Characterization of the BIPM low-energy x-ray facility following a change of x-ray tube and high-voltage generator

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1. Introduction

The negative high-voltage generator, which had served both the low- and medium-energy x-ray facilities since the early 1960s, failed in early 2000 and proved to be irreparable. In consequence, a new generator was installed and the opportunity was taken to replace the ageing positive generator serving the medium-energy facility, as well as adding a second negative generator to render the low- and medium-energy facilities independent.

Testing of the new low-energy generator showed some instability arising from an incompatibility of the new generator with the old x-ray tube, which in any event was due for replacement as it was no longer operable at potentials above 50 kV. Indeed, a new tungsten anode x-ray tube was purchased several years ago for this purpose and with the change of generator it was decided to install the new x-ray tube at the same time.

2. New generator and voltage stabilization

The new generator is manufactured by Seifert (ISOVOLT HS) and generates voltages up to 160 kV as well as supplying the filament current for the x-ray tube. The tube itself has a power limit of 1.6 kW. The factory calibration of the generator was found to be in error by around 1.5 kV at all generating potentials. However, with some modification of the existing voltage divider (whose divide ratio is 9999.23 with standard uncertainty 0.04) it was possible to couple this to the new generator so that the voltage could be determined with an accuracy below $1\ 10^{-5}$.

The voltage stability without additional stabilization was monitored over several weeks, and although generally stable at the level of 1 V there are occasional steps of several volts which compromise the dosimetry, particularly at 10 kV. To solve this problem, a relatively simple but effective stabilization was added, as shown schematically in Figure 1. Rather than connect the anode of the x-ray tube to ground potential, a programmable voltage supply is included. The sum V_a of this voltage and that generated across the resistor R (used to measure the anode current) is recorded by a computer which also records the output from the voltage divider. With the generator operated at around 20 V below the desired generating potential, the tube voltage $V_{gen} - V_a$ is compared with the desired generating potential and the programmable voltage supply is adjusted accordingly. This loop is controlled by the TestPoint software with a period of around 0.5 s. The net result is a tube voltage whose standard deviation is below 0.1 V and whose mean value is within $1\ 10^{-5}$ of the desired generating potential.

3. Matching of new radiation qualities to old

The new x-ray tube has a beryllium window approximately 1 mm in thickness, compared with the old tube with window thickness around 2.5 mm. To best take account of this difference, a series of measurements was made in which combinations of thin beryllium filters were added. For each filter combination, the mean air attenuation coefficient at 10 kV (no aluminium filtration) was determined using the usual method at the BIPM - reduction of the air pressure in a tube of active length 268.87 mm placed between the filters and the free-air chamber (the beryllium windows for this tube, of combined thickness 0.42 mm, form part of the 'inherent' filtration and are used at all times for all reference radiation qualities). The previous value for this air attenuation coefficient, under standard conditions of air temperature and pressure, was 1.757 m^{-1} (0.002 m^{-1})

In addition, the transmission of a given aluminium filter (number US20, thickness 25.05 μm) was measured for each beryllium filter combination, the previous value for this transmission being 0.6140 (0.001 2). By comparing the newly measured air attenuation coefficient and transmission for filter

US20 with the old values, a combination of three beryllium filters with total thickness 1.738 mm was found to give the closest values – 1.763 m^{-1} (0.002 m^{-1}) for the air attenuation coefficient and 0.6147 (0.000 3) for the transmission of filter US20. These beryllium filters are now included as part of the 'inherent' filtration and are used for all reference radiation qualities.

With these filters in place and with no other changes made to the filtration, the aluminium half-value layers (HVLs) and mean air attenuation coefficients were measured for the five radiation qualities used for comparisons and calibrations in the low-energy x-ray range. The results are given in Table 1 alongside the previous values for these quantities. From these it is evident that the new qualities are very close to the old qualities. The effect of the small changes in HVL on the calibration of the BIPM reference Shonka chamber is described in Section 6.

Table 1. Characteristics of the new and previous BIPM reference radiation qualities

Radiation quality		10 kV	30 kV	25 kV	50 kVb	50 kVa
Generating potential / kV		10	30	25	50	50
Addition Al filtration		0	0.2082	0.3723	1.0082	3.989
Al HVL / mm	new	0.0368	0.169	0.242	1.017	2.262
	previous	~0.036	0.176	0.250	1.020	2.257
m_{air} † / m^{-1}	new	1.763	0.435	0.310	0.090	0.045
	previous	1.757	0.415	0.304	0.091	0.046
K_{air} / mGy s^{-1}	new	1.00	1.00	1.00	1.00	1.00
	previous	0.56	3.31	1.13	1.57	0.34

† Air attenuation coefficient at 293.15 K and 100 kPa, and for an air path length of 100 mm.

4. Improved air attenuation correction for 10 kV radiation quality

The air kerma rate for low-energy x-rays is determined for a reference air path L_{ref} = 59.44 mg cm^{-2} from the exit window of the x-ray tube; this is equivalent to 500 mm of air at 20 °C and 100 kPa, that is, air of density r_{ref} = 1.1888 mg cm^{-3}. For this air density and with the defining aperture of the BIPM standard at 500 mm from the exit window, the centre of the measurement volume (100 mm beyond the aperture) is at L_{meas} = 71.33 mg cm^{-2}. The value m_{air} = 1.763 m^{-1} noted above for the 10 kV radiation quality is the value determined under these reference conditions. The statistical standard uncertainty of 0.002 m^{-1} results in an uncertainty in the air kerma rate of 2 10^{-4}.

In practice, when the air density is high (for example), the air path L_{meas} to the measurement volume is greater and therefore the path difference $L_{meas} - L_{ref}$ is also greater. Thus the length over which an attenuation correction must be applied increases. This gives rise to an effective attenuation length defined by

$$A = \frac{L_{meas} - L_{ref}}{r_{ref}} \,. \tag{1}$$

Furthermore, since the air attenuation coefficient decreases with distance from the radiation source, the mean air attenuation coefficient over this greater path length will be lower. This effect has been measured at the BIPM and follows the relation

$$m_{air} = 1.763 \; - \; 0.000\,46 \; \left(A - 100\right) \quad m^{-1}, \tag{2}$$

where A is expressed in mm. This relation has been determined with values for A in the range from 0 mm to 150 mm. Figure 2 shows the relative effect on the attenuation correction

$$k_{\mathrm{a}} = \exp\left(m_{\mathrm{air}} A\right) \tag{3}$$

when using m_{air} derived from relation (2) rather than the constant value m_{air} = 1.763 m^{-1}.

This figure has three applications. Firstly, it enables better account to be taken of different air densities. For a relatively high air pressure of 103 kPa (and a temperature of 20 °C), A = 118 mm. The use of this value in relation (2) leads to an air kerma rate determination which is lower by a factor 0.999 0 than that determined using the value for m_{air} determined at A = 100 mm as at present. This should lead to better reproducibility of air kerma determinations at 10 kV.

Secondly, it can be used for visiting NMI standards which have a different attenuation length. For example, for a standard with attenuation length 50 mm and for air at 20 °C and 100 kPa, A = 50 mm; from the figure, it can be seen that the air kerma rate determined using the value m_{air} = 1.763 m^{-1} must be increased by the factor 1.001 1. Note that a very similar correction (1.000 9 under the same conditions) has been applied in the past and so this does not represent a change of more than 2 10^{-4}.

Thirdly, calibrations of secondary standard ionization chambers against the BIPM standard are carried out with the secondary standard positioned 500 mm from the exit window. Thus for air at 20 °C and 100 kPa, A = 0 mm for these chambers and no attenuation correction need be applied. However if the air pressure is, for example, 103 kPa (at 20 °C) then A = 15 mm and the ionization current must be increased by the factor 1.0006. Further, this effect is in the opposite sense to that noted for the BIPM standard above. The combined effect of the use of relation (1), for air at 20 °C and 103 kPa, is a change in the calibration coefficient at 10 kV by the factor 0.9984.

5. Ion recombination and polarity for the free-air chamber

Although the change of generator and x-ray tube should not affect the BIPM standard, the opportunity was taken to re-measure the ion recombination correction and the polarity effect for the standard, particularly since the ion recombination correction had not been measured since the standard was opened and cleaned in early 1998. The ion recombination was determined using the method proposed by De Almeida and Niatel [1] in which the relative response of the standard at polarizing voltages V and V/n is determined for a series of incident radiation intensities. The standard polarizing voltage V for the BIPM free-air chamber is 1500 V.

The results for values n = 2 and n = 3 are shown in Figures 3 and 4, respectively, the measured current ratios $I_V / I_{V/\mathrm{n}}$ plotted as a function of the current I_V measured at the standard polarizing potential V (note that the measured currents I_V and $I_{V/\mathrm{n}}$ are not corrected to a standard air temperature and pressure). All currents are the mean of those determined with positive and negative polarizing voltages. For a linear fit with intercept (1 + a_0) and gradient a_1, the component of initial recombination at voltage V is given by

$$k_{\mathrm{init}} = \frac{\mathrm{a}_0}{\mathrm{n}-1} \tag{4}$$

and that for volume recombination by

$$k_{\mathrm{vol}} = \frac{\mathrm{a}_1}{\mathrm{n}^2-1}. \tag{5}$$

The total recombination correction at voltage V is evaluated as

$$k_{\mathrm{s}} = 1 + k_{\mathrm{init}} + k_{\mathrm{vol}} I_V . \tag{6}$$

The results for k_{init} and k_{vol} are given in each figure and are in agreement within the stated uncertainties. For k_{vol}, the present values are in agreement with the value 8.74 (0.20) 10^6 A^{-1} determined by Boutillon [2] for the same standard (using n = 2), and the best estimate is taken to be the weighted mean value k_{vol} = 8.8 (0.1) A^{-1}. However, the present values for k_{init} are lower than the value 4.6 (1.1) 10^{-4} determined by Boutillon. The reason for this disagreement is unexplained, but may be related to the opening of the standard in 1998 (after the measurements of Boutillon). The best estimate is taken to be k_{init} = 3.0 (0.8) 10^{-4}. It is interesting to note that the value for k_{init} which one would deduce from the work of Böhm [3] for the BIPM standard operated at 1500 V is 2.4 10^{-4} (including back diffusion).

Since the new reference radiation qualities are different in air kerma rate (all being 1.00 mGy s^{-1}), new values for k_s have been evaluated using the best estimates for k_{init} and k_{vol} noted above. The use of these new values changes the BIPM air kerma determination at the reference radiation qualities by around 2 10^{-4}.

The polarity effect, defined as the ionization current measured for a polarizing voltage of –1 500 V divided by that measured for +1500 V, was determined for the reference radiation qualities. As can be seen from the results presented in Figure 5 as a function of HVL, the effect is independent of the radiation quality. A mean value of 1.000 92 was determined, with standard uncertainty 0.000 03. This result is in agreement with the previous value within the combined uncertainties.

6. Calibration of BIPM reference Shonka chamber

Immediately before and after the change of x-ray tube, the BIPM spherical Shonka chamber was calibrated at the 30 kV and 50 kV(b) radiation qualities, with a further point at 20 kV (no aluminium filtration, HVL = 0.072 9 mm Al). This is a very demanding test, since the calibration coefficient for this chamber changes by more than a factor of 3 between the 20 kV and 30 kV qualities.

The results are shown in Figure 6. At the 20 kV and 30 kV radiation qualities, the measured differences in the calibration coefficients before and after the change of x-ray tube are well explained in terms of the measured changes in HVL (within the resolution of the pre-change HVL values of 1 μm Al). At the 50 kV(b) quality, the calibration coefficients before and after, when corrected for the small difference in HVL, agree within the combined statistical uncertainty of 3 10^{-4}.

7. Conclusion

It can be concluded that the change of generator and x-ray tube should not have an effect, within the BIPM measurement uncertainty of typically 2 10^{-4}, on the results of comparisons made at the BIPM, nor on the results of ion chamber calibrations when account is taken of the small differences between the new and previous half-value layers. However, a change in the method of correcting for air attenuation at 10 kV to take better account of variations in the ambient air density may result in a change of 1 10^{-3} in the determination of the air kerma rate at extreme values of air pressure.

8. References

[1] C.E. De Almeida and M.T. Niatel, Comparison between IRD and BIPM exposure and air-kerma standards for cobalt gamma rays, *Rapport* BIPM-86/12 (BIPM).

[2] M. Boutillon, Volume recombination parameter in ionization chambers, *Phys. Med. Biol.* **43** (1998) 2061 – 2072.

[3] J Böhm, Saturation corrections for plane-parallel ionization chambers, *Phys. Med. Biol.* **21** (1976) 754 – 759.

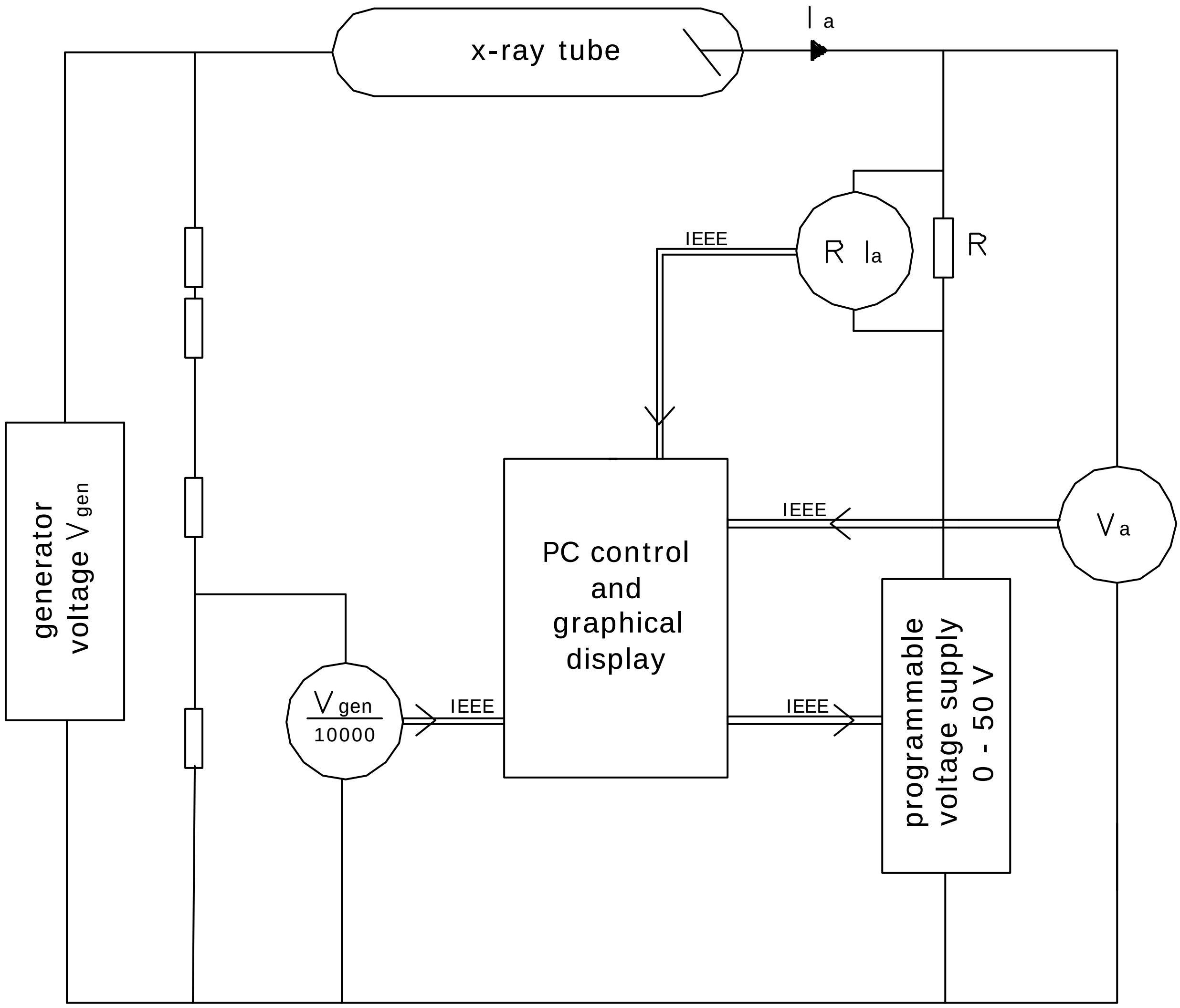

Figure 1. Schematic representation of the circuitry used to stabilize the x-ray tube voltage. A programmable voltage supply in the anode chain is used to offset any difference between the output of the high-voltage generator and the desired generating potential.

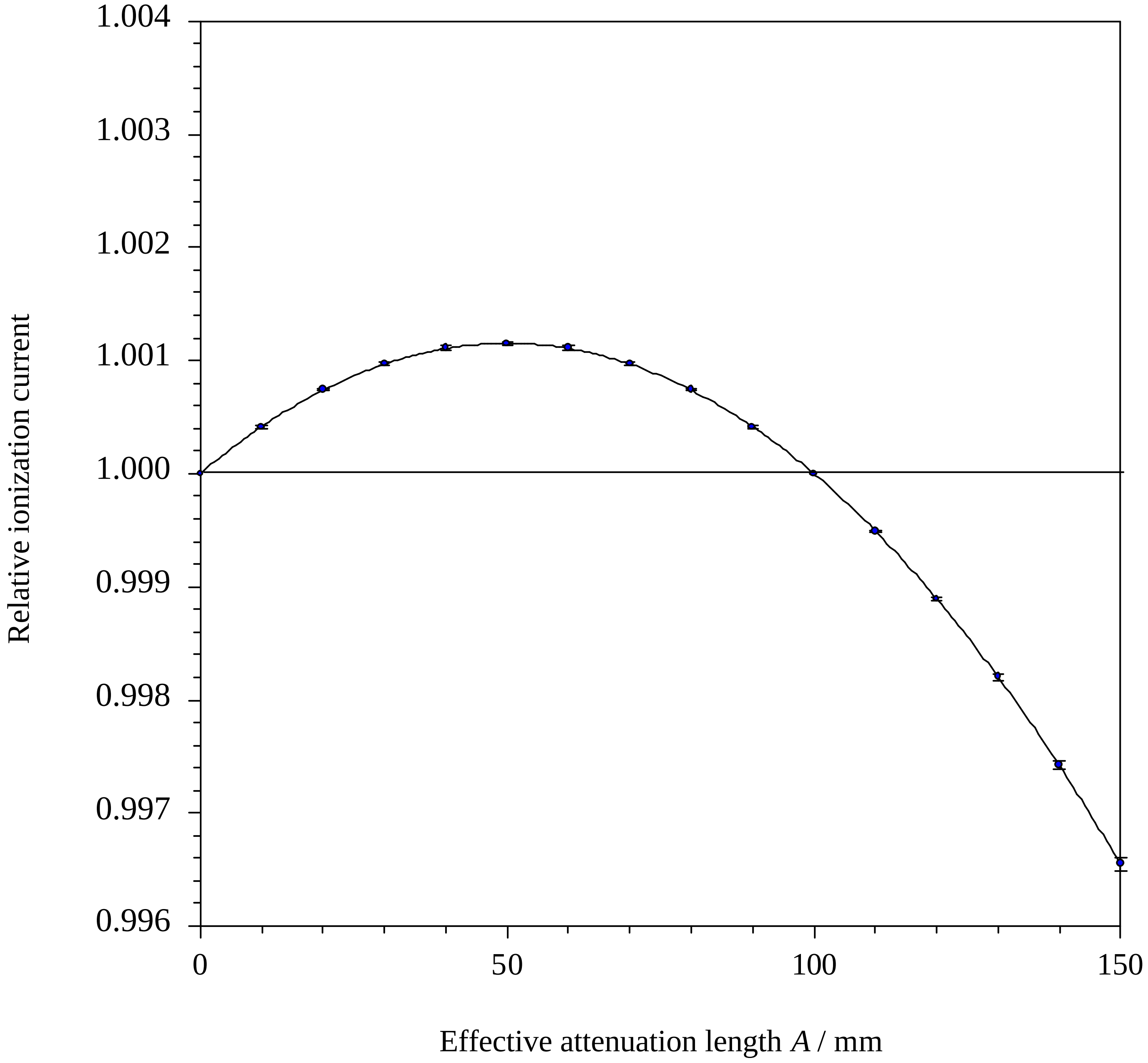

Figure 2. Relative effect on the corrected ionization current of using an attenuation correction k_s based on relation (2) for the air attenuation coefficient at 10 kV rather than using the constant value 1.763 m^{-1}.

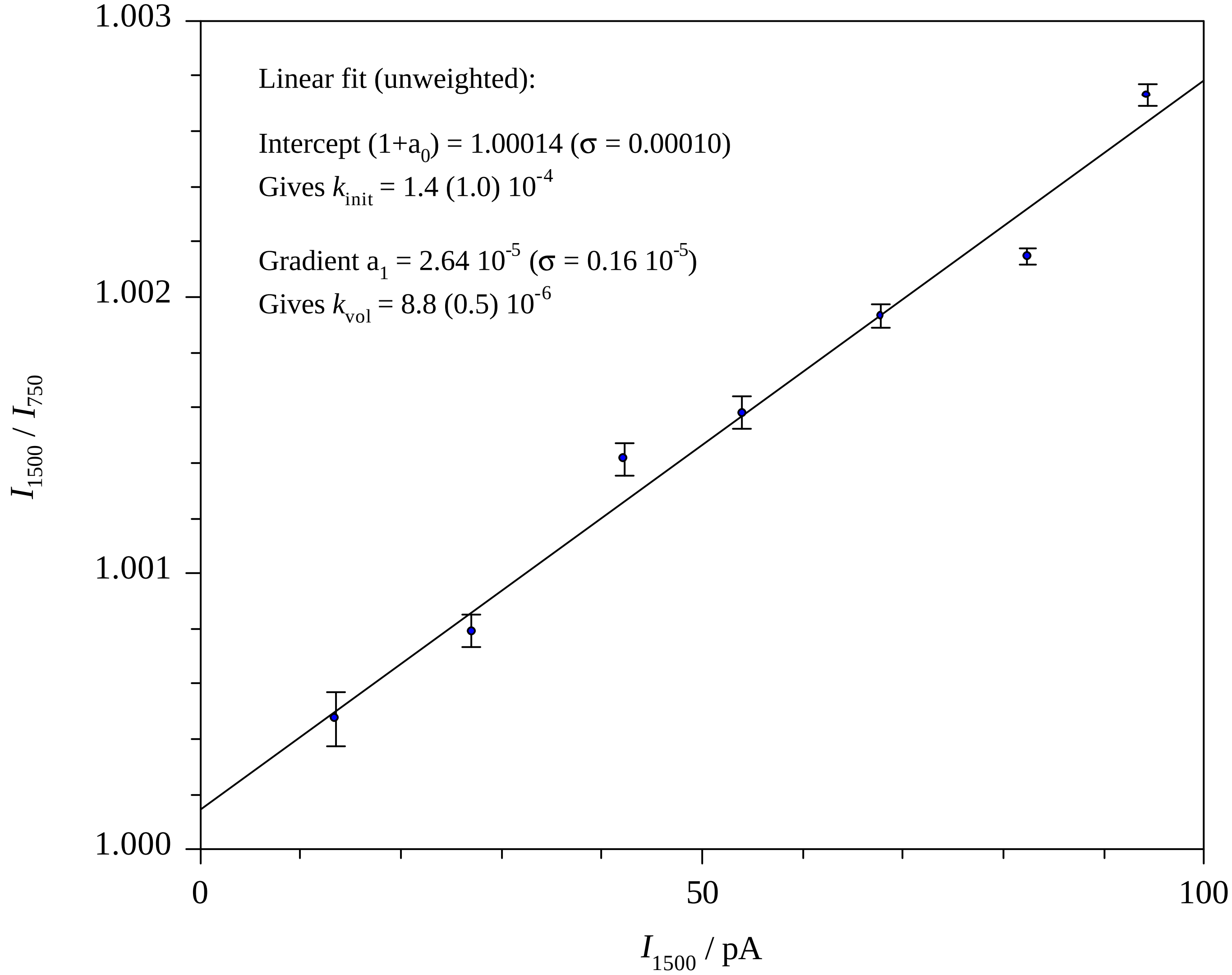

Figure 3. Measurement of the ion recombination coefficients k_{init} and k_{vol} for the BIPM low-energy free-air chamber using the polarizing voltages 1500 V and 750 V (both polarities).

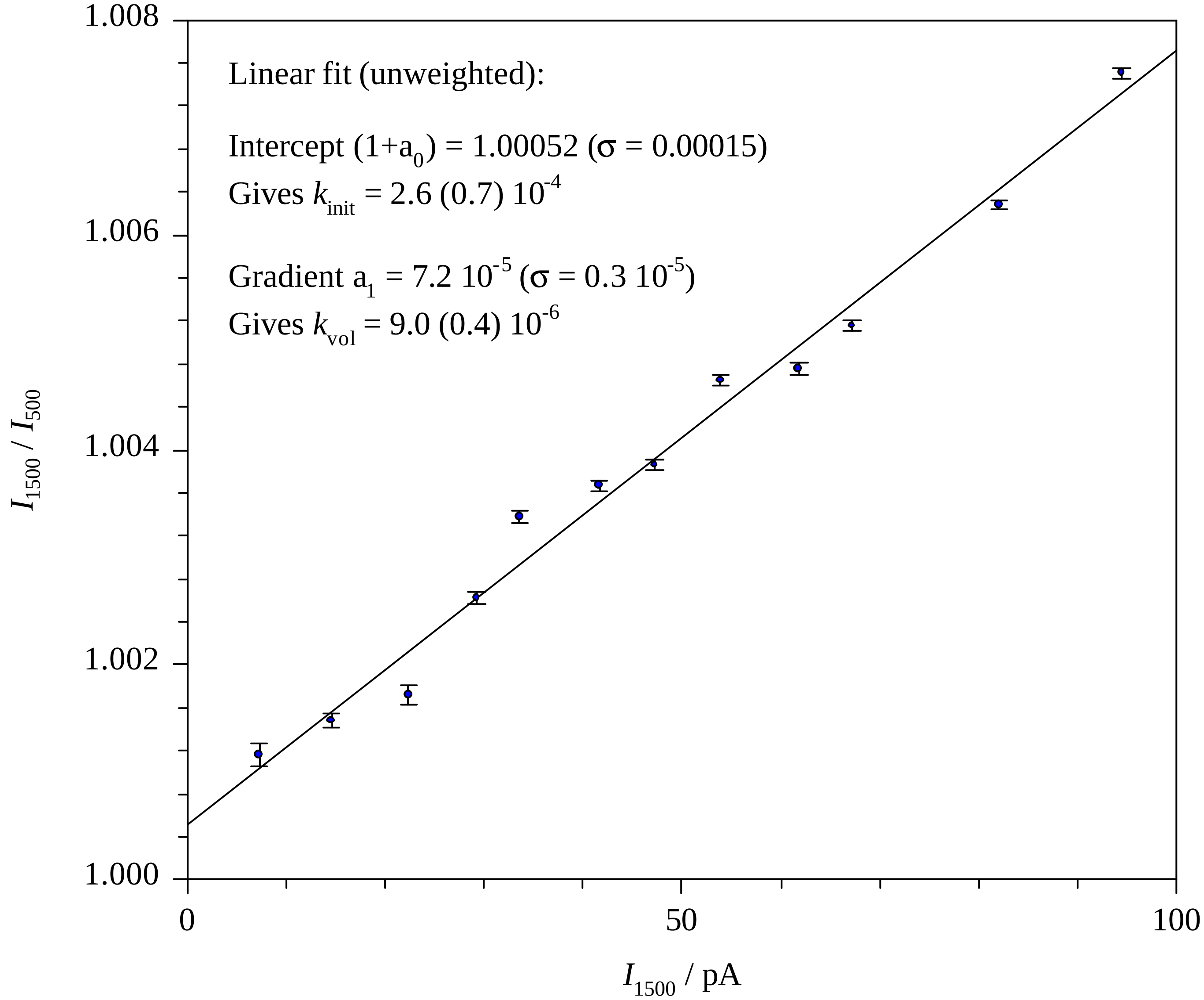

Figure 4. Measurement of ion recombination coefficients k_{init} and k_{vol} for the BIPM low-energy free-air chamber using polarizing voltages 1500 V and 500 V (both polarities).

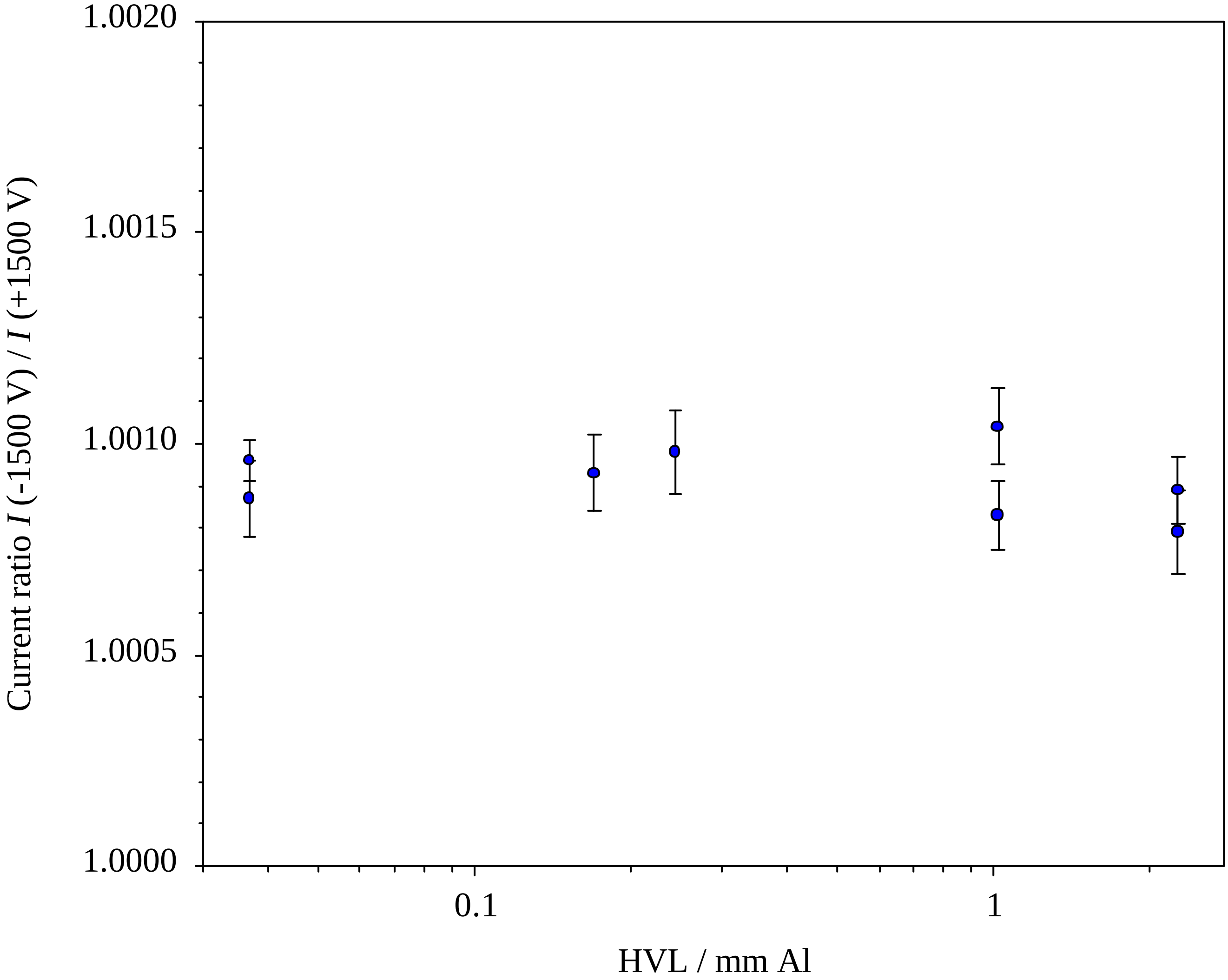

Figure 5. The polarity effect in the BIPM low-energy free-air chamber at the standard operating potential of 1500 V, as a function of HVL.

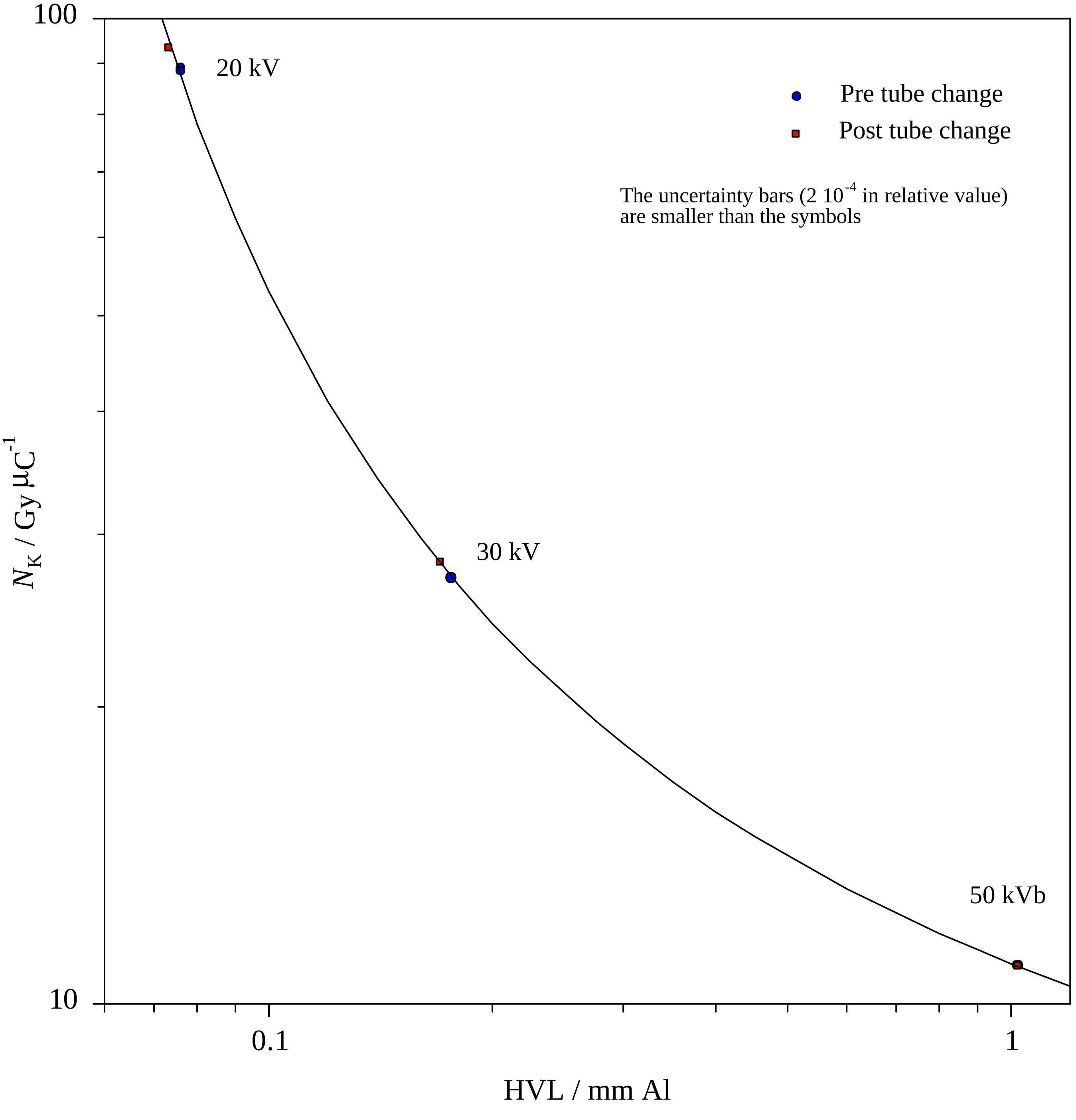

Figure 6. Calibration coefficient of the BIPM Shonka chamber in low-energy x-rays before and after the change of x-ray tube. For the 50 kVb quality, the different symbols overlap.