OPERATIONAL STATUS AND FURTHER ENHANCEMENTS OF THE HIT ACCELERATOR FACILITY

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Abstract

Since November, 15th 2009 patients are treated with protons and carbon ions at the Heidelberg Ion-Beam Therapy Center (HIT). The accelerator system of the facility – two ion sources, an injector linac and a compact synchrotron – is operated in 24/7-mode, 335 days/year with high availability. In this paper the HIT beam time schedule is discussed along the statistics automatically generated by the control system. In parallel, an upgrade program for the accelerator is under way: at first a test bench for a third ion source, later on dedicated to helium beams, will be used to study several ideas to increase the injector performance including an optimized RFQ structure. Furthermore operation mechanisms are under progress to control directly the synchrotron dipole and quadrupole fields as well as to regulate the spill structure – the aim of both developments is to form a uniform and extremely stable extracted beam with high duty cycle.

HIT FACILITY AND OPERATION

Layout of the Accelerator Complex

The core of the Heidelberg Ion-Beam Therapy (HIT) Centre [1] is an accelerator facility designed to optimally support the raster scanning dose delivery method [2] by producing light ion pencil-beams having energies that allow for the treatment of deep-seated tumours.

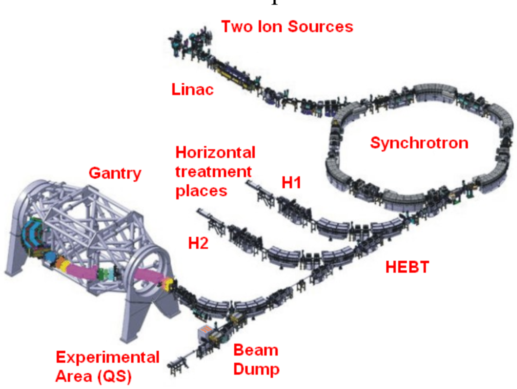

Figure 1: Layout of the HIT Accelerator Facility.

It is comprised of the following subsystems, see Fig. 1:

- Two ECR ion sources for the routine operation of proton and carbon beams at 8 keV/u; other ion species like helium and oxygen can also be produced [3].
- A compact 216 MHz linac consisting of an RFQ and an IH-DTL with end energy of 7 MeV/u for all ions; a foil stripper directly located behind these cavities to produce fully stripped ions.
- A synchrotron of 65m circumference capable to accelerate protons, helium, carbon and oxygen to predefined end energies e.g. for carbon ions from 88 to 430 MeV/u in 255 steps.
- A system of high energy transport lines to serve five destinations: the two horizontally-fixed patient treatment rooms H1 and H2, the Gantry treatment room, an experimental area (QS) and a beam dump equipped with dedicated beam diagnostics.

Operational Status of HIT

After several commissioning steps of the accelerator by GSI and HIT [4] and finally the implementation of the certified medical product IONTRIS by Siemens Health Care in a joint activity of Siemens and HIT [5] the first patients were treated on November, 15th, 2009 [6]. To achieve highest precision in the sub-mm range and to allow for intensity-modulated dose delivery the raster scanning method is used at HIT exclusively [2]. In order to preserve the geometrical accuracy of the dose delivery an accurate patient positioning system consisting of a robotic table, a 3D laser system and a ceiling-mounted robot-imager is needed, see Fig. 2.

Figure 2: Patient positioning in the horizontal treatment room H1 before treatment start.

In the first half year of clinical operation around 100 patients were treated in the first horizontal treatment room H1. Mostly carbon ions were used as can be seen from the statistics displayed in Fig. 3, where all synchrotron cycles sorted by destination and ion species are shown.

Fig. 3 also illustrates that HIT is under full operation now delivering proton and ion beams to all destinations. In parallel to the patient treatment in H1 an upgrade of the IONTRIS-package is under test by Siemens in the second horizontal room H2, gantry commissioning by the HIT staff takes place (see below) and furthermore a broad pre-clinical R&D-program at the experimental cave (QS) with proton and ion beams. During the daily quality assurance of the accelerator settings beam is also sent to the dump,

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which allows simultaneous use of the HIT facilities under full radiation protection in all other places without interaction with machine operation.

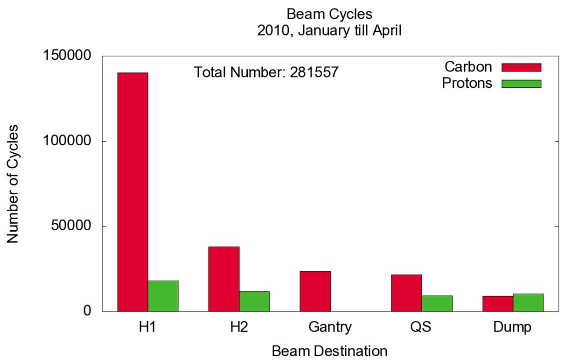

Figure 3: HIT operation statistics, Jan. – April 2010.

The overall operation scheme and performance of the accelerator facility is described by the following facts:

- 335 days of operation per year, interrupted by two shutdowns of two weeks each for maintenance of infrastructure and accelerator subsystems.
- 7/24 operation in three shifts per day with one maintenance shift per week.
- The availability of "beam on target" amounts to about 98%. A retuning of the spill structure and the transport line settings for position and beam radii is only necessary within a span of 2–4 months.

Gantry Commissioning

After some initial studies of the system characteristics the gantry commissioning started again in February 2010 using at first carbon beams for the higher magnetic rigidities from 2.6 up to 6.6 Tm, in a second step later on this will be expanded to proton beams having magnetic rigidities from 1.0 up to 2.3 Tm [7].

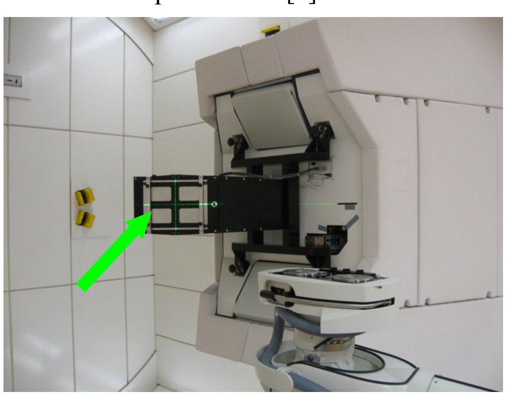

Figure 4: Ion gantry nozzle with adapted fluorescence screen; alignment via laser cross (marked by green arrow).

Using a predefined optics model, first settings for five different carbon energies between 89 and 430 MeV/u and 6 – 10 angles between 0° – 360° were semi-automatically adjusted; see the used measurement set-up at the isocentre position in Fig. 4. The magnet settings for intermediate energies and gantry angle dependent focussing strengths will be calculated from polynomial fit curves for the whole variety of needed beam properties, i. e. 255 energy steps, 4 beam radii and 36 predefined gantry angles. This amounts to a total number of 36,720 parameter combinations for one ion species, excluding 10 intensity steps and intermediate gantry angles. With the results reached so far the beam position varies within a few mm on the fluorescence screen placed at the isocentre. These variations will be reduced by further modification of the matching at the gantry entrance point and, as a further option, by gantry angle dependent corrections of the beam position in near future; the remaining transversal residuals can be corrected in real-time using beam position information generated in the patient monitors that is fed back to the controls of the raster scanning system.

HIT UPGRADE AND ENHANCEMENT PROGRAMME

Third Ion Source Branch

Based on strong medical arguments we decided in 2009 to install a third ion source at HIT to offer helium beams regularly for patient treatment in near future in order to reduce the lateral penumbra of the dose distributions produced by proton beams. An open question still to be investigated is the choice between ^{3}He and ^{4}He; for the latter due to larger mass the lateral scattering in tissue is relevantly reduced. As contaminations with other ion species in the source, e.g. $^{16}O^{8+}$ have to be kept below 1 ‰, a series of high-resolution ion beam spectra with different gases and mixtures under different conditions needs to be studied to define production rates of wanted and unwanted isotopes. These measurements will be carried out at a test bench which is under installation at HIT using the components of the third ion source branch.

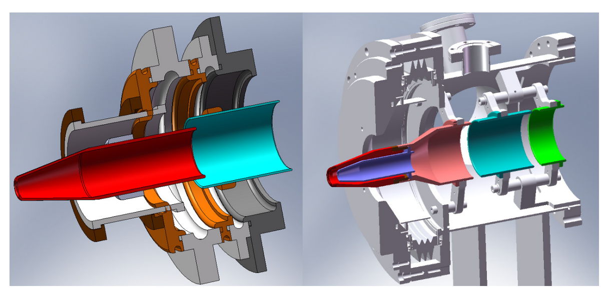

Figure 5: Extraction system in use at HIT (left) and new design under test (right).

Test Bench for Linac Upgrade

To overcome existing current limitations of the linac an upgrade programme was initiated at HIT, which addresses the following topics:

- Increase of the beam currents from the ion sources and simultaneous reduction of the emittance: A new extraction system with three electrodes and enhanced mechanical characteristics was designed and built, see Fig. 5. Intense simulations carried out in before showed decreased emittances, in particular for hydrogen and helium and enhanced space charge compensation along with improved alignment capabilities [3].

- Test of a more compact LEBT set-up with higher acceptance and minimized space charge effects; tests of a pepper pot measurement system [8].
- Investigation of the new RFQ with an enhanced electrode design and optimized alignment [9]; see Fig. 6 for the actual installation status.

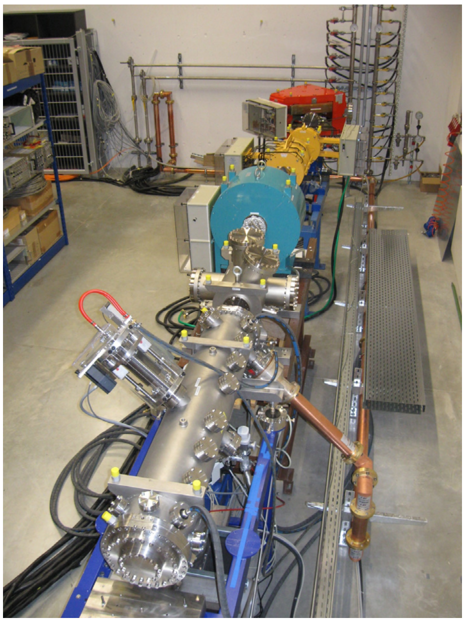

Figure 6: Test bench under installation at HIT for ion source, LEBT and RFQ optimization measurements.

Magnetic Field Control in the Synchrotron

Due to hysteresis and eddy current effects in the main dipole and quadrupole groups in the HIT synchrotron additional latencies and conditioning procedures had to be added to the machine cycle to ensure stable beam qualities for the patient treatment scanning system [10]. A feed-back control system for the magnetic fields is under installation and will be operational this year to reduce cycle periods by up to 30% [11].

Spill Structure Control by Active Feedback

A further aim for the future accelerator operation consists in enhancing the functionality and efficiency; the slow extraction at HIT is mainly induced by the transverse RF knockout exciter, having a variable but predefined reference-value for its amplitude curve [12]. As the phase-space distribution of the particles is not homogeneously and can vary slightly from pulse to pulse, intensity-fluctuations of the extracted beam appear during one spill (Fig. 7 left).

To keep the intensity constant on the pre-defined level, it is planned to implement a feedback loop. The intensity signal provided by an ionisation-chamber within the BAMS (Beam Applications Monitoring System of IONTRIS) located directly in-front of the patient is used to quickly adapt the amplitude of the knockout exciter during extraction. Fig. 7 (right) shows a first attempt for a carbon beam with the highest energy of 430 MeV/u. Last imperfections like the spike at the spill beginning should be improved in near future together with an enhanced bandwidth of the control loop for further reduction of beam fluctuations.

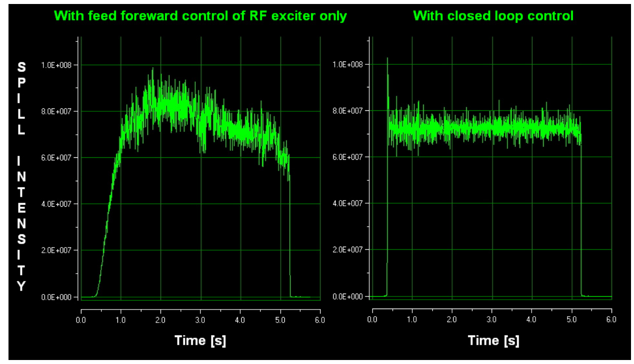

Figure 7: Spill structure measurements with an ionization chamber – preliminary results of closed loop control of the RF knockout exciter (right).

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