COMMISSIONING OF THE ION BEAM GANTRY AT HIT

M. Galonska, S. Scheloske, R. Cee, K. Höppner, T. Winkelmann, A. Peters, T. Haberer
Heidelberg Ion Beam Therapy Center, D-69120 Heidelberg, Germany

Abstract

The Heidelberg Ion Beam Therapy Facility (HIT) is the first dedicated proton and carbon cancer therapy facility in Europe. It uses a full 3D intensity controlled raster scanning dose delivery method. The ion energy ranges from ca. 50 to 430 MeV/u corresponding to ion penetration depths of 20 to 300 mm in water.

The HIT facility comprises the only heavy ion gantry worldwide designed and built for the beam transport of beams demanding a magnetic rigidity from 1 to 6.6 Tm. The gantry rotation of 360° enables beam scanning patient treatment from arbitrary directions. The libraries of carbon and proton pencil beams at the gantry are now offered with the whole variety of ion beam properties, i.e. 255 energy steps, 4 beam foci, and 10 intensities (10^6-10^{10}/spill). The beam has to be adjusted only for a fraction of possible combinations of energy, focus, and gantry angle. These are taken as interpolation points for a calculation of an overall number of about 37,000 different set values per ion type, and one intensity step according to the process data supply model.

This paper gives an outline of the practical concepts and results of adjusting the required beam properties independent of the gantry angle.

INTRODUCTION

Figure 1 shows the HIT facility consisting of an injector linac accelerating ions to 7 MeV/u, and a compact synchrotron which provides protons, carbon, oxygen, and –in the future– helium ions with variable energy (see above) to the four high energy beam transport lines using KO-extraction. The first two beam lines guide the ion beam to horizontally fixed raster scanning systems for patient treatment (H1 and H2 in Fig. 1). A third horizontal target station is frequently used for quality assurance, research and development in a broad range of disciplines (Q-A in Fig. 1).

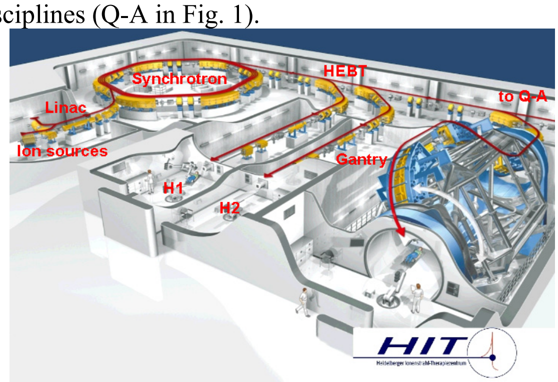

Figure 1: Overview of the HIT accelerator.

Finally, HIT comprises the worldwide first heavy ion gantry (isocentric) with integrated beam scanning capability providing for an optimum dose application by patient treatment from arbitrary directions. While the first proton and carbon beams were transported to the isocenter in January 2008, the commissioning was interrupted in March 2008 in order to focus on the start of the clinical operation in the horizontally fixed treatment lines. In February 2010 comissioning restarted aiming at the efficient provision of the pencil beam libraries for the raster scanning dose delivering for these ion species, and –as a future extension– for other ion beams (^{4}He, ^{16}O, …), and 6 beam foci (up to 20 mm FWHM), summing up to approx. 220,000 entries in the library of beam characteristics (4 ion species, 1 intensity step considered only).

THE HEAVY ION GANTRY

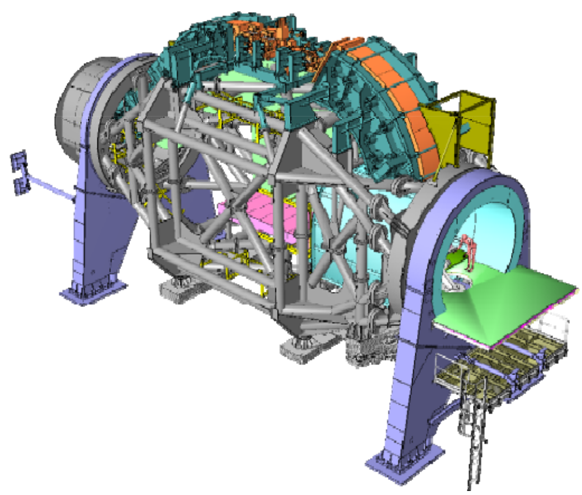

Figure 2: Drawing of the heavy ion gantry at the HIT including mechanics, beam line components and patient treatment room (MT Mechatronics).

The main mechanical characteristics of the gantry are:

- Length / diameter: 25 m / 13 m
- About 600 t; rotating parts, and fixed components such as main supporting stands
- Construction and integration by MT Mechatronics (former MAN Technology) finished by the end of 2007 [1]

ION BEAM CHARACTERISTICS

Figure 3 gives an overview of the gantry beam line with the beam diagnostic devices. In order to keep the gantry design compact, the two scanner magnets are located in front of the 90° dipole [2] so that ion optical characteristics of this dipole in especially with the beam deflection of the scanners have to be strongly considered. Beam size and position in the isocenter are measured with a viewing target and camera mounted on the rotating nozzle of the gantry (Fig. 4).

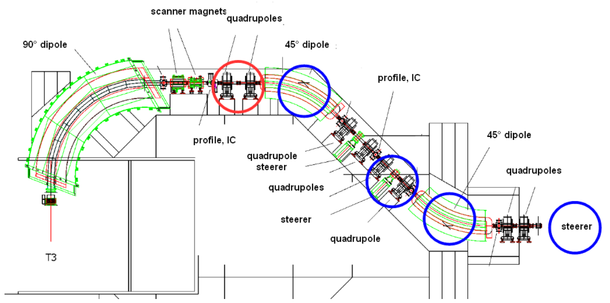

Figure 3: Gantry beam line with beam diagnostic devices (profile grid, ionization chamber (IC), not shown: scintillator, viewing screens); red circle: final focus setting quadrupoles; blue circles: final position setting dipoles/steerer.

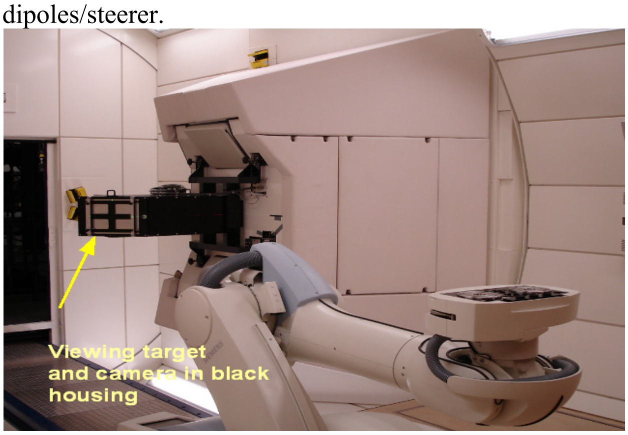

Figure 4: Viewing target and camera in black housing at the gantry nozzle (patient treatment room).

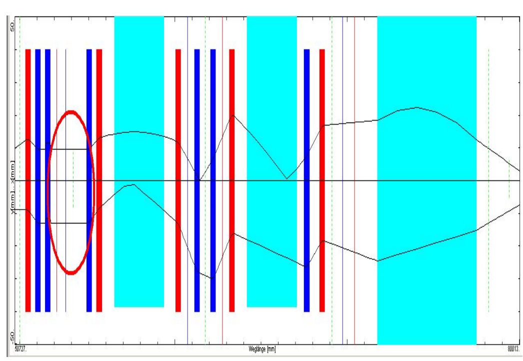

Figure 5: Beam envelopes along the gantry; red marked: envelopes at the gantry entrance point (MIRKO simulation [3]).

The general requirements on the beam demand: a) full transmission (beta functions within aperture limits even with beam scanning along the requested irradiation field of 20*20 cm in the isocenter; b) an optical setting keeping dispersion in isocenter within small limits, and keeping beam focus and position independend of gantry angle yet compensating the coupling of horizontal and vertical phase space. This includes the optimisation of the ion beam at the gantry entrance point, i. e. size and divergence (equalized at the gantry entrance) for a single energy (Fig. 5, see also [4-6]). Since the vertical emittance depends on the beam energy (due to adiabatic damping) the matching at the entrance point depends on the energy as well. c) a phase advance which is a multiple integer of 180° (minimum position dependance on the gantry angle).

For a single energy the control data for the accelerator components is calculated from physical input parameters. The data supply model (part of control system) accounts for scaling of the control data with the magnetic and electric rigidity for different energies. Other energy dependend effects have to be compensated by semi-automated adjusting of components, i. e. quadrupoles, dipoles, steerer in the HEBT and gantry. The final beam focus is adjusted by means of the last quadrupole doublet, the final beam position with dipoles and steerer magnets (s. Fig. 3, red and blue framed magnets). These control values are set or calculated, and stored individually not only for different energies, but for gantry positions, and foci.

In order to minimize the commissioning effort only a small subset of input parameters is determined as interpolation points; i. e. for a few energy steps (ca. 10), foci (4), and gantry angles (ca. 8) making up for about 1 % of the overall library of beam characteristics. This turned out to be a sufficient number of interpolation points which was not evident from first principles. Missing physical data is calculated by means of a polynomial fit between these points. The interpolation algorithm has been optimized for the special needs of interpolation in energy and gantry angle space. As an example, Fig. 6 shows a typical interpolation (a small correction to the integral field gradient of a quadrupole) as a function of the gantry angle and beam energy. The position of the extrema in the fit curves reveals the periodic structure of the input parameter corresponding to the gantry angle.

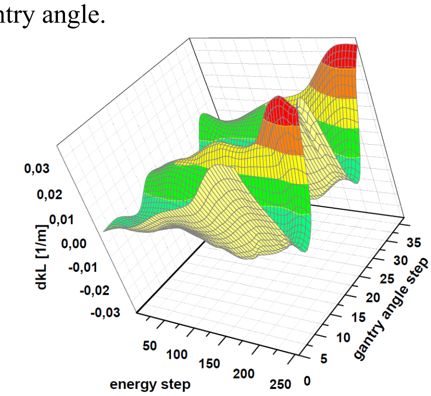

Figure 6: Correction to a quadrupole integral field gradient (dkL) as function of the gantry angle step (1 step ≡ 10°), and energy step with fit (surface) between the nodes for a fixed beam focus.

This procedure ensures that the beam size ranges in a 25 % limit compared to the values needed for patient treatment within the whole library of desired beam properties for the carbon and proton beam with only a few exceptions. The beam position of the “centered” beam ranges so far within ± 2 mm with only a slight dependence on the gantry angle. This deviation can be easily compensated by the beam scanning system. The beam quality in the isocenter is routinely determined by measuring about 1 % of the overall combinations. This covers the full range of energies, beam widths, and gantry angles. As an example, Figs. 7 and 8 are showing the the focus and position over a full rotation for a fixed energy in the horizontal (x) plane (fixed gantry coordinate system).

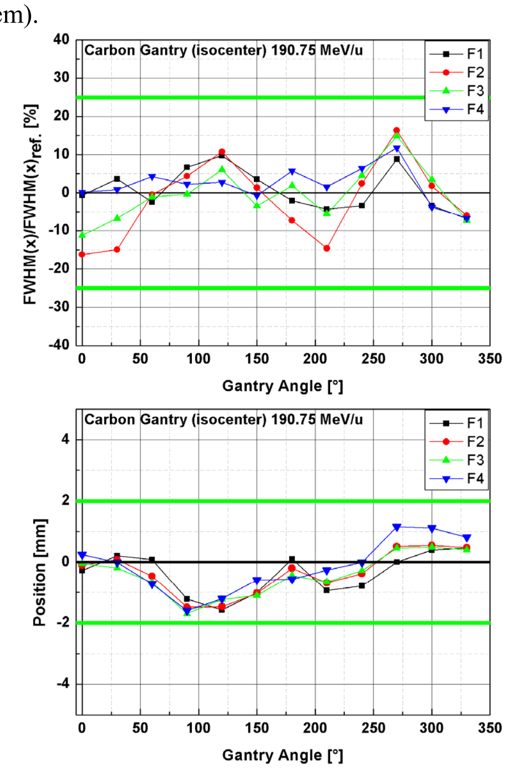

Figure 7: Carbon (190.75 MeV/u), isocenter; top: different beam widths F1-F4 (x, FWHM), relative deviation from reference values over a full gantry rotation; bottom: beam position (x) over a full gantry rotation; green lines indicate permitted limits.

OUTLOOK

It is proven that for the whole variety of ion beam properties, i.e. 37,000 combinations (carbon ions and protons), the beam foci, and the center position (all energy steps, and gantry angles) are within the given tolerances (with a few exceptions) taking a small number of interpolation points (approx. 1 %) and the calcuation of set values by an interpolation, all based on a basic setting of the gantry optics and adequate beam injection into the gantry considering all requirements mentioned.

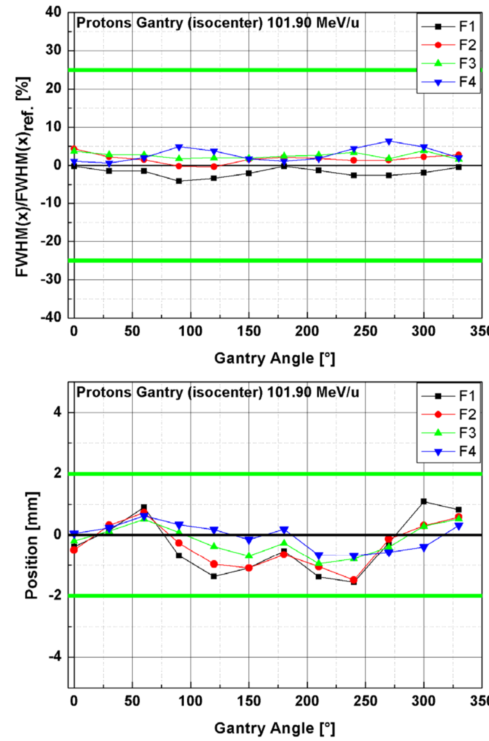

Figure 8: Protons (101.9 MeV/u), isocenter; top: different beam widths F1-F4 (x, FWHM), relative deviation from reference values over a full gantry rotation; bottom: beam position (x) over a full gantry rotation; green lines indicate permitted limits.

It can be concluded that the described procedures provide an efficient way of setting the ion beam properties of an heavy ion gantry in a reasonable time.

The future research activities will include the scanning process, i.e. the survey and improvement of beam properties for the non-centered beam with a scanning field ± 100 mm yet accounting for the ion optical properties of the 90° dipole (predicted focus variations, position deviations, transmission etc.).

ACKNOWLEDGEMENT

The authors would like to thank the HIT staff for many helpful discussions, preparation, and maintenance of the accelerator parts.

REFERENCES

[1] R. Fuchs et al., Proc. of the EPAC 08, Genoa, Italy
[2] H. Eickhoff et al., Proc. of the EPAC 02, Paris, France
[3] MIRKO, B. J. Franczak
[4] M. Pavlovic, Nucl. Instr. Meth. A 438 (1999) 548-559
[5] C. M. Kleffner, U. Weinrich, Proc. of the EPAC 08, Genoa, Italy
[6] P. Spiller et al., Proc. of the EPAC 00, Vienna, Austria