GANTRY DESIGN FOR PROTON AND CARBON HADRONTHERAPY FACILITIES

U. Weinrich, GSI, Darmstadt, Germany

Abstract

The depth dose profile of protons or carbon ions is a major advantage in radiotherapy with respect to photons. Therefore the number of hadrontherapy centres in the world is rapidly growing. In order to be able to direct the beam from many directions, the use of gantries is the standard way for photon therapy. Therefore the hadrontherapy also aims for gantries – despite the higher magnetic rigidity. The major challenge lies in the production of large and heavy gantries still achieving the same position stability of the beam. In proton therapy several facilities are already running gantries in routine operation with a magnetic rigidity of about 2.5 Tm. This situation is not yet reached in carbon therapy due to higher magnetic rigidity of about 6.3 Tm... In the HIT (former called HICAT) facility in Heidelberg, Germany the first carbon gantry of the world is actually being assembled. After an introduction to hadrontherapy this paper reports about the several proton and carbon gantries used at different places in the world – with a focus on the HICAT gantry.

INTRODUCTION TO HARDRONTHERAPY

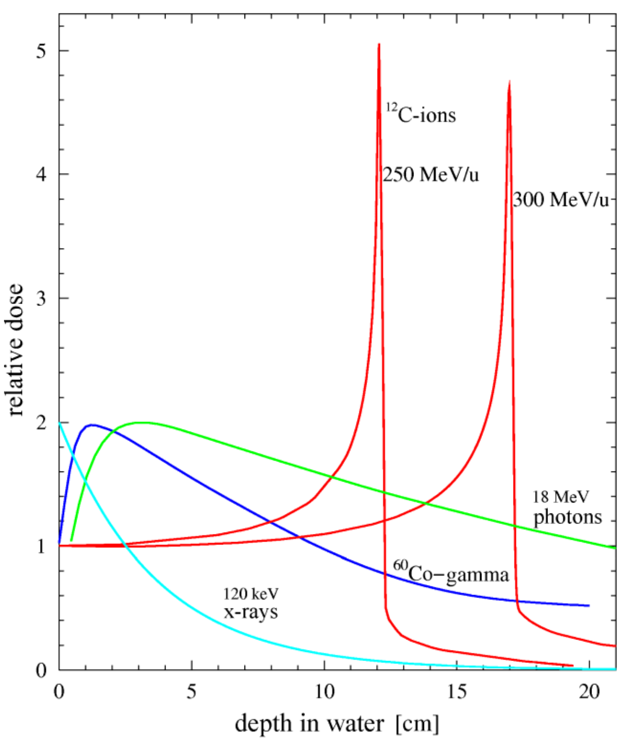

Figure 1: Depth dose profile comparison of photons and carbon ions for different energies.

The major challenge in radiotherapy is always to apply sufficient effective dose to the cancer to stop his growth while maintaining the dose in the surrounding healthy tissue within tolerable limits. One important feature of the radiation is the dose with respect to the penetration depth. Figure 1 shows the corresponding curves for photons, and carbon ions of different energies. Hadrons as protons and carbon ions yield a maximum of dose deposition just before being stopped. The position of this Bragg Peak depends on the energy of the incoming ion beam. By directing the Bragg Peak into the tumour volume one can immediately see that the dose applied to the healthy tissue in the entrance channel is much lower. The situation is even better for the tissue behind the Bragg Peak. Since tumour volumes are usually larger than the Bragg Peak one applies a series of irradiations with different energies to reach a flat dose distribution along the tumour. A typical example for such a superpositioning is shown in Figure 2 for a carbon treatment.

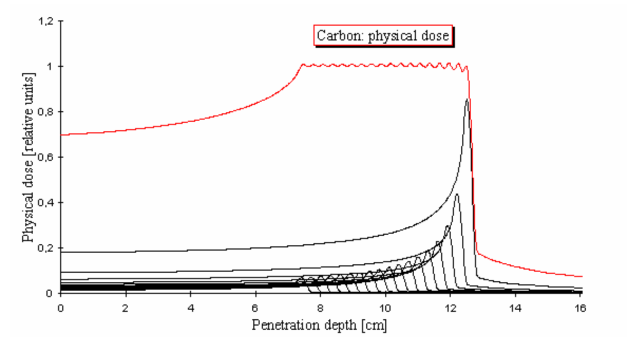

Figure 2: Superposition of different carbon beams to achieve a flat dose distribution.

In order to improve also the lateral conformity with the tumour target volume the raster scanning technology was developed and set in operation at GSI and PSI. The beam with a diameter of several millimetres is laterally scanned spot by spot with two fast scanner magnets along the tumour plane. This is done for every single ion energy. The schematics of this so called 3-D scanning is shown in Figure 3. This technology provides the best conformity to the tumour volume and is used at GSI to treat patients. Most of the other hadrontherapy centres in the world still use, however, collimators, boli and degraders to shape the beam to cancer volume.

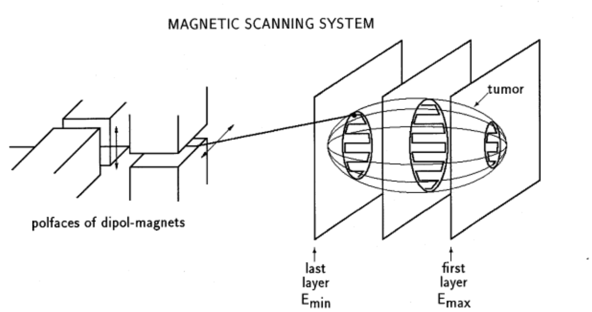

Figure 3: schematics of the lateral scanning with fast scanner magnets.

Due to the clinical perspectives of hadrontherapy its potential is actually explored in many countries around the world. Based on the experiences gained with the carbon treatment at GSI it was decided to build a dedicated facility at the university hospital of Heidelberg [1]. The key parameters of the facility will be the following:

- treatment with low and high LET-ions
- relatively fast change of ion species
- 3 treatment areas for up to 1000 patients per year
- integration of an isocentric gantry
- main ion-species: p, He, C, O
- ion-range in water: 20 -300 mm
- ion-energy: 50 -430 MeV/u
- extraction-time: 1 – 10 s
- beam-diameter: 4 – 10 mm FWHM
- ions/spill: $1*10^6$ to $4*10^{10}$

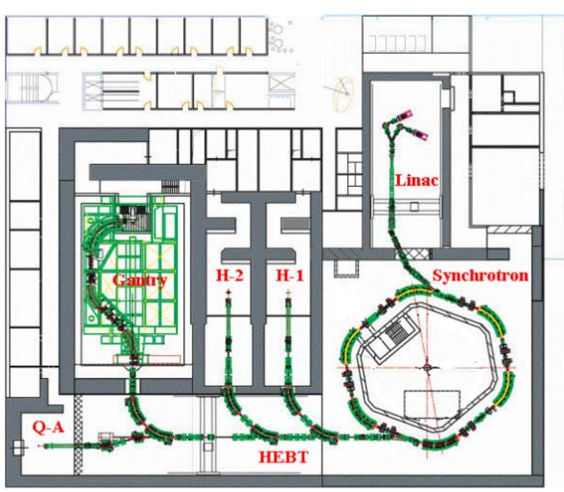

Figure 4: Layout of the first underground floor housing the accelerator complex of the HIT facility [2].

The general layout of this Heavy Ion Cancer Therapy Facility HIT is shown in Figure 4. The accelerator chain consists of an injector linac, accelerating the ions to an energy of up to 7 MeV/u, followed by a compact synchrotron with a circumference of about 65 m. The beam is distributed by the high energy beam transport line HEBT to the four beam stations. Station one and two are fixed horizontal beam stations for patient treatment. In station three the beam is guided along an isocentric gantry allowing irradiation from all directions. The fixed beam station number four will be used for quality assurance, development and research activities. All places will be equipped with rasterscan treatment equipment for a full 3D volume conformal irradiation.

For pure proton therapy facilities the synchrotron can be replaced by a cyclotron. The layout of the treatment places varies a lot depending on the clinical requirements. There are fixed beam treatment stations, some of them with vertical beam lines and different kinds of gantries in use.

INTRODUCTION TO GANTRIES

In order to reach full geometrical flexibility of the treatment gantries are used. They allow directing the beam from several directions onto the patient, who is usually lying on the treatment table.

Figure 5: Layout of a proton gantry delivered by Mitsubishi

One example for the treatment area for a proton gantry is shown in Figure 5. The gantry usually rotates around one axis and directs the beam from one side to the tumour. The tumour is generally positioned at the crossing of this two axis. This point is called the isocentre. Gantries which are built in this type are called isocentric gantries and are the standard layout in radiotherapy.

One exception is the proton Gantry 1 used at PSI. In this excentric gantry the patient table is fixed on the gantry and has a different position for each gantry angle. The advantage is that the gantry can be built in a more compact manner. This gantry is shown in figure 6.

Figure 6**:** The excentric Gantry 1 at PSI.

In table an overview of important parameter of some proton gantries in Japan are given.

Table 1: Proton Gantries in Japan

Town	Hyogo	Chiba	Tsukuba	Shizuoka
Number	2	2	2	2
Status	operation	operation	operation	operation
Type	isocentric	isocentric	isocentric	isocentric
energy	230 MeV	235 MeV	250 MeV	235 MeV
length	9.5 m	10.7 m	9 m	9 m
radius	4.8 m	5.0 m	5 m	4.8 m
dipoles	2	2	3	3
quads	7	9	6	4

The typical dimensions of proton gantries are 10 m in length and 5m in radius.

A picture of a supporting structure for proton gantries is shown in figure 7.

Figure 7: The supporting structure of a proton gantry from Mitsubishi.

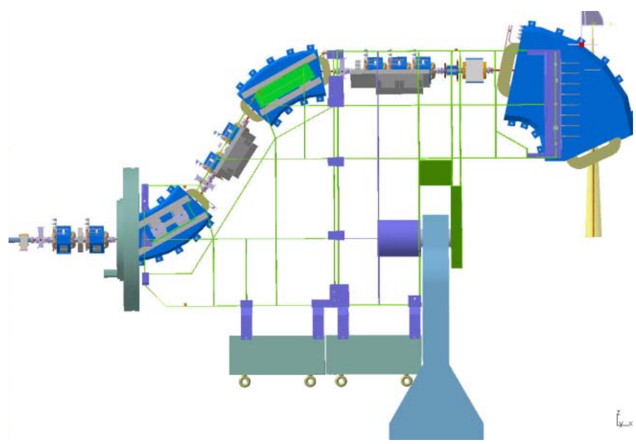

Figure 8: The layout of the isocentric PSI proton Gantry 2 also called PROSCAN.

In table an overview of important parameter of some proton gantries in Europe are given.

Table 2: Proton Gantries in Europe

Country	Germany	Switzerland	Switzerland
Town	München	Villingen	Villingen
Number	4	Gantry 1	Gantry 2
Status	validation	operation	assembly
Type	isocentric	excentric	isocentric
energy	250 MeV	230 MeV	230 MeV
length	10.1 m	10.2 m	11.6 m

Radius	5.0 m	1.4 m	3.2 m
number dipoles	2	3	3
number quads	7	7	7

The layout of the PSI Gantry 2 which is actually in the assembly phase is shown in figure 8.

THE HEIDELBERG GANTRY

Due to the even larger magnetic rigidity compared to proton machines carbon gantries have not yet been put into operation. There is only one in the assembly progress in Heidelberg. Intensive discussions led for the Heidelberg Gantry to an isocentric gantry design with the integration of the rasterscan components. Together with other components such as vacuum chambers and treatment monitor devices the following beam transport elements are included:

One 90°-dipole
Two 45°-dipoles
Eight quadrupoles
Two scanner magnets
Two steerer magnets
Two diagnostic chambers

In July 2003 the order was placed to the company MAN Technologie (now MT Aerospace) for the construction of the structure and the integration of the components [3].

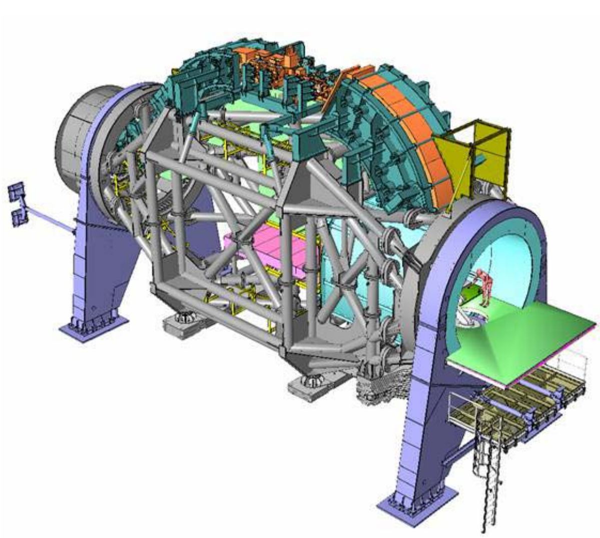

Figure 9: Detailed layout of the Heidelberg Gantry.

The 3D volume conformal rasterscan method requires reproducible beam positions for all gantry angles. Given the weight of the components to be integrated it was necessary to perform extensive FEM – calculations to optimise the supporting structure to the required stiffness without increasing too much the total weight of the system. Finally a solution was reached which satisfies the individual requirements for position and angular stability of the relevant beam guidance components. The functionality has to be maintained for up to 300 000 rotations over the envisaged life cycle of 15 years.
The final layout is shown in figure 9. There are two main supporting structures holding the rotating part vie two large bearings. The isocenter with the patient positioning system can be seen in the front.
The total weight of rotating parts in the final layout amounts to 570t out of which 140t are due to the beam transport components and about 120t due to the beam absorber. In addition there are 130t of room fixed components such as the main Gantry supports.

The part of the gantry which is close to the patient requires special design effort:

- There is a dense package of accelerator and treatment components in this area.
- For the position control two x-ray tubes and a PET-option have to be integrated in the rotating part.
- The isocentre will be more than 7 m above the floor level of the gantry room and more than 5 m away from a wall – so the realisation of a precise and reliable supporting structure for the patient has to be carefully designed.

The final layout is shown in figure 10 for an irradiation from the top.

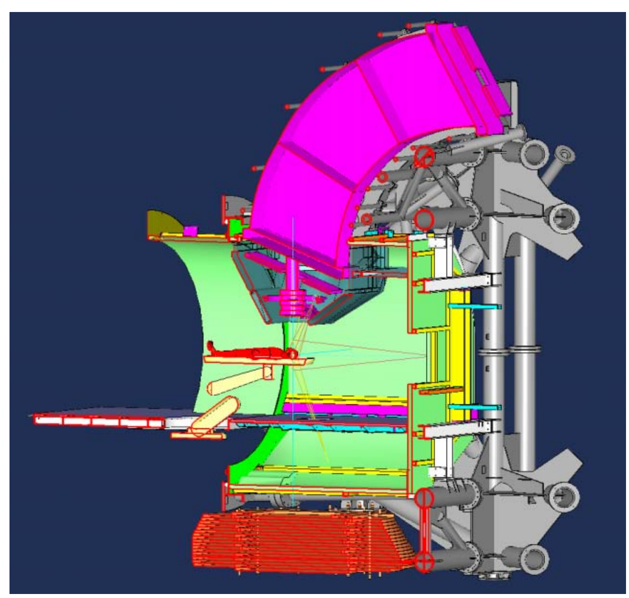

Figure 10: Patient environment in the Heidelberg Gantry.

One can see the patient is lying on his table, the 90 degree dipole together with beam diagnostics and a positioning laser above him. Below there are the X-Ray tubes and the beam absorber.

A lot of work was also necessary to clarify all links to the building as well as to assure compliance with the medical legislation. Because of the size and weight of the gantry, its integration into the building is a challenging issue. Assembly complications arise from the fact that the volume of the gantry room is minimized to reduce building costs. The ambitious overall time table of the project imposes commissioning with beam up to first two treatment places while the gantry room is still accessible.

The assembly has started beginning of June as can be seen from Figure 11. The overall assembly and commissioning of the components will last for at least 10 months.
Commissioning with beam will start in summer 2007 with the goal to finish it in the beginning of 2008. This work will be done by GSI.

Figure 11: Assembly of the main Gantry supporting structure in the Gantry room beginning of June 2006.

FURTHER DEVELOPMENTS

There are actually Studies performed at several places in the world to find solutions with less weight and corresponding costs. One example is given in the following table where some main parameters are compared to the Heidelberg Gantry. Apart from the Heidelberg Gantry some parameters of the new HIMAC Gantry Design [4] are shown in Table 3.

Table 3: Carbon Gantry designs

Country	Germany	Japan
Town	Heidelberg	Chiba
Number	1	1
Status	assembly	design
Type	isocentric	isocentric
energy	430 MeV/u	400 MeV/u
length	19.0 m	16.9 m
radius	5.6 m	7.1 m
number dipoles	3	3
number qpoles	8	7

Given the total weight of about 90t of the 90°-dipole there are also ideas to replace it by a superconducting magnet for future gantries. This is for example a way actually followed by the ETOILE project of Lyon, France for the technical design report.

SUMMARY

Hadrontherapy is evolving to become the state of the art radiotherapy due to its supreme dose depth distribution. In order to provide the same geometrical flexibility as photon therapy gantries have to be used for these facilities also. While already several proton gantries are in routine operation now this is not yet achieved for carbon treatment. The first gantry of this kind is actually assembled in Heidelberg, Germany. It represents a major technological and logistical challenge. Studies to lighten the carbon gantry design are on the way.

ACKNOWLEDGEMENT

Many thanks to the colleagues who sent in information from the gantries around the world and to those who participate to the fascinating work on the Heidelberg Gantry.

REFERENCES

[1] J. Debus et al., 'Proposal for a dedicated ion beam facility for cancer therapy', 1998
[2] H. Eickhoff et al.: 'HICAT-The Heavy Ion Cancer Therapy accelerator facility for the Clinic in Heidelberg, Technical description', GSI, 2000
[3] U. Weinrich et al.: The Heavy Ion Gantry of the HICAT Facility, EPAC 2004
[4] Y. Futami et al., NIM A430(1999)143.