection of carbon ions in the synchrotron.
2. Carbon ion synchrotron
3. Beam delivery system
4. Superconducting carbon ion gantry
5. Two cabins with fixed beam

Injection in synchrotron

JINR electron string ion source applied for formation of C4+ ions

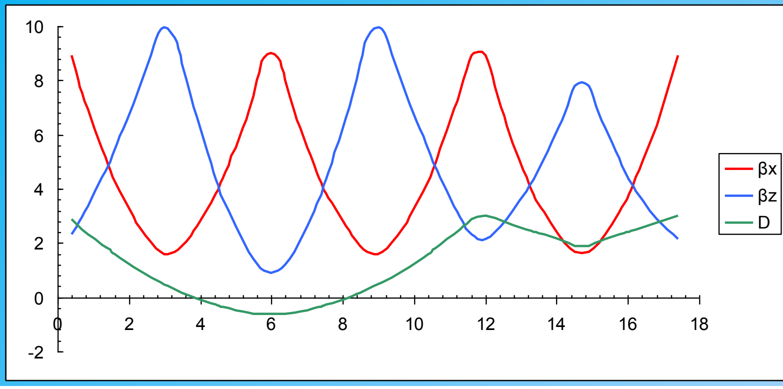


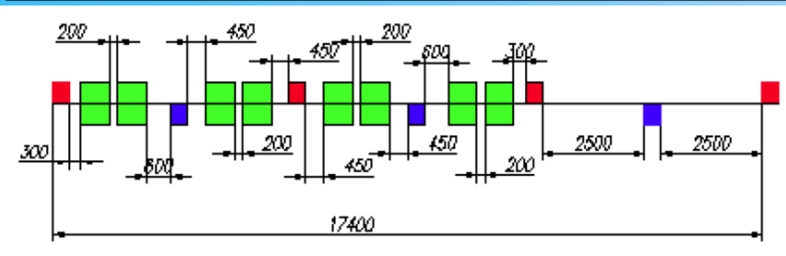
Beta-function in injection line

Base parameters of carbon linac corresponds to IH linac developed at NIRS

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

Carbon ion synchrotron





Injection/maximal energy	4/400 MeV/u
Maximal/ injection magnetic rigidity	6.36/0.59 T·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%

Synchrotron super period characteristics.

The FODO structure is more preferable for injection and extraction schemes and corrections of the closed orbit distortions.

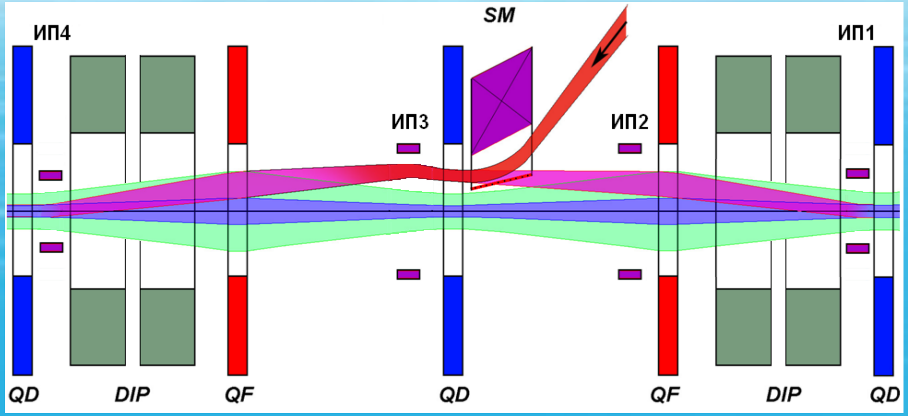
Synchrotron structure and magnetic elements

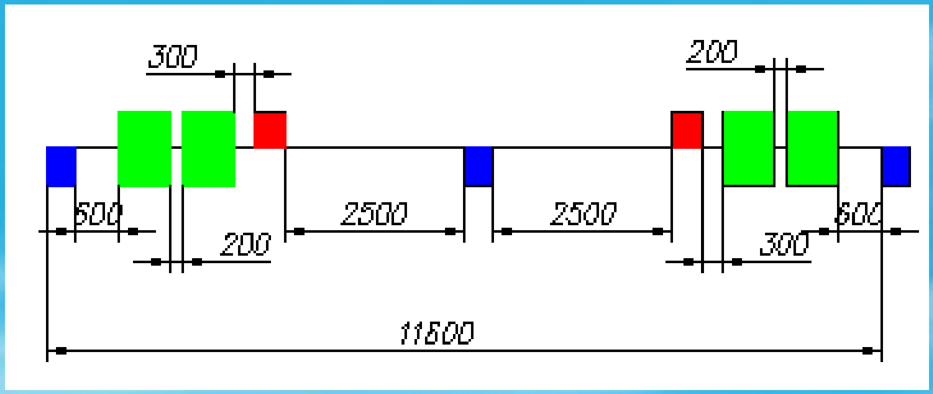
Betatron tunes	3,25
Chromaticity $DQ_x/(Dp/p)$	-3,1
$DQ_z/(Dp/p)$	-3,2
Parameter of orbit compaction	0,053
COD, mm	3
Horizontal/Vertical acceptance, π·mm·mrad	180/70
Emittance of injected beam, π·mm·mrad	10
Emittances of accelerated beam $\varepsilon_x/\varepsilon_z$, π·mm·mrad	20/1,5
Emittance of extracted beam $\varepsilon_x/\varepsilon_z$, π·mm·mrad	0.5/1,5
Relative momentum spread	$\pm 10^{-3}$
Relative maximal momentum spread	$\pm 2\times10^{-3}$

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

Injection in synchrotron

The multiturn injection is realized at fulfilling of the horizontal acceptance during 20 ion turns. The stored beam intensity is equal to 10^{10} ions per pulse.



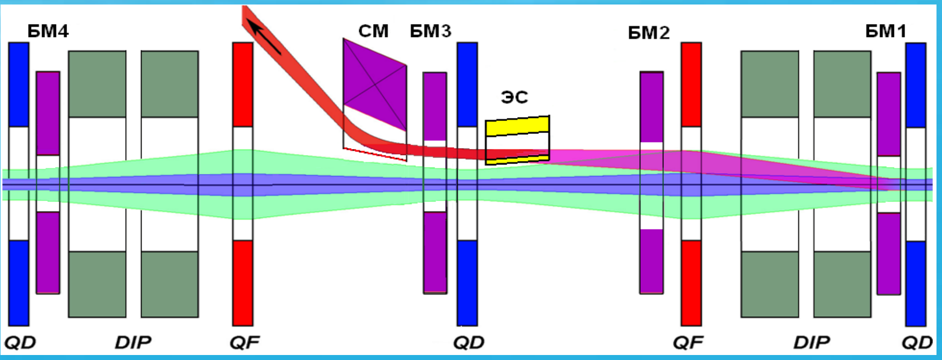


Multiturn injection scheme, orbit and beam envelope: red – injected beam, violet – deflected beam, blue – circulated beam after first injection, green - circulated beam.

Septum magnet and four inflector plates are used in injection scheme, emittance of injected beam 10π·mm·mrad, injection efficiency is 50%.

Extraction from synchrotron

The working point corresponds to betatron tunes Qx,z ≅3.25. Nonlinear 3 order resonance 3Qx=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 1E9 pps.



Scheme of slow beam extraction.

Four bump magnets, electrostatic septum and septum magnet are used in extraction system

Parameter	Meaning	
Energy range, MeV/u	140	400
Magnetic rigidity, T×m	3.54	6.36
Emittance of circulated beam $\varepsilon_x/\varepsilon_y$, π·mm·mrad	36/2.7	20/1.5
Emittance of extracted beam $\varepsilon_x/\varepsilon_y$, π·mm·mrad	0.5/2.7	0.5/1.5
Extraction time, s	0.5-10	0.5-10
Slow extraction efficiency, %	95	96
Effective length of quadrupole and sextupoles, m	0.25	0.25
Maximal meanings for derivatives of quadratic nonlinearities, T/m^2	15	40
Maximal meanings of gradients in LK1-LK4, T/m	0.9	0.15
Effective length of ES, m	1	1
Electric field in ES, MV/m	3.5	6

Dipole magnet characteristics

Number of magnets	32+1
Effective length/physical of magnet, m	0.7/0.9
Magnetic field changing rate, T/s	3.6
Nonhomogeneity of magnetic field for R=30mm	$\pm 6\times10^{-4}$
Aperture of vacuum chamber, mm	128×64
Angle of turn, degree	11.25
Horizontal/vertical gap between poles, mm	150×66
Length of iron yoke, m	0.65
Width/height of yoke, m	0.31/0.228
Weight of magnet, kg	260

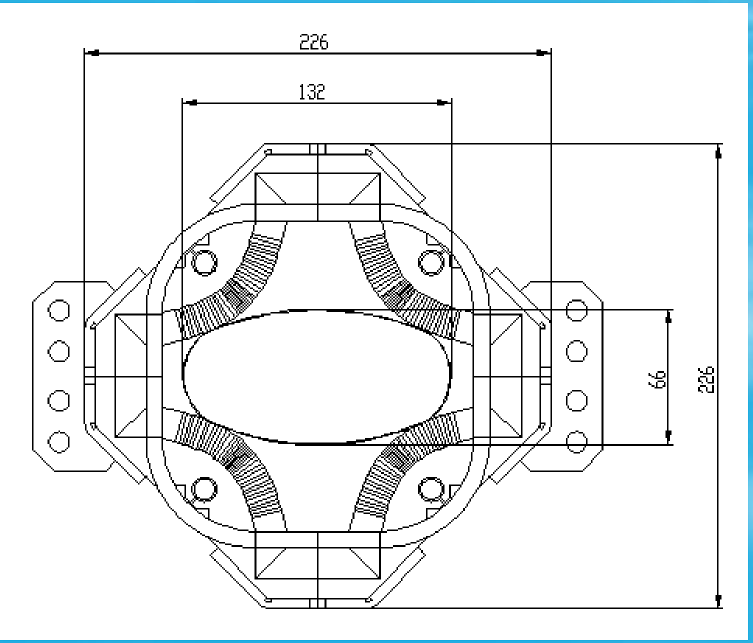
Current at maximum magnetic field, kA	12.1
Inductivity, mH	0.15
Energy losses per cycle at B=1.5 T, J	10
Total cycle duration, s	3-11
Dynamic thermal emission, W	<9.4
Diameter of cable, mm	8.2
Length of cable in the winding, m	15
Pressure differential between supplying and dispatching collectors, kPa	<25
Maximum temperature of helium in the winding, K	4.65

The Nuclotron type magnet winding is made of the superconducting tubular cable. The cable has internal cooling channel for the circulating two phase (boiling) helium flow.

Parameters of quadrupole lens

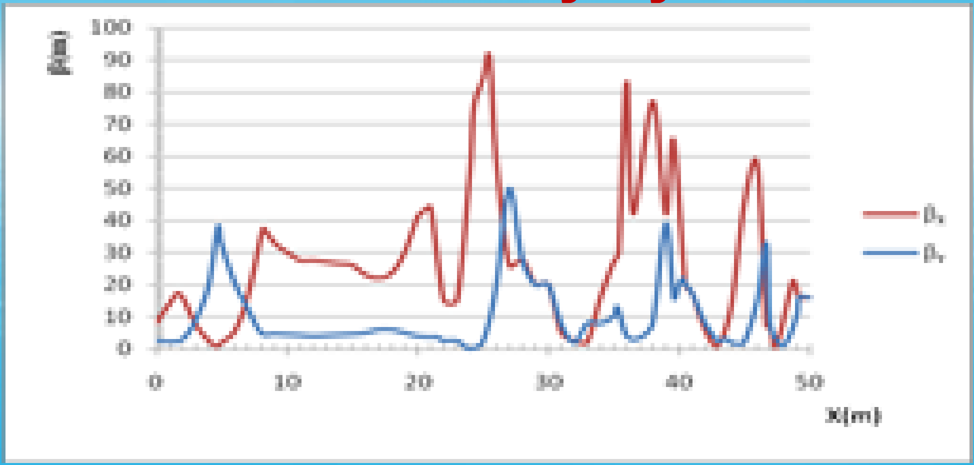
Number of lenses in synchrotron	24+2
Maximum/minimum gradient of magnetic field, T/m	8.5/0.8
Effective/physical length of lens, m	0.4/0.6
Magnetic field gradient change rate, (T/m)/s	17
Nonhomogeneity of magnetic field gradient	$\pm 6\times10^{-4}$
Distance between axis and pole, m	0.048
Aperture of vacuum chamber, mm	130×64
Width/height of yoke, m	0.226/0.226
Current of maximum field gradient, kA	8.2

Inductivity, μH	24
Energy losses per cycle at 10T/m, J	2.5
Total heat emission, W	3.6
Pressure differential for feeding and dispatching helium collectors, kPa	<25
Maximum temperature of helium in winding, K	4.65



The beam delivery system 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.

Beam delivery system



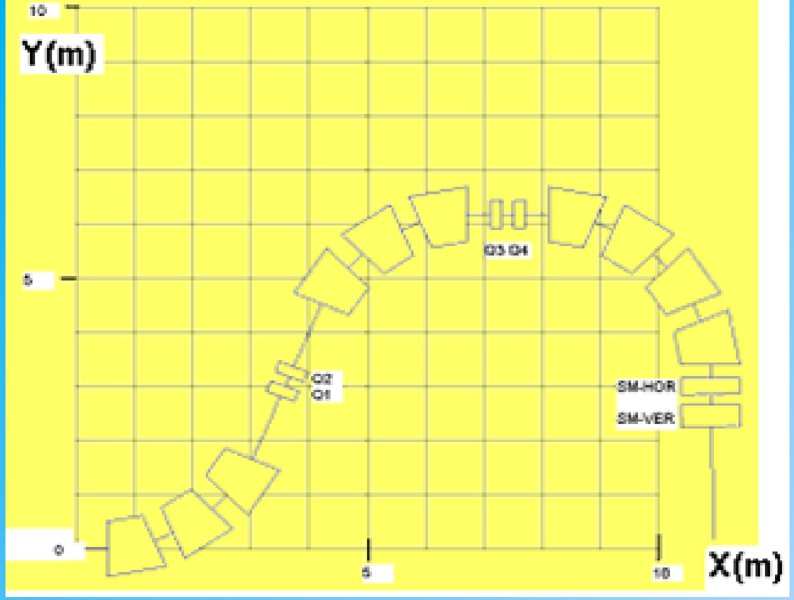
Beta-functions of beam delivery system

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.

The extracted carbon beam has non symmetric horizontal and vertical emittances. A special scattering foil is installed in the beam delivery system to provide both equal horizontal and vertical beam emittances.

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 gantry



Layout of the JINR superconducting carbon ion gantry.

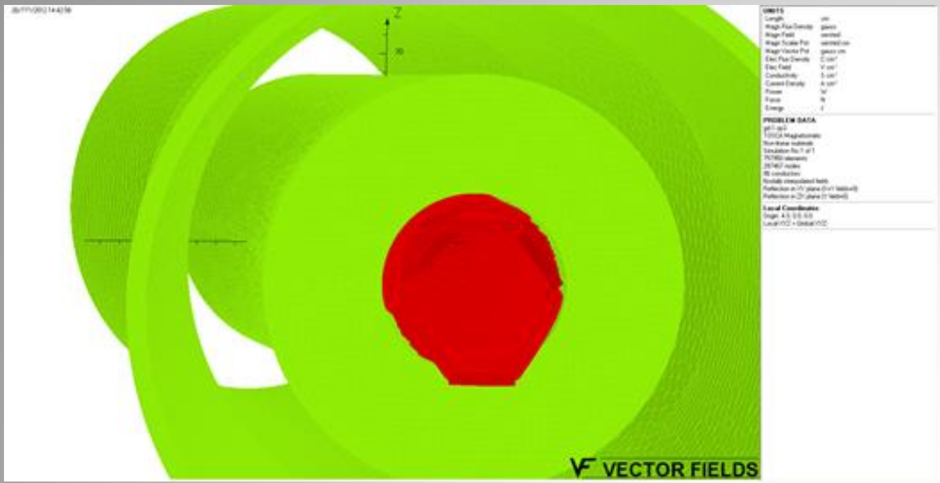
The gantry consists of two 67.5° and one 90° bending sections, each including similar dipole magnets with bending angle 22.5°

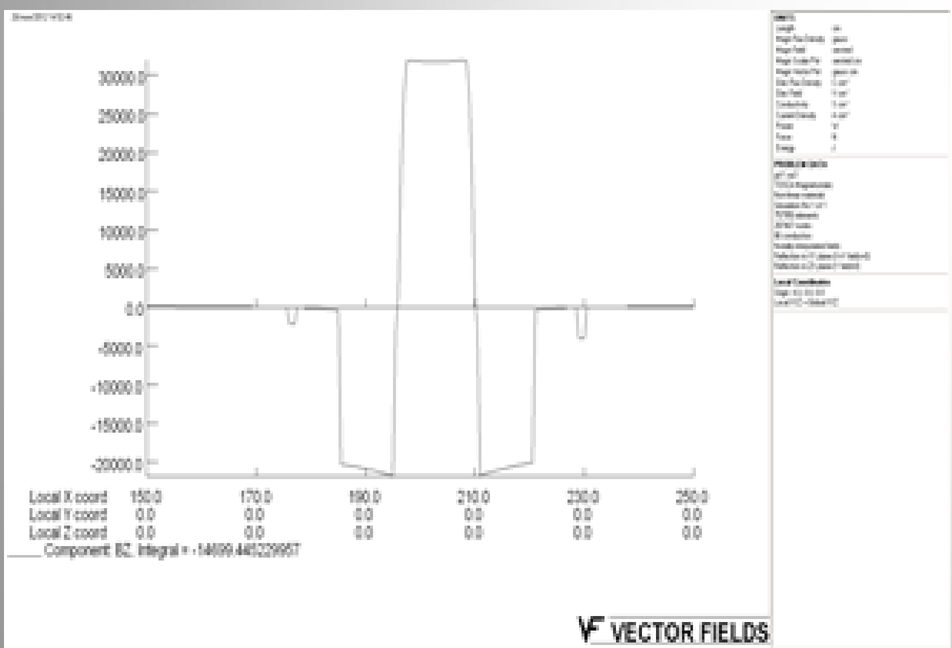
The total gantry size corresponds to 10.5*6.5 м. Two duplets of quadruple lenses (Q1-Q2), (Q3-Q4) are placed between dipole magnets.

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 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.

Such gantry is 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.

Superconducting dipole magnets

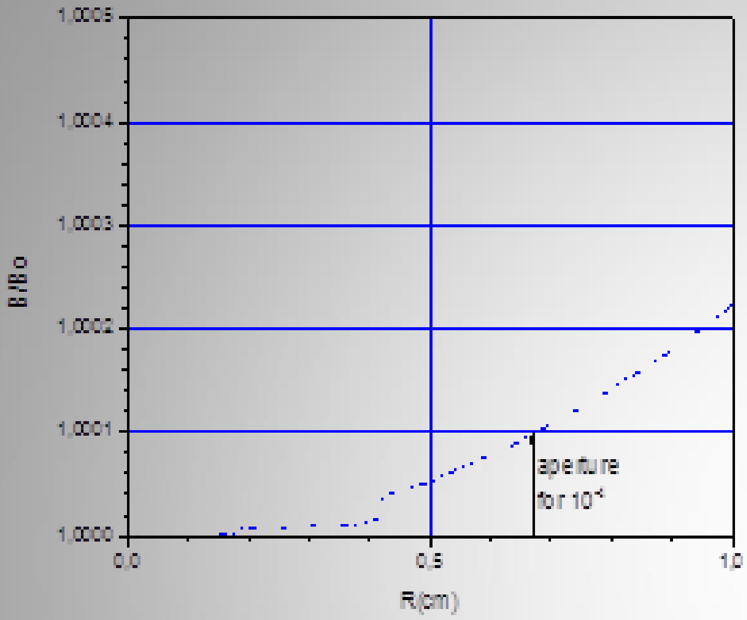


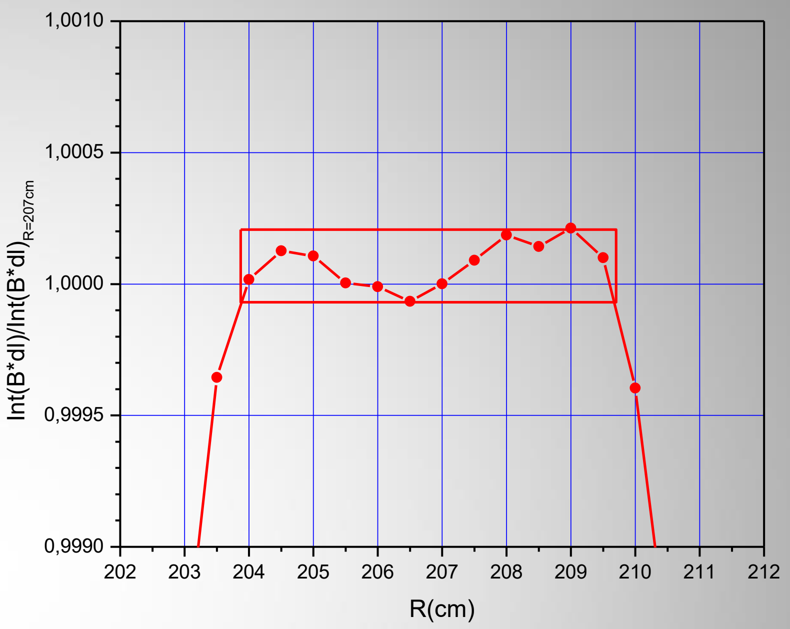


3D model of dipole magnet in OPERA simulations

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	$\pm 2.2 \times 10^{-4}$
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

Homogeneity of magnetic field





Dependence of magnetic field on transverse coordinate.

Uniformity of magnetic field integral in the dipole magnet.

Homogeneity of magnetic field 2×10^{-4} is performed in the magnet aperture of R~10 mm. The 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 $\pm1.4\times10^{-4}$ at transverse aperture of $\Delta X=\pm3$ cm.

Thanks for your attention