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EXPLORATIVE STUDIES OF AN INNOVATIVE SUPERCONDUCTING GANTRY*

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Abstract

The Heavy Ion Therapy Research Integration plus (HITRI*plus*) is an European project that aims to integrate and propel research and technologies related to cancer treatment with heavy ion beams. Among the ambitious goals of the project, a specific work package includes the design of a gantry for carbon ions, based on superconducting magnets. The first milestone to achieve is the choice of the fundamental gantry parameters, namely the beam optics layout, the superconducting magnet technology, and the main user requirements. Starting from a reference 3 T design, the collaboration widely explored dozens of possible gantry configurations at 4 T, aiming to find the best compromise in terms of footprint, capital cost, and required R&D. We present here a summary of these configurations, underlying the initial correlation between the beam optics, the mechanics and the main superconducting dipoles design: the bending field (up to 4 T), combined function features (integrated quadrupoles), magnet aperture (up to 90 mm), and angular length (30° – 45°). The resulting main parameters are then listed, compared, and used to drive the choice of the best gantry layout to be developed in HITRI*plus*.

INTRODUCTION

In the framework of the Heavy Ion Therapy Research Integration plus (HITRI*plus*) project [1], a new design of a gantry for carbon ions is being developed, based on superconducting (SC) magnets. The new design shall represent the next generation of gantries for hadrontherapy, targeting small dimensions, an affordable cost and a credible time scale for construction.

An international panel gathering experts in accelerator design and clinicians at the forefront of research in hadrontherapy suggested [2] to start the development from a recent gantry design proposed by a joint TERA–CERN team [3]. The reviewers put particular emphasis on reviewing and confirming the clinical requirements with the clinical staff of the hadrontherapy centers participating to the project and on decreasing the overall dimensions and weight of the gantry. For this reason, the panel suggested to push the field on the bending magnets beyond the state of the art of normal [4] and superconducting [5, 6] carbon–ion gantries up to 4 T. Prototyping the magnets was also indicated as a key achievement, in order to prove the feasibility of the design.

Starting from the clinical requirements, this contribution presents the main layout and optics solutions identified during a first exploratory phase of the development; key parameters are compared and the two most promising layouts are chosen for further development. Details on the chosen optics can be found at Ref. [7].

CLINICAL REQUIREMENTS

The clinical requirements were extensively discussed with medical physicists and doctors at CNAO [8] and MedAustron [9]. The most relevant ones are:

- the beam with the largest magnetic rigidity is $^{12}C^{6+}$ at 430 MeV per nucleon kinetic energy, corresponding to 6.62 Tm and 31 cm of range in water;
- the scanned area shall be as large as possible, indicatively 350 mm × 350 mm, at least 200 mm × 300 mm; the larger dimension is parallel to the gantry rotation axis. The minimum scanning speed shall be 20 m/s;
- the minimum set of beam sizes at the isocenter shall be 8 mm and 12 mm (FWHM) at the minimum extraction energy; at larger energies, the beam size will reduce following the adiabatic damping of the beam emittance;
- a source–to–axis distance (SAD) of at least 2 m – 2.5 m;
- possibly 360° rotation, minimum 220°;
- volumetric imaging at the isocenter.

LAYOUT EXPLORATION

All the layouts are based on the following assumptions:

- scanning magnets located downstream of the last bending section, to relax constraints on the aperture of the SC magnets;

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Table 1: Key gantry parameters among different layouts (numbered from 1 to 10) and optics: gantry length, radius, distance between end of last dipole and isocentre, number of main SC dipoles and bending angle, number of SC dipole families, and number of NC and SC quadrupoles. The required magnet aperture when matching with varying MF for a given value of input β function or when varying the input β function for a given value of MF are indicated; two values of beam momentum spread ($\Delta p/p$) are considered. The results in the table consider a parallel–to–point matching method but for layouts 3, 4, 7 and 10, for which point–to–point matching is performed.

Layout	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Geometry Parameters										
Length [m]	12.9	14.05	11.7	13.2	10.4	14.2	14.2	13.5	14.05	14.2
Radius [m]	6.4	5.75	5.75	7.3	6	5.55	5.55	5.25	5.75	5.1
After last bending [m]	4	3.5	3.5	4	3.6	~~3~~	~~3~~	~~3~~	3.5	~~3~~
SC dipoles: N × angle	7×30°	4×45°	7×30°	9×30°	9×30°	4×45°	4×45°	4×45°	4×45°	4×45°
SC dipole families	3	1	3	3	9	1	1	1	2	2
Quadrupoles: NC/SC	0/6	5/4	0/6	6/2	0/2	6/4	6/4	5/4	5/4	0/8
Aperture [mm]										
var. MF, $\Delta p/p = 0.1\%$	~~90~~	70	~~90~~	90	~~70~~	70	90	70	93	90
var. β, $\Delta p/p = 0.1\%$	90	70	93	90	70	70	90	70	~~96~~	90
var. MF, $\Delta p/p = 1\%$	~~90~~	~~163~~	~~105~~	~~174~~	~~90~~	~~156~~	~~111~~	~~162~~	~~120~~	~~165~~
var. β, $\Delta p/p = 1\%$	90	~~168~~	~~111~~	~~129~~	93	~~168~~	~~123~~	~~165~~	~~135~~	~~165~~

- 4 T SC dipoles, corresponding to a bending radius of 1.65 m for ${}^{12}C^{6+}$ at 430 MeV per nucleon. Depending on the optics, a quadrupole field may be necessary: this would not be obtained via dedicated trimmable coils, but by an asymmetric arrangement of the coils (left–right taken on the magnet cross section). In addition, the magnet aperture should be 70 mm – 90 mm. The maximum ramp rate $\dot{B}$ should be 0.4 T/s;
- achromatic optics solutions at the isocentre, implying that the spot size and position at the isocentre is independent of the beam momentum distribution;
- beam dimensions at the isocentre independent of the gantry angle of rotation. This implies that either a "rotator" [10–13] is installed upstream of the gantry or that the incoming beam is round, i.e. has the same dimension or divergence in the two transverse planes, depending on the matching method (see later).

Such parameters pose important challenges to the design of the SC dipoles, especially concerning handling the high magnetic energy stored by the dipole for a very small curvature radius and the $\dot{B}$. Both in the framework of HITRI*plus* and other European R&D collaborations, several magnet options have been investigated, both in terms of conductors (i.e. Nb–Ti, Nb_3Sn, REBCO,Bi–2212, MgB_2), and in terms of coil layouts (i.e. CosineTheta, Canted Cosine Theta (CCT) or race–track [14, 18]). For design and construction of a prototype the HITRI*plus* collaboration has chosen as baseline Nb–Ti wound as CCT. The use of CCT magnets have been already proposed for high momentum acceptance proton gantries [19] operating in steady–state; however, in the analysed HITRI*plus* gantry we are investigating low loss former and coil technology to optimise the performances for a ramped magnet. In addition, the higher magnetic field, different aperture and curvature radius require a complete re–design of the CCT.

The choice of locating the scanning magnets downstream of the last bending section is another source of important challenges. In fact, on one hand, the scanning magnets must be normal conducting (NC) to guarantee the necessary scanning speed; on the other hand, they must provide quite substantial magnetic fields in the gap in order to bend beams of the maximum magnetic rigidity by some tens of mrad, in order to scan an area of some hundreds of mm about 2.5 m downstream. The specific challenges pertaining the scanning system are not addressed in this contribution.

As done in the optics design of other gantries [10–13, 16], the gantry is considered as a 1:MF telescope (MF stands for "Magnification Factor"). The two beam sizes as per the clinical requirements can be obtained either by varying the MF for a given set of optics functions in input to the gantry ("var. MF", see Table 1), or by varying the input optics functions for a specific MF ("var. β", see Table 1). Similarly, the optics can be matched "point–to–point", by which the beam dimension in input to the gantry is directly mapped onto the beam dimension at the isocentre, or "parallel–to–point", by which the beam divergence in input to the gantry is mapped onto the beam dimension at the isocentre.

For every explored layout, monitors and correctors were inserted in the layout, to estimate the accuracy in correcting the beam orbit in presence of magnet misalignment and magnetic field errors. For each optics, the residual orbit was calculated and taken into account together with the *spread* and *offset* in beam momentum to evaluate the beam envelope (including the betatron part), which identifies the so–called "good field region" (GFR). As commonly done in magnet design, the GFR sets the magnet aperture, obtained as 3/2

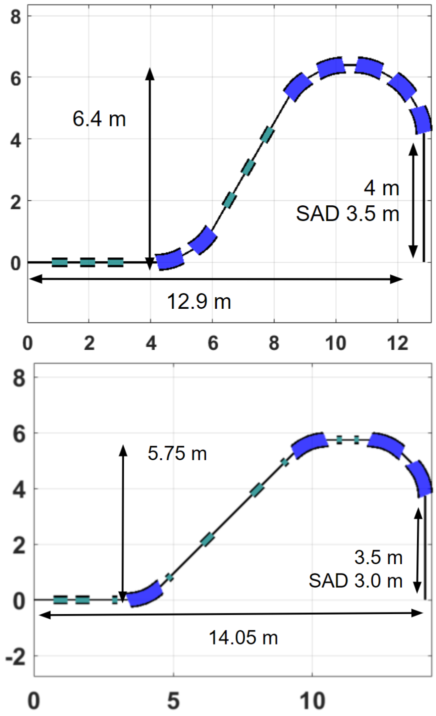

Figure 1: Schematics of the chosen layouts: layout 1 (upper frame) and layout 2 (lower frame). Arrows indicate essential dimensions; the radius is the distance between the gantry rotation axis and the beam height.

of the GFR as a first approximation. Two values of momentum spread have been considered for each layout and optics, i.e. $\Delta p/p = 0.1\%$ and $\Delta p/p = 1\%$; the former value is close to what operationally attained with CNAO beams, whereas the latter considers the possibility of operating with off–momentum beams with a fixed current in the superconducting magnets for a few tumor "slices".

A detailed study on the mechanics rotating the gantry is being carried out. First results [17] favour statically–balanced solutions to ease operation and safety requirements, versus the solution initially proposed by TERA [3, 16] with no counterweight and lower mass. Moreover, a wide range of solutions has been considered; optimisation is on–going focussing on a few figures of merit like acceleration and breaking, safety and space required.

LAYOUT COMPARISON

Table 1 summarises the key parameters of the most relevant layouts and optics solutions. The number of bending magnets is indicated, along with the bending angle and the number of dipole families; the number of quadrupoles, both NC and SC, is reported as well. The required aperture for different matching configurations is indicated for two values of beam momentum spread.

Layouts with a distance between the last bending section and the isocentre smaller than 3 m are discarded, because there would be not enough space for the scanning magnets and the desired SAD. Moreover, solutions requiring a magnet aperture beyond the allowed range (i.e. 70 mm – 90 mm) are discarded as well. Few solutions require separate circuits for dipoles and quadrupoles in the superconducting magnets (nested magnets), which have been discarded too.

As shown, only "Layout 1" allows transporting beams with a 1% beam momentum spread. This layout operates with combined–function dipoles, that would require varying the quadruple gradient independently from the dipole field, i.e. a nested magnet, for changing magnification factor. Therefore, "Layout 1" can be operated only in the scenario for which the input β functions are varied. As complementary layout, i.e. with SC combined–function dipoles of 45°, working with a beam momentum spread of 0.1%. "Layout 2" is optically matched by varying the MF without the need of changing the quadrupole gradient in the dipole. This layout is the only one with enough room downstream of the last bending section and requiring an aperture of 70 mm.Both layouts are optically matched parallel–to–point; their schematics are shown in Fig. 1.

The total cost of the gantry has been estimated based on the experience of the teams responsible for the development of the different aspects of the gantry design. The total cost estimation considers superconducting magnets (R&D and construction), NC magnets, power supplies, ancillary systems, rotation mechanics and building (only gantry room). There are small variations among the cited items for all the four configurations, apart from procuring the hardware of the dipoles, more relevant for Layout 1 than for Layout 2, as expected. In general, Layout 1 results to be more expensive than Layout 2, with an estimated cost difference in the order of 10%. Moreover, the difference in total cost between the two layouts in the 220°and 360°configurations is about 15%.

CONCLUSION

In the context of the HITRI*plus* project, a new design of a SC ion gantry is under development. The new gantry shall transport ion species of present and future interest for hadrontherapy, with the maximum beam rigidity set by fully stripped carbon ions at 430 MeV per nucleon. The design is based on SC bending dipoles with the main field at 4 T, corresponding to a radius of 1.65 m. The aperture should be in the range 70 mm – 90 mm, marking a world record in terms of stored magnetic energy for such a small curvature radius, though expected to be at reach; the fast ramping rate of $\dot{B}$ =0.4 T/s is another parameter requiring particular attention in the magnet design. Among dozens of possible layouts and optics solutions, the two most promising ones have been discussed, highlighting differences and challenges of the two designs. An overall cost estimation was made for these two layouts, as well as for the complete and partial rotation options. The layout that will be selected by the HITRI*plus* collaboration will be further developed and optimised.

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