THE CNAO QUALIFICATION MONITOR

C. Viviani*, G. Balbinot, J. Bosser, M. Caldara, H. Caracciolo, M. A. Garella, V. Lante, A. Parravicini, M. Pullia, CNAO, Pavia, Italy

Abstract

The CNAO (Centro Nazionale di Adroterapia Oncologica) Foundation is the first Italian center for deep hadrontherapy. It will treat patients using Protons and Carbon ions in the next coming months. Patient safety is the first priority and many diagnostics devices have been developed to guarantee it. This work presents the so-called Qualification Monitor (QM). It is mounted in the common part of the four extraction lines, in front of the Chopper Dump, and it aims to qualify the extracted beam profile and intensity, before sending it to the treatment rooms. The QM is working with beam since a few months, first results and future upgrades are presented.

QUALIFICATION MONITOR OVERVIEW

The Qualification Monitor (QM) is an interceptive detector installed in the first sector of CNAO extraction line and it has been designed and built by the "Louis Leprince Ringuet" (LLR) laboratory, which belongs to the French CNRS, according to the specifications provided by CNAO. It is composed by two different detectors: the Qualification Profile Monitor (QPM) that measures beam position and size and the Qualification Intensity Monitor (QIM) that checks beam intensity value and ripples. The QM is placed in front of the extraction line dump, and it is aimed to check beam quality at the beginning of each spill. The beam is deviated from the Dump in such a way to go to one treatment room when the four chopper magnets are switched on, at the occurrence of the "BEAM OK". Timing event trigger is generated if the characteristics of the beam measured by the QM fall in the defined ranges. In this case the beam is considered to be good, the chopper is switched on and the beam sent to the treatment room, where a beam monitoring system, installed in the vicinity of the patient, monitors in real time the whole spill.

QM DETECTOR

The Qualification Monitor [1] has to check both profile and intensity of the beam. For this reason two different detectors are implemented in the same vacuum tank on the same actuator.

QPM Description

The Qualification Profile Monitor (Fig. 1) is made by two orthogonal harps of scintillating fibers. The active area has a rectangular shape, 17 mm width (x–plane) and 45 mm height (y–plane). The Horizontal plane has 34 square section contiguous fibers (l=0.5 mm), while the vertical one is made by 90 contiguous fibers of the same cross-section. The fibers are aluminized on their surface (excepted for the readout end) in order to avoid crosstalk and light dispersion.

*claudio.viviani@cnao.it

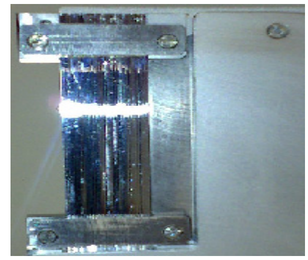

Figure 1: Details of the QM monitor, beam view.

When the beam intercepts the fibers, the released energy produces photons. The number of created photons in each fiber is proportional to the number of crossing particles and depend on their energy. The generated light is collected on a viewport of the vacuum tank and then directed onto the CCD chip of a digital camera (12 bits) by the use of one optical lens. The camera (HAMAMATSU, Peltier cooled, Digital CCD camera C8484-03G) can work at maximum rate of 50 Hz with a camera binning of 8x8 pixels. The CCD binning can be change and the single pixel can be acquired. This increases the dynamic range of the CCD camera but implies a reduction of acquisition sample rate down to 8.9 Hz. Moreover the exposure time can be set between 0.01 ms and 10 s. The large camera dynamic range permits to optimize the acquisition configuration with respect to the beam characteristics. The collected image is finally processed and the X and Y beam profiles can be reconstructed frame by frame by a dedicated software.

QIM Description

The Qualification Intensity Monitor consists in a scintillating plate coupled with a photomultiplier (Hamamatsu, H6780-20) placed in air side. The scintillating plate active area is the same as the QPM (17 mm x 45 mm) and it intercepts the full beam after the QPM. The PM gain can be tuned changing the supply voltage and the output current is proportional to the beam current (and so to the number of particles). PM signal is filtered by an amplifier (two different gains: G0 equal to 10^5 [V/A] or G5 equal to $5*10^5$ [V/A]) mounted close to detector and having a bandwidth of 20 kHz.

Detector Installation

The Qualification Monitor is installed in front of the HEBT dump in the so called OUT position, and during treatment it does not intercept the beam (Figure 2A). However there is the possibility to move the QM onto the beam trajectory, in the IN position by means of a pneumatic actuator. The IN position cannot be used during patient treatment but only during commissioning to check the correct beam trajectory. The Figure 2B shows the IN and OUT positions with respect to the tank centre.

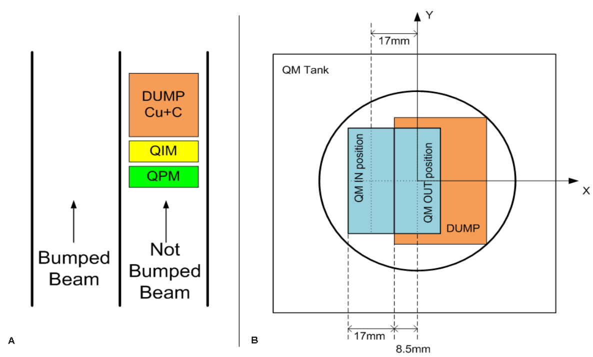

Figure 2A: Top view of the QM position – 2B: IN and OUT Qualification Monitor position with respect to the tank and the dump.

Detector Electronics and Acquisition

The main issue of the Qualification Monitor is the generation and distribution of the "BEAM OK" timing event only if the beam fulfils the requirement in terms of average intensity and ripples, position and dimension, previously fixed according to beam parameters required in the treatment room by the treatment planning.

The QPM Front End Electronics (FEE) is made by a box including the camera power supply, the optical transmitter and the trigger receiver. On the other hand the QIM scintillating plate is coupled with a photomultiplier and its FEE consists in photomultiplier power supply and in a multi-gain current to voltage amplifier for the signal readout.

The signals are managed by the low level control that acquires data, makes the computation and then provides the "BEAM OK" to the Master Timing Generator that gives and receives the timing event used as triggers by all the subsystems.

SIGNAL PROCESSING

The QM has to qualify the position, the dimension and the intensity of the beam [3]. A beam profile is validated, with a given confidence level, if both its centre of gravity and dimension fall inside the corresponding region, determined on the basis of the likelihood ratio for normally distributed populations. The beam should be centred and the FWHM of beam have to be between 4 and 10 mm according with the treatment planning request. On the other hand, the main requirement the beam intensity has to satisfy does not concern its bare value but its modulation: The maximum intensity measured in a spill has not to exceed twice the mean value of spill intensity.

The main issue of QM is the beam qualification procedure, when the monitor is in OUT position measuring the beam before it reaches the treatment room. In this case the beam is not chopped for a nominal time of 100 ms during which it goes on the HEBT dump. Another mode occurs when the beam is completely intercepted by the QM during the full extraction process. This mode is used in the commissioning phase and the measures can be used by the experts to improve the software algorithm that manages the first working mode.

The "long" acquisition can be used also to check the stability of the beam position and the intensity ripple along the spill. The QPM has to provide a profile every 20 ms in order to understand if a position drift is present. In parallel, the photomultiplier signal is acquired (maximum sample rate is 20 kHz) to provide the beam intensity. Also the FFT of intensity signal is computed in order to monitor the ripple due to magnets and power supply. A cross check with the synchrotron DC Current Transformer should be done during long acquisition to crosscheck the current variation in the synchrotron with respect to the extracted current. The formula that converts the QIM output voltage in number of particles per time unit is:

$$N = \frac{V_{PM}^{out}}{P_e \cdot Q_e \cdot G_p \cdot V_{ctr} \cdot q_e \cdot G_{amp}} \qquad (1)$$

Where N is the number of particles per second, V_{PM}^{out} [V] is the PM output voltage, P_e is the number of photoelectrons that reach the photomultiplier, Q_e is the PM quantum efficiency, G_p [1/V] is the PM gain, V_{ctr} [V] is the voltage applied to the photomultiplier, q_e [C] is the electron charge and G_{amp} [V/A] is the amplification gain.

During the commissioning, data analysis can be done offline at the end of the spill. The Beam Diagnostic expert can analyse data and optics experts can operate to improve the extraction consequentially. On the contrary, during treatments, the analysis and the computation will be much more complicated because the control has to react without any operator intervention. The available time for this operation will be 100 ms. In particular 80 ms will be dedicated to the acquisition and 20 ms to analysis and decision taking. Since the acquired data have to be compared with the acceptance ranges that can be different at each cycle, the software has to load the information regarding the spill characteristics at the beginning of the cycle when information are distributed to all systems through the timing. At the "Start Extraction" timing event the camera starts to acquire 4 beam profiles (20 ms each one) while the QIM acquires one "long" beam intensity trace. If the crosscheck will give a positive response the "BEAM OK" timing event will be generated and distributed to the Master Timing, otherwise the qualification goes on and after a timeout the beam will be dumped in the synchrotron.

An important application will be the implementation of the intensity signal FFT in the ripple compensation system. The frequency spectrum can be used to set the parameters of the Air Core Quadrupole power supply. The Air Core Quad is a quadrupole magnet without iron yoke, installed in the synchrotron, that can react with a bandwidth of 10 kHz and it is installed to compensate the intensity ripple of the beam.

QM PRELIMINARY DATA

The CNAO synchrotron is in the final commissioning phase with protons [2], and the extraction line is under test. In this situation the Qualification Monitor can play a very important role in the beam optimization. Figure 3 and 4 show two consecutive (Δt = 20 ms) vertical and two horizontal profiles acquired by the Qualification Profile Monitor with a beam intensity of about $2*10^8$ protons to avoid the possible saturation of the camera CCD pixel.

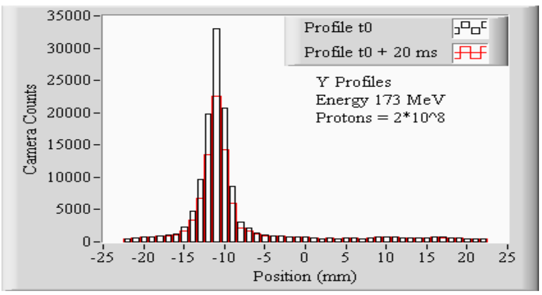

Figure 3: Vertical profiles on QPM: on the y axis are plotted the camera counts while on x axis there are the position (mm).

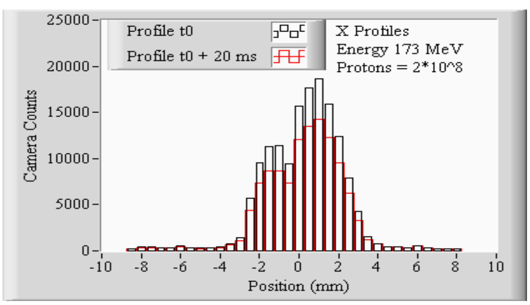

Figure 4: Horizontal profiles: camera counts vs position.

The profiles are acquired with a camera exposure time of 1ms and they provide beam position and dimension (the y–fibers are acquired two by two). Preliminary studies confirm that a non uniform beam with intense spikes can saturate the camera giving wrong information. A reduction of beam intensity (through the degrader placed in the injection line) or a short exposure time avoid saturation and permit a good acquisition and analysis as shown in the previous figures. The saturation will be corrected introducing a optical filter between fibers and CCD camera during next months.

Figure 5 shows the QIM beam intensity during a complete spill. In this case the degrader was not used and the total intensity is collected by the scintillating plate. A beam of $2*10^9$ protons is acquired by the QIM and the signal analyzed.

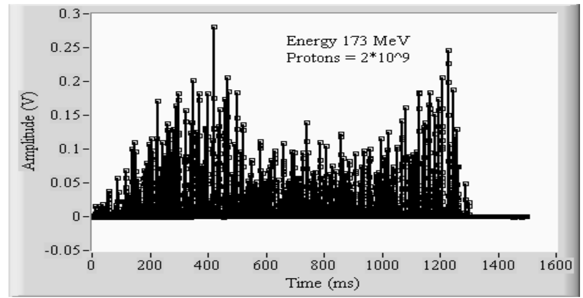

Figure 5: Beam intensity versus time. The amplifier gain is G5 and the acquisition rate is 10 kHz.

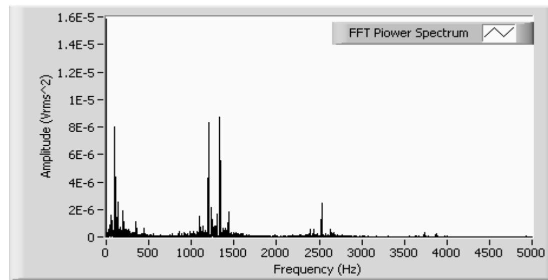

Figure 6: FFT power spectrum of the signal shown in Figure 5.

The plot shows that the uniformity of the extracted spill is not yet optimized; the compensation of intensity ripple is under study. Signal FFT can be of great help in this scenario. Figure 6 shows the power spectrum of the signal in Figure 5 and the peaks at 100 Hz, 1200 Hz (both due to the dipoles power supply ripple) and at 1330 Hz are clearly visible.

CONCLUSION

The Qualification Monitor is a detector placed in the CNAO extraction line that has to guarantee the beam qualification before the patient treatment. The main issue of QM is the characterization of the beam in position, dimensions and intensity and it has to return the goodness of the beam after fast online analysis. During the commissioning phase, the QM can be used to check the behaviour of the beam during the full spill and it helps in the beam optimization. At the present time the Qualification Monitor is properly working, giving strong information about the behaviour of the beam and being a useful detector in the commissioning phase for the beam optimization.

REFERENCES

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[2] G. Bazzano, “Status of the Commissioning of the Centro Nazionale di Adroterapia Oncologica (CNAO)”, Proceeding IPAC'10, Kyoto, Japan.
[3] V. Lante, “Beam qualification at CNAO: a Preliminary numerical investigation”, TNRI master thesis (2009).