BEAM DIAGNOSTICS IN THE CNAO INJECTION LINES COMMISSIONING

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Abstract

The Centro Nazionale di Adroterapia Oncologica (CNAO) [1] is the first Italian center for deep hadrontherapy, namely an innovative type of oncological radiotherapy using hadrons.

The CNAO machine installation is in progress and alternates with lines commissioning [2] [3], started in the Summer 2008.

The present paper reports about Beam Diagnostics (BD) choices, status and post-commissioning evaluation, as concerns the Low Energy Beam Transfer (LEBT) line monitors.

THE CNAO LEBT LINE

The CNAO Machine

The CNAO heart is made by a 25 m diameter synchrotron. One injection line, starting from one of the two available sources, brings the 8 keV/u ion (C^{4+} or H_3^+) beams to the RFQ-IH, that accelerates particles to 7 MeV/u, which is the energy of the Medium Energy Beam Transfer (MEBT) line beam. At the beginning of the MEBT line, electrons are stripped out from carbon or hydrogen ions, that become C^{6+} or protons, respectively.

The MEBT line brings particles into the synchrotron, where C^{6+} and protons can be accelerated up to 250 MeV/u and 400 MeV/u, respectively, according to the deepness of the tumour to be irradiated.

Finally, particles are extracted towards one of the four extraction lines (3 horizontal and 1 vertical), that deliver the beam to one of the three treatment rooms (i.e., the central treatment room is equipped with horizontal and vertical beam lines).

The LEBT Beam Diagnostics Layout

The CNAO beam originates from one of the two ECR sources, both able to produce C^{4+} or H_3^+ ion beam. The beam produced by a source contains 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 the other species. A switching dipole magnet merges the two source lines into one, which is bent by a 75°-dipole and, finally, enters the RFQ (Fig. 1).

Ahead the RFQ, a Chopper magnet changes drastically the beam parameters: upstream the Chopper the beam is continuous; after the Chopper it is pulsed, with 50-100 µs long batches, every about 2 s. BD monitors for a continuous or a chopped beam are significantly different. The present paper mainly focuses on the BD monitors designed for a continuous beam, namely installed upstream the Chopper, or downstream the Chopper but to be used when the Chopper is off.

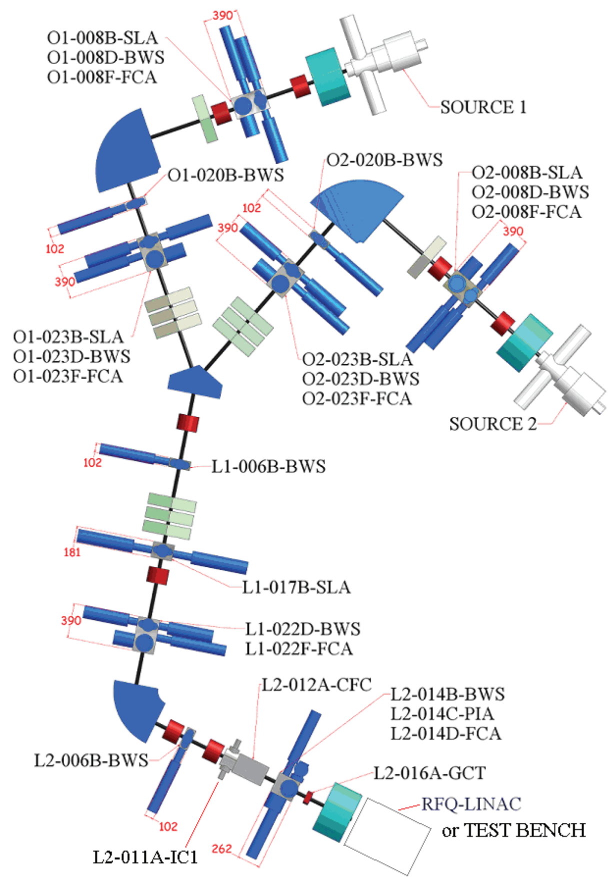

Figure 1: LEBT line layout. Sketch of magnets and beam diagnostics monitors, from the sources to the test bench installed at the end of the LEBT line, during LEBT commissioning, in place of the RFQ. Legend: SLA= Slit monitor, FCA= Faraday Cup monitor, BWS= Wire Scanner, CFC= Chopper Faraday Cup monitor, GCT= AC- Current Transformer, PIA= Wires Harp, IC1= Chopper magnet.

As concerns BD devices, vertical and horizontal wire scanners are used as profile and position monitors. Six 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 plates are 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.

As a rule of thumb, two profile monitors (each made of one vertical and one horizontal wire) are installed along each straight sector, at least, in order to permit the measurement of beam profile and barycentre position at the beginning and at the end of the sector, and to determine the trajectory angle, in the vertical and the horizontal plane.

At the end of each straight sector, a beam current intensity monitor is usually installed.

Slit monitors are installed before and after each spectrometer, and a little before the 75°-dipole.

An additional full set of monitors (i.e., horizontal and vertical slit, horizontal and vertical wire scanner and one Faraday cup) was installed in the temporary test bench mounted at the end of the LEBT line, at commissioning time. In this case, a harp monitor, used for chopped beam profile measurements, is installed, too.

A standardization strategy was adopted in order to make monitors production cheaper, their maintenance easier, and to improve more quickly the experience about hardware problems and monitors behaviour. As a consequence of this strategy, a 390 mm long tank was designed [4], able to house four slit plates, one vertical and one horizontal wire scanner and a Faraday cup. Five tanks of this type are mounted along the LEBT line and two others made the temporary test bench installed at the end of the line itself, at commissioning time.

In the case longitudinal space is not a limitation, this tank was installed even if not all the monitors are required, closing down the unused tank ports with blind flanges. In few other cases, if not all the monitors are required and the available space was rather small, a shorter and dedicated tank was designed.

BD MONITORS IN THE LEBT COMMISSIONING

Wire Scanners Monitors

A wire scanner monitor is usually made by one vertical and one horizontal Tungsten wire, with 0.1 mm diameter. Each wire is driven perpendicularly to beam direction, by a brushless motor up to 250 mm/s (100 mm/s, typically). Wire position is measured by means of a linear potentiometer, with about 20 µm accuracy.

Wire scanners (Fig. 2) vacuum-side cables resulted very fragile and they often broke down, during the first period of commissioning. As soon as the problem appeared in all its seriousness, the design was revisited and the broken wires not only repaired, but also improved. Once all the wires have been reviewed, this kind of problem didn't occur any more.

During commissioning, the wire scanner spatial resolution (0.1 mm, nominally) with respect to a fixed-wires device (e.g., a multi-wires chamber) resolution was greatly appreciated. On the other hand, measurements stressed out the importance of a careful alignment of the wires with respect to the beam reference path, that could be improved at CNAO.

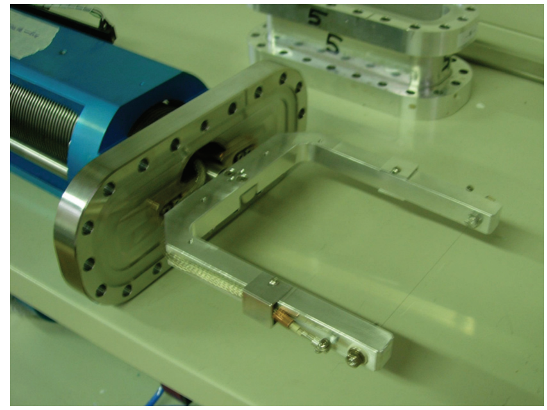

Figure 2: Picture of the Wire Scanner monitor wire, mounted on its fork. Wire fork is screwed to the brushless motor shaft that drives the wire IN /OUT the beam path.

The resolution obtained with the wire scanner was the key-element to allow emittance measurements (Fig. 3), within 150 mm only, namely by using slit and wire scanners housed in the same 390 mm long tank. Of course, a higher resolution in particles divergence measurement is reached behind the switching magnet, where slit (L1-017B-SLA, Fig. 1) and wire scanners (L1-022B-BWS, Fig. 1) are about 1 m away from each other.

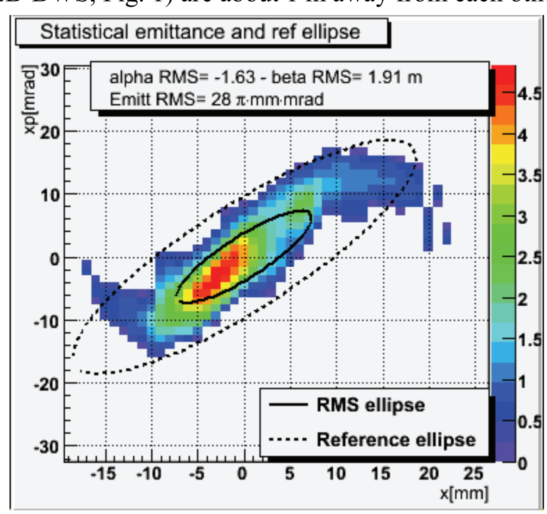

Figure 3: Phase space distribution at the level of O1-023B-SLA monitor, for the vertical plane. The measurement is performed moving the vertical plates from -30 mm to +30 mm, with 1 mm step, and keeping left and right plates at -5 mm and +25 mm, respectively, in order to select H_3^+ peak and stop all the other species. By using statistical emittance definition, we derive the RMS Twiss parameters and emittance value at 1 σ. The corresponding ellipse is draft on the plot with full line. The dashed line ellipse is a reference ellipse the user can fix.

Wire scanner heating was tested leaving the wire on the beam spot for a long time. It never exceeded the 300°C temperature, which is far below the tungsten melting point (i.e., 900 °C). On the other hand, if wire temperature changes, its resistance changes, too. Despite that, beam profile measurements are not affected, since the wire scanner amplifier is a trans-conductance amplifier, whose output current does not depend on the wire resistance.

Wire scanner amplifier works from 1 nA to 1 mA, with five different gains (i.e., 10^4 to 10^8 V/A). It has a 400 Hz bandwidth that fully covers the 50 Hz bandwidth of the expected physical phenomena.

Faraday Cup Monitors

Commissioning operations showed up the good quality of the Faraday cup (Fig. 4) CNAO-developed front–end amplifier. It was designed in order to measure DC-beam current and to detect any ripples due to sources or power supplies, up to 15 kHz. It allowed to measure satisfactorily the chopped beam pulse, consequently, making the detector very versatile. Faraday cup amplifier works from 100 nA to 100 mA, with seven different gains (i.e., 10^2 to 10^8 V/A).

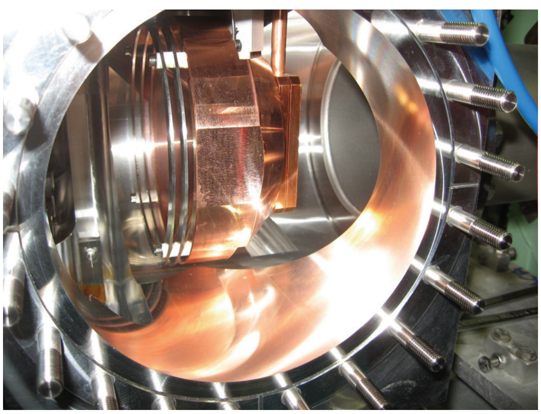

Figure 4: Faraday cup monitor installed on its tank and looked at from a side port (beam should come from the left). One can recognize the Copper cup, from its typical colour. Two stainless steel rings are mounted in front of the cup: the repeller ring (on the left), and the guard ring (on the right).

We could also appreciate the advantage of a large diameter (i.e., 135 mm) cup that can be used as beam stopper, as well, since it closes down the whole beam pipe section. Despite the large diameter, secondary emitted electrons are fully repelled when about -350 V are applied to the repeller ring. Repelling voltage can be set from 0 V to -1 kV.

Faraday cup vacuum-side insulators presented some troubles due to the fact that ions are deposited on them, they become conductive. This accident more often occurred at the Faraday cup monitors just behind the sources, where beam is larger and particles more scattered around the vacuum chamber. A shielding is under design to protect the insulators from carbon ions and reduce the occurrence of this drawback.

A water-cooling system was designed to avoid overheating of the Faraday cup monitors left on the beam path for a long time, upstream the spectrometers, before ions selection, where the expected beam current was more than 10mA (i.e., about 360 W full beam power). To be conservative, the same cooling system was installed on all the Faraday cups of the LEBT line. It warranted monitors safety even in case they are used as beam stopper for an *infinite* time.

An additional monitor, belonging to the Faraday cup family is the Chopper Faraday Cup (CFC) (Fig. 5). It is installed just downstream the Chopper magnet.

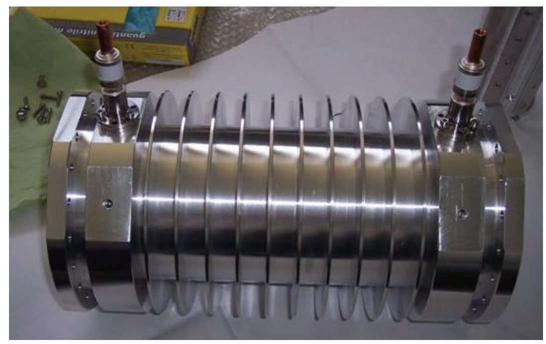

Figure 5: Chopper Faraday cup body, that is the vacuum chamber section just behind the Chopper magnet. Thin metallic tabs are machined on the body itself, in order to enhance heat evacuation by air-convection.

It is an innovative monitor, developed at CNAO, and still under commissioning with beam. It is based on the Faraday cup principle, namely it aims to measure beam intensity by stopping the beam and measuring the collected charge. In fact, the "cup" stopping the beam to be measured is made by the 390 mm long vacuum chamber, installed just downstream the Chopper magnet and insulated from the rest of the LEBT beam pipe. A inner cylinder, opened on the side the beam is deviated towards by the Chopper, is grounded, while the "cup" can be polarized up to 1.25 kV, in order to capture secondary emitted electrons.

Differently from the usual Faraday cup, the CFC can be retained not destructive, since it measures the beam deviated by the Chopper magnet against the vacuum chamber and doesn't intercept the beam entering the RFQ.

Since the beam is deviated against the vacuum chamber by Chopper for 99.99% of the time, the CFC will allow a basically continuous beam current monitoring, without perturbing the beam delivered to the patients.

No water cooling is foreseen for the CFC: air cooling is retained sufficient, for the current intensities expected at the LEBT end. On the other hand, heat evacuation is enhanced by thin metallic tabs, machined all around the vacuum chamber acting as the cup.

Slit Monitors

Each one of the metallic plates (Fig. 6) used as halo suppressor or slit, is driven by a brushless motor up to 250 mm/s (100 mm/s, typically). Its position is measured by means of a potentiometer with about 20 µm accuracy, like for the wire scanner.

Care must be taken in manufacturing the plates with edge-angle borders, in order to avoid cutting the high-divergent particles: it was taken into account during plates design, but it was necessary increasing the angle, at commissioning time.

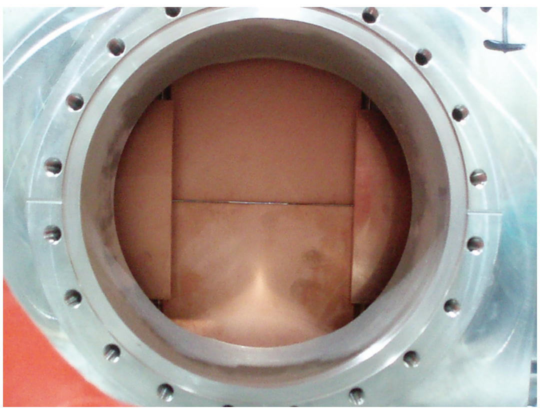

Figure 6: The four Copper plates, making one Slit monitor, installed on their tank. Left and right plates are positioned at beam border; top and bottom plates are making a very thin slit at about tank center.

Measurements (Fig. 7) with polarized (50 V) slit plates cancel the effect of the secondary electrons emitted by the plates hit by the beam, on the particles distribution, as seen by a wire scanner, downstream the slit plates. The effect is visible if the plates are grounded rather than polarized. Repelling voltage can be set from 0 V up to 1 kV.

Slit plates are equipped with the same water cooling system used on the Faraday cup monitors.

Watch-Dog Strategy

After commissioning, when CNAO machine will treat patients for most of the time, measurements perturbing the beam shall be avoided. The opportunity of monitoring beam parameters, without interfering with the beam, guided BD team at the time of monitors choice.

Wire scanners can be used in Watch-Dog mode, positioning a wire at beam spot border and measuring its current. If it suddenly increases or decreases, a warning is delivered to the user, since it could be due either to a beam transverse displacement or to a significant source current variation.

Similarly, slit plates will be used during treatments as beam halo suppressor, positioning the four plates at beam spot border.

Information about beam intensity without affecting the beam delivered to the patients is provided by the Chopper Faraday cup. As already discussed, it can monitor beam current at the end of the LEBT line and warn the operator in case of significant changes, without intercepting the beam entering the RFQ.

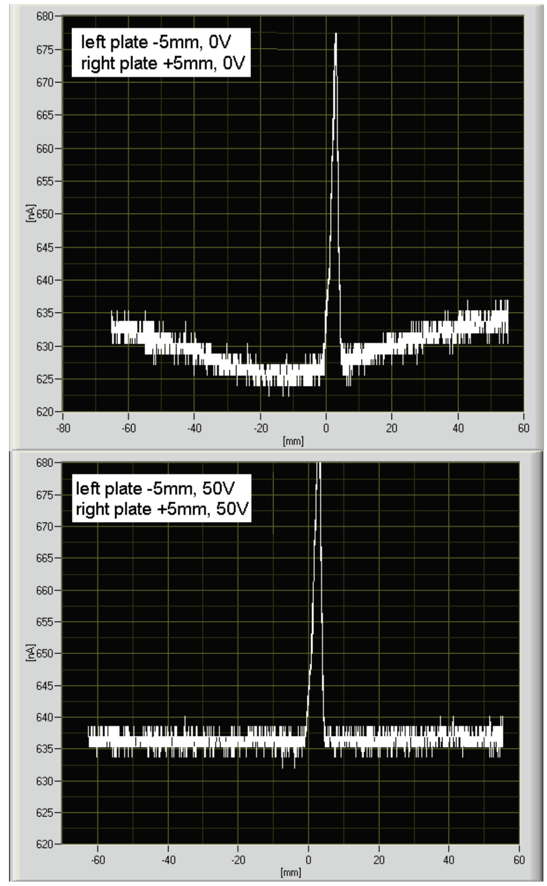

Figure 7: The two pictures show a horizontal beam profile, acquired with the O2-023D-BWS horizontal wire scanner, while upstream left and right slit plates (O2-023B-SLA) are placed at -5 mm and +5 mm, respectively. In the picture on the left, slit plates are grounded and we notice the profile baseline having a deformed shape, like a negative current is induced on the wire at beam peak sides. Secondary electrons produced by the beam impinging on plates border could be responsible for such a negative current. The effect disappears in the right picture, taken while slit plates are polarized at +50 V. Polarized slit plates re-capture their emitted secondary electrons and the wire doesn't detect a negative current at beam border, any more.

CONCLUSIONS

After some hardware wavers due to the innovative designs and the lack of pre-commissioning with beam, monitors installed in the CNAO LEBT line provided reliable and reproducible measurements.

The LEBT line commissioning was surely slowed down by the fact that monitors user's interface debugging was still in progress. On the other hand, the choice of monitor types and their layout along the line resulted well fulfilling operation needs, in order to reach source and LEBT commissioning goals within 15 weeks.

Complicated mechanical designs were repaid by high-performing devices.

The CNAO-developed electronics comprising high voltage polarization, pneumatic actuator and brushless motor control, and interlock systems management worked successfully. The most deserving aspect surely concerns signals amplification and delivery, since it worked perfectly over a wide dynamic range (6 decades) and bandwidth (DC to 15 kHz for the Faraday cup and DC to 400 Hz for the wire scanner).

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