Watch Dog detector for beam diagnostic in hadrontherapy application

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Watch Dog detector for beam diagnostic in hadrontherapy application

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Abstract. The "Watch Dog" is a beam monitor designed for medical accelerators, that will be installed at the end of the CNAO (Centro Nazionale di Adroterapia Oncologica) extraction lines. Its main goal is to achieve a real time monitoring of the beam position during patient treatments; the system can generate an interlock signal in case the measured quantity is out of the nominal range. In this paper the Watch Dog is described, and preliminary tests are presented.

1. Introduction

Hadrontherapy [1] is a radiotherapy technique which uses non elementary charged particles (in particular protons and carbon ions) instead of photons or electrons.

The CNAO (Centro Nazionale di Adroterapia Oncologica) is the first Italian Centre for deep hadrontherapy. Patient treatments began in September 2011 with protons and in November 2012 with carbon ions. An elaborated beam control is required to ensure patient safety and a correct dose delivery to the tumor volume. For this purpose a sizeable amount of beam diagnostic instrumentation has been developed [2].

The "Watch Dog" (WD) is a position and profile beam monitor, based on the scintillation process, that will be installed at the end of the CNAO extraction lines. The hardware is designed, built and assembled and a first release of motion and data acquisition software is ready. Preliminary laboratory tests and with beam have been performed.

The first part of the paper presents the CNAO facility and the HEBT (High Energy Beam Transfer) lines. The second one describes the WD detector. The third one deals with preliminary tests in lab and with beam. In the conclusions the open points are discussed.

2. The CNAO facility and the HEBT lines

The CNAO accelerator (figure 1) consists mainly of a 25 m diameter synchrotron that accelerates the proton or the carbon ion beam until the desired kinetic energy. Four HEBT (High Energy Beam Transfer) lines (three horizontal and one vertical) (figure 2), deliver the accelerated beam to three treatment rooms. The beam is continuously extracted from the synchrotron with a slow extraction process, during a period variable from 1 to 10 seconds. The range of extraction

energies for protons is 60 to 250 MeV, while that for carbon ions is 120 to 400 MeV/u.
The dose is delivered to the patient using an active technique. The target volume is divided in slices, each one corresponding to a defined beam kinetic energy, and the pencil beam is deflected by two fast magnets on the horizontal and the vertical plane in order to "paint" each slice. Beam size at the entrance of the two Scanning Magnets varies with the energy of the particles from 4 to 10 mm for each direction (horizontal and vertical) independently. Beam position at the entrance shall be fixed with a great precision (between 0.1 and 0.2 mm) to allow the Dose Delivery System ([3], [4]) to work properly and efficiently[1].

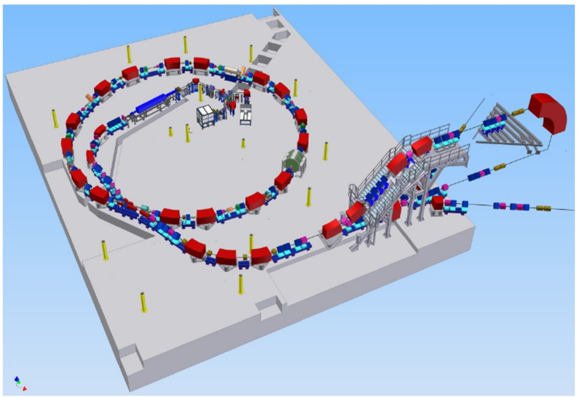

Figure 1: The CNAO facility.

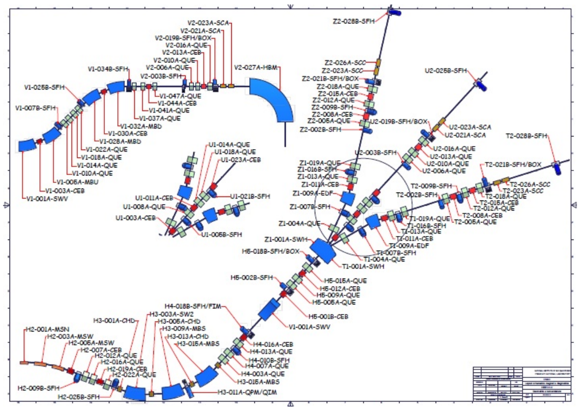

Figure 2: The HEBT lines.

3. The Watch Dog detector

The WD detector (figure 3) is a beam monitor that will be installed almost at the end of each HEBT line, just before the Scanning Magnets entrance (before the thin window, i.e. under vacuum). Its main goal is to monitor in real time and in a non destructive way the beam position and to generate an interlock signal if the measured quantity is out of the nominal range. It may also scan the full beam spot to provide horizontal and vertical beam profiles.
The WD consists of two couples of scintillating fibers (type SCSF-3HF(1500)) displaced transversely to the beam direction, in the horizontal and the vertical beam planes, and coupled to Avalanche Photo-Diodes (APDs, made by Hamamatsu, model S8664-10K). Particles crossing fibers release energy and produce light which is converted by the APDs to a current signal proportional to the number of particles crossing the fiber.
Each fiber is mounted on a movable mechanism, actuated by a brushless motor. Fiber position measurement is constantly provided by a linear potentiometer, whose analog signal output is proportional to the absolute fiber position.

3.1. Use: Watch Dog Mode and Scanning Mode

This detector can be used both in Watch Dog and in Scanning Mode. In the first case the WD can be used during patient treatments, because it doesn't perturb the beam. Fibers are moved up to a fixed position, at beam spot borders, in order to intercept only the tails of the beam. The fiber positions are decided *a priori* according to the beam characteristics and the information about the position is distributed by the Timing System before each cycle. The beam center of

[1] The dose must be delivered to the target with a 2% precision. The Dose Delivery System is designed in order to give an interlock if the position of the beam on the target is out of the range that guarantees such a precision on the dose delivered.

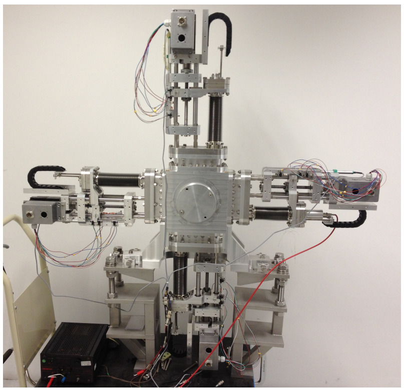

Figure 3: WD detector layout.

gravity (c.g.) can be reconstructed by measuring the normalized quantity:

$$\frac{I_1 - I_2}{I_1 + I_2} \propto c.g. \tag{1}$$

where I_1 and I_2 are the output signals of two APDs connected to a couple of parallel fibers. In the second case each fiber scans the entire beam spot. The transverse beam profile can be reconstructed by plotting $I_{fiber}\ Vs\ Position_{fiber}$. In this modality the WD cannot be used during patient treatments because it perturbs the beam.

4. Preliminary results with a light source

Preliminary tests on the WD were performed to study the detector response to a light source and its performances. A collimated light beam[2] was delivered in the WD vacuum chamber in place of the beam; the potentiometer output signal was acquired synchronously with the APD output signal. The first one is proportional to the fiber position, and the second one is converted to a voltage signal by a current-to-voltage amplifier. Figure 4 shows the light profiles obtained by scanning the light beam with the fiber, and plotted after the raw data processing. Each profile corresponds to a particular value of the High Voltage provided to the APD.

4.1. APD gain curve and dark current trend

Figure 5 shows the APD gain and the dark current trend as function of HV, expressed in decibel[3]. The gain was obtained by processing data used to reconstruct the light profiles. For each value of the HV provided (from 200 V to 440 V), the APD output signal was integrated over the number of samples and then scaled with respect to the integral value obtained for HV equal to 200 V. To perform dark current measurements the fiber was shielded from the ambient light and placed in a fixed position. Data were acquired by changing the HV provided to the APD from 200 V to 440 V. The dark current curve was obtained by integrating the APD output signal over the number of samples[4] for each HV value, and by scaling with respect to the integral value obtained for HV equal to 200 V [5]. We find that the experimental curves are in good agreement

[2] The light source was collimated through an alluminium plate with a hole (1 cm of diameter) placed in front of the tank (housing the fibers) aperture.
[3] With reference to 35.61 V, the integral value calculated for an APD supply voltage of 200V.
[4] 8000 samples were acquired with a 5kHz rate both for the gain and for the dark current measurements.
[5] The dark current value for the APD supplied with 200V is 60pA (from the APD datasheet).

with those reported on the APD data sheet.

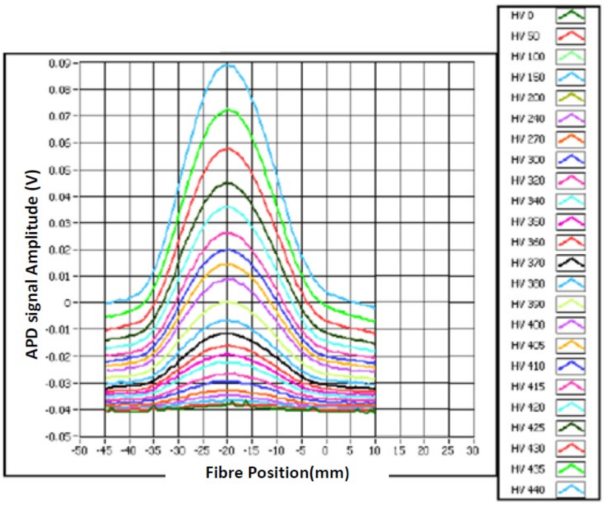

Figure 4: Light Profiles obtained by scanning the light beam with one fiber (plot obtained after raw data processing). Each colored line corresponds to a different value of the High Voltage provided to the APD.

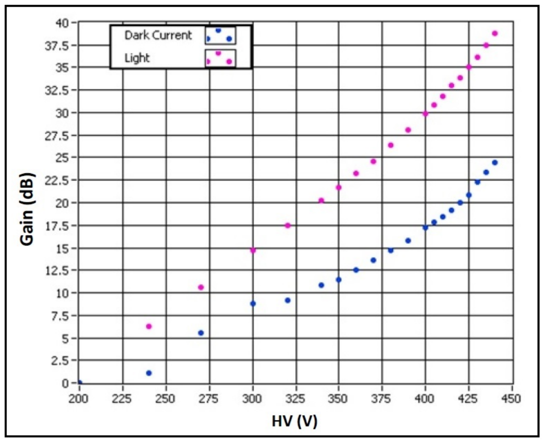

Figure 5: APD gain curve and dark current trend in the provided HV range 200 V to 440 V.

4.2. WD spatial resolution and accuracy

For this test the APD was supplied by 420 V, in order to obtain a quite high signal amplitude at the output. The light was sent to the detector sensitive area through a vertical slit. The slit was horizontally displaced in ten different equally spaced fixed positions. For each configuration ten light beam scans were performed, and the peak average position and the standard deviation were computed: they are reported on the vertical axis in figure 6. Standard deviation values are quite small (of the order of tenths of mm), which implies a good spatial resolution. On the horizontal axis of the plot the ten horizontal slit positions are reported, with the error due to the imprecision in displacing the slit (± 1mm). We observe a linear relation between the slit position and the peak average position, that implies also a good accuracy of the detector in measuring a beam position displacement.

5. Preliminary beam tests

In beam tests the WD was placed in air, at the isocenter of a treatment room. One fixed fiber, placed at the center of the active area, was aligned with the proton beam. The APD was supplied by 420 V and the output signal was acquired. Asynchronous acquisitions were performed every six seconds[6] with the beam and they are compared with dark current measurements. Figure 7 shows data obtained by sampling at 5 KHz (raw data). By averaging the acquired samples over a 20 ms period it is possible to obtain a good signal to noise ratio, as shown in figure 8, where the spill duration (about one second) is also visible.

6. Conclusions

The usefulness and the innovation of the WD are related to its capability in monitoring on-line the beam position during patient treatment giving a fast interlock in the case it is out of the

[6] While beam cycles are of five seconds.

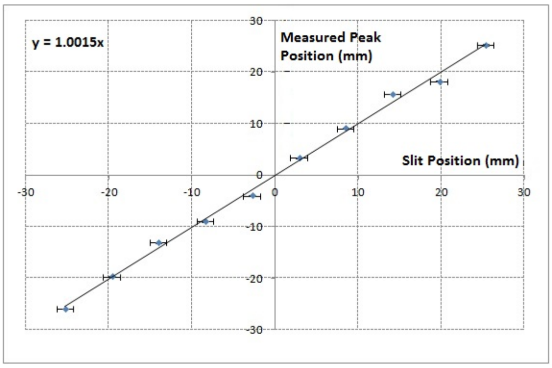

Figure 6: Measured peak position (mm) plotted versus the slit position (mm). A linear fit is performed on data. The equation of the fit line is expressed in red on the top.

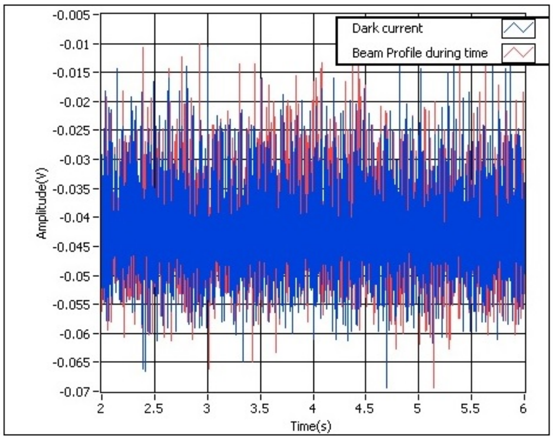

Figure 7: APD output amplitude during time for an acquisition rate of 5 kHz. The red line is the signal generated by the beam, the blue line is the dark current measurement.

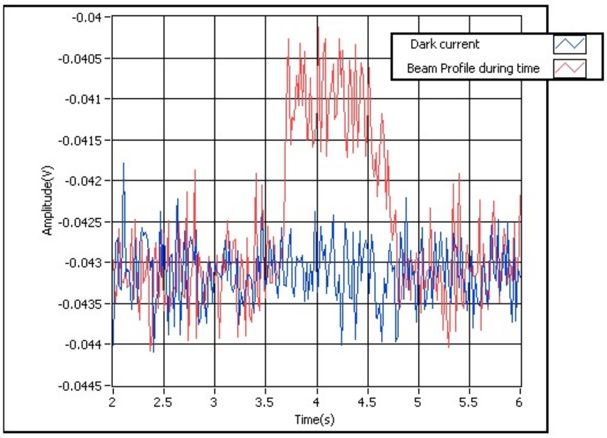

Figure 8: APD output amplitude during time after raw data processing: the acquired samples were averaged over a period of 20 ms. The red line corresponds to the signal generated by the beam, while the blue line is the dark current measurement

nominal range. Until now a prototype has been built and assembled and a first version of the motion and acquisition software has been delivered. Preliminary tests have been performed to study the detector response and its performances and to check the acquisition software. More beam tests will be performed in the next future (i.e. beam scans, tests with different particles and energies, time resolution of the detector and time response), the software will be integrated in the accelerator Control System, and the detector will be eventually installed on the beam line.

References

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