STATUS REPORT ON THE RIESENRAD ION GANTRY DESIGN

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Abstract

The paper describes the “Riesenrad” gantry - a novel concept for a rotating ion gantry. Special attention is paid to the structural design of the gantry and to the study of the beam position accuracy in the gantry isocentre.

1 INTRODUCTION

Most of the currently proposed ion-therapy facilities in Europe plan to install a rotating gantry equipped with a pencil-beam scanning system. Such a gantry improves the dose-to-target conformity, but the pencil-beam scanning increases the demands on the beam transport accuracy. Sub-millimetre beam position accuracy at the patient (i.e. in the gantry isocentre) is required. So far, experience exists only for proton gantries using passive [1] or hybrid [2] beam delivery systems, or for a fixed beam line using the pencil-beam scanning [3].

For carbon beams, a novel gantry concept - the Riesenrad gantry - has been developed in the framework of the Proton-Ion Medical Machine Study (PIMMS) hosted by CERN in collaboration with the Med-AUSTRON Project. Considerable effort was put into the analysis of the beam position accuracy in order to assess realistically the achievable precision as well as to specify the misalignment tolerances for beam transport elements.

2 MECHANICAL CONCEPT

In the Riesenrad (Fig.1), the 90° bending magnet terminating the transfer line is placed on the axis of gantry rotation that coincides with the axis of the incoming beam. The magnet can be rotated around this axis. The patient is placed *eccentrically* in a special cabin that follows the magnet rotation. The Riesenrad concept minimises the amount of equipment rotated off-axis, which simplifies mechanical design of the gantry compared to any *isocentric* variant.

Basically, the Riesenrad gantry consists of three separate structures (Fig. 2): the central cage, the patient cabin and the rotator.

The central cage supports three scanning magnets (1.5 t) and the 90° dipole (62 t, bending radius ≈3.5 m). The total weight is ≈127 t, of which 23 t are due to the counterweight. About half of the dipole's weight is taken by the front ring, the other half is taken by two transverse shear walls (vertical gantry position) or a pair of "balancing tongs" (horizontal gantry position). The balanced tongs intrinsically compensate part of the vertical elastic deformation along the beam line inside the gantry. The front ring rests on two pairs of rollers that withstand a radial force of 240 kN each. The other support of the cage is a tapered roller bearing unit. A front structure cantilevered out from the front ring supports the scanning magnets.

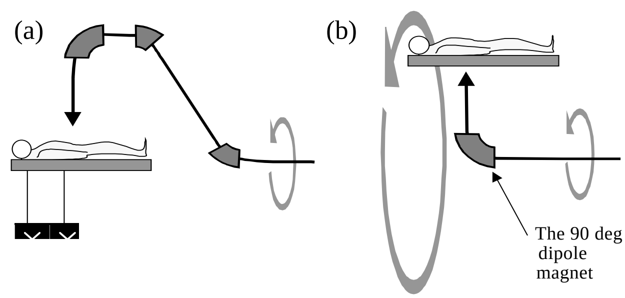

Fig. 1: Principle of an isocentric and a Riesenrad gantry.

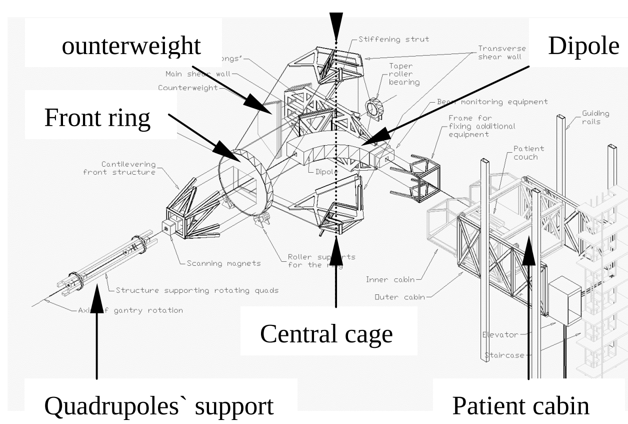

Fig. 2: Principal elements of the Riesenrad gantry.

The patient cabin is an independent structure with no mechanical link to the central cage. It travels up to ±5.6 m vertically with respect to the entrance level by using two guide-rails on each side of the cabin. The rails are fixed to the building walls. The lateral movement is performed by telescopic motion of the treatment platform up to 5.6 m. Access to the platform is always possible by a lift. The telescopic action keeps the platform in constant contact with the back wall on which an emergency staircase is mounted. The patient couch is precisely aligned with respect to the 90° dipole by a photogrammetric system achieving relative couch-to-magnet position accuracy better than 0.1 mm (1σ).

The rotator is a special matching section needed for ion-optical reasons that turns with the half of the gantry angle [4]. Its supporting structure is a trussed girder ≈10 m long holding 7 quadrupoles. A similar structure holds 4 quadrupoles between the rotator and the gantry. Each structure is supported by sets of rollers. The weight is about 2 tons each.

3 STRUCTURAL ANALYSIS

Because of the slow gantry rotation, the structure was analysed as being static. Due to the high-precision requirements, the mechanical design is governed by the permissible deflections and, generally, no problems concerning maximum stress and stability were encountered (i.e. a deformation-driven design). Actual stress levels in the members rarely exceed 10 N/mm^2, only a few highly-loaded struts of the tongs show maximum stresses of about 20 N/mm^2. Consequently, safety factors of 1.0 for resistances and loads have been applied.

3.1 Elastic Deformations

Elastic deformations due to gravity have been assessed. They are expressed as deviations of the mechanical axis of the beam transport system with respect to its ideal shape. Figure 3 illustrates the vertical elastic deformations of the gantry's beam transport system for different gantry angles.

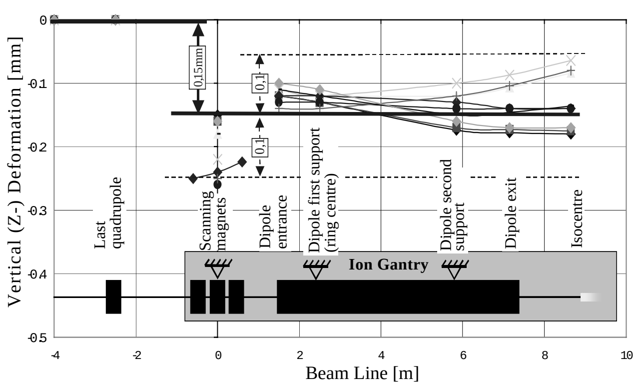

Fig. 3: Vertical elastic deformations of the gantry for different gantry angles.

The uniform vertical displacement of the dipole and its relative independence of the angular position yields the opportunity to lift the whole structure by approximately 0.15 mm at the bearings in order to better match the gantry to the preceding beam line. Under these circumstances, only the differential deformations of about ±0.1 mm will have an influence on the beam transport. Larger deformations at the scanners are not critical. Their ion-optical effects can be eliminated if the scanning magnets are designed with adequate safety margins for the good-field region. The analysis showed that the elastic deformations affecting the beam transport hardly exceed ±0.1 mm.

3.2 Temperature Effects

It is foreseen to keep the temperature in the gantry hall within ±1 K. Under these conditions, the deformations due to various temperature fluctuations have been studied. They were lower than 0.07 mm and 0.01 mrad.

4 BEAM POSITION ACCURACY

The structural analysis served as input for the ion-optical analysis. The goal was to investigate the influence of the mechanical misalignments of the beam transport elements (due to the deformations of the gantry structure) on the beam position accuracy in the gantry isocentre. The analysis has been restricted to the rotating parts of the gantry, thus comprising 7 quadrupoles of the rotator plus 4 quadrupoles, 3 scanners and the 90° dipole of the gantry. It is assumed that the beam enters the rotator exactly on axis and that the beam transport elements are perfect, but slightly displaced along and/or rotated around each of the local co-ordinate system axes (the co-ordinate system of TRANSPORT [5] has been adopted). The action of the scanning magnets is not taken into account, hence it is investigated how precisely the non-scanned beam can hit the ideal gantry isocentre.

The overall transfer matrix from the rotator entrance to the isocentre is a function of the gantry angle α, because the angle $\alpha/2$ appears between the exit of the rotator and the entrance of the gantry. That is why, ion-optical effects related to the misalignment of the beam transport elements of the rotator depend on the gantry angle.

The misalignments have been classified into two categories: systematic and random. The *systematic* misalignments are a reproducible function of the gantry angle. They cover also constant errors independent of the gantry angle. *Random* misalignments represent all possible effects with no reproducibility as a function of the gantry angle (like temperature fluctuations). These misalignments are expected to have a gaussian distribution superimposed on the systematic misalignments. The position of each beam transport element is therefore characterised by a particular value of the systematic misalignment and a standard deviation of the element position probability distribution.

The systematic and random misalignments must be treated differently. The systematic misalignments represent the situation where all elements are misaligned by a known amount. The position of the beam in the gantry isocentre is obtained by tracing the beam through this misaligned beam line by a computer code.

Random misalignments are considered as an uncertainty of the actual element position. If the parameters of the element misalignment are interpreted as one standard deviation of its position probability distribution, then the calculated beam position represents one standard deviation of the *beam position probability distribution*. The beam transport calculations were performed by TRANSPORT [5] and WinAGILE [6].

4.1 Systematic Misalignments

Typically, elastic deformations of the gantry supporting structures cause a systematic beam-excursion in the isocentre. The values obtained by the structural analysis were used as the input data for the beam transport calculations. The maximum beam excursions due to the elastic deformations were less than 0.2 mm.

4.2 Random Misalignments

It is difficult to assess the random misalignments in the same way as the systematic ones and a different strategy has been chosen. The *sensitivity* of the beam transport system to random misalignments was investigated. For this purpose, a corresponding analytical model has been developed based on the beam transport matrix formalism. The model showed that the standard deviation of the beam position probability distribution in the isocentre was proportional to the standard deviation of the position probability distribution of the beam transport elements. Four different effects (quadrupole-shift, quadrupole-tilt, dipole-shift and dipole-tilt) were considered and their effects were added quadratically.

"Reference" input data for the sensitivity analysis were $3\sigma_{shift} = 0.1$ mm and $3\sigma_{tilt} = 0.1$ mrad for all elements. Maximum overall values for the corresponding beam position probability distribution in the isocentre were $3\sigma_{total} = 0.96$ mm and 1.4 mm (horizontal and vertical plane, respectively, see Fig. 4). The results obtained for the reference misalignments were then scaled to the expected random misalignments due to the temperature fluctuations. Finally, a contribution from the photogrammetric alignment system of the patient couch ($3\sigma = 0.3$ mm) was added. The overall beam position uncertainty in the isocentre regarding these contributions was $3\sigma_{total} < 0.6$ mm.

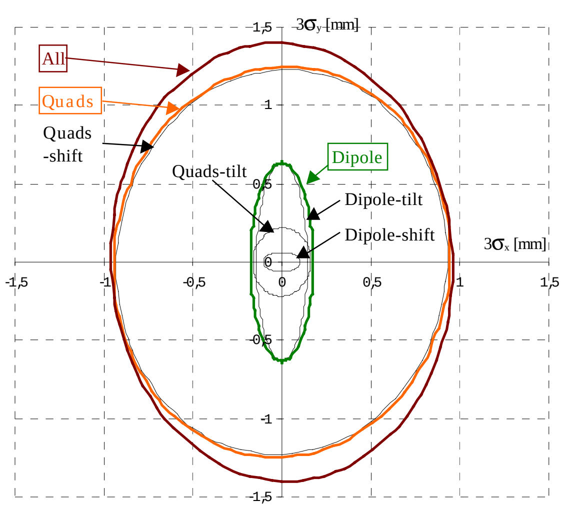

Fig. 4: Beam position uncertainty 3σ due to *reference* random misalignment and its contributors.

The results show that in order to achieve the sub-millimetre precision ($3\sigma_{total} < 1$ mm) in the isocentre, random misalignments have to be lower than the chosen reference values. However, not all misalignments are that critical. The dominating contribution comes from the quadrupole shift. A misalignment tolerance of $3\sigma < 0.07$ mm is required for the transverse position of the quadrupoles. The effect of quadrupole tilt is about 6 times lower. For the dipole, the angular misalignments are more critical compared to the shift, especially in the vertical plane. The reference misalignment tolerances are acceptable for the dipole, a reduction of tilt to $3\sigma_{tilt} = 0.05$ mrad would, however, provide a higher tolerance budget for the quadrupole shift.

5 DISCUSSION AND CONCLUSIONS

The Riesenrad is a realistic concept for a rotating ion gantry capable of delivering the beam by active scanning with a sub-millimetre precision. The elastic deformations along the beam line will not exceed ± 0.1 mm and the corresponding beam excursions in the gantry isocentre are less than 0.2 mm. Other components of systematic misalignments, for example manufacturing errors, are not included in the present analysis, because their exact values are not known yet. Nevertheless, by virtue of their reproducibility as a function of the gantry angle, they can be compensated by a set of fixed corrections.

The beam position uncertainty due to the reference random misalignments ($3\sigma_{shift} = 0.1$ mm, $3\sigma_{tilt} = 0.1$ mrad) expressed as 3σ of the beam position probability distribution in the isocentre is about 1.4 mm. The effects of random misalignments have been particularly assessed for temperature fluctuations and finally a contribution from the alignment system of the patient couch was added. Regarding these contributions, a precision of $3\sigma_{total} = 0.6$ mm is feasible. Misalignment tolerances for beam transport elements have been specified. In order to achieve $3\sigma_{total} = 1$ mm in the isocentre, the random component of the most critical alignment error - transverse quadrupole shift - should be around 0.07 mm.

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