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PAPER

Development and characterization tests of a homemade ionization chamber with silver collecting electrode for use in electron beams

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Abstract

Ionization chambers are special detectors for radiation beam dosimetry in hospitals. In this work, a PMMA parallel-plate ionization chamber with air sensitive volume was designed and built for use in electron beams of linear accelerators. This ionization chamber has a PMMA collecting electrode covered with silver paint. Several characterization tests were undertaken following international recommendations. The ionization chamber showed good performance in the characterization tests of its electrical properties and in most of the tests performed in the linear accelerator beams.

1. Introduction

Teletherapy is a radiotherapy modality that uses external beams directed to a target volume. Nowadays the modern teletherapy equipment is the linear accelerator that can emit x-rays or electron beams. Superficial lesions can be treated with electron beams. In this case, as in any treatment, the dose delivered to the target needs to be very well defined. Radiation dosimetry is an important process that assures a treatment with an efficient quality control.

There are two types of protocols used to determine the absorbed dose of clinical radiation beams by the American Association of Physicists in Medicine (AAPM) and the International Atomic Energy Agency (IAEA). The former protocols include AAPM TG-21 (1983), IAEA TRS-277 (1987), and IAEA TRS-381 (1997). Thwaites *et al* (1996) reported about the recommendations of electron dosimetry. Afterwards, the dosimetry of radiotherapy beams based on air kerma calibration changed to absorbed dose to water calibration. The updates of the protocols are AAPM TG-51 (1999) and IAEA TRS-398 (1997) that updated to IAEA TRS-398 (2000). In special, there is a report by

Thwaites *et al* (2003) that contains the recommendations of the electron dosimetry.

Ionization chambers are the most often used detectors for radiation beam dosimetry in hospitals. There are many studies about the applications of the commercial ionization chamber using radiation beams. At the Medical Physics Department of the University of Wisconsin, the behavior of the mammographic ionization chamber was studied (DeWerd *et al* 2002), Snow *et al* (2013) investigated the applicability of a wide range of microionization chambers; and DeWerd and Mackie (2003) compared the behavior of ionization chambers with various volumes for intensity-modulated radiation therapy (IMRT) absolute dose verification.

McEwen (2010) tested 27 different types of thimble-type ionization chambers. The objective was to determine the absorbed dose beam quality conversion factors using photon beams according to the TG-51 protocol (1999). Muir *et al* (2014) obtained the ion chamber calibration coefficients relative to secondary standard reference chambers in electron beams using depth ionization measurements.

Table 1. Technical specifications of the developed ionization chamber.

Characteristics	Dimensions and specifications
Wall material	PMMA, acrylic
Electrode material	PMMA coated with silver paint
Thickness of the silver coating	0.015 cm
Entrance window	Aluminized polyester
Entrance window thickness	0.032 mm
Collecting electrode diameter	1.70 cm
Electrode separation	0.15 cm
Insulating width	0.15 cm
Guard ring width	0.30 cm
Nominal volume	0.34 cm ³

At the Nuclear and Energy Research Institute (IPEN/CNEN) different kinds of ionization chambers were developed for use at diagnostic radiology, mammography, radiation protection, radiotherapy and computed tomography beams (Yoshizumi and Caldas 2010, Silva *et al* 2014, Nonato *et al* 2014, Perini *et al* 2013).

In this work, a PMMA parallel-plate ionization chamber, with air sensitive volume, was designed, built and characterized at IPEN for use in electron beams of linear accelerators according to some reports: IAEA TRS-381 (1997), IAEA TRS-398 (2006) and IEC 60731 (2011).

2. Materials and methods

The parallel-plate ionization chamber was developed (designed and built using Brazilian low cost material) at the Calibration Laboratory of IPEN.

The materials for this ionization chamber were PMMA (for the body of the ionization chamber), a silver paint (to coat the PMMA collecting electrode) and an aluminized polyester foil (for the entrance window). A commercial BNC connector and a banana connector for triaxial cable were utilized.

An ionization chamber was designed according to the specifications of the reports TRS-381 (1997) and TRS-398 (2006). The sensitive volume should be between 0.05 cm³ and 0.5 cm³; the volume depends on the parameters of the collecting electrode diameter and the electrode separation. The air sensitive volume of the developed ionization chamber is 0.34 cm³. Another important specification is the guard ring width parameter that should be equal or greater than 0.3 cm because of the scattering perturbation correction. The gap between the collecting electrode and the guard ring has 1.5 mm of width. The effective point of this ionization chamber is situated in the center of the front surface of the air cavity. All the parameters, characteristics and dimensions are presented in table 1.

An acrylic dowel was used to machine the ionization chamber. It consists of 11 acrylic parts which are coupled to one another forming a single piece. The collecting electrode and the guard ring made of

PMMA were coated with silver paint. A scheme of the ionization chamber can be observed in figure 1.

Other materials used in this work were:

- A polystyrene circular build-up cap, with a thickness of 4.0 mm and internal diameter of 4.6 cm, was developed to be used in the ⁶⁰Co source beam. It can be used as a protection cap to the ionization chamber too;
- A polystyrene solid phantom made of PMMA in slab form was developed, to hold the homemade ionization chamber. This phantom, with an area of 30 × 30 cm², enabled to localize the ionization chamber on the patient support assembly of the linear accelerators and to arrange solid water phantoms above the ionization chamber;
- Solid water phantoms in slab form of the radiotherapy clinics, with areas of 30 × 30 cm² and different width dimensions;
- A goniometer developed at IPEN;
- Three electrometers: two Physikalisch-Technische Werkstätten (PTW) Unidos E electrometers, one of IPEN and another of the São Paulo State Cancer Institute (ICESP) and one Keithley electrometer, model 35617EBS, of the Israelita Albert Einstein Hospital (IAEH).

The radioactive sources from IPEN utilized in this work were:

- ⁹⁰Sr+⁹⁰Y PTW check device, with nominal activity of 33 MBq in 1994;
- ⁹⁰Sr+⁹⁰Y source of the beta secondary standard system BSS1, with nominal activity of 1.85 GBq in 1981. This beta radiation source has a certificate from the German primary standard laboratory Physikalisch-Technische Bundesanstalt (PTB);
- Gammatron II S 80 ⁶⁰Co source, with an air kerma rate of 0.487 mGy s⁻¹ in 09/16/2014.

The radiation beams from the clinics utilized in this work were:

- Linear accelerator Varian, model 2100C of the IAEH, with energies of 6, 9, 12 and 16 MeV for electron beams;
- Linear accelerator Elekta Synergy, of the ICESP, with energies of 4, 6, 9, 12 and 15 MeV for electron beams.

The developed ionization chamber was submitted to several tests; some of them were performed in the Calibration Laboratory of IPEN to show the stability and the reproducibility of its response. For these tests, a check device source was used. Other testes as linearity of

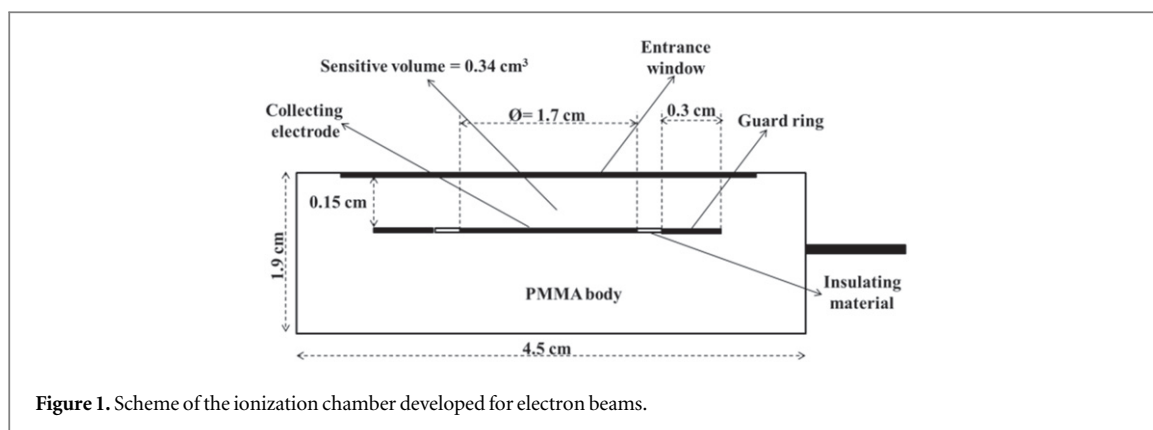


Figure 1. Scheme of the ionization chamber developed for electron beams.

response, leakage current, saturation curve and ion recombination were also performed using the same source. Another very important test was the determination of the calibration factor of the ionization chamber, using a cobalt source. It is used as one of the correction factors applied in clinical radiotherapy.

If the response of the ionization chamber for all these tests was adequate, the ionization chamber would be considered able for the tests in electron beams.

Linearity of response, polarity effect, angular dependence and cable effect are important tests to study the behaviour the ionization chamber response in electron beams.

All measurements were corrected for the reference environmental conditions of temperature and pressure.

3. Results

The ionization chamber, with silver collecting electrode, was developed and tested according to the international recommendations.

3.1. Short-term stability test

For the short-term stability test, the developed ionization chamber was placed in the device before the first measurement during 30 min. After, ten measurements were taken, using the $^{90}\text{Sr} + ^{90}\text{Y}$ PTW check device, during 30 s in each measurement, for positive and negative polarities using the PTW Unidos E electrometer. The recommended limit of the standard deviation was $\pm 0.5\%$ (IEC 2011). The test was repeated eight times, and the maximum standard deviation of this test was not greater than $\pm 0.02\%$ for both the positive and negative polarizing voltages, and therefore within the recommended limit.

3.2. Medium-term stability test

The medium-term stability test is part of the permanent study of the constancy of the chamber response. The short-term stability test was repeated eight times and a relative response of the ionization chamber to the mean measurement value was obtained and presented in figure 2. Pre-irradiations were not necessary. The

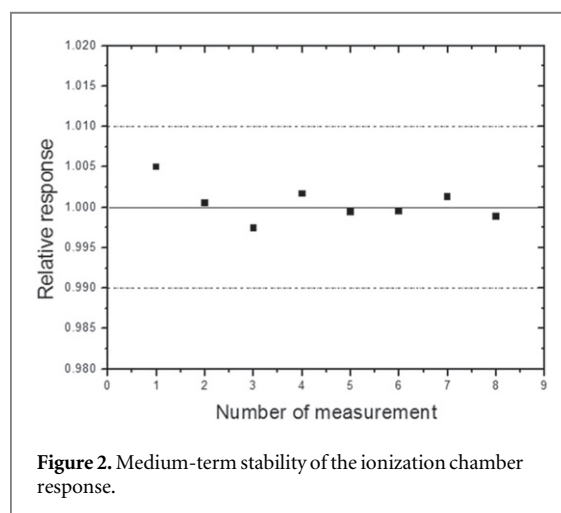


Figure 2. Medium-term stability of the ionization chamber response.

maximum variation obtained was 0.05%, and it agrees with the IEC 60731 recommendations (IEC 2011); the limit of the medium-term stability test is 1%.

3.3. Leakage current test

The leakage current test was obtained using two measurements, before and after the short-term stability test.

Firstly, the ionization chamber was placed in the device before the first measurement starting for 30 min. Then, a measurement was taken, without the source, during 20 min.

After, the short-term stability test was undertaken. The measurement without the source was compared with the average of the measurements obtained from the short-term stability test. The leakage currents were 0.01% and 0.02% for respectively magnitudes of 10^{-4} pA for the positive and 10^{-4} pA for the negative polarities. These results are within the recommended limit (0.5%) of the IEC 60731 standard (IEC 2011).

3.4. Saturation curve and ion recombination

The voltage applied to the ionization chamber was varied from 0 to ± 400 V, in steps of 50 V, using the $^{90}\text{Sr} + ^{90}\text{Y}$ check device. The polarizing voltage chosen to be used in this ionization chamber was +300 V. The saturation curve is presented in figure 3. It

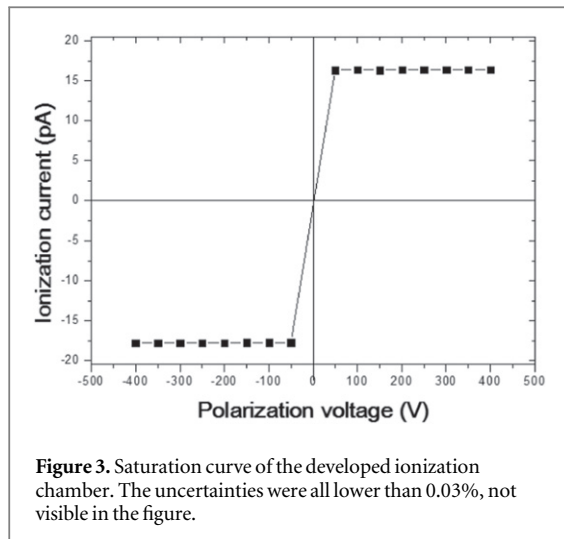


Figure 3. Saturation curve of the developed ionization chamber. The uncertainties were all lower than 0.03%, not visible in the figure.

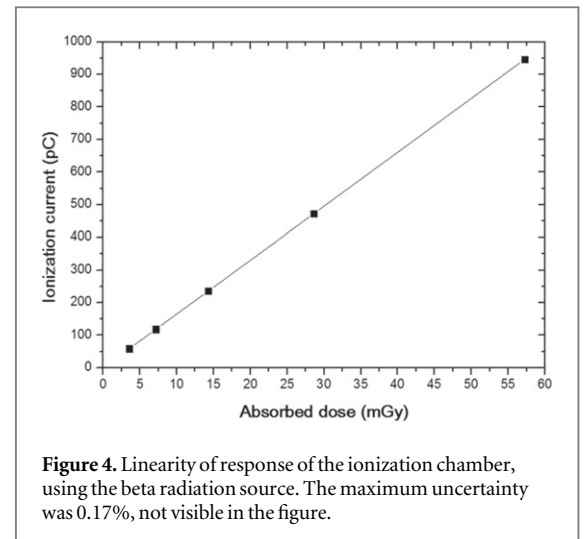


Figure 4. Linearity of response of the ionization chamber, using the beta radiation source. The maximum uncertainty was 0.17%, not visible in the figure.

presents a symmetrical behavior to the positive and negative polarities.

The ion recombination that is named collection efficiency K_s was determined by (IAEA 2009):

$$K_s = a_0 + a_1 \left(\frac{M_1}{M_2} \right) + a_2 \left(\frac{M_1}{M_2} \right)^2,$$

where M_1 and M_2 are the collected charges at V_1 and V_2 respectively; the constants a_i are given from the standard TRS 398 on page 52.

The ion recombination K_s was determined using the saturation curve data and the above equation. The result was 1.0037 for the positive and 1.0021 for the negative polarities. The result agrees with the international recommendation of K_s to be less than 1% (IEC 2011). The uncertainties were lower than 0.03%.

3.5. Linearity of response

The linearity of response curve was obtained using the $^{90}\text{Sr}+^{90}\text{Y}$ source of the BSS1 system, taking five measurements at different irradiation times: 15, 30, 60, 120 and 240 s, at the reference source-chamber distance of 11 cm. The linearity of response was obtained, and can be observed in figure 4 where the correlation coefficient was obtained as 1.000 ± 0.010 .

The linearity of response was also obtained using the electron beams of the linear accelerator Elekta Synergy, with energies of 6 and 9 MeV, and taking three measurements at different monitor units (MU) that correspond to absorbed doses of 100, 200, 400, 600, 800 and 1000 cGy, at the reference source-chamber distance of the 100 cm. The linearity curves are presented in figure 5 where the correlation coefficients for the curves were obtained as 1.000 ± 0.020 for both cases.

3.6. Polarity effect

3.6.1. Polarity effect in relation to the depth

The polarity effect in relation to the practical range, according to the IEC 60731 recommendations

(IEC 2011), was determined in electron beams of the linear accelerator 2100C using two energies, 6 and 12 MeV, and of the linear accelerator Elekta Synergy with energies of 6 and 9 MeV. The ionization chamber was tested in approximate depths of $0.1 \times R_p$; $0.3 \times R_p$; $0.5 \times R_p$; $0.7 \times R_p$; where R_p is the practical range of the electron beam. A solid water phantom in slab form was used to determine the practical range depth.

The measurements were taken for each depth for both positive and negative polarizing voltages, 100 MU in each measurement. The field size was $15 \times 15 \text{ cm}^2$ for the linear accelerator 2100C and $14 \times 14 \text{ cm}^2$ for the linear accelerator Elekta Synergy. The polarity effect curves are presented in figures 6 and 7 respectively for the linear accelerators 2100C and Elekta Synergy.

The behaviour of the ionization chamber response in figures 6 and 7 is similar to that of the Capintec and the Memorial Chamber responses of another work (Gerbi and Khan 1987). A small polarity effect was observed near to d_{max} ($0.1 \times R_p$), and it grows while the depth is below d_{max} . The value obtained at $0.7 \times R_p$ is lower than the values obtained at other practical ranges; the polarity effect is greater in relation to the polarity effects obtained by others, because the ratio of the lower values tend to exhibit great variations.

For the energies of 9 and 12 MeV, figures 6 and 7, the polarity effect was lower than for 6 MeV, and just to the $0.7 \times R_p$ the polarity effect it was higher than 1%. This behavior is similar to the Calcam chamber data presented by Havercroft and Klevenhagen (1994).

The recommended limit of the IEC 60731 (IEC 2011) for the polarity effect is less than 1%, or a correction factor is recommended.

The correction factor, k_{pol} , can be determined by:

$$k_{\text{pol}} = \frac{|M_+| + |M_-|}{2M},$$

where M is the electrometer reading for the polarity used routinely (it can present positive or negative

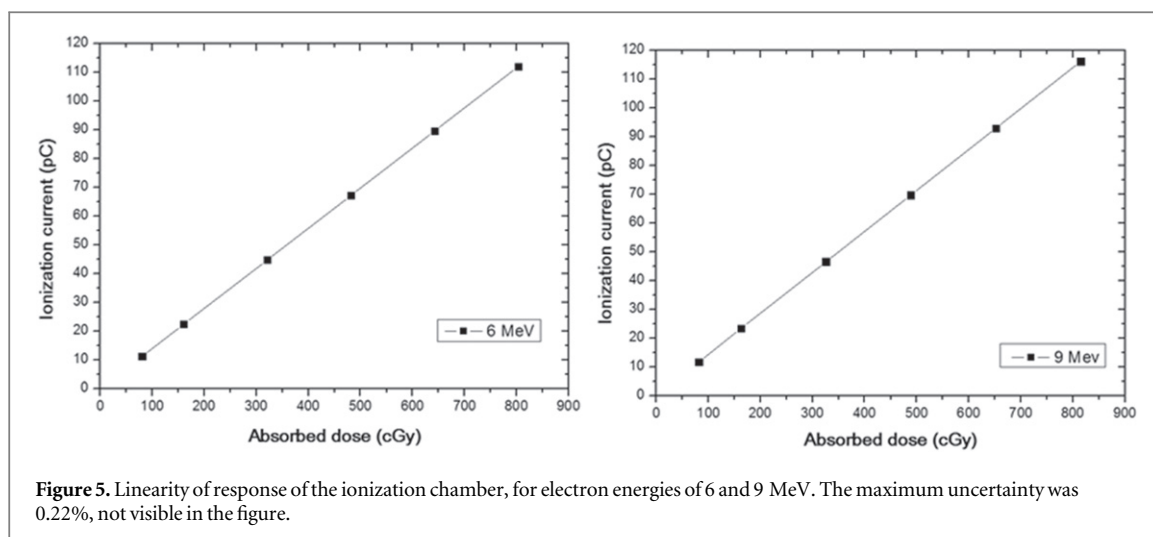


Figure 5. Linearity of response of the ionization chamber, for electron energies of 6 and 9 MeV. The maximum uncertainty was 0.22%, not visible in the figure.

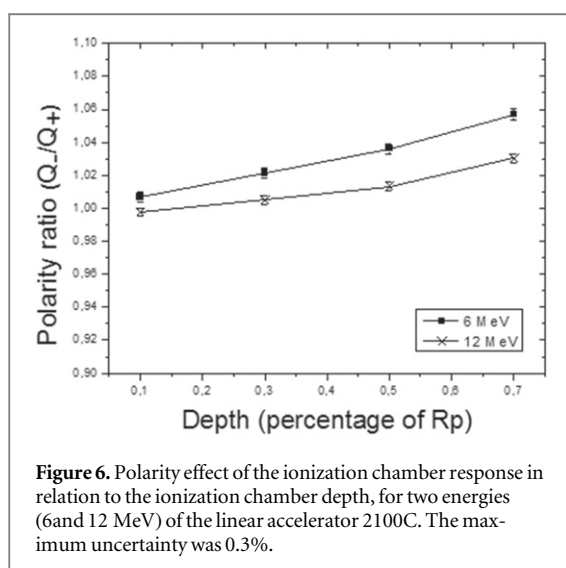


Figure 6. Polarity effect of the ionization chamber response in relation to the ionization chamber depth, for two energies (6 and 12 MeV) of the linear accelerator 2100C. The maximum uncertainty was 0.3%.

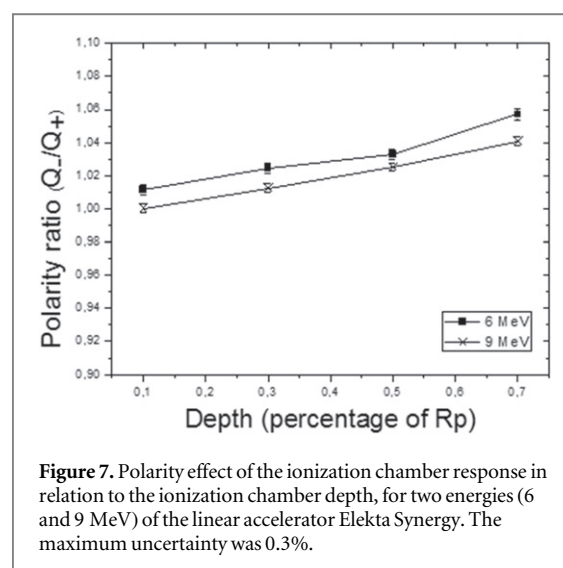


Figure 7. Polarity effect of the ionization chamber response in relation to the ionization chamber depth, for two energies (6 and 9 MeV) of the linear accelerator Elekta Synergy. The maximum uncertainty was 0.3%.

polarity); and M_+ and M_- are the electrometer readings to the positive and negative polarity respectively (IAEA 2009).

The correction factors, k_{pol} , were determined at an approximate depth of $0.7 \times R_p$.

They were obtained for the energies of 6 and 12 MeV of the linear accelerator 2100C respectively: 0.108 and 0.088, with a maximum uncertainty, for both energies, of 0.28%.

And for the energies of 6 and 9 MeV of the linear accelerator Elekta Synergy, the correction factors were respectively: 0.105 and 0.091, with a maximum uncertainty, for both energies, of 0.3%.

3.6.2. Polarity effect in relation to the field size

The polarity effect in relation to the field size was determined in electron beams of the linear accelerator Elekta Synergy with energies of 6 and 9 MeV. The ionization chamber was tested in field sizes of $6 \times 6 \text{ cm}^2$, $10 \times 10 \text{ cm}^2$, $14 \times 14 \text{ cm}^2$ and $20 \times 20 \text{ cm}^2$. The measurements were taken for each field size for both positive and negative polarizing voltages, during 100 MU in each measurement. The 1 MU equates to 1 cGy of the

absorbed dose. The polarity effect in relation to the field size is presented in figure 8.

The polarity effect tends to grow due to the increase of the backscattering when the radiation field size increases.

It is noted that the polarity ratio in relation to the radiation field, in figure 8, is lower than the polarity ratio in relation to the depth, in figures 7 and 6. In figure 8, the solid water phantom, that attenuates the radiation beams, was not used in this case.

3.7. Angular dependence

The study of the angular dependence was performed varying the goniometer angle from 0° to 360° , in steps of 45° . Therefore, the ionization chamber was rotated around only one axis. The measurements were taken in the electron beams of the linear accelerator Elekta Synerg with energies of 6 and 9 MeV. Each measurement was obtained with 100 MU. The 1 MU equates to 1 cGy of the absorbed dose. For each angle, five measurements were taken. The reference source-chamber distance was 100 cm.

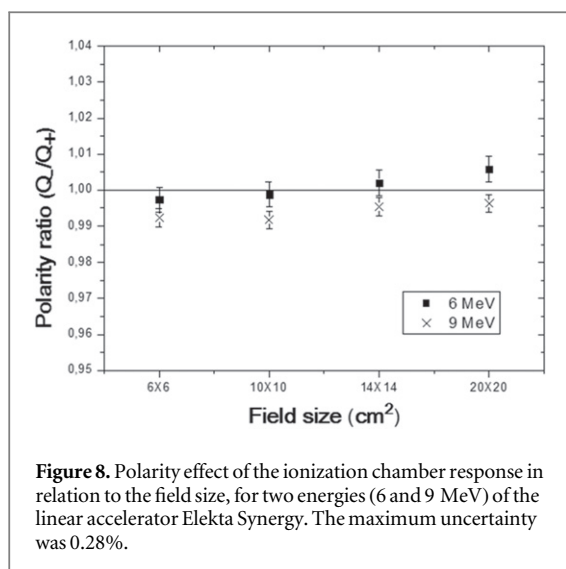


Figure 8. Polarity effect of the ionization chamber response in relation to the field size, for two energies (6 and 9 MeV) of the linear accelerator Elekta Synergy. The maximum uncertainty was 0.28%.

The results obtained show that the ionization chamber do not present angular dependence, comparing the response of the ionization chamber in angles from 45° of to 360° in relation to the angle 0° .

3.8. Cable effect

The cable effect was studied comparing the measurements obtained, firstly, when the cable was exposed to an electron beam and, after, when the cable was protected in relation to the electron beam of the linear accelerator Elekta Synergy. A PMMA shield with thickness of 0.8 cm was used in this test to protect the cable. Five measurements were taken with 100 MU for each case and the uncertainty was the statistical uncertainty. The reference source-chamber distance was 100 cm. The cable factor (N_{cable}) was determined using the ratio of the measurements with the cable protected and without protection.

The N_{cable} was obtained as (1.000 ± 0.004) for both energies of 6 and 9 MeV.

3.9. Calibration factor for the developed ionization chamber in ^{60}Co beam

The cross-calibration of the developed ionization chamber against a calibrated reference chamber, PTW TN 30013 Farmer was performed at the Gammatron II S 80 ^{60}Co source. The reference point of the ionization chambers was: for the Farmer chamber it was at the center of the cavity volume, and for the developed ionization chamber it was on the inner surface of the window at its central position. The size of the water phantom was $30 \times 30 \text{ cm}^2$, and the size field of the gamma beam was $10 \times 10 \text{ cm}^2$, with its reference point at 5 g cm^{-2} in accordance with the reference conditions.

The calibration factor in terms of absorbed dose to water for the developed ionization chamber was obtained as $(67.17 \pm 1.01 \text{ mGy/nC})$. The Farmer calibration factor was $(53.59 \pm 1.50 \text{ mGy/nC})$ determined at the Calibration Laboratory of IPEN. The Farmer ionization chamber response uncertainty was

greater than that of the developed ionization chamber uncertainty, because for the developed ionization chamber the uncertainty was just considered as the statistical uncertainty.

4. Conclusions

The homemade ionization chamber, with silver collecting electrode, was developed using Brazilian low cost materials. In Brazil, all of the commercial ionization chambers utilized are imported. Furthermore, the homemade ionization chamber body was developed entirely with PMMA material, without metallic materials, and with a collecting electrode of a thin layer of silver paint.

The ionization chamber showed good performance in the characterization tests of its electrical properties, as the short-term and medium-term stabilities; leakage current; saturation curve; collection efficiency; and linearity of response. Other tests were undertaken in linear accelerators, and the ionization chamber presented also good performance for the linearity of response; polarity effect in relation to the field size; angular dependence and cable effect tests. An exception was the result for the polarity effect test in relation to the depth, but a polarity effect is not a problem if the chamber is always used at the same polarity and potential, as it usually occurs. The response of the ionization chamber for the polarity effect is similar to the response of other commercial ionization chambers from the literature.

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