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Abstract A direct comparison has been made between the air-kerma standards of the PTB and the BIPM in the low-energy x-ray range. The results show the standards to be in agreement at the level of one standard uncertainty.

1. Introduction

A direct comparison has been made between the air-kerma standards of the Physikalisch-Technische Bundesanstalt (PTB), Germany, and the Bureau International des Poids et Mesures (BIPM) in the x-ray range from 10 kV to 50 kV. Additional measurements were made at 80 kV and 100 kV to provide information on the electron-loss correction for the BIPM standard at these qualities. The comparison took place at the BIPM in March 1999 using the reference conditions recommended by the CCRI [1].

2. Determination of the air-kerma rate

For a free-air ionization chamber standard with measuring volume V, the air-kerma rate is determined by the relation

$$\dot{K} = \frac{I}{\rho_{\text{air}} V} \frac{W_{\text{air}}}{e} \frac{1}{1 - g_{\text{air}}} \prod_i k_i \qquad (1)$$

where ρ_{air} is the density of air under reference conditions, I is the ionization current under the same conditions, W_{air} is the mean energy expended by an electron of charge e to produce an ion pair in air, g_{air} is the fraction of the initial electron energy lost by bremsstrahlung production in air, and $\Pi\, k_i$ is the product of the correction factors to be applied to the standard.

The values used for the physical constants ρ_{air} and W_{air}/e are given in Table 1. For use with this dry-air value for ρ_{air}, the ionization current I must be corrected for humidity and for the difference between the density of the air of the measuring volume at the time of measurement and the value given in the table[1].

3. Details of the standards

Both free-air chamber standards used in the present comparison are of the conventional parallel-plate design. The measuring volume V is defined by the diameter of the chamber aperture and the length of the collecting region. The BIPM air-kerma standard is described in [2] and [3]. Details of the PTB PK100 standard, which has not previously been compared with the BIPM standard, are given in [4]. The main dimensions, the measuring volume and the polarizing voltage for each standard are shown in Table 2.

[1] For an air temperature $T \sim 293$ K, air pressure P and relative humidity ~50 % in the measuring volume, this involves a temperature correction T / T_0, a pressure correction P_0 / P, a humidity correction $k_h = 0.9980$, and the factor 1.0002 to account for the change in the compressibility of dry air between $T \sim 293$ K and $T_0 = 273.15$ K.

Table 1. Physical constants used in the determination of the air-kerma rate

Constant	Value	u_i †
ρ_{air} ‡	1.293 0 kg m^{-3}	0.000 1
W_{air} / e	33.97 J C^{-1}	0.001 5

† u_i is the relative standard uncertainty.
‡ Density of dry air at T_0 = 273.15 K and P_0 = 101 325 Pa.

Table 2. Main characteristics of the standards

Standard	BIPM	PTB PK100
Aperture diameter / mm	9.941	10.008
Air path length / mm	100.0	97.2†
Collecting length / mm	15.466	20.021†
Electrode separation / mm	70	234
Collector width / mm	71	240
Measuring volume / mm^3	1 200.4	1 575.0†
Polarizing voltage / V	1 500	6 000

† These are the values for collector 1. For collector 3 (used for the 80 kV and 100 kV radiation qualities), the air path length is 162.2 mm, the collecting length is 49.970 mm and the measuring volume is 3930.9 mm^3.

3. Comparison procedure

3.1 BIPM irradiation facility and reference radiation qualities

The BIPM low-energy x-ray laboratory houses a constant-potential generator and a tungsten-anode x-ray tube with an inherent filtration of 2.9 mm beryllium. Both the generating potential and the tube current are stabilized using feedback systems constructed at the BIPM; this results in a very high stability and obviates the need for a transmission current monitor. The radiation qualities used in the range from 10 kV to 50 kVa are those recommended by the CCRI [1] and are given in Table 3 in ascending half-value layer (HVL) from left to right. Supporting measurements were also made at the 80 kV and 100 kV qualities indicated in the table.

The irradiation area is temperature controlled at around 20 °C and is stable over the duration of a calibration to better than 0.1 °C. Two thermistors, calibrated to a few mK, measure the temperature of the ambient air and the air inside the BIPM standard. Air pressure is measured by means of a calibrated barometer positioned at the height of the beam axis. All ionization current measurements are corrected for air temperature and pressure. The relative humidity is controlled within the range 47 % to 53 % and consequently no humidity correction is applied to the current measured using transfer instruments.

3.2 Correction factors

The correction factors applied to the ionization current measured at each radiation quality, together with their associated uncertainties, are given in Table 4 for the BIPM standard and in

Table 5 for the PTB standard. In the range from 10 kV to 50 kVa, collector 1 of the PTB standard was used, whereas for the 80 kV and 100 kV qualities collector 3 was used. In each case, the appropriate correction factors are given in the table.

Table 3. Characteristics of the BIPM reference radiation qualities

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa	80 kV	100 kV
Generating potential / kV	10	30	25	50	50	80	100
Additional Al filtration / mm	0	0.208 2	0.372 3	1.008 2	3.989	3.041	3.453
Al HVL / mm	0.036	0.176	0.250	1.020	2.257	3.01	4.00
$\mu_{air}^{\dagger}$ / m^{-1}	1.757	0.415	0.304	0.091	0.046	0.042	0.035
$\dot{K}_{BIPM}$ / mGy s^{-1}	0.56	3.31	1.13	1.57	0.34	0.61	0.84

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

Table 4. Correction factors for the BIPM standard

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa	80 kV	100 kV	u_{iA}	u_{iB}
Air attenuation $k_a^{\dagger}$	1.192 1	1.042 4	1.030 9	1.009 1	1.004 6	1.004 2	1.003 5	0.000 3	0.000 1
Scattered radiation k_{sc}	0.994 4	0.995 6	0.995 7	0.996 6	0.997 1	0.997 4	0.997 4	-	0.000 7
Electron loss k_e	1.000 0	1.000 0	1.000 0	1.000 0	1.000 0	1.010 0	1.020 7	-	0.000 1‡
Ion recombination k_s	1.000 7	1.001 9	1.001 0	1.001 1	1.000 6	1.000 6	1.000 6	0.000 2	0.000 1
Field distortion k_d	1.000 0	1.000 0	1.000 0	1.000 0	1.000 0	1.000 0	1.000 0	-	0.000 7
Aperture edge k_l	1.000 0	1.000 0	1.000 0	1.000 0	1.000 0	0.999 7	0.999 7	-	0.000 1
Wall transmission k_p	1.000 0	1.000 0	1.000 0	1.000 0	1.000 0	1.000 0	1.000 0	0.000 1	-
Humidity k_h	0.998 0	0.998 0	0.998 0	0.998 0	0.998 0	0.998 0	0.998 0	-	0.000 3
$1 - g_{air}$	1.000 0	1.000 0	1.000 0	1.000 0	1.000 0	1.000 0	0.999 9	-	0.000 1

† Nominal values for 293.15 K and 100 kPa; each measurement is corrected using the air density measured at the time.
‡ The value for the 80 kV and 100 kV qualities is around 0.000 7.

The largest correction at low energies is due to the attenuation of the x-ray fluence along the air path between the reference plane and the centre of the collecting volume. The correction factors k_a applied to each standard are evaluated using the measured air-attenuation coefficients μ_{air} given in Table 3. In practice, the values used for k_a take account of the temperature and pressure of the air in the standard and of the ambient air between the radiation source and defining plane of the chamber aperture.

Two differences in the correction factors are noted. The PTB standard involves a correction for attenuation due to guard strip wires that are not present in the BIPM standard. At low energies this is a relatively large correction and so, despite having been characterized by measurement and calculation at the PTB as a function of radiation quality, additional measurements were made in the 10 kV and 30 kV beams at the BIPM (see Section 4.2). The PTB correction factor for ionization gain k_{sc} includes not only the effect of scattered photons, but also that of fluorescence photons. The effect of fluorescence photons in the BIPM chamber is discussed in Section 6.

All measured ionization currents are corrected for ion recombination. For the PTB standard, the values for k_s given in Table 5 are derived from measurements at the PTB and evaluated for the BIPM air-kerma rates given in Table 3.

Table 5. Correction factors for the PTB PK100 standard †

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa	80 kV	100 kV	u_{iA}	u_{iB}
Air attenuation k_a ‡	1.1862	1.0412	1.0300	1.0089	1.0045	1.0068	1.0057	0.0003	0.0001
Ionization gain k_{sc} §	0.9860	0.9895	0.9904	0.9927	0.9938	0.9944	0.9948	-	0.0005
Electron loss k_e	1.0000	1.0000	1.0000	1.0000	1.0000	1.0002	1.0002	-	0.0005
Ion recombination k_s	1.0018	1.0059	1.0027	1.0033	1.0015	1.0020	1.0022	0.0005	0.0005
Polarity k_{pol}	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0005	0.0005
Field distortion k_d	0.9920	0.9920	0.9920	0.9920	0.9920	0.9990	0.9990	0.0015	-
Aperture edge k_l	1.0000	0.9997	0.9996	0.9991	0.9987	0.9991	0.9982	-	0.0005
Wall transmission k_p	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0005	-
Guard strip atten k_{ap}	1.0306	1.0078	1.0050	1.0020	1.0010	1.0011	1.0009	0.0005	-
Humidity k_h	0.9980	0.9980	0.9980	0.9980	0.9980	0.9980	0.9980	-	0.0003
$1 - g_{air}$	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9999	-	0.0001

† Component uncertainties below 0.0002 have been neglected.
‡ Nominal values for 293.15 K and 100 kPa; each measurement is corrected using the air density measured at the time.
§ This corrects for the re-absorption of scattered radiation and of fluorescence photons.

3.3 Chamber positioning and measurement procedure

The PTB chamber was positioned close to the BIPM chamber and both remained fixed throughout the comparison; the alternation of measurements between chambers was carried out by displacement of the radiation source. Alignment on the beam axis was measured to around 0.1 mm and this position was reproducible to better than 0.01 mm. An off-axis displacement of 0.1 mm changes the measured current by no more than 0.03 % at 10 kV and at 50 kV. No correction is applied for the radial non-uniformity of the beam since the aperture diameters are closely matched. For each chamber, the defining plane of the aperture was positioned at 500 mm from the radiation source for all qualities up to 50 kVa, and at 750 mm for the 80 kV and 100 kV qualities. This distance was measured to 0.03 mm and was reproducible to better than 0.01 mm. The beam diameter in the reference plane is 45 mm for all qualities up to 50 kVa and 68 mm for the 80 kV and 100 kV qualities.

The air temperature for the PTB chamber was measured using a BIPM mercury thermometer calibrated to 0.01 K and positioned in the holder of the PTB chamber. The leakage current was measured before and after each series of ionization current measurements and a correction made based on the mean of these leakage measurements. For the BIPM chamber the leakage current, relative to the ionization current, was less than 1×10^{-4} and for the PTB chamber less than 3×10^{-4}. The relative standard uncertainty of the mean of a series of five measurements was typically less than 2×10^{-4}. Two such series were made for each standard. Taking into account a relative standard uncertainty of 3×10^{-4} arising from the typical repeatability over the duration of a comparison of current measurements using a given standard, a type A relative standard uncertainty of 4×10^{-4} is taken for current measurements using either chamber. For the BIPM standard, measurements were made at both polarities to correct for any polarity effect. The measured difference was typically 1.0×10^{-3} in relative value. The PTB standard was used at positive polarity only with a correction for the polarity effect as given in Table 5.

4. Supporting measurements

4.1 Comparison of methods for measuring air attenuation

The air-attenuation correction for each standard was determined using the air-attenuation coefficients μ_{air} measured at the BIPM, as given in Table 3. These are measured using a tube of length 270 mm positioned approximately midway between the added filters and the reference plane. By reducing the air pressure in the tube to approximately 64 kPa and measuring the increase in the ionization current, μ_{air} is determined for an air path length of 100 mm (starting at 500 mm from the beam exit window). Note that the thin beryllium windows of the tube are included in the stated inherent filtration (2.9 mm beryllium).

The PTB method for determining μ_{air} makes use of the multiple collectors of the PK100 chamber. Measurements were made at the BIPM using collector 1 (length 20.021 mm), which is centred 97.2 mm from the defining plane of the aperture, and collector 4 (length 20.011 mm), centred 197.2 mm from the defining plane. Correcting for the different field distortions for the two collectors (0.992 0 and 1.002 0, respectively), μ_{air} for an air path length of 100 mm (starting at 500 mm) was measured to be 1.666 m^{-1}, compared with the BIPM value of 1.757 m^{-1}. The use of the PTB value would result in air-kerma rate determinations lower by 0.009 1 in relative value. Around 0.002 0 of this difference is accounted for by the larger photon scatter for collector 4, but the remaining difference is unexplained.

4.2 Measurement of guard wire attenuation for the PTB standard

The design of the PTB PK100 standard involves thin guard wires that intercept the beam behind the aperture and result in additional attenuation. A correction factor k_{ap} is applied for this effect, as noted in Table 5. The variation of k_{ap} with HVL has been determined at the PTB. However, because this correction is relatively large at low energies, measurements were made at the BIPM for the 10 kV and 30 kV radiation qualities using a dummy set of wires positioned just in front of the chamber aperture. Measurements were made with the wires rotated with respect to the vertical chamber wires, to account for possible shadowing effects. The values for k_{ap} given in Table 5 for these qualities are those measured at the BIPM. For the other radiation qualities k_{ap} is less that 1.005 0 and correction factors evaluated as a function of HVL are used.

5. Uncertainties

The uncertainties associated with the primary standards and with the results of the comparison are listed in Table 6. The uncertainties associated with the measurement of the ionization current and with chamber positioning are those which apply to measurements at the BIPM and are different from those in routine use for air-kerma rate determinations at the PTB.

The relative combined standard uncertainty u_{c} of the ratio $\dot{K}_{\text{PTB}} / \dot{K}_{\text{BIPM}}$ takes into account correlations in the type B uncertainties associated with the determination of the ionization current, the humidity correction and the physical constants.

6. Results and discussion

The comparison results are given in bold in Table 7. There is general agreement at the level of one standard uncertainty, although there is a significant trend in the results between 30 kV and 50 kVa. This is in part due to the treatment of fluorescence radiation, which is included in the PTB value for k_{sc} but not in the BIPM value. The effect of fluorescence for the BIPM standard has been calculated by Burns [5] using the Monte Carlo code EGSnrc [6]. The values for k_e, k_{sc} and the fluorescence correction k_{fl} calculated in this way are given in Table 8, and the effect of including these new values in the present comparison are given in Table 7. It should be noted, however, that these new correction factors for the BIPM standard have not yet been adopted.

A similar set of calculations were made by Burns for the PTB PK100 chamber, the results of which are also given in Table 8. The effect of including these results in the present analysis, rather than the existing PTB values (evaluated using the previous Monte Carlo code EGS4 [7]) are given in the final row of Table 7. The use of this consistent set of calculations for both standards has removed much of the trend between 30 kV and 50 kVa.

Table 6. Uncertainties associated with the comparison results

Standard	BIPM		PTB PK100	
Relative standard uncertainty	u_{iA}	u_{iB}	u_{iA}	u_{iB}
Ionization current	0.000 4	0.000 2	0.000 4	0.000 2
Volume	0.000 3	0.000 5	0.000 6	-
Positioning	0.000 1	0.000 1	0.000 1	0.000 3
Correction factors (excl. k_h)	0.000 4	0.001 0	0.001 8	0.001 1
Humidity k_h	-	0.000 3	-	0.000 3
Physical constants	-	0.001 5	-	0.001 5
$\dot{K}_{Standard}$	0.000 6	0.001 9	0.001 9	0.001 9
	0.002 0		0.002 7	
$\dot{K}_{PTB} / \dot{K}_{BIPM}$	$u_c = 0.002\,6$ †			

† Takes account of correlations in type B uncertainties.

Table 7. Comparison results

Radiation quality	10 kV	30 kV	25 kV	50 kV b	50 kV a	80 kV†	100 kV †
$\dot{K}_{PTB} / \dot{K}_{BIPM}$	**1.000 0**	**0.995 2**	**0.996 3**	**0.996 9**	**0.998 2**	0.998 7	0.998 2
Using Burns [5] for BIPM std	1.003 7	0.996 9	0.997 9	0.997 9	0.999 0	1.002 1	1.000 3
Using Burns [5] for both stds	1.002 7	0.996 9	0.997 2	0.997 2	0.998 2	1.001 2	0.999 5

† The results are 80 kV and 100 kV are supplementary and are not considered as comparison results.

The result at 10 kV is significantly different from the others. This is not uncommon and raises a number of possibilities, for example the large corrections for air attenuation and guard wire attenuation, or unexplained aperture effects that have arisen in certain comparisons [2,8,9]. In this respect, it is possible that the uncertainties for the 10 kV quality are underestimated.

The measurements at 80 kV and 100 kV were made principally to test the correction factors k_e for the BIPM standard, making use of the fact that the large electrode separation of the PTB PK100 chamber results in very little electron loss. For this purpose, the best estimates of the ratio of the two standards are those given in the final row of Table 7 in the range from 30 kV to 50 kVa. The mean value of these four results is 0.997 3. If one treats the k_e values for the BIPM standard at 80 kV and 100 kV as free parameters, then the values required in order to obtain this same ratio 0.997 3 are k_e = 1.011 2 at 80 kV and k_e = 1.021 3 at 100 kV, with standard uncertainty estimated as 0.000 4 (taking into account the large number of correlations involved in a ratio of comparison results at two beam qualities). This latter value is in very good agreement with the value 1.020 7 (0.000 7) in use at present and in reasonable agreement with the recent Monte Carlo value 1.019 1 (0.001 5). At 80 kV, there is also good agreement with the present value 1.010 0 (0.000 7) but rather poor agreement with the Monte Carlo value 1.007 3 (0.001 5). It is thought that this discrepancy may results from the spectrum used for the 80 kV calculation, which is evaluated using the IPEM catalogue [10] in contrast to the measured spectra used for all other radiation qualities.

Table 8. Values for correction factors calculated by Burns [5]†.

Radiation quality	10 kV	30 kV	25 kV	50 kVb	50 kVa	80 kV	100 kV
BIPM standard							
k_e	1.000 0	1.000 0	1.000 0	1.000 0	1.000 0	1.007 3	1.019 1
k_{sc}	0.996 2	0.997 3	0.997 4	0.997 8	0.998 0	0.998 1	0.998 1
k_{fl}	0.994 7	0.996 6	0.996 7	0.997 8	0.998 3	0.998 6	0.998 8
PTB PK100 standard							
k_e	1.000 0	1.000 0	1.000 0	1.000 0	1.000 0	1.000 0	1.000 0
k_{sc}	0.992 7	0.994 5	0.994 6	0.995 3	0.995 5	0.995 7	0.995 9
k_{fl}	0.992 3	0.995 0	0.995 1	0.996 7	0.997 5	0.998 0	0.998 3

† The type A uncertainties associated with the stated values are less than 0.000 1. The type B uncertainties have yet to be evaluated rigorously, but approximate values are: 0.000 5 for k_{sc}, 0.000 7 for k_{fl} and 0.001 5 for the two k_e values which are greater than 1.000 0 (and less than 0.000 2 where k_e = 1.000 0).

A summary of the results of BIPM comparisons of air-kerma standards for low-energy x-rays, including the present comparison, is presented in Figure 1.

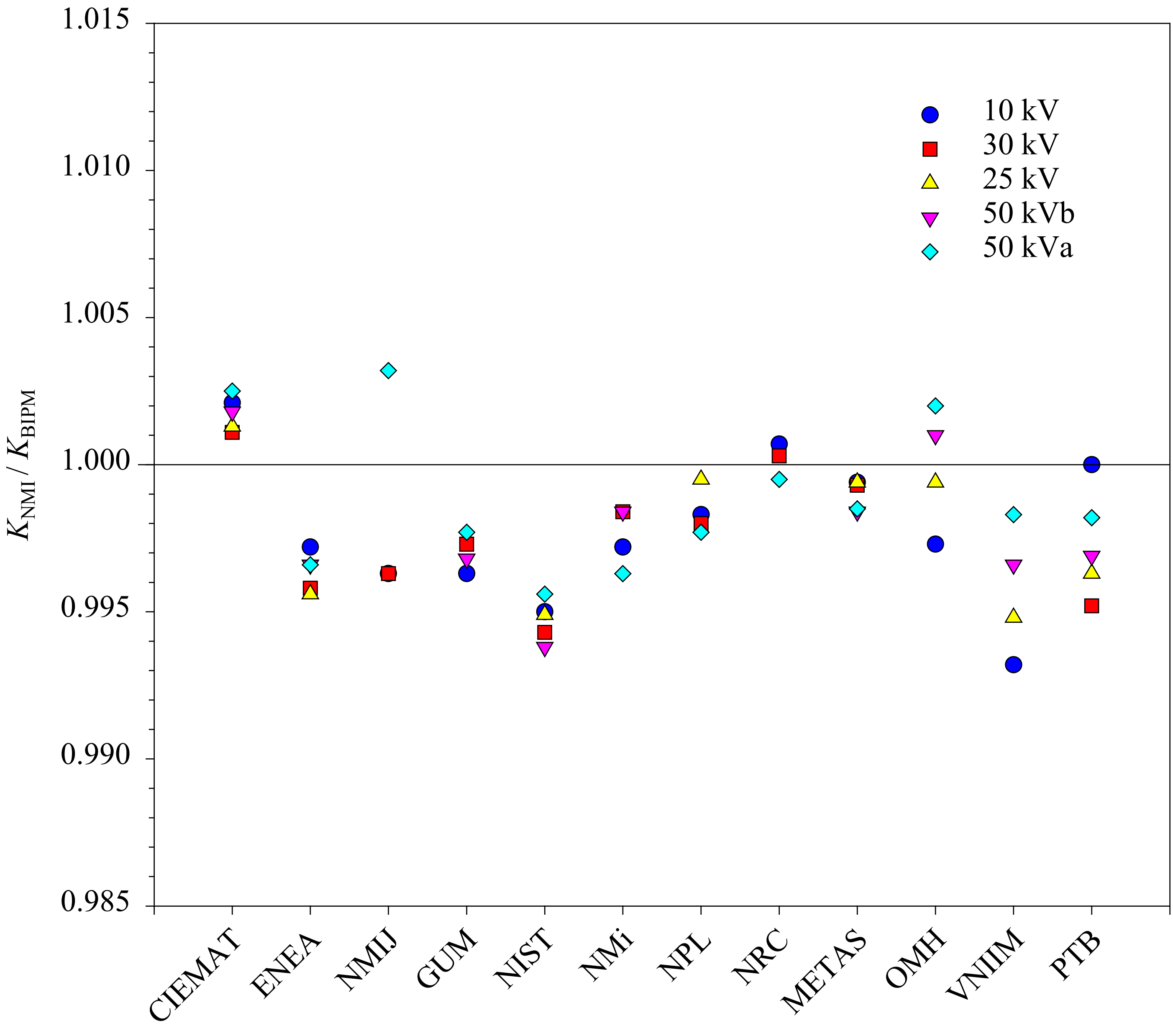

Figure 1. Results of BIPM low-energy x-ray comparisons, expressed as the ratio of the air-kerma rate determined by the standard of the national metrology institute (NMI) to that determined by the BIPM standard. For NMIs that have compared more than once at the BIPM, only the results of the most recent comparison are included.

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