COMMISSIONING OF THE LINAC FOR THE HEIDELBERG HEAVY ION CANCER THERAPY CENTRE (HIT)

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Abstract

A clinical accelerator facility for cancer therapy using energetic proton and ion beams (C, He and O) is currently under commissioning at the Radiologische Universitätsklinik in Heidelberg, Germany. It consists of two ECR ion sources, a 7 MeV/u linac injector, and a 6.5 Tm synchrotron to accelerate the ions to final energies of 50 – 430 MeV/u. The linac comprises a 400 keV/u RFQ and a 7 MeV/u IH-DTL operating at 216.8 MHz. The commissioning of the linac was performed in three steps for the LEBT, the RFQ, and the IH-DTL. For this purpose a dedicated beam diagnostics test bench was used. In this contribution the procedures and the results of the successful beam commissioning of the linear accelerator in the year 2006 are reported.

INTRODUCTION

The accelerator chain of the heavy ion cancer therapy centre (HIT) [1] at the Radiologische Universitätsklinik in Heidelberg, Germany consists of two ECR ion sources, a 7 MeV/u linac injector and a 6.5 Tm synchrotron to accelerate the ions to final energies of 50 – 430 MeV/u.

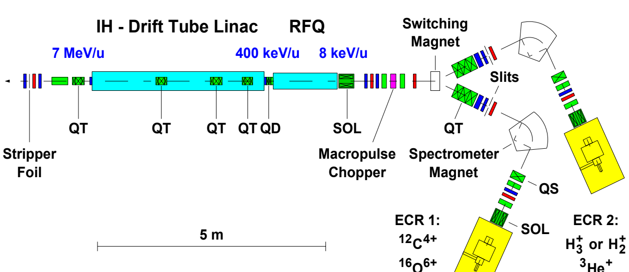

Figure 1: Layout of the HIT injector linac [2]. QS, QD, and QT means quadrupole-singulet, -doublet and -triplet, respectively, SOL means solenoid magnet; focusing and steering magnets (green), profile grids and tantalum screen (red), and beam current monitors (blue).

Table 1: Main design parameters at the HIT linac exit

Design ion	$^{12}C^{4+}$
Operating frequency	216.816 MHz
Final beam energy	7 MeV/u
Beam pulse length	300 µs
Beam repetition rate	5 Hz
Pulse current after stripping	100 eµA ($^{12}C^{6+}$)
Transverse emittances (95%) [1]	0.8 µm (norm.)
Exit energy spread [1]	±0.3%
Total linac length [2]	≈ 13 m

[1] straggling effects in the stripping foil not included
[2] as shown in Fig. 2, i.e. including ECRIS, LEBT and foil stripper

Table 2: Milestones of the HIT linac commissioning

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 2007	Linac	50% performance, C^{6+} injection into synchrotron

The injector linac [2] shown in Fig. 1 comprises the low energy beam transfer lines (LEBT), a 400 keV/u Radio Frequency Quadrupole (RFQ) accelerator [3], and a 7 MeV/u IH-type Drift Tube Linac (IH-DTL) operating at 216.8 MHz [2][4]. Table 1 gives the design parameters for carbon beams. The commissioning of the linac injector was performed in three consecutive steps for the LEBT, the RFQ, and the IH-DTL as listed in Table 2.

MOBILE TEST BENCH

In order to measure the beam performances behind the different linac sections a mobile beam diagnostics test bench was used. After installation of each section, this diagnostics bench was placed at the very end of this section. The bench comprised all instrumentation needed

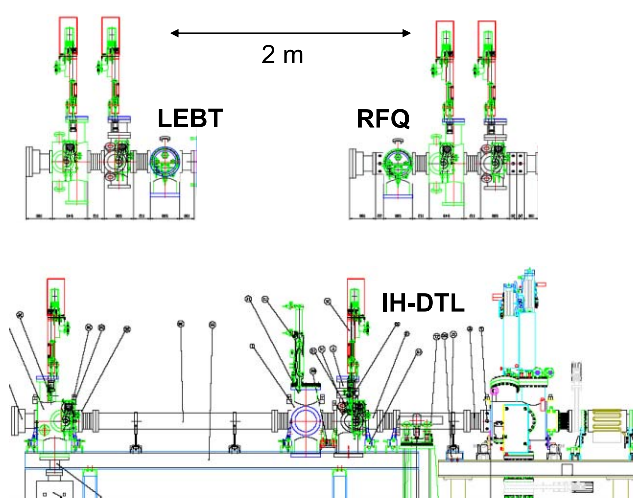

Figure 2: Mobile beam diagnostics benches used during beam commissioning of the different linac sections. The beam enters from the right, respectively.

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 the commissioning of a section finished the next linac section was installed, and the set-up was reinstalled behind the next section to be commissioned.

For the commissioning of the RFQ and of the IH-DTL three phase probes were included to measure the beam energy via the time-of-flight (TOF) technique. To preserve the measurement resolutions at higher beam energy, the IH-DTL set-up was extended with respect to the RFQ set-up. The different set-ups of the bench are shown in Fig. 2.

LEBT

The two-branch LEBT (Fig. 3) comprises a solenoid magnet directly behind each ion source, a single quadrupole lense to match into the 90° analyzing dipole followed by a quadrupole triplet, a switching magnet, and a solenoid in front of the RFQ.

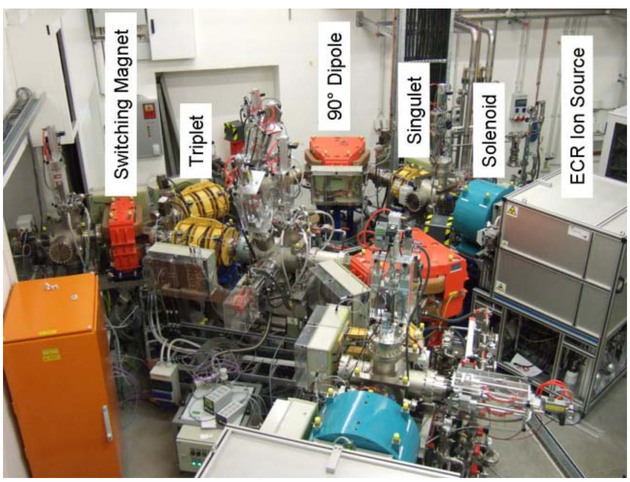

Figure 3: The two LEBT branches of the HIT linac.

Table 3: Ion species, specified as well as measured beam intensities behind the analyzing dipoles

Ion	I / µA (spec.)	I / µA (meas.)	U_{source} / kV
$^{1}H_3^{+}$	700	≈ 710	24
$^{3}He^{1+}$	500	≈ 840	24
$^{12}C^{4+}$	200	≈ 200	24
$^{16}O^{6+}$	150	≈ 170	21.3

The goal of the LEBT commissioning was to provide the matched-beam settings for the ion species listed in Table 3. After the spectrum analyzing bend the ion beams could be transported to the end of the LEBT with a transmission of ≥ 90%. 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. At the LEBT exit normalized transverse emittances up to 1.2 µm were measured. The design value is 0.75 µm. A detailed report on the LEBT commissioning is given in Ref. [5].

RFQ

The RFQ cavity was delivered to GSI in March 2005. Rf-testing with an rf power up to 200 kW was 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 [6] in order to verify the output beam energy by TOF measurements and to check the correct function of the two-gap rebuncher drift tube set-up integrated into the RFQ tank. The test bench also allowed for testing of the final rf amplifier, the control system, and the beam diagnostics components.

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

The RFQ working point was determined by measuring the beam energy and transmission as functions of the applied rf input power. Fig. 4 shows the measured beam energy at the RFQ exit as function of the applied tank voltage. The working point is defined by achieving the design output energy. An rf pulse power of 190 – 200 kW is needed for $^{12}C^{4+}$ operation.

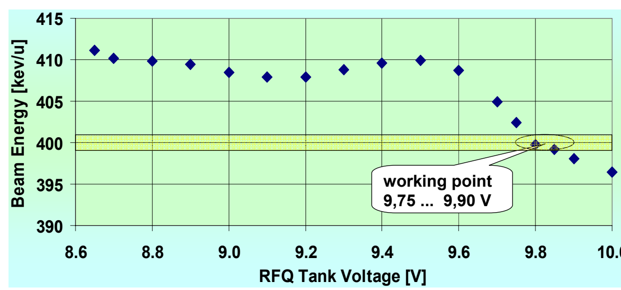

Figure 4: Measured RFQ output energy as function of the (scaled) tank voltage for $^{12}C^{4+}$ operation.

A strong dependence of the steering on the rf voltage was observed. Accordingly, the steerers at the RFQ exit had to be set for each tank voltage individually. Significant misalignment of the RFQ electrodes was partly corrected during RFQ commissioning.

IH-DTL

The 3.8 m long IH-cavity (Fig. 5) includes three internal quadrupole triplets and applies the KONUS beam dynamics scheme [7]. 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 [8] the cavity was installed on site in October 2006.

The working point of the IH cavity is given by the rf input power and -phase with respect to the preceding RFQ. Fig. 6 shows the measured linac beam energy as function of the rf voltage and the rf phase. An rf pulse power around 830 kW is needed for $^{12}C^{4+}$ operation.

The final beam emittances measured as 0.7 µm (norm.) agree well with the design values [4]. C^{4+} currents of

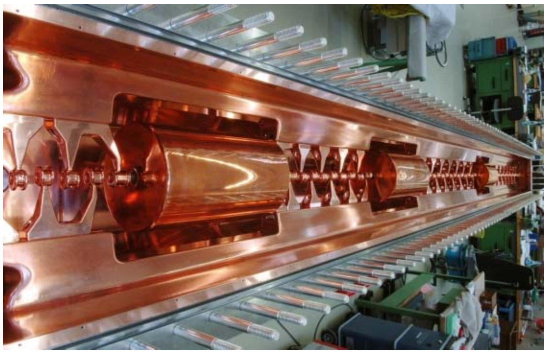

Figure 5: Open IH cavity after copper plating and installation of the drift tubes; the beam enters from the left.

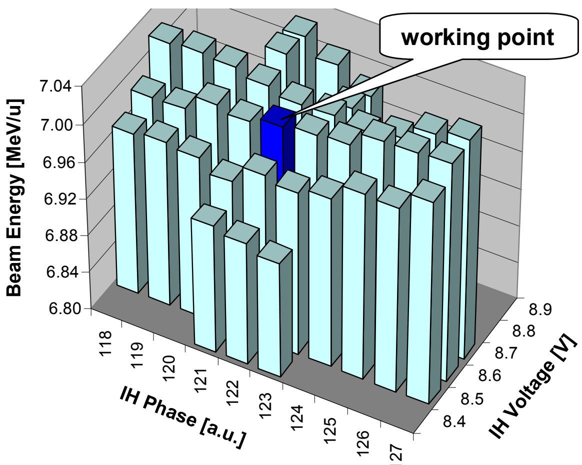

Figure 6: Final beam energy behind the linac as function of the (scaled) IH tank voltage and its rf phase (for $^{12}C^{4+}$).

35 to 40 eμA are achieved routinely in front of the foil stripper, resulting in C^{6+} currents of about 50 eμA at synchrotron injection.

CONCLUSIONS AND OUTLOOK

Finally, the linac could be commissioned successfully with carbon and hydrogen ion beams. Parameter sets for routine operation of the linac were defined. These include design optics for setting up the beam focusing as shown in Fig. 7. Beam commissioning of the synchrotron and later on of the treatment systems started in February 2007 using C^{6+} as well as proton beams. First C^{6+} beam was delivered to the treatment caves in March 2007. Start of patient irradiation is envisaged for winter 2007/2008.

The 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. The misalignment of the RFQ structure results in a reduction of the RFQ acceptance. Finally, the beam divergence behind the RFQ is much larger as expected, causing strong beam losses in the subsequent doublet.

To enhance the performance of the linac front-end and to reach the design intensities an upgrade program has been defined. The solenoid magnet in front of the RFQ will be replaced in a shutdown period in summer 2007. A new design of the RFQ electrodes with an improved radial input matcher is in progress. It is also intended to reduce the strong beam divergence at the RFQ exit. A new RFQ tank has been built with larger wall thickness and an improved suspension in order to increase the rigidity of the RFQ and to reduce the misalignment and deformation of the RFQ structure. The new RFQ should be available for installation in Heidelberg in 2008.

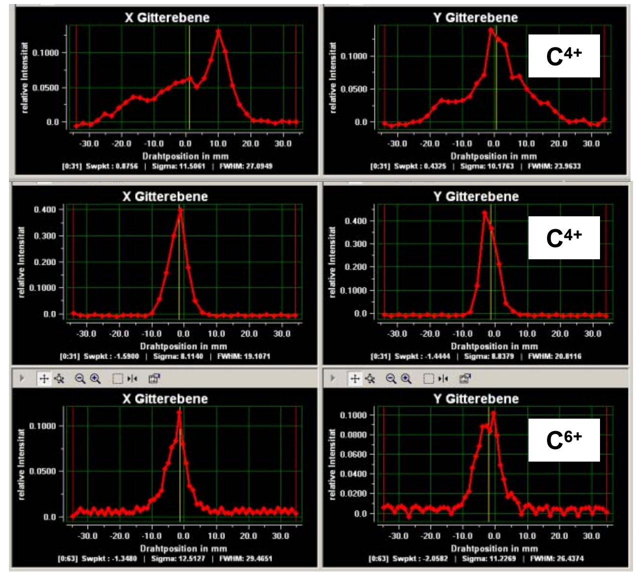

Figure 7: Horizontal (left) and vertical (right) LEBT beam profiles (top), behind the IH-DTL, and before synchrotron injection.

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