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RESEARCH ARTICLE

REVISED Comparative study on scenarios for rotating gantry mechanical structures

[version 4; peer review: 2 approved]

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Abstract

Background

This paper outlines a comparative study on scenarios of gantries mechanical design for ion-therapy of cancer, which is a crucial step toward the development of the next ion medical machine.

Methods

Multiple scenarios were considered based on robustness of the design, size, weight and complexity, deformation and precision performances and costs, as well as environmental impact. Four prospective scenarios were identified, each of them capable of providing beam to at least 220°around the patient. One scenario is capable of providing treatment angles of 360°. This report will describe the unified methodology performed during the study in order to achieve unbiased results in a comprehensive manner.

Results

Results show that in statically balanced scenarios, considerable improvements can be reached in terms of safety, deformation, precision performances, complexity and costs of implementation.

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Any reports and responses or comments on the article can be found at the end of the article.

Conclusions

All scenarios are deemed suitable for further gantry design development.

Keywords
Particle Therapy, Ion Therapy, Gantry, Mechanical Design



This article is included in the Horizon 2020 gateway.



This article is included in the Medical Physics collection.

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REVISED **Amendments from Version 3**

With the new version the authors hope to clarify the open questions raised by reviewers.
A paragraph in the "Costs of components manufacturing" has been modified. The choice of Stainless steel rather than a structural steel has been clarified highlighting that the cost of raw material is estimated 0.35% to 1% of the total cost of the gantry facility. The choice was then focused on a material that guarantees the best corrosion resistance and is commonly considered to fit the tight requirements for a medical machine.
A section, named "Material activation" has been added to add to the comparison an evaluation of the potentially different material activation for the scenarios proposed.

Any further responses from the reviewers can be found at the end of the article

Introduction

In 2020, 2.7 million people in the European Union were diagnosed with cancer, and another 1.3 million people died as consequence of the same disease. Today, Europe hosts a tenth of world's population but contributes to a quarter of world's cancer cases. Lives lost to cancer are expected to rise by more than 24% by 2035. Although cancer is an individual diagnosis, it has non-negligible impacts on the lives of the patient's relatives and social group. The overall economic impact of cancer in Europe is estimated to cost more than €100 billion per year[1].

In addition to traditional cancer treatments such as surgery, chemotherapy, immunotherapy and classical radiation therapy, during the last 60–70 years hadron therapy emerged as a new field in radiation therapy. In particular it demonstrated to be a key option for treatments of pediatric solid tumours, tumours of the brain, skull base, spinal cord, upper respiratory tract, chest, pelvic and others[2].

CERN is active in knowledge and technology transfer from physics to medicine and society in general. In 1996 the Proton-Ion Medical Machine Study (PIMMS)[3,4] group was formed with commitment to design a cancer therapy synchrotron. CERN agreed to host this study in its Proton Synchrotron Division. One of the many results of this study has been the implementation of a synchrotron and a fixed gantry in the medical environment of the Italian National Center of Oncological hadron therapy (CNAO) and MedAustron in Austria.

With the definition of the European Strategy for Particle Physics in 2006, in one of its statements, CERN Council recognized the need to promote the impact of particle physics research on society proposing 'to create a technology transfer forum to analyse the keys to the success in technology transfer projects in general'[5]. Since 2006 regular updates have been required by the European Strategy Group. Environmental and societal impact has been one of the pillars in every update, the most recent being in 2020[6]. Meanwhile, to further formalize the commitment of CERN in knowledge and technology transfer in medical applications, in 2014 the CERN Medical Applications Steering Group was founded by council decision, being this the very first organizational structure created with this scope. In 2016 a more robust structure was established[7] guided by CERN Medical Applications Steering Commitee.

As CERN did with PIMMS in the past, its commitment to develop next-generation ion therapy facilities resulted in the establishment of the Next Ion Medical Machine Study (NIMMS)[8], an initiative funded by the CERN Knowledge Transfer for Medical Applications and intended to stimulate wide European collaborations. NIMMS is organised in three work packages (superconducting magnets, linacs, gantries). The aim of the gantries work package is to design a superconducting ion gantry that is more efficient in term of costs and size with respect to existing ones, both normal-conducting and superconducting. Indeed, ion therapy requires a rotating gantry to maximize its efficacy giving to clinicians a tool that is able to provide 3D optimized treatments, necessary for example to better spare an organ at risk or to minimize the radiation dose in healthy surrounding tissues. Existing gantries for heavy ions, are massive (300 tons for the superconducting unit of HIMAC in Chiba[9] and 600 tons for the normal-conducting one of HIT in Heidelberg[10]) and require high standard technologies, thus expensive. The cost makes these facilities a luxurious investment for countries, limiting general public accessibility to such treatments.

In the development of gantry technologies two projects approved and funded by European Commission Horizon 2020 Research Infrastructure are integrating the NIMMS resources with those of collaborating institutes throughout Europe, namely: HITRI *plus* (Heavy Ion Therapy Research Integration)[11] for the development of ion therapy accelerator technologies, and I.FAST (Innovation Fostering in Accelerator Science and Technology) for the development of curved superconducting magnets. These activities are additionally supported by the State Research Programme in High Energy Physics and Accelerator Technologies of Latvia[12]. The combined efforts of these projects aim to answer the needs of the medical accelerator community for latest state of the art technologies associated to ion therapy.

Main developments on rotating isocentric gantries before the start of HITRI *plus* in April 2021 were concentrated on an innovative scenario named SIGRUM (Superconducting Ion Gantry with Riboni's Unconventional Mechanics[13,14]), developed by TERA Foundation in collaboration with CERN. A following study was mainly focused on a possible mechanical optimization of the structure[15].

This note reports on a new collaborative effort between CERN EN-MME (Mechanical and Materials Engineering department), CERN TE-MSC (Magnets, Superconductors and Cryostats Technology department), RTU (Riga Technical University) and UNIBS (University of Brescia) consulting experts from the CNAO ion therapy centre as part of the HITRI *plus* project. Several scenarios of mechanical structures for isocentric gantries have been identified, a series of parameters to evaluate the compliance to main requirements for the selected scenarios have been defined and eventually the result of the comparison is reported.

Challenges

The first major challenge is the control of the cost of the complete and functional machine that has to remain within some price limits defined in the HITRI *plus* project[16]. Since

a reduction in the load carried by the mechanical structure is expected from the use of bent superconducting magnets of new design, there are opportunities to reduce weight and cost. Moreover, a second challenge is to provide a comprehensive and impartial analysis to obtain reliable results while still in a preliminary phase of the project. The multidisciplinary nature of the gantry is in itself another relevant challenge, requiring to acknowledge interdisciplinary connections and to evaluate their influence on studied parameters. In general terms, the improvement of the Technology Readiness Level (TRL)[17] of this design is the final outcome of the project. Starting from the presently evaluated TRL 1 for the mechanical structure and its motion system, whose technology concepts have been proposed, reaching TRL 2.

Main requirements

Table 1 summarizes the main desirable characteristics for the next generation of rotating gantries.

Design robustness is guaranteed by relevant mechanical design choices. This requirement obviously comes as first rule while designing a machine or component that meets safety specifications.

Size requirements were set in accordance with CNAO based on expected available on-site space for a possible first implementation of the gantry, corresponding to an internal volume of about 20×20×20m^3 room (width × length × height). The HITRI *plus* project has placed specific requirements on weight and complexity to favour a subsequent industrialization of the design. The target in this case is to maintain the weight at about 100 tons, which is a substantial reduction when compared to the 600 for HIT (with a gantry hall of 15×26×16m^3) and 300 tons of HIMAC respectively (gantry length of 13m and beam orbit radius of 5.45m, estimated gantry hall of 15×20×16m^3). Deformation and precision performances requirements are obtained by translating the needs of the medical community to ensure the proper accuracy in the beam delivery to the patient.

Environmental requirements, mainly related to the minimization of energy consumption, shall be considered as well. The machine consumes energy in multiple systems: cryogenic, transfer line magnets, accelerator magnets and gantry motion. However, the consumption of the latter is orders of magnitude lower than the others; its relevance is proportionally weighted in our study, since it is not heavily impacting the total efficiency of the system.

Important clinical requirements come from the necessity of maximizing effectiveness of treatment plans by using multiple treatment angles, thus a gantry rotation between ±110° and ±180° (measured from the horizontal plane) is required.

Methods

The study has been done using a comprehensive approach aiming at being impartial in providing objective tools to compare mechanics advantages and disadvantages of each proposed scenario. This note reports about challenges related to the mechanical structure and its motion system, without considering aspects related to medical treatment. However, general inputs from clinicians have been considered, such as: estimated size of patient couch and its motion, desired volumetric imaging system at the isocenter and the gantry angular speed. The study was subdivided into three steps:

- Definition of relevant scenarios,
- Definition of relevant comparison parameters,
- Analysis of selected parameters.

This study has evolved directly from the SIGRUM analysis[13,14]. The proposal of scenarios was carried out during periodic meetings. Comparison parameters were proposed by taking into account the ones related to project requirements and challenges, with the expansion or addition of new parameters. The analysis of such parameters has been done by using the following tools:

- 3D modelling and Finite Element Analysis (FEA) software, Inventor and Solidworks,
- Computation software, Wolfram Mathematica and Microsoft Excel.

Results or hypotheses have been validated by double checking with different methods in the case of quantitative data (i.e. for mathematical models) or, if qualitative, by reaching common agreement during constant discussions within the group of experts mentioned above. Results have been summarized in a final table by ranking the scenarios with respect to each parameter. The arbitrary ranking system consists in levels from one to five, related to a rising level of compliance to the specific parameter. During the study development, the awareness of crucial medical needs for appropriate treatment was always present.

Comparison and analysis of scenarios for rotating gantry

The transfer line proposed in 13,14 was used as general input for this study:

- 3T magnets,
- Overall radial position of the center of gravity of the line: 3.5m,

Table 1. List of relevant desirable characteristics for a rotating gantry.

Safety	**robustness of the design**
Technological prerequisites	size weight and complexity performances: deformation and precision
Environmental	minimal energy consumption
Clinical requirements	treatment angle coverage

- Mass of the line: ≃ 12 ton.

The comparison of scenarios was done assuming independence of the mechanical structures from the transfer line general layout unless its mass and radial position of the center of gravity varies much (i.e. using 5T magnets). However, even in that case it is believed that relative advantages and disadvantages would not change much between scenarios. Between 10 and 15 scenarios, considering both balanced and unbalanced variants were proposed during discussion sessions with experts. However, not every scenario satisfied all general technological requirements (i.e. design robustness, energy consumption or size limits). Therefore, a screening process has been applied, mainly driven by considerations related to the robustness of the design and failure scenarios:

1. Scenarios can be categorized as 'balanced' (statically), if their center of gravity stands on the rotation axis, or 'unbalanced' otherwise. Balanced structures are achieved by the integration of a counterweight. All scenarios proposed in Table 2 are fully balanced.

2. The same equation of motion has been applied to simulate the movement of the gantry (three step constant acceleration-constant speed-constant deceleration). The time to make half a rotation has been assumed to be 30s, while any other rotation time is proportional. Thus, the maximum angular velocity is approximately 0.21 rad s^{-1}, independently for balanced and unbalanced.

3. Unbalanced scenarios can behave like physical pendulums in high danger situations (i.e. caused by lost of braking action, lost of hydraulic pressure, mechanical failure of ropes). Hence, the system accelerates due to gravity, the worst case being when the system is already at its maximum speed and a high danger failure occurs. It has been assumed that the reaction time of the braking system is 0.2 s and that balanced structures have double the moment of inertia with respect to unbalanced. Since the speed of unbalanced structures doubles during the reaction time, the rotational kinetic energy increase overall by a factor of two, with respect to balanced scenarios.

Prospective scenarios

The scenarios that sufficiently satisfied requirements mentioned in the previous paragraph were more thoroughly investigated. They are the balanced variants shown in Table 2, their main properties being listed in Table 3.

Dimensions of 20 × 20 × 20 m^3 (width × length × height) have been specified by the responsible physicists of a medical facility that is interested in the installation of the machine; the study of the present article is intended to be as general as possible and new facilities may have less stringent requirements. Relating the size requirement to the cost of the facility, cost which is highly influenced by the volume of the building, all the proposed structures have an overall internal volume lower than 20 × 20 × 20 m^3. All structures exceed the length by 0.5 meters, which is not impacting the comparison. Only SSG structure exceeds the height by 3 meters, while keeping the overall internal volume less than the required one. Additionally, the height is considered to be of less concern in the space reservation, not impacting the allocated footprint.

Analysis of main parameters

Taking into account the technological requirements in Table 1 and the challenge related to costs, Table 4 lists a series of decisive parameters that have been proposed and analysed following the methodology explained in the homonym Section. The minimum clinical requirement of ±110° rotation is satisfied by all scenarios proposed, while only the FTG can cover the full ±180° rotation.

The main decisive parameters are explained in the following sections, those not described explicitly are thought to be deductible from the summary Table 6 that will appear at the end of the analysis of all parameters.

Failure scenarios

Addressing failure scenarios, two key aspects have been considered: the acceleration due to gravity, and the malfunctioning of the driving system. The model of non-damped physical pendulum has been taken into account with Equation 1 in the case of an unbalanced gantry accelerating due to gravity:

$$\vartheta'' = \frac{mgR_{COG}}{J}\sin\vartheta \tag{1}$$

where: m is the mass of the gantry, g is the gravitational acceleration, R_{COG} is the radial position of the center of gravity with respect to the rotation axis, ϑ is the angular position of the gantry (measured from the top vertical position) and J is the moment of inertia of the gantry. Equation 2 models the case of a malfunction of the driving system for balanced scenarios.

$$\vartheta'' = \tau/J \tag{2}$$

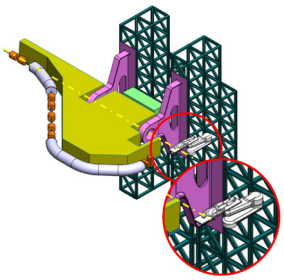
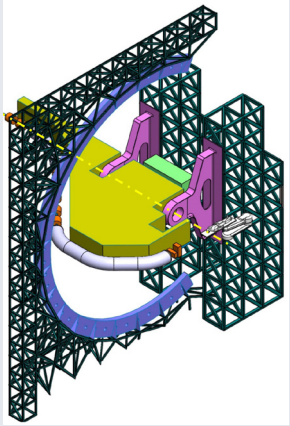
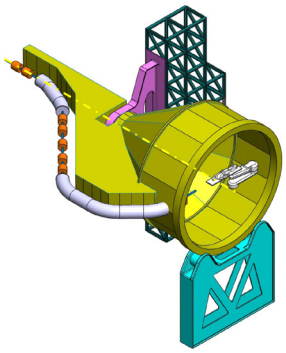
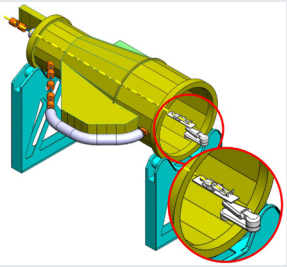
where τ is the torque applied to the gantry. The torque τ is assumed to be constantly applied and be twice the maximum nominal value of the torque.

The software Mathematica has been used to calculate the rotational kinetic energy for a base case (SIGRUM) and for the other balanced scenarios proposed (Python could have been used alternatively to obtain same results). This was done by solving numerically the differential Equation 1 and Equation 2 calculating the angular speed with a starting value of 0.21 rad s^{-1} (as discussed above): results are reported in Figure 1. The value of 0.2 s represents the time before a collision of balanced structure with walls, assuming a clearance of 5° starting from the nearest available treatment position. This requirement shall also be used to design the treatment room environment avoiding dangerous collisions. Furthermore, the values of the kinetic energy after the reaction time have been used to rank structures in relation to the 'failure scenarios' parameter in Table 6.

Deformation of the structure and its improvement margin

Deformation performances of the structure were already addressed in the preliminary stage of the study: an estimation of displacement of transfer line elements was done for the SIGRUM in 15,18. Whenever a requirement needs to be

Table 2. Prospective scenarios of mechanical structure for rotating isocentric gantries.

	**Balanced SIGRUM (B-SIGRUM)** A balanced structure with two side supports, driven by an electric motor (and gearbox) directly mounted on the axis. Proposed to improve robustness of the design of SIGRUM only by the addition of a relatively simple counterweight (in green). • ±110° deliverable treatment angle range. • External volume of construction: 21.5 × 28.5 × 27m^3 • Internal volume of construction: 11.5 × 20.5 × 20m^3 • Rotating mass about 70 ton. • Relevant moment of inertia: 500000 kgm^2
	**Simply Supported Gantry (SSG)** Two side supports and one perimetrical support balanced structure. Driven by an external electric motor through off-axis rope and pulley transmission system. Proposed to reduce absolute displacement without unconventional compensation methods. • ±110° deliverable treatment angle range. • External volume of construction: 22×28.5× 30m^3 • Internal volume of construction: 12×20.5× 23m^3 • Rotating mass about 70 ton. • Relevant moment of inertia: 500000 kgm^2
	**Side and Cradle Supported Gantry (SCSG)** One side and one ground support balanced structure. Driven by off-axis friction rollers, coupled to an electric motor, or by external hydraulic system through rope transmission system. Proposed as intermediate solution between SIGRUM and Full Turn Gantry. • ±110° deliverable treatment angle range. • External volume of construction: 21.5 × 28.5 × 27m^3 • Internal volume of construction: 11.5 × 20.5 × 20m^3 • Rotating mass about 120 ton. • Relevant moment of inertia: 700000 kgm^2
	**Full Turn Gantry (FTG)** Two ground support balanced structure, driven by off-axis friction rollers, coupled to electric motor. Proposed to cover a full turn, minimizing bed couch movements. • ±180° deliverable treatment angle range. • External volume of construction: 28×28.5×27m^3 • Internal volume of construction: 16×20.5×20m^3 • Rotating mass about 120 ton. • Relevant moment of inertia: 700000 kgm^2

satisfied from the mechanical point of view it must be noted that stricter requirements (i.e. lower displacement) usually require higher stiffness, adding weight to the structure. Therefore, to achieve the compromise between stiffness and weight within the requirements set for this study, an innovative method of mechanical optimization to recover the rigid part of the displacement was proposed[15,18], reducing the displacements by one order of magnitude (from several mm to less than a mm, see Figure 2 and Figure 3). Aforementioned results have been obtained assuming to use stainless steel (Young's modulus 200 GPa) for the main structure due to magnetic properties.

This optimization process has been proved to be particularly effective if applied to structures that behave like 'cantilever'

Table 3. List of scenarios main properties.

	B-SIGRUM	SSG	SCSG	FTG	
Treatment angle range	±110	±110	±110	±180	deg
External volume of construction	21.5 × 28.5 × 27	22 × 28.5 × 30	21.5 × 28.5 × 27	28 × 28.5 × 27	m^3
Internal volume of construction	11.5 × 20.5 × 20	12 × 20.5 × 23	11.5 × 20.5 × 20	16 × 20.5 × 20	m^3
Rotating mass	70	70	120	120	ton
Relevant moment of inertia	500000	500000	700000	700000	kgm^2

The size of the support ring varies between SCSG and FTG, influenced by a different positioning of the patient couch which has to compensate the limited rotation of ±110° of the SCSG.

Table 4. List of key parameters.

Robustness of the design	
• Failure scenarios	Consider the possibility of the gantry to accelerate uncontrollably due to gravity or a failure of the motion system
• Possible safety brakes position	Evaluates the possibility to have safety brakes in strategical positions
• Number of systems to brake	Estimates the number of systems to brake
Size	
• Room space requirements	Evaluates the volume of the scenario
Weight and complexity	
• Weight and inertia	Evaluates the weight and moment of inertia of scenarios
• Complexity	Evaluates the complexity of the assembly i.e. R&D needed for the supports
Performances: deformation and precision	
• Load properties	Express the max value of the load on the supports and if it is related to the angular position of the gantry during the treatment phase.
• Deformation performances (structure)	Evaluates the scenarios based upon displacements of the transfer line
• Improvement margin of deformation performances	Estimates the margin of mechanical optimization based upon knowledge
• Deformation performances (supports)	Assesses the deformation of the supports
• Tolerances	Estimates the difficulty in achieving tolerances in different scenarios
Costs	
• Cost of manufacturing components	Estimates relative costs of manufacturing components for each scenario
• Cost of the driving system	Estimates relative costs of the driving system
Environmental	
• Minimal energy consumption	Estimates the energy consuption
• Material activation	Estimates the impact of material activation for the gantry structure

beams (with a portion of structure hanging while one end is fixed). There is no reason to believe that this method is not applicable to B-SIGRUM with almost equal results. Furthermore, even if applicable this method has not yet been applied neither to SCSG nor to FTG, because the iterative mechanical optimization has not been performed. However, it is possible to assume that similar results can be reached for SCSG and FTG. Although the aforementioned method is not applicable to the SSG scenario, this is expected to benefit of similar displacement reduction thanks exclusively to its support configuration, acting like a simply supported beam (a structure supported at both ends, see Table 5). The advantage between a simply supported structure and a cantilevered one is independent from the material properties, given that the two structure are made of the same material.

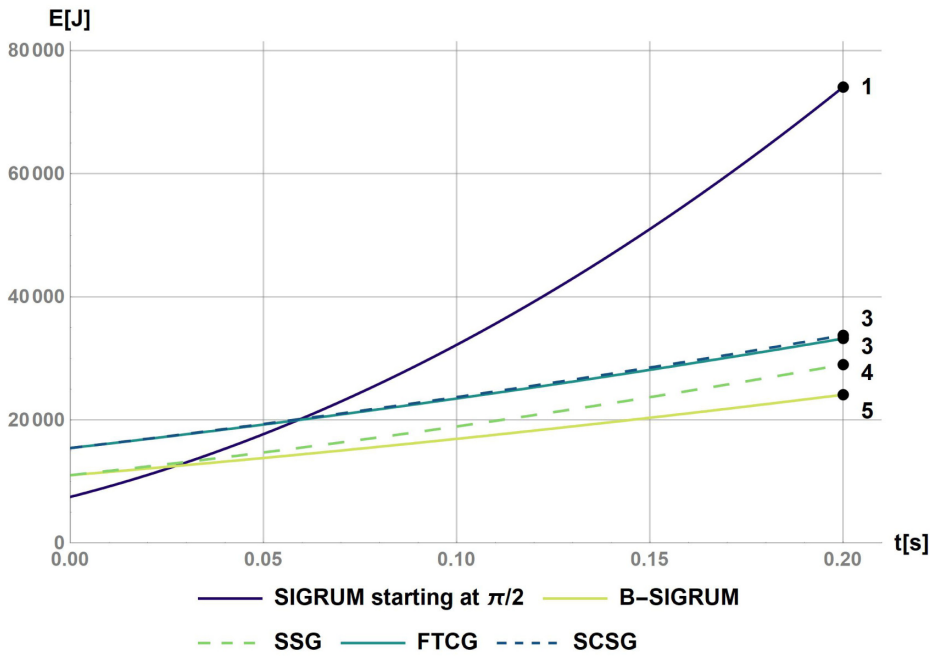


Figure 1. Kinetic energy of proposed scenarios within a reaction time of 0.2s. The values at t = 0.2s were used to rank the scenarios with the values reported on the figure.

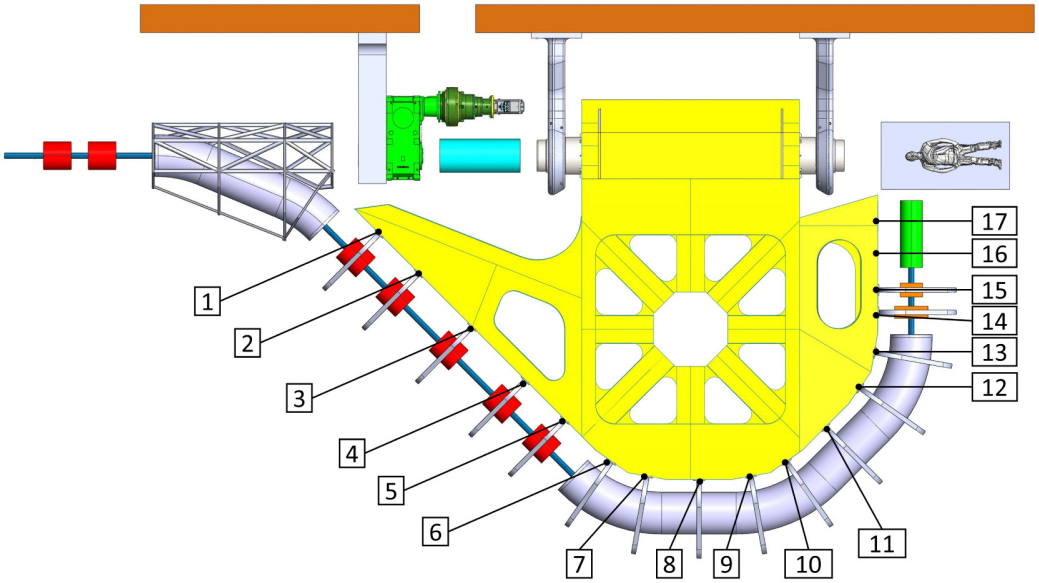


Figure 2. View of the mechanical optimized structure of the SIGRUM, numbers refer to analysed nodes for the displacement recovery.

All the scenarios have been ranked at the same level according to deformation performances (Table 6). An estimated improvement margin of structure deformation has been defined. This evaluates the possible improvement in deformation analysis deriving from the mechanical optimization of a scenario with respect to the current knowledge. Therefore, SSG, SCSG and FTG are ranked better than B-SIGRUM, in relation to this parameter (Table 6).

Deformation of supports

Each scenario has a different combination of weight and support configuration, therefore side supports of B-SIGRUM

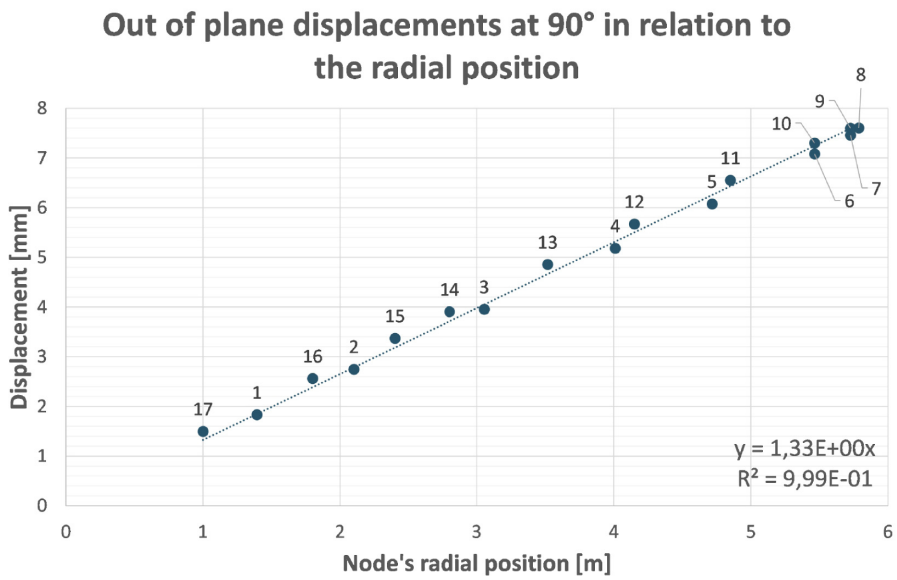
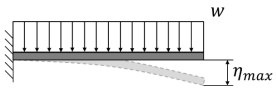
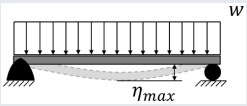


Figure 3. Out of plane (screen plane) displacement of analysed nodes (Figure 2) in function of their radial position with respect to the rotation axis. The remaining displacement after recovery of its rigid component is the distance between nodes and the straight line through the origin.

Table 5. Comparison of maximum deflection between cantilever and simply supported beams. Where w is the weight per length unit, L is the length of the beam, E is the Young's modulus of the material of the beam and I is the area moment of inertia of the cross section of the beam.

Supports configuration		Maximum displacement
Cantilever beam		$\eta_{\max} = \frac{1}{8}\frac{wL^4}{EI}$
Simply supported beam		$\eta_{\max} = \frac{5}{384}\frac{wL^4}{EI} \approx \mathbf{0.104} \times \frac{1}{8}\frac{wL^4}{EI}$

are mainly subject to bending moments while bottom supports of FTG are loaded by compression forces. Since for balanced scenarios, during the treatment phase, these loads are not related to the angular position of the gantry, the supports will deform and the axis will be displaced by a constant value: this systematic error can be compensated finding a new origin for the patient couch or using adjustment systems (i.e. rails and shims between the supports and the gantry) to fine tune the position of the gantry in the assembly phase. As the loads are different for each scenario, side supports have been designed in SOLIDWORKS and studied with preliminary FEA in order to reach the same performances, namely the same horizontal and vertical displacement. Thus, differences in load values are decoupled from the evaluation of deformation performances and incorporated in the cost analysis (cost of components manufacturing): to achieve the same displacement under different loads, different amounts of material are needed. However, due to the different type of loads, adjustment systems have respectively different design complexity. Therefore, scenarios that have side supports have a lower rate than FTG which has two ground supports, as represented in Table 6.

Geometrical tolerances

The errors due to tolerances can be compensated at different levels: between the gantry and its supports, between the gantry and cryostats, or fine tuning the position of magnets inside cryostats. Furthermore, the ability to reach strict tolerances is usually in competition with the size of the component to manufacture, therefore, it is believed that a relatively small shaft like for B-SIGRUM and SSG would be easier to manufacture within a given range of tolerance if compared with large rings of SCSG and FTG. It is underlined that tolerances were qualitatively discussed.

Costs of components manufacturing

Costs of manufacturing components were estimated on the basis of previous knowledge on costs of main manufacturing

Table 6. Summary table of scenario rankings with respect to each decisive parameter listed in Table 4.

Robustness of the design	Failure scenarios	Possible safety brakes position	Number of systems to brake	**Size**	Room space requirements	**Weight and complexity**	Complexity	Weight and inertia	**Performances: deformation and precision**	Tolerances	Deformation performances (structure)	Improvement margin of structure deformation	Deformation performances (supports)	Load properties	**Costs**	Cost of manufacturing components	Cost of the driving system	**Environmental**	Energy consumption and material activation
SIGRUM	5	3	5		5		5	5		5	5	3	3	4		4	1		5
SSG	4	5	5		3		3	5		5	5	5	3	4		4	5		5
SCSG	3	4	5		5		4	3		4	5	4	4	3		2	4		4
FTG	3	4	5		1		4	3		4	5	4	5	5		2	4		4

processes that are necessary for this machine. The total cost of manufacturing components is composed by:

$$C_{\text{manufacturing}} = C_{\text{rot-structure}} + C_{\text{supports}} + C_{\text{counterweight}} \qquad (3)$$

where:

- $C_{\text{rot-structure}}$ is the cost of the rotating structure manufactured in stainless steel.
- C_{supports} is the cost of support structures manufactured in construction steel.
- $C_{\text{counterweight}}$ is the cost of the counterweight manufactured in lead.

The rotating structure and supports necessary for the functioning of each scenario were modeled and checked in simplified FEA to estimate the amount of material necessary to satisfy requirements. For example, for side supports, the amount of material was estimated to satisfy a maximum displacement of $L/500$-$L/250$ (common values for steel structures in engineering sound practice, where L is the span) and to have the same displacement between side supports of different scenarios (computed to be around 5mm or $L/1800$). The supports of magnets cryostats and instrumentation are related to the given transfer line layout (same for all scenarios), thus their cost can be neglected in the comparison. Therefore, Table 6 reports a ranking associated to relative costs between scenarios: it has been estimated that B-SIGRUM and SSG are lower in cost by a factor of two with respect to SCSG and FTG. Given the high cost of other components of the machine, such as superconducting dipole magnets, cryogenic cooling system, civil engineering, the choice of material was judged of much less impact on the total cost; for instance, the total cost of the material for the structure in the worst case would be 1/3 of the estimated cost of a single superconducting dipole. In fact, the cost of raw material is estimated 0.35% to 1% of the total cost: the choice was then focused on a material that guarantees the best corrosion resistance and is commonly considered to fit the tight requirements for a medical machine. The use of the same material for the studied structures does not impact the relative comparison performed in this section for different structures.

Costs of the driving system

The costs of the driving system are related to the maximum power (25–40kW), torque and speed required by the load. These data were calculated by assuming the equation of motion of the gantry (the same for all scenarios) and as a function of the properties of the gantry (mass, inertia) and the geometric properties of the transmission (i.e for the FTG, the radius of the ring and rollers on which the gantry is supported). Scenarios are ranked mainly based on the output torque of the required gearbox. These costs are between one and two orders of magnitude smaller with respect to the cost of components manufacturing.

Minimal energy consumption

The evaluation of the energy consumption was done analytically by calculating the work of the motor for a 180° rotation subdivided in equal δ steps. The results are reported in Figure 4:

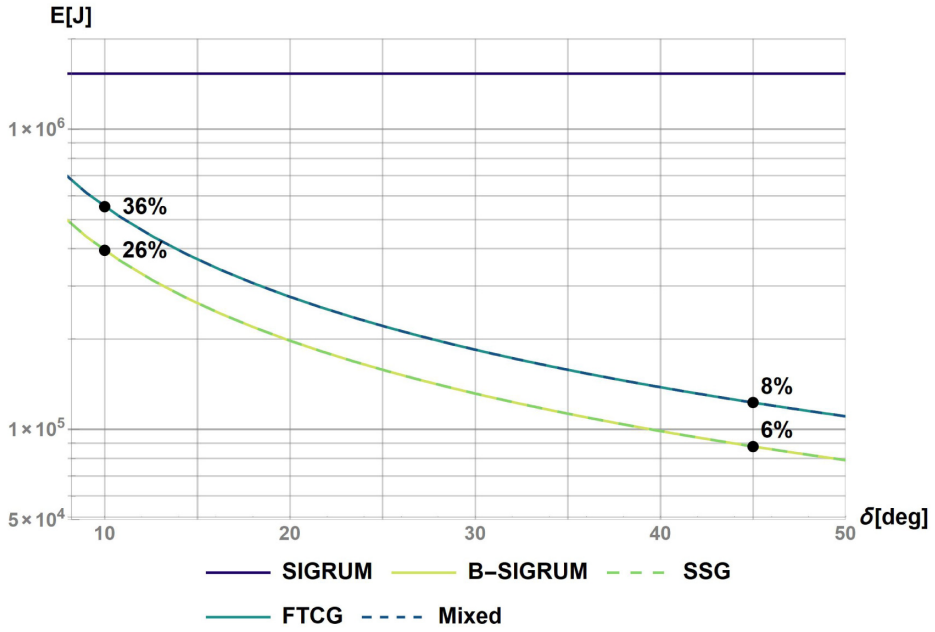


Figure 4. Work done by the motor (ideal) for a 180° rotation divided in equal δ angle steps.

the percentages shown on the plot represent the energy ratios between different scenarios and the SIGRUM, the base example. The energy ratios are evaluated for two reference values, δ = 10° and 45°, respectively related to the minimum angle step between approved treatment angles, and a possible realistic number of treatment angles for a patient (4–5 angles). The expected energy ratio will range between these two values. In conclusion, the motion system of B-SIGRUM and SSG consume less energy with respect to SCSG and FTG, all four consuming less than the SIGRUM.

Material activation

Detailed studies on material activation have not been conducted at the stage of the comparative analysis. However, further discussions have been done with experts in the field who operate a vertical beam of carbon ions: the proposed structures in Table 2 have been judged to not behave drastically differently from an activation point of view. This is because for the different scenarios the morphology of the structure in proximity of the transfer line is comparable with a similar amount of mass, leading to a similar relevant material activation.

In a conservative way, if it is assumed for sake of simplicity that activation is proportional to volume of the gantry structure, the solution B-SIGRUM and SSG behave better than solution SCSG and FTG. Scenarios are rated accordingly in Table 6, combining the energy consumption criteria with the material activation one. Following that bigger structure have bigger volume and higher inertia, those that consume less energy are also those that would have less material activated.

Results of the comparative study

All proposed scenarios are safe, however, SSG is estimated to be the safest. B-SIGRUM and SSG are expected to be lower in cost by a factor of two with respect to SCSG and FTG. Statically balanced scenarios, by means of a relatively simple integrated counterweight, come with several advantages. Although some of the following considerations were not estimated quantitatively, they are not negligible:

1. Less kinetic energy during emergency braking, allowing to design less complex braking and driving systems,

2. Displacements of the rotational axis of the gantry not related to its angular position during the treatment phase: the related error can be compensated during the assembly phase once, reducing or excluding the need of a dedicated online control system,

3. Less cost per operation and environmental impact: the energy that the driving system need to supply is between 10% and 40% that for unbalanced ones,

4. Easier process for machinery certification according to the European applicable laws.

Conclusions

Multiple scenarios were defined during discussions with experts of CERN EN-MME group, TE-MSC group, RTU and UNIBS in consultancy with CNAO experts in the framework of NIMMS and HITRI *plus* project. Main requirements (Table 1)

and challenges were acknowledged following HITRI *plus*[16] requirements and general designing rules for a machine of this kind. The comparative study has been performed in a comprehensive manner following a unified methodology providing objective results, summarized in Table 6. The main conclusions are:

1. Observations related to safety, deformation and precision performance, cost of operation, complexity of service systems, and potential certification costs, lead to the decision to focus only on statically balanced structures,
2. All four scenarios proposed are suitable for further development of gantry conceptual design,
3. All scenarios can be considered safe, however, SSG is estimated to be the safest,
4. B-SIGRUM and SSG are expected to be lower in costs with respect to SCSG and FTG by a factor of two.

Data availability

Zenodo: Comparative Study on Scenarios for Rotating Gantry Mechanical Structures, https://doi.org/10.5281/zenodo.6516846[19]. Data are available under the terms of the Creative Commons Attribution 4.0 International license (CC-BY 4.0).

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http://www.doi.org/10.5281/zenodo.6516846

Open Peer Review

Current Peer Review Status: ✔ ✔

Version 4

Reviewer Report 17 October 2024

https://doi.org/10.21956/openreseurope.20146.r44948

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✔ **Alexander Gerbershagen**
University Medical Center Groningen, Groningen, The Netherlands

The authors have explicitly addressed all the questions raised by the reviewer. They have stated the dimensions of the HIMAC gantry in the article text, provided a rough estimate for the portion of the costs for the gantry material, addressed the environmentally important point of material activation and addressed the displacement due to gantry deformation and its potential compensation. The article delivers now a more realistic information about the scope of the validity of the study and can be indexed.

Competing Interests: No competing interests were disclosed.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Version 3

Reviewer Report 30 June 2023

https://doi.org/10.21956/openreseurope.17504.r33254

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? **Alexander Gerbershagen**
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The authors have made a minor rework of the article and have addressed some of the issues raised by the reviewer, which resulted in the overall improvement of the article. However, several specific issues have not been addressed. The reviewer recommends the authors either to address those, or to explain in the Amendments comment section why those cannot (or should not) be addressed. The comments are stated below:

The size of the HIT gantry was added, but the size of HIMAC gantry was not, although they are listed in the same sentence. To help the authors - HIMAC gantry length is 16.9 m, the radius is 7.1 m (from Proceedings of EPAC2006, TUYFI01).

In the environmental requirements, the decommissioning aspects are still not mentioned. The power consumption for gantry rotation is much less of a practical concern than 100s of tons of activated gantry material, which needs to be disposed after several decades of operation.
All external volumes of construction summarized in Table 2 are above the envisaged dimensions of 20 m x 20 m x 20 m. Please address if that is an issue or not.

“Aforementioned results have been obtained assuming to use stainless steel [...]” – This is a costly solution, compared with the commercially available alternatives, which use iron. So it might be of advantage to make a simplified comparison of the mass you have stated (70/120 tons) multiplied with the present stainless steel price, and compare it with the price of iron-based existing gantries (e.g. HIT).

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Accelerator physics

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Version 2

Reviewer Report 09 June 2023

https://doi.org/10.21956/openreseurope.17058.r32106

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?

Alexander Gerbershagen
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The article describes the analysis of the mechanical stability of several proposed gantry layouts for ion therapy. The article commences with a summary of efforts of CERN in developing ion therapy centres in CNAO and MedAustron. After a brief description of the overall concept, it focusses on the parameters the design aims to optimize. The authors describe the examined options and the methods used for analysis of designs' mechanical suitability. However, no explicit effort in improving or optimizing the mechanical rigidity of the specific designs is described. Many aspects of the study remain qualitative, as designs are compared with each other, but not with the performance of the existing solutions or how close the expected performance relates to the clinical requirements. I suggest the authors to address the points mentioned below, as at the current stage the article, while addressing important issue with the correct methodology, lacks specific data to be of a high value for the readers.

Specific comments:

"Figures are expected to rise by more than 24% by 2035." -> What of the figures mentioned above is expected to rise - the absolute numbers of cancer cases?

"improvement of the Technology Readiness Level (TRL) of this design is the final outcome of the project, from the presently evaluated TRL 2" -> What TRL level is envisaged to be achieved at the end of the improvement process?

Table 1 is not a list of requirements, but only a list of parameters targeted for the optimization, as no specific values are stated.

Size of 20 m x 20 m x 20 m is stated, but it would be good for comparison to give the numbers for the existing systems (HIT, HIMAC).

For the environmental requirements, the decommissioning aspects might need to be examined or at least mentioned. E.g. what materials would be used for the gantry construction and if those are recyclable, and how much activated material will be produced. Many old accelerators stand in the research centers for decades, because no plan of their decommissioning has been developed and their components cannot be recycled, as they have long-term activation.

"Results have been summarized in a final Table"- no capital "T", unless you are referring to a table with a specific number.

The magnets referred to in [13] and [14] were first proposed by W. Wan[1]. It might be appropriate to cite the article.

All external volumes of construction summarized in Table 2 are above the envisaged dimensions of 20 m x 20 m x 20 m. Please address if that is an issue.

"The scenarios that sufficiently satisfied requirements…" – what requirements did the other scenarios fail to satisfy? Only the lack of balance?

"Aforementioned results have been obtained assuming to use stainless steel […]" – this sounds like an outstandingly costly solution, compared with the commercially available alternatives, which use iron. It obviously improves the rigidity of the system and decreases the overall weight, but the

reason that it is not used for the commercial solutions is that the cost becomes unjustifiably high. So in the paper section describing the cost it would be good to see explicit numbers, at least based on the weight you have stated and the present stainless steel prices.

Figure 3: Displacement of up to 8 mm is very notable. It would be good to have an estimate on what it implies for the beam position displacement. The displacement is maximal at the entrance region of the final dipole and might have a large impact on the beam deflection by this dipole. Also, will the dipole be flexible enough to accommodate these constant mechanical stresses without impact on its performance, short and long-term?

Table 6: I suggest to put the name of the design into the first row.

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Is the work clearly and accurately presented and does it cite the current literature?
Yes

Is the study design appropriate and does the work have academic merit?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Not applicable

Are all the source data underlying the results available to ensure full reproducibility?
Partly

Are the conclusions drawn adequately supported by the results?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Accelerator physics

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 21 Jun 2023

Luca Piacentini

We would like to underline that the study at moment of publication was and still in its early stages, therefore it was (and still is) not possible to include studies detailed enough to fully reply to some comments. Regarding the comment on Environmental requirements, the transfer line, that is closer to the beam than any other structures would be the same for all gantry solutions. A study on the impact of radiation on the mechanical structure could be done in the future. The article suggested has been mentioned in [13]. In general, it was not in the aim of this study to define in detail the technology to use. Indeed, as mentioned, the comparison of structures is relatively independent from the transfer line used. The displacement for the structure is maximal at point 8, just after the middle of the transfer line (Figure 2 and 3). The displacement of 8 mm alone is indeed notable. However, as cited in this article, studied in [15] and reported in Figure 3, the points where elements of the transfer line are connected lay around a common plane (dashed line). Around this common plane, the relative displacement between two adjacent elements of the line is of the order of tenths of mm. The impact on the beam is currently subject of research and was not in the aim of this article. Additionally, we would like to comment that between dipoles or cryostats are present flexible elements that allow for deformation. The length of life of these components could also be investigated in the future.

Competing Interests: No competing interests were disclosed.

Version 1

Reviewer Report 01 August 2022

https://doi.org/10.21956/openreseurope.15860.r29727

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Claire Z. Antoine
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This paper describes a comparative study of a dozen different scenarios for the mechanical design of the gantries for an ion-therapy accelerator. Three main parameters were retained: minimization of the size and complexity of the set-up, without giving up on safety parameters, minimal energy

consumption and treatment angle coverage with a minimum ± 110°. After a first screening, all unbalanced structures were eliminated because of their intrinsic danger, and only 4 balanced scenarios were retained and more thoroughly studied.

This work is well written, in a language appropriate for the multiple backgrounds of the possible readers (accelerator scientists, mechanical engineers, therapeutic teams...). Some details from the exact calculation are not detailed and remain obscure to the non-specialist, but such details would be beyond the scope of this paper. References are proposed for those who want more details.

I have only one critic, the distribution of table and figures, that are sometimes far from the corresponding paragraph, makes the reading (at least on screen) somewhat difficult.

In particular, I propose that p6, where the first mention of table 6 appears, you replace “deductible from the summary Table 6” by “deductible from the summary Table 6 that will appear at the end of the comparative study (or something similar), and that Table 6 indeed appears at the end of the study (e.g. just before the conclusion). If some effort can be made to put other figures and tables closer from the text where they are mentioned, it will improve the readability, but it still understandable like it is.

Is the work clearly and accurately presented and does it cite the current literature?
Yes

Is the study design appropriate and does the work have academic merit?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Partly

If applicable, is the statistical analysis and its interpretation appropriate?
Not applicable

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: I have been working in the field of superconducting accelerators for more than 30 years. Although I am not an mechanical engineer, I was already familiar with the the issues for gantry design.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.