Ion collection efficiency of ionization chambers in ultra-high dose-per-pulse electron beams

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(Received 19 June 2020; revised 30 September 2020; accepted for publication 18 November 2020; published 3 January 2021)

Purpose: The ion collection efficiency of vented ionization chambers has been investigated in an ultra-high dose-per-pulse (DPP) electron beam. The role of the chamber design and the electric field strength in the sensitive air volume have been evaluated.

Methods: An advanced Markus chamber and three specially designed parallel plate air-filled ionization chambers (EWC: End Window Chamber) with varying electrode distance of 0.5, 1, and 2 mm have been investigated. Their ion collection efficiencies were determined experimentally using two methods: extrapolation of Jaffé plots and comparison against a DPP-independent reference detector. The latter was achieved by calibrating a current transformer against alanine dosimeters. All measurements were performed in a 24 MeV electron beam with DPP values between 0.01 and 3 Gy. Additionally, the numerical approach introduced by Gotz et al. was implemented taking into account space charge effects at these ultra-high DPPs. The method has been extended to obtain time-resolved and position-dependent electric field distortions within the air cavity.

Results: The ion collection efficiency of the investigated ionization chambers drops significantly in the ultra-high DPP range. The extent of this drop is dependent on the electrode distance, the applied chamber voltage and thus the field strength in the sensitive air volume. For the Advanced Markus chamber, a good agreement between the experimental, numerical and the results of Petersson et al. could be shown. Using the three EWCs with different electrode spacing, an improvement of the ion collection efficiency and a reduction of the polarity effect with decreasing electrode distance could be demonstrated. Furthermore, the results revealed that the determination of the ion collection efficiency from the Jaffé plots and therefore also from two-voltage method typically underestimate the ion collection efficiency in the region of high dose-per-pulse (3 to 130 mGy) and overestimate the ion collection efficiency at ultra-high dose-per-pulse (>1 Gy per pulse).

Conclusions: In this work, the ion collection efficiency determined with different methods and ionization chambers have been compared and discussed. As expected, an increase of the electric field in the ionization chamber, either by applying a higher bias voltage or a reduction of the electrode distance, improves the ion collection efficiency and also reduces the polarity effect. For the Advanced Markus chamber, the experimental results obtained by comparison against a reference agree well with the numerical solution. Based on these results, it seems possible to keep the recombination loss less than or equal to 5% up to a dose-per-pulse of 3 Gy with an appropriately designed ionization chamber, which corresponds to the level accepted in conventional radiotherapy dosimetry protocols. © 2020 The Authors. Medical Physics published by Wiley Periodicals LLC on behalf of American Association of Physicists in Medicine. [https://doi.org/10.1002/mp.14620]

Key words: FLASH, ion collection efficiency, ionization chamber, ultra-high dose-per-pulse

1. INTRODUCTION

Vented ionization chambers are used as the standard dosimeter for clinical reference dosimetry. The methodology to determine the absorbed dose-to-water using an ionization chamber is described in dosimetry protocols like TRS-398,1 TG-512 or DIN 6800-23 based on a calibration performed using 60Co source that can be traced back to a primary or
secondary standard laboratory. Ideally, the measured signal shall represent the total charge carriers liberated within the sensitive air volume by the radiation field. In this case, to obtain the absorbed dose-to-water, the measured signal is multiplied by the calibration coefficient. Additionally, the energy dependence of the water-to-air stopping power ratio according to the cavity theory and detector’s perturbation factors between $^{60}$Co beam and the beam quality under investigation is considered by the beam quality correction factor. However, the measured signal can be also influenced by ion recombination and polarity effects so that further corrections are required.

To consider the loss of charge carriers through recombination processes, the so-called saturation correction factor $k_S$ is defined as the inverse of the charge collection efficiency. Generally, the recombination loss can be grouped into three categories: initial recombination, recombination by diffusion and the volume recombination. The latter effect is known to be more dominant at high dose rates or doses-per-pulse (DPP) compared to the other two. At the present time, high DPP electron beams are often clinically used in intra-operative radiation therapy (IORT). The high DPP range of medical linear accelerators for IORT lies between 3 and 130 mGy per pulse. With typical pulse repetition frequencies (PRF) of 5 to 60 Hz, nominal dose rates of 2.5 to 40 Gy/min are achieved. The pulse duration is typically between 2 and 4 μs. In the high DPP range, the formalisms for recombination loss adopted in the dosimetry protocols for conventional radiation therapy that account only for the conduction of positive and negative ions are not valid anymore. To minimize the recombination loss, ionization chambers with small electrode distance are commonly used with high chamber voltage applied that results in an increased proportion of free electrons. Due to the fraction of free electrons directly collected at these high dose rates without attachment to oxygen molecules to form negative ions, the electric field within the chamber’s cavity becomes distort. This will influence the saturation behavior of the detector and has not been considered in the standard Boag’s model adopted in the current dosimetry protocols. Therefore, the use of the approaches in TRS-398, TG-51 or DIN 6800-2 may lead to an underestimation of the ion collection efficiency.

The most comprehensive description for the ion collection efficiency $f = 1/k_S$ under consideration of the free electron component has been formulated by Boag et al. They presented three models of charge collection processes based on the assumptions of different distributions of negative ions between the electrodes directly after the clearance of free electrons that escape oxygen attachment. The first model was originally presented by Hochhäuser and Balk it assumed that the negative ion density is uniform across the ionization chamber. The other two more realistic models account for the deficit of negative ions within a region adjacent to the negative electrode, of which the third proposed model closest resembles the theoretical distribution of negative ions. Several experimental works have then followed with the aims to validate and extend the applicability of Boag’s formalisms to determine the correction factor $k_S$ for ionization chambers in high DPP beams by utilizing DPP-independent detectors as the reference. (Piermattei et al., Di Martino et al., Laitano et al. circumvented the need to use a reference detector by employing the two-voltage method to numerically solve for the detector-dependent parameters needed to apply the Boag’s formulæ. This same approach has been applied by Pimpinella et al., where they also assumed that the third Boag’s model provides the best description for the ion collection efficiency in high DPP IORT beams. Extensive investigations and comparisons of the different approaches have been performed by Cella et al., Scalchi et al. and Besheli et al. Despite the better agreements to experimental results achieved through the modified Boag’s equations to account for the free electron component, Boag et al. have questioned the validity of their own models at even higher DPP due to the non-negligible distortion of the electric field caused by the space charge distributions produced within the chamber. Gotz et al. have proposed a numerical solution to account for the ion collection efficiency of plane-parallel ion chambers due to volume recombination taking into account the space charge effect when irradiated with high DPP beams. The approach presented included improvements to the numerical solution first presented by Karsch. Gotz et al. demonstrated that none of the Boag’s models could provide good agreement with data experimentally determined with the Advanced Markus chamber for chamber voltages $> 100$ V in the range of ultra-high DPP values (up to 1 Gy/pulse). Their results agree to a more recent study conducted by Petersson et al., who have also investigated the Advanced Markus ionization chamber from high to ultra-high DPP electron beam range (10 mGy/pulse – 10 Gy/pulse). They presented an empirical model for the correction of recombination loss based on the comparison against DPP-independent Gafchromic EBT3 film and showed that the standard two-voltage analysis (TVA) to determine the correction factor $k_S$ only yields satisfactory results for DPP values up to about 10 mGy for the Advanced Markus ionization chamber.

The availability of radiation machines with higher performance that allow for irradiations with increased dose rate in modern radiation therapy has raised the interest to further investigate the ion collection efficiency of clinical dosimeters to increase their accuracies for dose measurements under these conditions. One application is the dosimetry under the so-called FLASH radiation condition, which has been described in 2014 by Favaudon et al., who revealed that healthy tissues can be better spared for the same amount of applied dose if irradiated at ultra-high dose rates of $> 40$ Gy/s. Acknowledging the promising outcome of FLASH radiotherapy, many studies have been performed in this area in the recent years, where the first human was treated by FLASH radiotherapy in 2019 (Bourhis et al.). A comprehensive review on FLASH radiotherapy has been made by Wilson et al.

In this work, a systematic investigation of the dependency of the ionization chamber’s ion collection efficiency on the
detector’s construction has been performed. For this purpose, three specially designed parallel plate chambers with different electrode distances were constructed. For comparison, the Advanced Markus chamber frequently investigated in the literature was also included in this study. Measurements were performed using an ultra-high DPP electron beam extended into the FLASH regime. The ion collection efficiencies of the chambers have been evaluated using Jaffé plots, by comparison against a reference independent of DPP and the numerical approach proposed by Gotz et al. The validity of each method in different DPP regions have been examined and discussed.

2. MATERIAL AND METHODS

2.A. Beam characteristics

All measurements have been performed at the research electron accelerator at the German National Metrology Institute (Physikalisch-Technische Bundesanstalt, PTB, Braunschweig). This research electron accelerator works on the same principle as medical accelerators. A current transformer (ICT) from Bergoz (in-flange version, turns ratio 50:1) is integrated in the beamline as a beam monitor. This instrument allows charge measurement of each single beam pulse with a precision of ±0.03 nC. Thus, the average charge of 100 beam pulses with a pulse charge greater or equal to 0.5 nC, as used in this work, can be determined with an uncertainty smaller than 0.6%. With increasing charge per pulse, the uncertainty decreases and is smaller than 0.15% for a charge per pulse ≥ 2 nC. The beamline has a thin exit window, which acts as scattering foil. A more detailed description of the accelerator can be found in Schüller et al. A 24 MeV electron beam was used for the measurements. The lateral shape of the radiation field was Gaussian with a full width at half maximum (FWHM) of about 10 cm at the depth of interest (see next subsection) in the water phantom. The charge per pulse was varied from 0.5 nC to 160 nC. The pulse repetition frequency was 5 Hz with a constant pulse duration of 2.5 µs.

2.B. Ionization chambers’ measurements

Three specially designed parallel plate chambers with different electrode distances (0.5, 1 and 2 mm) were constructed. These chambers are named the End-Window-Chambers (EWCs) in the following text. The nominal diameter of the collecting electrode is 4.4 mm. The collecting electrode is surrounded by a small guard ring. This allows a very compact design compared to typical parallel plate chambers, where the guard ring is broad in relation to the electrode distance. All electrodes are made of pure graphite. The high voltage electrode is surrounded by a PMMA sleeve. A cross-section of the EWCs is shown in Fig. 3. For comparison, the Advanced Markus chamber (Advanced Markus) type 34045 with 1 mm electrode distance and 5 mm collecting electrode diameter was also studied. The geometrical details of the investigated chambers are given in Table I. All chambers were manufactured by PTW-Freiburg.

Measurements were performed in a 30 × 30 × 30 cm³ water phantom with 2 cm thick walls made of PMMA using a precise motorized XYZ positioning system to place the chamber at the reference depth zref according to DIN 6800-2.

\[ z_{ref} = 0.6 \cdot R_{50} - 0.1 \text{cm} \]  

To determine the zref of the investigated beam, a depth ion dose distribution was first measured with an Advanced Markus chamber. The half-value depth \( R_{50,ion} \) was converted according to DIN 6800-2 to the radiation quality index \( R_{50} \) in cm. The reference depth \( z_{ref} \) was calculated according to Eq. (1) and was found to be 5.5 cm. The surface of the phantom was positioned at 70 cm from the exit window of the beamline resulting in a source-to-surface distance (SSD) of 70 cm. The current of the ionization chamber was measured using a Keithley 616 electrometer (in current mode). The reading of the electrometer was recorded by means of a 16-bit analog to digital converter and acquired by a self-developed software. The complete system was calibrated by means of a calibrated current source. The chamber voltage was varied in the range between 50 and 500 V at both polarities, which was controlled by a self-constructed PTB voltage source (“PTB-Mod.2002-06”) with HV modules from Matsusada (TM-0.8N and TM-0.8P) with a maximum output current of 2 mA, and a ripple of 2 mVpp.

As the ion recombination loss and polarity effect are both strongly influenced by the electrical field within the air volume of the chambers, the magnitude of the electric field inside the ionization chambers were studied using finite element methods (FEM) with the software ANSYS Maxwell Electromagnetics Suite 15.0.0. For this purpose, the CAD models of the chambers were imported and the corresponding materials were assigned. For this calculations, the measuring electrode as well as the guard ring were grounded, and the high-voltage electrode was set to 300 V.

2.C. Determination of ion collection efficiency

2.C.1. Jaffé plots

The Jaffé plots were obtained at eleven charges per pulse settings. The ionization current was measured at chamber voltages \( U \) of 50, 75, 100, 200, 300, 400, and 500 V. Each measurement point was averaged over 100 beam pulses. All measurements were performed with both polarities and corrected for polarity effect by taking the mean. This methodology was applied for all ionization chamber types in this study.

The ion recombination correction factor \( k_S \) at each charge per pulse value was derived from the linear relationship between the reciprocal values of the ionization current \( 1/M \) and the reciprocal of the chamber voltages \( 1/U \) and can be expressed according to Eq. (2).
The beam quality correction factor 

\[ k_{E} = 0.878 \pm 0.001 \] (Advanced Markus)
\[ 0.879 \pm 0.001 \] (EWC2)
\[ 0.882 \pm 0.002 \] (EWC1)
\[ 0.882 \pm 0.002 \] (EWC0.5)

2.C.2. Comparison to reference dose

According to DIN 6800-2, \(^{3}\) the absorbed dose-to-water can be obtained with a calibrated vented ionization chamber using Eq. (3).

\[ D_w = (M - M_0) * N'_{Co,60,Dw} * \prod_{i=1}^{n} k_i \]  (3)

Here \( N'_{Co,60,Dw} \) is the calibration coefficient of the ionization chamber for absorbed dose to water at \(^{60}\)Co, \( M \) is the reading of the dosimeter, \( M_0 \) is the reading of the dosimeter without irradiation and \( \prod k_i \) is the product of all correction factors applied to the reading.

For a known reference dose value \( D_w \) (see below), the ion collection efficiency of the chamber \( f \) is given by

\[ f = \frac{1}{k_s} = \frac{N'_{Co,60,Dw} * (M - M_0) * k_{elec} * k_p * k_{E} * k_{T,P} * k_{h}}{D_w} \]  (4)

The correction factors in the above equations are defined as follow:

- \( k_s \) is the factor to correct for the lack of complete charge collection (due to ion recombination)
- \( k_{elec} \) is calibration factor of the used electrometer
- \( k_p \) is the factor to correct for the polarizing voltage effect
- \( k_{E} \) is the beam quality correction factor for electron beams
- \( k_{T,P} \) is the air density correction factor.
- \( k_{h} \) is the factor to correct for the effect of humidity on the response of an ionization chamber

The air humidity during the measurements was close to 50%, therefore the corresponding correction factor \( k_h \) was assumed as 1. For the used electrometer with its data acquisition system, a correction factor \( k_{elec} \) of 1.01 to 1.03 depending on the used measuring range applied. A calibrated current source was used to determine \( k_{elec} \).

All ionization chambers were calibrated using both polarities with a \(^{60}\)Co source under calibration conditions at the PTW secondary standard laboratory. The calibration coefficients \( N'_{Co,60,Dw} \), as mean values obtained at both polarizing voltages are listed in Table I.

The beam quality correction factor \( k_{E} \) for the Advanced Markus chamber was determined according to DIN 6800-2. \(^{3}\) The factor \( k_{E} \) is the product of a chamber-independent factor \( k_{E}' \) and a chamber-dependent factor \( k_{E}'' \). At the reference depth, \( k_{E} \) can be calculated using the following equation.

\[ k_{E} = 1.106 - 0.1312 * (R_{50}) * 0.214 \]  (5)

The chamber dependent factor \( k_{E}' \) of the Advanced Markus chamber taken from the DIN 6800-2 is 0.985. The corresponding correction factors \( k_{E}'' \) for the EWCs were simulated using the Monte Carlo package EGSnrc with the user-code eggs_chamber. The chambers’ models were implemented according to the constructional drawings. A 10 cm \( \times \) 10 cm parallel 24 MeV monoenergetic electron beam was used during the simulations. The chambers were positioned with the inner side of their entrance windows at the reference depth. The simulation was also carried out for the Advanced Markus for comparison.

2.C.3. Numerical approach

Gotz et al.\(^{15}\) presented a numerical approach to solve a system of one-dimensional partial differential equations (PDE) (Equation system (6)) taking into account charge creations by the radiation, their transport and reaction in an applied electron field.\(^{15,33}\)

\[ \frac{\partial \rho_+}{\partial t} = \frac{\alpha}{\varepsilon} \rho_+ \rho_- - \nabla (\mu_+ E \rho_+) - \frac{\beta}{\varepsilon} \rho_+ \rho_e \]
\[ \frac{\partial \rho_-}{\partial t} = \frac{\gamma}{\varepsilon} \rho_e - \frac{\alpha}{\varepsilon} \rho_- \rho_+ + \nabla (\mu_- E \rho_-). \]
\[ \rho_e = R - \gamma \rho_e + \nabla (\mu E \rho_e) - \frac{\beta}{\varepsilon} \rho_+ \rho_e \]
\[ E = - \nabla (\varphi) \]
\[ \rho_+ - \rho_- - \rho_e = c \nabla (E) \]  (6)
The symbols in the above equations are defined as follow:

- $\rho_+ - \rho_- - \rho_e$ are the unsigned densities of positive ions, negative ions and electrons
- $R$ is the charge liberation rate due to irradiation
- $\alpha$ is the ion-ion recombination rate, $\beta$ is the electron-ion recombination rate, $\gamma$ is the electron attachment rate and $e$ is the elementary charge
- $\mu_+, \mu_- , \mu_e$ are the mobilities of positive ions, negative ions and electrons
- $\phi$ is the electric potential and $E$ is the electric field

All values for the above mentioned parameters were taken unchanged from Gotz et al. The readers are referred to the original work for more details and a discussion of the associated uncertainties. Their approach to solve the system of PDE, in the one-dimensional case based on an explicit Euler time step with first order upwind spatial discretization, has been implemented in this study using Julia (version 1.3.0) programming language that allows for a time resolved evaluations of the problem. The electron mobility and attachment rate used in our calculations were identical to those described by Gotz et al. Nevertheless, the field strength used in this study exceeded the range for which data on electron mobility and attachment rate, are available. Therefore, as a first approximation, the last available value was used if the field strength in the ionization chamber under irradiation exceeded the range for which data are available.

As input for the calculation the calibration coefficient $N_{Co-60,Dw}$ was multiplied with the beam quality correction factor $k_E$ to determine the liberated amount of charge $R$ in the sensitive volume of the chamber for the different DPP values. The electrode distance $d$ and the diameter $D$ are used to define the sensitive volume. Calculations were performed for a pulse duration of 2.5 $\mu$s and the chamber voltage under investigation. As a good compromise between accuracy and speed of the calculation, a grid size of 1000 nm was used for the solution of the equation system as proposed by Gotz et al.

2.D. Beam monitor calibration

To calibrate the ICT beam monitor, reference dose measurements were performed using alanine pellets with a diameter of 4.8 mm and a height of 2.7 mm. The alanine pellets were irradiated with about 15 Gy at different charge per pulse values. For each charge per pulse, a stack of eight alanine pellets were irradiated simultaneously in a PMMA tube at the same depth as the measurements with the ionization chambers. The dose response of alanine is known to depend on the temperature during the irradiation. Thus, sufficient time was allowed for the alanine pellets to achieve thermal equilibrium in the water phantom. The water temperature during the measurements was recorded and was taken into account during the evaluation of the alanine pellets. The alanine pellets were read out using a Bruker EMX 1327 electron spin resonance (ESR) spectrometer at PTB. The methodology used in this work has been described in details by Anton. A beam quality correction factor of 1.012 was applied for the used 24 MeV electron beams. The absorbed dose-to-water determined from the alanine measurements were then used to calibrate the ICT beam monitor. In the subsequent measurements, the charge obtained using the ICT was used to determine the DPP according to this calibration function.

The calibration function of the beam monitor was calculated based on five measurements with charge per pulse values ranging between approximately 1.5 and 120 nC. The corresponding dose values measured with the alanine range between 0.03 and 2.39 Gy per pulse. The calibration function of the beam monitor derived is shown in Fig. 1 and is linear with $R^2 = 1.000$. The coefficient that relates the charge per pulse to the absorbed dose in water at the reference depth was determined as $0.01957 \pm 0.00006$ Gy/nC.

3. RESULTS
3.A. Ionization chamber characteristics

The chamber designs including the electrical field strength calculated from the FEM analysis of the ionization chambers investigated are presented in the Figs. 2 and 3. Since the chambers are rotational symmetrical, only one half is shown. All ionization chambers are fully guarded. Due to the wide guard ring relative to the electrode distance of the Advanced Markus, the electric field is more homogeneous within the sensitive volume than in EWCs. In the later, regions with lower field strengths appear at the upper corner of the high voltage electrode.
The measured current of the ionization chambers averaged over 5 pulses per second vs the applied chamber’s voltage (I-V characteristics) for three exemplary DPP values are shown in Fig. 4 for both polarities and the mean values. The measured current increases with the applied voltage but the course of the I-V characteristic is steeper at higher DPP. With increasing DPP and chamber’s voltage, the difference between the measurement signals for the two polarities is also increasing, indicating the existence of a voltage-dependent polarity effect. This is particularly evident with the EWCs, where the effect is more pronounced at larger electrode distances.

3.B. Jaffé plots

The Jaffé plots obtained for all investigated DPP values using the different ionization chambers are presented in Fig. 5. Only the polarity corrected values are used in this evaluation. The data were normalized to the nominal voltage of 300 V and fitted by linear regression. The steepness of the linear regression increases with DPP. As a result, the determined ion collection efficiency decreases with DPP. However, above a certain DPP value that is detector-dependent, the steepness approaches a constant value.

3.C. Ion collection efficiency

In Fig. 6, the ion collection efficiency for the ionization chambers at a voltage of 300 V is shown. The results from the Jaffé plots were derived from the polarity corrected values as shown previously. The ion collection efficiency obtained using the numerical approach is also presented. Good agreement has been obtained between the chamber’s collection efficiency determined by comparison with the reference dose derived from the ICT calibration and the numerical approach. However, the values determined from the Jaffé plots are typically lower compared to the other methods in the lower DPP range. At higher DPP values, the results obtained from the Jaffé plots approach a nearly constant value resulting in a strong overestimation of the ion collection efficiencies. The DPP value from which this occurs is dependent on the chamber’s design and dominated by the electrode distance. For comparison, the model of Petersson et al.\textsuperscript{17} was presented also for the Advanced Markus. These values were calculated according to their fit function [Eq. (7)]

$$1 \frac{k_S}{1 + \left( \frac{\text{DPP}(\mu Gy)}{V/V} \right)^{-\alpha / \beta}}$$

(7)

![Fig. 2. Schema of the basic Advanced Markus chamber structure including the magnitude of the electrical field for a chamber voltage of 300V. The boundary between the sensitive volume above the collecting electrode and the insensitive volume above the guard ring is indicated by the black line. [Color figure can be viewed at wileyonlinelibrary.com]](image)
FIG. 3. Schema of the basic chamber structure including the magnitude of the electrical field for a chamber voltage of 300 V. The boundary between the sensitive volume above the collecting electrode and the insensitive volume above the guard ring is indicated by the black line. From left to right: EWC2, EWC1, EWC0.5. [Color figure can be viewed at wileyonlinelibrary.com]

FIG. 4. Current-voltage (I-V) characteristics of the ionization chambers for three different dose-per-pulse (DPP) values. The values in blue are for positive and the red ones for negative polarizing voltage. The black symbols are the means of both polarities. (a) Advanced Markus, (b) EWC2, (c) EWC1, (d) EWC0.5. [Color figure can be viewed at wileyonlinelibrary.com]
with the parameters $\alpha = 2.5$ and $\beta = 0.144$, which are the mean values obtained with three different Advanced Markus chambers for a pulse width of 1.8 $\mu$s and a voltage of 300 V.\textsuperscript{17}

By comparing with the reference dose, it can be observed from the three different EWCs that the ion collection efficiency increases with decreasing electrode distance. This is presented in Fig. 7 for the maximum used voltage of 500 V.

The comparison of the ion collection efficiency for the Advanced Markus and the EWC1, which both having a nominal electrode distance of 1 mm is presented in Fig. 8 for two polarizing voltages of 300 and 500 V. The ion collection efficiency is improved for both chambers at the higher polarizing voltage. Furthermore, it can be seen that the EWC1 needs a voltage of 500 V to achieve a comparable ion collection efficiency as the Advanced Markus with 300 V due to the higher non-uniformity of the electric field in the EWC1 adjacent to the guard electrodes.

3.D. Distortion of the electric field

The influence of space charge effect at high DPP radiation on the electric field within the chamber has been evaluated using the numerical approach for the Advanced Markus chamber with an electrode distance of 1 mm and an applied voltage of 300 V. Figure 9 shows the evolution of the electric field at different time points within a 2.5 $\mu$s pulse of 2 Gy. The location of the measuring electrode corresponds to the position 0 mm and the HV electrode to 1 mm. Before the pulse ($t = 0$), a homogenous field of 3 kV/m exists throughout the sensitive air volume. Within the duration of the beam pulse ($t > 0$), a strong distortion of the field can be observed. As the time increases, the field distortion also becomes stronger.

In Fig. 10, the electric field inside the chamber at the end of the 2.5 $\mu$s pulse for the different DPP values is presented. For the lowest DPP value of 0.01 Gy, the electric field inside the chambers sensitive volume is nearly undisturbed. However, from 0.02 Gy per pulse onwards, a distortion of the electric field becomes visible that increases with the DPP. This results in a reduction of the field strength in a wider area of the ionization chamber.

4. DISCUSSION

Ionization chambers shall be operated in the plateau of the I-V characteristic curves. Nevertheless, as demonstrated in Fig. 4, the steepness of the chamber’s I-V characteristic increases strongly with DPP value, so that a plateau no longer exists at these very high DPP values. In addition, the polarity
FIG. 6. Ion collection efficiency for the ionization chambers with a polarizing voltage of 300 V. (a) Advanced Markus, (b) EWC2, (c) EWC1, (d) EWC05. [Color figure can be viewed at wileyonlinelibrary.com]

FIG. 7. Ion collection efficiency determined by comparison against the reference dose as a function of dose-per-pulse (DPP) for the three different EWCs for a polarizing voltage of 500 V. [Color figure can be viewed at wileyonlinelibrary.com]

FIG. 8. Comparison of the ion collection efficiency as a function of dose-per-pulse (DPP) for the Advanced Markus and the EWC1 for polarizing voltages of 300 and 500 V. [Color figure can be viewed at wileyonlinelibrary.com]
effect observed for the investigated chambers also becomes more pronounced at high DPP. Due to its wider guard ring that ensures a more homogeneous electric field within the sensitive air volume, the effect is less prominent for the Advanced Markus than for the EWCs. By increasing the electrode distance in the EWCs from 0.5 to 2 mm, the polarity effect also increases and at high DPP values, the required correction clearly exceeds the magnitude usually found in the DPP range of conventional radiotherapy, which is less than 1% for the advanced Markus chamber (e.g. Pearce et al.37). In this work, the polarity effect has been corrected by taking the mean of the values obtained with positive and negative polarity as suggested by dosimetry protocols such as TG-51 and TRS-398 and performed by Petersson et al.17 also under ultra-high DPP conditions. Although good agreements between the corrected results and the numerical results have been obtained as shown in Figs. 6 and 8, the validity and the uncertainty of this approach in these ultra-high DPP conditions should be further investigated.

As shown by Petersson et al.17 the TVA only works for DPP values up to about 10 mGy. The prerequisite for the validity of the TVA is the linearity of the Jaffé plot. As can be seen in Fig. 5, the nonlinearity of the Jaffé plot increases with increasing DPP. Consequently, at higher DPP values, the ion collection efficiency is overestimated due to the non-linearity in the Jaffé plots. A possible explanation for the non-linearity in the Jaffé plots and the sharp drop in the ion collection efficiency is the field distortion with increasing DPP, which is shown in Figs. 9 and 10. This field distortion reduces the field strength within the chamber’s sensitive volume resulting in higher recombination losses. At lower DPP, the ion collection efficiency is underestimated due to the effect of free electrons mentioned in the introduction.

For the Advanced Markus chamber, there is a good agreement between the ion collection efficiency obtained experimentally by using the reference dose derived from the ICT calibration and the numerical calculations. This can be attributed to the homogeneous field strength within the chamber’s sensitive air volume as shown in Fig. 2 that fulfills the assumption made in the numerical approach.

For the EWCs, the agreement with the numerical results is worse due to the field inhomogeneities arise within the air volume resulting from the narrow guard ring. These inhomogeneities are not considered in the numerical calculation. As expected, the systematic variation of electrode distance of the EWCs demonstrated that the ion collection efficiency can be improved by reducing the electrode distance (Fig. 7) and by increasing the chamber voltage (Fig. 8).

By comparing the results of the Advanced Markus chamber to the EWC with the same electrode distance of 1 mm, the advantages of an inherent homogeneous electric field within the chamber’s air cavity become apparent as the Advanced Markus chamber possesses higher ion collection efficiency and also a smaller polarity effect.

5. CONCLUSION

In this work, the results of Petersson et al.17 for the Advanced Markus chamber could be confirmed by a different method. They used EBT3 film to determine the reference
dose, whereas in this work an ICT calibrated against alanine was used. It has been demonstrated that the determination of the ion collection efficiency from the Jaffé plots and therefore also from TVA fail in the region of high and ultra-high DPP. The ion collection efficiency of the Advanced Markus chamber is in good agreement to the numerical solution based on the work of Gotz et al. The approximation to extend the range of field strength and therefore the range of DPP shows reliable results. Increasing the electrical field in the ionization chamber due to higher voltage and a reduction of the electrode distance help to increase the ion collection efficiency and to reduce the polarity effect. The time and DPP-dependent electric field distortion has been presented as potentially important factors influencing the ion collection efficiency of the chambers. Based on the experimental and numerical results, it seems possible to keep the recombination loss up to a DPP of 3 Gy less than or equal to 5% with an appropriately designed ionization chamber. This can be achieved by increasing the field strength by using a smaller electrode distance (Fig. 7) or a higher chamber voltage, and an improved guard design (Fig. 8) that ensures the homogeneity of the electric field within the air volume.

ACKNOWLEDGMENTS

We thank Christoph Makowski for the operation of the electron accelerator. The assistance of Markus Meier during the execution of the measurements is gratefully acknowledged.

This project has received funding from the EMPIR programme co-financed by the Participating States and from the European Union’s Horizon 2020 research and innovation programme.

CONFLICT OF INTEREST

Rafael Kranzer, Daniela Poppinga and Jan Weidner are PTW employees.

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