THE HIT GANTRY: FROM COMMISSIONING TO OPERATION

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Abstract

The patient treatment at the first 360° raster scanning heavy ion gantry of the Heidelberg Ion Therapy Facility (HIT) started in October 2012 using carbon ion and proton beams.

HIT is the first dedicated proton and carbon cancer therapy facility in Europe. It uses full 3D intensity controlled raster scanning dose delivery method of pencil beams. The ion energy ranges from 48 up to 430 MeV/u (ion penetration depths of 20 to 300 mm in water). Beams are provided by a linac-synchrotron-system to four high energy beam lines: 2 horizontal patient treatment rooms; 1 horizontal experimental cave for quality assurance, development, and research work; and the heavy ion gantry.

From the first commissioning the libraries of carbon and proton pencil beams at the gantry had been established with the whole variety of ion beam properties, i. e. 255 energy steps, 4 beam foci, 360°, and 10 intensities (10^6–10^{10}/spill) regarding the iso-centric beam.

This paper reflects the impact of the subsequent preclinical testing including beam size/position, and dose measurements within the irradiation field of $20 \times 20\,\mathrm{cm}^2$ on the further improvement of the ion optical settings of the gantry high energy transfer line.

INTRODUCTION

Figure 1 shows the HIT facility consisting of an injector linac (7 MeV/u), a compact synchrotron (protons, carbon, oxygen, helium scheduled; variable energy 48..430 MeV/u; KO-Extraction) to the four high energy beam transport lines: two horizontally fixed raster scanning systems for patient treatment (H1, H2, in operation since 2009 and 2011), a horizontal scanning target station for quality assurance, research and development in a broad range of disciplines (Q-A in Fig. 1); and the worldwide first heavy ion gantry (isocentric) with integrated beam scanning capability providing for an optimum dose application by patient treatment from arbitrary directions (360° in steps of tenth of degrees). The gantry went clinical in autumn 2012.

In the past it has been proven that for the whole variety of ion beam properties, i. e. about 37,000 combinations (carbon, protons each, 255 energy steps, 4 foci, 36 angle steps), the beam foci, and the center position for all energy steps, and gantry angles are within the given tolerances [1].

The beam size and position in the isocenter have been measured with a viewing target and camera mounted on the rotating nozzle of the gantry by analyzing the beam profiles in the two transversal planes in the rotating gantry coordinate system. Ion beam settings are based on a) a principle setting of the gantry optics resulting in a beam focus which is nearly independent of the gantry angle (with small corrections to the beam size/position as function of the angle orientation) and b) an adequate beam injection into the gantry [1].

Beams with any of the properties can be requested cycle by cycle including the change between two ion types (three ion types in the near future).

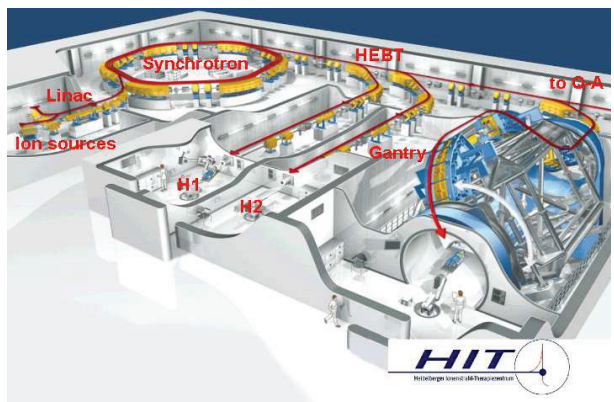

Figure 1: Overview of the HIT accelerator.

Having established the first pencil beam library the research activities focused on the dose delivery tests i. e. the analysis and improvement of ion beam properties (carbon and proton beam) for non-centered, i. e. scanned beams within a scanning field of $20 \times 20\,\mathrm{cm}^2$. These analysis included measurements of focus and focus deviations, position (deviations), transmission, and dose distributions in the isocenter as a result of the overall ion optical properties and the optics of the 90° dipole. It should be considered that this dipole is located behind the scanner magnets. These studies have been carried out by the medical physics team at HIT which is in charge of the final beam approval. Results have been incorporated into beam setting strategies; all in close collaboration of the medical physics team, the accelerator team and our industrial partner Siemens (SAG).

In order to start the patient treatment in time we restricted ourselves to a few selected gantry angles in the initial phase of commissioning. This applies to the acceptance tests for patient treatment, the ion beam (dose application) approval including regulatory issues, and further beam settings efforts [2].

This paper briefly reviews some of the issues and approaches that arose in the course from commisioning to clinical operation which started in 2012.

ISBN 978-3-95450-122-9

ION BEAM CHARACTERISTICS

Taking the beam properties of the iso-centric beams from the first commissioning run it was discovered that the horizontal beam size in the isocenter was reduced while scanning the beam horizontally and therefore minimizing the possible irradiation field (reduction of about 30 %!, Fig. 2). A small change of the beam shape by scanning of the ion beam has been considered for example in [3] caused by higher order image aberrations of the 90° dipole which the beam passes after deflection by the scanner magnets. But the impact of the beam position (by scanning the beam) on the beam shape was greater than it was expected.

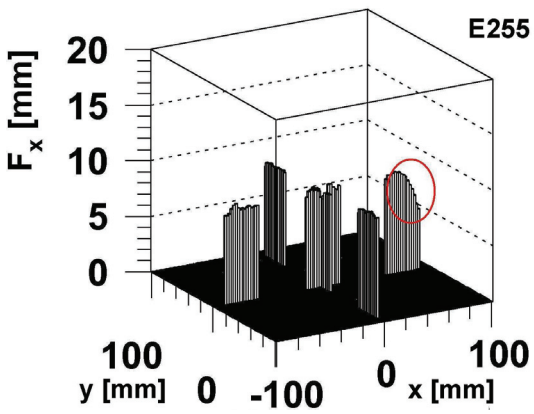

Figure 2: Beam focus (FWHM, hor.) in one of the medical beam application monitors as function of the beam position of the scanned beam (protons); red circle: beam size reduction [4].

It turned out that the beam size variation is due to particle losses while scanning through the last dipole in spite of the huge magnet chamber acceptance of more than $20 \times 20\,\mathrm{cm}^2$. Thus an optimization of the ion optical settings became inevitable by reducing the beta function on the gantry structure in front of the scanners and the dipole and by creating a convergent beam into the bend while keeping all other beam properties such as beam size, and dispersion in the isocenter at least unchanged (or improved) for all gantry angles (Fig. 3). In addition the beam size settings have been changed such that smaller beam foci ($F1 < F4$) need less quadrupole focussing i. e. integral gradient $kL(F1) < kL(F4)$ (cf. Fig. 4). This was performed using the partly automated standard routines developed in the past [1]. In addition, an auxiliary viewing target was installed in front of the 90° dipole in order to ensure a straight beam injection into this bend. A straight injection should force the beam motion on its reference orbit and therefore avoid beam losses by possibly passing the beam through vacuum chamber boundaries. With anticipation a spare diagnostic chamber in front of the 90° dipole has already been assembled in the past.

Another outcome of the analysis were dose inhomogeneities. These have been observed on films (in the isocenter) which have been irradiated by a scanned carbon ion beam. As a result, a periodic structure of dark and light grey stripes appeared on the film [4]. These dose distributions turned out to be an image of the structure of the ripple filter interacting with the carbon ion beam of small beam size. Ripple filters are essential insertions of mm thick Plexiglass with a periodic structure of fine grooves mounted approx. 60 cm upstream of the patient's position which broaden the Bragg maximum of ion beams for the raster-scan technique, smoothing the low energy Bragg peak and therefore reducing the number of energy layers required for ion therapy [5]. Since the ripple filter cannot be omitted in therapy some further restrictions have to be imposed on the ion optical settings of the carbon beam instead. As a solution, the ion beam size must be above a minimum of a few mm within the ripple filter (vertical beam size, depends on the geometric orientation of the filter's grooves). The beam size has to be determined in the vicinity of the ripple filter, that is in the beam application monitors at the gantry nozzle.

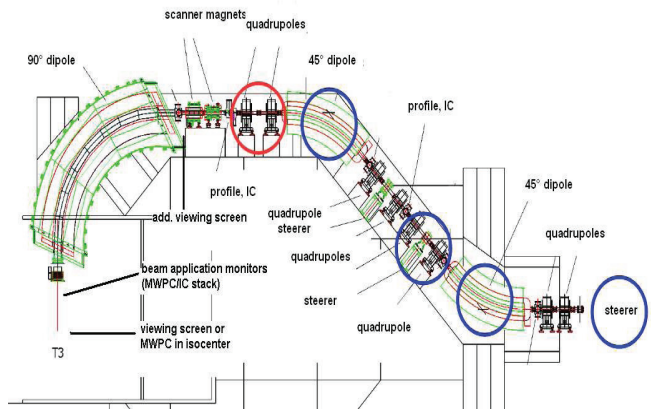

Figure 3: Gantry beam line with beam diagnostic devices (profile grids, ionization chamber (IC), viewing screens, beam application monitors (MWPC/IC stack); not shown: scintillator); red circle: final focus setting quadrupoles; blue circles: final position setting dipoles/steerer.

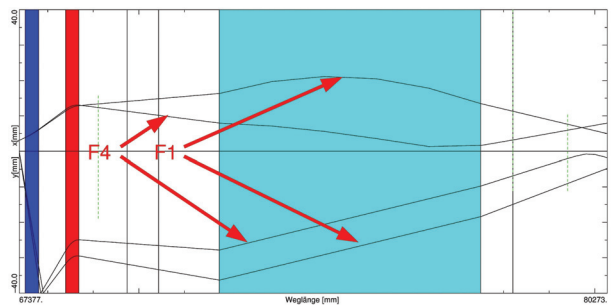

Figure 4: Beam envelopes focus index 1 and 4 along the rear part of the gantry (carbon beam, shown: final focussing quadrupoles and 90° bend); $kL(F1) < kL(F4)$; MIRKO simulation [8].

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ACCELERATOR PERFORMANCE CHECK

Medical treatment requires a stringent quality assurance, a detailed reporting on beam quality, device failures and technical problems [6]. Thus in advance of the daily patient treatment a performance and reliability check is inevitable which is shared amongst the medical physics and accelerator staff. The quality assurance by the medical physics team is more comprehensive and ends with a "room approval for therapy" (for instance [7]).

The accelerator performance check concerning the gantry beam quality was partly adopted from that of the horizontal treatment rooms, but it had to be extended for gantry needs by a beam size and position measurement on the gantry top for a few selected angles. In addition the beam sizes and beam positions at the gantry entrance point are measured daily because this is a crucial factor in the beam optics settings. Since no further beam diagnostics has to be installed for these automated measurements the time required is limited to about 30 min. only (accelerator and gantry only).

ACCELERATOR CONTROL SYSTEM (ACS)/BEAM DIAGNOSTICS

It turned out to be essential to build an interface between the medical beam application system and the accelerator control system in order to link measurement data of the medical beam monitors (BAMS, an MWPC and IC stack) to the accelerator control system which in turn is directly used for the beam setting procedures: a) in order to assure a proper beam position and parallel (scanned) beams it is fundamental using at least one of the medical beam monitors at the beam nozzle in addition to the commonly used viewing target which sometimes was replaced by a portable rotating MWPC mounted on the isocenter; b) in order to fulfill the requirements on the beam size at the position of the beam nozzle/ripplte filter (s. above) the adoption of the medical beam monitors became crucial; c) measurement data from the medical beam monitors, in particular from automated beam request and data acqusition sequences within the ACS, is stored in the ACS database and is accessible via ACS applications.

In addition advantage can be taken of the high time resolution of the medical beam monitors in beam size, position (order of 50 µs), and intensity (circa 2 µs) setting and measurement. Furthermore there is an improved reproducibility of data from beam setting (accelerator) to beam approval (medical physics) on the basis of the same diagnostic devices.

SUMMARY AND OUTLOOK

During the process from commissioning to operation some modifications of the ion beam optics became inevitable because the preclinical testing revealed some shortcomings of the preliminary optics settings of isocentric beams from the first commissioning run. These modifications have been successfully accomplished by using the partly automated routines developed in the past.

The accelerator performance check for the daily gantry beam quality analysis has been constituted, i. e. beam quality check for different angle position and injection into the gantry beam line.

The beam diagnostic abilities as part of the ACS have been extended by implementing an interface to the medical beam monitors as an essential part for beam setting procedures.

Future activities will include further studies on the beam quality for carbon and proton beam for a greater variety of gantry angles as well as some modifications and additions to the ACS for the specifics of gantry issues such as modifications to the interpolation algorithm of set values of the power supplies (see [1]) and the implementation of more sophisticated data handling routines for data generation, storage, recovery. etc.

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