CERN

Summer Student Programme 2023

Dairis Rihards Irbe
BSc student at Riga Technical University of the Study Programme:
"Mechanical and Instrumental Engineering"

CERN Summer Student project report

Design of support structure for nozzle components in heavy ion therapy gantry.

Supervised by:
MSc Luca Piacentini
Dr. sc. Ing. Andris Ratkus
Prof. Toms Torims

CERN, CH-1211 Geneva, Switzerland

Abstract

Hadron therapy is a form of radiation therapy for cancer treatment. This cancer treatment approach shows multiple advantages to conventional radiotherapy such as higher precision, better effectiveness, minimal healthy tissue damage. Unfortunately, currently hadron therapy is hardly accessible due to complexity and high cost of infrastructure needed to accelerate and direct the beam of heavy particles. One of the most mechanically complex parts of this infrastructure is machine called *gantry*. It allows tumour irradiation from multiple desired angles by supporting part of beam transfer line that rotates around patient. "HITRI*plus*" is a project with the aim to introduce new technologies and improvements in hadron therapy providing the blueprint for the next state of the art hadron therapy center, hence improving the accessibility to the treatment. As a part of this project, this work proposes, the mechanical design of a gantry component called *gantry nozzle* that supports last part of beam transfer line. Topology optimisation is used as initial design followed by iterative manual optimisation for final design proposals. Two possible solutions of nozzle design are developed and compared. The total mass supported by the nozzle structure is estimated to be around 1.2t and the achieved mass of both proposals is lower than 1t while keeping transfer line component displacements within estimated required linear and angular tolerance of $\pm 0.2mm$ and $\pm 0.5\, mrad$ respectively. In addition to that, a design workflow is developed foreseeing its use to update the nozzle structure designs due to ongoing development of the whole system.

Contents

1. Introduction

Radiation therapy (RT) is one of the treatment options for cancer patients. This treatment uses radiation to damage cancer cell DNA and eventually kill them. External beam radiotherapy and brachytherapy are the two main branches of RT. Conventionally in external beam RT photon beam is used. [1] Photon beams e.g., X-rays or γ-rays, deposit highest radiation dose near the surface of the human tissue and diminishingly smaller dose thereafter. Therefore, also healthy tissue is irradiated for deep-seated tumour treatment. Hadron beams also can be used. In this type of therapy heavy ions and protons are used to irradiate the target. The dose distribution of these particle beams is entirely different in human tissue; the radiation dose slowly increases along beam path and transitions to a peak of deposited dose as the particle's energy decreases (see Figure 1). This peak is called Bragg peak. With hadron beam RT it is possible to accurately irradiate the tumour and minimise damage to healthy tissue.

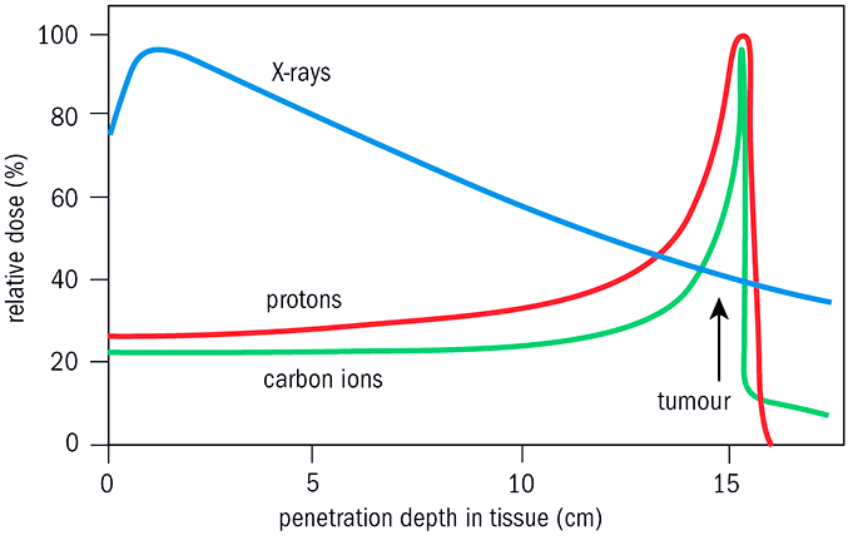


Figure 1: *Bragg curves of X-rays, protons and carbon ions. [2]*

Unfortunately, according to beam rigidity, the equipment necessary for hadron therapy is usually much larger in scale than that used for conventional photon therapy. For example, if X-ray therapy equipment can be considered as one room equipment that is relatively easily implemented in existing medical facilities, then hadron therapy equipment usually requires dedicated building. This increases the cost and complexity of creating facility capable of performing hadron therapy. By improving performance of components necessary for hadron therapy, there is possibility to minimise these drawbacks and make this treatment more accessible.

It is desirable to be able to irradiate tumour from different sides. This can be achieved in two ways – by rotating the beam around patient or moving the patient itself in respect to fixed beam. The first approach is preferred to minimise potential errors caused by internal movement of organs due to acceleration forces. In this case the beam transfer line is supported by a structure called gantry which allows the line to rotate around the patient and direct the beam at necessary angles. The beam transfer line supported by the gantry includes dipole magnets to bend the beam in perpendicular direction of the rotational axis (see Figure 2). These magnets and other transfer line components have significant mass that needs to be supported while maintaining alignment accuracy during rotation. In combination with other requirements this is a challenging task to design the gantry structure.

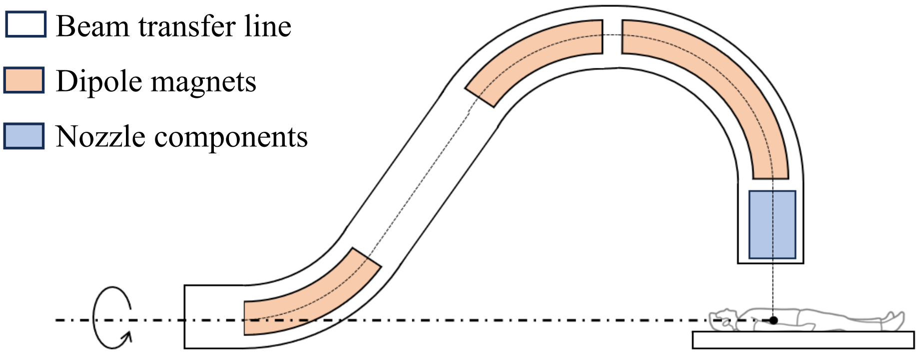


Figure 2: *Schematic representation of beam line supported by gantry.*

Some examples of gantries can be found in facilities such as Heidelberg Ion Therapy Center (HIT) in Heidelberg, Germany, where the complete gantry structure with attached beam transfer line weights approximately 660t [3] or in Heavy Ion Medical Accelerator in Chiba (HIMAC) in Japan where the gantry structure with beam transfer line weights approximately 300t [4]. One of the lightest carbon ion gantries with approximate mass of 200t is located in Yamagata University Hospital, Japan [5]. By optimising the gantry structure to minimise weight and size a cost reduction of the gantry structure and consequently of the hadron therapy facility could be obtained.

In this work the focus is on the structural design and optimisation of the gantry nozzle support structure which is a part of the gantry that supports the last section of the beam line (see Figure 2).

2. Design requirements and goals of the project

The gantry design proposed by Luca Piacentini shown in the Figure 3 is used as the basis for the nozzle structure design in this work.

The main components supported by the gantry nozzle are two warm dipole magnets also called scanning magnets (SMx and SMy) and the dose delivery system (DDS) (see Figure 3). These components have the most significant mass from all nozzle components therefore nozzle structure in this work has been mainly designed around them.

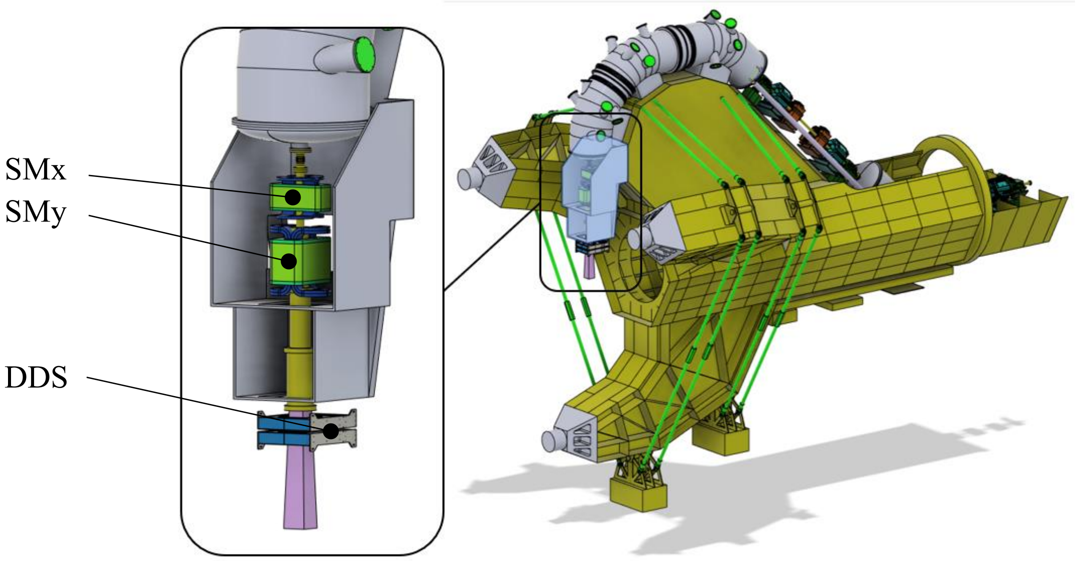


Figure 3: *Gantry and gantry nozzle components. (courtesy of Luca Piacentini)*

The gantry is designed to rotate $\pm 180°$ around its axis. During the rotation the gantry is elastically deformed due to its own weight and the weight of the transfer line elements, as a consequence these get displaced from their ideal position. The estimated maxim allowable linear and angular displacements for each of the beam transfer line components is $1\ mm$ and $1\ mrad$ respectively, but for sufficient safety margin in this work values are decreased to $0.2mm$ and $0.5mrad$. The displacement is measured in centre of mass of each component. Estimated component masses are listed in Table 2.

In combination with the maximum allowable displacements of the supported elements multiple requirements were set for nozzle structure design:

Table 1: *Requirements for the nozzle structure.*

No.	Requirement
F.1.	Nozzle structure shall support components SMx, SMy and DDS while maintaining linear displacement of each components centre of mass in range of ± 0.2 mm during gantry rotation.
F.2.	Nozzle structure shall support components SMx, SMy and DDS while maintaining angular displacement of each components centre of mass in range of ± 0.5 mrad during gantry rotation.
F.3.	Component alignment shall be possible in 3 perpendicular axes linearly in range of ± 5mm.
F.4.	Component alignment shall be possible in 3 perpendicular axes axially in range of $\pm 2°$.
D.1.	The weight of nozzle structure shall be minimised[1].
D.2.	Nozzle structure shall not exceed dimensional limits discussed in chapter 3.3.
D.3.	Nozzle structure shall not interfere with other components.
D.4.	The design shall take into account assembly procedures.
D.5.	Conventional manufacturing methods may be preferred for the nozzle structure.

It is important to note that many parts of the system are still in development phase and most input parameters are prone to change. Therefore, instead of a single design, it is important to create a design workflow that allows easy updates during other component development. Another goal of this project is to develop understanding of estimated nozzle structure characteristics such as weight, size, material, etc.

Table 2: *Estimated mases of nozzle components.*

Component	Mass, kg
SMx	260
SMy	690
DDS	210

[1] Currently there are no clear definition on maximum allowable mass for the nozzle structure, although it is crucial to minimise it as much as possible because it will directly influence further gantry design.

3. Nozzle structure design

As mentioned previously, the nozzle structure design in this work is based on current gantry design by Luca Piacentini, but approaches discussed below may be adoptable after design changes. The steps of the nozzle design are described more in detail in each of the subchapters.

3.1. Choice of the component supports

As for the first step it is important to understand the forces that are applied to the nozzle structure. The nozzle structure is supported by the rest of the gantry trough the attachment interface illustrated in Figure 4 (in red). The forces are applied mainly by nozzle components due to Earth's gravity. The fixturing solution between nozzle components and nozzle structure will define the direction, location and magnitude of forces applied to the nozzle structure.

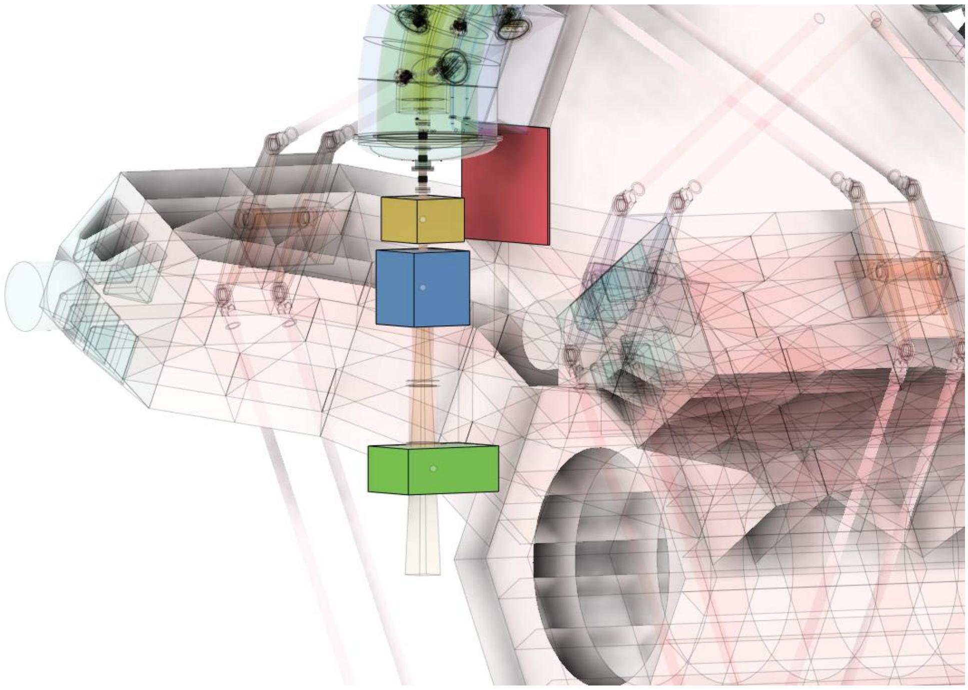


Figure 4: *Representation of nozzle components (SMx, SMy, DDS in yellow, blue and green colours respectively) and nozzle structure attachment interface in red.*

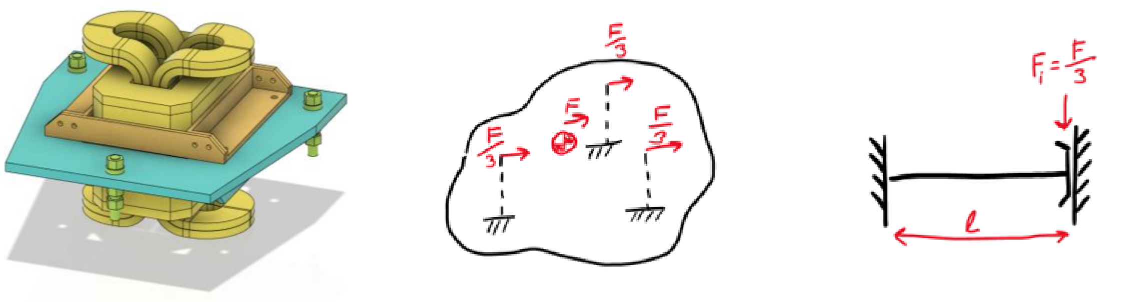
The fixturing method of nozzle components shall allow adjustability in all 6 degrees of freedom as defined by requirements F.3 and F.4 (see Table 1). Conventionally warm magnets are supported by 3 parallel adjustment screws (providing 3 degrees of freedom – one transversal along screw axis and two rotational) in combination with planar adjustability perpendicular to screw axis (providing 3 more degrees of freedom – two transversal and one rotational). This method further in the work will be referred to as "3-screw" fixturing method. Other fixturing methods such as parallel kinematics approach (similar to Stewart–Gough platform [6]) also might be used but, in this case, "3-screw" approach was favoured as a first consideration, because of its simplicity.

To verify suitability of "3-screw" approach for fixturing nozzle components the displacements introduced by this fixturing method were calculated both analytically and with finite element method (FEM).

Analytical displacement calculation for “3-screw” fixturing

Few assumptions about the fixturing design were made to simplify calculations:

1) Screws experience most of the strain, therefore all other parts in the fixturing system can be considered rigid.
2) Screws can be assumed to be homogeneous beams with circular cross section.
3) Bottom part of all 3 screws is rigidly restrained on a base plane.
4) Axes of all 3 screws are perpendicular to the base plane.
5) Screws are similar in length.
6) Supported body is rigidly connected to the top of all 3 screws.
7) Centre of mass for supported body is located on a plane that coincides with the top of all 3 screws.
8) Supported body cannot have angular displacement.
9) Maximum strain in the system is produced when applied force is perpendicular to screw axes.
10) Force (F) between screws is distributed equally, therefore strain in all screws is equal.



***(a)** the real system* ***(b)** overall structural schematic* ***(c)** single screw simplified model*

***Figure 5:** “3-screw” fixturing approach.*

By applying virtual work principle to loading case shown in Figure 5-c it is possible to find relation between applied force (F) and maximum displacement in the end of the screw (Δ) as shown in the Equation (1).

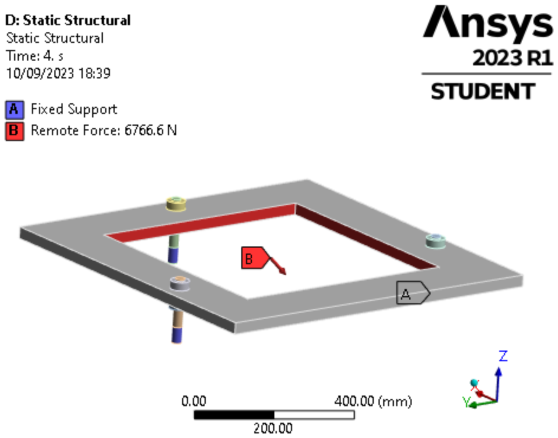
$$\Delta = \frac{Fl^3}{12 \cdot EI} \tag{1}$$

, where E - Young's modulus for the material of the screw, I – moment of inertia for the cross section of the screw; l – length of the screw.

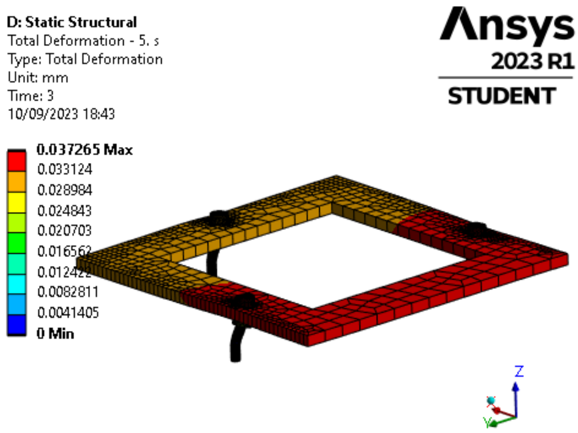
Based on the assumptions listed above maximum displacement of supported body’s centre of mass is the same as the displacement of calculated displacement for the end of single screw. Calculated results for different diameter screws are shown in Figure 7.

Displacement calculation for “3-screw” fixturing with FEM

In the geometry model used for displacement calculation of “3-screw” fixturing approach with FEM, screws were assumed to be cylindrical bodies, similarly as in analytical approach. Bodies representing nuts and washers were added to improve results of the simulation. Final model used in calculation with FEM is shown in Figure 6-a. Displacements were calculated for SMy at its centre of mass as it has the biggest mass of the nozzle components.



(a) Geometry and applied forces.



(b) Meshed geometry. Colours representing displacements in mm.

Figure 6: Geometry model used in displacement calculation with FEM.

Result evaluation for calculated fixture displacements

Both displacement calculation approaches were used to calculate displacement for SMy centre of mass. Screw length (l) were chosen to be 60mm to allow room for adjustments and additional components such as nuts, washers. Standard metric screw diameters according ISO724:2023 were evaluated in range of M20…M36. As shown in Figure 7 both methods give similarly exponentially distributed results. The difference between displacement values can be related to simplifications made in analytical calculations.

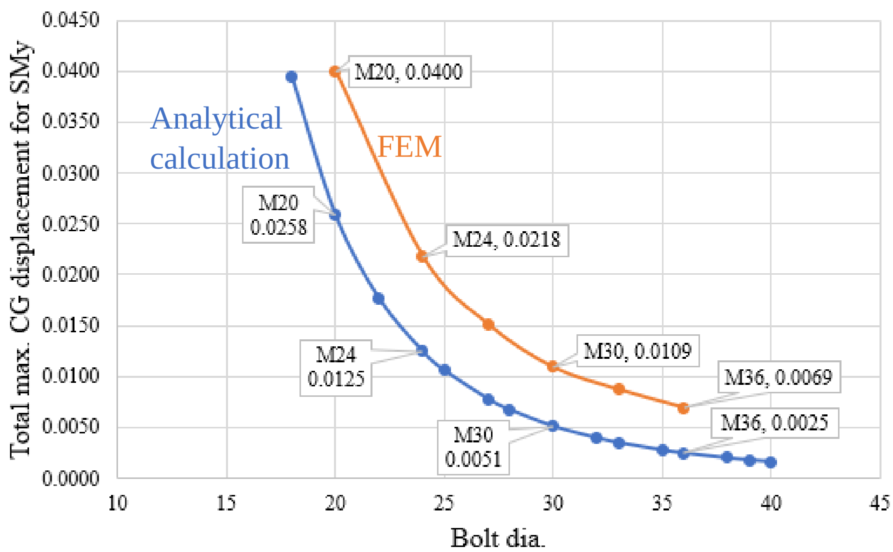


Figure 7: *Displacement of SMy centre of mass depending on screw diameter calculated by analytical and finite element method (FEM). Screw length* $l = 60mm$*; Young's modulus* $E = 200\ GPa$*; mass of SMy* $m_{SMy} = 690kg$*.*

If standard metric screw thread with nominal diameter of 30mm (largest diameter with 1mm standard pitch) is used, the displacements introduced by "3-screw" fixturing approach can be estimated to be $\cong 0.01mm$. It can be concluded that "3-screw" approach will introduce only negligible component displacements and can be used to support nozzle components.

Fixturing solution placement relative to components

It was chosen to orient adjustment screws for all fixtures in same direction so that all components could be adjusted simultaneously without necessity to rotate the gantry. There might be safety risks and possible adjustment complexity introduced if screws would be pointing in reverse direction for some component fixtures.

Additionally, it was chosen to orient adjustment screws pointing up, meaning that gantry needs to be in the vertical down position to align these components, the alignment of other elements of the line needs to be done instead in the vertical up position. The alignment of the elements in two stages does not seem to add major disadvantages. The mentioned choice provides easier accessibility to perform maintenance tasks and marginally simplifies the nozzle structure design.

The "3-screw" fixture placement that was used during the design of nozzle structure is illustrated in Figure 8.

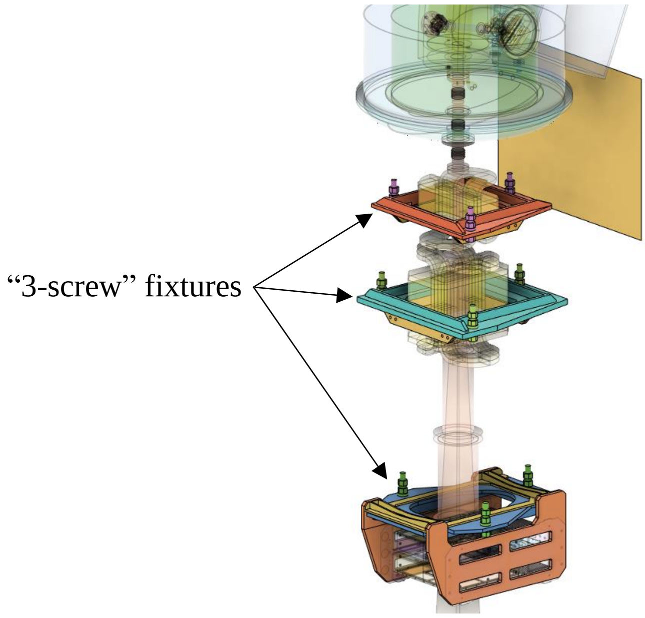


Figure 8: *Placement of "3-screw" fixtures.*

3.2. Assembly constraints

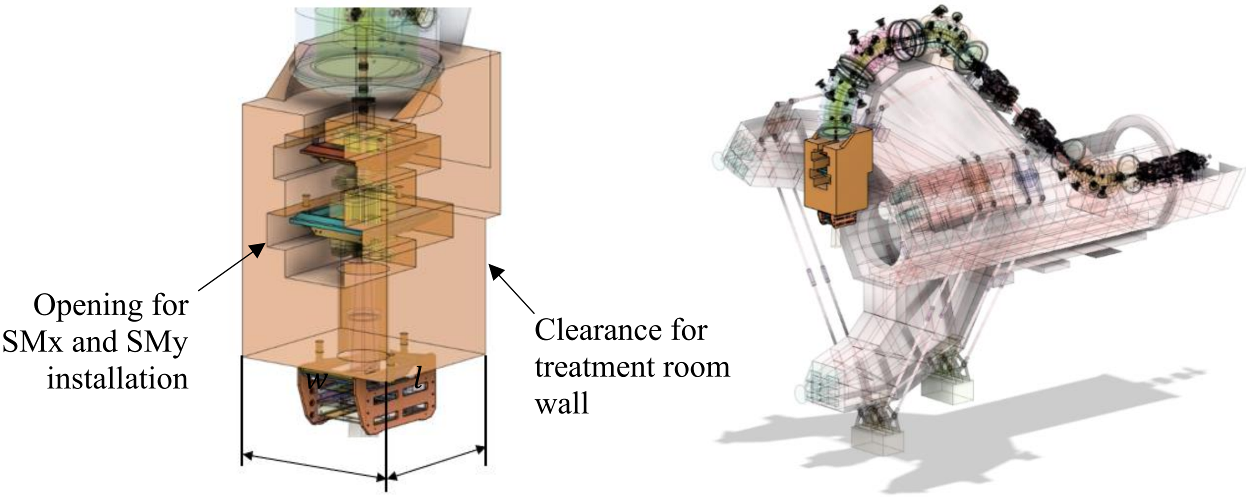
There are several assembly procedures that shall be respected during nozzle structure design. Firstly, the gantry nozzle is intended to be completely removable from rest of the gantry in case of larger maintenance task. Thus, the nozzle should be lifted by a crane vertically and moved to a dedicated place in the facility. The nozzle structure geometry must be designed so that the nozzle does not interfere with other components of the treatment room during the lifting procedure, hence minimising the number of other components that need to be disassembled/assembled.

Another assembly constraint arises from the fact that the beam pipe passing through both scanning magnets is planned to be installed before magnets are mounted in the nozzle structure, with the magnets split in halves and joined around the beam pipe first. Therefore, it must be possible to install both scanning magnets and the beam pipe as one sub-assembly.

3.3. Design domain for structure

In this step the initial design domain is defined for the nozzle structure. Overall dimensions of the nozzle structure are mainly governed by the fact that in the daily treatment room environment the nozzle must interfere minimally with other routine operations leaving the possibility of agile movements to the staff and the patient. It is preferred to keep the length (l) and width (w) (see Figure 9-a) to a minimum. In this case both dimensions were kept below $1.5m$. Also, to construct walls that divide the treatment room from gantry there must be sufficient clearance in the back of nozzle.

Constraints defined in chapter 3.2. have also been incorporated in the design domain, by creating opening for scanning magnet insertion; by providing sufficient clearance to other transfer line components and by creating clearance for nozzle structure removal.

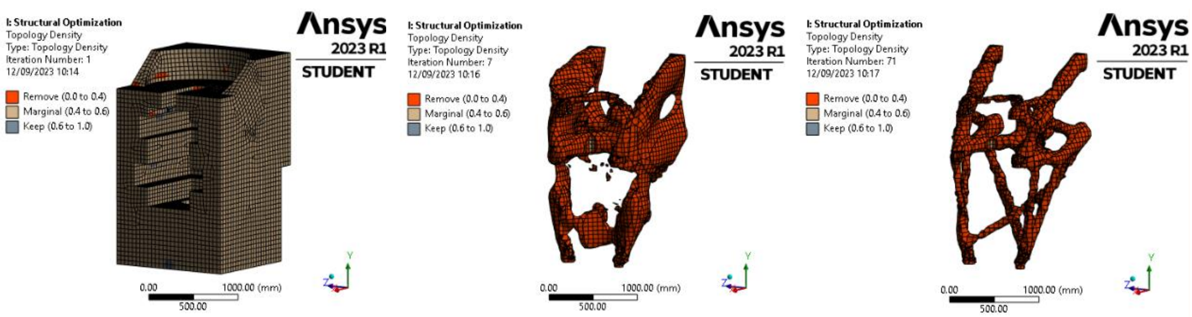


(a) *Design domain geometry.* ***(b)****Design domain (in orange colour) with respect to the gantry*

Figure 9: *Design domain for nozzle structure.*

3.4. Topology optimisation

Density based topology optimisation of design domain defined in chapter 3.3 was used to create a starting point for the nozzle structure design. Masses of SMx, SMy and DDS were attached in 3 locations for each component to simulate the "3-screw" fixturing. Finite element simulations for each optimisation iteration were done with 45° increments of gantry rotation. The objective of optimisation is to minimise strain energy while decreasing the mass.



(a) *Topology optimisation iteration number 1* ***(b)*** *Topology optimisation iteration number 7* ***(c)*** *Topology optimisation iteration number 71*

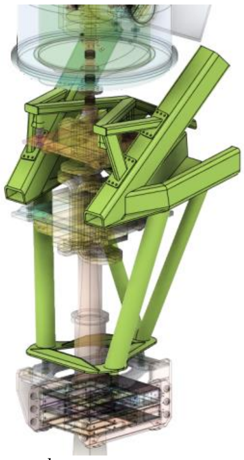
Figure 10: *Evolution of structure during topology optimization.*

3.5. Iterative structure design

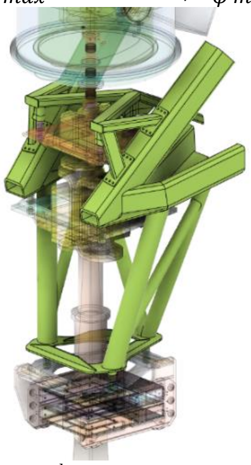
The topology optimisation provides a good starting point for the refined nozzle structure design. Unfortunately, with conventional manufacturing methods it is hard to manufacture optimised geometry directly. Based on preferred manufacturing method it is necessary to modify the design to enable manufacturability. As nozzle structure is fairly large for additive manufacturing, milling or casting, manufacturing from set of parts, primarily extruded beams connected by joints has been chosen. Standard size cross section beams and well-known joints (e.g. welded, bolted) have been used in this design.

Initial design of the structure is created by manually fitting beams and plates to the free-form geometry generated by topology optimisation. This first iteration (see Figure 11-a) of design can be relatively simple without focusing much on details because that will be improved in further steps. The material for the whole nozzle structure chosen is structural steel with Young's modulus of $200GPa$ and yield strength of $250MPa$. The displacements and stresses in the structure then are calculated with FEM. Based on the results improvements to the design may be made, such as beam placement and cross section adjustments. These design changes can also be automated by parameterizing the design and applying some optimisation algorithm. For designed nozzle structure multi objective generative algorithm (MOGA) was used to optimise beam cross section thicknesses (see Figure 11-c). The structure is iteratively updated based on FEM calculation results until satisfactory results are met.

(a) *1st nozzle design iteration.*
$m \cong 1300kg;\ \Delta_{s\,max} = 0.10mm; \Delta_{\phi\,max} = 0.05\ mrad$



(b) *2nd nozzle design iteration.*
$m \cong 730kg;\ \Delta_{s\,max} = 0.13mm; \Delta_{\phi\,max} = 0.30\ mrad$



(c) *3rd nozzle design iteration.*
$m \cong 620kg; \Delta_{s\,max} = 0.11mm; \Delta_{\phi\,max} = 0.22\ mrad$

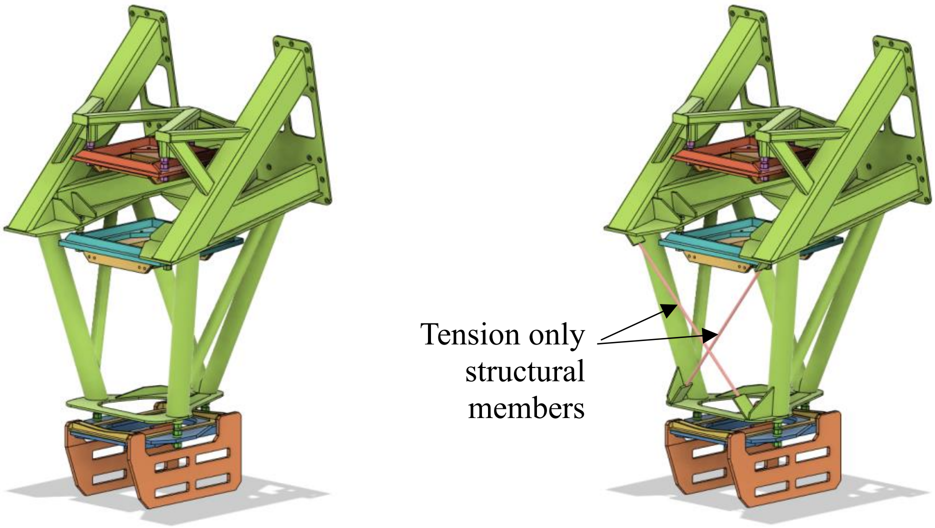
(d) *4th nozzle design iteration.*
$m \cong 760kg$[2]$; \Delta_{s\,max} = 0.12mm; \Delta_{\phi\,max} = 0.11\ mrad$

Figure 11: *Nozzle structure design iterations, where m-mass of the structure; $\Delta_{s\,max}$ and $\Delta_{\phi\,max}$- maximum linear and angular displacements of nozzle components calculated with FEM.*

[2] Mass increase in this iteration is related to added parts, such as attachment plate for connection to gantry.

4. Results

In the 4th design iteration (see Figure 11-d) 2 tension-only members were introduced to decrease angular displacements of DDS. Two final nozzle structure design candidates were created based on this 4th design iteration – 1st without and 2nd with these tension-only members. In Table 3 difference between nozzle component displacements for both designs is shown.



(a) Design 1. Nozzle structure without tension-only members.
(b) Design 2. Nozzle structure with tension-only members.

Figure 12: *Final nozzle structure designs.*

In the final design option 2 (see Figure 12) both tension-only structural members are prestressed to $\cong 1KN$. This ensures that they remain in tension during gantry rotation.

For both designs calculated maximum stress is around $30MPa$, which is well below steel endurance limit [7].

Result evaluation

Looking at Table 3 it is possible to see that tension-only members significantly reduced DDS angular displacement around x axis and reduced DDS linear displacement in y axis from $0.18mm$ to $0.12mm$ without adding much mass. Other component displacements stay practically unchanged.

Both designs fit in all displacement requirements (F.1; F.2), but the comparison demonstrates the potential of tension only members in the structure. If necessary, tension only members may be designed to be removable.

Based on design procedure described in chapter 3 it is possible to define workflow for nozzle structure design (see Figure 13).

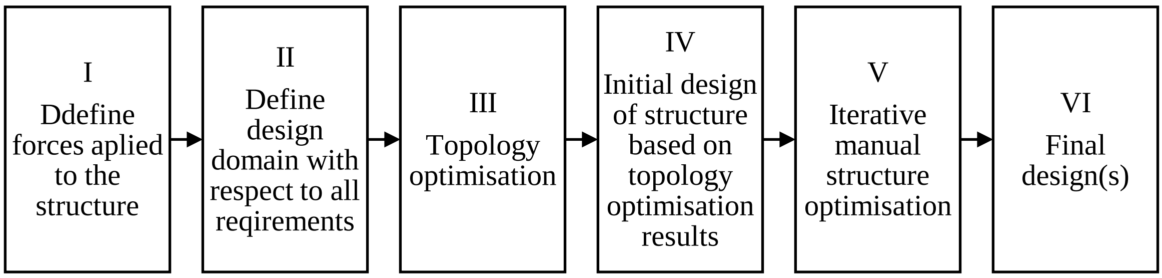
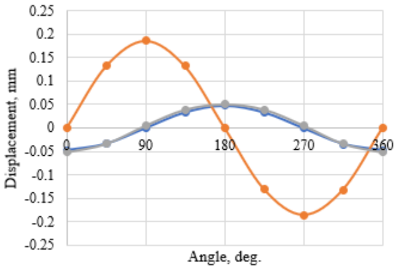
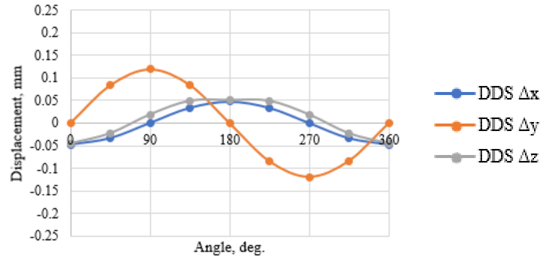
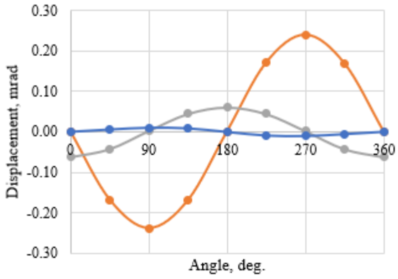
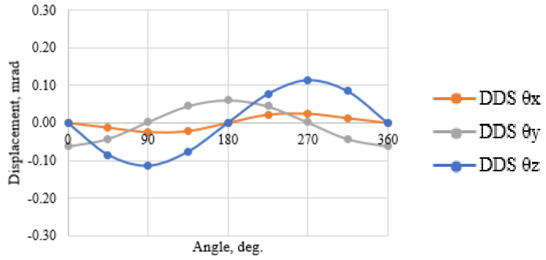
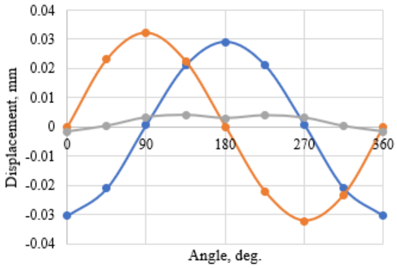
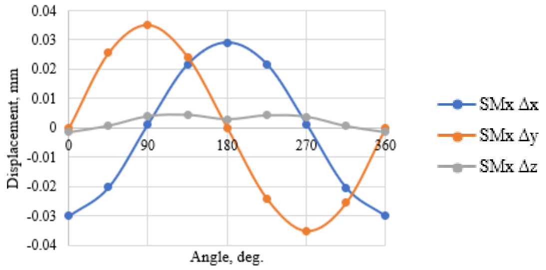
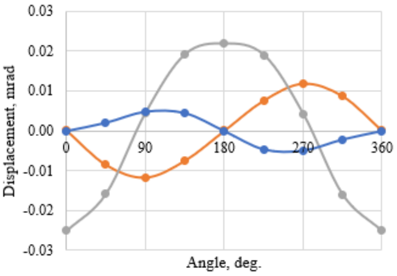
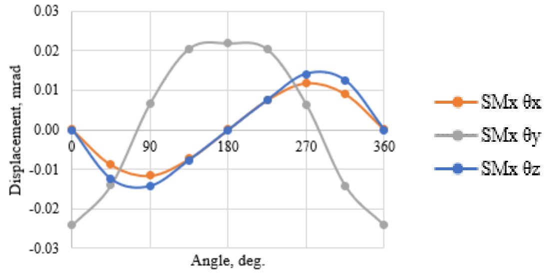
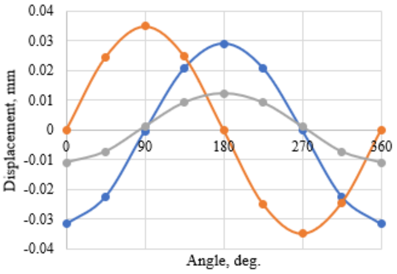
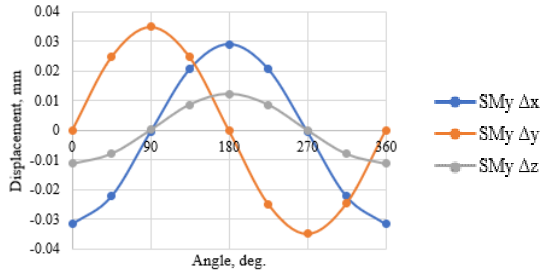
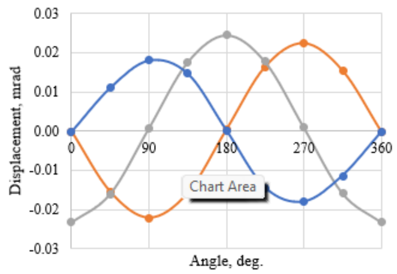
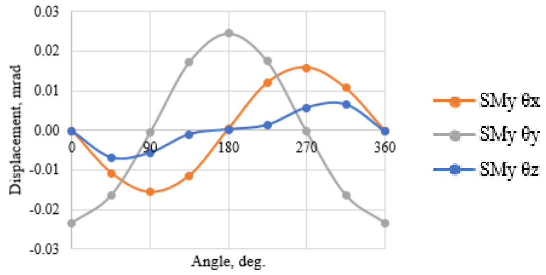


Figure 13: *Flowchart of the nozzle design workflow.*

__Table 3:__ Displacements of nozzle components during gantry rotation.

<table>
<tr><th>Parameter</th><th>Without tension-only members</th><th>With tension-only members</th></tr>
<tr><td>Approximate mass of structure</td><td>740 kg</td><td>760 kg</td></tr>
<tr><td>DDS linear displacement</td><td>
</td><td>
</td></tr>
<tr><td>DDS angular displacement</td><td>
</td><td>
</td></tr>
<tr><td>SMx linear displacement</td><td>
</td><td>
</td></tr>
<tr><td>SMx angular displacement</td><td>
</td><td>
</td></tr>
<tr><td>SMy linear displacement</td><td>
</td><td>
</td></tr>
<tr><td>SMy angular displacement</td><td>
</td><td>
</td></tr>
</table>

Conclusions

1) It is possible to design nozzle structure that meets all defined requirements and has a mass around 750 kg.
2) Conventional materials and manufacturing methods such as extruded steel beams and plates can be used for nozzle structure design.
3) To minimise displacements and mass of the structure it may be beneficial to implement tension-only components in nozzle structure.
4) Future work may include:
    a. Development of more complete gantry design to understand deformations in the gantry structure that might be a large contribution to nozzle component displacements. Currently only displacements introduced by nozzle structure are calculated.
    b. Other optimisation method implementation such as proposed by Nigel J.W. Morris et al. [8] that might be used to achieve better nozzle structure design. Structure optimisation approach discussed in this work may be sufficient, but it is possible that "local maximum" of the design had been reached and there are other better solutions.
    c. Consideration of other materials such as composite materials that might reduce mass of the structure.

References

[1] U.S. Department of Health and Human Services, National Institutes of Health, National Cancer Institute, “Radiation Therapy,” 8. Jan. 2019. [Online]. Available: https://www.cancer.gov/about-cancer/treatment/types/radiation-therapy. [Accessed 5. Sept. 2023].

[2] J. Hérault, P. Mandrillon, F. Demard and R. Trimaud, “CERN COURIER; Proton therapy enters precision phase,” 16 Sept. 2016. [Online]. Available: https://cerncourier.com/a/proton-therapy-enters-precision-phase/. [Accessed 5. Sept. 2023].

[3] O. Jäkel, G. Kraft and C. P. Karger, “The history of ion beam therapy in Germany,” *Zeitschrift für Medizinische Physik,* vol. 32, no. 1, pp. 6-22, 2022.

[4] K. Nobuyuki, F. Takuji, H. Yousuke, I. Taku, I. Yoshiyuki, M. Kota, M. Shinichiro and S. Toshiyuki, “New technologies for carbon-ion radiotherapy — Developments at the National Institute of Radiological Sciences, QST, Japan,” *Radiation Physics and Chemistry,* vol. 162, pp. 90-95, 2019.

[5] C. Graeff, L. Volz and M. Durante, “Emerging technologies for cancer therapy using accelerated particles,” *Progress in Particle and Nuclear Physics,* vol. 131, 2023.

[6] A. A. Markou, S. Elmas and G. H. Filz, “Revisiting Stewart–Gough platform applications: A kinematic pavilion,” *Engineering Structures,* vol. 249, 2021.

[7] The Engineering ToolBox, “Steels - Endurance Limits and Fatigue Stress,” 2011. [Online]. Available: https://www.engineeringtoolbox.com/steel-endurance-limit-d_1781.html. [Accessed 15 Sept. 2023].

[8] N. J. Morris, P. K. Jayaraman and A. Butscher, “BeNTO: Beam Network Topology Optimization,” *Computer-Aided Design,* vol. 156, 2023.