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Chapter 42

The accelerator facility of the Heidelberg Ion-Beam Therapy Centre (HIT)

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1 Introduction

In 1946, Robert Wilson at FermiLab laid the foundation for hadron therapy with his famous article in *Radiology* about the therapeutic interest of protons for treating tumors [1]. He combined the discovery of the Bragg peak by William Henry Bragg in 1904 [2] with the fast inventions and development in accelerator technology in nineteen thirties and forties [3]. Only eight years later, the first patient treatments were started in 1954 at the Radiation Laboratory in Berkeley with proton, deuteron and helium ion beams from the 184 inch synchrocyclotron. From the sixties to the end of the eighties of the 20th century particle radiotherapy was based exclusively on accelerator facilities developed for nuclear physics, with beam-lines and treatment rooms adapted to the needs of radiotherapy. Then the first hospital based installations occurred: at first, the MC60 62.5 MeV proton cyclotron, delivered by Scanditronix, operating at the Clatterbridge Oncology Centre (UK) since 1989 and then from 1990 a dedicated 250 MeV proton synchrotron, developed by FermiLab at Loma Linda University (California, USA), the first dedicated clinical facility equipped with three rotating gantries [4].

Inspired by the Berkeley experiences biophysics studies were started at GSI in Germany in the late seventies, using the beam of the heavy ion linac UNILAC (<20 MeV/u). From 1989 high energetic beams were available from the SIS18 expanding the possibilities for in-depth experiments — 30 cm penetration depth in water demands a $^{12}C^{6+}$ beam of 430 MeV/u. In parallel, technical developments took place to create 3D conformal therapy options. While at PSI, Switzerland, a spot scanning proton gantry was built up [5], using a 1D magnetic pencil beam scanning plus passive range stacking (digital range shifter), in parallel at GSI a 2D magnetic pencil beam raster scanning system plus active range stacking (energy, spot size, intensity) in

Fig. 1. The HIT building with the cupreous front embedded in the Heidelberg hospital ring (left: National Centre for tumor diseases (NCT); Head Clinics and Medical Hospital in the background; right: Children's Clinics).

the accelerator was developed [6]. From 1993 a pilot project at GSI was set-up using this technology for treating around 450 patients with carbon beam from 1997–2008 [7, 8].

Based on the experiences from this installation and a first proposal for a clinical facility in 1998, the technical design study was worked out and after evaluation the HIT project started in 2002 [9, 10]. The building was constructed from 2003–2007, the accelerator installation started in 2006.

2 Beam parameters

The HIT accelerator facility and its beam parameters were driven by the raster scan technique of delivering an optimized 3D dose distribution into a predefined treatment volume, which is converted into a series of N × 2D fluence distributions, i.e. the number of stopping particles per cm^2. Namely, the treatment volume is virtually dissected into a series of iso-energy slices

Table 1. Requested accelerator parameters for the HIT facility.

Ion species	p, ^{4}He, ^{12}C, ^{16}O
Penetration depth (in water)	20–300 mm
Energies	p: 48–221 MeV, He: 51–221 MeV/u, C: 88–430 MeV/u, O: 103–430 MeV/u
Max. beam intensities (particles per spill)	p: 4×10^{10}, He: 1×10^{10}, C: 1×10^{9}, O: 5×10^{8}
Intensity variation	$(10^{-3}–1) \times N_{\max}$
Beam spot sizes	4–10 mm FWHM (at full energy)
Max. irradiation field	$20 \times 20\,\mathrm{cm}^2$

(IES). Each IES will then be irradiated using, wherever possible, a single synchrotron cycle to scan the focused beam along a precalculated pattern of beam positions. Following these requirements, together with biological demands (like the necessary penetration depth), the requested beam parameters were deduced, which are shown in Table 1. From the beginning, the treatment and/or research both with low LET (p, He) and high LET (C, O) ions were foreseen.

3 General layout of the HIT facility

The Heidelberg Ion-Beam Therapy (HIT) Centre has two patient treatment rooms with fixed horizontal beams and one with the worldwide first ion beam gantry providing 360° angular freedom. The accelerator facility is comprised of the following subsystems, see Fig. 2:

- Two ECR ion sources for the routine operation of proton and carbon beams at 8 keV/u; in the meantime a third ion source was added to produce especially helium beams [11].
- A compact 216.8 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 is designed to produce fully stripped ions.
- A synchrotron of 65 m 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.

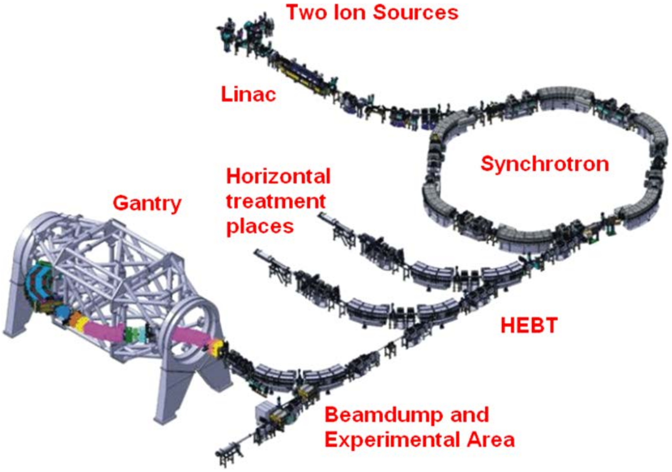

Fig. 2. Layout of the HIT accelerator facility (status 2007), in the meantime a third ion source for parallel helium production was added.

- Besides the three patient treatment rooms the high energy transport lines serve two additional destinations, an experimental area for research activities and a beam dump equipped with dedicated beam diagnostics, which can be operated independently.

In order to guarantee a high degree of reliability the design of most of the components was rather conservative and no operation up to the technical limits was foreseen. Most of the proposed operation modes at the different sections are well established. The special requirements of the raster scan method (beam properties, safety aspects), evaluated and successfully tested at GSI, were fully embedded in the layout.

4 The accelerator chain in detail

4.1 *Injector linac*

The injector consists of three 14.5 GHz permanent magnet ECR ion sources from PANTECHNIK with a modified extraction system by HIT [11]; the requested beam intensities are listed in Table 2. After selecting the desired ion species with the slits following the 90° analyzing magnet, a cylindrical beam shape along the straight section downstream of the switching magnet is produced by a quadrupole triplet. After adjusting the beam center along the whole LEBT with the steerer magnets, a transmission of typically 80–100% is achieved up to the RFQ entrance.

Table 2. Specified ions and intensities behind the 90° analyzing magnet.

Ion	$I/\mu\text{A}$	$U_{\text{source}}/\text{kV}$
$^{3}\text{H}^{1+}$	700	24
$^{4}\text{He}^{2+}$	500	24
$^{12}\text{C}^{4+}$	200	24
$^{16}\text{O}^{6+}$	150	21.3

The 216.8 MHz injector linac comprises a 400 keV/u radio frequency quadrupole accelerator (RFQ) of 1.4 meter length and a 20 MV IH-type drift tube linac (IH-DTL), built as a 3.8 m long milled steel tank [12]. The cavities are fed by a 200 kW amplifier from THOMSON for the RFQ and a 1.5 MW amplifier from BERTRONIX using a THALES tetrode TH 526 B for the IH-DTL tank.

4.2 *Synchrotron*

The synchrotron is the key to the enormous variety of beam parameters provided by the HIT accelerator [13]. Its maximum magnetic rigidity is 6.6 Tm, corresponding to carbon ions at 430 MeV/u and 30 cm range in water. Three bumper magnets allow for multi-turn injection; six dipoles, twelve quadrupoles and two sextupoles are used for the ion beam optics and two redundant cavity gaps are fed by HITACHI amplifiers in the frequency range from 1–7 MHz for acceleration. The beam is extracted horizontally using 3rd order resonance extraction above $Q_h = 5/3$ by RF noise excitation (so-called "knock-out" extraction). The synchrotron RF is kept active during extraction to smoothen the spill microstructure. 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 three times per second, thus enabling the irradiation of disjoint iso-energy slices of the target volume in a single acceleration cycle. In the first years of operation, care was 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. Meanwhile, the synchrotron dipoles are also driven using magnetic field control, the four quadrupole groups will follow soon [14].

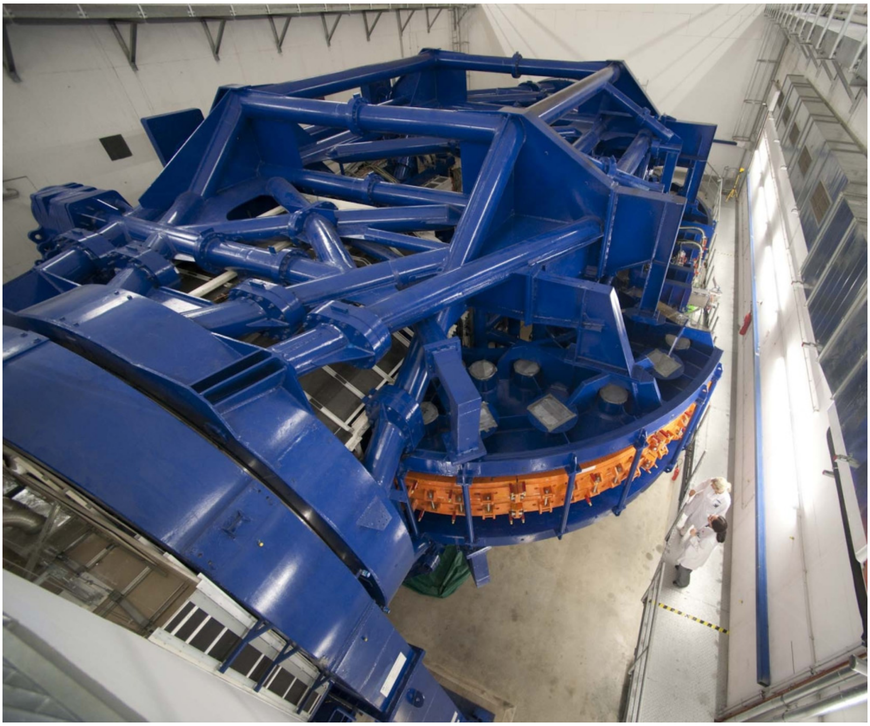

Fig. 3. The HIT 360° ion beam gantry.

4.3 *Gantry*

Besides the two horizontal treatment rooms (see Fig. 2), where the clinical operation started in November 2009 and September 2010, the HIT facility houses in addition the worldwide first 360° rotatable ion beam gantry — Figure 3 gives an impression of the mechanical structure of the HIT gantry, more details on the beam transport assembly can be found in [15]. In order to keep the gantry design compact, the two scanner magnets are located upstream to the 90° dipole so ion optical characteristics of this dipole have to be strongly considered.

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 $20 \times 20\,\mathrm{cm}^2$ in the iso-center); (b) an optical setting keeping dispersion in iso-center within small limits, and keeping beam focus and position independent 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 (equalised at the gantry entrance) for a single energy. 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 dependence 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 the control system) accounts for scaling of the process data with the magnetic and electric rigidity for different energies. Other energy-dependent effects have to be compensated by semi-automated adjustment of components, i.e. quadrupoles, dipoles, steerers 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. Beam size and position in the iso-center are measured either with a viewing target and camera mounted on the rotating nozzle of the gantry or a multi-wire proportional chamber (MWPC) fixed on a rotatable mechanics installed on the patient positioning robot.

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 (about 10–15), foci (4), and gantry angles (about 8–12) making up for about 1–3% of the overall library of beam characteristics. The achieved procedures ensure that the beam size ranges within a ±25% limit around 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.

After two longer commissioning phases [16] the first patients were treated at the gantry with protons from October 2012 and with carbon beams from November 2012, see Fig. 4 for an illustration of the patient positioning procedure. The completion of the beam line settings for all angles of proton and carbon beams, which have to pass all necessary medical qualification steps, took until the beginning of 2014.

5 Operational aspects of a particle therapy facility

Besides designing, manufacturing, installation and commissioning of the accelerator and medical systems a lot of further aspects have to be taken into account for a successful management of such a particle therapy facility:

- Economics: In contrast to a research institute, a public (university) hospital has to operate cost-covering, whereas private clinics aim at generating substantial yields. Therefore the investment costs of such a particle therapy facility (about 100–150 M€) as well as the running annual costs of about 20–25 M€ for staff, capital charges, energy and maintenance costs, etc., need to be financed through refunds of costs by the health insurances. With a treatment capability of about 1000 patients per year after running up, a reimbursement of about 20–25 k€ per patient is thus necessary — in the case of HIT the numbers are a little bit more relaxed, because of a government aid of 50% for the investment costs. (All data are valid for Europe, the conditions in the US and Asia may differ.)

- Operations: For the most part, the particle therapy facility belongs to the radio-oncological section of a hospital. The daily therapy workflow with 50–80 patients demands a high degree of availability of the dose delivery system, including the whole accelerator. Only a well-trained technical team can guarantee the reliable operation and short reaction times in case of failures; see Section 6 for a detailed discussion.
- Safety and regulatory aspects: A particle therapy facility is a medical product and has to comply with comprehensive legal requirements, which also influence the operation and the maintenance procedures of the accelerator part, see Section 7 for more details.

6 24/7 accelerator operation at 335 days per year

The HIT accelerator core team hired in 2004 and 2005 only comprised of six employees. The team grew by about a factor of three in the period from mid-2006 to mid-2008 in order to operate the facility, at first in two shifts from Monday to Friday, stepwise expanding to a 24/7 mode. Continuous training by the GSI commissioning team on one side as well as intense briefing on the supplied devices by the contracted companies was organized besides "training on the job". This was necessary because only 1/3 of the employed persons worked in the accelerator field before or had to be retrained as most of the HIT equipment was newly designed or has undergone substantial changes in contrast to the original GSI designs. Within one year it was possible to operate the whole accelerator chain by the newly formed HIT team [17].

The accelerator shifts consist of two operators coming from the three technical teams. The physicists among the HIT accelerator crew are also responsible for retuning the optic parameters in case the performance deviates from the predefined limits for intensity, beam position and foci at the treatment location. These conditions are checked every morning. Although the intensity adjustment is done regularly in time intervals of some days, retuning of sections of the linac, synchrotron or the beam lines is only

Fig. 4. Patient positioning procedure at the HIT gantry treatment place — for rotation of the gantry the closed folding ground floor is bent down.

necessary every two to six months. The stability is mainly influenced by stable temperatures of ambient air and cooling water.

Up until the end of 2011, two longer shutdowns of 2–4 weeks per year were used for maintenance and new installations as well as single device service shifts every 2–3 weeks. During these relatively long maintenance intervals the patients have to be phased out, resulting in “ramping down” the patient numbers before the shutdown and “ramping up” afterwards; this reduces the available time for patient treatment. Together with the medical management of HIT the following maintenance slots were defined from 2012.

(a) Six maintenance blocks with four days length (from Thursday to Sunday), two of the four days reserved for service only, followed by the restart of the accelerator, retuning of ion source and beam optics, if necessary, and the comprehensive quality assurance of the medical treatment systems.
(b) Maintenance shifts on Monday morning once every three weeks between the service blocks for shorter (visual) inspections, smaller repairs and update works.

Within these boundary conditions all regular maintenance tasks and deferrable repairs must be carried out to guarantee around 335 operation days of the HIT accelerator per year.

All maintenance activities are documented in detail. Those which could influence the properties of the medical product are directly checked, before the patient treatment is again resumed; the other documents have to be transmitted within a fixed time interval. Nearly all documents are double-checked from the technical point of view as well as on quality management aspects, e.g. completeness and hints to upcoming defects. The aim is to deduce additional pre-emptive maintenance measures.

7 Safety and regulatory aspects

The whole accelerator chain forms an industrial product as part of a medical product, which in the case of HIT is certified as an in-house manufactured device. To handle this complex situation, clear interfaces were defined between the accelerator devices and the medical systems, which apply the planned dose distributions in a correct and qualified manner to the patient. At first, a secure protocol and handshake between the accelerator control system (ACS) and the therapy control system (TCS) — part of the IONTRIS system from SIEMENS — was necessary to link both worlds by dedicated and safe interconnects. In this way it is ensured that the beam characteristics requested by the TCS are safely produced by the accelerator. In addition, the personnel safety system (PSS) has a dedicated interface to the TCS. Major components of this interconnection are secure interruptions of magnet power supplies, e.g. for switching dipoles leading the beam to the treatment rooms. Furthermore the TCS reads out all position information of vacuum valves and beam diagnostic devices in the HEBT to guarantee that the correct energy is delivered to the patient treatment place, unaffected by any matter in the beam line. Interfaces like these ensure that the beam can be redundantly stopped in case of emergencies. The functions of all these safety systems have to be checked regularly, especially after maintenance procedures [18]. All these measures are part of a comprehensive quality management system to comply with all legal requirements.

8 Status and perspectives

In March 2014 the two-thousandth patient was treated at HIT and routine operation is fully established with up to 60 patients per day. This is based on more than 98% availability of the accelerator throughout the planned operation periods, short maintenance times and, first of all, an excellent cooperation of highly-motivated technical and medical teams at HIT.

Increasing numbers of treated patients per year — 2012: 560, 2013: 640, 2014: 670, 2015: 700 planned — are the result of a continuous improvement process in addition to the daily operation. Further upgrades like spill feedback and magnetic field control in the synchrotron have been implemented, which have led to significant shortened dose delivery times [19, 20]. Treatment-plan-specific spill feedback was implemented in 2014 [21]. A big potential for faster treatment is offered by the multiple-energy operation within one synchrotron cycle, presently studied at HIMAC [22]. HIT has seized this suggestion and plans a similar prototype installation using its very flexible control system in the near future. However a full implementation will take some years.

Altogether it was a long, but very successful route from the first HIT proposal in 1998 at GSI to the full routine operation in Heidelberg about 15 years later. But there are still a lot of improvements possible in the whole chain from the accelerator facility to the dose delivery systems. HIT as the first clinically based installation in Europe producing proton and ion beams will sustain the necessary progress in the field of particle therapy to give more patients the chance to be treated with this highly effective method. A next step is already done, the University Clinics in Heidelberg took over the responsibility for the Marburg Ion-Beam Theraphy Center [23], where patient treatment started in October 2015.

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