COMMISSIONING OF THE CNAO LEBT AND SOURCES

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Abstract

The Centro Nazionale di Adroterapia Oncologica (CNAO) [1] is the Italian centre for deep hadrontherapy, namely an innovative type of radiotherapy using hadrons.The wide range of beam parameters (i.e. energy and intensity) at patient level together with the advantages of hadron-therapy with respect to traditional radio-therapy nourishes the hopes for more effective patient recovery. After the LEBT and the RFQ commissioning [2], the IH commissioning is now in progress. First patients are expected to be treated in 2010. The present paper summarizes and evaluates the Low Energy Beam Transfer (LEBT) line commissioning, which has been carried out between July 2008 and January 2009.

THE CNAO MACHINE

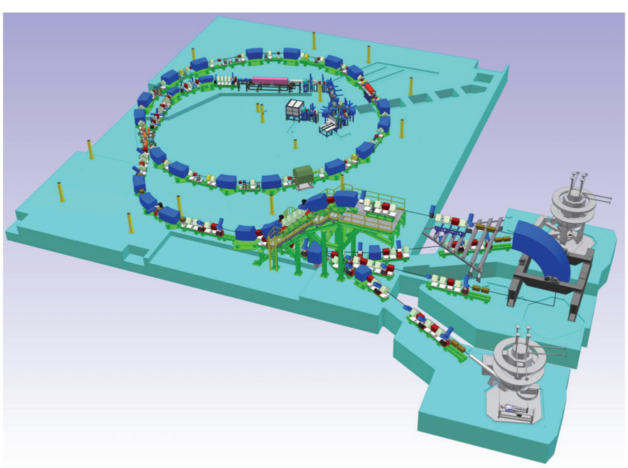

Figure 1: Sketch of the CNAO machine complex.

CNAO machine is depicted in Fig. 1. CNAO beam originates from one of the two Electron Cyclotron Resonance (ECR) sources, producing either C^{4+} or H_3^+ ions, it then travels along the LEBT line, the LINAC and the Medium Energy Beam Transfer (MEBT) line. It turns around a 25 m diameter synchrotron and, finally, is extracted into one of the four extraction lines, delivering either C^{6+} or proton beam to one of the three treatment rooms.

Particles are emitted by the sources at 8 keV/u, accelerated by the RFQ and the IH to 7 MeV/u, and then injected into the synchrotron. Extraction energy depends on treatment requirements: the deeper is the tumour to be irradiated, the higher is the required energy. Extraction energy can vary from 120 to 400 MeV/u for Carbon ions and from 60 to 250 MeV/u for protons. Extraction process nominally lasts one second.

Nominal beam intensity at patient level is 3.8 nA and 0.16 nA, for protons and Carbon ions, respectively. It can be reduced up to a factor 1000, by closing down LEBT slit plates, inserting pepper-pot filters in the MEBT line and extracting the beam with spills over a longer extraction time.

THE LEBT LINE

The LEBT line (Fig. 2) begins with two ECR sources, both able to produce either H_3^+ and C^{4+} ions. A source produces a beam containing many ion species. Downstream each source, a 90°-dipole (also called Spectrometer) allows to select particles with different Z/A ratio and thus to separate H_3^+ and C^{4+} beams from other species. A switching dipole magnet merges the two source lines into one. After being bent by a 75°-dipole, the beam enters the RFQ.

Upstream the RFQ an electrostatic deflector, called Chopper, is installed. The beam is continuous from the sources to the Chopper, while it is pulsed (i.e., 50-100 us pulse, approximately every 2 s) behind it, if the Chopper is switched on.

Particles running along the LEBT cross many magnets and beam diagnostics monitors.

Three solenoids, four dipoles, eleven quadrupoles and eight correctors are used to focus, bend and steer the beam.

As far as Beam Diagnostics (BD) is concerned [3], vertical and horizontal wire scanners are used as profile monitors. Some Faraday cups and one Chopper Faraday cup measure beam intensity. Sets of four metallic plates, mounted on top, bottom, left and right tank ports, each one driven by a motor, altogether called Slit monitor, are used either to suppress beam halo, if positioned at beam border, or to select thin beam slices, in case one plate is positioned close to the opposite one, making a slit. This last use allows both phase space distribution measurements, if beam profiles are measured behind the slit, and beam profile measurements at slit level, if beam intensity is measured downstream. Faraday cups and slit plates are cooled and can be polarized to capture secondary emitted electrons.

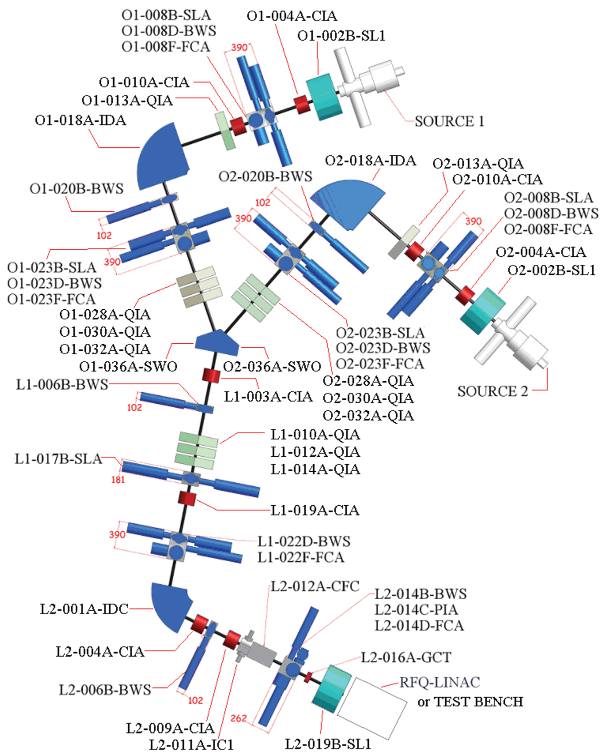

Figure 2: LEBT line layout. Sketch of magnets and beam diagnostics tanks, from the sources to the test bench installed at the end of the LEBT line. Legend: SLA= Slit monitor, FCA= Faraday Cup, BWS= Wire Scanner, CFC= Chopper Faraday Cup, GCT= AC- Current Transformer, PIA= Wires Harp, CIA= corrector, QIA= quadrupole, SL1= solenoid, SWO=switching magnet, IDA= 90° dipole, IDC=75° dipole, IC1 = Chopper dipole.

In four positions along the line, a full set of BD monitors (i.e., four-plates slits, one horizontal and one vertical wire scanner, one Faraday cup) are installed in the same tank, 390 mm long [4]. In other two positions, this tank is installed, but not fully equipped.

This compact tank, equipped with all the monitors, was the main tool for most of the measurements here after reported. The high wire scanner spatial resolution and the comparatively large beam divergence allowed accurate emittance measurements in less than 150 mm, namely by using the instrumentation installed in a single tank.

COMMISSIONING MEASUREMENTS

Commissioning started with a coarse study of the first part of the LEBT line. Sources spectra were measured, the wished species (i.e., H_3^+ or C^{4+}) peak was selected and the resulting beam current intensity and ripples were studied versus source parameters, in order to obtain stable source operation and accurate ions species selection.

The beam is guided along the rest of the line. Optics parameters as dispersion, phase space distribution, beam width and barycentre position were measured along the full line. Their behaviour versus magnet settings was studied, as needed to define repeatable and reliable optics settings.

Beam current intensity was measured at Faraday cup levels to optimize beam transmission.

Finally, the LEBT line-end commissioning was performed, aiming to produce a beam matching with RFQ input requirements.

Ion Species Selection

Source spectra are measured by selecting a beam vertical slice with the slit downstream the spectrometer and changing spectrometer current, at the same time. The resulting beam current versus time pattern (Fig. 3) measured by the Faraday cup shows the different ion peaks and allows to select the required one.

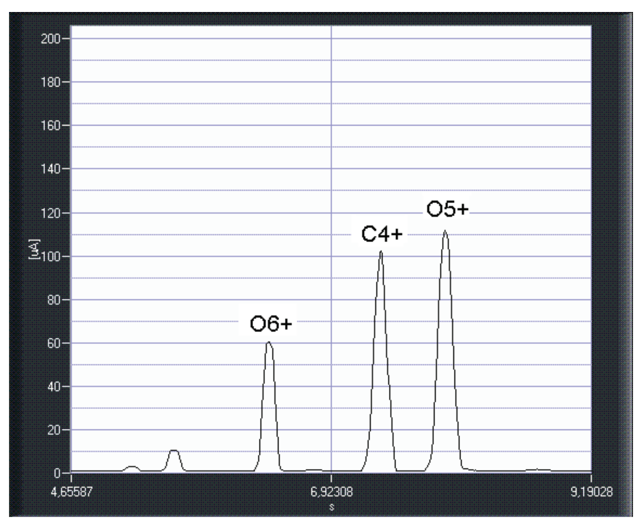

Figure 3: Source spectrum measured at the O2-023-FCA Faraday Cup, while ramping the O2-sector spectrometer from 30A to 60A. O2-023-SLA plates are positioned as follows: top and bottom plates fully out from beam path, left plate at -5 mm and right plate at +5 mm with respect to the vacuum chamber centre. One can notice the C^{4+} peak surrounded by other species peaks.

Emittance and Twiss Parameters Measurement

The same metallic plates, making vertical or horizontal thin slits, are used to perform vertical or horizontal emittance measurements (Fig. 4), respectively. Particles phase space distribution is derived step-by-step moving a slit from one side of the beam spot to the opposite one, and measuring beam profile with the wire scanner for each step. The distance between slit and wire scanner installed in the same 390 mm long tank is about 150 mm, that guarantees a good angular resolution. Spatial resolution is enhanced by increasing the number of steps, with the drawback that measurement time increases consequently. In L1-sector, slit and wire scanner distance is as large as 1 m and angular resolution is improved, accordingly.

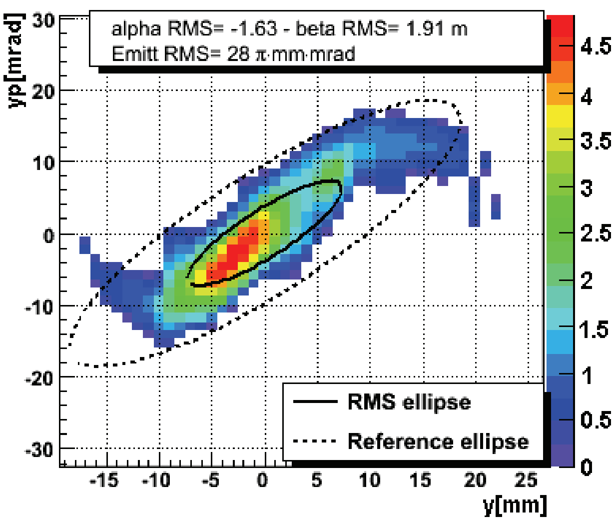

Figure 4: Phase space distribution at the level of O1-023-SLA, for the vertical plane. By using statistical emittance definition, we retrieve the RMS Twiss parameters and emittance value at 1 σ. The corresponding ellipse is drawn on the plot with solid line. The dashed line ellipse uses alpha and beta parameters obtained from the measurement and a 180π mm mrad emittance. While vertical plates are moved from -30 mm to +30 mm, left and right plates are kept in place to select the ion species.

Table 1: Horizontal And Vertical Twiss Parameters At O1(O2)-023B-SLA

Twiss Parameters At O1(O2)-023B-SLA						
Species	**Alpha**		**Beta [m]**		**Emitt RMS [pi mm mrad]**	
	Hor.	Vert.	Hor.	Vert.	Hor.	Vert.
H_3^+	-0.80	-1.21	0.49	1.49	28.05	21.03
C^{4+}	-0.04	0.78	0.16	1.17	40.90	34.04

Twiss parameters can be measured just downstream the spectrometers (Table 1) and behind the switching magnet (Table 2), where slit monitors are available. Twiss parameters at source level have been derived as back-tracking of downstream parameters and used to check beam optics models and understand downstream beam behaviour.

Table 2: Horizontal and Vertical Twiss Parameters at L1-017B-SLA

Twiss Parameters At L1-017B-SLA						
Species	**Alpha**		**Beta [m]**		**Emitt RMS [π mm mrad]**	
	Hor.	Vert.	Hor.	Vert.	Hor.	Vert.
H_3^+	2.91	0.49	2.17	0.89	25.74	24.08
C^{4+}	3.51	2.18	2.94	2.05	33.80	37.10

Beam parameters along the line resulted consistent and reproducible. They are being employed to define a theoretical model of the line providing simulations coherent with the measurements, which will help line setting-up.

Meantime, an experimental response matrix for the full line was measured for each optics settings: it allows to steer the beam taking into account the actual effects of magnets changes on beam optics. That is a key-point for a fast and reproducible beam steering.

Dispersion

Horizontal and vertical dispersion was measured at some points along the line, everywhere a profile monitor is present. Table 3 collects some significant results.

From dispersion value at the selection slits (i.e. at O1(2)-023-SLA), spectrum peaks resolution is estimated, as well. Profile monitors layout gives the opportunity to measure dispersion at different points along a drift and dispersion derivative can be computed, consequently.

Table 3: Horizontal and Vertical Dispersion Values Along The LEBT Line

Dispersion Values for Carbon Ions [m]						
Species	**O1(O2)-023D-BWS**		**L1-022D-BWS**		**L2-014B-BWS**	
	Hor.	Vert.	Hor.	Vert.	Hor.	Vert.
C^{4+}	1.45	-0.01	-0.58	0.17	5.11	-0.12

Beam Transmission

Beam transmission was measured along the line by means of the Faraday cup monitors.

Overall transmission, from the species-selection level (i.e. behind the spectrometer) to the LEBT line-end, have been obtained up to 97%.

In order to guarantee the beam current intensities needed for treatments (i.e. 10E+10 protons per spill and 4E+08 C^{6+} ions per spill), the minimum intensities at the LEBT end must be of 600 μA and 200 μA for H_3^+ and C^{4+}

beams, respectively, if we assume 90% transmission along the LEBT.

During the LEBT commissioning, beams up to 1400 µA and up to 230 µA for H_3^+ and C^{4+}, respectively, have been measured.

End-Line Test Bench

Beam optics parameters in the last sector of the LEBT line were carefully adjusted so to maximize RFQ transmission and minimize damaging beam losses against the RFQ itself.

A test bench was installed in place of the RFQ during this commissioning phase. It consisted of two tanks of 390 mm-long type. The first one was equipped with one horizontal and one vertical slit for phase space distribution measurements; one horizontal and one vertical wire scanner for beam profiles when the beam is continuous; a wires harp for horizontal and vertical beam profiles dedicated to chopped beam, but used with continuous beam, too. A Faraday cup equipped with both, AC and DC electronics, was installed in the second tank. An end-Faraday cup was used to close the beam pipe and measure AC-beam intensity.

Test bench slit is not made by drawing-up two opposite plates, but is cut on the plate itself. It provides a fixed-amplitude slit, not changeable by the user, but more accurate and occupying a shorter longitudinal space. A rather complicated mechanical design was required to install slit plates exactly at the RFQ entrance level, because of the short available space. These slits resulted in a powerful tool to investigate particles distribution in the phase space, exactly at the matching point between LEBT and RFQ.

Table 4: Theoretical and Measured, Horizontal and Vertical Twiss Parameters at LEBT-End

Twiss Parameters @ Test Bench						
Species	**Alpha**		**Beta [m]**		**Emitt RMS [π mm mrad] (*)**	
	Hor.	Vert.	Hor.	Vert.	Hor.	Vert.
Theoretical	1.3	1.3	0.035	0.035	36	36
H_3^+	1.64	1.17	0.06	0.03	25	33
C^{4+}	0.56	0.49	0.03	0.03	37	32

(*) According to CNAO hypothesis on particles distribution, total emittance is given by 5 times the RMS emittance.

Beam trajectory was centred and aligned with respect to the RFQ entrance point and axis by using wire scanners and correctors of the last sector of the LEBT line (i.e. L2-sector), while beam emittance measurements performed with the test bench checked the actual position and divergence at the RFQ level. Test bench monitors were of great help while preparing the beam for RFQ. RFQ acceptance was also investigated by means of a probe beam, defined by upstream slit plates, which is smaller than the full beam in position and divergence.

A cylindrical beam (Table 4) was produced at the test bench level. This was required as a pre-condition for starting the RFQ commissioning, in order to best fit with RFQ cylindrical symmetry and maximize the transmission. Indeed, beam transmission through the RFQ resulted above 60% for both the species.

CONCLUSIONS

Source and LEBT line commissioning took 15 weeks, alternated with installation periods.

BD monitors well fulfilled commissioning requirements, providing reproducible and reliable measurements. Wire scanner spatial resolution (nominally 0.1mm) resulted a great advantage to investigate particles angular distribution over short distances.

The use of a test bench measuring beam distribution in the phase space, exactly at the matching point between LEBT and RFQ, was very effective for preparing the beam outgoing the LEBT line.

Faraday cup and wire scanner CNAO-developed amplifier worked successfully, over a wide dynamic range and bandwidth.

Optics settings repeatability was poor initially since correctors share the same iron yoke and thus the two planes interfere with each-other. Then stabilization cycles were carefully defined and these effects minimized.

CNAO LEBT commissioning was carried on with satisfactorily results. Measurements were good and their results allowed to define reliable and reproducible magnet settings for the line.

An experimental response matrix for the full line allows a fast and effective beam steering. Beam transmission over the full line is good (up to 97%) and beam intensities at the LEBT-end are larger than what required for treatments.

Beam parameters at test bench level well match with RFQ input beam requirements, resulting in a fast and fruitful RFQ commissioning.

LINAC commissioning is now in progress.

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