GANTRY STUDIES FOR THE PROPOSED HEAVY ION CANCER THERAPY FACILITY IN HEIDELBERG

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Abstract

The Heavy Ion Cancer Therapy Facility HICAT [1] proposed for the clinic in Heidelberg will contain three treatment rooms - one treatment room will be equipped with a fixed horizontal beam line and two treatment rooms will contain heavy ion gantries. In parallel to the design of the accelerator facility, the heavy ion gantries were subject of detailed studies at GSI during the last years. Different layouts of the gantry ion optical system and of the gantry structure have been compared. The mechanical stability during rotation was analyzed and the effects of deformations on the beam transport were studied. Finally, an integrated gantry concept was found which satisfies the requirements on beam position stability in the ISO center.

1 INTRODUCTION

A gantry provides the capability to treat patients from arbitrary directions perpendicular to the original horizontal beam axis. Unfortunately, the magnetic rigidity of heavy ion beams with a suitable range is about three times higher than the rigidity of proton beams. Therefore, a main design criteria for heavy ion beam gantries is to restrict the growth of the geometrical extension and weight. However, the size and weight of the main dipole magnets is defined by the maximum allowed flux density in the iron yoke. Therefore, the total gantry weight is given by the weight of the beam guiding elements and the weight given by the the enhanced volume of the gantry structure. However, beside the layout of the ion optical system, a careful study of the mechanical properties is required. Gantry structure designs and analysis were performed by means of finite element programs. Such programs enable the calculation of mechanical stress and deformations for arbitrary gantry angles. The misalignment of the gantry magnets caused by structure deformations or by other reasons like temperature variations have been determined.

2 THE GANTRY ION OPTICAL SYSTEM

The proposed heavy ion beam gantry consists of 8 quadrupole magnets, two 45^o and one large aperture 90^o dipole magnet. The gantry height is minimized by placing the raster scan system upstream the 90^o dipole magnet. Thus, the height is mainly defined by the bending radius of the 90^odipole and the distance of the ISO center from the dipole nozzle. The horizontal extension decreases with choosing a large bending angle and a maximum flux density in the up-bending dipole (45^o).

The gantry quadrupole system must allow the generation of spot radii between 2 to 5 mm in the ISO-plane. This range of spot radii must be achievable at all rigidity levels and at all expected transverse emittance ratios up to $\epsilon_{x(y)}/\epsilon_{y(x)} = 1/5$. Furthermore, the focusing properties should be independent from the gantry rotation angle (Fig. 1).

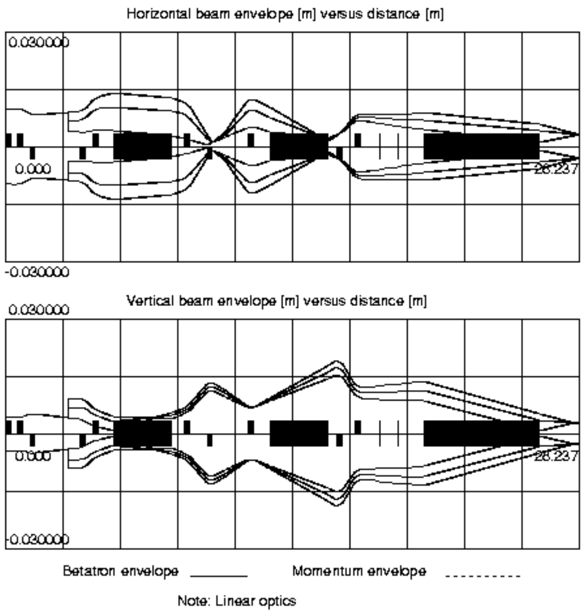

Figure 1: Gantry angle independent focusing. Envelopes are plotted for a beam with non-equal transverse emittances (ϵ_x = 5 mm mrad - ϵ_y = 1 mm mrad) at 90, 45 and 0 degree rotation angle.

In general the final beam radius R is determined by the final beta function and the beam emittance $R = \sqrt{\epsilon\beta}$. The final β-function can be calculated by transfering the Twiss parameters (β, α, γ) from the entrance of the gantry system to the ISO-plane : $\beta_f = (X,X)^2\beta_i - 2(X,X)(X,X')\alpha_i(X,X')^2\gamma_i$. The so called magnification terms (X,X) and (Y,Y) of the gantry system can be fitted to be zero or at least very small. Typically values of less than 10^{-3} can be achieved for a realistic gantry system. Thus the final beam radius does not depend significantly on the initial twiss parameters β_i and α_i. The final beam radius, which is in this case only given by the dependence on the initial twiss parameter γ_i, is constant for different rotation angles, if the beam divergence $\sqrt{\gamma_x\epsilon_x} = \sqrt{\gamma_y\epsilon_y}$

are equal at the take-over point and (X,X') and (Y,Y') are equal. The terms (X,X') and (Y,Y') are typically between 1 - 10 (about 1000 times larger) and can be fitted to be equal. A variation of the beam radius in the ISO plane at varying transverse beam emittances must be compensated by the matching system in front of the gantry. At non-equal horizontal and vertical emittances the final beam cross section stays circular at rotation if $\gamma_x \epsilon_x = \gamma_y \epsilon_y$ is realized at the gantry entrance.

At resonance extraction mainly the vertical beam emittance is damped according to the final energy. Thus, the aspect ratio of the transverse emittances will vary according to the beam energy. Furthermore, the final beam radius must be independent from the beam momentum spread. Thus the gantry optics must be achromatic. This means that the dispersion function at the entrance of the gantry and the dispersion in the ISO plane must be zero (Fig. 2).

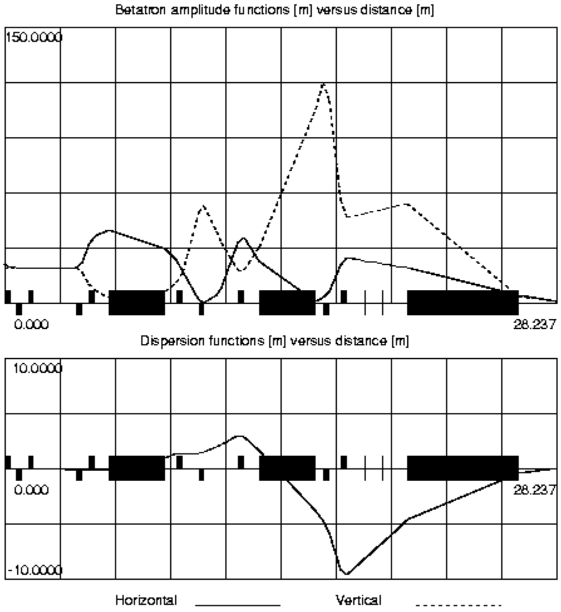

Figure 2: Beta-and dispersion functions resulting from a suitable setting of the gantry optical system.

The vanishing dispersion D_x and derivative of the dispersion dD_x/dz at the gantry entrance and in the matching system has to be generated by the beam delivery system upstream the matching system.

An adequate angle independent gantry optics requires the following boundary conditions :

a) (X,X) = (Y,Y) = 0

b) (X,X') = (Y,Y')

c) (X,P) = 0

d) R_x = R_y = Goal value

These properties must be realized without generating beam losses due to restricted magnet apertures. This means that the beam radius should not exceed the acceptance of the system even when the emittance aspect ratio is large and the gantry rotates. Critical positions are the exit of the second 45 ^{o} dipole magnet and the following two focusing quadrupoles. A displacement of the gantry quadrupole elements causes a certain dipole kick on the beam. The kick angles scale in first order linear with the quadrupole displacement and the quadrupole gradient. Therefore, the magnitude of the individual kick angles depend on the specific setting of the gantry quadrupole magnets. The expected horizontal dipole kicks of misaligned quadrupole magnets are listed in the following table under the assumption of a lateral displacement of 0.1 mm. The quadrupole number counts in forward direction starting from the gantry entrance :

Gantry Quad. Number	Kick [mrad]
Q1	-0.028
Q2	0.021
Q3	0.032
Q4	-0.033
Q5	0.001
Q6	0.037
Q7	-0.032
Q8	0.038

Due to the dipole kicks the beam experience a displacement in the ISO plane. The calculated beam position displacements resulting from the kicks listed in the table above are drawn in the bar chart. As the example indicates, a relevant beam displacement ($\approx$ 0.5 mm) in the ISO center may be expected starting from a misalignment of 0.1mm.

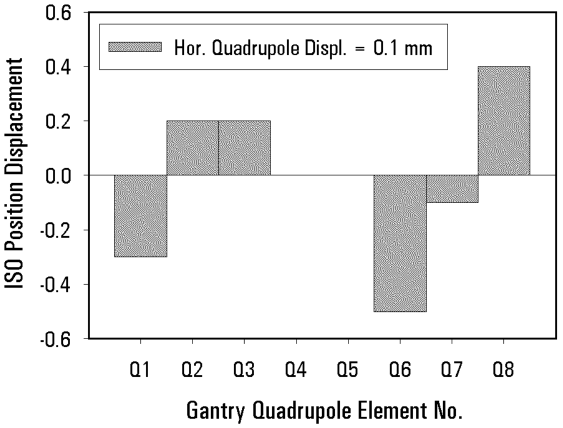

Figure 3: Beam displacement in the ISO plane caused by dipole kicks resulting from a misalignment of individual gantry quadrupole magnets.

3 THE GANTRY STRUCTURE

The mechanical design [2] of the gantry structure was optimized with respect to the position stability of the ion optical elements at arbitrary gantry angles. Three different concepts were investigated. The most promising layout, which is described here, will be subject of more detailed optimization studies in near future. The highest stability may be achieved with a box-girder construction (Fig. 4). Such a construction has the advantage that the pushing strength of the plates is superimposed to the flexural strength of the truss construction. A most realistic estimate of the maximum deformation can be obtained by a finite element analysis. For this purpose a three dimensional computer model was generated including a realistic modeling of the effects of the contact area. The total weight of the overall structure was calculated to be 675 t at a wall thickness of 20 mm for the central part and a thickness of 50 mm for the wheels. The contact area covers 90 degree of the wheels. The maximum calculated lateral deformation is about 0.3 mm (Fig. 5). The calculations have shown, that due to the increasing weight of the structure, the deformations can not be improved arbitrarily by using thicker structure walls. The wheel supports are dimensioned according to a weight distribution of 460 t on the front wheel and the 216 t on the back wheel. The number of rolls for the front wheel is 12 with a maximum force in the main bearing of 2.54 MN. The number of rolls for the back wheel is 6 with a maximum force of 1.2 MN in the main bearing. The length of the carrying lines of the rolls is for the front wheel 473 mm and the back wheel 438 mm.

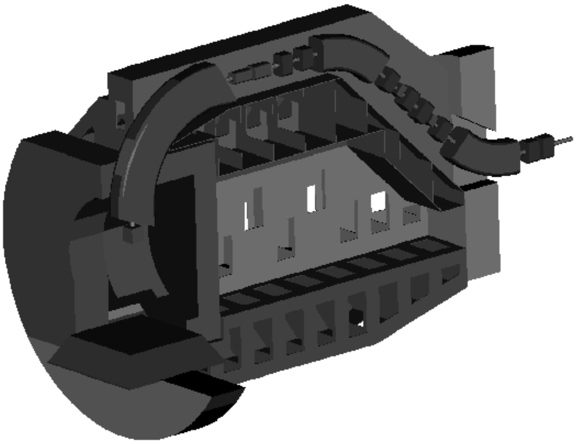

Figure 4: The gantry structure design.

Furthermore, the displacement of the ion optical elements caused by temperature variations of the gantry structure was estimated. Temperature effects must be added to a the described displacement of the optical elements and contribute thereby to the displacement of the beam position in ISO center. The maximum calculated displacement of the optical axis was calculated to be 0.2 mm /^{o}C.

4 CONCLUSION

The angle dependent deformation of the optical axis during gantry rotation and the temperature effects may lead to a displacement of the beam position in the ISO plane. The critical amplitude for the deformation is given by the tolerable beam displacement for the different beam radii. Attempting to keep the deformation below this critical amplitude ($\leq$ 0.2 mm) just by a substantial enlargement of the wall thickness leads to a major increase of the gantry weight. Therefore, a compromise between sufficient mechanical stiffness of the gantry structure and possible correction mechanisms (e.g. by steerer magnets) must be choosen.

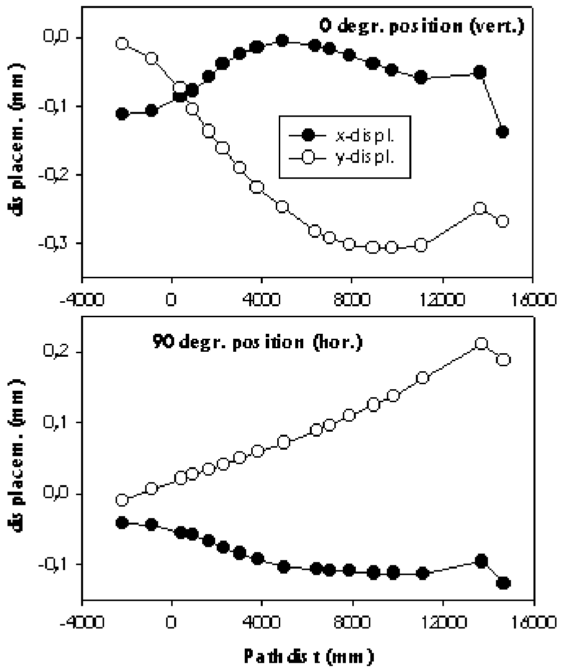

Figure 5: Calculated horizontal and vertical displacement of the optical axis at different gantry angles (0^o and 90 ^{o}).

REFERENCES

[1] Proposal for a dedicated ion beam facility for cancer therapy, Radiolog. Univ. Klinik Heidelberg, (1998)

[2] Abschlussbericht Gantry Studie, 0947-BP-0473-0, ACCEL Instr.(00)