RECENT DEVELOPMENT OF GANTRY DESIGN ACTIVITIES AT GSI DARMSTADT

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Abstract

It is important for application of accelerators in light-ion cancer therapy, that all beam-shaping procedures should be carried out without inserting materials into the beam. That is why an active energy variation from the accelerator and inclusion of the beam scanning into the gantry are the crucial tasks. Recent development of gantry design activities at GSI Darmstadt is reviewed in the paper. The latest versions of superconducting gantry with two-direction raster scanning option are presented.

1 INTRODUCTION

Beams of light ions (Z<=8) have favourable properties for the use in radiotherapy. Their advantages are best pronounced if the beam is delivered by a tumour-conform way. The highest degree of conformity could be achieved by combination of rotating gantry with an active beam scanning. However, because of high rigidity of ion-therapy beams, the rotating gantry is one of the most complicated, expensive and challenging parts of light-ion medical accelerators. To date, rotating gantries have been built only for neutrons and protons [1] while light-ion therapy beams have been applied using fixed beam lines. Nevertheless, there are few design studies of light-ion gantries. In 1992, Carli et al. designed four different gantry modifications for the EULIMA Project [2] and beam optics studies of the gantry were commenced also at GSI Darmstadt by Janik and Müller [3]. Carli's gantries had only one-direction scanning option. Janik and Müller attempted to include two-direction magnetic scanning system developed at GSI [4] into the gantry optical layout [5]. We have modified their original design in order to improve mainly the ion-optics properties as well as to reduce the overall gantry size.

1.1 Main gantry specifications

The most important constraints upon gantry characteristics as used in our beam optics design are listed below.

- *Isocentric configuration.*
- *Achromatic beam optics.*
- *Adjustable beam size from 3 to 10 mm.*
- *Beam rigidity of 7 Tm.*
- *Overall gantry size and weight as small as possible.*
- *Scanning field as large as possible*; the values quoted in literature are usually 20 x 20 cm^2; in our designs the scanning field is 10 x 10 cm^2.
- *Parallel or low-angle scanning mode*; this means that the angle of incidence measured between the axis of the incoming beam and the axis normal to the scanned surface must be less than 1^o [6].
- *Beam-waists at the isocentre.*
- *Drift from the gantry exit to the isocentre 1.2 m.*
- *No pole face rotation at superconducting dipoles.*

The first-order beam transport calculations were done by TRANSPORT, SLAC version 4.8, March 22, 1974. The input beam parametres in all presented cases are: 5 mm x 5 mrad waist, momentum 2.08 GeV/c and momentum spread 0.2%. The same input parametres are assumed in both bending and non-bending planes. Although this assumption is not really true for slow extraction from synchrotrons, the symmetric beam at the coupling point (the exit of the transfer line and the entrance of the gantry) is often used as an approximation at the first stage of gantry design. The problem is discussed in [7].

2 GENERAL GANTRY LAYOUT

Various modifications of the gantry shape were investigated in order to find the most space-saving concept. Special attention was paid to the position of the scanning system. The volume of the room occupied at 360^o gantry rotation was taken as a criterion for this research. Apart from cork-screw solution which represents a different approach and can hardly be compared with other designs the result of our study showed that a cylindrical gantry with the minimum radius can meet best the above mentioned specifications. This is a natural consequence of the fact that the volume generated by gantry rotation is proportional to the product of gantry length and the square of gantry radius. In other words, one can save more space by minimizing the radius rather than the length. That is why the scanners were favourably placed in the upper straight section of the gantry. The gantry length was considered nearly as a free variable parametre for optimizing the beam optics properties of the gantry.

In order to avoid any confusion concerning the terminology we always consider the gantry in its top position. In accordance with this policy the cylindrical gantry consists of straight section, bend-up shoulder,

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upper straight section and bend-down shoulder (head). The situation is illustrated in Figure 1.

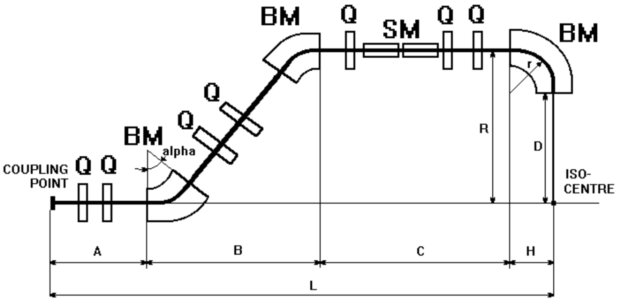

Figure 1 Definitions of the gantry parts and dimensions: A - straight section, B - bend-up shoulder, C - upper straight section, H - head (bend-down shoulder), D - drift to the patient, R - gantry radius, L - gantry length, Q - quadrupoles, BM - bending magnets (alpha - angle of bend, r - bending radius), SM -scanning magnets.

3 SUPERCONDUCTING GANTRY WITH PARALLEL SCANNING MODE

This gantry, originally designed by Janik [5], represents an attempt to achieve parallel scanning mode in both scanning directions. For this reason, its beam optics layout was strictly derived from the guiding principle, that scanners must be placed into the focal points of the system. Additional quadrupoles had to be inserted between the scanners and the bend-down shoulder in order to form “point-to-parallel” imaging. The gantry configuration and beam envelopes calculated by TRANSPORT are shown in Figure 2.

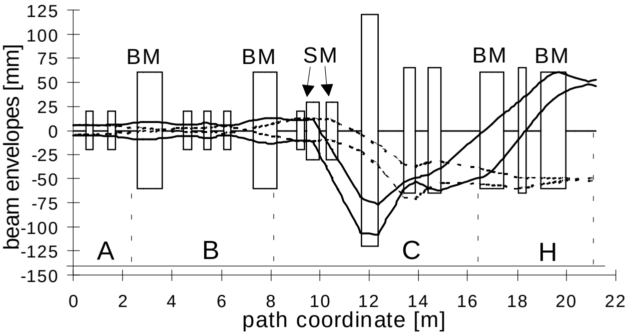

Figure 2 Superconducting gantry with parallel scanning: beam transport. Solid line - bending plane, dashed line - non-bending plane, non-labeled elements are quads.

There are several disadvantages of this design.

- *The optics is not achromatic;* zero dispersion is achieved at the isocentre but zero derivative of the dispersion function is not.
- *The gantry radius is large* (because of using two dipoles and one quadrupole in the bend-down shoulder).
- *The aperture of the elements which follow the scanners must be large.*
- Misalignment, mispowering or higher-order effects of the quadrupoles behind the scanners may lead to a *wrong beam position* at the gantry exit.

4 SUPERCONDUCTING GANTRY WITH LOW-ANGLE SCANNING MODE

In order to fix the above problems the parallel scanning mode was abandoned and replaced by a low-angle mode. The optical and scanning systems were rearranged. Three essential changes in the gantry design were done. The ion optics reasons for such changes are discussed in [8].

- *The bend-down shoulder was diminished by using only single 90 ^{0} superconducting dipole;* this brings the gantry radius to the theoretical minimum which is obviously equal to the sum of bending radius of the dipole and drift to the patient.
- *The scanning system was moved to a new position; it became the last element of the upper-straight section.* The main advantage of this solution is decoupling the optical system from the scanning system. The “point-to-parallel” transformation is no longer required from the optical system, which makes it more flexible. The gantry is achromatic. Except for the last bend-down dipole there are no large aperture elements because the beam is deflected from the optical axis just before entering the gantry head.
- *A new configuration of the scanning system has been proposed;* three scanning magnets are used instead of two, one for non-bending plane and two for bending plane. This was necessary in order to compensate for focusing action of the last bend-down dipole. One can say that simplification of the optical system made the scanning system more complicated. However, the optical properties of the whole beam transport system have been improved, which is demonstrated in [8].

Figure 3 shows the new gantry configuration and beam envelopes calculated by TRANSPORT.

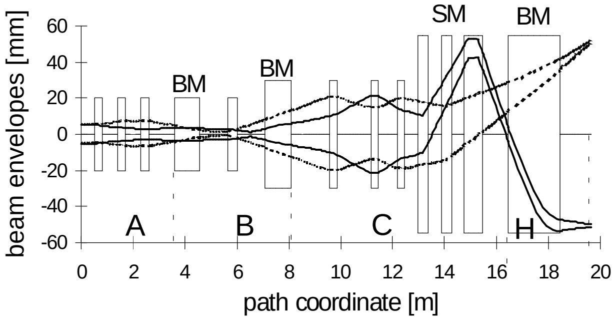

Figure 3 Superconducting gantry with low-angle scanning: beam transport. Solid line - bending plane, dashed line - non-bending plane, non-labeled elements are quads.

Figure 4 shows a detail of the scanning system.

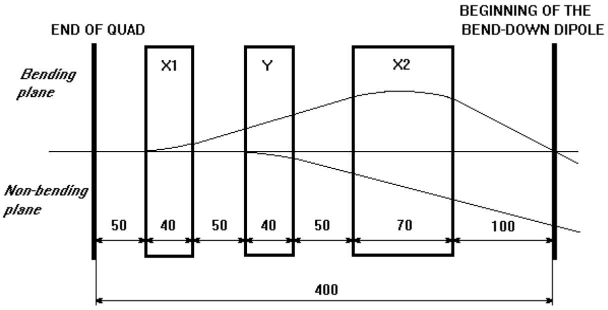

Figure 4 Proposed configuration of the scanning system. X1, X2 - scanners in bending plane, Y - scanner in non-bending plane. Dimensions in cm.

4.1 Hybrid gantry

There are many mutations of the gantry configuration possible using the advantage that optical and scanning systems are decoupled. The hybrid gantry was created from the superconducting gantry by replacing the superconducting magnets in the bend-up shoulder by conventional magnets. In order to keep the same gantry radius, two 30^o normalconducting magnets are used instead of 45^o superconducting ones. Also a quadrupole singlet in the bend-up shoulder was changed to doublet mainly to reduce the vertical gap of the bend-up dipoles.

5 DISCUSSION AND CONCLUSIONS

The principal advantage of the new proposed ion-optics concept is **decoupling the optical system from the scanning system.** The optical system is not involved in forming the “point-to-parallel” transformation and can be much more effectively used to control the beam parametres at the gantry exit. In all presented cases the optics is fully achromatic, the beam size can be tuned from 2 to 10 mm and the beam has always waists in both planes at the isocentre. Both optical and scanning systems can be designed and optimized nearly independently of each other unless the scanners are too large to fit the space reserved for them. That is why large number of different mutations are possible and the gantry is still open to further optimization.

Table 1 summarizes the main parametres of the superconducting gantries designed at GSI Darmstadt. The reduction of the volume generated by gantry rotation is clearly demonstrated.

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Table 1 Summary of the main gantry parametres. Dipoles (if not identical) are numbered from the coupling point, ‘S’ means Superconducting and ‘N’ Normalconducting magnet. For quads, the maximum aperture and effective length are given. The first straight section A does not contribute to the volume generated by gantry rotation, hence $V=\pi.R^2.(L-A)$.

	SG-parall. scanning	Sup.G.- low-angle scan.	Hybrid gantry
A[m]	2.6	3.6	3.2
B[m]	4.4	3.5	6.33
C[m]	8.2	8.4	8.3
H[m]	2.3	1.25	1.25
D[m]	1.04	1.25	1.2
R[m]	3.35	2.5	2.45
L[m]	17.5	16.75	19.08
$V[m^3]$	525	258	300
Dipoles	Numb.: 4S r = 1.25m $\alpha = 45^0$ field 5.56T *all dipoles identical*	Number: 3S r = 1.25m $\alpha1=\alpha2=45^0$ $\alpha3 = 90^0$ field 5.56T	Numb.:2N+1S r1= r2=3.86m $\alpha1 = \alpha2 = 30^0$ field 1.8T r3 = 1.25m $\alpha3 = 90^0$ field 5.56T
Quads *(max.)*	Numb.: 10 ap.= 24cm L_{eff}=70cm	Number: 7 ap. = 6cm L_{eff} = 35cm	Number: 8 ap. = 6cm L_{eff} = 35cm

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