THE RECOMBINATION CORRECTION AND THE DEPENDENCE OF THE RESPONSE OF PLANE PARALLEL CHAMBERS ON THE POLARIZING VOLTAGE IN PULSED ELECTRON AND PHOTON BEAMS

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Abstract

Based on an experimental investigation of the recombination effect in plane parallel chambers, a relation is deduced that allows the correction to be calculated from the electrode spacing and from the dose per pulse. It is shown that the uncertainties caused by the application of the Boag formula for volume recombination (recommended in the International Code of Practice TRS-381) amount to not more than about 0.1% for conventional beams. Calculated recombinations are compared with experimental results concerning the dependence of the response of various commercial plane parallel chambers on the polarizing voltage. Since it cannot be excluded that particular chambers collect a non-negligible amount of charge from regions outside the designated collecting volume or that the effective polarizing voltage is reduced by poor contacts, it seems advisable to experimentally check the chambers before use and before application of the analytical relations.

1. Introduction

The experimental determination of the recombination correction in pulsed beams is based on an extrapolation of the reciprocal of the reading $1/M$ as a function of the reciprocal of the polarizing voltage $1/U$ towards $1/U = 0$ in order to get the corrected value of 1/M [1, 2]. This implies, of course, that the voltage exclusively affects the degree of saturation. This assumption is, however, usually not fulfilled in the case of plane parallel chambers. Before the preparation of the International Code IAEA TRS-381 [3] it was shown [4] that most of the commercial plane parallel chambers show a pronounced curvature at the highest voltages, where theory essentially demands a straight line. This indicates that other effects may play an important role. As an example it was discussed that the dependence of the response of the Schulz chamber on the polarizing voltage is predominantly caused by the dependence of the collecting volume on this voltage. Any type of extrapolation therefore does not yield useful results as regards the degree of saturation in such cases.

Since the two-voltage method essentially consists in a linear extrapolation, it is strictly not applicable in such cases. It was therefore suggested to apply it twice, upon calibration (even if the recombination correction is in fact negligible as in the case of ^{60}Co-γ radiation) and in the users beam (using the same two voltages, of course). In this case the single corrections may be incorrect, but the quotient is approximately correct since the falsifying effects may, at least partly, cancel. This is obvious in the example of the voltage-dependent collecting volume.

It must, however, be borne in mind that, due to the long equilibration times of most of the chambers [5], the experimental determination of the correction (amounting to only a few tenths of a percent in most cases) seems to be unnecessarily laborious. In fact, depending on the equilibration time of the chambers and on the inherent drifts of the accelerator/ monitor/ dosimeter system, the uncertainty of the correction may be comparable to its magnitude. It was, therefore, suggested using the analytical formula by Boag, included in TRS-381 [3], for volume recombination [1] in such cases.

The present paper investigates the recombination in plane parallel chambers exposed to conventional pulsed beams and evaluates the uncertainties introduced by the application of the

Boag formula. In addition, the dependence of the response of commercial plane parallel chambers on the polarizing voltage is studied and compared with the respective saturation properties.

2. Results and discussion

2.1. Evaluation of the uncertainties introduced by the application of the Boag formula to volume recombination

The recombination in chambers with plane parallel orientation of the electrodes is well understood [1]. The restrictions as regards the applicability of the two-voltage method are not caused by a lack of theoretical knowledge but by peculiarities of chamber designs and of individual chambers. In fact, well designed and carefully constructed chambers show usually a more or less wide range of polarizing voltages where the dependence of response on the voltage is in accordance with the theoretically expected saturation behaviour. This allows a physically well-reasoned extrapolation of the reciprocal of the reading $1/M$ as a function of the reciprocal of the polarizing voltage $1/U$ towards $1/U = 0$.

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

initial recombination [6]: $$f_i = 1 - e_i \cdot d / U \tag{1a}$$

diffusion loss [7]: $$f_d = 1 - 2 \cdot k \cdot T / (U \cdot e) \tag{1b}$$

volume recombination [8]: $$f_v = 1 - \frac{1}{2} \mu \cdot q \cdot d^2 / U \tag{1c}$$

The resulting collection efficiency f is the product of three factors:

$$f = f_i \cdot f_d \cdot f_v \tag{1}$$

The corresponding recombination correction factor $k_S = f^{-1}$ is, therefore, a linear function of the reciprocal of the polarizing voltage U:

$$k_s = 1 + a / U \tag{2}$$

with $$a = e_i \cdot d + 2 \cdot k \cdot T / e + \frac{1}{2} \mu \cdot q \cdot d^2$$

e	1.6022×10^{-19} C	electron charge
k	1.3807×10^{-23} J/K	Boltzmann constant
T	air temperature	
U	polarizing voltage	
d	electrode spacing	
q	initial charge density per pulse	
e_i	constant with the dimension of a field strength	
μ	constant involving the recombination coefficient and the ionic mobilities [1]	

A plot of the reciprocal of the reading as a function of the reciprocal of the polarizing voltage should therefore result in a linear relation if the dependence of the response on the polarizing voltage is exclusively given by the recombination effects discussed. In the case of plane parallel chambers with small electrode separation, the free electron component has to be taken into account in addition [1]. It causes, in a first approximation, only a decrease of the slope of the $1/M$ vs. $1/U$ plot. Various models are available for the description of the influence of the free electron component [9]. Depending on the model used, the free electrons may cause a slight deviation from linearity in the direction of higher efficiency at the highest voltages (out-of-voltage range of the measurements). The maximum deviation caused by this curvature in comparison with a linear relation towards $1/U = 0$ is, however, in practice well below 0.1% in the range of the pulse charge densities of interest. If the free electron fraction is assumed to be proportional to the polarizing voltage (which is compatible with the data available [9]), or if it is independent of it, the linear extrapolation of the observed plot to 1/U = 0 furnishes the charge corresponding to complete saturation.

In order to determine the recombination correction experimentally, a plane parallel chamber of the type FK6 [4] with an electrode spacing of 2 mm (common with most of the commercial chambers used in electron dosimetry) was carefully checked in order to exclude effects such as gas multiplication, dependence of the collecting volume on the voltage and charge collection from regions outside the designated collecting volume. The charge (normalized to a monitor reading) was measured for various pulse charge densities around the range of interest, applying different polarizing voltages. The experimental features were described in [10].

Figure 1 shows the results for various pulse charge densities: the reciprocal of the reading normalized to 1 at 100 V has been plotted as a function of the reciprocal of the polarizing voltage. The polarity effect of this chamber is small and almost independent of the absolute value of the polarizing voltage. The dotted lines are linear fits to the data. The experimental data show the expected linear behaviour, and the corrected values were obtained by linear extrapolation towards $1/U = 0$.

Figure 2 shows the resulting charge deficit for a polarizing voltage of 100 V as a function of the pulse charge density (solid circles). In order to obtain a larger range of pulse charge densities, part of the measurements were performed in photon beams. The cross, obtained from measurements in an electron beam, demonstrates that the results hold for both high-energy photon and electron beams, as theoretically expected. A linear fit to the data yields

$$a = 0.12\ \mathrm{V} + 0.51\ \frac{\mathrm{V}}{10^{-5}\,\mathrm{C/m^3}} \cdot q \qquad (3)$$

A comparison of Eq. (3) with Eq. (2) leads to

$$k_s = 1 + (e_i \cdot d + 2 \cdot k \cdot T/e + \frac{1}{2}\mu \cdot q \cdot d^2)/U$$

with $e_i = 35\ \frac{V}{m}$ and $\mu = 2.55 \cdot 10^{10}\,\mathrm{Vm/C}$

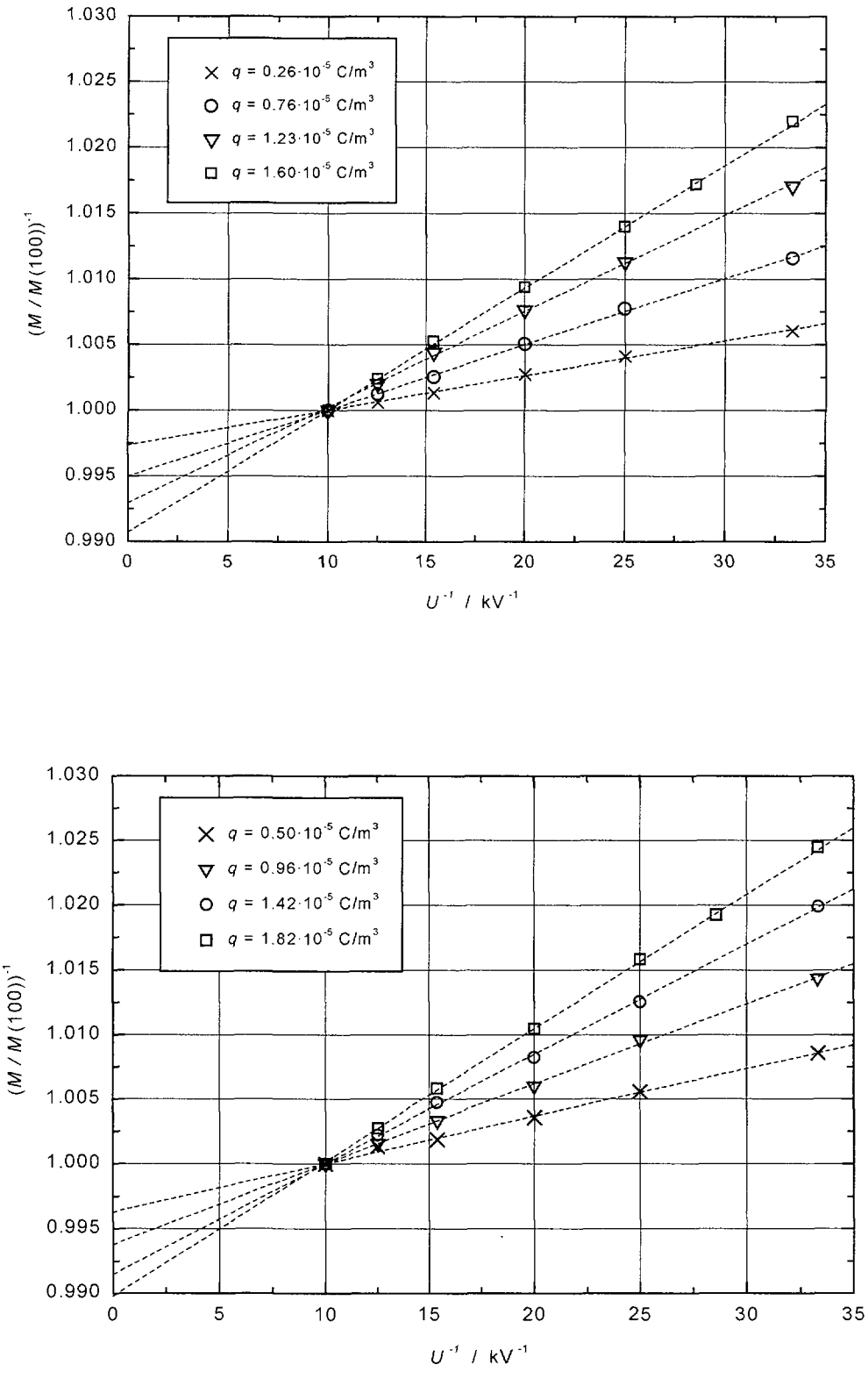

FIG. 1. Reciprocal of the reading M *of an FK6 chamber, normalized to 1 at 100 V, as a function of the reciprocal of the polarizing voltage* U *for various pulse charge densities* q. *The dotted lines are linear fits to the data (for discussion see text).*

This may be expressed as

$$k_s = 1 + (0.12 + 0.46 \cdot d^2 \cdot D_i)/U \qquad (4)$$

d = electrode spacing in mm

D_i = absorbed dose to air per pulse in mGy

U = polarizing voltage in volts

Equation (4) allows recombination correction factors to be calculated for well guarded plane parallel chambers with an electrode spacing $d = 2$ mm. It may, however, also be used for a spacing deviating by a few tenths of a millimetre from this value. It is sufficient to approximate the absorbed dose to air D_i per pulse by the absorbed dose to water per pulse.

The reason for the restriction of the electrode spacing is the dependence of the parameter μ [1] on the spacing. This parameter is implicitly contained in Eq. (4). It involves the ionic mobilities and the recombination coefficient and is defined [1] as a fitting parameter to the recombination models as used in the present work. It therefore allows in addition for the free electron component, space charge effects, etc. and, therefore, depends on the chamber type. For sufficiently guarded plane parallel chambers the μ value depends essentially on the electrode spacing because of the influence of the free electron component which depends on the spacing. The value $\mu = 2.55\ 10^{10}$ V m / C obtained from the above fit is considerably smaller than the value $\mu = 3.02\ 10^{10}$ V m / C included in the Boag formula [1]. It is valid for plane parallel chambers with an electrode spacing of about 2 mm, whereas the latter value is rather valid for different chamber types with a larger electrode spacing, resulting in a smaller free electron component (and sometimes in a considerably different space charge distribution).

The dotted line in Figure 2 represents Boag's relation for volume recombination only [1]. The deviation of this relation from the experimental results is essentially caused by the missing initial recombination and by the contribution of the free electron component, affecting the apparent value of parameter μ [1]. These deviations are, however, not larger than about 0.1% in the range investigated, and since the polarizing voltages of the different chamber types are usually considerably higher than 100 V, the deviations may be even smaller in practice. This can be inferred from the respective formulae (1c) and (4).

The results of investigations of the recombination correction made by Burns and McEwen [11] using NACP plane parallel chambers are in agreement with the present ones. McEwen, DuSautoy and Williams [12] also report recombination corrections for NACP chambers, which are in agreement with the results of [11] within about 0.1%. Nisbet and Thwaites [13] estimated ion recombination correction factors for NACP, Markus and Roos chambers using the two-voltage method. The authors claim accordance of their results with the Boag formula within about 0.2% for corrections which are not larger than about 1%. It has, however, to be borne in mind that the two-voltage method was not strictly applicable in most of the examples given there.

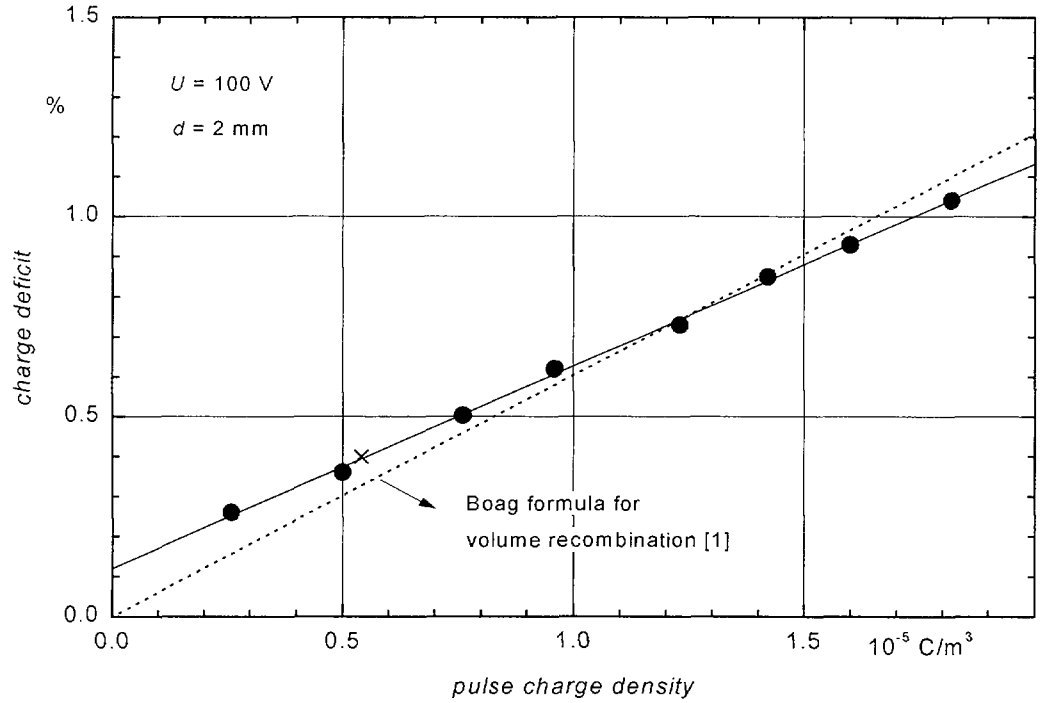

FIG. 2. Experimental results of the charge deficit as a function of the pulse charge density measured in photon beams (solid circles) and in an electron beam (cross) for an electrode spacing of 2 mm and a polarizing voltage of 100 V. The solid line is a linear fit to the data (expressed in Eq. (4) of the present work as a function of the absorbed dose to air per pulse D_i*). The dotted line is Boag's relation [1] for volume recombination.*

3. Investigation of the dependence of response on the polarity and the absolute value of the polarizing voltage

An investigation of the dependence of the response on the polarizing voltage of an ionization chamber requires that the "saturation curve" at both polarities be measured. The respective measurements were performed in the 12.5 MeV electron beam of an SL 75-20 linac using various commercial plane parallel chambers. The pulse repetition frequency was 300 Hz and the pulse length was not larger than 2 μs; the field size was 10 cm × 10 cm and the source-to-surface distance was 100 cm. The chambers were placed at the depth of maximum dose rate in a water phantom for the water-proved chambers and in a PMMA phantom for the others. The reading of the chambers was normalized to the mean value of the readings of two thimble chambers placed to the right and to the left of the chamber under test at the same depth in the phantom. Every day, the current measuring system was calibrated in a traceable route to the national primary standards over the whole measuring ranges at both polarities in order to eliminate the influence of non-linearity and of offset effects.

Since the equilibration times of various chamber types are rather long, each measurement at a given chamber voltage was followed by a measurement at a voltage of 100 V, in order to check the influence of drifts and to eliminate it.

Figures 3–5 show the results for various chambers at pulse doses D_i of about 0.17 mGy. The reciprocal of the reading $1/M$ (normalized to 1 at 100 V for both polarities) has been plotted as a function of the reciprocal of the voltage $1/U$ for both polarities. The arithmetic

means of the absolute values of both polarities have been connected by straight solid lines. All chambers, apart from the Roos chamber PTW34001, show an essential polarity dependence of the "saturation curves", or, vice versa, the polarity effect of these chambers depends on the absolute value of the polarizing voltage. It is particularly pronounced in the case of the NACP and RMI Attix chambers.

The dotted lines in Figures 3–5 represent the relation by Boag [1] and the relation of the present work, Eq. (4). Due to the normalization, the corrections to the reciprocal of the reading at 100 V may be taken directly from the intersections with the y-axis. This normalization to a relatively low voltage has been performed in order to make the effects clearly visible. To get the correction for a deviating voltage, a straight line must simply be drawn parallel to the dotted line of the relation of choice, through the respective data point. The correction is given by the difference of the reciprocal of the normalized reading at the voltage of choice and the intersection of this line with the y-axis.

Figure 4 shows the results for two Markus chambers, both manufactured by PTW. The only nominal difference is given by the plug: in the case of the chamber denoted W23343 (upper part of the figure), a different plug has been mounted, fitting the Wellhöfer electrometer system. In the case of this chamber, the slope of the curve is steeper than for the chamber denoted M23343 (lower part of the figure). This is accompanied by a more pronounced curvature at the highest voltages and a stronger dependence of the polarity effect on the polarizing voltage. A check showed that the different plugs are not responsible for the differing behaviour.

In the case of Markus chambers it must be taken into account that the electrodes are not essentially plane parallel, but most of the surface of the high voltage electrode is perpendicular to the collecting electrode. This can be seen in Figure 6. The high-voltage electrode (solid line) covers not only the entrance foil but in addition almost completely the side walls (reducing the polarity effect). The electrical field-strength is, therefore, essentially reduced over a large part of the collecting volume. Due to the saturation behaviour of the recombination the decrease of the collection efficiency within these regions may not be compensated by the increase within the regions of increased field strength close to the guard-ring. The relations for plane parallel chambers are, therefore, not strictly applicable in this case.

Figure 5 shows the results of the RMI Attix chamber. In addition to the results obtained according to the two formulae for the actual electrode spacing $d = 0.7$ mm [4] of this chamber, the results for the "nominal" spacing d = 1 mm, as stated by the manufacturer, have been included. It may be seen that, even for a polarizing voltage of 100 V, the respective deviations of the correction for 0.7 mm from those for 1 mm are far below 0.1%.

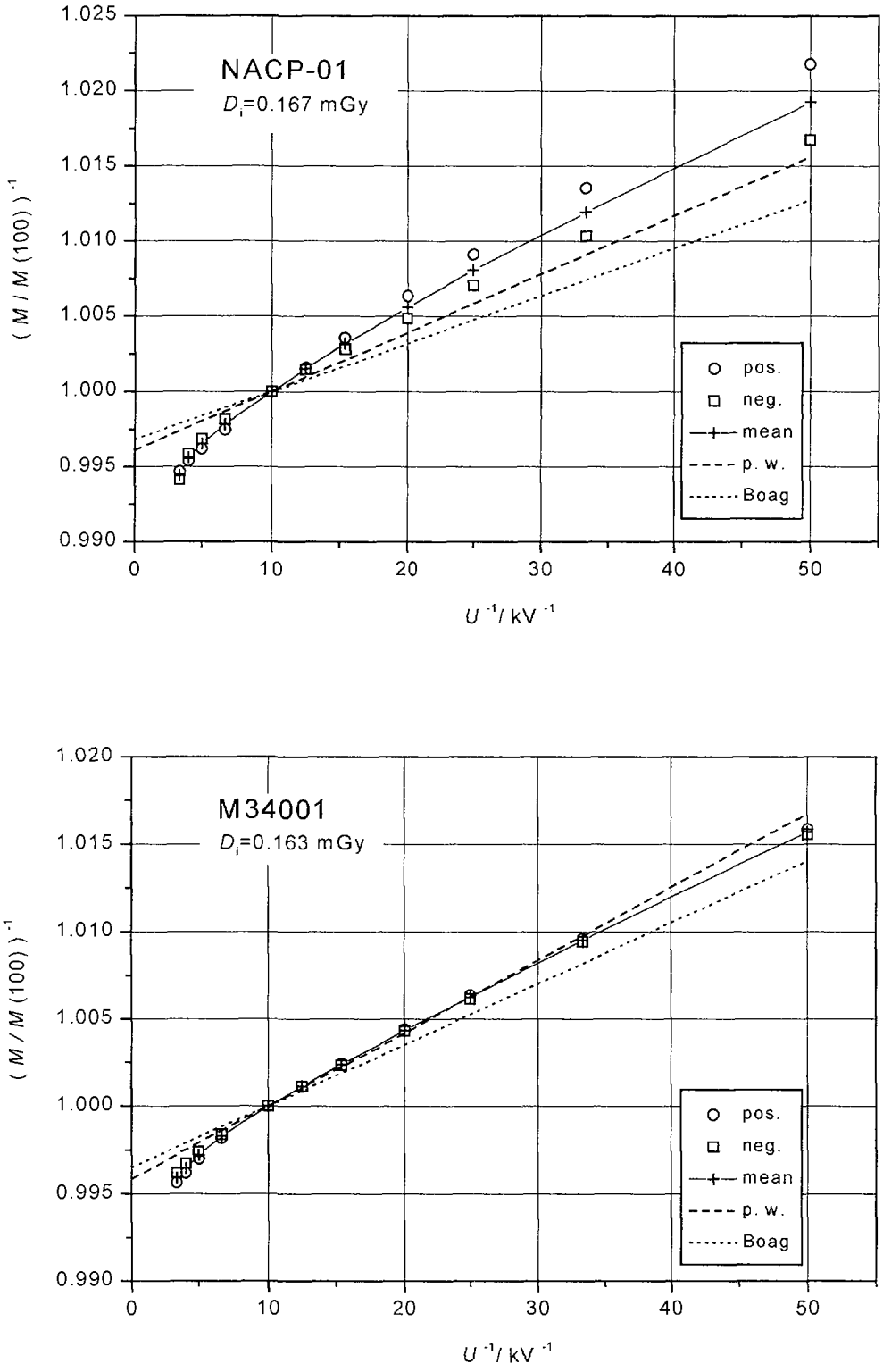

FIG. 3. Reciprocal of the reading M *(normalized to 1 at 100 V for both polarities) as a function of the reciprocal of the polarizing voltage* U *for both polarities of a chamber Scanditronix NACP-01 (upper part) amd PTW Roos M34001 (lower part) at pulse doses* D_i *of about 0.17 mGy. The means of the absolute values of both polarities have been connected by straight solid lines. The dotted lines are the results according to the Boag formula [1] and according to formula (4) of the present work, respectively.*

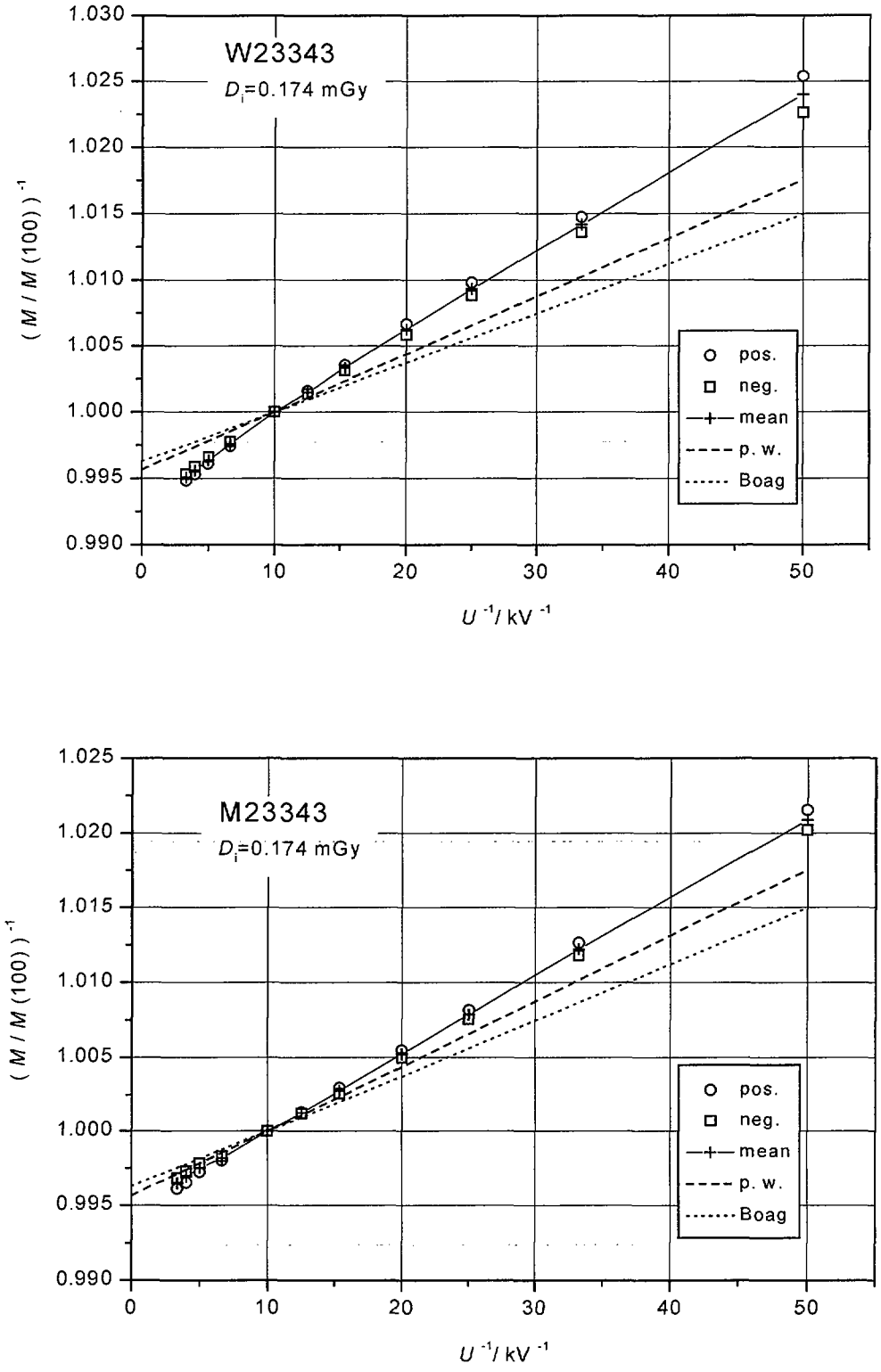

FIG. 4. Reciprocal of the reading M *(normalized to 1 at 100 V for both polarities) as a function of the reciprocal of the polarizing voltage* U *for both polarities of a chamber PTW Markus W23343 (upper part) and M23343 (lower part), at pulse doses* D_i *of about 0.17 mGy. The means of the absolute values of both polarities have been connected by straight solid lines. The dotted lines are the results according to the Boag formula [1] and according to formula (4) of the present work, respectively..*

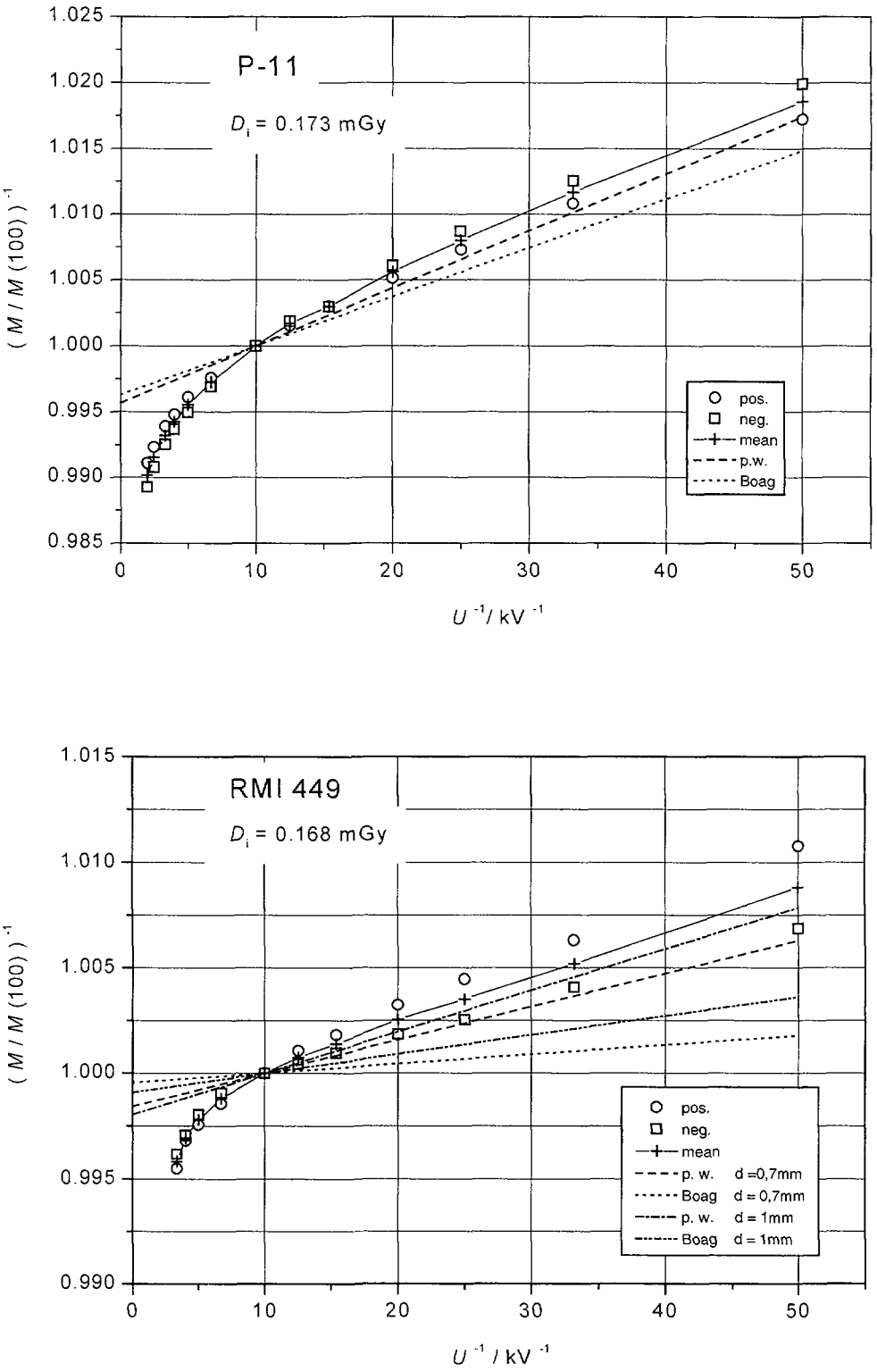

FIG. 5. Reciprocal of the reading M *(normalized to 1 at 100 V for both polarities) as a function of the reciprocal of the polarizing voltage* U *for both polarities of a chamber Exradin P-11 (upper part) and RMI Attix 449(lower part) at pulse doses* D_i *of about 0.17 mGy. The means of the absolute values of both polarities have been connected by straight solid lines. The dotted lines are the results according to the Boag formula [1] and according to formula (4) of the present work, respectively. The results for the nominal electrode spacing (1 mm) and for the actual spacing (0.7 mm) of the Attix chamber RMI 449 are included in the figure.*

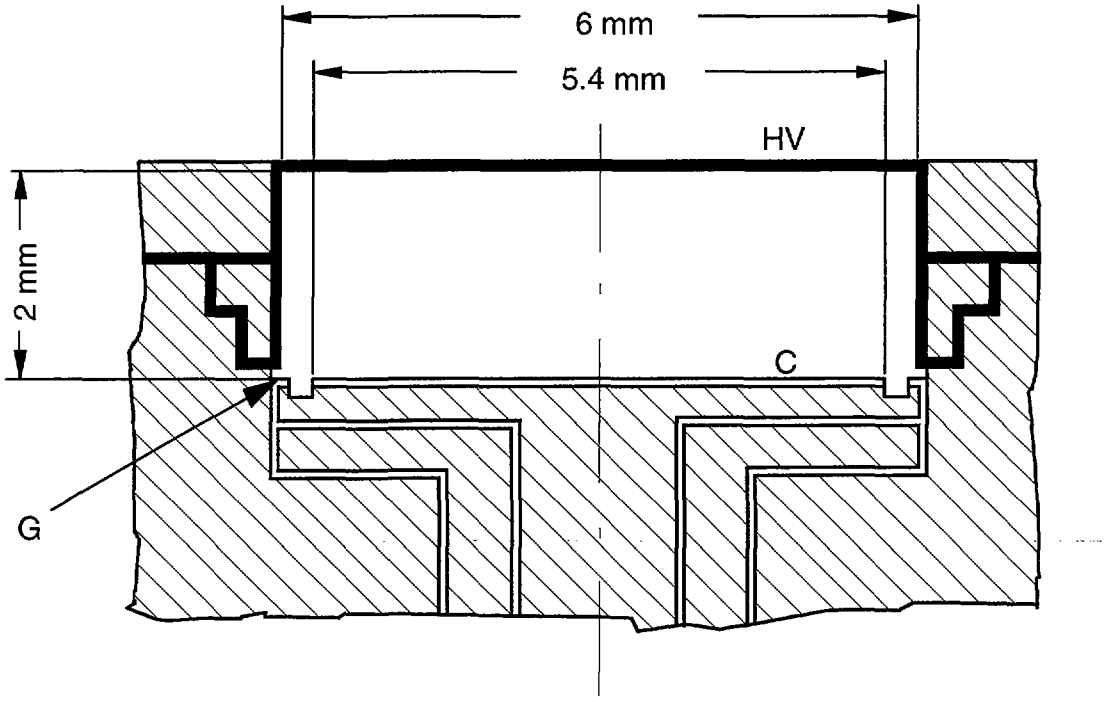

FIG. 6. Design features of the Markus chamber PTW 23343 with high-voltage electrode (HV), collecting electrode (C) and guard-ring (G). The high-voltage electrode (solid line) covers not only the entrance foil but in addition almost completely the side walls.

4. Conclusions

The determination of the recombination correction may be facilitated by the application of analytical relations allowing the correction factor to be calculated from the electrode spacing and from the pulse dose. Since the correction amounts to not more than about 1% for conventional beams, deviations of the electron spacing from the nominal value do not restrict applicability in practice.

The present investigations show, however, that particular chambers may collect a considerable amount of charge from regions outside the designated collecting volume, where the field strength may be far lower than in the designated volume. This is usually caused by an incomplete internal shielding of the chambers and shows a remarkable chamber-to-chamber dependence. This complicates the saturation behaviour, and the application of analytical relations for recombination tends to underestimate the recombination correction. In addition, in single cases poor contacts were observed which reduce the effective polarizing voltage in comparison with its nominal value. An experimental check of the chambers before use and before the application of analytical relations seems useful.

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