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PRELIMINARY STUDY OF THE GANTRY DESIGN FOR THE CENTER OF PROTON RADIATION THERAPY OF THE NRC "KURCHATOV INSTITUTE"

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Abstract

NRC "Kurchatov Institute" is creating a center for proton radiation therapy (PRT), which will include a synchrotron with an energy of 250 MeV, gantry beam installations with a 360° rotation angle and a stationary channel installation. This article presents a block diagram of a gantry beamline installation and a project of a magneto-optical channel of a gantry beam installation with the main magnetic elements. In addition, a turning frame will be presented to accommodate the magnetic elements of the considered project of the gantry beamline installation.

INTRODUCTION

NRC "Kurchatov Institute" is developing a PRT center, which will become part of the Kurchatov Scientific and Educational Medical Center of Nuclear Medicine. In the future, this facility will be used for long-term development of equipment and technologies for new generation PRT and training of personnel (medical physicists and clinicians).

The second purpose of the project and the first product to be introduced into the Russia practical healthcare is a modular clinical center PRT.

A center of PRT will include a synchrotron, two treatment rooms with a 360-degree gantry and a fixed channel. This article presents the main design considerations for the turning frame of the 360-degree gantry and its beamline, which include layout of the beamline with physical and technical characteristics main elements, design and layout of the turning frame.

The main characteristics of the gantry beamline are shown in Table 1.

Table 1: Main Specification of the Gantry Beamline

Parameter	Specification
Energy range from ESS	70 - 250 MeV
Gantry type	±185 degrees
Nozzle type	Combined (Downstream scanning/passive beam)
Virtual SAD	3 m
Max. dose rate	3 Gy/min
Field size	250 mm x 250 mm

Basic requirements for the turning frame: (1) Overall dimensions length no more than 10 m, diameter no more than 13 m; (2) Angle of rotation of the gantry is not less than ± 185° (overlap in the down position); (3) Accuracy of gantry rotation + 0.3°; (4) Isocentricity of gantry rotation <0.5 mm.

IMAGE OPTICS DESIGN FOR THE GANTRY BEAMLINE

Based on the results of modeling various options for the arrangement of the gantry beamline, it is proposed to consider the arrangement made according to the "barrel" type scheme (- 60, + 60, +90 degrees) as a working option. Fig. 1 shows a diagram of a beamline for transporting a proton beam of the gantry facility. MDH 60-1 and MDH 60-2 are two 60-degree dipoles, and MDH 90-1 is a 90-degree dipole with zero angular bevels in the inlet and outlet sections. To focus the proton beam, seven MQ 50-1 - MQ 50-7 quadrupole lenses and three CHV-1 - CHV-3 correctors are installed between the dipole magnets. Five lenses and two correctors on the drift section between 60-degree dipole magnets and two lenses and a corrector on the drift section between 60- and 90-degree dipole magnets, respectively. The longitudinal size of the gantry is 8.2 m, the diameter (along the axis of the proton duct) is 10.24 m.

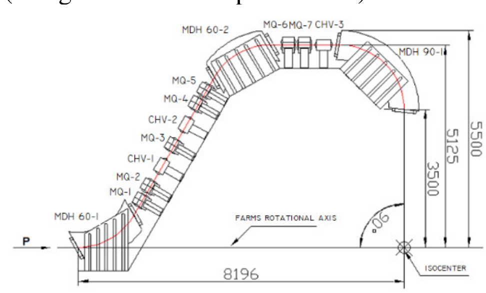

Figure 1: Diagram of the gantry beamline.

The main considerations when choosing the scheme of the gantry beamline are: (1) when an active system for generating a dose field is placed after the MDH 90-1 rotary dipole magnet, large field sizes in the isocenter can be achieved: 250 mm x 250 mm; (2) The arrangement with two 60-degree and one 90-degree dipole magnets reduces the longitudinal dimension of the gantry turning frame and avoids the more complex design of the last dipole.

The diameter of the gantry beamline is largely due to the need to ensure the maximum perpendicularity of the dose distribution entrance into the patient's body, both in the passive and in the active method of its formation. In the case of active method at small distances from the last scanning magnet to the patient's body, the non-parallelism of the beams leads to an increase in the dose on the patient's body surface. To compensate for this effect, a longer SAD L ~ 3.0 m is incorporated in the gantry design. For this

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configuration, the maximum deflecting magnet angle of the active dose field formation system can be reduced, which makes it possible to increase the scanning speed.

The beam is transported in a vacuum chamber. The vacuum tube in the gantry starts at the junction with the fixed beam transport route to the gantry, and ends at the exit from the MDH 90-1 dipole magnet. Vacuuming is used to reduce the scattering of the beam in air. In vacuum windows, a Mylar film will be used as the window material, and the air space in the area of the equipment for the dose field formation system can be filled with gaseous helium.

GANTRY BEAMLINE PROJECT

For a gantry with a 360-degree rotation angle, the presence of a transversely symmetric beam at the input is a fundamental condition, this means the equality of the envelopes of the function βx = βz = 1.0, the zero value of the angular deflection function αx = αz = 0, and zero variance DX = DDX = 0 in two mutually perpendicular planes OX and OY, respectively [1]. Under this condition, the parameters of the gantry beamline can remain identical for all angles of rotation.

Figure 2 shows the optical functions for the proton beam transport channel at its energies Wmin = 70 MeV and Wmax = 250 MeV, respectively. The calculation of the gantry beamline was carried out using the specialized computational program WINAGILE [2], with the following requirements for the beam parameters: throughout the entire transportation interval from the exit of the 90-degree magnet to the isocenter (the point of intersection of the proton-conductor axis after the 90-degree magnet and the axis of rotation of the gantry) independently from the energy must be formed, an axisymmetric beam with a radius of 5 mm. Taking into account the dependence of the beam emittance on energy, the requirements for optical functions were obtained: for an energy of 70 MeV - βx = βz = 9.458 m; αx = αz = 0; for an energy of 250 MeV - βx = βz = 18.832 m; αx = αz = 0. Thereby, various distributions of optical functions, depending on the beam energy, are obtained.

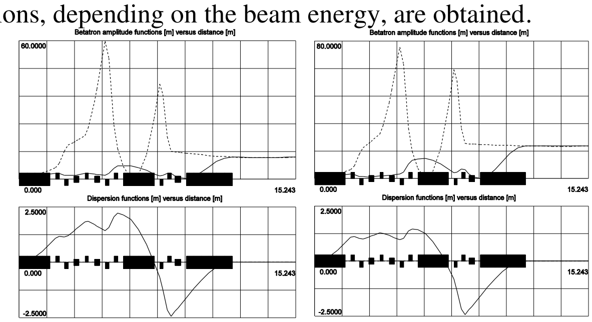

Figure 2: Optical functions of the gantry beamline at energies Wmin = 70 MeV (A) and Wmax = 250 MeV (B).

Figure 3 shows the beam envelopes for energies Wmin = 70 MeV and Wmax = 250 MeV, respectively. In both cases, axisymmetric beams with a radius of 5 mm were obtained. The maximum values of the envelopes are: at an energy of 70 MeV - 10.5 mm horizontally and 12.5 mm vertically; at an energy of 250 MeV - 9.9 mm horizontally and 10.0 mm vertically. In Fig. 3, the dashed curves show the contribution to the envelopes due to dispersion and momentum spread, and the solid curves give the total envelopes taking into account the emittance.

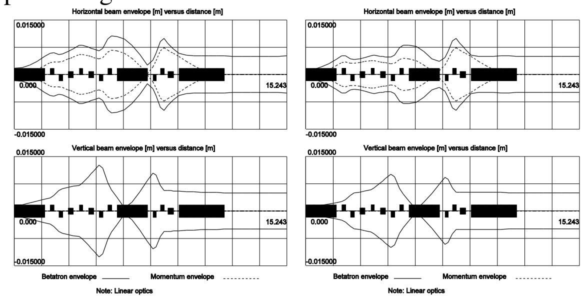

Figure 3: Beam envelopes of the gantry beamline at energy Wmin = 70 MeV (A), Wmax = 250 MeV (B).

MAGNETIC ELEMENTS

The gantry beamline includes 3 dipole, 7 quadrupole and 3 correcting magnets. The detailed characteristics of the magnets are listed in Table 2.

Table 2: Characteristics of Magnetic Elements

Type	Parameter	Specification
MDH-60	Rending radius	1620 mm
	Max field	1,5 T
	Quantity	2
	Tilt angel	0 degree in and out
	Pole distance	50 mm
	Weight	3,7 ton
	Core type	W-shaped
MDH-90	Rending radius	1620 mm
	Max field	1,5 T
	Quantity	1
	Tilt angel	0 degree in and out
	Pole distance	50 mm
	Weight	4,7 ton
	Core type	W-shaped
MQ-50	Aperture	50 mm
	YOKE	
	- height	320 mm
	- width	320 mm
	- length	200 mm
	- weight	135 kg
	WINDING	
	- wire	Copper bus
	- number of turns	22
	Max gradient	19,926 Tl/m
	Max current	237.3 A
	Resistance	0,0392 Om
	Voltage	9,7 B
	Max. power	2297 W
	Quantity	7

The main requirements for dipoles and quadrupoles are: (1) Constant quality of the magnetic field for high and low fields, which covers the magnetic rigidity for a proton beam from 70 MeV to 250 MeV (for example, ± 0.08% for integral homogeneity of the field of dipoles); (2) maintaining the linearity of the field, which is important for the

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dynamic properties of magnets during fast energy switching for treatment; (3) Compact design of magnetic elements, which can optimize both the total weight of the gantry turning frame and the installation space.

The choice of two 60-degree dipole magnets for parallel transfer of the proton conductor axis is a compromise between the longitudinal length of the gantry (as shown in Fig. 1, the distance between the middle of the entrance of the first MDH 60-1 dipole and the isocenter is about 8.2 m) and the space for the inclined part of the beam channel which contains 5 quadrupoles and 2 correcting magnets.

TURNING FRAME DESIGN

The design of the turning frame is proposed to be realized in the form of a cylindrical tube assembled from three sections. Support rims are located at the outer ends of the outer sections, which are directly placed on roller bearings. The turning frame is set in motion by means of a gear motor with a gear transmission, the driven crown of which is located on one of the supporting rims. The gantry beamline is located on three main support platforms (Fig. 4), which in turn are located on the frame of the cylindrical tube of the turning frame. Adjustment of the position of each magnetic element can be realized using independent fasteners.

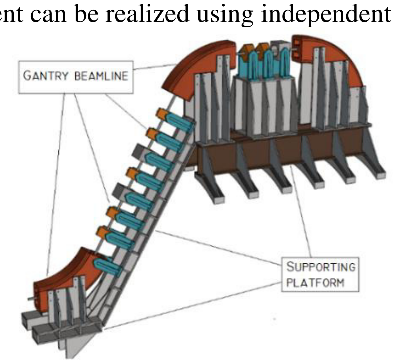


Figure 4: Layout of the gantry beamline and support platforms for magnetic elements.

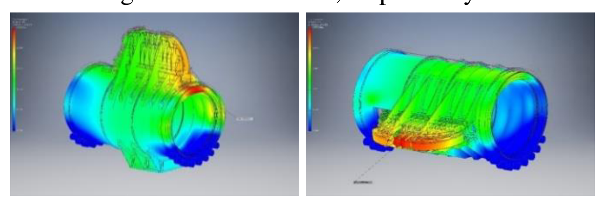
STATIC ANALYSIS OF STRESSES IN THE TURNING FRAME STRUCTURE

A turning frame with support platforms for placing elements of the magneto-optical gantry channel must withstand a weight of about 30 ~ 50 tons during the working process, therefore, stress analysis in structural elements of the pivot frame at various angles of its orientation is necessary to ensure the rigidity of the proposed structure. A three-dimensional model of a gantry turning frame with the corresponding weight and size characteristics was introduced into the stress analysis module of the Autodesk INVENTOR Professional software (Fig. 5). For the preliminary analysis, two directions of the angular orientation of the turning frame were selected - vertical and horizontal. Figure 5 shows the boundary conditions for the applied load on the frame. The yellow arrow shows the vector of the direction of the gravity force acting on the turning frame in the studied position.

A) B)

Figure 5: The boundary condition for the load on the turning frame in the vertical position (A), in the horizontal position (B).

Figure 6 shows a displacement diagram. Obviously, the maximum displacement of the structure falls on the support platform of the 90-hadus magnet and the rectilinear section of the magneto-optical channel from the 60-degree to the 90-degree magnet for the vertical and horizontal orientation of the turning frame, respectively. The maximum displacement is 0.35 mm and 0.56 mm for vertical and horizontal turning frame orientations, respectively.



A) B)

Figure 6: Diagram of the displacement of the turning frame structures in the vertical position (A), in the horizontal position (B).

CONCLUSION

The article presents the results of a preliminary study of the gantry design for the PRT center of the NRC "Kurchatov Institute". Based on the analysis of functional requirements, a structural diagram of a beamline for transporting a proton beam in a gantry and a design of a turning frame for placing all magneto-optical elements on it have been developed. The calculation program WINAGILE was used to calculate the beamline, determine the main parameters of the magnetic elements, and obtain axisymmetric beams with a radius of 5 mm for energies of 70 and 250 MeV. Static analysis using Autodesk INVENTOR Professional software has shown the rationality of the proposed design of the turning frame to accommodate of the gantry beamline.

The preliminary studies of the gantry design laid the foundation for the further implementation of the technical project and the manufacture of the main elements of the installation.

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