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BEAM OPTICS STUDIES FOR A NOVEL GANTRY FOR HADRON THERAPY*

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Abstract

The design of smaller and less costly gantries for carbon ion particle therapy represents a major challenge to the diffusion of this treatment. Here we present the work done on the linear beam optics of possible gantry layouts, differing for geometry, momentum acceptance, and magnet technology, which share the use of combined function superconducting magnets with a bending field of 4 T. We performed parallel–to–point and point–to–point optics matching at different magnification factors to provide two different beam sizes at the isocenter. Moreover, we considered the orbit distortion generated by magnet errors and we introduced beam position monitors and correctors. The study, together with considerations on the criteria for comparison, is the basis for the design of a novel and compact gantry for hadrontherapy.

INTRODUCTION

In the context of the European project HITRI*plus* [1], the study and design of a novel superconducting gantry has been undertaken. Following up the studies performed by the TERA Foundation on superconducting gantries [2, 3], a wide explorative study on dozens of gantry layouts and optics configurations was performed [4, 5]. This manuscript presents the assumptions made and methods used to analyse and compare the different optics solutions. Furthermore, the two most promising layouts are described in more detail.

GANTRY DESIGN CHOICES

Before entering in the details of the optics studies, it is important to highlight the design choices that defined the perimeter of the explored parameters space. The first fundamental choice was to position the scanning magnets after the last bending section. Although this approach poses relevant challenges on the design of the scanning magnets, it allows to operate with standardized dipoles in the whole gantry, avoiding an increase of aperture in last bending section.

The second fundamental choice was the selection of the bending field. While state of the art gantries operate with fields up to 3.5 T [6–8], we decided to push toward 4 T superconducting dipoles [9], aiming for a further reduction of the gantry weight. Depending on the layouts, these dipoles may need a superimposed gradient that can be obtained through an asymmetric assembly of the coils [10]. Even if it would be possible to wind the magnet with separate circuits for dipole and quadrupole (nested magnets), this option was discarded in the context of this study to favor the easiness of construction and operation of the superconducting magnets. To standardize the comparison between the different gantry layouts, two options were considered for the magnet aperture: 70 mm and 90 mm in diameter. Optics layouts that require an aperture larger than 90 mm are considered not suitable for the proposed study. In the same way, two options were considered for the dipoles angle length: 30 ° and 45 °.

GANTRY BEAM OPTICS

The main constraints to the beam optics of the gantry, resulting from the continuous interaction with medical doctors and physicist of CNAO (Italian National Center for Oncological Hadron Therapy) and MedAustron (Center for Ion Therapy and Research, Austria), were identified:

- operation with $^{12}C^{6+}$ up to 430 MeV/u kinetic energy, equivalent to 31 cm of range in water;
- beam characteristics at the isocenter independent on the angle of rotation;
- two different beam sizes at the isocenter: 8 mm and 12 mm (FWHM) at the minimum extraction energy;
- global achromaticity to avoid distortion of beam size and position due to the beam momentum spread.

A more thorough and detailed list of medical constraints and requirements is reported in [5].

Matching Procedures at the Isocenter

In order to obtain a beam size independent of the gantry angle, two different types of telescopic matching were implemented between the coupling point and the isocenter [11]:

- “point–to–point” matching, where particles with the same initial position in (x, y) end up in the same position independently of the initial divergence (x’, y’). In this case, an input round beam in (x, y) maintain its size at the isocenter independently from the gantry rotation angle;
- “parallel–to–point” matching, where particles with the same initial divergence (x’, y’) end up in the same position independently of the initial position (x, y). In this case, an input round beam in (x’, y’) maintain its size at the isocenter independently from the gantry rotation angle.

For both matching methods, it is possible to impose a magnification factor (MF), i.e. the factor by which the input beam size is increased to obtain the output beam size at the end of the beam line.

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Beam Size Regulation at the Isocenter

As already specified, for a given beam energy, two spot sizes are required at the isocenter, which can be obtained each with two operating modes:

- varying the MF, keeping the same input beam parameters: the gantry optics is flexible enough to accommodate the change of output beam parameters varying the quadrupole gradients along the line;
- keeping constant the MF, varying the input beam parameters: the gantry gradients are fixed, and all the changes required to attain the output beam parameters are demanded to the beam line upstream of the gantry.

In the first case, the gantry is an active optic element and it is used for beam size control. Although the optics optimization for different MF may be more complex, this results in a simpler overall operation, where the gantry can be operated independently from the upstream line. In the second approach, changing the quadrupoles upstream the gantry to change beam size would requires re-steering the orbit both in the upstream line and in the gantry.

Achromaticity

The gantry optics must be at least globally achromatic, i.e. for an input beam free of dispersion, the output beam at the end of the beam line is still free of dispersion. Such a requirement is necessary otherwise the characteristics of the delivered beam spot at the isocenter would depend on the momentum distribution of the beam particles and on the gantry angle. The gantry optics can also be made locally achromatic, i.e. the beam will stay free from dispersion in all non–bending sections. This option can be used to reduce the maximum value of dispersion along the line and in general to increase the gantry momentum acceptance. However, given the reduced sizes of the gantries, a locally achromatic optics implies large gradients in the quadrupoles between dipoles, strongly increasing the beam dimension in the non–bending plane and generating large orbit distortions for small alignment errors.

Momentum Acceptance

Momentum acceptance refers to the maximum $\Delta p/p$ that can be transported by the gantry beam line with a specific optics without beam losses. Having a small momentum acceptance implies that magnet currents must be set for each beam energy necessary for the treatment; on the contrary, a large momentum acceptance allows using fewer set points for magnet currents reducing the AC losses on the superconductors. It was estimated that at the minimum energy (120 MeV/u for carbon ions) a momentum acceptance of $\Delta p/p = 1\%$ would allow to effectively irradiate two consecutive tumor slices without changing the magnetic field of the dipoles. The number of slices increases with increasing energies, reaching up to eight slices at the maximum energy. However, a large momentum acceptance comes at the expenses of the magnet aperture. It is worth noting that detailed studies are needed to evaluate the effects of off–momentum operations on the beam size.

Errors and Corrections

The possibility to compensate for alignment and magnetic errors and restore an acceptable orbit and optics was evaluated as well. Alignment errors were distributed according to a Gaussian distribution truncated at 3 σ with $\sigma = 0.3$ mm (0.3 mrad) for the position (angle) error. Errors in the magnetic fields were distributed according to a Gaussian distribution truncated at 3 σ with $\sigma = 5 \cdot 10^{-5}$ to both dipole and quadrupole excitation errors (ΔB/B and Δg/g), describing errors coming from power supply (and thus common to both dipole and quadrupole components). In addition, a Gaussian distribution truncated at 3 σ with $\sigma = 2.5 \cdot 10^{-4}$ was added in order to consider construction errors, e.g. a displacement in the length of the filament, and thus an error in the magnetic length. Using monitors and correctors, one can correct the orbit deviation at the isocenter, but a residual orbit deviation (R_{corr}) is till present along the line (usually in the order of 5 mm–10 mm).The total (radial) space occupied by the beam (R_{tot}) is given by:

$$R_{\mathrm{tot}} = R_{\mathrm{env}} + R_{\mathrm{corr}} \tag{1}$$

$$R_{\mathrm{corr}} = \sqrt{R^2_{\mathrm{corr,x}} + R^2_{\mathrm{corr,y}}} \tag{2}$$

$$R_{\mathrm{env}} = \sqrt{R^2_{\mathrm{env,x}} + R^2_{\mathrm{env,y}}} \tag{3}$$

$$R_{\mathrm{env,x}} = \sqrt{\beta_x \varepsilon_x} + D_x \Delta p/p \tag{4}$$

where the terms of Eq.4 are summed linearly since we are interested in the space occupied by the beam during off–momentum operations, typical of the multi–energy extraction [12]. In the case of $\Delta p/p = 0.1\%$, the linear sum takes into account a small variation in momentum during the extraction. We considered R_{corr} as the maximum of the residual orbit deviation on each point along the line. The space occupied by the beam (R_{tot}) defines the required Good Field Region (GFR) for the magnets. As commonly done in designing accelerator magnets, in this study we consider that the GFR is 2/3 of the magnet aperture.

MOST PROMISING SOLUTIONS

Taking into account all the previous considerations, two optics layout were selected as the most promising out of more than 30 analysed configurations [4]. The overall parameters of the two layouts are summarized in Table 1, while in the following sections they are analysed in more detail.

Layout with 45° Dipoles

The first selected solution is composed of four identical 45° dipoles (i.e. one dipoles' family), with a modest superimposed quadrupolar gradient of 0.07 T/m. This solution, matched as parallel–to–point, allows the change of MF without acting on the gradients of the dipole, but relying on the use of the normal and superconducting quadrupoles. To optimize the gantry dimensions, the superconducting

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Table 1: Main Parameters of the 45 ° and 30 ° layouts. Both optics are matched as parallel to point.

Parameters	**45 ° Layout**		**30 ° Layout**	
Length | Height | Dipole Angle	14.1 m | 5.75 m | 4x45 °		12.9 m | 6.4 m | 7x30 °	
Dipole Quadrupolar Gradient	0.07 T/m		4.5 | -4.9 | 0.6 T/m	
Dipole Quad. Gradient to change MF	Fixed		±0.3 T/m	
Max R_{tot} along the gantry	**p/p = 0.1%**	**p/p = 1%**	**p/p = 0.1%**	**p/p = 1%**
MF=1.5, 2 for $\beta_{x,y} = 5m$	21	54	22	30
$\beta_{x,y}$ = 2.5, 5 m for MF=1.5	22	56	24	29
Dipole Aperture (diameter)	70 mm			90 mm

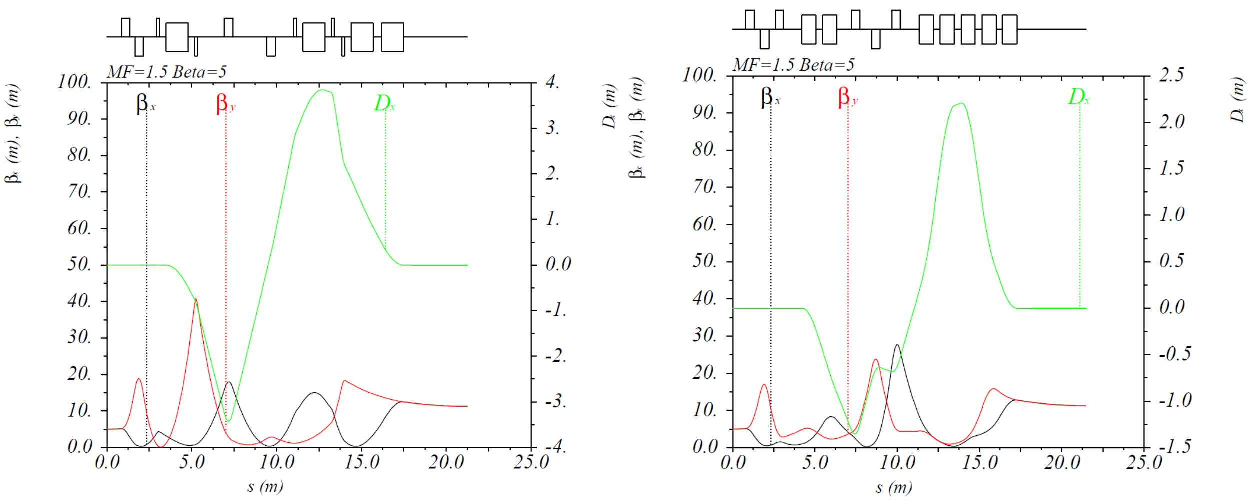

Figure 1: β (x in black and y in red) and Dispersion (in green) functions for the layout with 45 ° dipoles (left) and for the layout with 30 ° dipoles (right).

quadrupoles are considered to be directly bolted on the heads of the superconducting bending dipoles (like the spool–piece magnets of the LHC [13]). This layout, operated both changing MF and input β functions, requires a magnet aperture in diameter within 70 mm with a $\Delta p/p = 0.1\%$. Considering a 90 mm aperture, this layout can operate up to $\Delta p/p = 0.4\%$. However, if operated with a $\Delta p/p = 1\%$, the space required by the beam significantly exceeds the limit of 90 mm of aperture; therefore, this layout, cannot operate with a $\Delta p/p = 1\%$. Fig. 1(left) shows the optics functions along the gantry, together with the schematics of the line.

Layout with 30 ° Dipoles

The second selected layout operates with seven dipoles subdivided in three families: (i) three dipoles with equal positive quadrupolar gradient (4.5 T/m), (ii) three dipoles with equal negative quadrupolar gradient (−4.9 T/m), (iii) one dipole with a slightly negative quadrupolar gradient (−0.6 T/m). To change magnification factor, a limited variation of the gradients (±0.3 T/m) in the dipoles is required. This would imply the use of nested magnets, that have been excluded from this study. On the other hand, this layout can effectively operate by varying the input betas while maintaining the required aperture within 90 mm for both $\Delta p/p = 0.1\%$ and $\Delta p/p = 1\%$. Fig. 1(right) exhibits the optics functions and the schematics of this layout.

CONCLUSION

In this contribution, we reported the main beam optics studies done for the design of a new superconducting gantry for carbon ions. Among dozens of analysed configurations, here we presented the most promising solutions. The first layout is composed of four equal 45 ° dipoles with an embedded quadrupolar component defined by the coil geometry. This solution can operate both changing the magnification factor or the input beam parameters, but the momentum acceptance is limited to $\Delta p/p = 0.1\%$ for a magnet aperture of 70 mm ($\Delta p/p = 0.4\%$ for 90 mm).

The second layout is based on seven 30 ° dipoles, subdivided in three families differing by the amount of superimposed gradient. Given the limits we assumed on the magnet technology, this solution can change the beam size at the isocenter only by varying the input beam parameters. Considering a 90 mm magnet aperture, this second layout can operate with a momentum spread up to $\Delta p/p = 1\%$.

The presented work set the basis for future studies on the gantry design, that will have to include a complete and detailed integration between optics, mechanics of the structure, magnet technology, cryogenics and clinical environment.

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