Characterization and performances of a monitoring ionization chamber dedicated to IBA-universal irradiation head for Pencil Beam Scanning.

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Abstract

Every radiotherapy center has to be equipped with real-time beam monitoring devices. In 2008, the medical application group from the Laboratory of Corpuscular Physics (LPC Caen) developed an Ionization Chamber in collaboration with the company IBA (Ion Beam Applications). This monitoring device called IC2/3 was developed to be used in IBAs universal irradiation head for Pencil Beam Scanning (PBS). The objectives presented in this article are to characterize the IC2/3 monitor in the energy and flux ranges used in protontherapy. The equipment has been tested with an IBAs cyclotron able to deliver proton beams from 70 to 230 MeV. This beam monitoring device has been validated and is now installed at the Westdeutsches Protonentherapiezentrum Essen protontherapy center (WPE, Germany). The results obtained in both terms of spatial resolution and dose measurements are at least equal to the initials specifications needed for PBS purposes. The detector measures the dose with a relative precision better than 1% in the range 0.5 Gy/min to 8 Gy/min while the spatial resolution is higher than 250 m. The technology has been patented and five IC2/3 chambers were de-

livered to IBA. Nowadays, IBA produces the IC2/3 beam monitoring device as part of its Proteus 235 product

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1. Introduction

Protontherapy [1][2] is a special kind of radiotherapy using protons between 70 MeV and 230 MeV. Because proton beams undergo little scattering in matter and deliver most of the irradiation dose at a specific depth (Bragg Peak) depending on their initial energy, tumors can be precisely targeted while surrounding tissues might be spared. At first, Protontherapy was mainly limited to very specific kind of cancers, such as the eye cancer, but with time its uses got more and more diversified to become fully part of the cancer therapy toolbox. While the energy dose delivered by the beam to the tumor causes its inactivation, the dose prescribed by the physician and the dose delivered by the irradiation unit should be as close as possible. One of the main issues is to conform the delivered dose to the target volume whatever its shape might be. To this end, the IBA society and the Massachusetts General Hospital team have developed a dose delivery mode called Pencil Beam Scanning (PBS)[3]. It uses very narrow beam to scan the whole tumor in three dimensions while modulating the beam intensity to get the prescribed dose map. One of the fundamental safety requirements of the PBS technology is to check in real-time during the scanning process that the beam is at the right position in space with the right intensity.

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2. Description of the IC2/3 beam monitor

The Laboratory of Corpuscular Physics of Caen developed a 320 mm x 320 mm parallel plate ionization chamber composed of fifteen Mylar foil separated by 5mm air gaps. The detector is called IC2/3 for Ionization Chamber 2 and 3 while it is composed of two identical and fully independent (High Voltage alimentation and electronic setup) units IC2 and IC3. These two chambers allow achieving dose measurement redundancy that is a fundamental requirement for safety purposes. As sketched on Figure 1 each unit is composed of five 2.5 m Mylar electrodes covered in both side with metals. Three are connected to the High Voltage while the two others are measurements electrodes (virtually grounded), one being used for dose measurement (uniform film) and the second one for beam position measurement (striped film) along one axis (horizontal for IC2 and vertical for IC3). Apart from the two units, 3 other films are put to the ground and ensure the electrostatics pressure equilibrium. In addition, two Mylar are used to cover both entry and exit windows but those are much thicker (25 m) for strength purposes. The whole chamber is 6.86 cm thick for total water equivalent thickness of 187 m.

The specification for IC2/3 monitoring device were to have a global uniformity in the measurement response (dose measurement, spot size, spatial resolution, repeatability) of better than 1%.

Because the beam spot swipes the whole detector, the detector response should be position-independent. The beam-induced ionization of the detector air should be identical at any position in the detector; while the beam direction is orthogonal to the detector the only parameter affecting the response

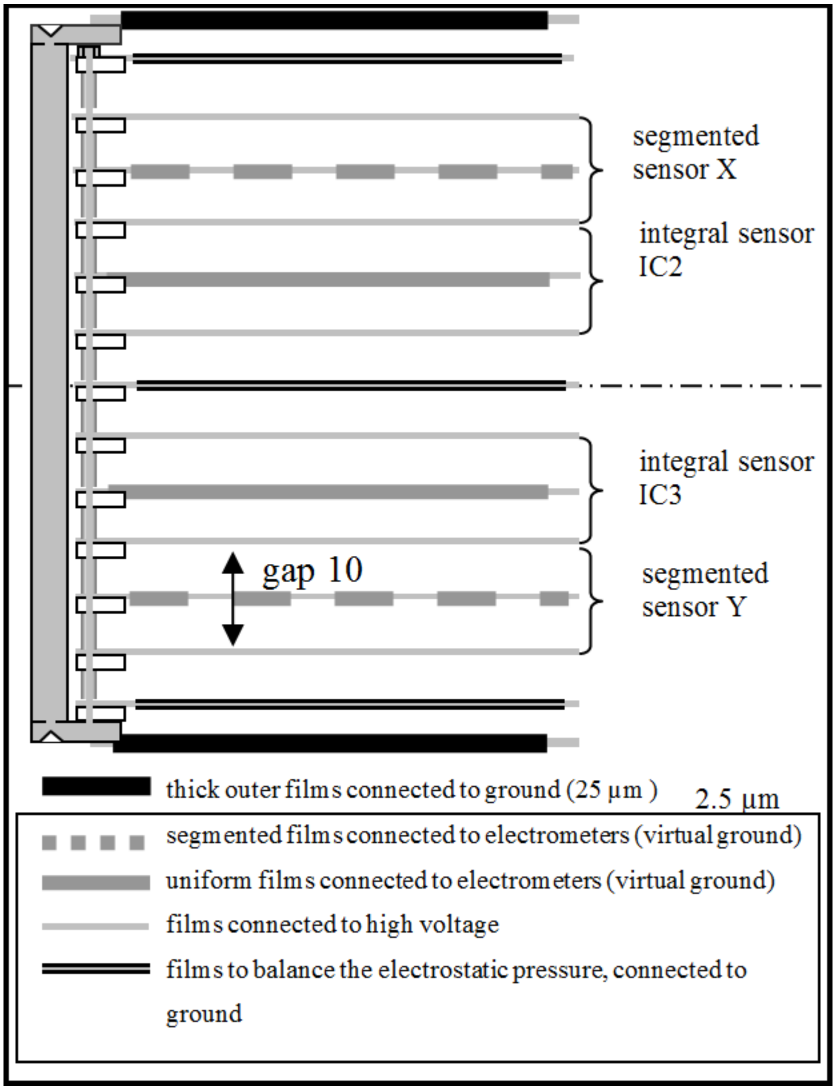

Figure 1: Vertical section of IC2/3.

is the eventual variation of the 5mm air gap between electrodes. The electrodes fixation spacing has to be carefully adjusted, but it is not enough to ensure parallelism between electrodes. This spacing has to be kept constant when the high voltage is turned on. The sandwich of electrodes, successively connected to the high voltage and the ground, allows getting electrostatic pressure equilibrium. The design study showed that the layers localized at the center of the detector are less affected by the electrostatic pressure and therefore have less variation in their gap width. That is why the dose measurement layers are located in the middle of the chamber and are surrounded by the position measurement Mylar films.

For the position measurement layer, plain Mylar films are covered by strips on both sides deposited by vacuum evaporation. There are 64 stripes with a 5 mm-periodicity on both IC2 and IC3. They are oriented to give the x position for IC2 and y for IC3. Instead of using strips to localize the beam, it is possible to use pixels that would give an x-y position with a single foil [4]. The dose measurement layers are single layer aluminized Mylar foils covered in the plain side by a thin gold layer (200nm). Gold was used for its better results in attaching to the Mylar films. The dose is measured by integrating the signal collected on each film every millisecond.

3. Set up

Three series of tests were performed at the Westdeutsches Protontherapiezentrum Essen to evaluate the performances of the IC2/3 detector with a proton beam. The WPE is equipped with an IBA Proteus 235 device, with a cyclotron producing proton beams between 70 and 230 MeV. The tests were realized in a treatment room with a Pencil Beam Scanning delivery technique and equipped with an isocentricgantry. Results of the first two IC2/3 prototypes were compared to those of a PTW ionization chamber ($Roos^{TM}$ Electron Ionization Chamber) placed in air one meter away from the isocenter. During the test four beam configurations (Table 3) were used with different energies, intensity and sizes.

Energy	Beam Intensity	σ_{beam}
100 MeV	1 nA	4.76 mm
100 MeV	2.8 nA	4.76 mm
230 MeV	2 nA	2.85 mm
230 MeV	20 nA	2.85 mm

Table 1: Beam configurations

4. Results

4.1. Repeatability Measurement

To assess the repeatability of the response of IC2/3, eleven measurements were realized in identical conditions (operating mode, beam configuration) and in a short period of time. Measurements of both IC2 and IC3 were realized at the same time and normalized by the PTW measurement to prevent the beam fluctuation from interfering with measures. In table 4.1 the results of the measurements are presented normalized by the mean value.

The measured standard deviation is 0.6% for the repeatability test which is in good agreement with the desired specifications.

4.2. Collection efficiency

Positive and negative charges created in the chamber by the protons might recombine while traveling toward their own collection electrodes. This effect depends, among other factors, on the gas density and the drifting time of each charge. The saturation operating mode is reached when all charges created are collected (100% of collection efficiency) and this can be approached

Series	$\frac{Q_{IC2}}{Q_{PTW}}$ (%)	$\frac{Q_{IC3}}{Q_{PTW}}$ (%)	$\frac{Q_{IC2}}{Q_{IC3}}$ (%)
1	100.069	100.081	99.989
2	99.842	99.850	99.993
3	100.676	100.655	100.022
4	100.073	100.073	100.001
5	100.748	100.731	100.018
6	100.679	100.664	100.016
7	99.096	99.072	100.025
8	100.248	100.221	100.028
9	100.077	100.083	99.995
10	99.214	99.207	100.008
11	99.292	99.384	99.908
Mean value of Q_{IC}/Q_{PTW}	100.00	100.00	100.00
Relative standard deviation (%)	0.593	0.580	0.033

Table 2: Repeatability test measurements made with IC2/3 in relation to the reference chamber measurements (2.8 nA, 100 MeV, σ_{beam}= 4.76 mm and 1.2 kV)

when the polarization voltage of the electrodes is high enough. The goal was to determine the lowest polarization voltage allowing a collection efficiency better than 99%. The measurement has been performed irradiating the detector with a beam of constant current and decreasing the polarized voltage by step of 100 volts. Decreasing the voltage instead of increasing it allows preventing recombination to occur at some measurement and modifying results of the following steps. This way, only the last measurement (at lowest voltage) might be perturbed.

Measurements were done on both IC2 and IC3 but only the results Q_{IC3}/Q_{Ref} in function of the voltage for IC3 are presented (figure 2 and 3), normalized by the mean value of the measurement above 1200V (excepted for the 230 MeV - 20 nA measurement).

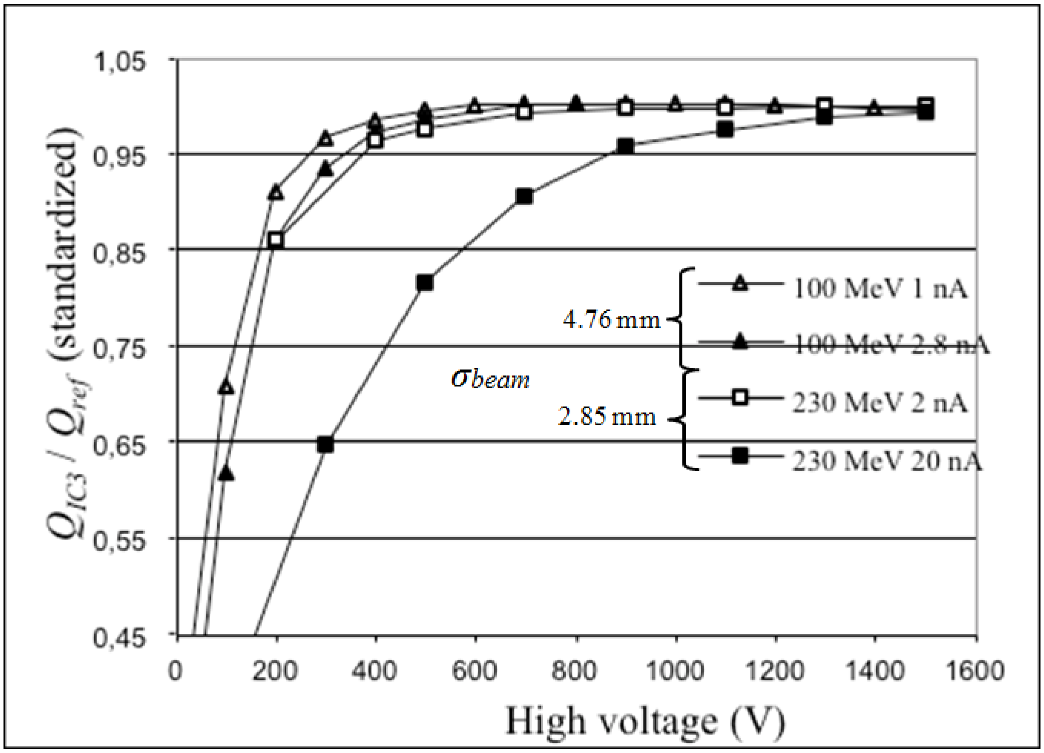

Figure 2: $Q_{IC}//Q_{Ref}$ standardized for three current values in relation to voltage and for two beam energy values.

The curve shows a tendency to saturation. A Q_{IC3}/Q_{Ref}ratio below one means that not every charge created is collected and that recombination still occurs. For a high beam intensity a 1500V potential difference ensure a collection efficiency above 99.5%. With a lower beam current, the ionization density decreases and so the probability of two charges of opposite sign to recombine is even lower and the polarization voltage needed to reach the saturation point could be lower than 1500V. With a standard beam condition

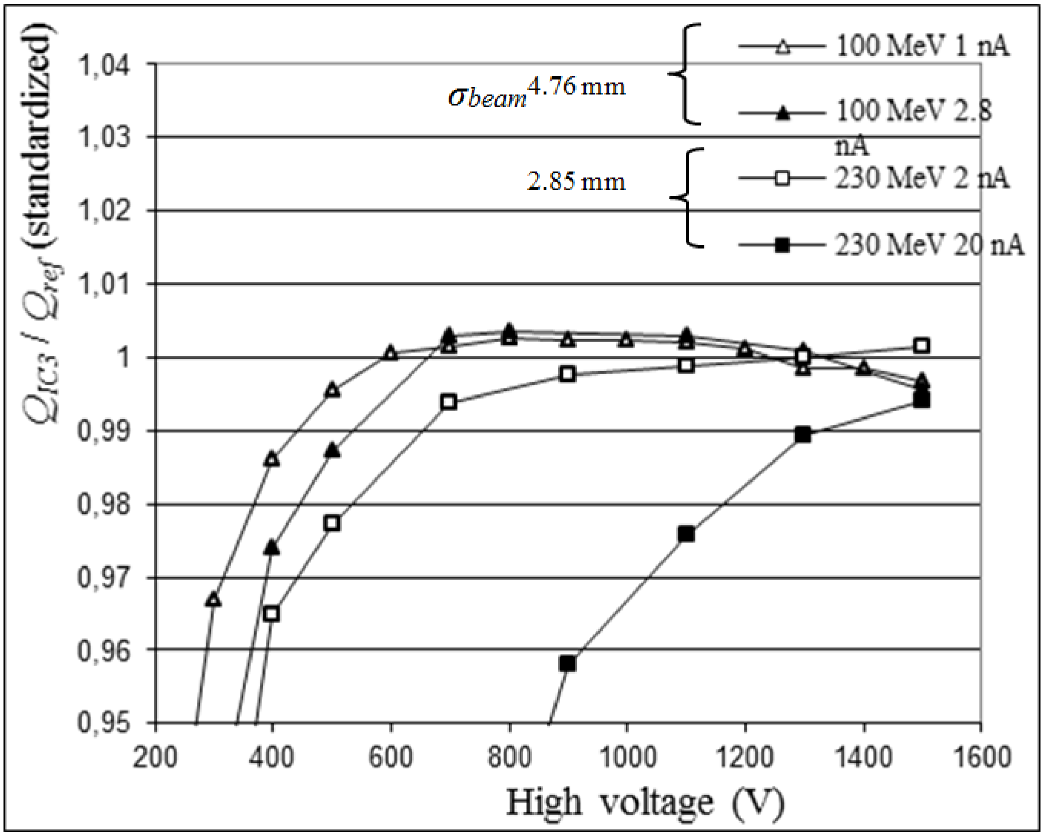

Figure 3: Zoom of the figure 2.

(100MeV, 2.8 nA), 1200 V is enough to get 99.5% collection efficiency.

The following curve presents the Q_{IC2}/Q_{Ref} ratio measured while increasing and decreasing the voltage to check for differences between the two situations.

As shown on figure 4 there is no noticeable difference between the measurements done when increasing or when decreasing the voltage.

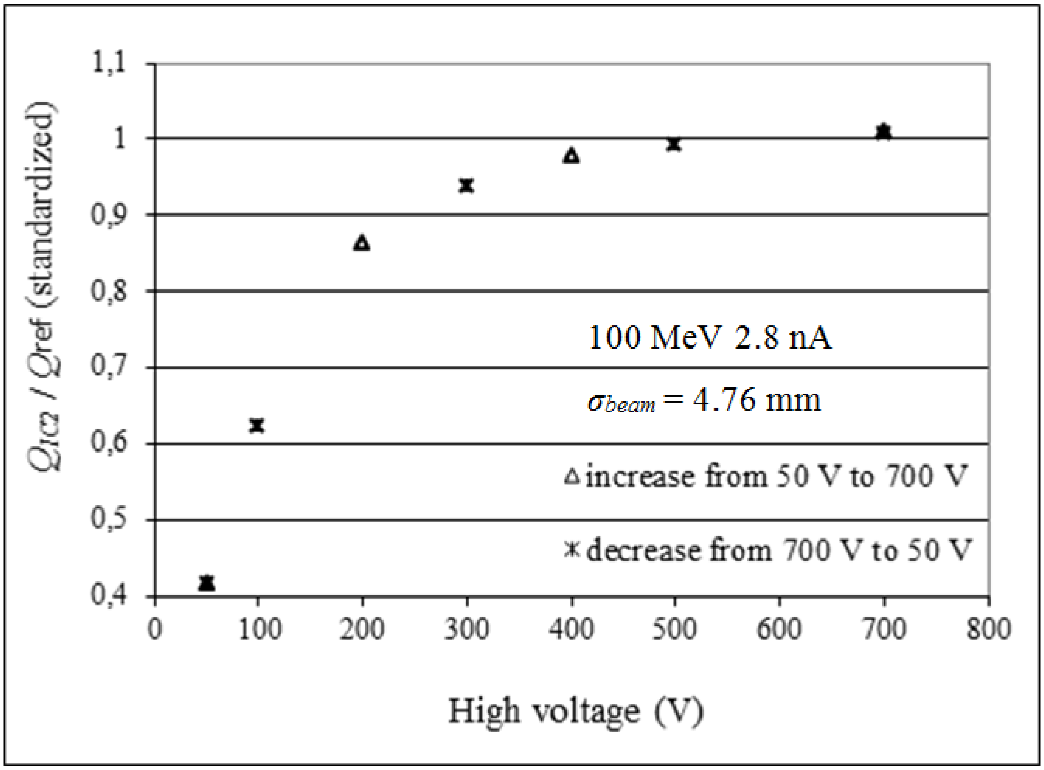

Figure 4: Test to evaluate the hysteresis phenomenon at 2.8 nA and 100 MeV.

4.3. Linearity

The aim of the linearity test is to check that the relation between the deposited dose and the measured charge is truly linear. The measurement is performed irradiating the detector with a beam intensity that is decreased from 3 nA to 0.5nA while keeping the integration time constant. In order to reduce the beam intensity investing the PTW reference chamber, this latter one was placed (in air) one meter away from the IC2/3 detector with a 3 mm thick lead foil between them enlarging the beam by scattering.

On figure 5, the ratio QIC2/QIC3 is nearly constant with a mean value

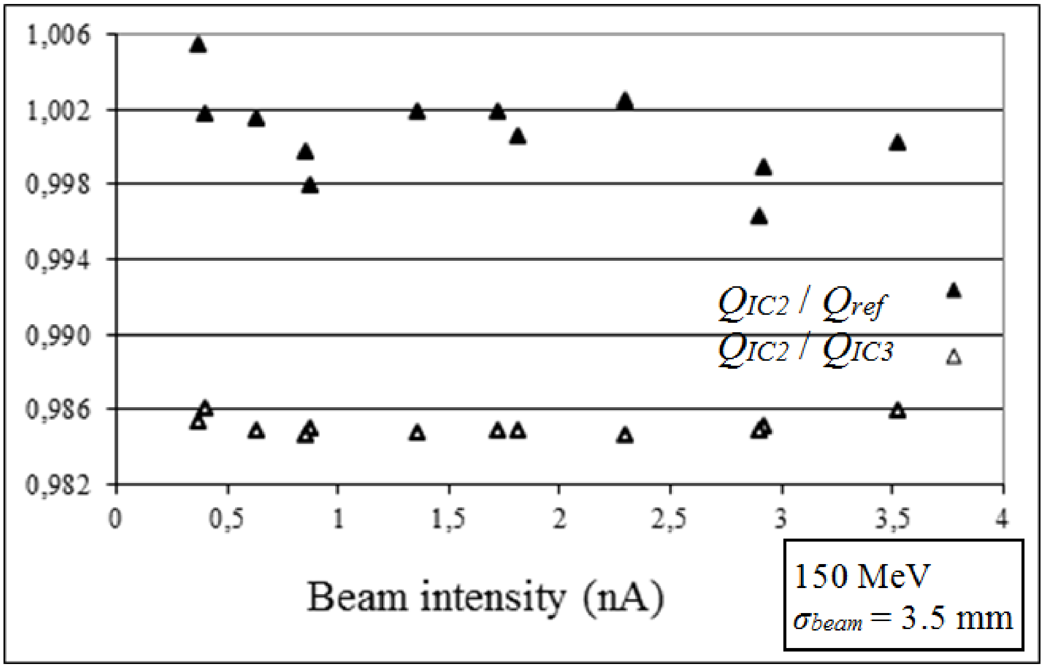

Figure 5: Q_{IC2}/Q_{Ref} and Q_{IC2}/Q_{IC3} in relation to beam intensity.

of 98.51% with a standard deviation of 0.047%. The curve Q_{IC2}/Q_{Ref} shows more fluctuations. In fact, the standard deviation of Q_{IC2}/Q_{Ref} and Q_{IC3}/Q_{Ref} is 0.24% which is higher but still under the 1% required.

4.4. Uniformity of the detector response

The detector can measure different characteristics of the beam: the beam flux integrated on the whole detector area or on each strip, allowing to infer beams position and size. The uniformity test allows testing that both dose flux and beam size are measured correctly on the whole detector area. As the required dose uniformity is 1%, the mechanical structure should insure that the variation in the gs gap is not larger than 1%. The experimental setup to measure such uniformity consists of two IC2/3 chambers (Fig. 6).

The first one is fixed on the nozzle and the second one is positioned further away (132cm) on a mobile treatment bed. The beam is not scanned and the bed is moved in a direction orthogonal to the beam axis so that the charge is measured always at the same position in the chamber 1 while it is measured in different positions on the detectors area of the chamber 2. Using two IC2/3 chambers allows avoiding the influence of beam inhomogeneities by dividing the charge measured at a given position in the chamber 2 by the one measured at the center of chamber 1 ($Q_2(x, y)/Q_1(0, 0)$).

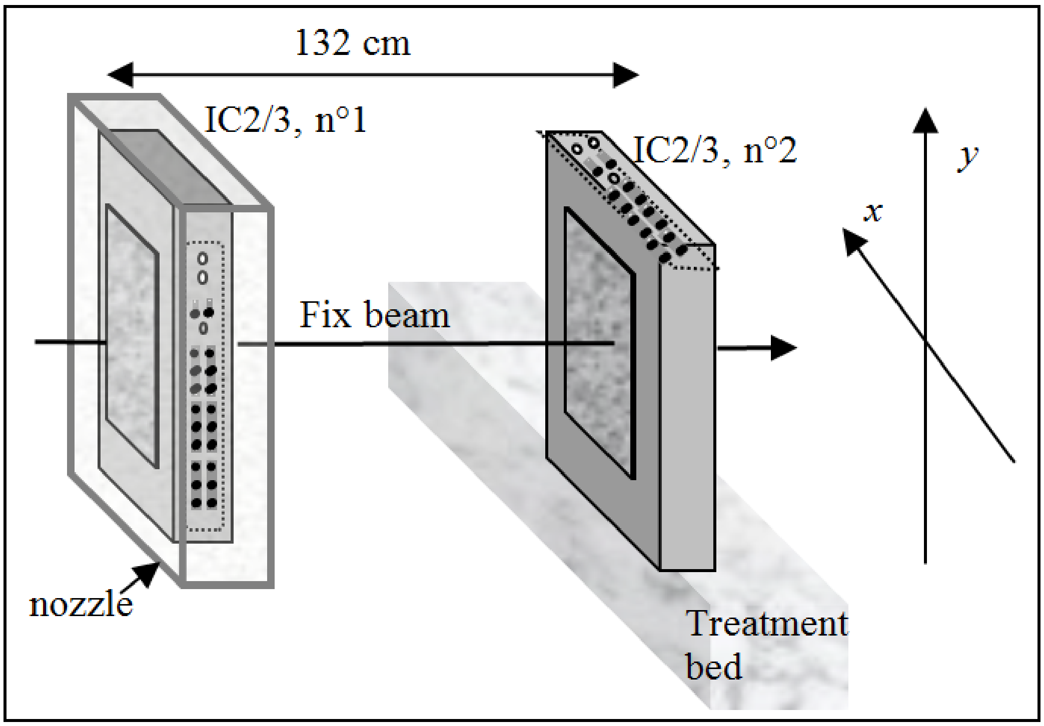

Figure 6: Protocol for uniformity test.

Results obtained measuring the charge collected indifferent points on both the x and the y axes are presented on the figure 7. They show a 4% variation

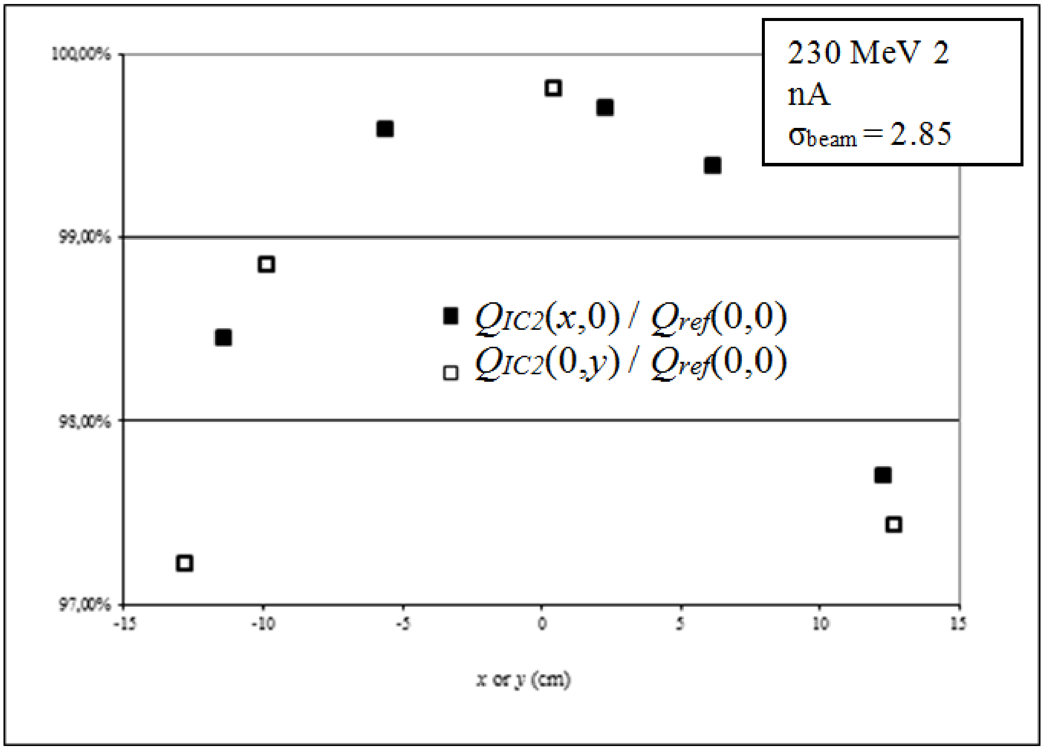

Figure 7: Uniformity test results.

in the charge collection between the center and the edges of the chamber. Nevertheless this 4% can be explained by the shape of the measured dose profile which is not perfectly Gaussian as shown on figure 8. In fact, while a Gaussian profile should decrease smoothly away from it center, the dose measurement shows a sharp decrease followed by a little increase and then a decrease again. Even if the charge measured in this region is little compared to the main peak charge, when the measurement position is the edge of the chamber this charge is lost and it does explain the 4% of charge missing on the edge. Indeed, the figure 9 shows the signal integral from the beams center, if the signal was only a Gaussian this integral would not change for an interval of integration larger than few sigmas and here it is still changing a lot after 2cm while the sigma value is under 4mm.

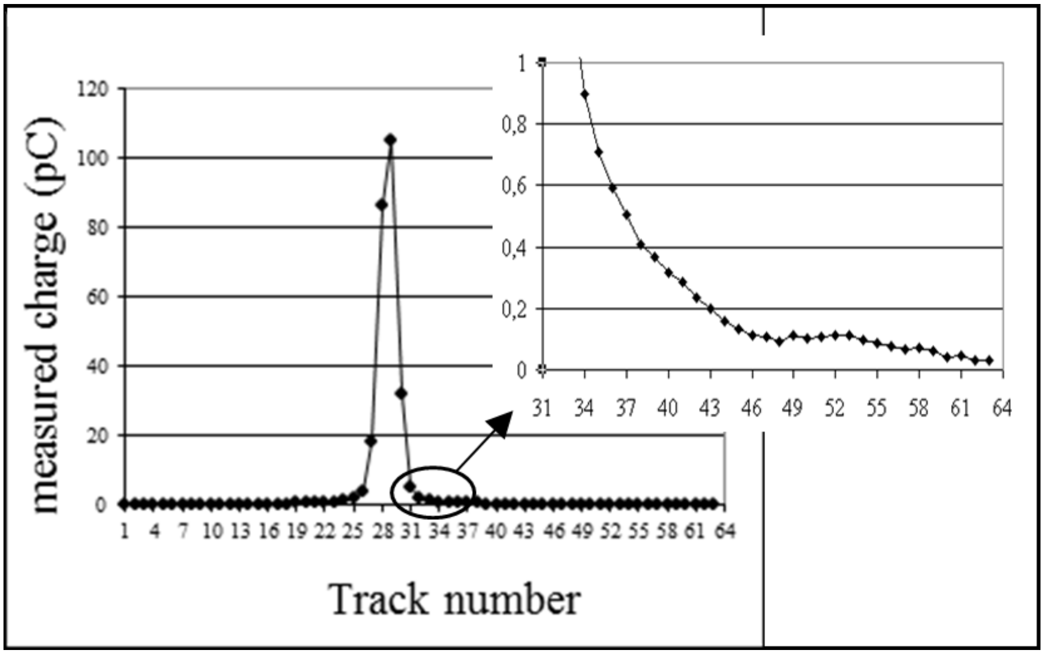

Figure 8: Beam transverse profile on x axis.

To compensate those missing charges when the beam is close to the chamber edge, correction factors have been applied. This factor is linked to the amount of the charge integrated by the detector in function of the distance between the charge deposition centroid and the chamber's center.

Results of such calibration of the data from figure 9are presented on figure 10. This calibration allows getting back to an uniformity better than 1%.

4.5. Spatial Resolution

The center of the beam needs to be measured with a high precision. Each strip of the chamber measures the charge created in the air volume traversed

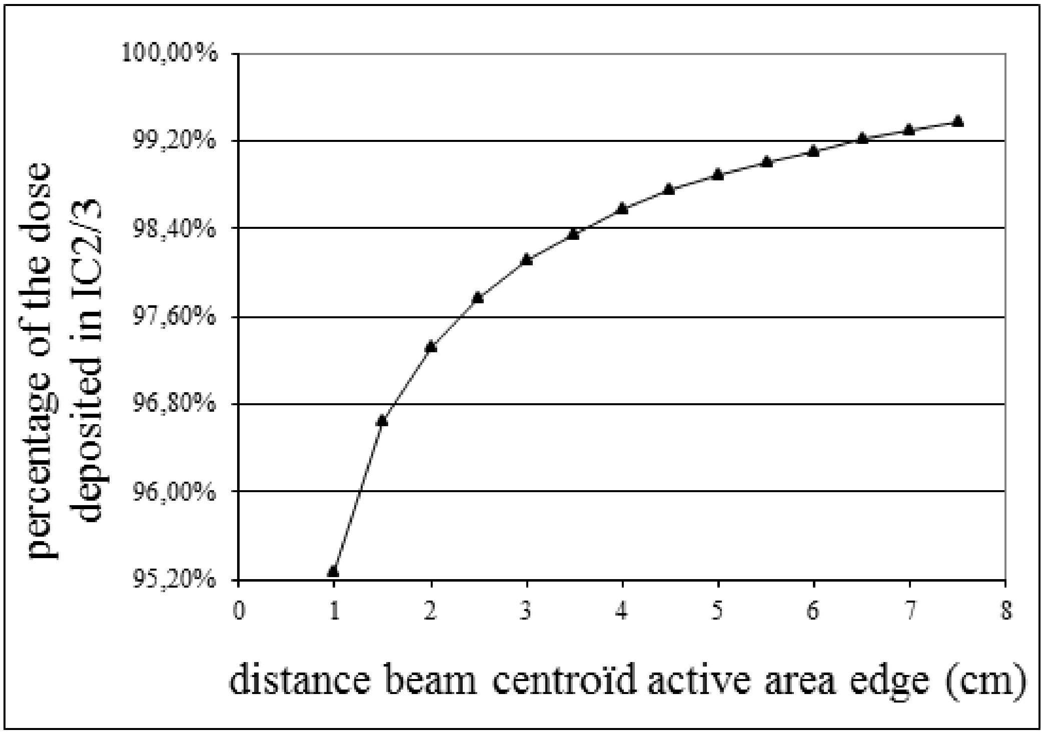

Figure 9: Percentage of the dose deposited in IC2/3 and measured by IC2/3 in relation to the centroid position functions on the chamber edge.

by the beam and facing the matching the strip area. In the plan orthogonal to the beam, the beam distribution is a two dimensional Gaussian. Therefore the signal integrated by each strip corresponds to a two dimensional Gaussian integrated over the strip surface. The strip surface is given by the strip width around its axis multiplied by its length along the opposite axis. Because this length can be considered infinite in respect to the Gaussian standard deviation, we only have to fit a single-dimension Gaussian on each strip layer. Matching the unknown Gaussian with the charge distribution measured by the two arrays of strips allows finding the height (hfit), the center (x0fit, y0fit)

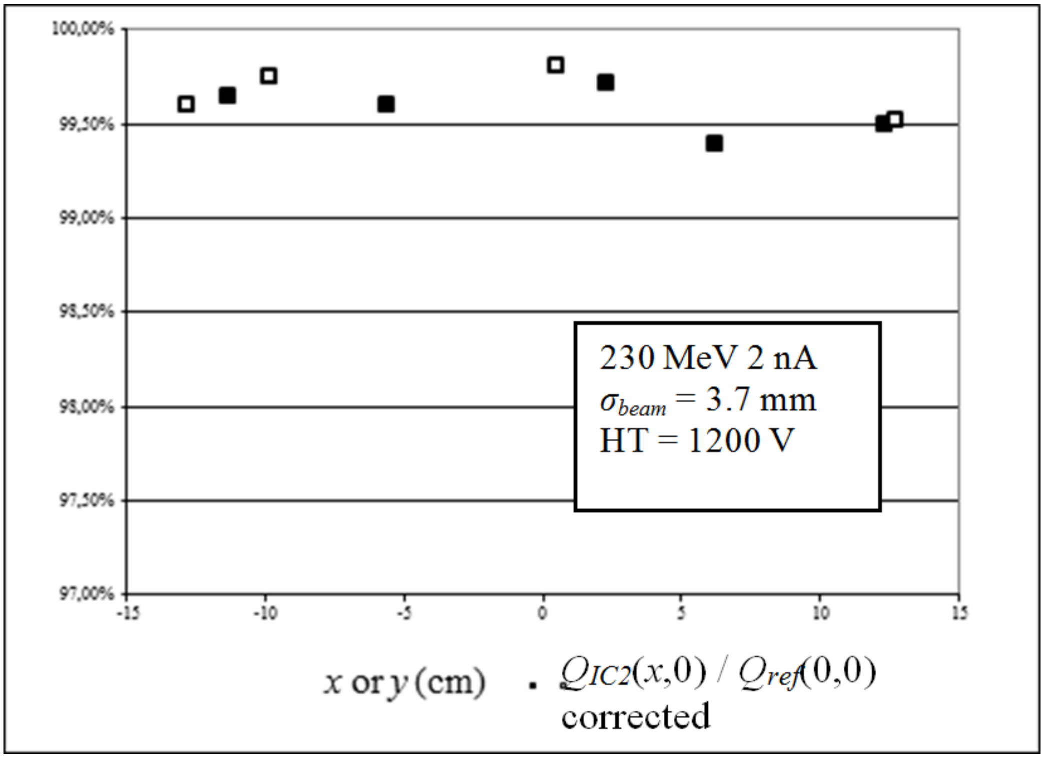

Figure 10: Measured dose for several centroid positions

and the standard deviation (sfit) of the Gaussian in two dimensions. The Gaussian fit is still possible on the edge of the chamber even if the measured dose profile is not perfectly Gaussian as show in the previous paragraph.

$$fit = h_{fit} \int_{x_n - 0.5 - x_{0fit}}^{x_n + 0.5 - x_{0fit}} Gaussian(a, s_{fit})\, da \tag{1}$$

5. Conclusion

The test realized in the WPE institute in Essen showed that the IC2/3 chamber has the ability to measure a proton fluency with a 1% precision in the 0.5-8Gy/min range. In addition, the spatial resolution in measuring the beam-spot center is better than 70 m while the time resolution is 500 s. This chamber has been designed to have little impact on the beam traversing it with a 187 m water equivalent thickness and is to be used with a high electrodes voltage ($>$ 1200 V) to ensure a collection efficiency better than 99.5%. The beam profile measurement shows a Gaussian shape with some wings on the edges. Those wings are not understood at the moment and even if they do not represent an issue for the dose measurement (if properly taken into account in the calibration) they need to be further investigated. Those characteristics of the chamber meet the requirements for the Pencil Beam Scanning monitoring. Nowadays, five units of the IC2/3 chamber are installed in the WPE Essen protontherapy center and they are part of the Proteus 235 IBA commercial product.

References

[1] ICRU Report 78 (2007).

[2] D. Schardt, T. Elsser and D. Schulz-Ertner, Reviews of Modern Physics 82 (2010).

[3] B. Marchand, et al., Proceedings of EPAC 2000.

[4] S. Giordanengo, et al., Nuclear Instruments and Methods in Physics Research Section A (2013).

Specification sheet	Results
equivalent water thickness	187 m
angular dispersion	about 1.15 mrad to 230 MeV
temporal resolution	500 s
collection efficiency	$> 99.5\%$ in saturated regime (> 1200 V)
noise to signal ratio	ambient noise must be less than 80 dB to have less than 1 pC of noise spatial resolution better than 70 m
precision on dose measurement	measurement uncertainty is $< 1\%$ in the entire chamber
response's uniformity of the integral chambers	1% peak-to-peak between the center and the edges of the active area
linearity of dose measurement	$\sigma = 0.24\%$
repeatability	$\sigma/\mathrm{Q} = 0.60\%$

Table 3: Specifications and test results.

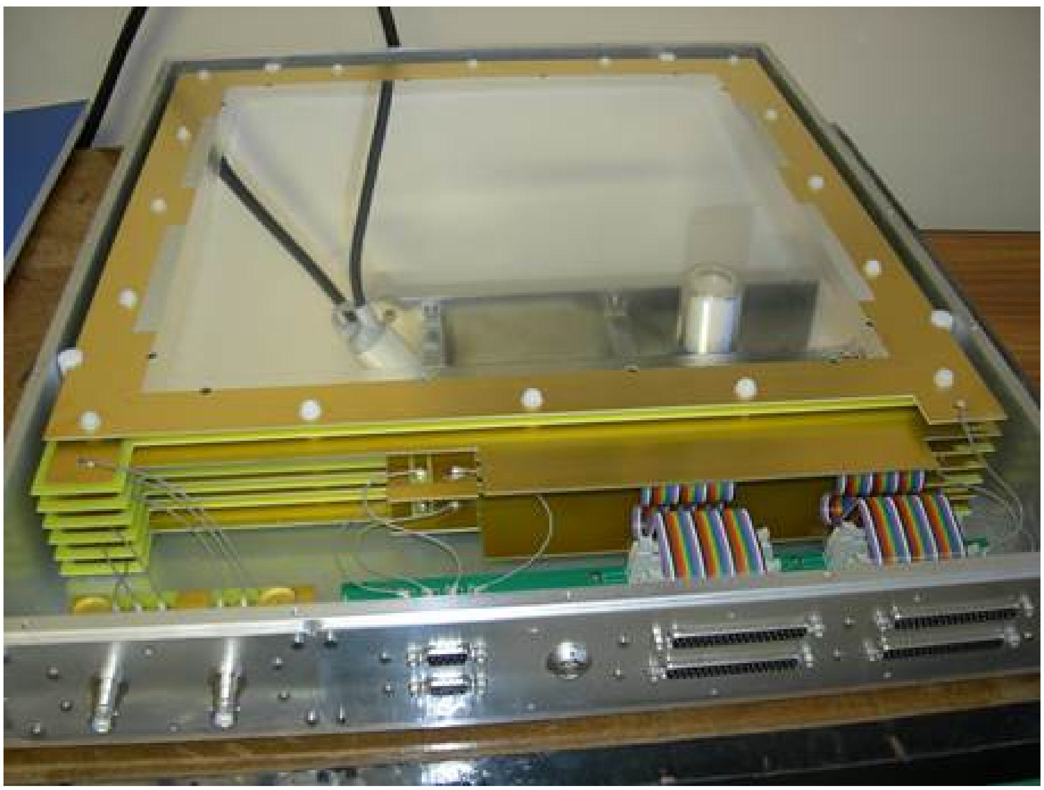

Figure 11: Opened prototype of an IC2/3 chamber.

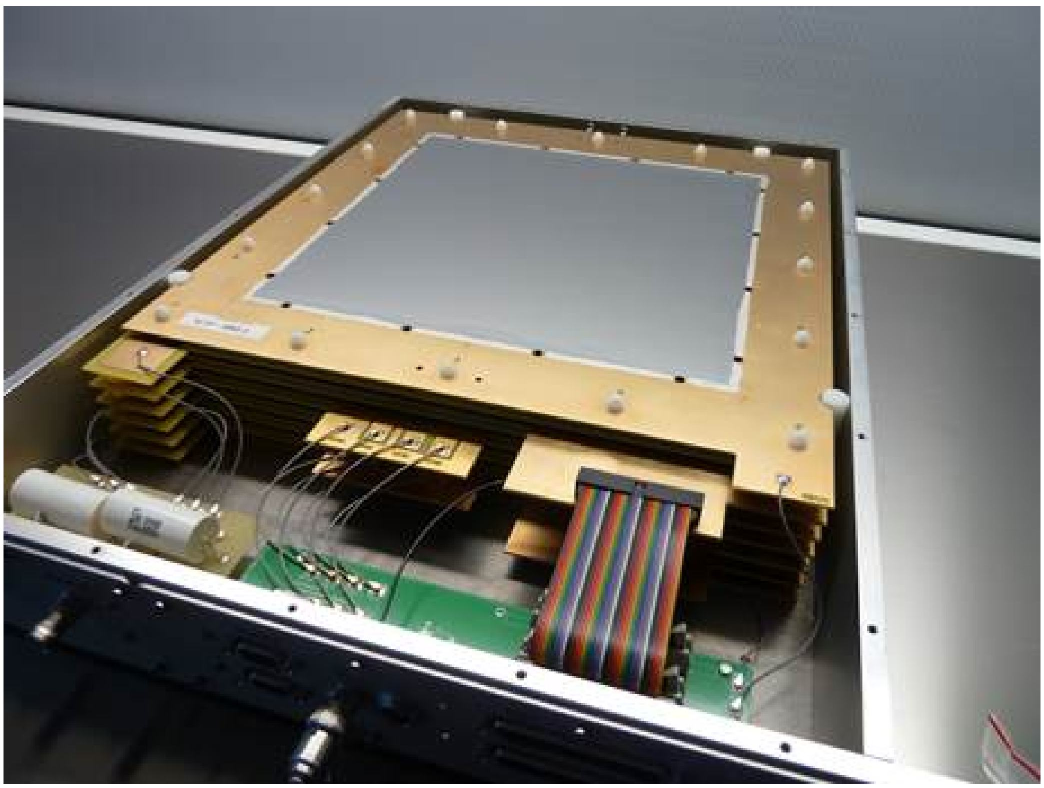

Figure 12: Opened commercial IC2/3 chamber.