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Determination of the recombination correction for the BIPM parallel-plate ionization chamber type in a pulsed photon beam

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Abstract

The correction factor for recombination losses k_s has been determined for the BIPM parallel-plate ionization chamber type in the pulsed photon beam of a clinical linear accelerator.

1. Introduction

To compare the absorbed dose to water standards of the National Metrology Institutes (NMIs) for accelerator photon beams, the Bureau International des Poids et Mesures (BIPM) developed a transportable standard for absorbed dose to water based on a graphite calorimeter [1, 2]. This ongoing comparison programme, currently involving ten NMIs, is registered in the BIPM key comparison database (KCDB) as BIPM.RI(I)-K6 [3].

The method adopted by the BIPM combines calorimetric and ionometric measurements with Monte Carlo simulations to determine the absorbed dose to water [4]. Two nominally-identical parallel-plate ionization chambers with graphite walls and collector have been fabricated at the BIPM to serve as transfer chambers, similar in design to the existing BIPM standards for air kerma and absorbed dose to water [5, 6]. One of these chambers is housed in a graphite jacket, nominally identical to the calorimeter jacket, and the other in a waterproof sleeve for measurements in a water phantom. The measurement equation for the determination of absorbed dose to water, D_w, is:

$$D_W = \frac{D_c}{Q_c} Q_W C_{W,c} \quad (1)$$

where D_c is the absorbed dose to graphite, Q_w and Q_c are the ionization charges measured in water and graphite, respectively, and $C_{w,c}$ is a dose conversion coefficient calculated using Monte Carlo methods [4].

The correction for recombination in the BIPM ionization chamber type has been measured many times in continuous beams [7], but until now has not been determined in pulsed beams for which the instantaneous charge density is generally very much higher. Although Equation (1) includes the ratio of the charges for the two chambers, such that the recombination correction should cancel, knowledge of the correction aids in the understanding of the influencing factors and might have an impact on uncertainty estimates. Moreover, the similarity of the ratio D_c/Q_c measured at different NMIs can serve as an independent verification of the measurements, but this is only possible if corrections are applied for all influencing factors, including recombination.

For this reason the correction factor for recombination losses k_s has been determined in a pulsed accelerator photon beam. The measurements were carried out using the clinical linear accelerator of the Laboratoire National Henri Becquerel (LNE-LNHB), Saclay (France), during the period from 18 to 21 April 2011.

2. Theory

The theory of Boag on volume (or general) recombination in pulsed radiation [8] predicts that, for a given charge per pulse Q_p[1], the reciprocal of the measured current, $1/I(V)$, will depend approximately linearly on the reciprocal of the applied voltage, $1/V$. The review by Boag [9] indicates that initial recombination in pulsed beams shows the same dependence. In the spirit of Burns and McEwen [10], with revised nomenclature, the total recombination correction k_s is expressed as

$$k_s = \frac{I_s}{I(V)} = 1 + k_{init} + k_{vol} Q_p , \qquad (2)$$

where the constants k_{init} and k_{vol} are to be determined experimentally. The variation with reciprocal voltage is evident when k_{init} and k_{vol} are expressed otherwise:

$$k_s = \frac{I_s}{I(V)} = 1 + \frac{A}{V} + \frac{B}{V} Q_p . \qquad (3)$$

Dividing through by I_s,

$$\frac{1}{I(V)} = \frac{1}{I_s} + \frac{(A + BQ_p)}{I_s V} , \qquad (4)$$

we see that an experimental plot of $1/I(V)$ against $1/V$, for a fixed Q_p, permits I_s to be determined from the intercept, but does not give information on A and B separately

[1] Strictly, Q_p is the charge *produced* per pulse, which is greater than the charge *measured* per pulse by the recombination correction. In practice, however, Q_p can be approximated by the measured charge per pulse without significant loss of accuracy.

(that is, on k_{init} and k_{vol}). This information can be deduced from similar measurements made at other values for Q_p. This is essentially the method used by Boutillon [11] for continuous radiation, initially proposed by De Almeida and Niatel [12]. Equation (4) is re-written for a reduced voltage V/n:

$$\frac{I_s}{I(V/n)} = 1 + \frac{nA}{V} + \frac{nB}{V} Q_p \,. \tag{5}$$

Dividing equation (5) by equation (3) eliminates I_s and, ignoring higher order terms, one obtains

$$\frac{I(V)}{I(V/n)} = 1 + \frac{(n-1)A}{V} + \frac{(n-1)B}{V} Q_p \,. \tag{6}$$

If the 'two-voltage' ratio $I(V)/I(V/n)$ is plotted for a series of values of Q_p, the intercept c and gradient m directly yield values for k_{init} and k_{vol} for the use of the chamber at the higher voltage V according to

$$k_{init} = \frac{A}{V} = \frac{c-1}{n-1} \tag{7}$$

and

$$k_{vol} = \frac{B}{V} = \frac{m}{n-1} \,. \tag{8}$$

3. Experimental arrangement and measurements

The measurements were carried out in the LNE-LNHB Saturn 43 accelerator at two photon beam energies. The BIPM ionization chamber with reference 'calo6', mounted in its PMMA sleeve, was positioned in the LNE-LNHB water phantom. Dose monitoring was realized by two adjacent ionization chambers, just outside the radiation field at the accelerator exit, and the ionization charge and environmental parameters were measured using the LNE-LNHB facilities. For the main series of measurements the 12 MV beam was used, with a nominal dose rate of 2 Gy min^{-1} and a pulse repetition frequency of 100 Hz.

Chamber calo6 is normally operated at 80 V, positive polarity. Hence, V = +80 V. It was therefore decided to make measurements at +80 V and +20 V (that is, n = 4). Measurements were also made using 80 V and 20 V with negative polarity to take into account any polarity effect in the chamber. For each setting of the polarizing voltage, a series of seven measurements was made, each with an integration time of 120 s. Measurements were made at three depths in the phantom by setting the chamber at a fixed distance from the source (1 m) and altering the position of the water phantom. For each depth, two values of the RF power were applied. In this way, results were obtained for six values of Q_p at the nominal accelerator energy 12 MV. Two measurements were also made at 6 MV, where the pulse frequency is 200 Hz. The use of a different pulse frequency was designed to demonstrate that recombination depends on the dose per pulse rather than on the mean dose rate. Measurements at two beam qualities would also be expected to confirm the well-established independence of recombination on the photon spectrum [13].

4. Results and Analysis

The results are listed in Table 1. The values for Q_p are the measured values (that is, the measured charge per second divided by the pulse repetition frequency), while $I(V)$ and $I(V/n)$ have been normalized to standard pressure (101.325 kPa) and temperature (20 °C). The data are shown graphically in Figure 1. A polarity correction factor of 0.999 80(3) was measured for the use of the chamber at a positive polarity of 80 V, and 1.000 24(7) at 20 V.

Table 1. Results for the charge per pulse, Q_p, and the current ratio $I(V)/I(V/n)$ when V = 80 V and n = 4.

Nominal accelerator energy / MV	Q_p / pC	$\frac{I(V)}{I\left(\frac{V}{n}\right)}$
12	75.91	1.032 86
12	65.08	1.028 80
12	75.54	1.032 47
12	56.31	1.025 31
12	37.67	1.018 22
12	21.64	1.012 13
6	34.12	1.017 20
6	16.21	1.010 32

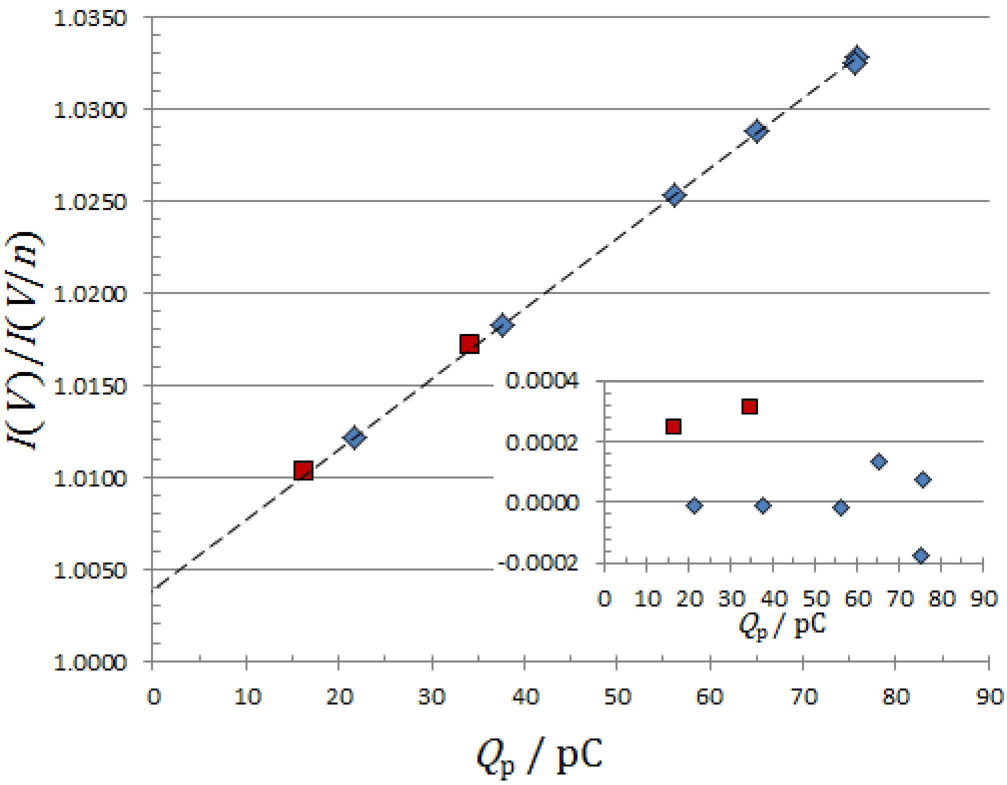

Figure 1. Measured data used to determine k_s. Blue diamonds represent data at 12 MV; red squares represent data at 6 MV. The dashed line is a linear fit to the 12 MV data only. The inset shows the differences between the observed data and the linear fit.

A linear function was fitted to the 12 MV data. Using Equation [8] (with V = 80 V and n = 4), the slope m of this fit yields the value B = 0.010 14(6) pC^{-1}V^{-1}, where the value in parenthesis represents the standard uncertainty in the last digit. While the rms deviation of the ordinate values from this fit is less than 0.01 % for the 12 MV data, it can be seen from the inset to Figure 1 that the two points at 6 MV are higher than the fit by around 0.03 %. With so few data, it is not clear that this small difference is evidence of a real effect and it was decided that the most reliable estimate for volume recombination would be obtained from the consistent data set obtained at 12 MV. For this reason the 6 MV data have not been used in evaluating the gradient. However, for the intercept c, an offset of 0.014 % has been added to the value obtained using the

12 MV data. This correction corresponds to half of the mean of the observed differences between the 6 MV data and the fitted 12 MV curve (cf. inset to Figure 1) and yields the value A = 0.108(4). Combining Equations (2), (7) and (8) gives the best estimate for k_s at 80 V:

$$k_s = 1.001\,35(5) + 1.268(8) \times 10^{-4} Q_p(\text{pC})\ . \qquad (9)$$

The values in parentheses represent the standard uncertainty in the last digit. The low uncertainty of the measured coefficients is evidence of the high precision of the beam monitoring employed on the LNE-LNHB accelerator. The data follow the form predicted by the Boag theory and no additional uncertainty has been included for the approximations inherent in the theory.

It is interesting to note that the present value for initial recombination is in agreement with the value 1.0014(1) obtained using the same two voltages for a series of nominally-identical chambers in the ^{60}Co reference beam at the BIPM. The similarity of initial recombination in ^{60}Co and pulsed high-energy photon beams was also recently reported by Palmans *et al*. [14] for other chamber types. Likewise, the mean value for the polarity correction factor at +80 V of 0.999 80(3) is in good agreement with the value 0.999 86(10) measured previously for the same chamber (calo6) in the BIPM ^{60}Co beam.

5. Conclusion

The correction factor for recombination losses for the BIPM parallel-plate ionization chamber type has been measured in a pulsed high-energy photon beam as a function of the measured charge per pulse. Initial recombination is in agreement with that obtained for the same chamber type in a continuous beam, while linearity in the volume recombination loss is confirmed at dose rates up to 80 pC per pulse, which corresponds to about 0.33 mGy per pulse (or around 2 Gy min^{-1} at 100 Hz).

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