LINAC COMMISSIONING AT THE ITALIAN HADRONTHERAPY CENTRE CNAO

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Abstract

The 7 MeV/u, 216.8 MHz injector linac at CNAO is a copy of the linac at the Heidelberg Ion-Beam Therapy Centre (HIT) and comprises a 4-rod type RFQ and an IH-type drift tube linac. A collaboration between CNAO and GSI was established for delivery and commissioning of the linac and for delivery of complete beam diagnostics systems. RFQ and thereafter IH linac were successfully commissioned on site in Pavia in 2009, both with H_3^+ and C^{4+} ion beams. Beam currents of 115 µA C^{6+} and 1.2 mA protons were achieved. Results of the linac commissioning are reported as well as a comparison to the HIT linac.

INTRODUCTION

The Centro Nazionale di Adroterapia Oncologica (CNAO) is presently under commissioning in Pavia, and will be the first clinical synchrotron facility for treatment of deeply seated tumours with high energy proton and carbon ion beams in Italy [1, 2]. The CNAO accelerator comprises two permanent magnet ECR ion sources (SUPERNANOGAN) [3], a 7 MeV/u injector linac, and a 400 MeV/u synchrotron. In 2004, a collaboration between CNAO and GSI was established for delivery and commissioning of the linac [4]; and the collaboration agreement between CNAO and INFN was extended in 2005 to linac installation and commissioning. The layout of the injector including ECR ion sources and LEBT is shown in Fig. 1. The linac (Fig. 2, Table 1) is a copy of the linac at the Heidelberg Ion-beam Therapy centre (HIT) [5, 6]. The 400 keV/u 4-rod type RFQ, and the 20 MV IH-type drift tube linac (IH-DTL) were developed in collaboration by GSI and by the Institute for Applied Physics (IAP), Goethe-University, Frankfurt am Main, Germany. GSI supervised the manufacturing of the linac and of its technical systems, performed copper-plating, assembly, and tuning [7] (together with IAP), and delivered complete beam diagnostics (BD) systems for linac and MEBT [8]. The RFQ was tested at GSI with proton beams together with the BD systems prior to delivery to CNAO [4, 9].

Table 1: Main Linac Design Parameters

Design ion	$^{12}C^{4+}$
Operating frequency	216.816 MHz
RFQ injection beam energy	8 keV/u
Final linac beam energy	7 MeV/u
Beam pulse length	≤ 300 µs
Beam repetition rate	≤ 5 Hz
Transv. norm. emittances (95 %) [1]	0.8 π mm mrad
Exit beam energy spread (95 %) [1]	≤ ±0.4 %
Total linac length [2]	6.95 m

[1] straggling effects in the stripper foil not included
[2] including RFQ, IH-DTL, and foil stripper section

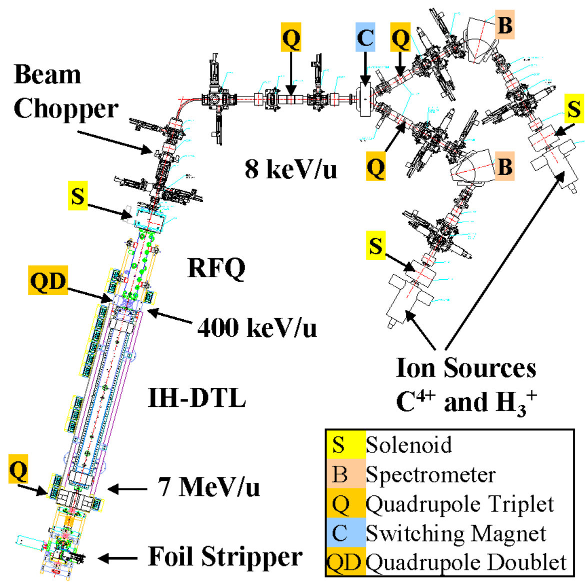

Figure 1: Layout of the CNAO injector.

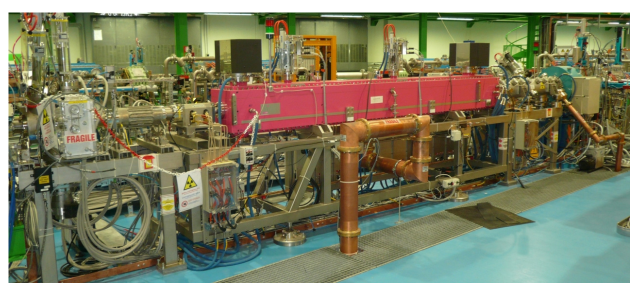

Figure 2: Complete linac with RFQ (right), IH linac (center), and foil stripper section (left).

COMMISSIONING PHASES

Linac installation and commissioning in Pavia took place during 2008/09 as listed in Table 2. H_3^+ and C^{4+} ion beams have been used for all beam commissioning phases. Final acceptance tests of all linac RF amplifiers as well as commissioning and beam tests of the MEBT were performed during autumn 2009 (including a debuncher resonator and BD devices delivered by GSI). The first turn in the synchrotron was achieved in December.

Three different beam diagnostics test benches were used behind LEBT [10, 11], behind RFQ (including the

Table 2: Commissioning Schedule and Milestones

Nov 07 – Dec 08	Linac Components	Installation & tests of RF systems & lines, power supplies, BD systems, linac control system etc.
May 08 – Jan 09	Ion Sources & LEBT	Final installation & beam tests down to LEBT end
Nov 08 – Jan 09	RFQ & ITM [1]	RF conditioning & tests at park position
Feb – Mar 09		Mounting at final position & full RF conditioning
Mar 12th – Apr 3rd		Beams at 400 keV/u
Apr – Jun 09	IH Linac & Foil Stripper	Installation, RF cond. & tests w/o beam
Jun 18th – Jul 15th		1st 7 MeV/u beams
Jul – Nov 09	MEBT & Debuncher	Completion of line, RF tests & conditioning
Nov 16th – Dec 09		H_3^+ beams at MEBT end, linac operation training
Dec 09	Synchrotron	First turn in synchrotron

[1] ITM = Inter-Tank Matching section, see text

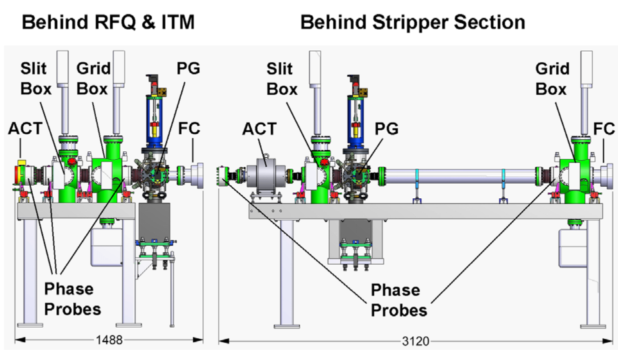

Figure 3: Beam diagnostics test benches used during beam commissioning of RFQ (left) and IH-DTL (right). Beam direction from left to right. ACT = fast beam Current Transformers, FC = Faraday Cup, PG = Profile Grid.

inter-tank matching section (ITM) comprising a pair of steerer magnets and a magnetic quadrupole doublet), and behind the stripper section, respectively, and allowed for beam current, profile, and emittance measurements. For RFQ and IH-DTL commissioning, the test benches comprised also a set of three phase probes for accurate time-of-flight beam energy measurements (Fig. 3). The slit and grid boxes contained two stepper-motor driven slits and two grids, respectively, for independent emittance measurements in the horizontal and in the vertical plane. To preserve the experimental resolution at higher beam energies, the IH-DTL set-up was extended with respect to the RFQ set-up.

RFQ

As an example, Fig. 3 shows beam energies measured behind the RFQ vs. tank voltage for different ion beams. The required beam energy for injection into the IH linac of 400 keV/u is reached for all ion species at the same RFQ working point – corresponding to a RF pulse power of 195 – 200 kW. Different LEBT beam energies (7.5,

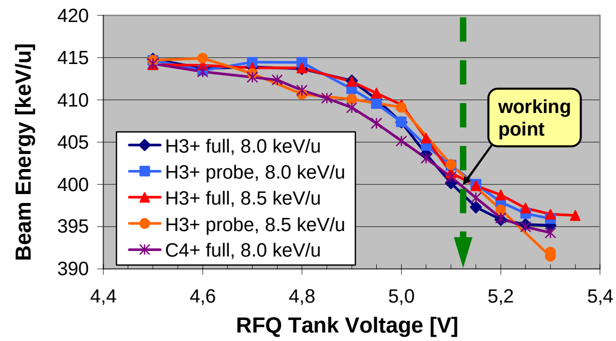

Figure 4: RFQ output beam energy as function of the scaled tank voltage for different ion beams (see text).

8.0, and 8.5 keV/u) were investigated. Finally, the design value of 8.0 keV/u was kept. To check the transverse acceptance of the RFQ and to optimize beam matching, H_3^+ beams with reduced emittances ("probe beams") were prepared by cutting the beam with adjustable slits in the LEBT. The probe beam position in phase space at RFQ injection was changed using the LEBT steerers, and the transmission along the RFQ was recorded. The measured acceptances agree well to simulation results, although the achieved transmission (up to ~70 % for probe beams) is lower than expected. For full beam currents, transmissions along the RFQ (including solenoid and ITM) up to 60 % were reached for H_3^+ as well as for C^{4+} beams for matched injection. Detailed LEBT and RFQ commissioning results are reported in Ref. [10, 11].

IH LINAC

More than 140 measurement series including numerous amplitude, phase, and emittance scans were performed with the IH linac. Different LEBT beam energies, RFQ settings, and IH tank RF plunger configurations were investigated. The linac was optimized with respect to high beam transmission, minimum beam emittances and optimized bunch signal amplitudes from the phase probes. Figure 5 shows the linac beam energy measured with the final setting for C^{4+} ion beams vs. IH tank voltage and phase. The final working point is marked in dark blue. It corresponds to about 7.2 MeV/u at a RF pulse power of

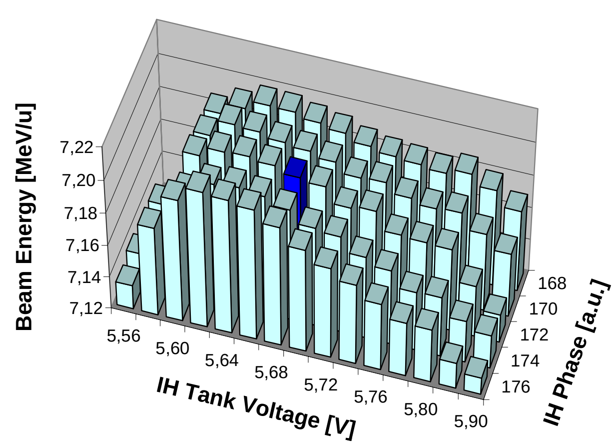

Figure 5: Beam energy of C^{4+} beams measured behind the IH linac as function of the scaled tank voltage and phase.

Table 3: Measured max. beam currents and transmission

Ion Species	Beam Current / µA			Linac Transmission [1]
	LEBT	Linac	Stripped	
C^{4+} / C^{6+}	~170	~85	~115	50 %
H_3^+ / p	1030	415	1200	40 %

[1] Including solenoid, RFQ, inter-tank section, IH-DTL, and external quadrupole triplet lens

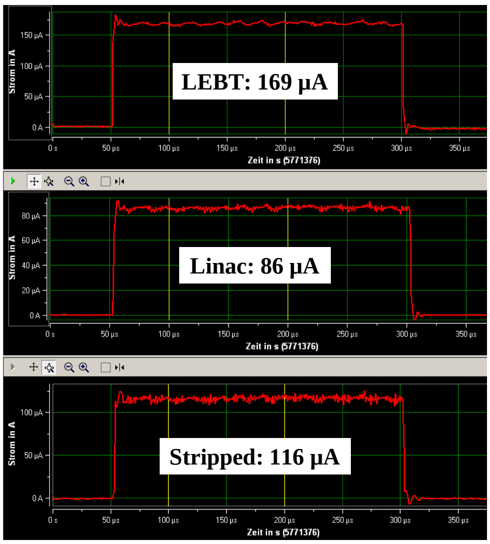

Figure 6: Measured C^{4+} / C^{6+} beam currents.

~910 kW. Table 3 summarizes maximum beam currents achieved at the LEBT upstream of the solenoid focusing into the RFQ, behind the IH linac, and behind the stripping foil. Design beam currents (120 µA for C^{6+} and 670 µA for protons) were reached and even exceeded. Usually, the H_3^+ ion source was operated at lower beam currents (~700 µA at LEBT end), yielding slightly higher linac transmission (~45 %, ~900 µA protons). A total linac transmission (incl. solenoid, RFQ, and IH linac) up to ~50 % was achieved for C^{4+}. Figure 6 shows examples of 250 µs carbon ion beam pulses.

The quadrupole settings behind the linac were optimized to achieve minimum horizontal beam diameters at the stripping foil in order to reduce emittance growth effects in the foils. Measured beam emittances for the final settings are listed in Table 4 and are shown in Fig. 7. Twiss parameters are similar in both transverse planes.

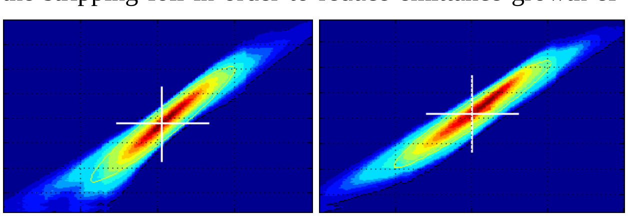

Figure 7: Horizontal (left) and vertical (right) proton beam emittances measured ~1 m behind the stripping foil. Axis ranges are ±10 mm and ±8 mrad, respectively.

Table 4: Measured beam emittances (4 × rms for ~90 % of the beam current) behind the stripping foil, and emittance growth in the foil (for ~70 % of the particles)

Ion Species	$\varepsilon_{4\times\text{rms},\,90\%}$ / π mm mrad		Emittance Growth	
	horizontal	vertical	hor.	vert.
C^{6+}	5.2	4.1	3 %	3 %
protons	6.4	6.0	7 %	36 %

COMPARISON TO THE HIT LINAC

A couple of improvements were achieved at CNAO with respect to the HIT prototype: Tuneable microwave frequency generators and a further optimized extraction system at the ion sources yielded higher beam currents and smaller emittances [3]. The beam diagnostics test bench used behind the LEBT was designed in order to provide for emittance measurements at nominal solenoid excitation [10, 11], which was not possible at HIT. Together with measurements of the RFQ acceptance using probe beams, an optimized beam matching to the RFQ could be achieved. Contrary to HIT, only little beam losses along the inter-tank matching section and only very small steering effects were measured behind the RFQ, probably due to improved alignment of the 4-rod structure. Finally, about two times higher C^{6+} beam currents and roughly four times higher proton beam currents were achieved behind the CNAO linac as compared to HIT.

CONCLUSIONS

Linac beam commissioning was successfully concluded by the CNAO-GSI-INFN collaboration and design beam currents were achieved – although the linac transmission is below the design value. The measured beam emittances agree well with expected values. Operating parameters have been established for the complete linac. Finally, twenty CNAO staff members were trained in linac operation in November 2009 – marking the end of the GSI services fixed in the CNAO-GSI contract.

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