ELECTROSTATIC PICKUP IN THE CNAO INJECTION LINE

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Abstract

The paper is about the electrostatic pickup installed in the Medium Energy Beam Transfer (MEBT) line of the CNAO (Centro Nazionale di Adroterapia Oncologica), the Italian facility for oncological hadrontherapy [1].

The MEBT Pickup (PUB) has been designed with the purpose of having a continuous and non-interceptive measurement of the horizontal and vertical beam position, close upstream the injection point in the synchrotron.

Detector commissioning, data-analysis algorithm and first year measurements are discussed in the paper.

DETECTOR OVERVIEW

Figure 1 shows the PUB assembly: the external vacuum pipe (AISI 316L, dark gray), the pickup body (AISI 316L, light gray) and the electrodes (OFHC Copper; orange) inside. The PUB is composed of two consecutive pickups: first the beam passes through the horizontal electrodes and then through the vertical ones. Electrodes are cylindrically-shaped, conveniently cut to pick left and right, or top and bottom signals. The PUB is 700-millimeters flange-to-flange long, with an inner diameter of 72 mm.
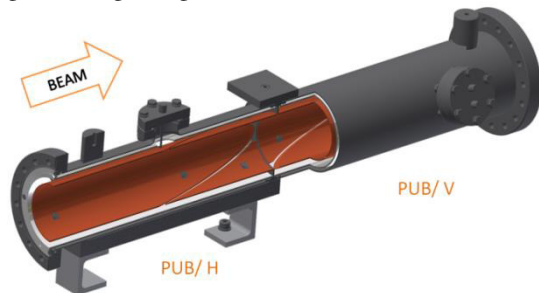

Figure 1: PUB 3D model with side section view. The beam, coming from left, enters the horizontal (H) electrodes first and the vertical (V) ones later.

The electronics has been designed with great attention to match the RC component of the 4 electrodes, in order to equalize their response to the beam passage. Each electrode signal is input in a commercial amplifier (HVA-10M-60-F by FEMTO) with 1 Hz-10 MHz bandwidth and 40 dB gain; the four resulting signals are digitized by a NI6132 DAQ board (maximum sample rate 2.5 MHz; typical working rate 1 MHz) [2]. Before installation, the PUB overall bandwidth, from mechanic to amplifier output, has been measured being more than 2 MHz, using a dedicated test bench.

Figure 2 shows the layout of the beam line around the PUB. Following the beam way, it is composed of: one corrector (CORR), one profile grid (G1), two quadrupole magnets, one diagnostic tank with degrader filters and emittance plates, one corrector, the AC-current transformer, the PUB passing through an additional corrector and, finally, a second profile grid (PG2).

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The beam crossing the PUB is made of 7 MeV/u protons or, alternatively, C^{6+} ions with nominal intensities of 1.4 mA and 0.2 mA, respectively. The upstream LINAC shapes the beam to form about 50-microsecond long batches, with about 2 us rise and 2 us fall time, at 0.5 Hz frequency. Table 1 reports typical beam position (X0, Y0) and dimension (σX, σY) measured at PG1 and PG2, for horizontal (X) and vertical (Y) plane, for protons (P) and C^{6+} ions (C).
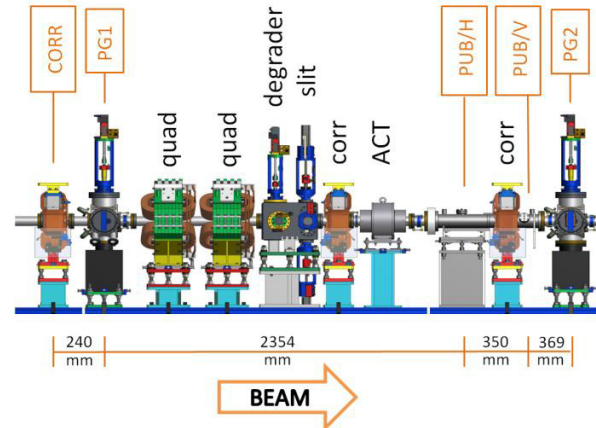

Figure 2: Line layout around the PUB, with correctors (CORR), profile grids (PG), quadrupoles (quad), the AC-current transformer (ACT), the emittance plates (slit) and the degrader filters (degrader). The outlined objects are used for the PUB calibration.

Table 1: Beam Parameters Measured at PG1 and PG2

Particle	X0(mm)	σX(mm)	Y0(mm)	σY(mm)
P @PG1	2.5	10.4	0.9	4.9
P @PG2	1.4	7.5	10.2	4.6
C @PG1	4.4	6.8	0.8	3.6
C @PG2	3.9	5.4	9.6	2.7

BEAM COMMISSIONING

First Measurements

The first measurements pointed out that the shape of the electric signals picked up by the four (right, left, top, bottom) electrodes was often different from the expectations, indicating alternatively positive (primary ions) or negative (secondary emitted electrons) particles impinging on the same electrodes (Fig. 3).

This effect becomes dramatic if one element (e.g., profile grids, degrader filters or emittance plates) is moved into the beam path in the PUB proximities. If this is the case, beam trajectory is deviated, its dimension is enlarged and secondary electrons are produced by the primary ions hitting the obstacle. Consequently, the probability that positive or negative particles strike the electrodes becomes very high. If no objects are on the beam

path, primary and secondary interactions are drastically reduced and electrode signals are much closer to the expectations, although some distortion effects remain evident.
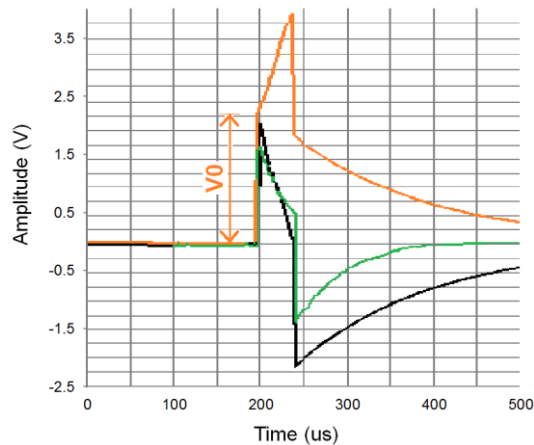

Figure 3: Expected electrode signal (green); signal if electrons hit the electrode (orange); signal if positive ions hit the electrode (black).

This observation led to restrict the use of the PUB to the situations where none of the immediately close objects is on the beam path. This is a low-impact restriction for the PUB operation, being the most common setup.

It remains the need to fix how to evaluate signal amplitude in the allowed situations to get reliable measurements of the beam transverse position.

A common solution to avoid particles on the electrodes consists in mounting a shielding / repeller ring at the pickup entrance. This solution is not easily practicable in this case, because its installation would require to dismantle a big sector of the MEBT line and consequently stop the treatments for an unacceptable long period. Waiting for a planned long shutdown period when it could be installed, it has been tuned a data analysis and post processing strategy strong against signal distortion.

The Algorithm

As usual for pickup detectors, the beam transverse position is calculated from the Delta over Sigma ratio, Delta being the difference and Sigma the sum of the signal induced on the two opposite electrodes (e.g., right and left electrodes for the horizontal beam position) by the passing through beam. The crux consists in how to define signal amplitude, the signal being far from a stepwise function.

In the ideal case, the signal, after the rise induced by the beam (e.g.: at t~200 us in Fig. 3), is expected to follow an exponential-decay with time constant (of about 150 us in the PUB case) defined by PUB resistance and capacitance versus ground. In case positive particles hit the electrode during the bunch transit time, the negative current, induced on the electrodes by the positive beam current, falls down faster; vice versa, if negative particles hit the electrodes, their charge sums up to the beam induced current and the electrode signal decreases less steeply or, even, increases after the beam induced rise.

Different algorithms have been evaluated in order to find a robust solution to evaluate the signal amplitude, despite these effects. The most immediate method, consisting in determining a "good" region of the signal after the beam induced rise and calculating signal amplitude as average on this samples subset, cannot work in this scenario, being significantly influenced by the signal shape after the rise.

A different approach has been preferred, based on the fact that particles lost on the electrodes change the signal shape, but don't contribute significantly to the rise amplitude, essentially determined by the current variation (from 0 to beam current, and vice versa) due to the bunch transit. Thus, signal amplitude is evaluated as the signal rise (V0 for orange signal in Fig. 3), induced by the bunch arrival. The PUB acquisition is performed at 1 MHz rate and is hardware triggered by the LINAC system: the beam bunch occurs at fixed delay from the acquisition start, consequently. Time has been spent tuning the script in order to determine the rise amplitude accurately, independently on the signal after-rise shape.

Although this solution has the important fragility of using single points rather than averages, many months of measurements have proved its success in attributing an efficient value to each electrode and a dependable beam position, consequently.

The Calibration

Once a reliable way to calculate Delta and Sigma was found, the detector has been calibrated in order to estimate A and B parameters, needed to obtain the beam position in millimetres:

$$x(mm) = \frac{1}{A}\left(\frac{Delta}{Sigma} + B\right).$$

Some measurements were performed with this purpose before installation, but an experimental calibration has been preferred, using PG1 and PG2. A PG is made up of two 64 wire harps, one horizontal and one vertical, with an effective resolution of 0.5 mm.

The PUB calibration is made independently for protons and carbon ions, horizontal and vertical plane. For each configuration, the procedure is the same: CORR power current is changed from a low to a high value (about ± 20 A for carbon and ± 10 A for proton), in 5 steps. For each step, the beam position is measured at PG1 and at PG2 and about 50 measurements are performed by the PUB, in such a way to calculate a reliable Delta/Sigma value for each corrector setting.

The A and B parameters are deduced by regression line of Delta/Sigma versus the expected position at PUB (Fig. 4), the last being calculated assuming a linear beam trajectory from PG1 to PG2. This assumption is rigorous only if all the magnets from PG1 to PG2 are off; in fact, all the correctors - except CORR for the scanning plane - are switched off, but the two quadrupoles in between are kept on, to avoid beam blowing up and the consequent losses. Beam optics simulations performed with MadX

show that the deviation from the linear path due to quadrupoles on can be neglected except for the most peripheral positions. The most external scan positions suffer of other troubles too: when the beam is very deviated by CORR, it goes out of the PG2 sensitive region and thus beam position at PG2 cannot be calculated accurately; in addition, if the beam is very kicked, the risk of hitting PUB electrodes becomes high and the Delta/Sigma values are more likely fake. On the other hand, the beam most peripheral positions are not reached in the usual operations, thus the linear beam path from PG1 to PG2 can be retained acceptable in the interesting region of work. The R-squared regression line coefficient is very close to 1 for all the particle / plane configurations.
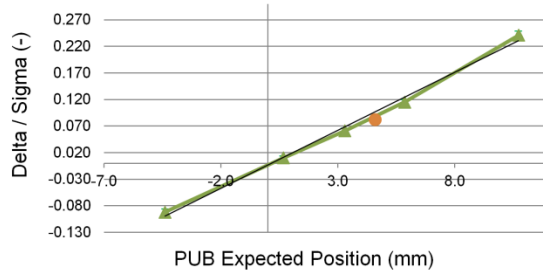

Figure 4: Delta/Sigma versus PUB expected position. Green points refer to the calibration scan (carbon beam, horizontal plane); orange point refers to the nominal magnets configuration; black line is the regression line (y=0.0218x-0.0034 with R²=0.9949).

IN OPERATION

After a long commissioning period, the PUB started regular operation in January 2016. It is presently working in watch-dog mode: the beam horizontal and vertical barycenters, measured by the PUB, are displayed in the main control room and automatically saved in a database every machine cycle. In case they result out of a preset range, an indicator warns the operator about the probable need of reviewing the line or LINAC settings.

Despite the successful strategy to evaluate the electrode signal amplitude, the PUB provides a fake measurement if the upstream machine (sources, LINAC, magnets) produces a slightly wider or offset beam, causing swarms of ions or electrons to hit the electrodes. It regards about the 3% of the acquisitions during the regular machine activity.

So far, no time has been invested in implementing an automatic data rejection for various reasons: fake data are rare and, as such, they do not affect significantly the hour-averaged values used for long-term monitoring, that is the main use of the detector. On the other hand, the same fake data rate can be used as indicator of the machine status and its eventual increase acts as a warning.

In the rare case the PUB is used for short-term (i.e., a few minutes) analysis, the saved data are processed offline calculating distribution centre and standard deviation. It has been proved that the barycentre mean value, after the rejection of eventual 2 sigma-out data, is 0.2 mm within the expected value, for a distribution of more than

20 samples and magnets at the nominal configuration. Barycenter distribution standard deviation results better than 0.6 mm for all the particle / plane configurations.

Studies are in progress about correlation of PUB with LINAC parameters and with the injected and accelerated synchrotron beam currents. The correlation results evident in particular with the IH high voltage signal, correlation coefficient absolute value being greater than 0.5, in the most of the analysed periods. Figure 5 shows the overlapping of proton vertical position trend over the IH high voltage trend, after proper rescaling, for the month of February 2016, where correlation factor is 0.65.
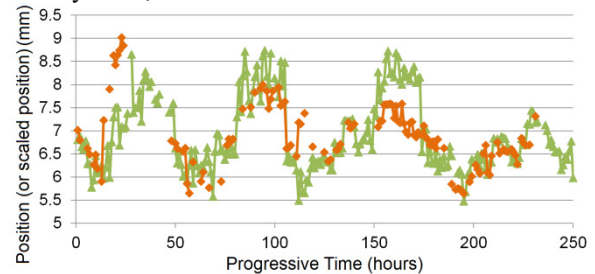

Figure 5: Vertical beam position measured by PUB (green) with proton beam from February 2nd to 29th, 2016, compared with the IH high voltage (orange) measured at the same time and properly scaled. One point is one hour averaged signal; data are not available for all the hours.

CONCLUSIONS

The PUB is installed at the end of the MEBT line, close to the synchrotron injection point. After a complex commissioning, it started to work as watch-dog monitor in January 2016. It permits a continuous measurement of the beam barycenter position, in the horizontal and vertical plane, just upstream the injection point, providing a global view over unavoidable instabilities of complex systems such as sources and LINAC. This information is immediate, xPUB and yPUB being available in the main control room every cycle, and with no side effects, the PUB being a non-interceptive detector.

Despite a signal sometime perturbed by ions and electrons striking the electrodes, an algorithm able to provide reliable measurements was tuned. Detector repeatability and accuracy results adequate for the purpose. Correlation between PUB measurements and LINAC parameters is evident.

REFERENCES

[1] S. Rossi, The National Centre for Oncological Hadrontherapy (CNAO): Status and perspectives, Physica Medica, http://dx.doi.org/10.1016/j.ejmp.2015.03.001

[2] G.Balbinot, M.Caldara, MEBT PU Measurement System, CNAO Internal Note.