

Evaluation of different methods for determining the magnitude of initial recombination in ionization chambers

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Abstract

The charge loss due to initial recombination was measured for various therapy level ionization chamber types. Different methods were applied. Measurements were performed in ^{60}Co beams, pulsed high-energy photon beams and pulsed high-energy electron beams. The results are mutually consistent within less than 0.05 %. Within this uncertainty initial recombination and diffusion do not depend on the radiation quality. For dose measurements in high energy photon or electron beams it is shown that the incomplete charge collection in an ionization chamber cavity can be corrected for within less than 0.05 % if appropriate procedures are applied.

1 Introduction

The incomplete charge collection in an ionization chamber cavity due to volume recombination depends on the dose rate and must be corrected for, whereas the effects of initial recombination and diffusion do not depend on dose rate. In pulsed beams it is recommended and widely accepted to measure the recombination correction factor k_s by extrapolating the inverse of the chamber reading M as a function of the inverse of the polarizing voltage U to $1/U = 0$ (e. g. [1]). This method accounts for initial recombination, volume recombination and for charge loss by diffusion as well, since all these effects depend linearly on $1/U$.

PTB calibrations in terms of absorbed dose to water performed in ^{60}Co radiation are not corrected for charge deficits due to effects which do not depend on dose rate. Initial recombination and diffusion are taken into account by the calibration factor itself. Thus, measuring absolute dose values with lowest possible uncertainty in pulsed beams, e. g. when comparing standards or when measuring k_Q values, requires to determine the magnitudes of initial recombination and volume recombination separately.

In this paper the charge loss in ionization chambers of types commonly used as transfer standards or as reference dosimeters is studied. The results of three different methods for determining the proportions of initial recombination and diffusion are compared. Measurements have been performed in ^{60}Co beams and in pulsed photon and electron beams.

2 Methods and Materials

2.1 Theory

The main mechanisms of charge loss are diffusion loss, initial recombination and volume recombination [2]. Near saturation the respective collection efficiencies may be calculated from

$$\begin{aligned} f_d &= 1 - 2 k T / (U e) && \text{for diffusion loss [3] and} \\ f_i &= 1 - E_i d / U && \text{for initial recombination [4].} \end{aligned}$$

In pulsed beams the dose rate dependent effect of volume recombination is described by [5]

$$f_v(\text{pulsed}) = 1 - \frac{1}{2} \mu q d^2 / U ,$$

The respective collection efficiency in continuous radiation is [5]

$$f_v(\text{cont}) = 1 - \beta j d^4 / U^2$$

e	$1.6022 \cdot 10^{-19} \text{ C}$	electron charge
k	$1.3807 \cdot 10^{-23} \text{ J/K}$	Boltzmann constant
T	air temperature	
U	polarizing voltage	
d	effective electrode separation	
j	current generated per volume	
q	charge generated per volume per puls	
E_i, μ, β	constants	

The resulting total collection efficiency is the product of three factors: $f = f_i f_d f_v$. In continuous radiation this relationship is approximately a quadratic polynomial function of the reciprocal of the polarizing voltage:

$$f(\text{cont}) = 1 - b/U - \beta j d^4 / U^2 \quad (1)$$

Its shape depends on the magnitude of the coefficients. At a dose rate of 1 Gy/min which is typical for ^{60}Co beams the relative charge loss due to volume recombination amounts to $3 \cdot 10^{-5}$ for chambers of type NE2571 ($d = 3 \text{ mm}$, $U = 300 \text{ V}$, $\beta = 6,73 \cdot 10^{13} \text{ V}^2/(\text{A}\cdot\text{m})$ from [5]). Volume recombination reaches the magnitude of initial recombination, approximately 0.1 %, at a dose rate above 30 Gy/min.

Thus, in typical ^{60}Co beams the reciprocal of the reading is expected to be an almost linear function of the reciprocal of the polarizing voltage with deviations at low polarizing voltages which become more pronounced at increasing dose rates.

In pulsed beams the total collection efficiency depends approximately linearly on the polarizing voltage:

$$f(\text{pulsed}) = 1 - a/U \quad \text{with } a = 2 k T / e + E_i d + \frac{1}{2} \mu q d^2 \quad (2)$$

The constant a sums all main effects. At a given pulse charge density q the proportions of diffusion loss, initial recombination and volume recombination cannot be separated.

The theory suggests three different methods to measure the proportions of volume recombination and initial recombination plus diffusion separately:

Method 1

- Measuring in a ^{60}Co beam the charge collected at constant dose as a function of the polarizing voltage at various dose rates.
- Applying a second degree polynomial fit simultaneously on all curves of one chamber. The fit function is $M(U)/M(V_1) = f(U)/f(V_1)$ with $f(U) = 1 - b/U - \beta j d^4 / U^2$. V_1 is any fixed polarizing voltage. In this work $V_1 = 100 \text{ V}$ is used. The parameters fitted are b and β .

Method 2

- Measuring in a ^{60}Co beam the charge collected at constant dose as a function of the polarizing voltage at a dose rate of less than 0.1 Gy/min .
- Fitting the function $M(U)/M(V_1) = f(U)/f(V_1)$ with $f(U) = 1 - b/U - \beta j d^4 / U^2$ and setting $\beta = 6,73 \cdot 10^{13} \text{ V}^2/(\text{A}\cdot\text{m})$. The parameter fitted is b only.

This is the most simple method. It works with sufficient accuracy, because of the smallness of the amount of volume recombination (see Fig.1).

Method 3

- Measuring in pulsed beams the charge collected at constant dose as a function of the polarizing voltage at various pulse charge densities.
- Fitting the function $M(U)/M(V_1) = f(U)/f(V_1)$ with $f(U) = 1 - a/U$. The parameter fitted is a . A set of values $a(q)$ will be obtained.
- Fitting $a(q) = b + \frac{1}{2} \mu q d^2$ (3)

2.2 Experiments

The measurements were performed at the PTB ^{60}Co irradiation facility and at the PTB electron accelerator ELEKTA SL75-20. Six types of thimble chambers and one type of plane parallel chamber were investigated. For some types various models were tested.

All measurements were performed in water. Chambers not waterproof were kept in close-fitting PMMA sheaths with a wall thickness of 1 mm. Each reading M is the mean charge collected at the two polarities of the polarizing voltage. After voltage switching measurements were repeated until the readings reached a stable value. The readings are corrected for air density.

In the ^{60}Co beam the dose rate was varied from $0,03 \text{ Gy/min}$ to 3 Gy/min by varying the depth in the phantom and the source-to-phantom surface distance.

In the accelerator beams the charge collected by the chamber under test was normalized to the mean collected charge of two adjacent monitor chambers. The monitors were placed 29 mm to the right and to the left at the depth of the effective point of measurement. Measurements were performed in high energy photon beams and electron beams as well. The pulse charge density was varied from $0.25 \cdot 10^{-5} \text{ C/m}^3$ up to $3 \cdot 10^{-5} \text{ C/m}^3$.

3 Results

3.1 Measurements in ^{60}Co radiation

For all chambers tested the reciprocal of the reading is as expected an almost linear function of the reciprocal of the polarizing voltage at dose rates below 0.1 Gy/min. As an example, Fig. 1 shows $1/M$ versus $1/U$ for an ionization chamber of type NE 2571 for various dose rates. The curves are normalized to the readings at 100 V ($M_{100\text{V}}$). Deviations from linearity occur at high dose rates and low polarizing voltages.

According to Method 1 a second degree polynomial function has been fitted simultaneously on all curves of one chamber. For the chamber volumes and the effective electrode separations the nominal values have been used. Table 1 lists the results for b and β , defined in Eq.1.

The constant β describing the magnitude of volume recombination is believed not to depend on the chamber construction and should thus be the same for all chambers. The observed variations reflect the small sensitivity of the data for this parameter due to the smallness of the effect. The mean value $\beta = (7.6 \pm 1.1) \cdot 10^{13} \text{ V}^2/(\text{A}\cdot\text{m})$ agrees within the uncertainty with the theory [5].

The value of b is the percentage charge deficit at 100 V polarizing voltage caused by initial recombination and diffusion. The charge deficits of different species of the same chamber type differ by not more than $2 \cdot 10^{-4}$ which is within the measurement uncertainty of about $5 \cdot 10^{-4}$. Measurements by Burns and Rosser who report $b = 0.28 \text{ V}$ for NE2561 agree well with this work.

Since the chambers are operated at polarizing voltages of 200 V or 300 V the relative charge loss due to initial recombination and diffusion is in the order of 10^{-3} for all chamber types. At typical dose rates the charge loss due to volume recombination is one order of magnitude smaller.

Method 2 is a simplification of Method 1. The data allow to conclude that Method 2 yields results consistent with Method 1 at dose rates below 0.1 Gy/min.

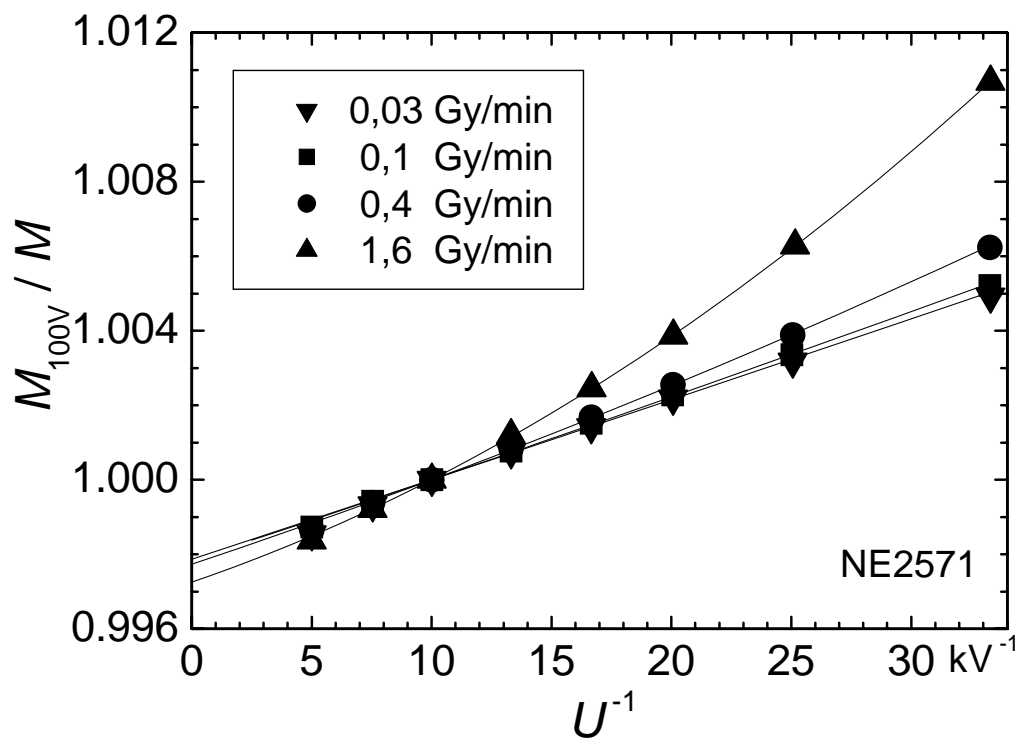


Fig. 1 Reciprocal of the reading M (normalized to 1 at 100 V) as a function of the reciprocal of the polarizing voltage U for an ionization chamber of type NE2571 in ^{60}Co radiation at different dose rates. The lines are a fit to the data.

Table 1 Results for the parameters b and β of Eq. 1 obtained from fits on measurements in ^{60}Co beams. Initial recombination plus diffusion are described by b , volume recombination is described by β .

chamber	b / V	$\beta / 10^{13} \text{ V}^2 / (\text{A m})$
NE 2561/244	0.27	7.7
NE 2561/293	0.27	7.9
NE 2561/297	0.27	6.0
NE 2571/977	0.24	9.3
NE 2571/2906	0.22	7.6
FC 65-G/771	0.17	7.3

3.2 Measurements in pulsed beams

Normally, the dose rate of photon beams from accelerators is varied by varying the pulse repetition frequency. The dose per pulse cannot be varied easily. It is difficult to realize a range of pulse charge densities sufficiently large for Method 3. This difficulty can be solved by measuring in electron beams as well. It must be checked if the photon and electron data are mutually compatible.

The numerical value of a in Eq. 2 can be interpreted as the percentage charge deficit at 100 V polarizing voltage. Fig. 2 shows this quantity as a function of pulse charge density for a plane parallel chamber of Roos type, Fig. 3 shows the same for a thimble chamber NE2571. In both cases the electron and photon data fit perfectly to the same line. No dependence of the charge deficit on the radiation quality is observed. Hence, parameter b can be derived from these fits according to Eq. 3.

Table 2 lists the results for various types of ionization chambers. The values for PR06C and PTW chambers result from former work with larger uncertainty, indicated by reporting one digit less.

Expressed in terms of charge loss at 100 V the results for NE2561 and NE2571 differ by at most $3 \cdot 10^{-4}$ from the values obtained in ^{60}Co radiation. This is within the measurement uncertainty of about $5 \cdot 10^{-4}$. Within this uncertainty no difference between ^{60}Co radiation and high energy pulsed radiation is observed for the charge deficit due to initial recombination and diffusion.

The chambers listed are operated at polarizing voltages of 200 V or 300 V. Therefore, a relative charge deficit of 0,1 % due to initial recombination and diffusion for all chamber types at typical operating conditions as published in [7] is a good estimate.

Table 2 Results for the parameter b of Eq. 3 obtained from fits on data measured in high energy photon and electron beams.

type of chamber	b / V
NE 2561	0.30
NE 2571	0.23
PR06C	0.3
PTW23331/2	0.3
Roos-type	0.12

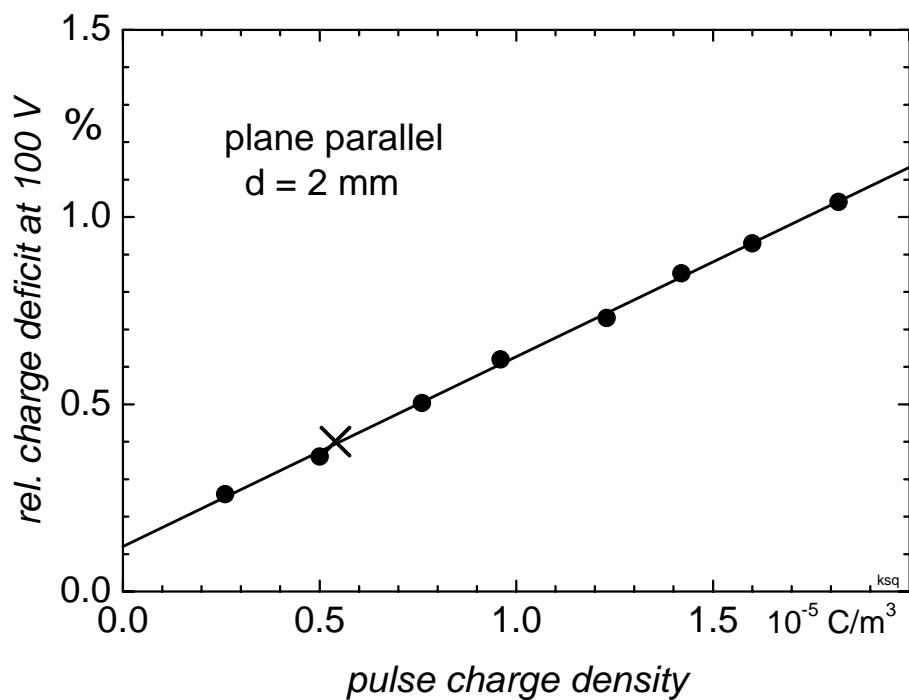


Fig. 2 Relative charge deficit at 100 V polarizing voltage as a function of the pulse charge density measured in photon beams (solid circles) and in an electron beam (cross) for a plane parallel ionization chamber of Roos type. The solid line is a fit to the data.

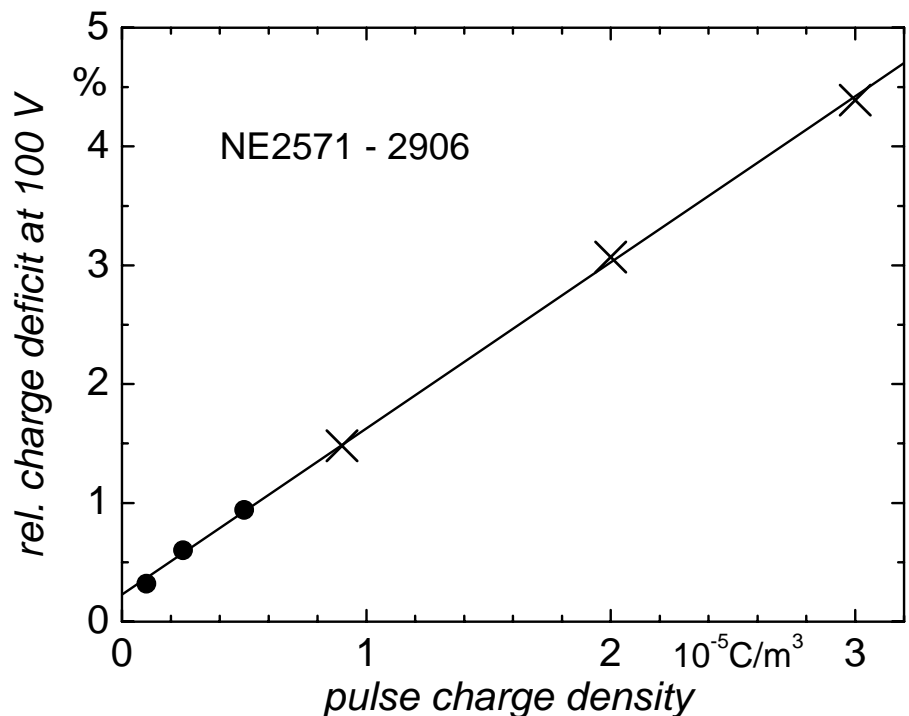


Fig. 3 Relative charge deficit at 100 V polarizing voltage as a function of the pulse charge density measured in photon beams (solid circles) and in electron beams (crosses) for an ionization chamber of type NE2571. The solid line is a fit to the data.

4 Conclusions

In ^{60}Co beams correction procedures for the effect of volume recombination based on a linear dependence of $1/M$ on $1/U^2$ are not appropriate since the dominant mechanisms of charge loss are initial recombination and diffusion. Volume recombination occurs in the order of 10^{-4} at dose rates below a few Gy/min for ionization chamber types commonly used in external beam radiotherapy. Thus, the PTB policy of not correcting the ^{60}Co calibration factor for charge loss is justified. Initial recombination and diffusion, both not depending on dose rate, are taken into account by the calibration factor itself.

In pulsed beams from accelerators the effect of volume recombination is almost two orders of magnitude larger than in continuous radiation. Extrapolation procedures based on extrapolating linearly $1/M$ to $1/U = 0$ do not separate the effects of diffusion, initial recombination and volume recombination. Neglecting initial recombination and diffusion is a potential source of measurement errors.

The proportions of initial recombination and diffusion can be measured in continuous radiation and in pulsed radiation as well. The results are consistent within less than 0.05 %. No dependence on the radiation quality has been observed. The method of choice can be selected according to the laboratory's measurement capabilities.

The incomplete charge collection in an ionization chamber cavity can be corrected for within less than 0.05 % if appropriate procedures are applied.

5 References

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