

Development of a parallel plate ion chamber for radiation protection level

Desenvolvimento de uma câmara de ionização de placas paralelas para proteção radiológica

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Abstract

A new parallel plate vented ion chamber is proposed in this paper. The application of this chamber was primarily intended to the measurement of stray radiation in interventional procedures, but the energy response of about 2.6%, which was obtained in the first prototype, on the range from 40 to 150 kV using ISO 4037-1 narrow qualities, provided the possibility of a wide modality application on radiation protection. Primary studies with Maxwell 2D electromagnetic field simulator revealed an optimized model regarding effective volume and saturation voltage levels, which conferred to the ion chamber a dual entrance window feature. The development of this ion chamber has the main contribution of Monte Carlo calculations as a support tool to the establishment of the effective volume of the chamber and determination of the best materials for housing mounting and conductive elements, such as guard rings, electrode, and windows. Even the composition of the conductive layers, which would be neglected due to their very small thicknesses (about 35 μm), had important influence on the results and could be better understood with Monte Carlo N-Particle Transport Code System (MCNP) simulations.

Keywords: ion chamber, Monte Carlo, energy response, radiation protection.

Resumo

Uma nova câmara de ionização de placas paralelas ventilada é proposta neste trabalho. A aplicação da câmara teve como objetivo principal a medição da radiação parasita nos procedimentos intervencionistas, porém as variações da resposta em energia de aproximadamente 2,6% na faixa de 40 a 150 kV, obtida no primeiro protótipo utilizando os feixes padrão estreitos da ISO 4037-1, possibilitou uma ampla aplicação na modalidade de proteção radiológica. Estudos iniciais feitos com o simulador de campo eletromagnético Maxwell 2D revelaram um modelo otimizado em relação ao volume efetivo e tensão de saturação, os quais conferiram à câmara de ionização a característica de janela de entrada dupla. O desenvolvimento desta câmara de ionização teve como principal contribuição as simulações de Monte Carlo como uma ferramenta de suporte para o estabelecimento do volume efetivo da câmara e para a determinação dos melhores materiais para os elementos de montagem e circuito condutivo, como por exemplo, os anéis de guarda, eletrodo e as janelas. Até mesmo as composições de camadas condutivas, que seriam negligenciadas devido a sua pequena espessura (aproximadamente 35 μm), tiveram uma importante influência nos resultados, que foi melhor compreendida com as simulações realizadas com o Monte Carlo N-Particle Transport Code System (MCNP).

Palavras-chave: câmara de ionização, Monte Carlo, resposta da energia, proteção radiológica.

Introduction

Interventional radiology equipments are extensively used in medical practice. In the last decades, the minimally invasive procedures, associated with technological improvements, resulted in the expansion of the equipment market all over the world. In Brazil, this panorama is not different and an increasing number of manufacturers are putting much effort in the development and production of interventional radiology machines to supply market necessities¹.

Medical electrical equipment certification process is compulsory in Brazil since 1995. In this process, type tests of these equipments are performed according to international standards from the International Electrical Commission (IEC) 60601 series. For interventional radiology equipment, such tests are also performed and some requirements of the applied IEC standards require particular instruments for the X radiation measurements, especially leakage and stray radiation profiles in significant zones of occupancy. These requirements include special dimensions and volume chambers².

For leakage radiation measurements, the most important requirements are the entrance window area of 100 cm² and linear dimensions not exceeding 20 cm. In this modality, some commercial chambers are available and the evaluation of their time and dose response function is very important. For the stray radiation profiles in significant zones of occupancy and also for measurements of isokerma maps of scattered radiation, the most important requirement is related to the volume of the chamber, 500 cm³, and linear dimensions that cannot exceed 20 cm. For this modality, no chambers are commercially available, since the old FLUKE 96010A was discontinued. Although FLUKE 96010A regards requirements for both leakage and stray radiation, it was designed with the specific purpose of leakage radiation measurement.

This paper presents a new purpose of vented parallel plate ionization chamber, according to the dimensions and volume requirements of IEC 60601 international standards series and regarding all the modalities of diagnostic X-ray equipment. It was specially designed to present energy response and sensibility necessary to the measurements of leakage radiation, stray radiation profiles in significant zones of occupancy, and scattered radiation in isokerma maps.

In the next section, the design method using Maxwell 2D electromagnetic field simulator and the Monte Carlo calculation code MCNP4C is presented³. Practical measurements and simulations of energy response, based on normalized X-ray qualities⁴, are reported in Results and the fundamental contributions of Monte Carlo calculations to understand the chamber behavior are discussed in Discussion and Conclusions sections.

Materials and methods

Electrical field design and simulation

The parallel plate ion chamber was designed with three fundamental aims: a low cost, robust, and easy manipulation detector. Such objectives lead to a first simple design with a single entrance window and a collector electrode surrounded by a guard ring.

First chamber model

The first chamber had polimetilmetacrilate PPMA cylindrical walls (red), windows and collector electrode (blue) made of polycarbonate, covered with conductive graphite (gray) in a way to state a chamber polarization and charge collection circuit. All the internal volume is filled with air (white) as in a vented chamber. This first model is shown in Figure 1. It was obtained from Maxwell 2D design tool and indicates a section of the central axis perpendicular to the window plane, where all the components can be seen. As with this free software, we are able only to simulate 2D electric fields, this section was chosen as a more representative plane to evaluate electrical field design and behavior.

The electrical field simulation obtained with the use of Maxwell 2D software is shown in Figure 2, and it was performed with a chamber voltage of 400 Vdc.

In Figure 2 one observes that there is a large area (orange) corresponding to the effective volume of the chamber, where the charges produced by ionization are collected. There are also two types of regions that determine dead volumes, where the produced charges are not collected due to different reasons. The first type of dead volume is represented from blue to yellow, where the electric field is very weak and corresponds to the region outside of the space between the collecting electrodes. The second type of dead volume corresponds to the region between the guard ring and the window, shown in red on the lower corners, which presents a higher electric field that deviates the charges to the guard ring, and consequently they are not collected by the measuring electronics.

Second chamber model

With the purpose to obtain a smaller dead volume, a second model of chamber was designed, which had almost the same material components, PMMA walls but now with two polycarbonate windows and a centralized polycarbonate collector electrode. All components were covered with conductive graphite to provide the chamber polarization and the charge collection circuit. The guard rings were placed at a different position, still surrounding the collecting electrode, but dividing the window circuit and chamber design symmetrically. This confers to the second model other interesting properties: reduced saturation voltage, reduced dead volumes and bilateral capacity of measurement. This new model is shown in Figure 3. Results of Maxwell 2D calculations are illustrated in Figure 4.

The electromagnetic field calculation for the second chamber was performed with 250 Vdc, almost half of the

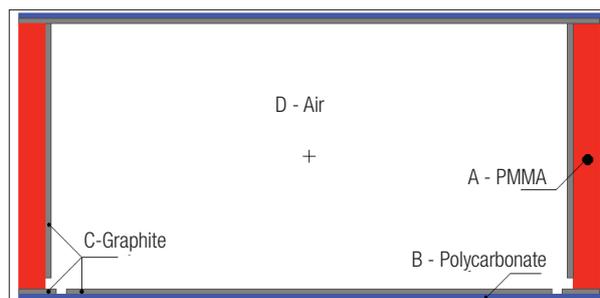


Figure 1. Section of the first chamber model design used in the electrical field simulation.

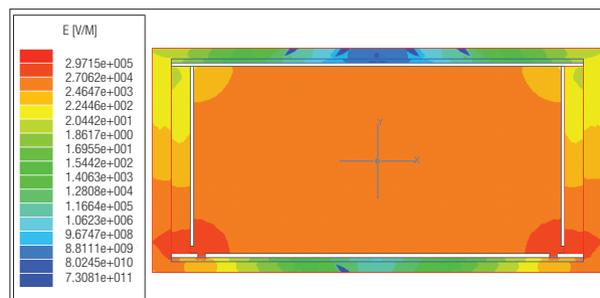


Figure 2. First chamber model electrical field simulation.

voltage used in the first chamber model. Figure 4 shows that the regions corresponding to dead volumes and low electric fields inside the collecting electrodes are significantly smaller than in the first chamber.

Prototype and Monte Carlo model

Prototype

The first prototype model is illustrated in Figure 5.

Water-based graphite was used to avoid corrosion of the PMMA, since almost all solvents in the most common graphite inks promote PMMA degradation with time. A painting procedure was developed in order to guarantee uniform ink distribution and thickness. A guiding layer was designed to facilitate the painting of the guard rings. The ion-chamber wiring was performed by pressing the conductors against the internal side of the windows and with nylon screws in guard rings and electrode.

Monte Carlo model

The same ion chamber was also modeled in the MCNP4C³ code to evaluate the energy response of the detector. A simplified geometry was stated, and details of wiring and internal nylon screws were neglected. In Monte Carlo calculations, null electron and photon importance was assigned to the dead volume and dead zone, because in MCNP4C the electric field would not be inserted in the input code. The components of walls (PMMA), windows and collector electrode (polycarbonate) were modeled using standard compositions. The chemical composition

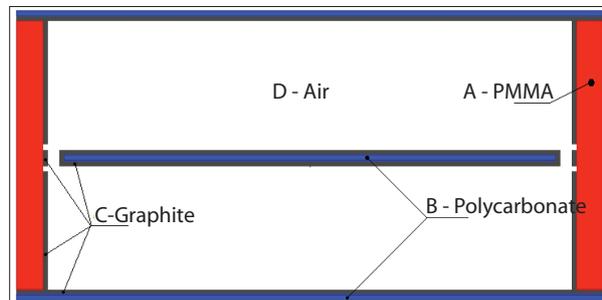


Figure 3. Section of the second chamber model design used in the electrical field simulation.

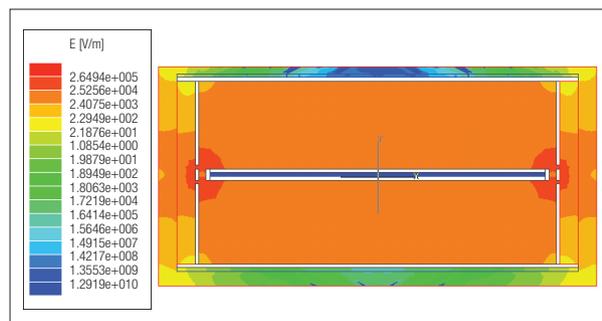


Figure 4. First chamber model design section for electrical field simulation.

of the graphite cover was modeled using the graphite ink manufacturer's specifications for dry ink: 100% graphite. The graphite thickness was based on the measurements made in the prototype chamber layers, with and without graphite coating, using a precise digital Mitutoyo micrometer model 389-251. The graphite mean thickness was 35 μm .

Measurement setup and qualities

As the main application of the detector is related to radiation protection, ISO 4037-1 narrow beams were selected within diagnostic range⁴. For the first evaluation, four X-ray qualities were used (N60, N80, N100 and N150 kV), based on the available qualities in IEE/USP and in IPEN/CMR, which are the reference laboratories for ion chamber calibrations in São Paulo. The reference kerma/ion chamber charge ratio was used to state the energy response evaluation and Monte Carlo comparison parameter.

The same qualities were implemented in STEEE/IEE, according to ISO 4037-1, where a PTW Freiburg GmbH 300 cm³ TA34055-0 model ion chamber was used to state the reference doses.

The measurements were then performed in both laboratories and a PTW UNIDOS 457 electrometer was used to collect charge of the ion chamber prototype during tests. In both laboratories, results were taken using the reference ratio (Eq. 1):



Figure 5. First chamber prototype.

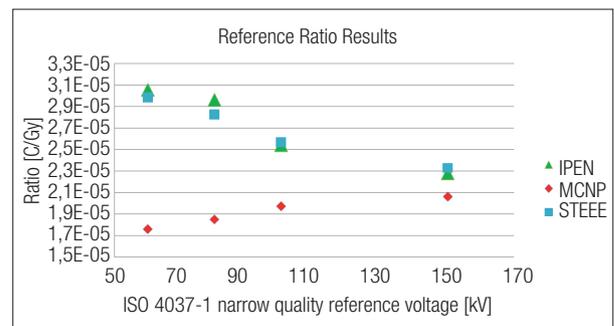


Figure 6. First results of Kerma/Charge ratio in reference and development laboratories and MCNP simulations.

$$R_n = \frac{C_n}{K_n} \quad (1)$$

where:

R is the dose/charge ratio;

K is the laboratory reference air kerma;

and C is the ionization chamber prototype collected charge.

All parameters are related to their ISO narrow quality n .

The same equation was employed for the results of the simulated data. The setup geometry of each laboratory was implemented in MCNP, and the input spectra were obtained from earlier simulations in GEANT4 code⁵. For the MCNP simulations, the reference air kerma K was obtained in a prior simulation setup with all narrow qualities over an air volume of 500 cm³ accomplishing the air kerma definitions. Further simulations with the ion chamber model were performed to collect data of charge C in the predefined effective volume.

Comparisons between experimental and simulated data are shown in the next section.

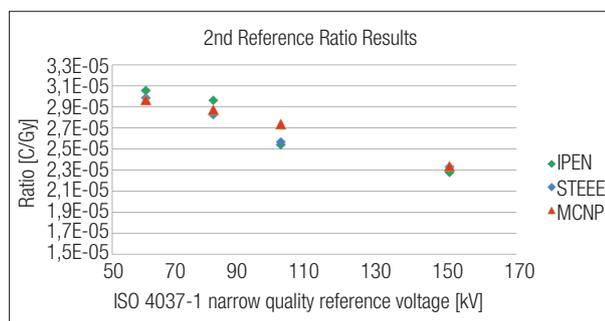


Figure 7. First results of Kerma/Charge ratio in reference and development laboratories and second results of MCNP simulations.

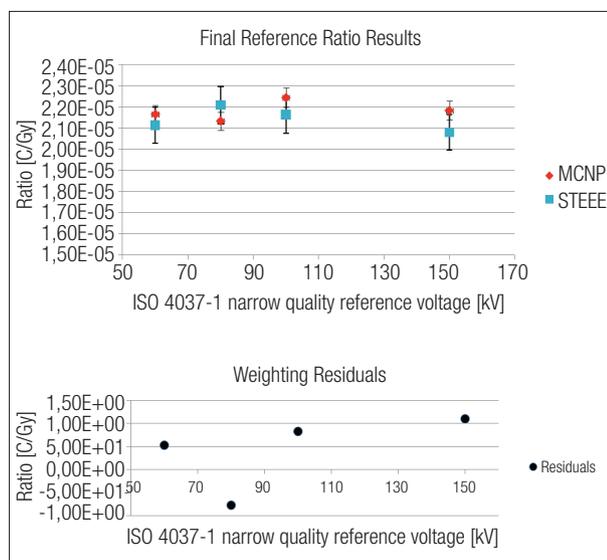


Figure 8. Final results of Kerma/Charge ratio in reference and development laboratories and MCNP simulations.

Results

A summary of results containing charge/kerma ratio is presented in the graphic of Figure 6. A good agreement between both laboratories results is clearly seen; however, a large discrepancy with simulated results is also presented. Both window sides were tested and no relevant differences were found.

Figure 6 clearly presents a detector response with considerable energy dependency. As ISO Narrow 70 kV quality was not available, an indication of the energy dependency was based on the c variation coefficient of the results. For the first results, the energy dependencies were very similar for both laboratories, 13.4% in IPEN/CMR and 10.8% in STEEE/IEE. However, in MCNP simulations, the result was 6.9%. All of them were not in agreement with ISO 4037-1 energy dependency requirements of less than 5%. Such discrepancies were evaluated, and two their possible sources were studied: MCNP cross-section library used and composition of the dry graphite ink.

While a new cross-section library was implemented, a spectroscopic characterization of the graphite ink was performed and a new chemical composition was found, which is different from the one specified by the manufacturer. The main components found, other than the graphite, were: SiO₂, CaO, MgO, Al₂O₃, and Na₂O. With such results, a new chemical model for graphite layer was implemented in the MCNP code. The new results are shown in Figure 7.

Both libraries that were used produced almost the same results, and a new graphite ink was used in a second prototype. The composition of this new ink was also evaluated by means of spectroscopy procedure. For this graphite ink, no other elements than carbon (graphite) were found and a third series of simulations was then performed. The results were very similar to that obtained in laboratories. Small adjustments in the dead volume were performed to fit results more adequately. The new radiation protection ion chamber had its MCNP model defined.

New data are plotted in Figure 8. The results show good agreement between experimental and simulated results. Unfortunately, no measurements could be performed in the reference laboratory of IPEN/CMR, but STEEE/IEE ISO qualities were found to be adequate, as they were validated in earlier measurements. Once again, both window sides were tested with no significant differences. A good energy response was also observed for both experimental and simulated results. In Figure 8 the uncertainties are also shown within 68% of confidence level, and weighting residuals were calculated in order to compare data.

Residuals are within one standard deviation, and the new data showed satisfactory results. The energy dependence of experimental and simulated data was also calculated: 2.1% for simulations and 2.6% for STEEE/IEE laboratory measurements. These results are within ISO 4037-1 specifications of 5%. Further tests and simulations with other interest spectra and practical application in type

tests in IEE laboratories are about to be performed, in order to attest compliance of the detector to be applied in radiation protection measurements.

Discussion

The parallel plate vented chamber presented many successful results and its knowledge could also be improved with some additional simulations to better understand its full energy response in the diagnostic range, including mammographic applications. This is very important as new IEC standard series are required for all modalities of diagnostic equipment, including mammographic, dental, fluoroscopic, conventional, and computed tomography X-ray generators, and the determination of stray radiation profiles. The bilateral property was confirmed in the practical tests with no relevant dependence during the measurements. Nevertheless, other practical measurements and performance tests should be executed to attest its compliance with international standards and to validate this detector for use on practical type tests.

Conclusions

Monte Carlo calculation is a very important tool in the development of many radiation detectors. The present study showed that it can be also applied in the development of ionization chambers. The parallel plate vented chamber proposed in the present paper corresponds to the final prototype version. Based on MCNP results, studies regarding the best materials to be used in the chamber

housing and main parts were performed, and a chamber model that can be further used to simulate its behaviour on other X-ray qualities was stated.

A satisfactory energy response was achieved and other performance tests are under execution in the laboratory, accompanied by MCNP calculations.

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