

COMMISSIONING AND OPERATION OF THE INJECTOR LINACS FOR HIT AND CNAO

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Abstract

The Heidelberg Ion-Beam Therapy Centre (HIT) is the first dedicated clinical synchrotron facility for cancer therapy using high energy proton and ion beams (C, He, and O) in Europe. The accelerator consists of a 7 MeV/u, 217 MHz injector linac and of a 430 MeV/u synchrotron. Installation and commissioning of the linac were performed in three phases for ion sources and LEBT, 400 keV/u RFQ, and 20 MV IH-type drift tube linac. The initial commissioning of the linac was finished successfully in December 2006, the commissioning of the synchrotron and the high energy beam lines was finished for both fixed-beam treatment places in December 2007. HIT intends to be ready for patient treatments by the end of 2008. The results of the linac commissioning are reported as well as the experience of more than one year of operation. To provide optimum conditions for patient treatment, an intensity upgrade program has been initiated for the linac. A copy of the HIT linac is presently being installed at the Centro Nazionale di Adroterapia Oncologica (CNAO) in Pavia, Italy. The status of the CNAO linac is also reported.

INTRODUCTION

The number of accelerator facilities dedicated to radiation therapy using high energy proton and heavy-ion beams – also called hadrontherapy – is remarkably growing during the last years [1]. Since the first dedicated clinical centres started operation in Loma Linda, California, and at HIMAC / NIRS in Chiba, Japan, a number of technical improvements have been developed, namely raster-scanning techniques as well as compact synchrotron facilities for heavy-ion treatment and heavy-ion gantries. Also the role of industry has changed and turn-key hadrontherapy facilities are now offered by a number of commercial companies, e.g. IBA, HITACHI [2], ACCEL / VARIAN, or SIEMENS / DANFYSIK [3]. In particular for heavy-ion synchrotron facilities, size and

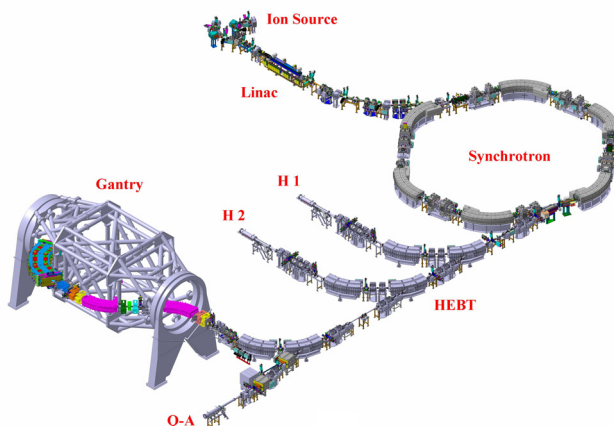


Figure 1: Layout of the HIT accelerator facility.

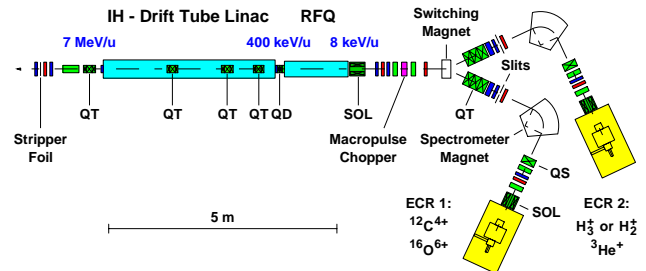


Figure 2: Layout of the HIT injector linac. QS, QD, and QT means quadrupole singulet, doublet and triplet, respectively, SOL means solenoid magnet; focusing and steering magnets (green), profile grids and viewing screens (red), and beam current monitors (blue).

Table 1: Main design parameters at the HIT linac exit

Design ion	$^{12}\text{C}^{4+}$
Operating frequency	216.816 MHz
Final beam energy	7 MeV/u
Beam pulse length	$\leq 300 \mu\text{s}$
Beam repetition rate	$\leq 5 \text{ Hz}$
Pulse current after stripping	100 μA ($^{12}\text{C}^{6+}$)
Transv. norm. emittances (95 %) ¹	0.8 $\pi \text{ mm mrad}$
Exit energy spread ¹	$\pm 0.3 \%$
Total injector length ²	$\approx 13 \text{ m}$

¹ straggling effects in the stripper foil not included

² including ECRIS, LEBT and foil stripper

availability of suitable injector linacs are of major technical and economical interests. Whereas compact injector linacs are commercially available for proton synchrotron facilities [2], new compact heavy-ion injectors based on IH linacs have been developed at NIRS [4][5] and at GSI (in close collaboration with the Institute of Applied Physics (IAP) at Frankfurt University) [6][7][8] during the last ten years.

In Europe, two clinical heavy-ion facilities are currently being commissioned: the Heidelberg Ion-Beam Therapy Centre (HIT) [9][10] in Germany and the Centro Nazionale di Adroterapia Oncologica (CNAO) [11][12] in Pavia, Italy. An additional centre is being constructed by SIEMENS / DANFYSIK [3] in Marburg, Germany. All three centres will use the GSI linac design.

The HIT accelerator facility is shown in Fig. 1. It consists of two all permanent magnet ECR ion sources (ECRIS) of the SUPERNANOGAN type, a 7 MeV/u linac injector, and a compact synchrotron of about 65 m circumference to accelerate ions to final energies of 48 – 430 MeV/u. The beam is distributed by the high energy beam transport lines (HEBT) either to two fixed horizontal beam treatment places (H1, H2), to the isocentric heavy-ion gantry, or to a fixed horizontal beam quality-assurance place (QA) for dosimetry as well as

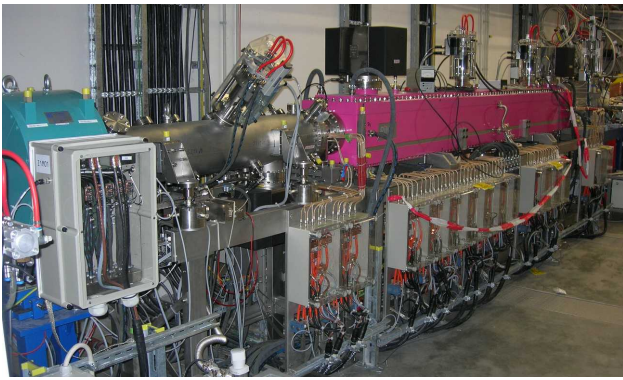


Figure 3: The HIT linac with solenoid magnet (left), RFQ, and IH linac during commissioning.

R&D activities. All four target stations are equipped with active raster-scanning beam delivery systems.

The linac injector (Fig. 2) comprises the ion sources, the low energy beam transfer lines (LEBT), a 400 keV/u Radio Frequency Quadrupole (RFQ) accelerator [13][14], and a 20 MV IH-type Drift Tube Linac (IH-DTL) [6][15][16][17]. Both, RFQ and IH-DTL, are operated at 216.8 MHz. Remaining electrons are stripped off the ions in a thin stripper foil behind the linac. Table 1 gives the design parameters for carbon ion beams, Fig. 3 shows the HIT linac. The linac (RFQ, intertank section, IH-DTL) has a length of about 5.4 m only, the complete injector including ion sources, LEBT, and the foil stripper tank a length of about 13 m.

COMMISSIONING PHASES

After construction of the HIT building during 2004 and 2005 and installation of the accelerator infrastructure (water cooling systems, cables, etc.), the installation of the HIT accelerator started in November 2005. The commissioning of the linac injector was performed during 2006 [6][7] in three consecutive steps for ion sources and LEBT, RFQ, and IH-DTL, followed by synchrotron and HEBT in 2007 and 2008 [10] (Table 2). Beam perform-

ance of proton and carbon ion beams had reached a level enabling patient treatment at both fixed beam treatment places H1 and H2 in December 2007. Commissioning of the gantry is still ongoing [18].

In order to measure the beam parameters behind the different linac sections, a mobile beam diagnostics test bench was used for LEBT, RFQ, and IH linac commissioning. After installation of each section, this diagnostics bench was placed at the very end of this section. The bench was equipped with all instrumentation needed to measure the relevant beam characteristics, i.e. a beam current transformer, a horizontal and vertical slit-grid emittance measurement device, and a Faraday end-cup. After commissioning of a section, the test bench was removed, the subsequent section was installed, and the test bench was reinstalled in a new configuration.

For commissioning of RFQ and IH-DTL three phase probes were included to measure the beam energy via the time-of-flight (TOF) technique. To preserve the experimental resolution at higher beam energy, the IH-DTL set-up was extended with respect to the RFQ set-up. The different test bench designs are shown in Fig. 4.

Table 2: HIT commissioning milestones

Nov 05 – Mar 06	ECRIS, LEBT	installation, testing of components
April – May 06	ECRIS	successful beam commissioning
May – July 06	LEBT	
July – August 06	RFQ	installation, rf commissioning
September 06		beam acceleration to 400 keV/u
October 06	IH-DTL	installation
November 06		rf commissioning
December 06		beam acceleration to 7 MeV/u
February 7 th , 2007	LINAC, Synchrotron	50 % Linac performance, 1 st turn in synchrotron (C ⁶⁺)
March 23 rd , 2007	HEBT	1 st accelerated beam in treatment places
December 16 th , 2007	H1 & H2	Beams in treatment quality (p + C ⁶⁺)

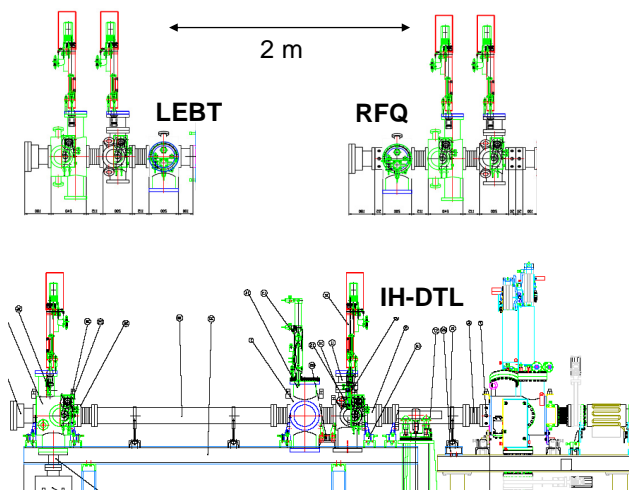


Figure 4: Mobile beam diagnostics benches used during beam commissioning of the different linac sections. The beam enters from the right.

ION SOURCES AND LEBT

Each branch of the LEBT (Fig. 2) features a solenoid magnet behind the ion source, a single quadrupole lens to match into the 90° analyzing dipole, the analyzing slit, and a quadrupole triplet, which restores the cylindrical symmetry of the ion beams in front of the RFQ. Ion species can be quickly changed by a switching magnet. Since DC ion beams are extracted from the sources, up to 300 μs long beam pulses are formed by an electrostatic macropulse chopper. Finally, a second solenoid is used to focus the ion beams into the RFQ.

All specified analyzed ion currents were achieved during the on-site ion source acceptance tests at HIT in 2006 as listed in Table 3 [19]. During routine operation, about 140 μA are produced for ¹²C⁴⁺ and more than 2 mA for ¹H₂⁺. Stable operation conditions and long runtimes

Table 3: Ion species, specified and measured analyzed electrical ion currents, and ion source potentials V_{source}

Ion	$I / \mu\text{A}$ (spec.)	$I / \mu\text{A}$ (meas.)	$V_{\text{source}} / \text{kV}$
$^1\text{H}_2^+$	1000	> 2000	16
$^1\text{H}_3^+$	700	≈ 710	24
$^3\text{He}^{1+}$	500	≈ 840	24
$^{12}\text{C}^{4+}$	200	≈ 200	24
$^{16}\text{O}^{6+}$	150	≈ 170	21.3

with only two maintenance periods per year are achieved. See Ref. [20] for details regarding ion source operation experience at HIT.

Many breakdowns of the ion sources occurred because of problems with the microwave generators. To reach long-term stable operation conditions with the oxygen beam, the original extraction system was revised by PANTECHNIK. The bias pipe caps of the ion sources were replaced by water-cooled ones.

Matched-beam settings were established for the LEBT during commissioning in 2006 [6]. After the 90° dipole the ion beams are transported to the end of the LEBT with transmissions $\geq 90\%$ (except for hydrogen beams).

A strong influence of the field strength of the solenoid for matched injection into the RFQ on beam steering and emittance was observed. An off-line field mapping revealed a strong transverse field bump with a relative strength up to 1.3% with respect to the main solenoid field. A new solenoid magnet with better field quality was produced by SIGMAPHI and installed at HIT in August 2007 [21][22].

Transverse beam emittances up to 300π mm mrad were measured at the LEBT exit in 2006 – depending on ion source and solenoid settings [6]. The design value is 180π mm mrad. Because of severe problems at RFQ injection, additional measurements were performed in front of and behind the second solenoid in August 2007 for detailed investigations of the matching to the RFQ [20][22]. Emittances of $150 - 200\pi$ mm mrad were measured for $150\mu\text{A}$ $^{12}\text{C}^{4+}$ beams and for $^3\text{He}^+$, and $60 - 70\pi$ mm mrad for $^{16}\text{O}^{6+}$. No severe dependence of the emittances on the solenoid field strength was observed at that time. In addition, beam profile measurements using a viewing screen were performed behind the second solenoid (Fig. 5). For low focusing strength of the solenoid a hollow beam was observed, whereas for larger focusing strength separated beam spots are visible. Simulations of ion beam extraction and transport can explain at least some of these observations [23][24].

RFQ

The RFQ was designed, assembled and RF tuned in the group of Prof. Schempp at IAP. After first beam tests at IAP [13], rf tests with an rf power up to 200 kW were performed successfully at GSI as well as the final low-level tuning of the field flatness. Prior to the commissioning in Heidelberg an RFQ beam test bench using proton beams had been set up at GSI [14] in order to verify the output beam energy by TOF measurements and to check

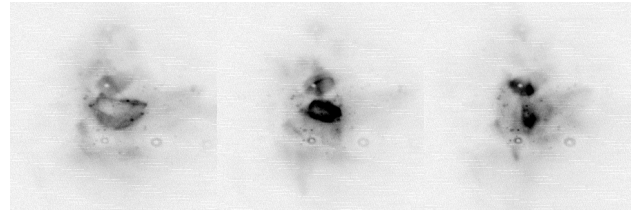


Figure 5: 2D beam profiles of a $^{12}\text{C}^{4+}$ beam behind the second solenoid, i.e. close to RFQ injection. The solenoid strength is 7, 10 and 12 1/m, respectively (from left to right). Nominal strength for operation is around 10 1/m.

the correct function of the two-gap rebuncher drift tube set-up integrated into the RFQ tank.

First C^{4+} beams at 400 keV/u were observed at HIT in September 2006. Right after the RFQ a pair of steerers and a quadrupole doublet provide for transverse matching to the IH-DTL. The mobile diagnostics bench was directly installed behind the doublet during RFQ commissioning.

The RFQ working point was determined by measuring beam energy and transmission as functions of the applied rf input power. Figure 6 shows the beam energy measured behind the RFQ versus the tank voltage. The working point is defined by the tank voltage corresponding to the design beam energy of 400 keV/u. An rf pulse power of 190 – 200 kW is needed for $^{12}\text{C}^{4+}$ operation.

A strong dependence of the beam steering on the rf

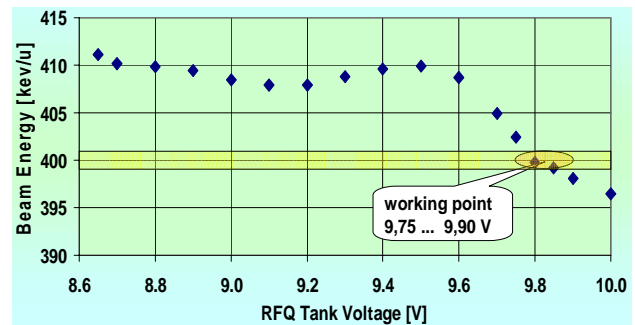


Figure 6: Measured RFQ output energy as function of the (scaled) tank voltage for $^{12}\text{C}^{4+}$ operation.

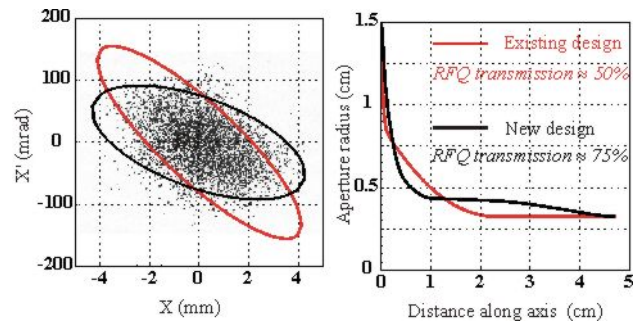


Figure 7: Results of beam dynamics simulations of the linac front-end using the DYNAMION code [22][25]. Left: RFQ acceptance for the original RFQ design (red) and for the new design of the input radial matcher (IRM) (black) together with a particle distribution deduced from beam measurements. Right: Comparison of the original and of the new design of the IRM.

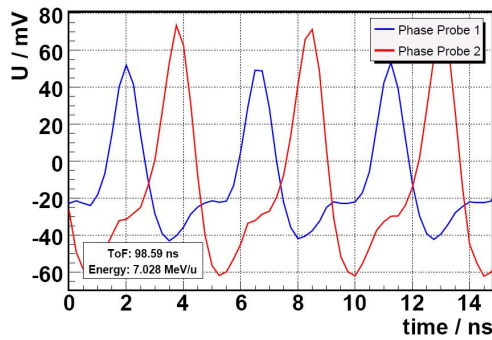


Figure 8: Phase probe signals of a $^{12}\text{C}^{4+}$ beam behind the linac [29]. The two probes are mounted at a distance of 3.61 m corresponding to a bunch number of 21. The signal resolution is limited by the acquisition electronics (1 GHz analogue bandwidth, 4 GS/s sampling rate, 8 bit).

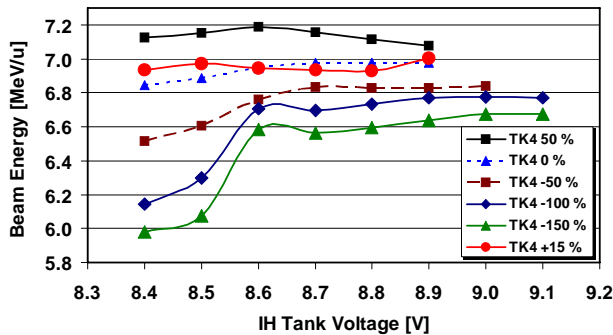


Figure 9: Final beam energy behind the linac as function of the (scaled) IH tank voltage for different settings of one of the RF plungers (for $^{12}\text{C}^{4+}$).

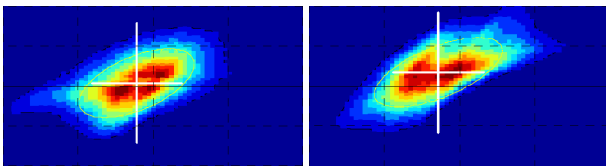


Figure 10: Measured horizontal (left) and vertical (right) beam emittances for a $^{12}\text{C}^{6+}$ beam behind the stripper foil. The coordinate axis range is ± 10 mm in each plot and the range in x' and y' is ± 4 mrad. The normalized $4 \times$ rms emittance is 0.67π mm mrad in the horizontal plane and 0.71π mm mrad in the vertical plane, respectively. The measured emittance growth in the stripper foil was about 25 % (horizontally) and 9 % (vertically).

voltage was observed. Significant misalignment of the RFQ electrodes was partly corrected during RFQ commissioning but a deformation of the RFQ electrode structure observed by telescope measurements could not be corrected. An unsatisfying beam transmission as low as about 30 % was achieved during commissioning in 2006 for carbon and hydrogen ion beams.

Detailed beam dynamics simulations of the linac front-end, consisting of solenoid and RFQ, using the DYNAMION code and particle distributions deduced from emittance measurements at the LEBT revealed a considerable mismatch at RFQ injection [25]. In addition, as shown by these simulations, the deformation of the RFQ structure

causes a significant reduction of the RFQ acceptance. To improve the matching and to prevent deformation of the RFQ structure, the RFQ design was revised at GSI applying a new shape of the input radial matcher (Fig. 7) as well as a more rigid RFQ tank with larger wall thickness and improved suspension [21][22]. The aim is an overall linac transmission above 60 %. This seems to be reasonable with the new RFQ design (Fig. 7). At present, beam tests of the new RFQ are being performed at DANFYSIK in Denmark [22]. Installation in Heidelberg is planned for 2009.

IH LINAC

The 3.8 m long IH-cavity includes three internal magnetic quadrupole triplet lenses and applies the KONUS beam dynamics concept [26]. It was delivered to GSI in summer 2005 followed by copper plating, final drift tube assembly, and vacuum testing. After rf tuning especially with respect to field flatness [17][27][28], the cavity was installed at HIT in October 2006.

Figure 8 shows phase probe signals as used for high-precision measurements of the beam energy behind the linac. Figure 9 shows the measured beam energy as function of the IH tank voltage for different settings of the rf plunger in the last drift tube section. Since this plunger is highly effecting the voltage distribution along the drift tube structure, it has a significant influence on the final beam energy. Finally, the position of the plunger was fixed in the position used to measure the red spots in Fig. 9. An rf pulse power around 830 kW is needed for $^{12}\text{C}^{4+}$ operation.

The final normalized beam emittances measured as 0.7π mm mrad (Fig. 10) agree well with the values expected from beam dynamics simulations [8][16]. During routine operation, C^{4+} currents of 45 – 50 μA are achieved in front of the foil stripper, and up to 60 μA C^{6+} at synchrotron injection. For protons, about 350 μA are typically achieved behind the foil stripper. By comparing the beam currents measured during RFQ and IH-DTL commissioning, respectively, a beam transmission above 90 % along the IH-DTL is estimated.

Similar measurements as shown in Fig. 8 are being performed during routine operation to check the linac beam energy as well as the energy loss in the stripper foil.

CNAO LINAC STATUS

A contract between CNAO and GSI was signed in 2004 regarding the construction and commissioning of the CNAO injector linac, which is mainly a copy of the HIT linac. GSI delivers technical support for all linac components [27][30]. In particular, copper-plating, assembly, RF tuning, and pre-tests of RFQ, IH-DTL, and a debuncher cavity were performed at GSI. All components were delivered to CNAO and are ready for installation and commissioning in Pavia, which will be supported by GSI.

In contrast to the HIT linac, the CNAO linac will be installed inside the synchrotron ring [11][12]. The LEBT has been installed completely and first beam emittance

measurements behind the LEBT have been performed recently using a special beam diagnostics test bench. After completion of the LEBT tests, RFQ installation and commissioning will start end of October this year.

The CNAO SUPERNANOGAN ion sources have been further improved with respect to the HIT sources [31]. In particular, an optimised extraction system and tuneable signal generators that drive the microwave amplifiers are used. Higher beam currents and very high beam stabilities have been achieved, and smaller beam emittances are expected.

CONCLUSIONS AND OUTLOOK

The HIT linac was commissioned successfully with carbon and hydrogen ion beams in 2006. Parameter sets for routine operation were established. High linac reliability and availability as well as stable linac beam parameters provided stable conditions during commissioning of synchrotron, HEBT, and treatment systems. The achieved beam quality behind the linac allows for efficient beam injection into the synchrotron using a multi-turn injection scheme. Beam intensities of 4×10^8 ions per spill for C^{6+} and 1×10^{10} for protons are routinely available at the treatment places [10] – well suited to start patient irradiation.

Whereas installation and commissioning of the HIT accelerator were performed under the direction of GSI, routine operation is now done by the HIT operating team 7 days a week and 24 hours per day. The present activities at HIT focus on getting the treatment equipment ready for patient irradiation, in which process GSI is not involved. HIT intends to be ready for patient treatments by the end of 2008.

Ion beam intensities are currently limited by the performance of the linac front-end system (ECRIS, final solenoid, RFQ): low brilliances of the ECRIS beams accompanied by strong aberration effects of the solenoid focusing into the RFQ are causing significant mismatch to the RFQ acceptance. To overcome these limitations and to reach full design performance at the treatment stations (1×10^9 ions per spill for C^{6+} and 4×10^{10} for protons), an intensity upgrade program has been initiated. A new RFQ has been designed and built and will be installed at HIT in 2009, and further improvements of the ion sources are planned [20].

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