THE HEIDELBERG ION THERAPY (HIT) ACCELERATOR COMING INTO OPERATION

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Abstract

The Heidelberg Ion Therapy Facility (HIT) is the first dedicated proton and carbon therapy facility in Europe. It uses full three dimensional intensity controlled raster scanning (3D-scanning) as basic treatment technique. Commissioning of the accelerator with beam was successfully finished for three fixed beam places in April 2008. Therefore, a library of 60000 combinations of beam properties (ion type, treatment place, energy, intensity, beam size) is now offered to the treatment technique teams preparing the treatment systems for the clinical use.

The HIT facility also comprises a gantry with full scanning properties constituting the only carbon ion gantry worldwide. The gantry can be rotated by 360 degree, so that the beam may be aimed at the patient from arbitrary directions. Commissioning with beam of the gantry was started in January 2008 when the first beams were transported successfully into the treatment room.

The talk will report on experiences and results of the commissioning of the accelerator sections. It puts special emphasis on the subject of preparing the enormous variety of beam properties in an efficient and reliable way.

INTRODUCTION

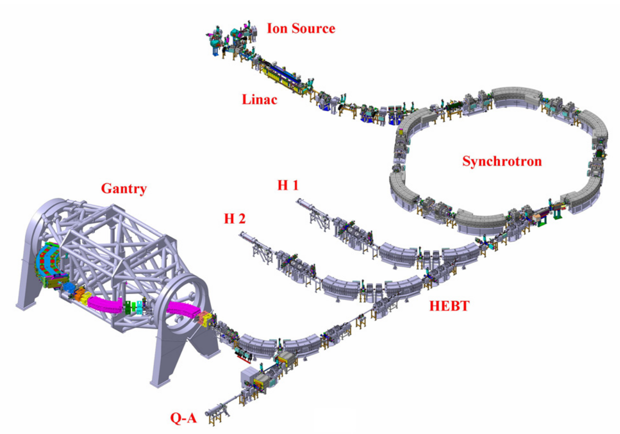

Figure 1: Overview of the accelerator part.

Figure 1 shows an overview of the HIT accelerator. The accelerator chain consists of two ion sources, an injector linac accelerating the ions to an energy of 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. Stations H1 and H2 are fixed horizontal beam stations for patient treatment. In station three the beam is guided along an isocentric gantry. The fixed beam station labeled QA is used for quality assurance, development and research activities. All places are fully equipped for a 3D rasterscan volume conformal irradiation.

The synchrotron [1] is the key to the enormous variety of beam parameters provided by the HIT accelerator. Its maximum magnetic rigidity is 6.6 Tm, corresponding to carbon ions at 430 MeV/u. For both protons and carbon, the range of extraction energies covers penetration depths in water from 20 mm to 300 mm. The beam is extracted horizontally using 3rd order resonance extraction above Qh = 5/3 by RF noise excitation (KO extraction). The synchrotron RF is kept on during extraction to smoothen the spill micro structure. No chromaticity correction is done. The extraction time is fixed to 5 s, but extraction may be aborted earlier by the treatment system. The spill may be interrupted asynchronously up to five times, thus enabling the irradiation of disjoint tumor slices in a single acceleration cycle. Care has been taken to avoid magnetic memory effects: In the synchrotron, this is done by ending each cycle with a conditioning ramp; in the beam lines, all bending magnets are field controlled using hall probes. In this way, ion type and energy can be requested from the accelerator in arbitrary sequences.

The commissioning of the HIT accelerator with beam started in 2006, when sources and injector linac were commissioned, followed by Synchrotron and HEBT in 2007 and 2008. The first turn in the synchrotron was achieved on Feb. 7th 2007, the first beam in a treatment place was seen on Mar. 23rd 2007. Beam performance for protons and carbons had reached a level enabling patient treatment at the two fixed beam patient treatment places by Dec. 16th 2007, at the QA place by Apr. 1st 2008. Gantry commissioning started on Jan. 4th 2008, but had to be suspended due to severe technical problems [2]. GSI has handed over the accelerator on Apr. 30th 2008 to the company HIT GmbH responsible for operating the accelerator. Table 1 summarizes the library (LIBC) of about 60000 beam parameter set values now available for request by the treatment technique systems.

Table 1: Beam parameter set values (LIBC)

Parameter	**Steps**	**Protons**	**Carbon**
Energy	255	48 – 221 MeV/u	88 – 430 MeV/u
Penetration	255	20 - 300 mm	20 - 300 mm
Beam Size	4	8 – 20 mm	4 – 12 mm
Intensity	10	$8\cdot10^7$ - $2\cdot10^9$ 1/s	$2\cdot10^6$ - $8\cdot10^7$ 1/s
Ions / Spill	10	$4\cdot10^8$ - $1\cdot10^{10}$	$1\cdot10^7$ - $4\cdot10^8$
Place	3	H1, H2, QA	H1, H2, QA

PERFORMANCE

In this section, we report on the beam performance of the HIT accelerator at the fixed beam places for carbon. Similar results hold for protons. We focus on the energy and time dependence of beam parameters. Measurements of transversal beam parameters are displayed mainly in the horizontal (X) plane, similar results applying to the vertical (Y) plane.

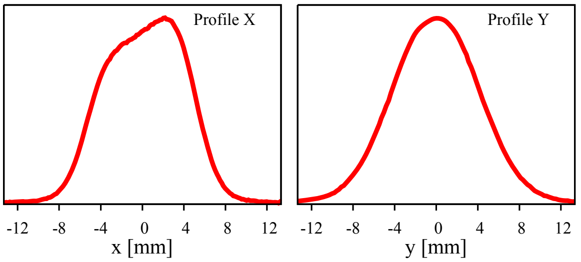

Figure 2: Beam profiles in the isocenter.

Figure 2 shows the two transversal beam profiles in the isocenter for a 250 MeV/u carbon beam with 10 mm width as measured with a viewing screen [3]. While the vertical profile has Gaussian shape, the horizontal profile resembles a trapezoid with rounded corners. This shape is a consequence of the horizontal extraction process. For smaller beam widths and lower energies the effect is compensated to some extent due to scattering in the beam exit window and the treatment monitoring system.

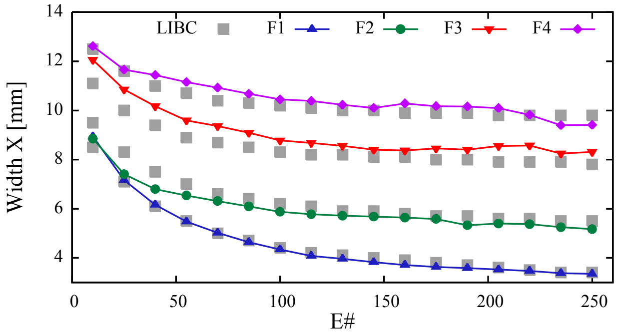

Figure 3: Measured horizontal width in the isocenter.

Figure 3 displays the horizontal width and position in the isocenter for the four width steps F1 through F4 as a function of energy step, measured with a viewing screen. The deviation from the requested LIBC set values is smaller than ±15%. Similarly, the deviation of the beam position from the exact location of the isocenter remains in a band of ±15% of the corresponding width value.

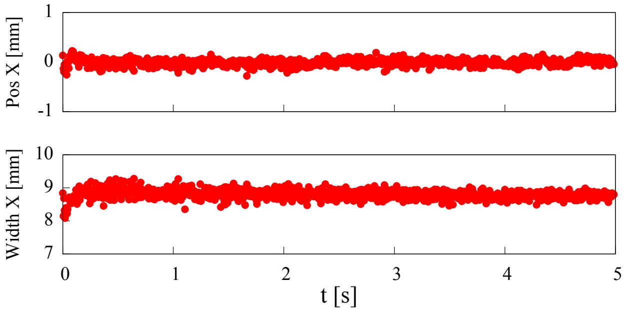

Figure 4: Horizontal position and width over the spill.

The stability of transversal beam parameters during the spill is very good, as can be seen from Figure 4, showing horizontal position and width as a function of time measured by the treatment monitoring system.

Figure 5 displays the time structure of a 250 MeV/u carbon spill [4] [5], measured with an ionization chamber in the HEBT [3]. Red and black curve represent particle number in 500 µs intervals and a 50 ms average, respectively. The nearly rectangular macroscopic shape is produced without feedback loop. Keeping the synchrotron RF voltage on during extraction leads to an excellent spill micro structure, as can be seen from the maximum over average of the red curve in a sliding 50 ms window shown in the bottom box. The spill duty factor is about 95 %.

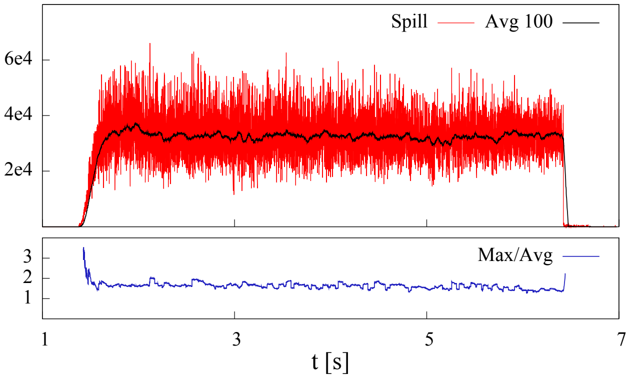

Figure 5: Time structure of the spill.

Figure 6 shows a spill with three interruptions of 1 s. The interruption is generated by switching off the KO exciter and shifting the frequency of the synchrotron RF by an amount corresponding to a momentum deviation of $dp/p = -0.5 \cdot 10^{-3}$. The shift moves the horizontal tune away from the resonance due to the negative chromaticity. To avoid intensity spikes when resuming extraction, the voltage of the synchrotron RF during extraction is set to the highest technically feasible value to maximize the area of the stationary RF bucket. In this way, the extracted intensity during interruptions can be reduced below $5 \cdot 10^{-4}$ of the nominal intensity [4] [5].

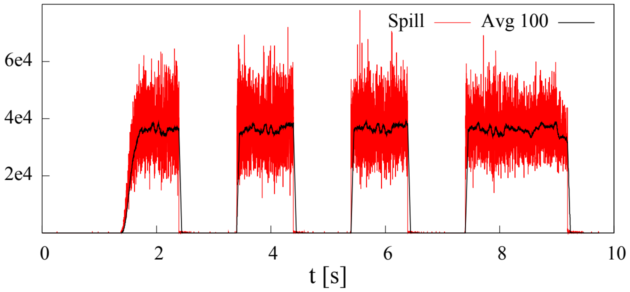

Figure 6: Spill with three interruptions.

Since February 2008, the beam performance is recorded daily through the HIT operating staff by measuring beam parameters at the synchrotron exit and at the treatment places for a representative sample of the parameter space. The acquired data are displayed in standard protocols including tolerance bands to facilitate validation of the beam performance. No significant changes of beam parameters have been observed so far.

COMMISSIONING

The major challenge in commissioning the HIT accelerator was the preparation of the accelerator settings for the 255 energy steps. For a single energy, the control data of the active accelerator components are calculated from a set of physical input parameters. While the scaling with magnetic or electric rigidity is accounted for by the data supply model, other energy dependent effects - e.g. adiabatic damping, magnet imperfections - must be corrected by manually adjusting the input parameters. Since it is impracticable to adjust 255 steps manually, a procedure was devised to determine the energy dependence of input parameters from a small number of settings. As an example for this correction process, consider the measured horizontal width in the beam line as a function of energy, compared in Figure 7 to the set values for the width in the isocenter (units are arbitrary).

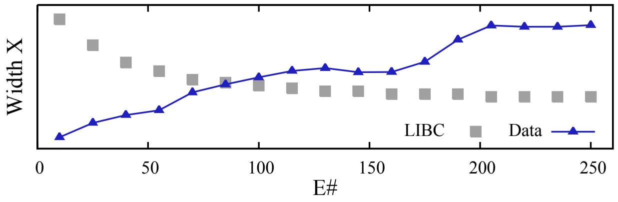

Figure 7: Uncorrected hor. width in the beam line.

The increase of the uncorrected horizontal width with energy is a consequence of optimizing the synchrotron for extraction efficiency. Matching the beam width in the isocenter to the set values requires an energy dependent variation of the focusing strength of the quadrupoles used to adjust the width. To determine the energy dependence, the focusing strength is adjusted manually for a small number of energy steps covering the energy range. From these base points a polynomial fit is generated which can be used to calculate the focusing strength for intermediate energies. Figure 8 displays the final result of this procedure: Solid curves represent the polynomial fits, symbols the base points. The correlation between the trend of the measured width in the beam line and the trend of the quadrupole strengths can be clearly observed.

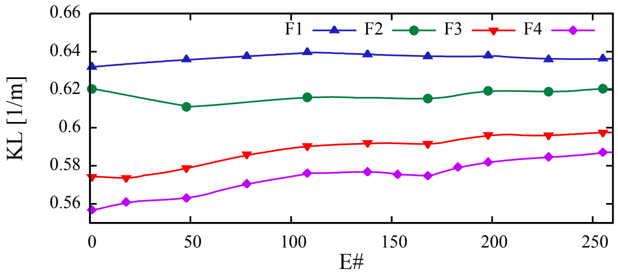

Figure 8: Focusing strength as function of energy.

Using a similar procedure to fix the energy dependence of all possible input parameters, synchrotron and HEBT were commissioned systematically along the following schedule: First, the closed orbit in the synchrotron was corrected on extraction level at the location of the sextupoles. Next, the normalized sextupole strengths were fixed by optimizing angle and phase of the distribution of sextupole strengths. Afterwards, the horizontal machine tune was adjusted by optimizing for extraction efficiency. The amplitude of the synchrotron RF during acceleration was then minimized to avoid a blow-up of longitudinal phase space, which would lead to undesired extraction when ramping up the sextupoles. After fixing extraction, these steps were taken to adjust the beam parameters in the isocenter for each treatment place in turn: First, a coarse correction of beam position was done. Next, the beam width was matched to the set values for each width step by adjusting the quadrupole dublet in front of the treatment place, following the procedure described above. With the quadrupole settings fixed, a final correction of the beam position in the isocenter was performed.

The intensity steps are adjusted by varying the optics in the source line to produce particle loss, keeping constant the vertical width behind the linac. The beam parameters at the treatment place do not depend on intensity, then.

To facilitate the adjustment of input parameters, the ion optics program MIRKO [6] was linked to the accelerator control system via an interface providing access to input parameters and beam diagnostics data. To eliminate width dependent steering effects of the last quadrupole dublet, a new method for correcting beam position based on position measurements in the isocenter with two different optics settings was implemented in MIRKO. Thus, MIRKO could be used for semi automated correction of the beam position and for adjusting the beam width.

OUTLOOK

GSI has completed commissioning of the accelerator to the fixed beam places with protons and carbon. The focus in the HIT project is presently on getting the treatment equipment ready for patient treatment, in which process GSI is not involved. However, GSI is still engaged in the HIT project by taking part in an upgrade program for the injector linac to improve beam intensity [7].

REFERENCES

[1] A. Dolinskii, “The Synchrotron of the Dedicated Ion Beam Facility for Cancer Therapy, proposed for the clinic in Heidelberg”, EPAC 2000, Vienna
[2] U. Weinrich et al., “Commissioning of the Carbon Beam Gantry at the HIT Accelerator”, presentation TUPP134 at this conference
[3] M. Schwickert et al., “Beam diagnostics for Commissioning the HEBT and Gantry Sections of the HIT Medical Accelerator”, presentation TUPC095 at this conference
[4] A. Peters et al., “Spill Structure Measurements at the Heidelberg Ion Therapy Centre”, presentation TUPP127 at this conference
[5] T. Hoffmann et al., “Beam Quality Measurements at the Synchrotron and HEBT of the Heidelberg Ion Therapy Centre”, BIW 2008, Lake Tahoe
[6] B. Franczak, ion optics simulation program MIRKO, GSI, Darmstadt
[7] R. Cee et al., “Intensity Upgrade Programme for the HIT Injector Linac”, presentation TUPP113 at this conference