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Original Article

Preliminary Characterization Tests of Detectors of on-Line Monitor Systems of the Italian National Center of Oncological Hadron-Therapy (CNAO)

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Abstract

Introduction

Hadron-therapy is an effective technique used to treat tumors that are located between or nearby vital organs. The Italian National Center of Oncological Hadron-therapy (CNAO) has been realized as the first facility in Italy to treat very difficult tumors with protons and Carbon ions. The on-line monitor system for CNAO has been developed by the Department of Physics of the University of Torino and Italian National Institute of Nuclear Physics (INFN). The monitoring system performs the on-line checking of the beam intensity, dimension, and beam position.

Materials and Methods

The monitor system is based on parallel plate ionization chambers and is composed of five ionization chambers with the anodes fully integrated or segmented in pixels or strips that are placed in two boxes. A series of measurements were performed that involve the background current and the detectors have been characterized by means of a series of preliminary testes in order to verify reproducibility and uniformity of the chambers using an X-ray source.

Results

The measured background currents for StripX, StripY and Pixel chambers are five orders of magnitude smaller than the nominal treatment current. The reproducibility error of chambers is less than 1%. The analysis of the uniformity showed that the monitor devices have a spread in gain that varies, but only about 2%.

Conclusion

The reproducibility and the uniformity values are considered as a good result, taking into account that the X-ray energy range is several orders of magnitude smaller than the particle energies used at CNAO.

Keywords: Active Beam Delivery System, Hadron Therapy, Ionization Chamber, On-Line Detectors

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1. Introduction

Radiation therapy is becoming increasingly sophisticated [1]. But, not all tumors respond positively to conventional radiation therapy, and are therefore classified as being radio-resistant. Moreover, some tumors are located very close to sensitive organs, such as the optic nerve or the spinal cord. For these tumors the excellent targeting properties of Hadrons can be used to deliver higher tumor doses while reducing the doses absorbed by the surrounding healthy tissues [2, 3]. The use of Hadron therapy as an advanced technique of radiation therapy is increasing. The advantage of the high accuracy of the dose deposition resulting from the physical properties of Hadrons and the higher radiobiological effectiveness make this kind of radiation a promising tool for cancer treatment. Protons and Carbon ions deposit their maximum energy density in the Bragg Peak at the end of their range, where they produce severe damage to the tumoral cells while sparing both the transversely adjacent, and deeper located healthy tissues. Proton and Carbon ions can easily be formed as narrowly focused and scanning pencil beams of variable penetrating depth, so that any part of the tumor can be accurately irradiated with optimal precision. They penetrate into the patient body in the forward direction the patient with minor lateral scattering and longitudinal straggling [3].

The Italian National Center of Oncological Hadron-therapy (CNAO) in Pavia (Italy) [4], is one of the few facilities in the world, that allows patient treatments with protons and Carbon ions by means of a synchrotron accelerator. Protons with energy range between 60-250 MeV and Carbon ions with an energy range between 120-400 MeV/u will be delivered at CNAO as the first Hadron-therapy center in Italy. However, the new modalities of dose delivery [5] for this type of radiation imply a high technology development, and the on-line monitoring of the beam plays a crucial role for a successful treatment. The beam monitoring system for the CNAO has been developed by the Department of Physics of the University of Torino and INFN in

collaboration with the CNAO. The beam delivery system performs the on-line check of the beam intensity, dimension and beam position, and the treatment practicality is mainly due to its ability and operation in case of right and faulty beam situations. Therefore, in this article the preliminary characterization tests on detectors of the monitoring system and evaluation of results as background current, reproducibility and gain uniformity will be presented.

2. Materials and Methods

2.1. Active Beam Delivery System (ABDS)

The particle beam produced by the synchrotron is delivered at different energies by an active spread-out system (figure 1). The target tumor is divided into slices at different depths and for each slice there is a corresponding level of beam energy. A magnetic deflection system is used to paint a slice, then the beam energy is decreased and the beam paints another slice until all the slices are painted and the volume is completely covered [5]. The pencil beam has to be monitored on-line in a non-invasive way, in particular beam position, shape, and intensity have to be measured just upstream of the patient in order to control in the treatment in real-time, and dump the beam in case of failure. This goal is achieved by the CNAO Active Beam Delivery System (ABDS) which includes all the elements between the scanning magnets and the patient (the nozzle, five ionization chambers, and passive filters) and the interfaces to control delivery of the beam during the treatment (figure 1).

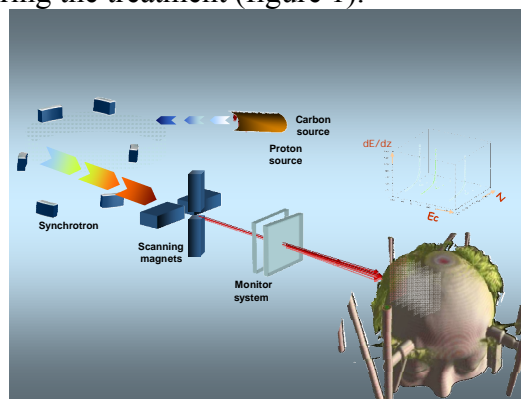


Figure 1. The Active Beam Delivery System of CNAO

2.2. On-line monitoring system

The on-line monitoring system of CNAO consists of five parallel plate ionization chambers placed at the end of the beam line (figure 2): two integral ionization chambers, two strip chambers and one pixel chamber installed for safety in two completely independent boxes named BOX1 and BOX2 (for read-out electronics and power supply). BOX1 includes three ionization chambers: an Integrall with a fully integrating anode and two segmented StripX and StripY with anodes segmented in oriented strips (vertically and horizontally)(figure 3). BOX2 contains two ionization chambers, an Integral2 the same as Integrall1 and one Pixel with the anode segmented in pixels (figure 4).

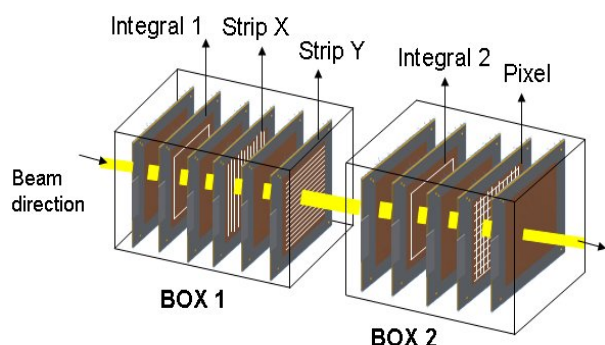


Figure 2. Sketch of the order of the monitoring chambers [13]

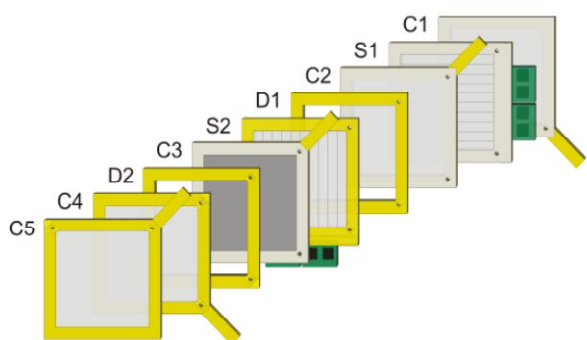


Figure 3. Schematic draw of BOX1. The cathodes and strip anodes are labeled as C and S, respectively. The integral anode is labeled as C3. The gap frames are labeled as D.

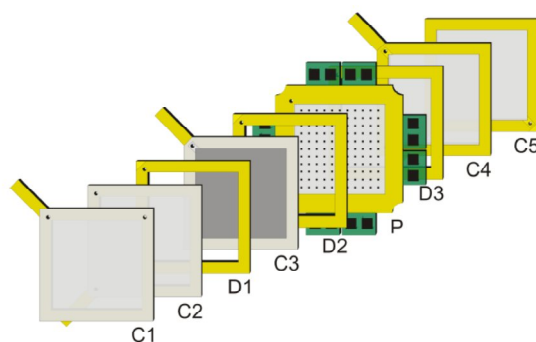


Figure 4. Schematic draw of BOX2. The cathodes and pixel anodes are labeled as C and P, respectively. The integral anode is labeled as C3. The gap frames are labeled as D.

2.3. Detector construction

The structure of monitor system detectors is based on parallel plate ionization chamber architecture. The integral ionization chamber has a 12 μm mylar foil aluminized on one side as cathode while the anode is a 25 μm kapton foil, covered by a 17 μm aluminum layer with a $24 \times 24 \text{ cm}^2$ complete sensitive area. The strip ionization chambers [6] are composed of one anode each one (StripX and StripY) made of 25 μm kapton foil that supports a 17 μm aluminum layer with 128 strips 1.55 mm wide and spaced 0.1 mm. The strip anodes oriented vertically (STPX) and horizontally (STPY) are mounted facing the cathode made of a 25 μm Mylar foil aluminized on both sides (figure 2). The pixel ionization chamber [7, 8] has a cathode made of a 12 μm mylar foil aluminized on one side, and the pixel anode made of 50 μm kapton foil that supports Copper pixels of 20 μm thickness. There are 1024 pixels ordered in a matrix of 32×32 pixels, the pixel pitch is 6.6 mm and the total sensitive area is $21 \times 21 \text{ cm}^2$ [9].

2.4. Detector characteristics

Every integral ionization chamber allows an intensity measurement of 1 μs . The strip ionization chambers allow the beam position measurement every 100-150 μs . Every strip ionization chamber measures the beam projection along the integration line. The beam position is then obtained with a precision of 100 μm through the evaluation of the centre of

gravity. The strip ionization chambers can also provide two measurements of the beam intensity. The pixel ionization chamber allows position and intensity measurements in two dimensions with a precision of 200 μm and reading rates of 20 kHz. There is a gap of 5 mm between the anode and cathode of each ionization chamber which is filled with Nitrogen to obtain the maximum efficiency of collected charge; also high voltage cathode polarization is +400 V, [9].

2.5. Measurements and tests of characterization

To characterize the designed and constructed detectors as the monitor system for the CNAO housed in BOX1 and BOX2 a series of measurements were performed that involved the background current, the reproducibility and the gain uniformity of the detector's sensitive area [10,11].

2.5.1. Background current

The background current is defined as the leakage current in the presence of high voltage and absence of the beam. This value has to be subtracted to determine the correct detector response when exposed to radiation and should be small compared to the expected signals.

2.5.2. Characterization of chambers using X-ray source

The monitoring system is composed of five parallel plates forming the ionizing chambers, which is characterized by means of a series of preliminary testes in order to verify reproducibility and uniformity of sensitive areas of chambers using X-ray source for clinical applications.

2.5.3. Experimental set-up

The experimental set-up that characterizes the chambers with X-rays is composed of an X-ray source working at 50 kV, with a current of 120 mA and an exposition time of 1.33 ms, which corresponds to 160 mAs with a Pb collimator of 2 mm in diameter, located at a distance of 10 cm from the detectors' entrance face. The data acquisition system used for the characterization of the beam monitor device is based on National Instruments PCI extensions for Instrumentation (PXI) and LabVIEW

software [12], the reading was performed with a time interval of 100 ms.

2.5.4. Reproducibility

To verify the reproducibility of the ionization chambers response (BOX1 and BOX2); ten sets of data were acquired by exposing each BOX1 and BOX2 individually to X-rays.

2.5.5. Uniformity of the sensitive area

The uniformity of a detector over the active surface is important, because it directly affects the smoothness of measurement. Ideally, a detector has the same sensitivity across its entire active area, within a given margin according to the specific application.

Alternatively, non-uniformity is experimentally determined and taken into account by an adequate signal analysis. In either case, it is important to measure the spread of uniformity [13].

3. Results

3.1. Background current

The operational quantum charge for these chambers is 200 fC. The background current was measured at 400 V. This value is special in the sense that it will be the voltage that is going to be used for monitoring the beam at the CNAO facility. Figure 5 shows the measured background current values for Integral1 and Integral2 chambers as a function of high voltage applied to the electrodes. Figure 6 shows the plot for the StripX, StripY and Pixel chambers. The measurements were taken at regular intervals of 60 s. However, it is worth mentioning that the currents of therapeutical beams will have values on the order of 10nA. Comparing this value with the background current values obtained for all the monitor devices measured, is easily deductable, so that they are about 5 orders of magnitude smaller[14].

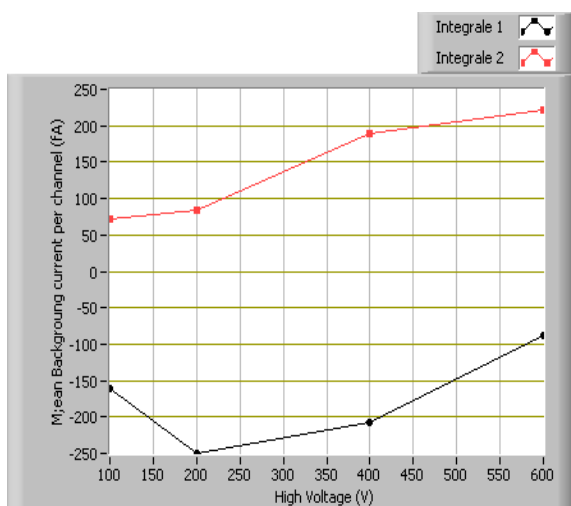


Figure 5. the measured background current values for Integrals 1 and Integral2 chambers as a function of high voltage applied to the electrodes.

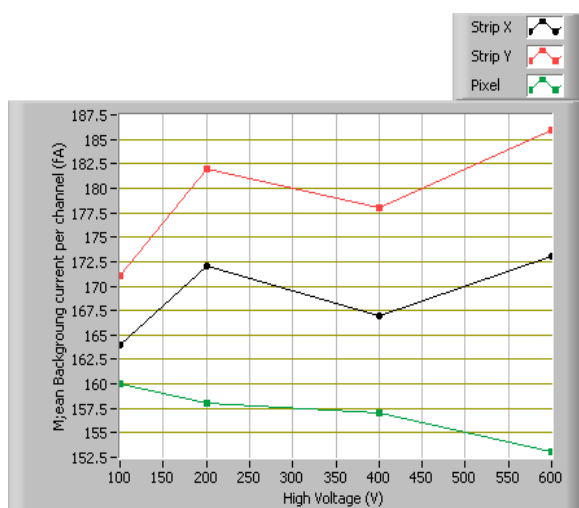


Figure 6. the measured background current values for StripX, StripY and Pixel chambers as a function of high voltage applied to the electrodes.

3.2. Reproducibility

Measurements were repeated aiming the beams at four selected points on five different positions over the sensitive area of the detectors as shown in figure 7. By analysis of data, of the reproducibility for BOX1 and BOX2, have been obtained error averages about 1% that show a good reproducibility response for the monitor devices. Figures 8 to 12 show counts versus measurement number in five points for Integrals 1, StripX, StripY, Integral2 and Pixel respectively. To limit the effect of the fluctuations due to the background in the case of the strip chambers, we chose to include only twenty strips around

the beam center, only those strips were taken into account for analysis which was hit by the beams. For analogous reasons, in the case of the pixel chamber only a 5×5 pixel area around the beam was analyzed [14].

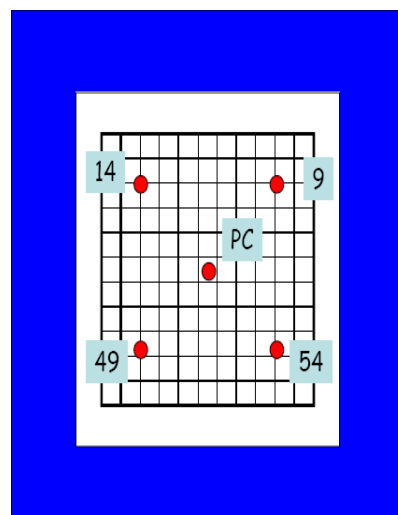


Figure 7. The selection criteria of five points of the sensitive area of chambers to perform the reproducibility test, 10 runs on each one.

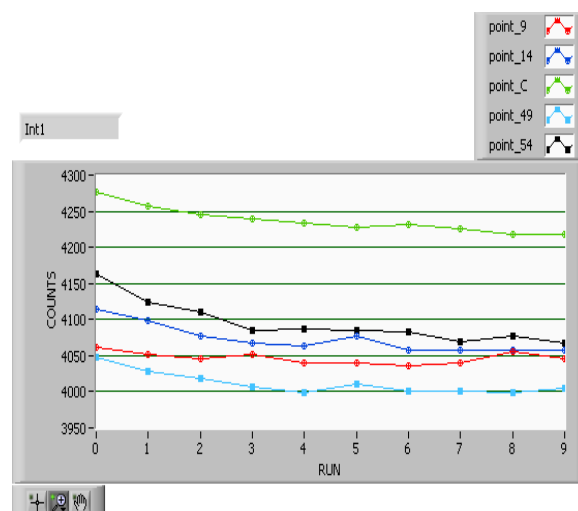


Figure 8. Integral counts vs. measurement number in five points, for Integral1 chamber (Int 1)

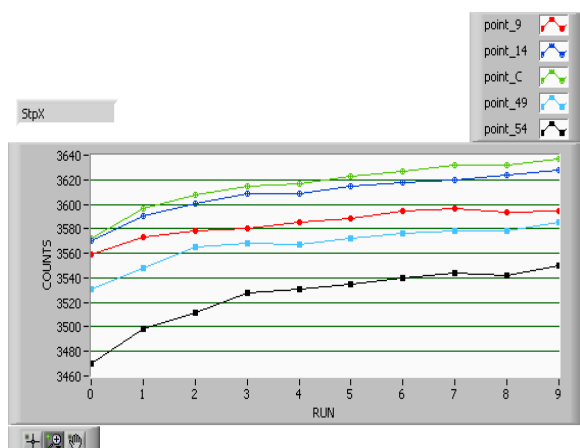


Figure 9. Integral counts vs. measurement number in five points for StripX chamber (StpX)

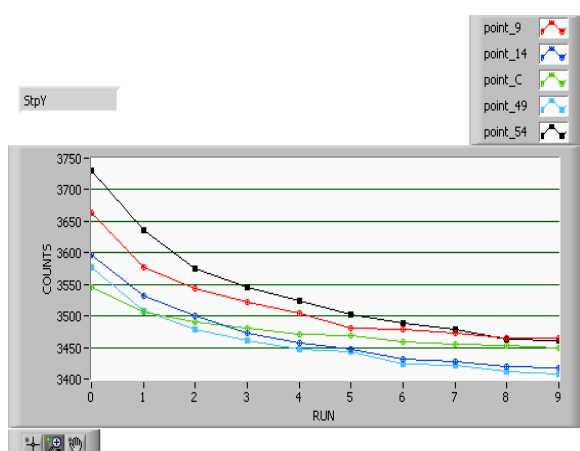


Figure 10. Integral counts vs. measurement number in five points for StripY chamber (StpY)

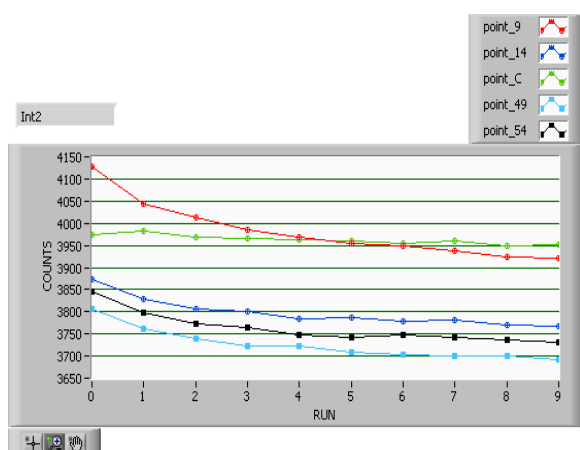


Figure 11. Total counts vs. measurement number in five points for Integral2 chamber (Int2)

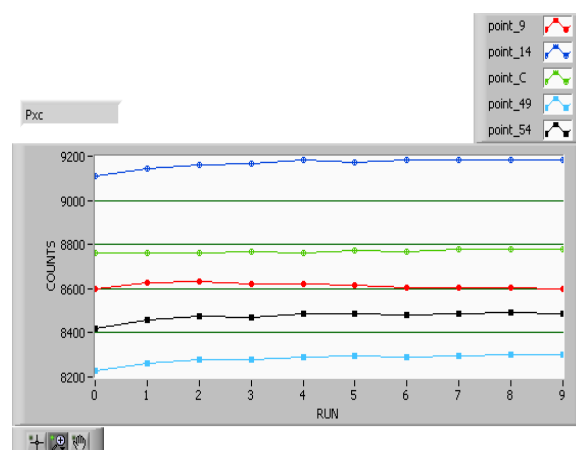


Figure 12. Total counts vs. measurement number in five points for Pixel chamber (Pxc)

3.3. Uniformity

The uniformity of the detectors housed in BOX1 and BOX2 was tested taking 64 expositions to X-rays aiming the beam to different spots spread over the whole sensitive area of the detectors. This procedure of uniformity testing was carried out following the path that is showed in figure 13, where the sensitive area was divided in to an 8×8 matrix. In order to follow the path it was necessary to move the detector horizontally and the head of the X-ray source vertically as shown in figure 13 by the arrows. Figure 14 shows uniformity values obtained for Integral1, StripX and StripY chambers, and figure 15 shows uniformity values obtained for Integral2 and Pixel Chambers. The analysis of the uniformity of BOX1 and BOX2 showed that the monitor devices have a spread in gain that varies (Table 1) only about 2% [14].

Table1. Percent errors reported for the uniformity

	StripX	StripY	Integral 1	Integral 2	Pixel
% σ	1.7	1.7	2	1.9	1.7

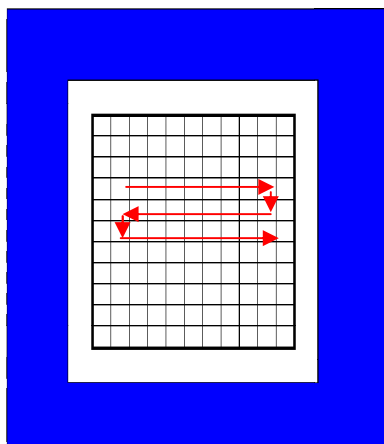


Figure 13. The path of X-ray source over the sensitive area of chambers during the uniformity test.

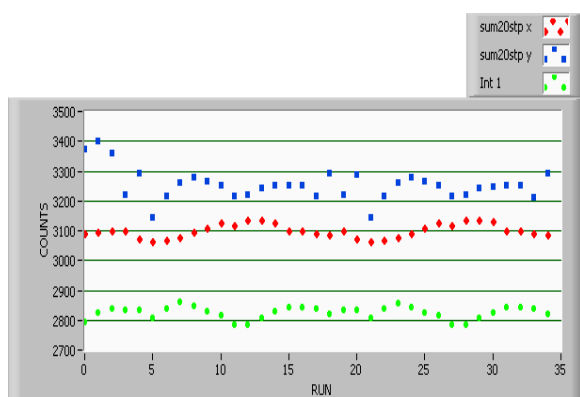


Figure 14. Values obtained for the uniformity test on the 36 points scanned with X Ray for Strip chambers (StpX, StpY) and Integral1 chamber (Int1)

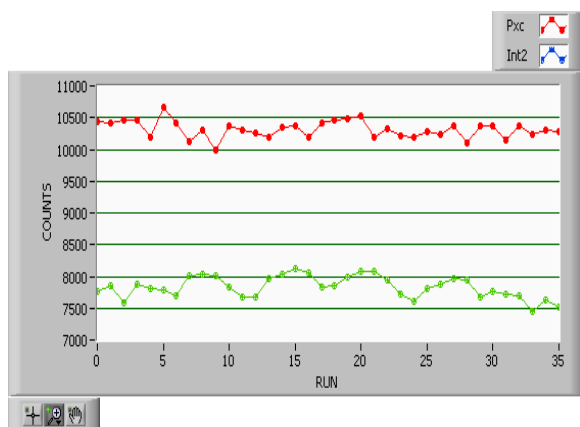


Figure 15. Values obtained for the uniformity test on the 36 points, scanned with X- Ray for Pixel chamber (Pxc) and Integral chamber (Int2)

4. Conclusion

The beam monitor system developed for CNAO to control intensity and position of the proton/ion radiotherapy beams has been built, and tested. The precision of the aimed position is less than $\pm 100 \mu\text{m}$. Temperature and pressure is measured and gas gain corrections are applied. Background currents are less than 200 fA, five order of magnitude smaller than the nominal treatment current ($\sim 10 \text{ nA}$). The detectors have been characterized by using X-rays, while statistical analysis of the data confirms their good performance. Reproducibility of the sensitive area on a single point defined as response constant with time, is better than 1%. Uniformity of the gain over the detector sensitive area is about 2 %. The reproducibility and the uniformity values are considered as a good result, taking into account that the X-ray energy range is several orders of magnitude smaller than the energy particles (protons and Carbon ions) that are used at CNAO.

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