EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
ORGANISATION EUROPÉENE POUR LA RECHERCHE NUCLÉAIRE

CERN - ST Division

CERN-ST-2000-057
February, 2000

DESIGN OF A 'RIESENRAD' ION GANTRY FOR HADRONTHERAPY

S. Reimoser [1]

Abstract

The benefit of hadrontherapy can be maximized by offering the possibility to deliver the particle beam from any direction in space towards the patient with the help of a medical gantry. For carbon ions, their increased (magnetic) beam rigidity yields considerable structural difficulties and has so far prevented a practical realization of an ion gantry. The concept of a 'Riesenrad' ion gantry promises to provide an effective and efficient solution. The basic idea is to deflect the ion beam with a single 90° dipole, which rotates around the incoming beam axis, and direct it towards the eccentrically positioned patient cabin. Inside the cabin similar conditions as exist in a classical isocentric treatment room prevail. The practical design of such a Riesenrad gantry, its structural principles and its function are presented. The underlying beam optics and its integration into the mechanical structure are explained. Aspects of safety, and flexibility are discussed.

[1] CERN, ST Division and Institute for Building Construction and Industrial Building, Vienna University of Technology.

Presented at the 3rd ST Workshop
Chamonix, France, January 25 - 28, 2000

1 INTRODUCTION

Medical machines capable of delivering a particle beam from every position and direction best suited for the treatment of cancerous tumours are called *gantries*. They allow the delivered dose to conform very closely to the tumour volume, while minimizing the dose deposited in healthy tissue and sparing critical organs.

Such machines have been used for conventional and recently also for protontherapy. Whereas for the classical radiotherapy the electron (linear) accelerators are light enough to be mounted directly on the gantry, this is not possible for protons and of course not for the even heavier ions. In this case, a horizontal particle beam, delivered by an accelerator, has to be directed onto the *supine* patient from all possible directions. Bending magnets can be used to deflect the beam. Somehow this beam line has to be moved and rotated relative to the patient. Various concepts to achieve this task have been proposed [1]. The principle of the classical — so-called isocentric — solution for a large gantry is shown in Fig. 1(a).

It seems desirable to provide the possibilities of a gantry also to the emerging and very promising application of ions in radiotherapy, as is currently proposed by several national European projects, like the German proposal for a dedicated ion beam facility [2], the Med-AUSTRON project [3] and TERA in Italy [4]. However, the rise in complexity of an ion gantry (compared to the already very complicated proton gantries) is considerable. The increased (magnetic) beam rigidity (~ 6.6 Tm) of the proposed carbon ions yields structural difficulties. The structure would have to support large and very heavy bending magnets (in the region of 60 t and more) and nevertheless deliver the beam with a sub-millimetre precision. It is this contradiction that has so far prevented any realization of an ion gantry.

2 PRINCIPAL FUNCTION OF THE RIESENRAD GANTRY

To overcome the deadlock mentioned above a novel system of gantry — the so-called ‘Riesenrad’ ion gantry — has been designed and evaluated. The main idea is to ‘invert’ the classical gantry geometry as indicated in Fig. 1(b). In the Riesenrad, a 90° dipole is placed at the end of the transfer line and rotated around the incoming beam axis. The magnet can be set at any angle and the beam will be deflected in the corresponding direction. The patient must, in this case, be placed eccentrically and follow the dipole rotation.

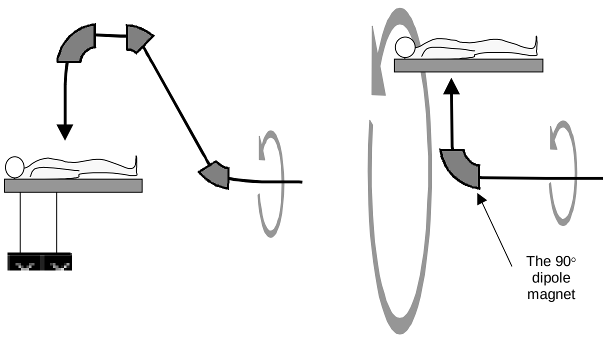

Figure 1: (a) Conventional isocentric gantry; (b) Exocentric Riesenrad gantry.

This design, which is schematically shown in Fig. 2, has the following advantageous features.

- The central ‘cage’ and the patient cabin are two independent and hence comparatively small structures.
- The patient cabin is spacious and essentially unlimited in size.
- The patient cabin is a low-precision lift structure with a telescopic floor. Only the patient couch requires precision alignment and this is done photogrammetrically with respect to the dipole.

- The patient cabin has continuous contact with the lateral wall of the gantry room and, by virtue of this, has permanent emergency access by a staircase at all times.
- The central cage containing only magnets and counter-balance weight is relatively light (support structure 40 t, counterweight 23 t, the dipole 62 t and scanning magnets 1.5 t, making a total of ~ 127 t) and compact, hence reducing the moment of inertia of the central cage and increasing its rigidity.
- The inner volume of the gantry room is 1700 m^3.

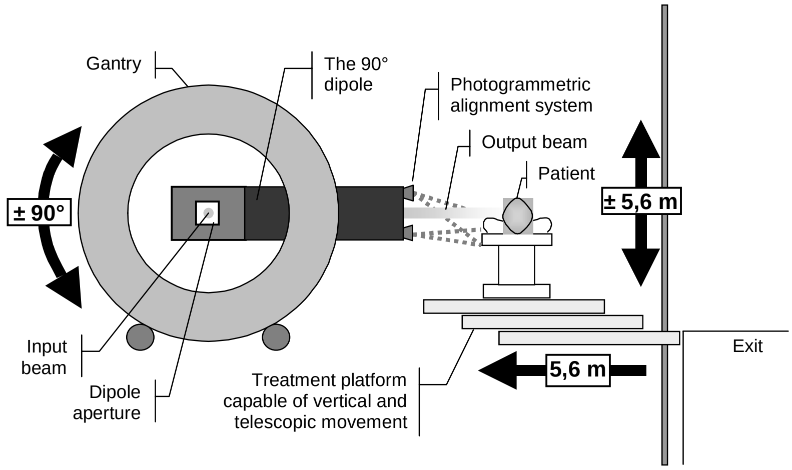

Figure 2: Riesenrad gantry with movable treatment platform. The patient is positioned corresponding to a particular dipole angle by vertical and horizontal translations of the platform. The dipole can rotate ±90° and the patient couch can rotate 360° around its vertical axis so as to achieve effectively any treatment angle.

3 BEAM OPTICS

The design of the gantry is based on a particle beam that is derived from a slow-extraction scheme in a synchrotron, as is proposed by the Proton-Ion Medical Machine Study (PIMMS [5]) that is hosted by CERN. To match the incoming dispersion vector to the gantry a special module called the *rotator* is used. Being about 10 m long this rotator supports seven quadrupoles and turns half the angle of the gantry. The mechanical gantry structure *(the gantry)* comprises the three scanning magnets and the large 90° dipole. The four quadrupoles between the rotator and the gantry (turning the same angle as the gantry) will be supported by a separate rotating structure similar to the rotator.

4 STRUCTURAL DESIGN

4.1 Central cage

The central cage (see Fig. 3) supports the three scanning magnets (1.5 t) and the large 90° dipole (62 t). The total weight is ~127 t, of which 23 t are due to the counterweight. The design of the central cage is driven by the desire to minimize sagging of the dipole no matter what gantry position is considered.

Approximately half of the dipole's weight is taken directly by the front *ring*. Unlike conventional isocentric gantries, this ring does not have to provide a large aperture to accommodate the treatment area. Instead, it is an extremely rigid cylindrical box (outer diameter 4.3 m) with a comparatively small ‘window’ to allow the dipole to enter the cage. Depending on the gantry rotation, the other half of the dipole load is taken by the two *transverse shear walls* (vertical gantry position) or a pair of *balancing tongs* (horizontal gantry position). Each of the truss-like tongs transfers its balanced load (dipole on one side, counterweight on the other) via the central diagonals and the inner girder onto the *main shear wall*. The outer girder is free to glide over the main shear wall (i.e. no mechanical connection). As a consequence, a relatively low force, which is applied via the *stiffening struts*, is sufficient to compensate for elastic deformations on the dipole-side of the structure and keep the magnet in the desired horizontal position. The front ring rests on two pairs of *rollers* of diameter 0.6 m that withstand a normal force of 240 kN each.

The *rear bearing* provides a second support that is a standard tapered roller bearing unit. Consoles guide the forces to the (diaphragm) walls of the building. A *front structure* cantilevered out from the front ring towards the incoming transfer line supports the scanning magnets.

4.2 Patient cabin

The patient cabin is an independent structure (see Fig. 3) with *no mechanical connection* to the central cage. The central cage therefore avoids an equivalent increase in its counterweight and is relieved of the task of holding the treatment room rigidly at a large radius. This affords a considerable reduction in the total weight and moment of inertia of the central cage, which is consequently more rigid and easier to build.

The exact alignment of the patient couch and the control of the 'gantry radius' (5.525 m) is guaranteed by a photogrammetric system that automatically and actively moves the patient table with four degrees of freedom (*x y, z* and rotation about vertical axis). Reflectors on the patient couch are monitored by four cameras attached to the face of the dipole, which calculate the relative position with an accuracy better than 0.1 mm (σ). Only a moderate positioning accuracy of the cabin itself is required. The patient cabin travels vertically by ±5.6 m with respect to the entrance level by using two guide rails on each side of the cabin that are fixed to the building walls. The lateral movement is assured by a horizontal telescopic motion of the treatment platform by 5.6 m. Access to the treatment platform is possible at all times by a lift. The telescopic action of the treatment platform keeps it in constant contact with the back wall of the shielded enclosure on which a staircase is mounted for emergency access.

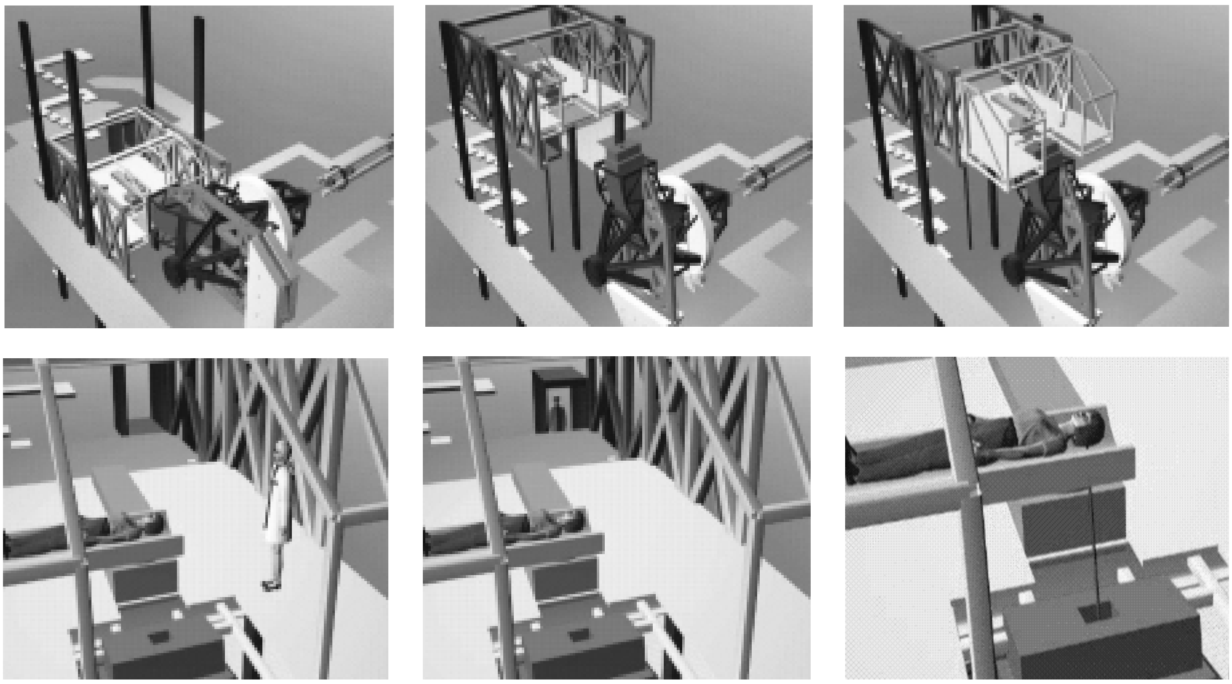

Figure 3: Standard treatment with a lateral field. Left to right (top): gantry in reference position, central cage in treatment position and cabin with patient and personnel lifted, and patient cabin telescoped forward. Left to right (bottom): patient couch rotated into treatment position, personnel leave the room by the rear lift, and irradiation starts.

5 FLEXIBILITY

Changing the dipole is possible without dismantling the gantry. For this purpose, the central cage is moved to the horizontal position, the front structure is dismounted, and the dipole is horizontally moved (rotated) out of the structure into a small hall between switchyard and the gantry, where there is a removable lateral wall. Initial installation will also be done in this way.

The large surface area in the patient cabin guarantees maximum flexibility for the positioning of medical equipment, facilitates the setting-up of the patient and provides a generous working space for handling devices (in particular, the bulky patient moulds). A CT scanner that is directly accessible by the patient positioning system can be placed inside the cabin. Cabin loads can be increased without affecting the alignment procedure and precision. The 2 m drift between the dipole and patient facilitates collision prevention. Up to 0.8 m of this drift can be used to mount instruments for beam position monitoring and dose verification.

6 SAFETY

For an exocentric gantry, where the patient is moved in space to the final treatment position before being irradiated, two aspects of safety become decisive:

- quick access to the patient during all modes of operation,
- avoidance of collisions between movable parts and the patient.

The Riesenrad gantry guarantees constant access by providing two independent active systems to connect the entrance level (chicane) and the treatment position. First, the patient cabin with a maximum travelling time of ~ 60 s and, second, the elevator with a maximum of 5.6 m to travel in ~ 15 s. In the event of a complete system breakdown, access via the staircase is always possible and emergency procedures do not have to rely on the availability of any mechanically-driven system.

Collision between the cabin (including the patient table) and the gantry has to be avoided, calling for the possibility of rapid gantry stops. The situation can be ameliorated by the following guidelines.

- The central cage and the fully retracted patient cabin can be moved independently (requiring a minimum free drift without any monitoring equipment of 1.2 m in front of the isocentre.
- The central cage is only rotated when the patient cabin is in the fully retracted position.
- The patient cabin and/or central cage are only moved when the patient couch is in its reference (backward) position (highest priority).

Since the gantry rotation is restricted to ±90°, the gantry speed (and therefore the angular momentum to be absorbed) can be relatively low.

7 STRUCTURAL ANALYSIS

The structural analysis was performed with the software CUBUS [6], using the modules Statik-3 (analysis of space trusses) and Fagus-3. The steel grade is S355, the joints of the analysed static model were assumed to be rigid, and shear deformations were taken into account (increasing the deflections by approx. 10%). Because of the slow rotation of a gantry, the structure was analysed as being static. A mass-less beam cantilevering perpendicularly from the 90° dipole aperture indicated the movements of the local isocentre.

Because of the high-precision requirements, the structural and mechanical design of the ion gantry is governed by the permissible deflections and, generally, no problems concerning maximal stress and stability were encountered (i.e. 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, the analysis was carried out applying safety factors of 1.0 for resistances and loads.

Based on the results of the structural analysis, one can get an idea of the deformed beam path inside the gantry. Figure 4 plots the calculated vertical deflection (*Z*) along the beam line due to elastic deformation of the gantry structure at various gantry angles. The comparatively uniform vertical displacement of the whole beam line in the gantry and its relative independence of angular position yields the opportunity to slightly lift the whole structure (by 0.15 mm) at the bearings in order that only the differential deformations of about ±0.1 mm become visible.

The comparatively large deformations (up to –0.25 mm vertically and 0.03 mrad rotationally around the horizontal axis) occurring at the scanning magnets, are non-critical, as their influence on the eventual misalignment of the particle beam is negligible.

Deformations in the two other directions (*X* and *Y*) also show values below ±0.1 mm, hence, from a mechanical point of view, one can suggest that elastic deformations in any direction and at any point along the beam trajectory inside the gantry will hardly exceed ±0.1 mm. Deformations of the treatment platform are irrelevant because the photogrammetric alignment system will ensure the online correction of all movements.

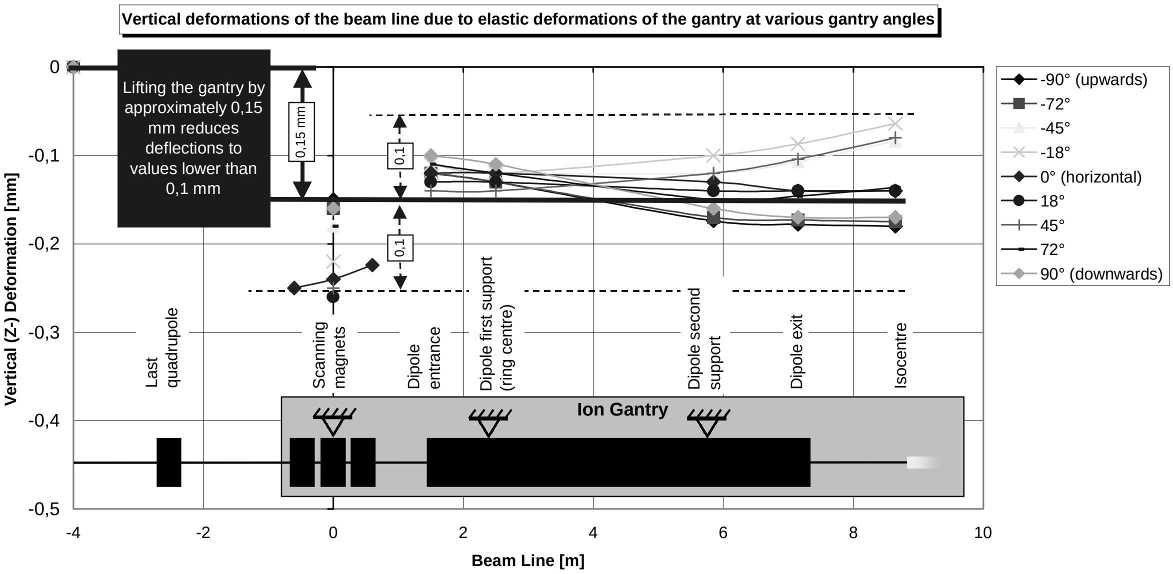

Figure 4: Vertical elastic deformation of the beam line inside the gantry. The deformed shape of the dipole and the sagging of the central scanning magnet are indicated for nine different gantry angles; the deformed position of the other two scanning magnets is only shown for the horizontal gantry position.

8 CONCLUSIONS

Patient and staff will hardly realize that they are not in a fixed room, but in a patient cabin guiding them smoothly into the treatment position. An elevator provides quick and redundant access and there is always the possibility of using a conventional staircase for a maximum of two floors vertical distance. The exocentric Riesenrad, or 'independent-cabin', gantry yields a high efficiency in terms of structural weight to supported load. The elastic deformations are calculated to be lower than for any existing proton gantry. The future treatment procedures have been partly anticipated by the large area of the patient cabin.

REFERENCES

[1] E. Pedroni, Beam delivery, in U. Amaldi, B. Larsson (eds.), Hadrontherapy in Oncology, Elsevier Science B.V., Amsterdam (1994).

[2] J. Debus (spokesman), K.D. Gross, M. Pavlovic (eds.), Proposal for a dedicated ion beam facility for cancer treatment, Radiologische Universitätsklinik Heidelberg, Deutsches Krebsforschungszentrum Heidelberg (DKFZ), Gesellschaft für Schwerionenforschung (GSI) in co-operation with Forschungszentrum Rossendorf (FZR) (1998).

[3] T. Auberger, R. Pötter, M. Regler (eds.), Med-AUSTRON - Ein Österreichisches Krebsforschungs- und Behandlungszentrum zur Hadronentherapie in Europa, Wiener Neustadt (1998).

[4] U. Amaldi (ed.), The National Centre for Oncological Hadrontherapy at Mirasole, *The TERA red book* (1997).

[5] PIMMS Group, Proton-Ion Medical Machine Study (PIMMS), Part I, CERN–PS/99–010 (DI), Part II to be published.

[6] CUBUS Software, Statik-3 Benutzeranleitung, Berechnung von ebenen und raumlichen Stabtragwerken, Zurich (1998).