STATUS OF LINAC BEAM COMMISSIONING FOR THE ITALIAN HADRON THERAPY CENTER CNAO

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Abstract

The CNAO (Centro Nazionale di Adroterapia Oncologica), located in Pavia (Italy), is a dedicated clinical synchrotron facility for cancer therapy using high energy proton and Carbon beams. The 400 MeV/u synchrotron is injected by a 216.8 MHz 7 MeV/u linac composed by a low energy beam transport (fed by 2 ion sources), a 400 keV/u 4-rod type RFQ and a 20 MV IH-DTL. The commissioning of the two ECRIS ion sources and the low-energy line was successfully completed at the end of January 2009 reaching the proper beam conditions for injection into the RFQ. After installation and conditioning, the RFQ was commissioned with beam by the GSI-CNAO-INFN team in March 2009. The beam tests results are presented and compared to the design parameters.

INTRODUCTION

The CNAO [1] (Centro Nazionale di Adroterapia Oncologica) is the Italian center for deep hadrontherapy. It will deliver treatments with active scanning both with proton and Carbon ion beams. The accelerator complex (Fig. 1) is based on a 25 m diameter synchrotron capable of accelerating carbon ions up to 400 MeV/u and protons up to 250 MeV. Four treatment lines, in three treatment rooms, are foreseen in the first stage. In one of the three rooms a vertical and a horizontal fixed beam line are provided, while in the other two rooms the treatment will be administered with horizontal beams only.

The injection chain is based on a copy of the linac already working at HIT center [2, 3, 4], whereas the upstream components are similar but not identical. The linac was designed by GSI and IAP Frankfurt. At CNAO GSI also delivered technical support for installation, commissioning and integration of all technical systems, including control system [5, 6].

The injector is positioned inside the synchrotron ring itself, to save space and to better exploit the two non-dispersive regions in the synchrotron.

The Injector

The linac injector (Fig. 2) comprises the two ECR Ion Sources (ECRIS), the Low Energy Beam Transfer lines (LEBT) at 8 keV/u, a 400 keV/u Radio Frequency Quadrupole (RFQ) accelerator [7], and a 20 MV IH-type Drift Tube Linac (IH-DTL) [8] to reach the synchrotron injection energy (7 MeV/u). Both RFQ and IH-DTL are operated at 216.8 MHz; their overall length is 5.4 m. Beam pulses are ≤ 300 μs long at a repetition rate ≤ 5 Hz. At the end a stripping station breaks up H_3 molecules into protons or strips electrons from the Carbon ions. The total injector length is about 19 m.

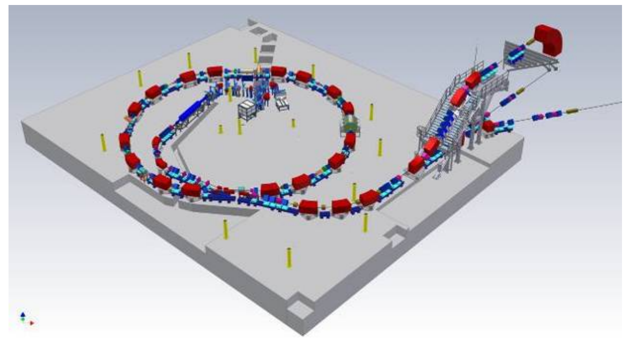

Figure 1: Bird's eye view of the CNAO complex.

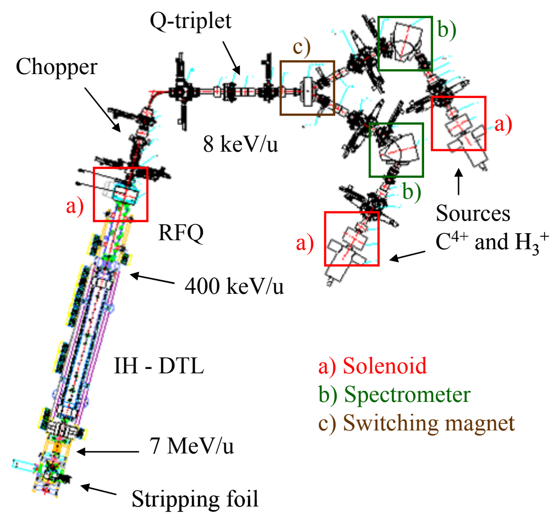

Figure 2: Layout of the CNAO injector.

Two ECRIS of the Supernanogan family have been built by Pantechnik [9] under the supervision of INFN/LNS and they were optimized for H_3^+ and C^{4+} extracted beams ($A/q = 3$, $V_{ext} = 24$ kV). Triggered by previous experiences gained at INFN/LNS, further R&D was carried out on the optimization of the extraction gap distance [10] and on the use of a tuneable signal generator that drives the main travelling wave tube amplifiers. As a result, it was possible to extract steadily a current of

1.1 mA of H_3^+ and 250 μA of C^{4+}, much more than the requested values (see Tab. 1). For this reason it was decided to reduce the plasma electrode hole diameter to 6 mm resulting in a smaller total normalized emittance, namely 0.5 π mm mrad..

Table 1: Injector Main Parameters

Sources Specifications	
Extraction Voltage	24 kV
Current H_3^+	>700 μA
Current C^{4+}	>200 μA
Transv. norm. emitt. (95%)	< 0.75 π mm mrad
LINAC Parameters	
Operating frequency	216.816 MHz
Final beam energy	7 MeV/u
Beam pulse length	≤ 300 μs
Beam rep. rate	≤ 5 Hz
Transv. norm. emitt. (95%)	0.8 π mm mrad
Exit energy spread	±0.3%
Total injector length	~19 m

COMMISSIONING PHASES

The buildings construction started in autumn 2005 and now it has been completed along with the installation of the accelerator infrastructure (water cooling systems, cables, etc.). Installation of the CNAO accelerator started in May 2008 after the ECRIS commissioning [11] and by January 2009 the full characterization of the LEBT was performed. At the end of January the RFQ was installed, RF conditioned and commissioned with beam in March [12]. The IH-DTL was installed in April and at the moment it is under RF conditioning (see Table 2).

Table 2: CNAO Commissioning Milestones

	From	To	Section	Activity
2008	May	July	Source I	Test Source, LEBT installation and test
2008	September	Jan. 09	Source II LEBT+TB0	Commissioning with beam
2009	February	March	RFQ+TB2	Installation
2009	25th Feb.	12th Mar.	RFQ	RF Conditioning and test
2009	12th Mar.	3rd April	RFQ	Commissioning with beam
2009	April	May	IH+TB3	Installation
2009	18th May	17th June	IH	RF Conditioning and test
2009	18th June	15th July	IH	Commissioning with beam

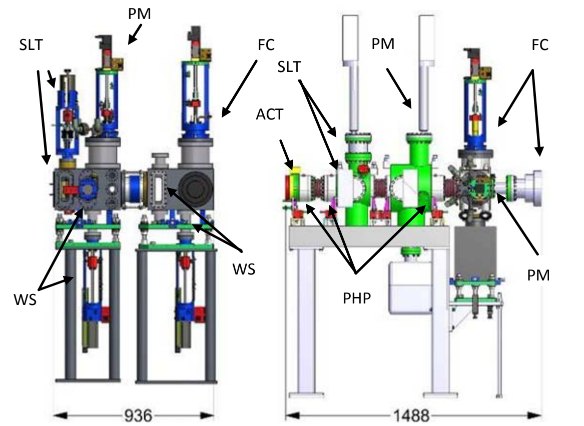

Figure 4: TB0 and TB2 layout. The beam enters from the left. Legend: ACT = Alternate Current Transformer, FC = Faraday Cup, PM = Profile Grid, PHP = Phase Probe, SLT = Emittance Slit, WS = Wire Scanner.

The Test Benches

Three modular beam diagnostics test benches (TB) were designed in order to measure the beam parameters (current, profiles and transverse emittance) behind the 3 different injector sections LEBT (TB0), RFQ (TB2) and IH-DTL (TB3). After installation of each section, the diagnostics bench is placed at its end and then removed only once the machine tests have been completed; the subsequent section is installed and the test bench is mounted in a new configuration.

In TB0 (Fig. 4) DC devices designed by CNAO and AC diagnostics from GSI are installed in order to measure the characteristics of both DC and chopped beam, whereas in TB2 and TB3 only AC devices are mounted. Thanks to the use of a Wire Scanner (WS) the emittance measurement system of TB0 has large angular acceptance (±150 mrad) and allows the beam measurements at nominal field of the last LEBT solenoid at the RFQ matching point. In TB2 and TB3 three phase probes (PHP) were included to measure the beam energy with the time-of-flight (TOF) technique. To preserve the experimental resolution at higher beam energy for both emittance and TOF measurements, TB3 setup comprises a longer drift between the diagnostics boxes respect to TB2 (2 m instead of 0.7 m).

LEBT COMMISSIONING

CNAO has commissioned the LEBT very carefully to obtain consistent and reproducible beam parameters at the entrance of the linac [13]. Optimisation of the ECRIS sources was carried out in collaboration with INFN/LNS. The beam diagnostics instrumentation including the very compact emittance chamber has been presented in [14, 15].

A further big effort was spent as well to define a theoretical model of the line providing simulations coherent with the measurements. Overall LEBT transmission was always larger than 90% and for special optics reached even up to 97%.

Solenoid Effect

Once the whole linac is installed, the effect of the last LEBT solenoid on RFQ injection can be seen only in the diagnostics downstream the IH-DTL as an effect on the linac transmission. Since the solenoid acts on beam focalization, steering and transverse planes mixing, it was important to check the behaviour of the beam under various solenoid settings at TB0.

Since it was already known that the solenoids provided by SigmaPhi to HIT showed a poor geometric to magnetic axis alignment [4], a field distribution measurement campaign on the three CNAO solenoids was carried out in autumn 2006 [16]. The aim was to choose the best one among the three to be installed in front of the RFQ.

The beam positions of Fig. 5, measured 290 mm behind the solenoid exit, show that the steering is well predictable by a 1st order approximation. No significant emittance growth was measured.

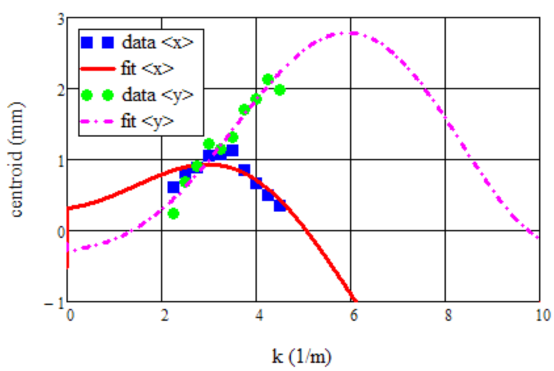

Figure 5: Beam centroid displacement at TB0 as function of the solenoid focal length. The best fit is given with x=-1.3 mm, x'=2.8 mrad, y=-0.1 mm, y'=-0.3 mrad as initial conditions before the magnet.

Matching Conditions

The nominal Twiss parameters necessary for a correct matching at the RFQ entrance are $\beta_{x,y} = 0.035$ m and $\alpha_{x,y} = 1.3$ with the nominal geometrical emittance of 180 π mm mrad. Due to the design of TB0, it was possible to measure the distribution in Fig. 6a/b at the RFQ matching point, just 48 mm behind solenoid exit: more than 90% of the beam is included in the yellow ellipse, which represents the theoretical RFQ acceptance (180 π mm mrad).

The H_3^+ 'Probe-Beam'

Thanks to the high current of H_3^+ and to the LEBT design it was possible to prepare what is called a 'probe-beam' [17], which is a beamlet of much smaller emittance compared to nominal beam (5÷10 π mm mrad versus 45 π mm mrad RMS) but still with reasonable current (~120 μA): using the slits of the two LEBT emittance meters [14] the beam is cut both in width and divergence and the final Twiss parameters are close to the matching ones. The resulting small physical dimensions of the beam compared to the RFQ electrodes aperture allow to decouple longitudinal and transverse effects along the acceleration is such a way that it is possible to investigate the linac transverse acceptance experimentally.

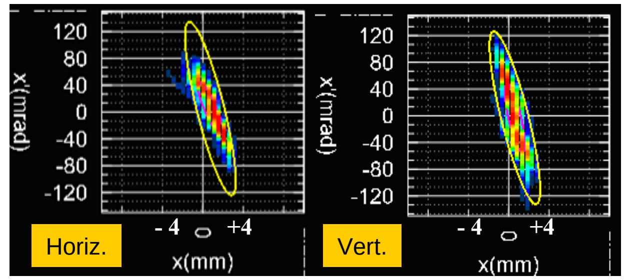

Figure 6a: H_3^+ at 8 keV/u emittance (TB0).

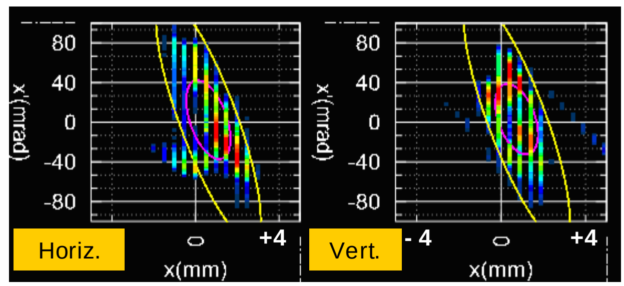

Figure 6b: C^{4+} at 8 keV/u emittance (TB0).

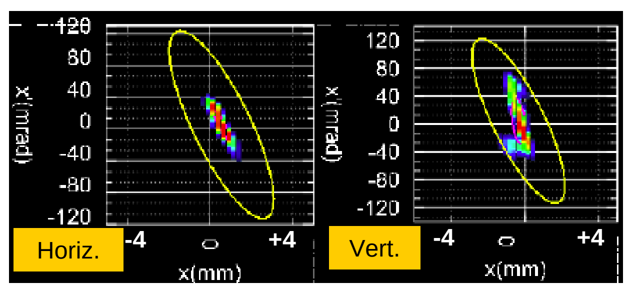

Figure 7: H_3^+ 'probe-beam' at 8 keV/u emittance (TB0).

RFQ COMMISSIONING

The RFQ was designed, assembled and RF tuned at IAP Frankfurt. After first beam tests, the final low level tuning of the field flatness was performed successfully at GSI. Prior to the commissioning at CNAO a proton beam test bench had been set up at GSI [18] in order to verify the RFQ 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 cavity [19].

Installation and Alignment

The RF conditioning of the RFQ was initially carried out in parallel to LEBT commissioning, before the cavity was moved to its final position in the beam line together with the inter-tank matching (ITM) section. This section consists of a quadrupole doublet and a steerer to match the RFQ beam to the IH-DTL. At its end a phase probe monitors the bunch signals and allows adjustment of the phase between bunch and the RF amplifier for the IH-DTL. Finally TB2 was installed and all components were aligned.

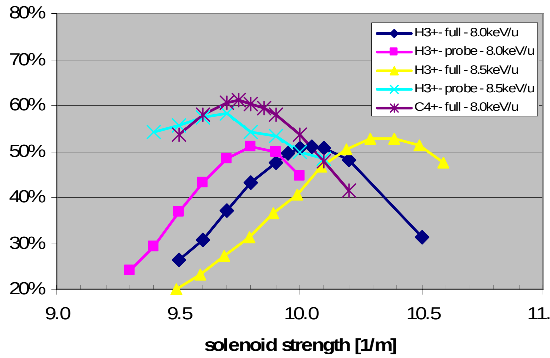

Figure 8a: RFQ transmission as function of the solenoid strength (RFQ tank voltage 5.1 V).

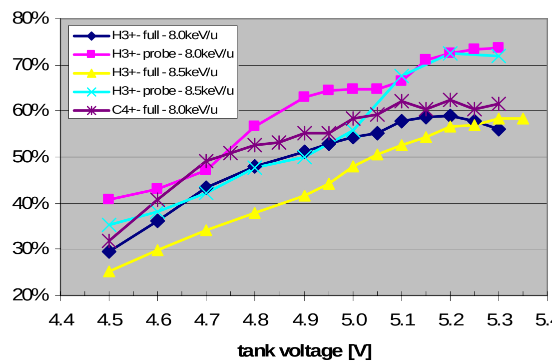

Figure 8b: RFQ transmission after optimization as function of the scaled tank voltage.

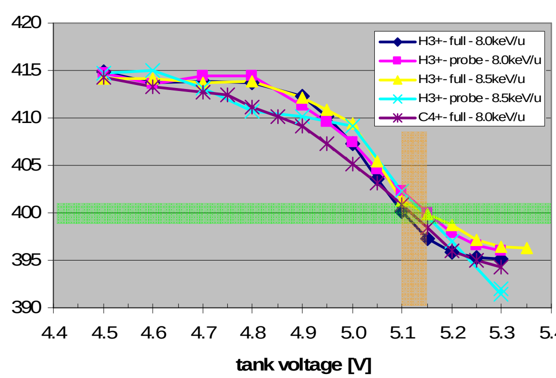

Figure 8c: RFQ output energy [keV/u] after optimization as function of the scaled tank voltage.

Commissioning Procedure

The RFQ commissioning was supported by INFN/LNL and GSI throughout the beam time. During working periods CNAO operated the ion sources continuously to maintain a constant beam quality. LEBT settings and beam parameters were carefully documented, at least once a day, before RFQ measurements were carried out.

For a given ion species (H_3^+ or C^{4+}), beam energy (7.5, 8.0 or 8.5 keV/u), input emittance ('probe' or 'full-beam') and LEBT setting, the optimization procedure foresaw to fine adjust the solenoid strength (Fig. 8a) to reach the best transmission at nominal RFQ tank voltage (5.1 V) and ITM settings. Then the RFQ beam was characterized as function of the tank voltage measuring the transmission (Fig. 8b), the steering effect, the output energy (Fig. 8c), and the transverse emittance (Fig. 9). Once the right energy for IH-DTL injection (~400 keV/u) was found, the transmission was further optimized by means of the quadrupole triplet or the last two LEBT steerers, defining the new nominal LEBT operation parameters.

The optimization of the ITM quadrupoles was tried afterwards in order to verify whether an increase of the transmission was still possible and to investigate the matching with the IH-DTL.

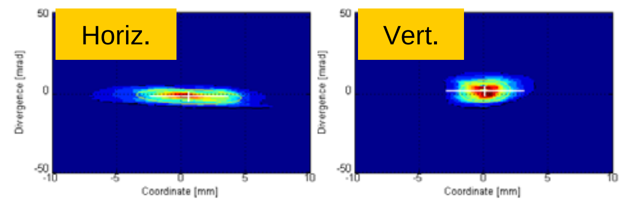

Figure 9a: H_3^+ at 8.0 keV/u emittance (TB2).

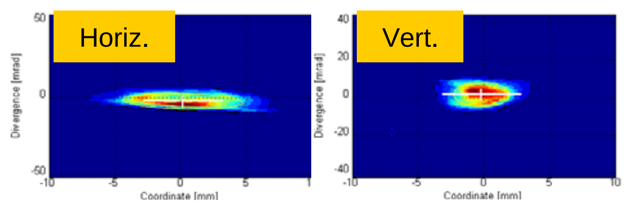

Figure 9b: H_3^+ at 8.5 keV/u emittance (TB2).

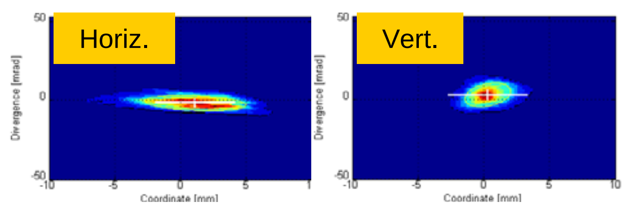

Figure 9c: C^{4+} at 8.0 keV/u emittance (TB2).

Table 3: RFQ Commissioning Results

Ion		H_3^+			C^{4+}
E (keV/u)		7.5	8.0	8.5	8.0
Tank Volt. (V)		5.15	5.10	5.15	5.10
Max. transm. 'full-beam'		4.6%	58%	59%	62%
Max. transm. 'probe-beam'		3.4%	71%	69%	n.a.
Normalized transverse output emittance (π mm mrad)					
Hor.	RMS	n.a.	0.14	0.15	0.13
	95%	n.a.	1.02	1.02	0.90
Vert.	RMS	n.a.	0.10	0.11	0.09
	95%	n.a.	0.78	0.68	0.67

Commissioning Results

For H_3^+ beam (Tab. 3) three different injection energies were tried in order to determine the best RFQ working point. As expected, the lowest energy (7.5 keV/u) has

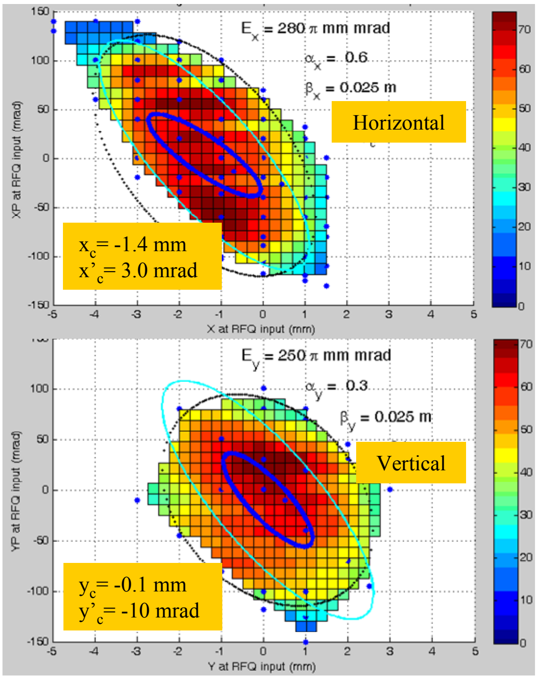

Figure 10: Horizontal and vertical RFQ acceptance measurement with H_3^+ 'probe beam' at 8.0 keV/u. The blue ellipse represents the RMS beam of Fig. 6, the azure one the 180 π mm mrad matched ellipse and the black one the 90% acceptance fitting the experimental data.

very bad performances in terms of transmission, whereas the highest (8.5 keV/u) is equivalent to the nominal one (8.0 keV/u): The operating parameters may be adjusted later depending on the measured beam quality behind the IH-DTL. Very moderate steering effect was found and the use of the ITM steerers seems to be not required.

The RFQ transmission is though limited to ~70% for the 'probe-beam' whereas the design one is greater than 90% [20] for a 'full-beam' of 180 π mm mrad emittance.

Measurement of RFQ Acceptance

A deformation of the RFQ electrodes (a longitudinal bump of ~0.5 mm) was observed for CNAO RFQ after installation by telescope measurements. A similar 'banana-shape' deformation had been detected during HIT RFQ commissioning [4] as well.

In order to check whether the acceptance is reduced by this 'banana-shape' causing the low transmission, by means of the steerers in the last LEBT section and their previously measured response matrix, it was possible to misalign the 'probe-beam' at the entrance of the RFQ up to ±3 mm and ±120 mrad starting from the setting of maximum transmission. The RFQ transmission as function of the misalignment is reported in Fig. 10 and shows that the vertical acceptance is reduced by more than 10% in divergence, which confirms that the simulations on HIT RFQ [21] describe the RFQ transverse behaviour with good approximation, but it does not explain why the transmission is limited to 70%.

The transverse emittance out of the RFQ seems also to be directly connected to the 'banana-shape': the reduced vertical acceptance and the related losses causes the vertical emittance to be lower than the horizontal one by ~50% (Tab. 3). Given that the measured maximum beam transmission through the RFQ is limited to ~70% even for a very small and on axis beam (the axis is defined by the transmission map itself), it seems that the RFQ has a problem of longitudinal capture. Nevertheless the IH-DTL has a transverse acceptance twice as large as the RFQ output emittance and very likely the beam will be accelerated up to 7 MeV/u without additional losses.

CONCLUSIONS

After the source and LEBT optimization, the RFQ has been fully commissioned. The RFQ working point has been established and more than 500 µA of H_3^+ and 70 µA of C^{4+} are accelerated to 400 keV/u at 195 kW RF power. The design transmission could not be achieved (the maximum achieved is about 60%). The output beam is very stable and shows almost no steering. The measured transverse output emittances are well within the IH-DTL acceptance.

Measurements at 7.5, 8.0, and 8.5 keV/u RFQ injection energy delivered similar results for the two higher energies, but at 8.5 keV/u at a higher RFQ power level.

Finally, the 'probe-beam' data allowed to verify the RFQ acceptance experimentally, and to analyse and partly improve the performances for the 'full-beam'.

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