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Variants for a Riesenrad Ion Gantry

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Abstract

Hadrontherapy is widely believed to improve cancer treatment. The Bragg-peak effect of hadrons (protons and ions) makes them suitable for high precision and conformal scanning of tumours. To maximise the benefit it should be possible to deliver the particle beam from any direction in space towards the patient. A machine capable of performing such a task is called a *medical gantry*. So far only proton gantries have been built. The increased (magnetic) beam rigidity of say carbon ions yields considerable structural difficulties and has so far prevented realisation of an ion gantry. The structure would have to support large and very heavy bending magnets (50 t and more) and nevertheless deliver the beam with a sub-millimetre precision onto a patient in a supine position. The promising concept of a *Riesenrad Gantry* is suited to overcome this deadlock. 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 (rotating) cabin similar conditions as in a classical isocentric treatment room prevail. The objective of this paper is to present and – to a certain degree - evaluate different versions of a Riesenrad gantry with clear focus on the mechanical performance. Two different ideas of how to achieve the specified accuracy are presented. Emphasis is also given to the decision making process leading to the designs.

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1 Intro

Hadrontherapy is widely believed to improve cancer treatment [1]. The Bragg-peak effect of hadrons (protons and ions) makes them suitable for high precision and conformal scanning of tumours. To maximise the benefit it should be possible to deliver the particle beam from any direction in space towards the patient. A machine capable of performing such a task is called a medical gantry.

So far only proton gantries have been built [2]. The increased (magnetic) beam rigidity of say carbon ions yields considerable structural difficulties.

Based on a detailed program for an ion gantry facility [3] it was decided to investigate more closely the promising idea of a so-called *Riesenrad gantry*. 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 (rotating) cabin similar conditions as in a classical isocentric treatment room prevail.

The objective of this paper is to present and – to a certain degree - evaluate different versions of a Riesenrad gantry with clear focus on the mechanical performance. The driving questions were: "What structural concepts seem promising for a Riesenrad gantry?" and "How small can elastic deformations of the gantry reasonably be kept?"

2 Ion Gantry Specifications

2.1 Beam Optical Concept

The design of the gantry is based on a particle beam that is derived from a slow-extraction scheme in a synchrotron [4]. 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 [5]. The mechanical gantry structure *("the gantry")* comprises the scanning magnets and the large 90° dipole. The quadrupoles between the rotator and the gantry will be supported by a separate rotating structure about 10 m long. The latter and the rotator will weigh approximatly 5 t each (plus the weight of the quads, which is about 400 kg each). Support will be given statically determinate via roller bearings. Elastic deformations are kept within +/- 0,1 mm.

The magnetic rigidity of the carbon ions beam and the assumed magnetic field of the 90° bending magnet (1,8 T) yield a bending radius of around 3,6 m. Consequently, a "gantry radius" of 5,5 m was assumed.[2] The free drift between the exit of the dipole and the (local) isocentre (1,9 m) will be further reduced by several instruments for beam position monitoring and dose verification and possibly an insertable x-ray camera.

In accordance to [4] the assumptions for the 90° dipole were the following: radius 3,6 m, cross section 150 cm x 100 cm, weight 60 tons. A larger gantry radius as well as a larger cross section would require a redesign of the gantry, other changes of the

[2] The "gantry radius" always corresponds to the distance between beam axis before the last 90° bending and the target centre.

magnet properties are feasible to a certain degree. Naturally, a lower weight would have beneficial effects to the precision of the gantry and a lower cross-section would facilitate magnet handling and maintaining. Nevertheless, for accessibility of the dipole, space for a working area around the magnet and its fixation is foreseen in all proposed gantry variants.

2.2 Safety Concept

In case any medical emergency occurs during treatment, the personal present in the control room can interrupt the treatment and immediately initiate re-positioning of the gantry to access position. As the maximum angle of rotation to travel is 90°, time to reach access position should not be considerably higher than it takes the personal to enter the gantry room.

Concerning technical breakdowns the rescue system is based on the providence of *two independent systems*: the gantry itself and a "second access system". One functions as a rescue system for the other. At least the second access system and – if technically feasible also the gantry – will provide the possibility to be lowered manually after a system failure. Rescue from the ground level of the gantry room is via a maintenance access.

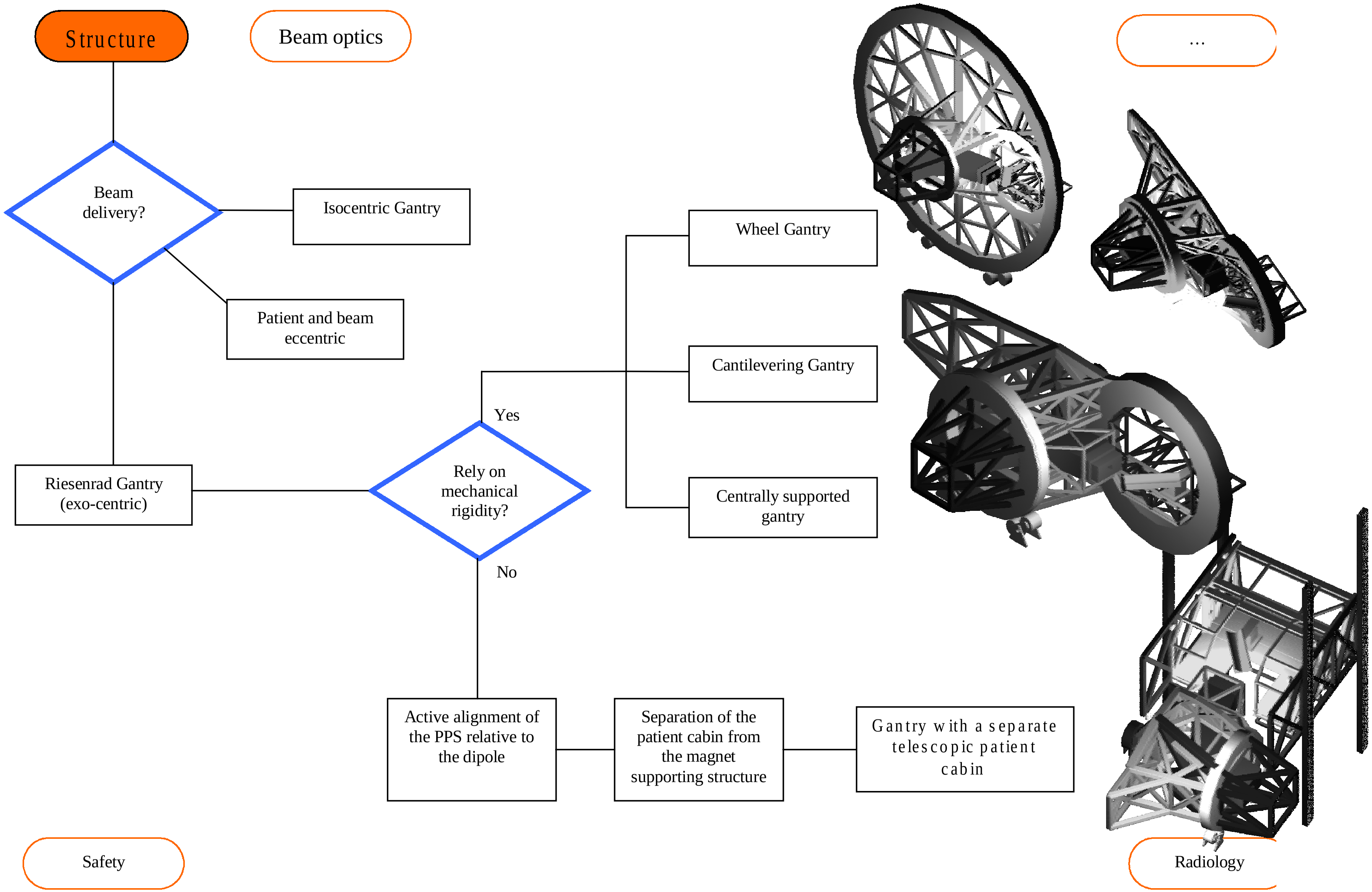
3 Design Process and Decision Making

Certainly, the process of gantry design is an iterative one: defining requirements, developing variants and deciding for a solution will see many feedback loops. Nevertheless, a superior path for the decision making can be found. Figure 1 roughly illustrates this process in the form of a decision tree. The decisions shown are taken mainly under the aspect of mechanics and, to a certain degree, beam optics. Other aspects like safety or radiology will see different decision paths. An interdisciplinary approach should however "canalise" the process towards similar solutions.

For efficiency reasons and to keep the complexity of the system as low as possible the concept of a Riesenrad Gantry was chosen for further investigation [5]. The decisive question to address afterwards is whether it is possible to reach the specified precision of +/- 0,5 mm while relying on mechanical rigidity only. From the point of simplicity and reliability such a system would be preferable. Several variants were investigated (including extreme solution to show the structural limits), they will be described in detail in the following chapters.

Eventually, the proposed variant following the above principle is a *centrally supported Riesenrad Gantry* with a cantilevering cabin. Absolute deflections are slightly above the specification. However, on one hand they can be partly corrected by modifying the gantry rotation angle, on the other hand *absolute* maximum deflections are less significant when the patient is mounted directly on the gantry structure.

Following page:
Figure 1: Decision tree for the development of an ion gantry focussing on the mechanical structure.


Structure
Beam optics
...
Beam delivery?
Isocentric Gantry
Patient and beam eccentric
Riesenrad Gantry (exo-centric)
Rely on mechanical rigidity?
Yes
No
Wheel Gantry
Cantilevering Gantry
Centrally supported gantry
Active alignment of the PPS relative to the dipole
Separation of the patient cabin from the magnet supporting structure
Gantry with a separate telescopic patient cabin
Safety
Radiology

In order to a further reduction of the elastic deformations one has to consider an active (feedback) alignment system for the PPS towards the magnet. The structural consequence is the - now reasonable - separation of the patient cabin from the central part carrying the dipole, because precision requirements for the two parts are different. The Riesenrad Gantry with a separate telescopic cabin allows having a large patient cabin continuously accessible via an emergency staircase. However, this separation of the structure will considerably increase the complexity of the control and safety system.

4 Methodology

4.1 Structural Analysis

The structural analysis of the various gantry proposals was performed with the software CUBUS [6], using the modules Statik-3 (analysis of space trusses) and Fagus-3. Standard square profiles between RHS 100/100/5 and RHS 400/400/20 (steel grade S235) were used. Because of the slow turning speed of a gantry, its structure was analysed as being static.

Due to the high precision requirements the structural and mechanical performance of the ion gantry is dominated by the permissible deflections and no problems concerning maximal stress and stability are expected. (Most of the actual stresses occurring in the members are in the region of 0 to 2 kN/cm^2.) Consequently, the analysis was carried out applying safety factors of 1,0 for resistances and loads. The latter were: gravity, main dipole (600 kN), the patient positioning system (PPS) in the patient cabin (25 kN), scanning magnets (20 kN) and necessary counterweights.

For the PPS a conservative approach was taken: the (upper limit) weight of 25 kN was split into two point loads acting on the structure at the most adverse positions depending on the gantry rotation angle.

The nodes of the analysed static model were assumed to be rigid, shear deformations were taken into account (increasing the deflections by approx. 10 %).

The magnet was modelled not to be rigid but to deflect elastically. A three-point magnet support was assumed in the analysis: two supports in a kind of “front ring” and one further down the beam path. Generally, increasing the number of the supports for the magnet will have a beneficial impact on the structural performance of the gantry. A mass-less beam cantilevering perpendicular from the (deflecting) magnet aperture represented the movements of the local isocentre.

4.2 Sources of Uncertainty - Idealisations

Apart from the idealisations mentioned above, which led to the model eventually analysed, several uncertainties remain. They will have an impact on the real system. The following list of possible effects is non-comprehensive and confined to structural matters. It should act as a warning to interpret the results of the elastic analysis as a lower bound, giving an approximation of what final deformations can be expected:

- Supports are never perfectly aligned as assumed in the analysis.

- Manufacturing tolerances will alter the intended geometry. Reasonable tolerances for the machining of the large bearing rings are in the region of 0,1 mm.
- Local deformations due to high point loads were neglected in the analysis. This concerns mainly the rollers of the supports subjected to large Hertz pressures.
- Settlement of the extremely heavy gantry room (concrete shielding) will be considerable over the time (cm region). Certainly the gantry supports will be made re-adjustable, but this error – as other systematic errors – has to be detected and corrected during operation.
- Measurement tolerances, backlash of driving motors, free play of bearings will add random errors.
- A uniform temperature rise in the gantry room by 1° C would enlarge the structure roughly by 0,15 mm. The effect of temperature gradients may be even more severe.

The outcomes of the elastic analysis of the gantry have to be seen with respect to the whole system in order to draw correct conclusions:

- In what region are other sources of uncertainty (patient fixation, diagnostic, etc.)?
- Particularly, what do the mechanical deformations of the dipole and scanning magnets supported by the gantry mean for the actual isocentre of the beam?
- Is it necessary to correct systematic errors by using a correction map giving correction values for each gantry status (feed forward)?
- In which range are the random errors and do they perhaps demand for an online beam correction system?

Only when regarding the complete system, the harmfulness of the elastic gantry deformations can be properly evaluated.

5 Gantry Variants: General Principles

When addressing the actual structural design of a Riesenrad gantry some general principles will always crystallise:

- As the 90° dipole is the main load of the system, one would always like to support it as close to its centre of gravity as possible, which suggests to fix it on a ring supported on rollers. The geometrical position of the ring is a trade-off between its necessary radius and the actual percentage of magnet weight taken.
- If one wants to avoid large torsion-forces in the structure, a large amount of counterweight has to be integrated into the ring (acting on a very short lever arm). The value is proportional to the percentage of magnet weight taken by the ring.
- The main difficulty of the design is – when the gantry is in horizontal position – to provide a second, sufficiently stiff magnet support as close to the magnets output aperture as possible to take the remaining weight of the magnet.

Of the 4 gantry variants presented in the following chapters, only two are proposed for further investigation. Nevertheless, the other two versions are presented very shortly because they illustrate the design process.

In all drawings and graphs following, the plane of gantry rotation is represented by the Z (vertical upwards) and X co-ordinate. Y points in the direction of the incoming beam axis.

6 Wheel Gantry

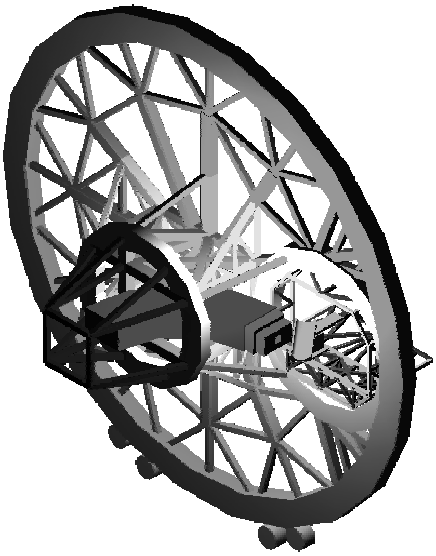


Figure 2: Perspective of the Wheel Gantry

6.1 Principal elements and structural system

The weight of the central 90° dipole is shared by the smaller front ring (taking approximately two thirds, outer diameter 5,6 m) and a large, trussed "wheel" of 18 m outer diameter (Figure 2). The distance between the two rings is 3 m. Both rings rotate on roller bearings. The patient cabin is inserted into an eccentrically "hole" of the big wheel. From this "hole" it cantilevers into the gantry room. The cabin can rotate around its axis to keep the patient horizontal during gantry rotation.

The patient positioning system (PPS) is mounted on rails running in the plane of the wheel to transfer its load directly onto the wheel and avoid large moments acting on the cabin structure. The cabin was modelled separately; its reactions were applied as forces to the main model.

The counterweight (35 t) is distributed on the two rings in order not to introduce any torsinal forces to the system. A lift travels vertically and horizontally in front of the wheel and serves the cabin laterally providing a second access system. The rails for horizontal travel can be mounted on the floor, the ceiling or – in a recess – the front wall.

6.2 Deflections

The difference in diameter of the two wheels results in their different (absolute) deflections. The level of the bearings of the smaller front ring is adjusted in a way, that the centres of the two rings show similar vertical displacements of about 0,3 mm. However, the changing stiffness of the large wheel leads to corresponding ups and downs during gantry rotation. Because the smaller front ring runs more stable there will be considerable differential movements resulting in tilting and thus unwanted horizontal deflections of the wheel. This tilting also affects the dipole and yields out-of-plane isocentre deflections of around +/- 0,5 mm.

6.3 Conclusion

The system is based on the provision of a mechanically fixed distance between the incoming beam and the isocentre. The rigidity is maximised by transferring the loads directly to the supports via normal forces resulting in deflections, which are within the specification of +/- 0,5 mm. However, a consequence of this rigidity is the large overall dimension of the gantry and the heavy cross-sections, which have to be used throughout the entire structure. Its weight exceeds 75 t, giving a total weight of the gantry of around 185 t. The two roller bearings on the front ring have to withstand forces of about 550 kN.

The design of the big wheel is dominated by its self-weight and not by giving support to the patient cabin. The effort to achieve smooth rolling (avoiding ups when a spoke crosses the bearing) is considerable (one third of the structural weight is due to the large ring only, i.e. 25 t). And still the “hole” remains the weak spot of the wheel, resulting in high deflections when – during a rotation – bearing forces eventually act on this part. Additionally, accurate machining of such a large ring is extremely difficult to achieve. All these arguments suggest that competitiveness will not be reached with this gantry variant.

7 Cantilevering Gantry

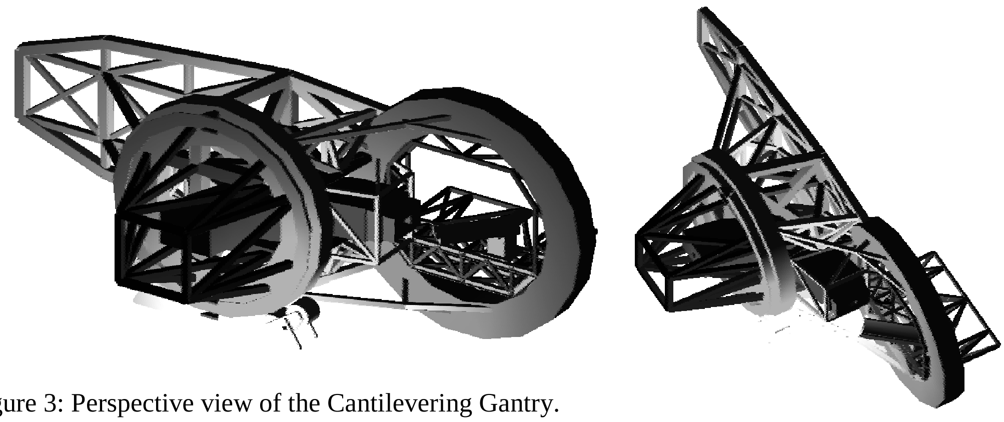


Figure 3: Perspective view of the Cantilevering Gantry.

7.1 Principal Elements and Structural System

The basic idea of this gantry proposal is to reduce the structural elements to the absolute necessary, i.e. a balanced girder carrying the eccentric patient cabin, one main ring taking all the loads and one vertical and two horizontal shear walls connecting the two parts. The *whole* structure cantilevers out from the ring, which transfers the vertical loads *and* the resulting moment (via a pair of horizontal forces) into the rear wall of the gantry room (figure3).

7.2 Deflections

When the gantry is in horizontal position, the transfer shear wall is assisted by two additional shear walls, each of them with the same stiffness to avoid tilting of the girder. On the magnets side this "assistant" has to be divided into two parts to let the dipole pass. In fact the achievable stiffness of this divided shear wall governs the vertical deflections of the structure to a very large extent.

The main girder is a high truss to maximise bending resistance. It has to provide a ring-like opening to support the cylindrical patient cabin. This ring is a very sensitive part although the loads of the patient cabin are comparatively small. Therefore the ring has to provide large cross section resistances in both planes and in torsion; the cantilever-moment due to the own weight of the patient cabin is taken partly by torsion and partly by a pair of horizontal forces.

Despite the effort the elastic deformations in plane and out of plane *exceed* the value of +/- 0,5 mm.

7.3 Conclusion

The benefit of studying such a "puritanical" gantry solution is to see what is feasible and where are the structural limits of the system while minimising the weight of the gantry (40 t). Its deficiencies turned out to be:

- The specification for the permissible deflections cannot be reached (an online position correction system for the PPS would be needed). Additionally, the excessive deformation of the cabin ring spoils the mechanics and position accuracy of the patient cabin.
- Conventional roller supports are hardly capable of providing the required load capacity (2 x 800 kN), therefore requiring more sophisticated bearing techniques.
- Space for the magnet itself and its maintenance is very limited.

However, the solution could become interesting again if the dipole could be made considerably lighter and smaller.

8 Centrally Supported Riesenrad Gantry

The gantry version is based on the extreme approach of a cantilevering gantry, however, several crucial design changes were made in order to restrict the deflections to the specified maximum while still relying on mechanical rigidity only.

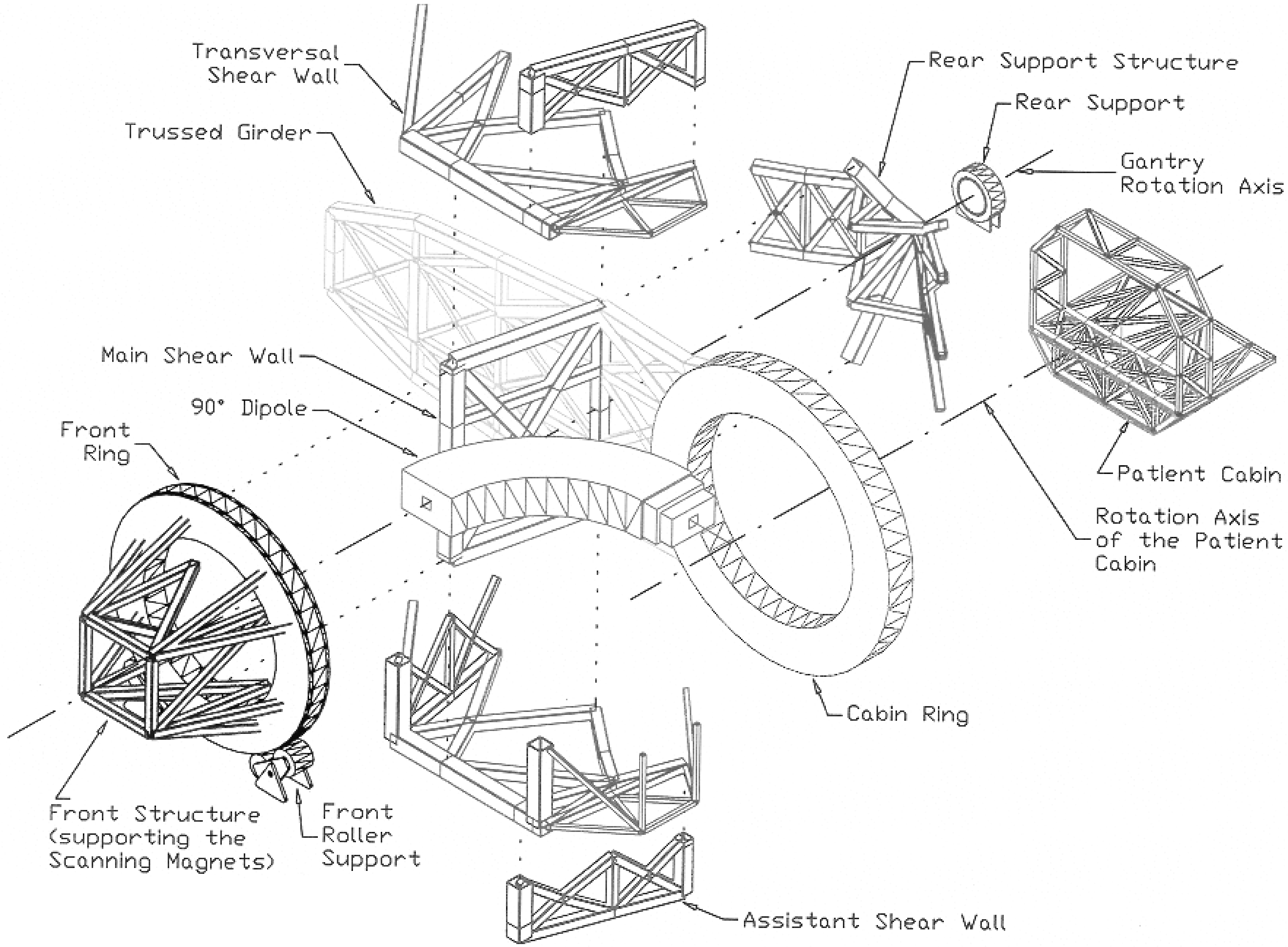


Figure 4: Principal elements of the centrally supported Riesenrad Gantry.

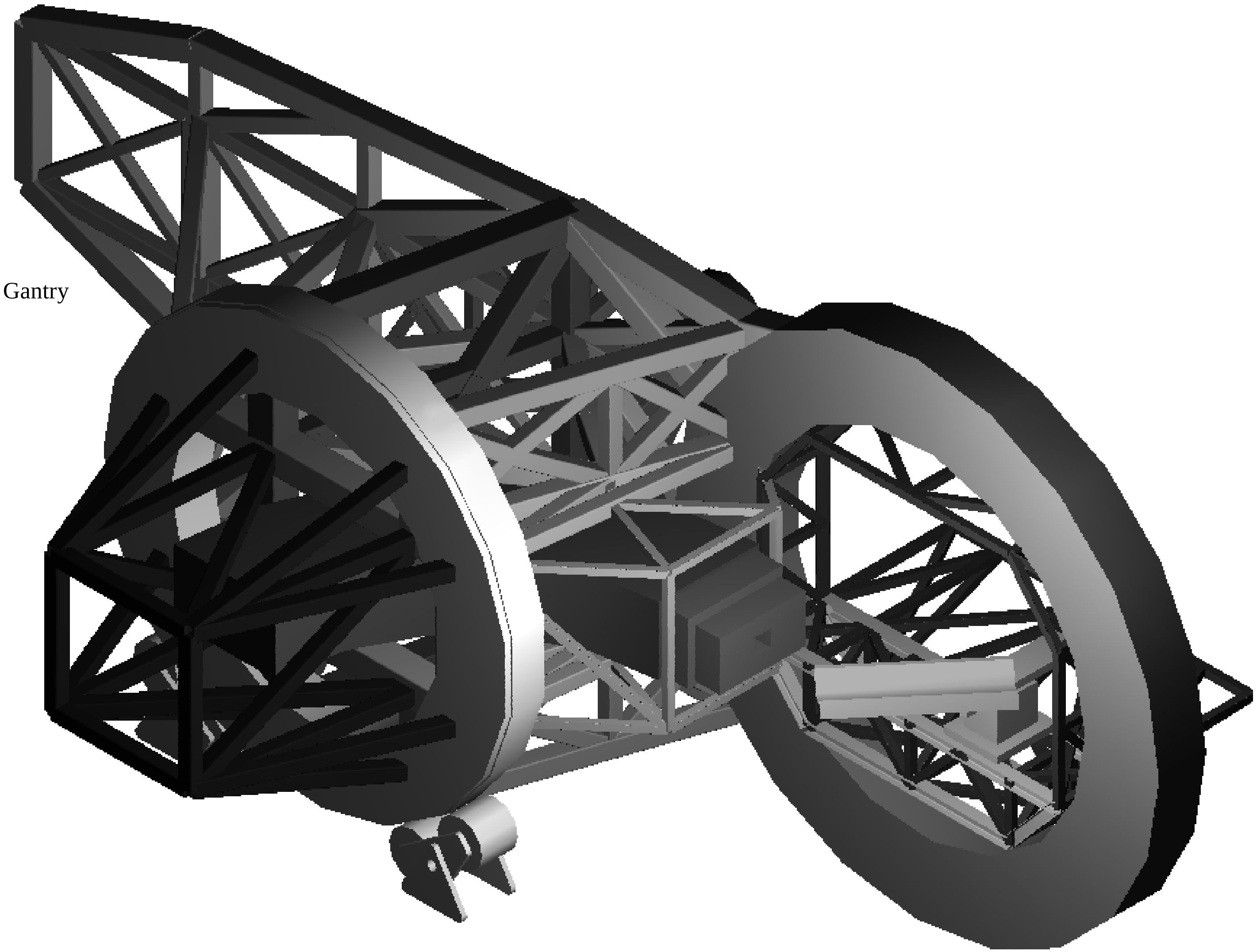


Figure 5:
Perspective view of
the centrally supported Riesenrad Gantry

8.1 Principal elements and structural system

The gantry, which can rotate 360°, is supported on a *front ring* (two self-aligning roller supports) and an additional support at the opposite end of the structure (*rear support*). The main bearing elements spanning between the supports are:

- in horizontal position a *main shear wall* slightly tilted out of axis and assisted by *two lateral assistant shear walls* of similar stiffness,
- in vertical position the *two transverse shear walls (see fig. 4, fig. 5 and annex A).*

Perpendicular to the shear walls runs the *trussed girder,* which gives support to the eccentrically positioned *patient cabin* and the opposite counter weight. The cabin ring provides the support for the cylindrical patient cabin, which cantilevers towards the maze and rotates around its longitudinal axis. The table of the PPS is inserted into the beam, a light casing around the isocentre fixed on the magnet frame gives the patient the impression of being in a conventional treatment room.

The front structure cantilevers from the front ring and supports the scanning magnets. Compared to the previous cantilevering gantry, the third support reduces the global bending moments in the structure (and therefore the normal forces acting in every truss member). Cross sections can be made smaller or – with the same dimensions used above – deflections reduced. The total necessary counterweight is smaller because a higher proportion can be put on the edge of the trussed girder. Loads to the front bearings are reduced to around 600 kN.

The third support is lifted by 0,1 mm to counter-balance deflections. A higher rise will – while generally being beneficial to the gantry deflections – lead to an increased sagging of the scanning magnets (approx. by half the value applied to the support).

In comparison to the cantilevering gantry the trussed girder is placed closer to the rear support, thus the cabin is better balanced (reducing the out of plane moment acting on the ring). From the deflections point of view the patient cabin (3,5 t) could be made considerably lighter but resonance possibilities would have to be checked. Improvements seem possible with the cabin ring, where conservative dimensions were assumed. A higher slenderness ratio of the cross-section could be used to increase its height or decrease the weight of the ring.

The analysed gantry model is externally supported in a determinate way and highly balanced. Remaining turning forces are (conservatively) taken by a support acting in X-direction at the central bottom of the front ring. The cabin was modelled separately, its reactions were applied as forces to the main model. The deflections of the rotating cabin platform itself are less than 0,1 mm and were neglected.

The second access system is provided by two elevators (e.g. rack and pinion system) which can also travel horizontally to serve the patient cabin laterally.

8.2 Deflections

The primary concern during the design of the gantry was to limit the vertical displacement of the local isocentre when the gantry is in horizontal position (0 °). Eventually, in this respect the current design does not quite reach the desired specification of +/- 0,5 mm (fig. 6). However, adjusting the angle of gantry rotation can to a great extent compensate this excessive flexure. For example, to eliminate the calculated maximum of –0,7 mm, an angular correction of 0,007° would be necessary.

When the gantry is in horizontal position approx. 40 % of the vertical deflections of the cabin ring centre are due to the own weight of the structure, another 40 % are caused by the cabin and the PPS, and only 20 % by the dipole. Contrarily, when regarding the isocentre deflection modelled as a straight line from the aperture of the magnet, around 80 % of the vertical deflection are caused directly by the weight of the magnet. Consequently, the following steps would seem most promising when trying to meet the specification directly:

- a more rigid fixation of the magnet onto the structure to couple the deformations more intensively,
- a reduction in the weight of the PPS
- a stiffness increase of the main girder and the cabin ring.

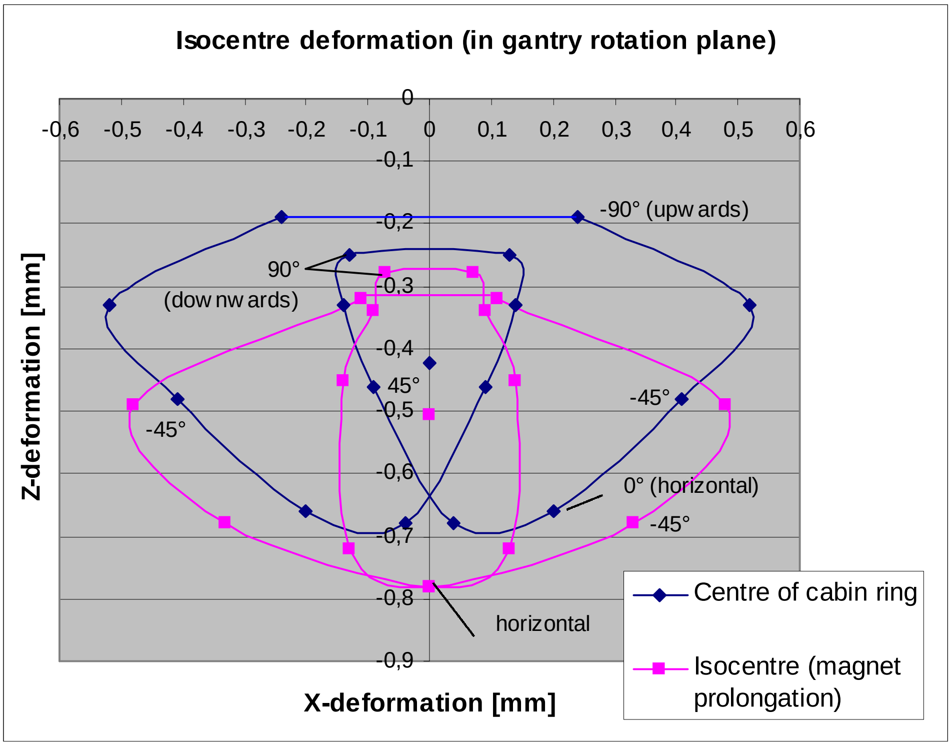


Figure 6: Isocentre deformations of a centrally supported Riesenrad gantry during a 360° turn. Deformations in Z (vertical) and X (horizontal) direction are shown, i.e. deflections in the plane of the gantry rotation. The PPS was considered to be in its most adverse position. In the top and downward gantry position the PPS was shifted from one side to the other, which is indicated by two separate points for the single position.

Figure 6 gives an impression of the isocentre movement during gantry rotation. Graphs are drawn for the actual isocentre (modelled as a straight prolongation of the beam from the magnet aperture) and the centre of the cabin ring. As mentioned above, for a single gantry position, relative contributions of the various load-cases are quite different for each of the two points. The absolute differences are strongly governed by the magnet and magnet fixation modelling in the structural analysis. In a refined model – with more precise stiffness data of the magnet available – it will be possible to further reduce these differences (in all three dimensions).

The difference of the two curves also indicates how the patient cabin deforms relative to the magnet (or vice versa). A gantry concept where the patient cabin is *not* mounted on the same structure as the magnet would have to compare its patient cabin alignment capability to these values.

When the gantry is close to the upward position, the system reacts very sensitively and shows considerable horizontal (X-) deflections depending on the position of the PPS. The symmetric (to the Z-axis) counterparts for the points indicating the upward and downward gantry position in figure 5 represent the horizontal shift of the gantry when moving the PPS from the far right to the far left position and vice versa.

The maximum calculated X-deformation is around 0,5 mm when the gantry is 18° from the upward position. About 0,2 mm of this horizontal deflection are already present at the top points of the *front* (!) ring suggesting that increased bracing is needed there, which can be done by structurally incorporating the counterweight. Additionally, with a refined modelling of the PPS-impact the horizontal deflection can be expected to decrease considerably.

Deflections out of plane (Y-direction) are – due to the dipole and the cantilevering cabin – most critical when the gantry points downwards. Values of +/- 0,3 mm are encountered. In particular the dipole shows the tendency to bend out of plane (see annex A – deformed structure). This movement strongly depends on the magnet stiffness and the magnet fixations; again improvements seem possible here. The lifting of the rear support by 0,1 mm is responsible for beneficial effects in the order of 0,05 mm both with the in-plane as well as out-of-plane deformations.

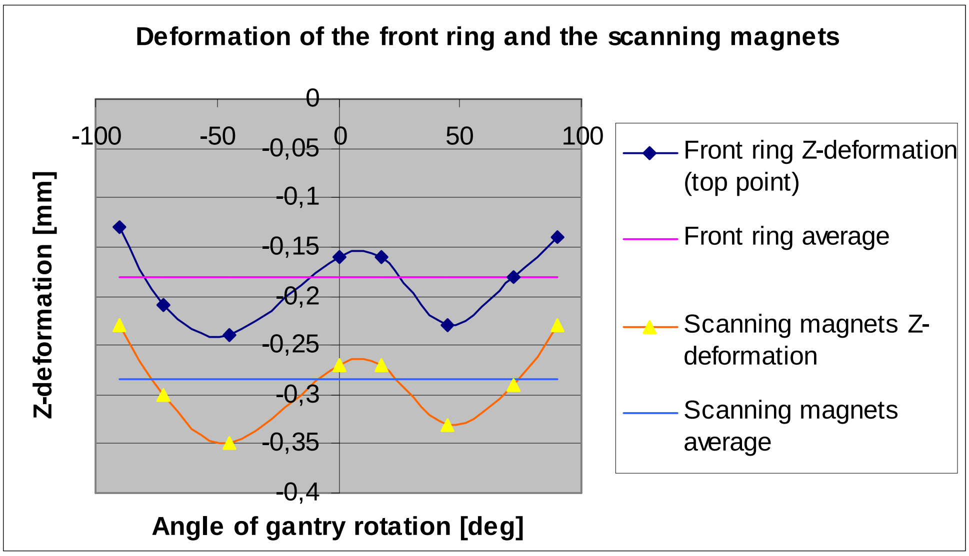


Figure 7: Deformation of the front ring and the scanning magnets of a centrally supported Riesenrad Gantry. For each rotation angle of the gantry the vertical (Z-) deflection of two points is indicated: the *top* point of the main ring and the (virtual) intersection point where the beam enters the front structure carrying the scanning magnets.

As can be seen from figure 7 the top point of the front ring is sagging between -0,15 and -0,25 mm during a gantry rotation. For the virtual point in the centre of the ring half the average value, i.e. -0,1 mm average deflection, can be expected. However, the analysis is based on a two-point support of the front ring, whereas there will be at least 4 in reality. The scanning magnets follow the movements of the front ring on a "lower" level, average Z-displacement is around –0,3 mm.

The calculated deformations give an idea of the vertical deflection of the beam path in the gantry (fig. 8).

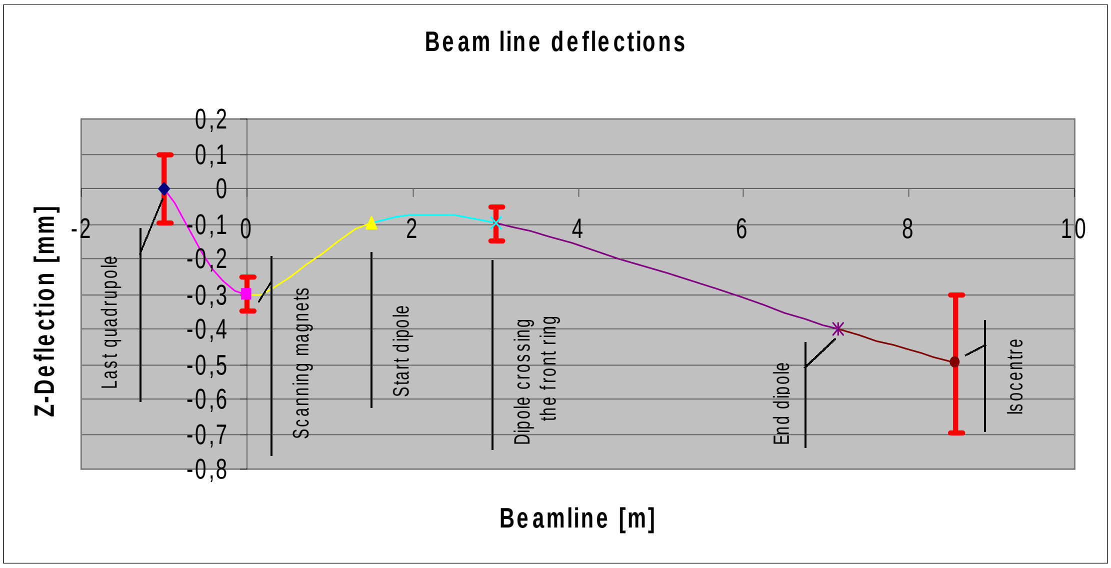


Figure 8: Vertical (Z-) deflections of several points along the beam path in a centrally supported Riesenrad gantry. Only the points with the range bars were calculated. The line between is a possible interpretation.

8.3 Summary

- The structure of the centrally supported Riesenrad gantry weighs about 55 t including the patient cabin structure. Counterweight is 28 t (13 t on the front ring and 15 t on the trussed girder). The total load of the gantry is 146 t.
- Maximum elastic deformations of the loaded structure: out of rotation plane is +/- 0,3 mm, in plane (vertical and horizontal) +/- 0.7 mm. However, the patient is fixed onto the gantry structure, which makes relative deformations between the dipole and the PPS relevant, and these are only a fraction of the value stated above. Additionally, adjusting the gantry rotation angle can compensate most of the vertical displacements when the gantry is close to a horizontal position.
- Normal forces acting on the bearings: 2 x 600 kN, 1 x 400 kN
- Inner volume of the gantry room: 2300 m3

9 Riesenrad Gantry with a Separated Telescopic Cabin

The basic idea of this gantry is to separate the patient cabin from the magnet-supporting structure in order to minimise the masses of the movable sub-structures and therefore the elastic deformations. A central rotating part is carrying the 90° dipole whereas a telescopic platform functions as a lateral patient cabin and supports the PPS. Only 180° of gantry rotation are necessary (fig. 9 and fig. 10).

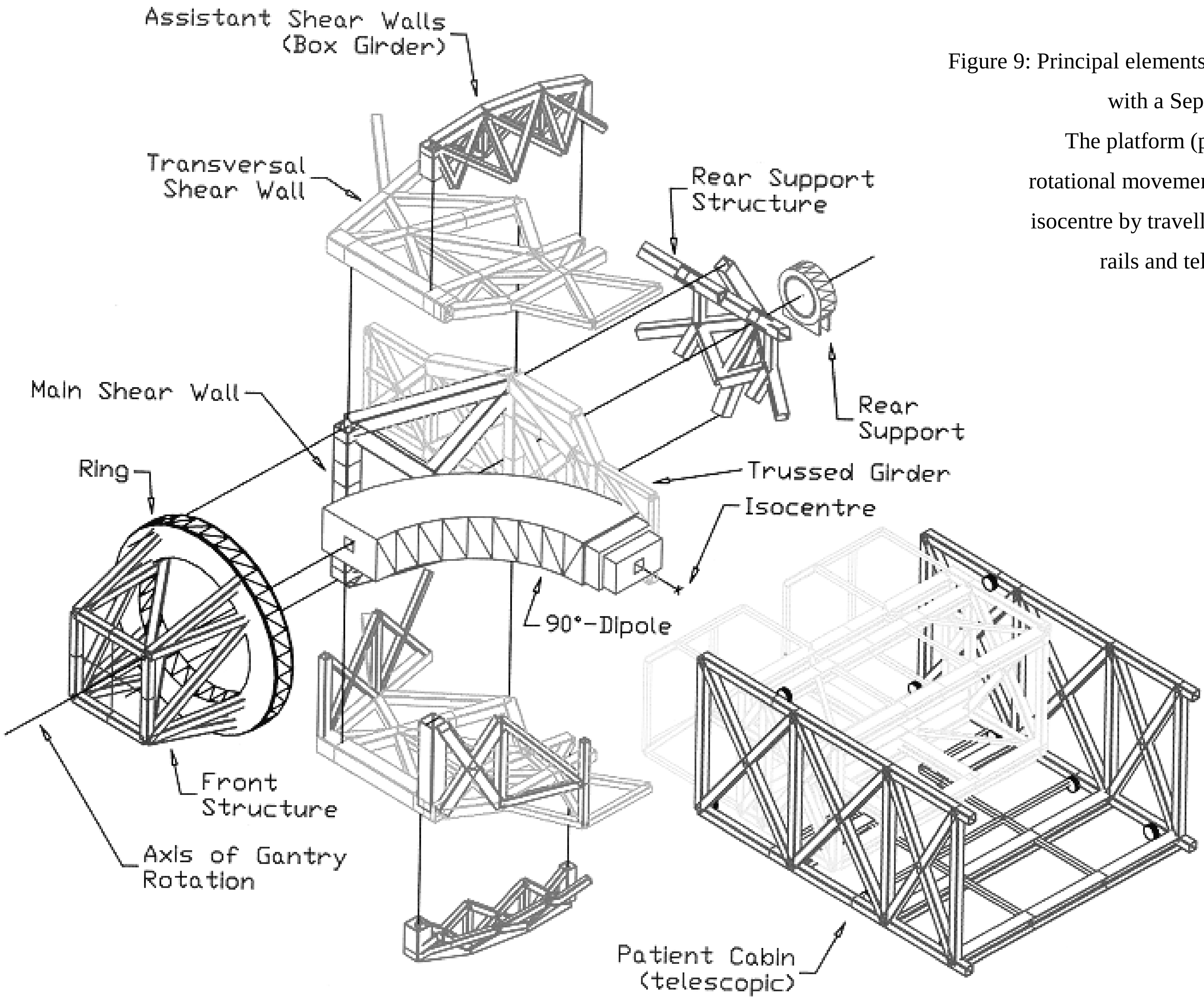
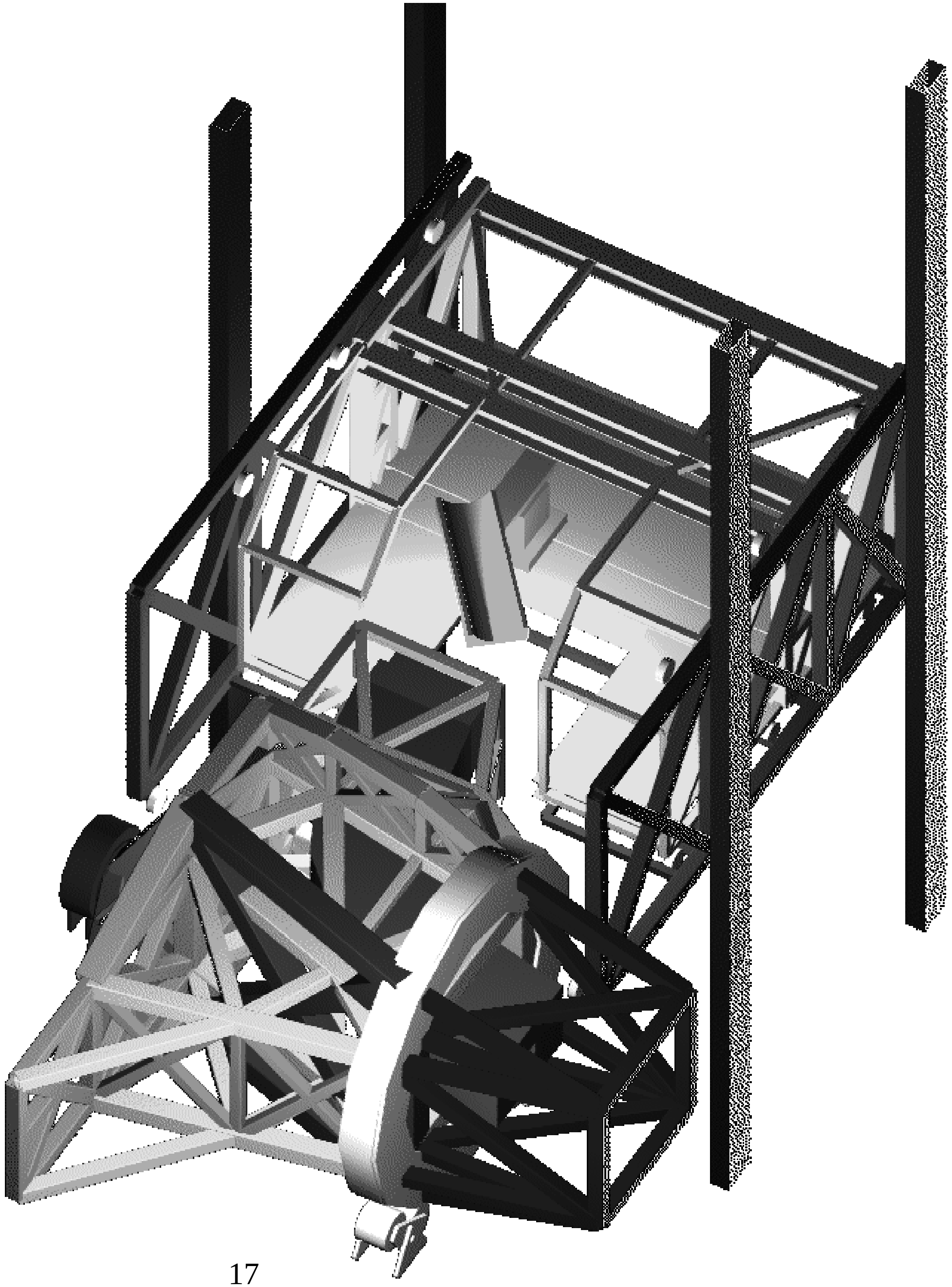


Figure 9: Principal elements of the Riesenrad Gantry with a Separated Telescopic Cabin.
The platform (patient cabin) follows the rotational movements of the magnet and the isocentre by travelling vertically on guiding rails and telescoping back and forth.

Figure 10:
Perspective view of the Riesenrad Gantry with a Separated Telescopic Cabin.
The platform (patient cabin) follows the rotational movements of the magnet and the isocentre by travelling vertically on guiding rails and telescoping back and forth



For the independence of the two sub-systems the mechanically secured correctness of the “gantry radius” is sacrificed, the correct position of the platform has to be “artificially” maintained and collision protection requires considerable effort.

As magnet support and patient cabin are separated structures, there is no point in demanding a high initial rigidity for the whole system. It is in this case sufficient and reasonable to align *only* the actual PPS with respect to the high rigidity magnet-supporting structure. Positioning of the platform and the rigidity of the platform itself is less critical, industrial standard systems can be adapted for this purpose. Consequently, competitiveness of this gantry variant depends a lot on the development of an alignment system for the PPS, its implementation and integration in the superior safety system.

9.1 Principal elements and structural system

The magnet support structure (gantry) is basically an arrangement of shear walls – most of them modelled as trusses – similar to the previous gantry versions. The gantry is supported structurally determinate on two roller groups, acting on a large *front ring* (outer diameter 4,5 m), and a single *rear support*. To span the distance in-between two *transversal shear walls* and a single *main shear wall* take the load when the gantry is in a vertical and horizontal position respectively. The main shear wall is slightly tilted to make way for the dipole. It is relieved by two smaller lateral *assistant shear walls*, one of them itself is made out of two *triangular shaped box girders* to let the dipole pass.

The ring supports the dipole close to its centre of gravity, taking about two thirds of its weight. When the gantry is in vertical position the other third is taken by the transversal shear walls, guiding the forces directly to the supports. However, in horizontal position the two triangular-shaped box girders running to the rear, 3,6 m high trussed girder, perform this task. A *front structure* cantilevering from the front ring into the switchyard supports the scanning magnets. Counterweights of 130 kN and 148 kN are acting on the front ring and the rear girder respectively.

The independence of the telescopic platform allows generous dimensions of this *“patient cabin”* therefore improving flexibility. A PPS being able to rotate horizontally around the (local) isocentre reduces the need for gantry rotation to ± 90°.

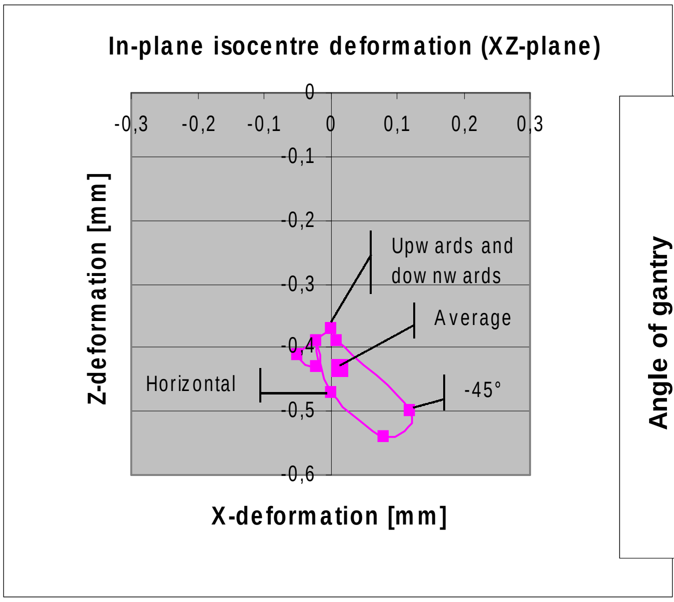
The necessary (relative) alignment of the PPS towards the magnet can be done by means of photogrammetry (optical non-contact co-ordinate measuring system). Standard systems provided by industry easily achieve an accuracy of less than ± 0,15 mm (σ). A feasible solution would be to mark the PPS with reflective targets (also at the bottom) and attach some cameras on the end face of the dipole or the frame carrying the beam position monitoring devices.

The platform (patient cabin) is designed to travel 11 m vertically and to telescope 5,5 m horizontally. This feature makes it possible to *constantly* keep contact to the lateral wall giving the advantage that continuous direct access via a staircase is easily possible. An intrinsic safety system can be provided. For the vertical travel a possibility for the design would be to use two guiding rails on each side of the gantry room, which take the moment and the vertical load of the platform via a pair of normal forces. A rack and pinion drive seems suited. An elevator provides quick access to the platform.

The patient cabin dictates the depth of the gantry room. By enlarging the room size in the longer direction the counterweight on the trussed girder could be reduced.

9.2 Deflections

Due to the comparatively low weight of the magnet supporting structure elastic deformations are very small and the corresponding specifications can be achieved easily. However, because the gantry is not one solid structure but comprises two independent subsystems, the problem of precision is shifted to the PPS and its alignment qualities.



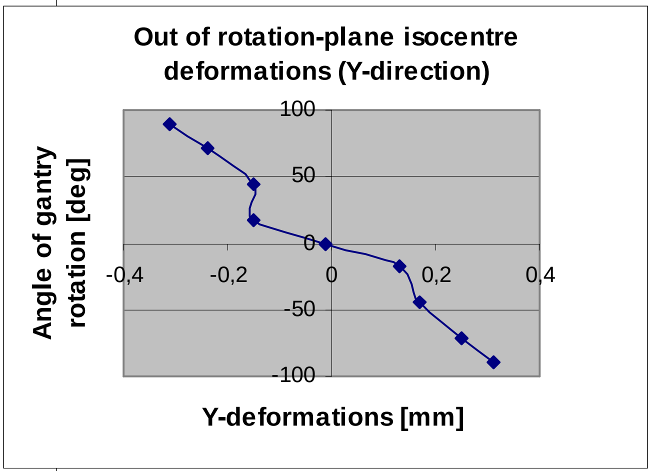


Figure 11 and 12: Deformations of the isocentre of the Riesenrad gantry with a separated patient cabin. Deformations in Z (vertical) and X (horizontal) direction are shown on the left, i.e. deformations in the plane of the gantry rotation. Deformations in the (Y-) direction (out of the gantry rotation plane) are presented on the right. The isocentre position was modelled as the end of a straight line originating perpendicular from the centre of the deformed magnet aperture.

When regarding the (local) isocentre deflections (figure 11 and 12) during 180° of gantry rotation one can observe that:

- The downwards (Z-) deflection is more or less stable at around 0,4 mm.
- The horizontal deflection in the rotation plane (X) is negligible.
- An out of plane (Y-) deflection of +/- 0,3 mm is building up when the gantry is rotated from a horizontal into a vertical position.

The small increase in vertical deflection when moving from horizontal position upwards can be explained by then less beneficial position of the ring-supports (larger ring deformation).

With a more detailed modelling of the magnet and the magnet fixations to the structure even lower values for the deflection can be expected. Deflections could be further reduced by slightly lifting the rear support.

Figure 13 shows the up and down of the top point of the ring during gantry rotation. The range is about 0,1 mm. Correspondingly, the ring shows – at some gantry positions - considerable deformations at the supports in the order of +/- 0,1 mm. Both displacements can be expected to be considerably lower in reality as one (single) support reaction force calculated will be taken by at least two rollers.

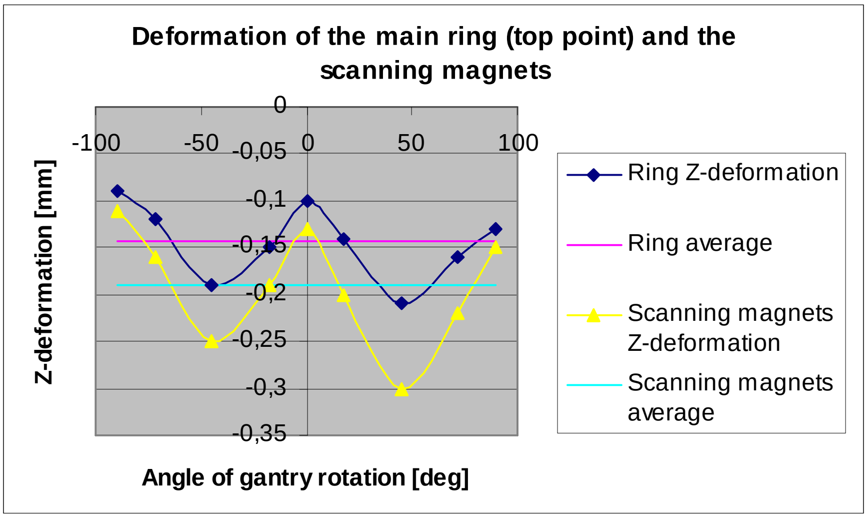


Figure 13: Vertical movements of the top point of the ring and of the scanning magnets during rotation of the Riesenrad gantry with a separate telescopic cabin. The virtual point where the beam line enters the front structure models the deflection of the scanning magnets.

Scanning magnets oscillate around a vertical (Z-) deflection of -0,2 mm. Larger cross sections in the front structure could improve this value, a stiffer ring would help to reduce the amplitudes.

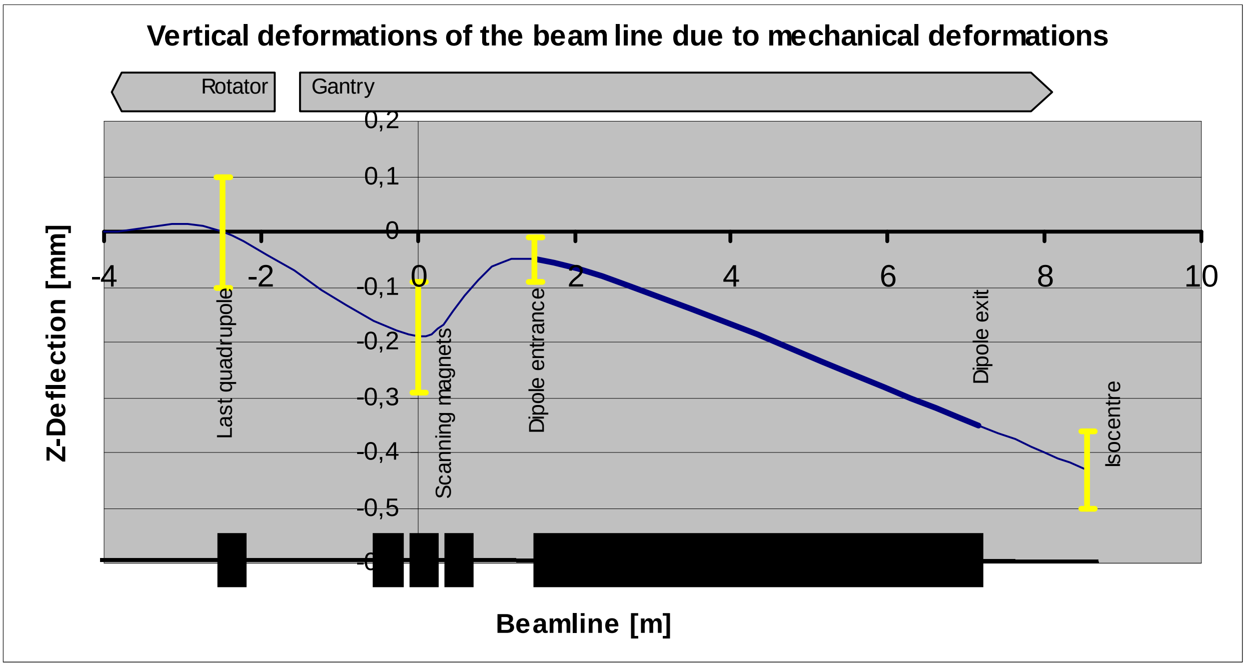


Figure 14: Vertical deformations of the beam path due to elastic deformations of the structure and the magnet in a Riesenrad gantry with a separate telescopic cabin. The line represents the average values. Error bars (only these values were calculated) indicate the variation during gantry rotation.

Figure 14 gives an idea of the vertical displacement of the beam line in the gantry due to elastic deformations of the structure and the magnet. The main dipole rests comparatively stable in a slightly inclined position (i.e. a more or less rigid body rotation around the X-axis) during gantry rotation. The faces of the magnet show maximum rotations of about 0,004°.

9.3 Summary

- The structure supporting the magnet weighs about 30 t, counterweight is 28 t. The total load is 120 t. The separate telescopic cabin is estimated to weigh around 20 t, however the manufacturing tolerances for the cabin are far less severe than for the magnet structure.
- Maximum elastic deformations of the loaded structure: out of rotation plane +/– 0,3 mm, in-plane vertical +/– 0.5 mm, in-plane horizontal is negligible. Normal forces acting on the bearings: 2 x 500 kN, 1 x 390 kN
- Inner volume of the gantry room: 1700 m^3
- The large platform (patient cabin) gives high flexibility in the arrangement and positioning of medical equipment and provides a generous working space.
- Continuous “hardware”-access via an emergency staircase is possible.
- The correct “gantry radius” is not intrinsic but has to be secured by the alignment procedure.

10 Conclusion

The results presented in this report suggest that a Riesenrad Gantry is feasible, even when a very heavy large aperture 90°-dipole is used.

It is possible to build a mechanical structure that is rigid enough to keep the (local) isocentre within the specified +/- 0,5 mm from the ideal position during gantry rotation. However, this is true only from the mechanical point of view. The desire to interpret elastic deformations in a larger context raises questions like:

- How do the deflections of the structure affect the large dipole and its magnetic field?
- What misalignment has to be expected for the “real” isocentre, where the beam eventually deposits its energy?
- How does the dipole itself deform under gravity and what kind of system for its support should be chosen?

In case the mechanical rigidity alone is not sufficient, one would probably try to align the PPS somehow with respect to the real isocentre. For the structure this means the separation of the patient cabin from the magnet supporting part in order to reduce movable masses and gain rigidity. A Riesenrad Gantry following such a principle is proposed in this report. Again questions remain:

- If positioning correction is applied, which should be the reference point?
- Where should the misalignment be measured – on the gantry or on the PPS?
- Which patient positioning and set-up methods seem suited?

The need for an interdisciplinary approach for such a decision-making is evident.

11 Literature

[1] Amaldi U, Larsson B, Hadrontherapy in Oncology, Elsevier, 1994

[2] Reimoser S, “Protonengantries”, in: Med-AUSTRON - Ein Österreichisches Krebsforschungs- und Behandlungszentrum zur Hadronentherapie in Europa, Vol. II, Ed.: R. Pötter, T. Auberger, M. Regler, Wiener Neustadt, 1998

[3] Reimoser S, “Program for a Novel Ion Gantry”, European Organisation for Nuclear Research, CERN-ST/98-036, 1998 and: Med-AUSTRON - Ein Österreichisches Krebsforschungs- und Behandlungszentrum zur Hadronentherapie in Europa, Vol. II, Ed.: R. Pötter, T. Auberger, M. Regler, Wiener Neustadt, 1998

[4] Badano L, Benedikt M, Bryant P J, Crescenti, M, Holy P, Maier A, Pullia M, Rossi S, Knaus P, CERN-TERA-Med-Austron-Oncology 2000 Collaboration, “Proton-Ion Medical Machine Study (PIMMS)”, Part I, CERN-PS-99-010, 1999

[5] Benedikt M, Bryant P, Holy P, Pullia M, Med-Austron - Oncology-2000 Foundation - TERA Foundation Collaboration, "Riesenrad" Ion Gantry for Hadron Therapy, Part III, CERN-PS-99-009-OP, 1999, Publ. Ref.: Nucl. Instrum. Methods Phys. Res., A.

[6] CUBUS Software, Statik-3 Benutzeranleitung, Berechnung von ebenen und raeumlichen Stabtragwerken, Februar 1998, Zuerich

12 Annex A: Design Drawings of the Centrally Supported Riesenrad Gantry

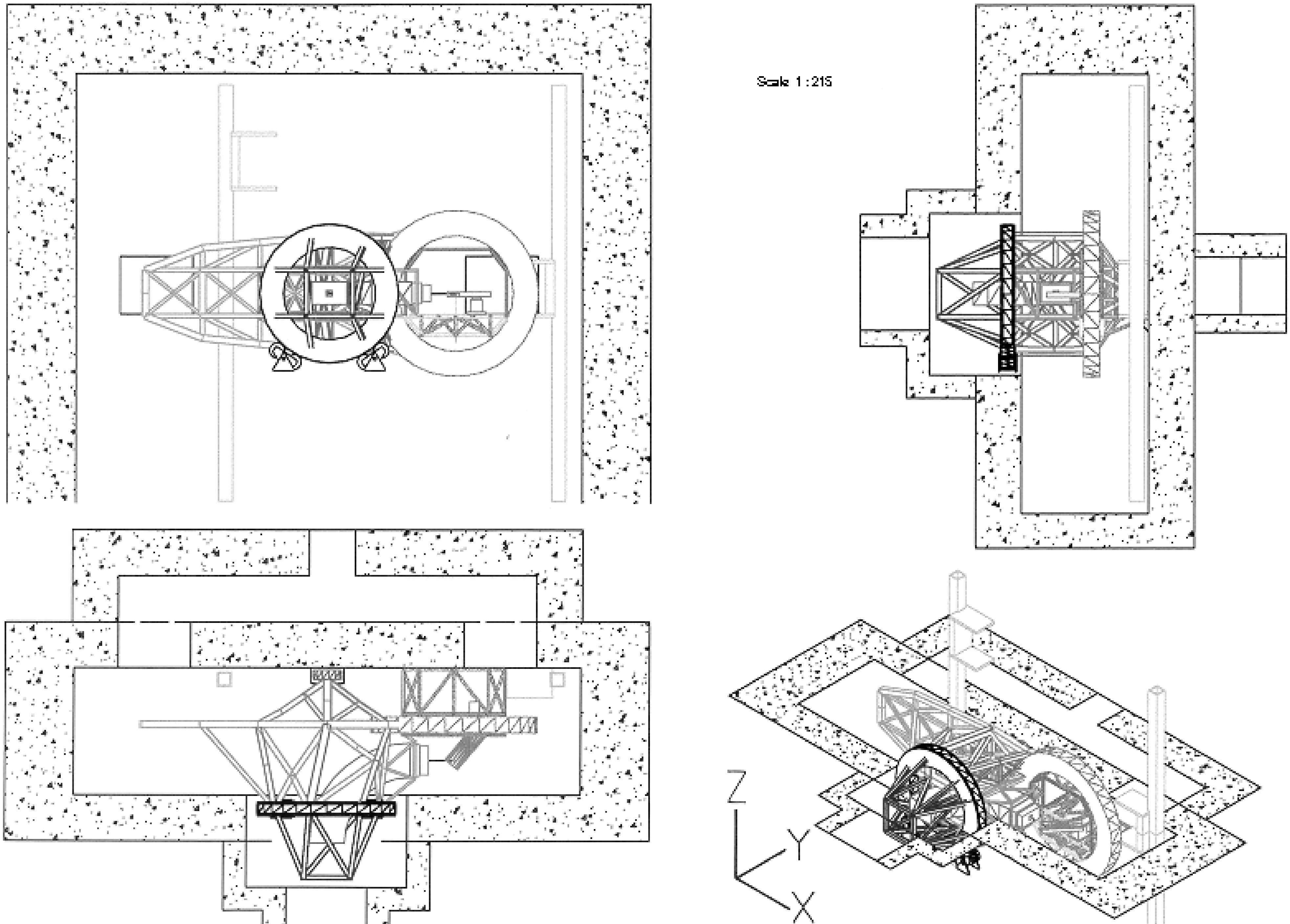
Figure 15 (following page): Plan, elevation and perspective of the Centrally Supported Riesenrad Gantry.

Figure 16 (page 24): Deflection plot of the Centrally Supported Riesenrad Gantry gantry pointing downwards.

13 Annex B: Design Drawings of the Riesenrad Gantry with a Separate Telescopic Cabin

Figure 17 (page 25): Plan, elevation and perspective view of the Riesenrad Gantry with a Separate Telescopic Cabin.

Figure 18 (page 26): Deflection plot of the Riesenrad Gantry with a Separate Telescopic Cabin pointing downwards.



Centrally supported Riesenrad Gantry

Stefan Reimoser CERN - ST/CV - 22.4.1999

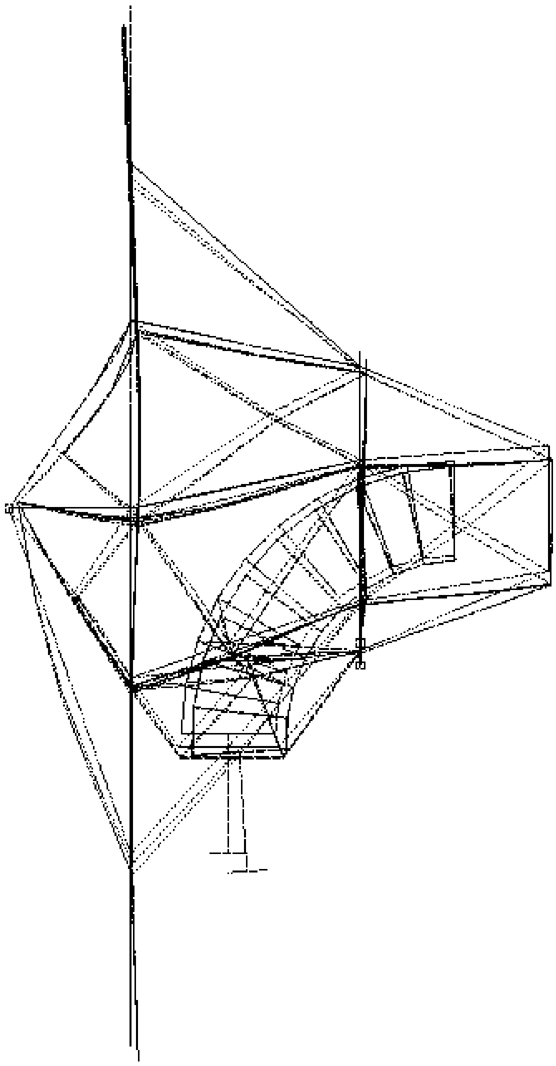
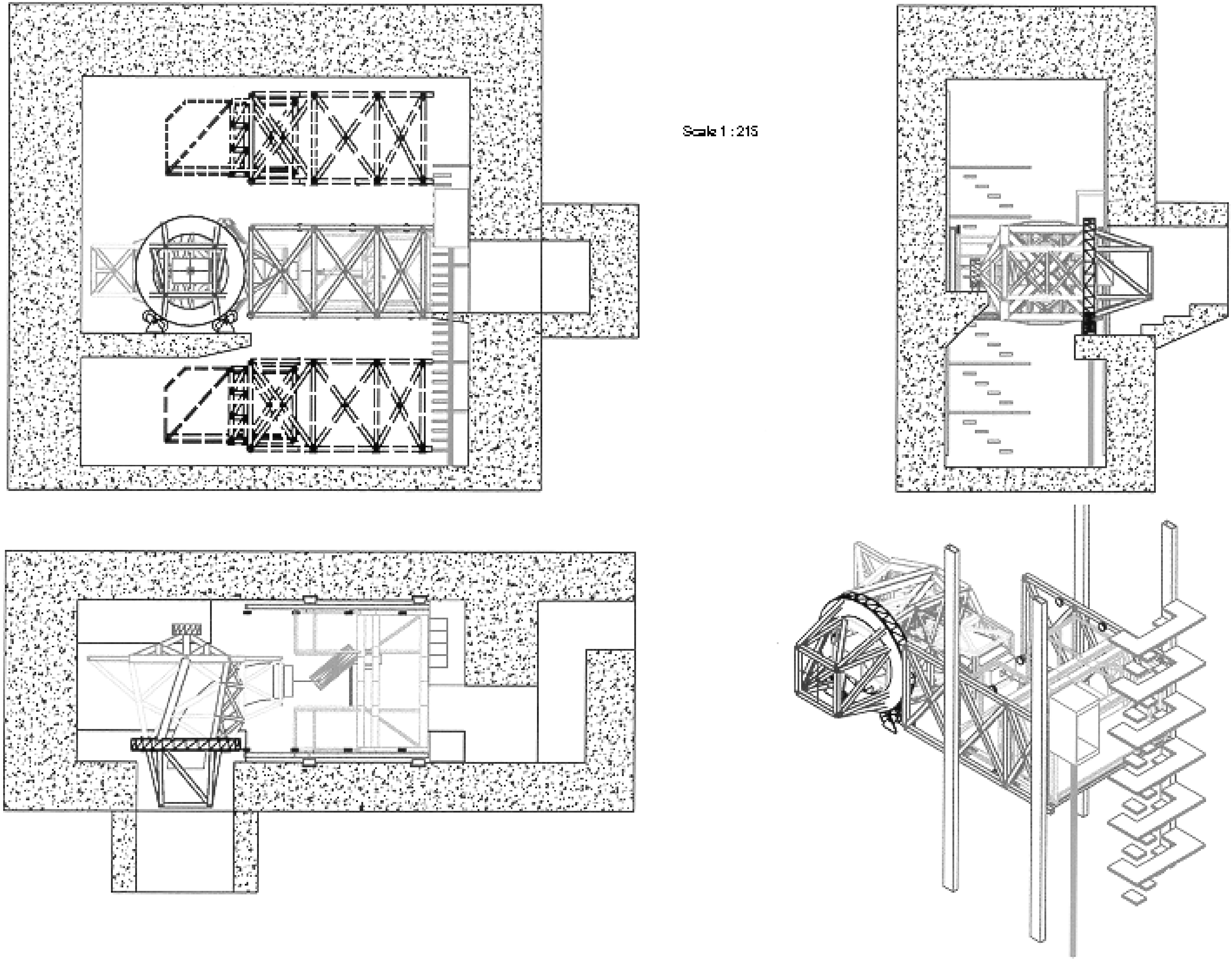


Figure 16: Deflection plot of the Centrally Supported Riesenrad Gantry pointing downwards (scale 1:100).



Riesenrad Gantry with a separate telescopic cabin

Stefan Reimoser, CERN - ST/CV - 22.4.1999

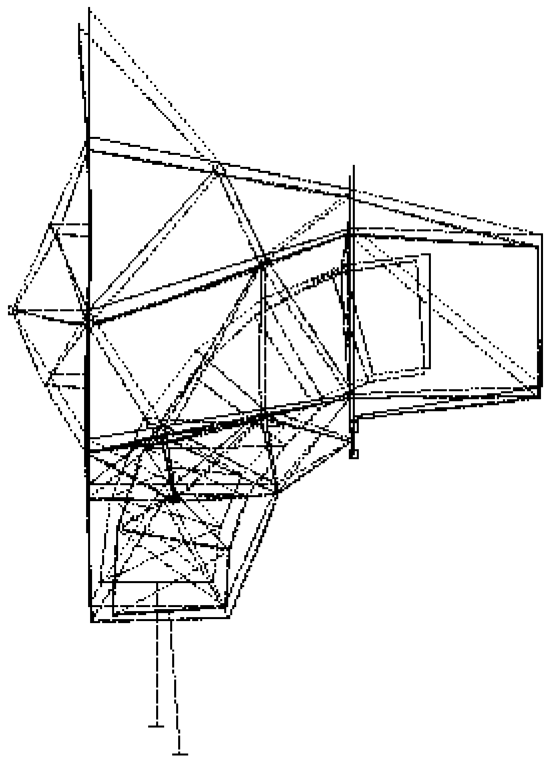


Figure 18: Deflection plot of the Riesenrad Gantry with a Separate Telescopic Cabin pointing downwards (scale 1:100).