Rapport BIPM-99/11

Bureau International des Poids et Mesures

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November 1999

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Comparison of the air-kerma standards of the ENEA-INMRI and the BIPM in the low-energy x-ray range

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Abstract A direct comparison has been made between the air-kerma standards of the ENEA-INMRI and the BIPM in the low-energy x-ray range. The results show the standards to be in agreement to around 0.35 % at reference beam qualities up to 50 kV. Measurements were also made at the 80 kV quality in order to estimate the electron-loss correction for the ENEA standard at this quality.

1. Introduction

A direct comparison has been made between the air-kerma standards of the Istituto Nazionale di Metrologia delle Radiazioni Ionizzanti (ENEA-INMRI) and the Bureau International des Poids et Mesures (BIPM) in the x-ray range from 10 kV to 50 kV. The comparison took place at the BIPM in September 1998 using the reference conditions recommended by the CCRI [1]. Additional measurements were made at 80 kV to determine the electron-loss correction for the ENEA-INMRI standard at this quality. This required the measurement of aperture and wall transmission correction factors.

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

$$\dot{K} = \frac{I}{\rho_{\mathrm{air}} V} \frac{W_{\mathrm{air}}}{e} \frac{1}{1 - g_{\mathrm{air}}} \prod_i k_i \tag{1}$$

where I is the ionization current, ρ_{air} is the density of air under reference conditions, W_{air} is the mean energy expended by an electron of charge e to produce an ion pair in dry air, g_{air} is the fraction of the initial electron energy lost by bremsstrahlung production in air, and $\Pi\ k_{\mathrm{i}}$ 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 value for ρ_{air}, the ionization current I must be corrected 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].

[1] For an air temperature T and pressure P in the measuring volume, this involves a temperature correction T / T_0, a pressure correction P_0 / P, a humidity correction $k_{\mathrm{h}} = 0.9980$, and the factor 1.0002 to account for the change in the compressibility of air between $T \sim 293$ K and $T_0 = 273.15$ K.

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 ENEA-INMRI 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 chamber are shown in Table 2.

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

Constant	Value	$s^{\dagger} \times 10^2$
ρ_{air} ‡	1.293 0 kg m^{-3}	0.01
W_{air} / e	33.97 J C^{-1}	0.15

† s 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

Chamber	BIPM	ENEA-INMRI
Aperture diameter / mm	9.941	8.014
Air path length / mm	100.0	65.12†
Collector length / mm	15.466	40.738
Electrode separation / mm	70	60
Collector width / mm	71	60
Measuring volume / mm^3	1 200.4	2 054.9
Polarizing voltage / V	1 500	1 600

† This is the quoted value of 64.30 mm plus 0.82 mm due to three screws supporting the aperture.

3. Comparison procedure

3.1 BIPM irradiation facility and reference beam qualities

The comparison was carried out in the BIPM low-energy x-ray laboratory, which houses a constant-potential generator (maximum usable generating potential 80 kV) 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 variation in the measured ionization current over the duration of a comparison introduces a relative standard uncertainty of typically 4×10^{-4}. The radiation qualities used in the range from 10 kV to 50 kV are those recommended by the CCRI [1] and are given in Table 3 in ascending half-value layer (HVL) from left to right. Measurements were also made at the 80 kV quality indicated in the table.

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 ENEA-INMRI standard (the correction factors for the ENEA-INMRI standard at the 80 kV quality are discussed in Section 4.3).

Table 3. Characteristics of the BIPM reference radiation qualities

Generating potential / kV	10	30	25	50(b)	50(a)	80
Al filtration / mm	0	0.208 2	0.372 3	1.008 2	3.989	3.041
Al HVL / mm	0.036	0.176	0.250	1.020	2.257	3.01
μ_{air}† / 10^{-3} mm^{-1}	1.757	0.415	0.304	0.091	0.046	0.042
$\dot{K}_{BIPM}$ / mGy s^{-1}	0.56	3.31	1.13	1.57	0.34	0.61

† Air attenuation coefficient at 293.15 K and 100 000 Pa, measured at the BIPM for an air path length of 100 mm.

Table 4. Correction factors for the BIPM standard

Generating potential / kV	10	30	25	50(b)	50(a)	80	$s \times 10^2$	
							type A	type B
Air attenuation k_a†	1.192 1	1.042 4	1.030 9	1.009 1	1.004 6	1.004 2	0.03	0.01
Scattered radiation k_{sc}	0.994 4	0.995 6	0.995 7	0.996 6	0.997 1	0.997 4	-	0.07
Electron loss k_e	1.000 0	1.000 0	1.000 0	1.000 0	1.000 0	1.010 0	-	0.01‡
Ion recombination k_s	1.000 7	1.001 9	1.001 0	1.001 1	1.000 6	1.000 6	0.02	0.01
Field distortion k_d	1.000 0	1.000 0	1.000 0	1.000 0	1.000 0	1.000 0	-	0.07
Aperture edge transmission k_l	1.000 0	1.000 0	1.000 0	1.000 0	1.000 0	0.999 7	-	0.01
Wall transmission k_p	1.000 0	1.000 0	1.000 0	1.000 0	1.000 0	1.000 0	0.01	-
Humidity k_h	0.998 0	0.998 0	0.998 0	0.998 0	0.998 0	0.998 0	-	0.03
$1 - g_{air}$	1.000 0	1.000 0	1.000 0	1.000 0	1.000 0	1.000 0	-	0.01

† These are nominal values for 293.15 K and 100 000 Pa; each measurement is corrected using the air temperature and pressure measured at the time.
‡ For the 80 kV quality, the value for $s \times 10^2$ is 0.10.

The largest correction at low energies is that 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 factor k_a is calculated using the measured air-attenuation coefficients μ_{air} given in Table 3 (in units of inverse length). In practice, the values used deviate slightly from those given in the tables. This is because the attenuation varies with the temperature and pressure of the air in the chamber and the values for k_a used are corrected for this effect. The value for k_a for the ENEA-INMRI chamber at 10 kV has been increased by the factor 1.000 9 to account for the larger mean air-attenuation coefficient for an air path length of 65.12 mm (the values given in Table 3 were measured at the BIPM for an air path length of 100 mm). This effect is negligible at the other radiation qualities. All ionization measurements are also corrected for changes in air attenuation arising from variations in the temperature and pressure of the ambient air between the radiation source and the reference plane, using the air-attenuation coefficients given in Table 3.

All measured ionization currents are corrected for ion recombination. The measured values for the ion recombination correction k_s for the BIPM standard are given in Table 4. For the ENEA-INMRI standard, the values for k_s given in Table 5 were calculated for the BIPM air-kerma rates given in Table 3 using [5]. These values were checked by performing the same calculation for the air-kerma rates at the ENEA-INMRI; these latter values agree within 0.01 % with the values measured at the ENEA-INMRI[2].

Table 5. Correction factors for the ENEA-INMRI standard

Generating potential / kV	10	30	25	50(b)	50(a)	$s \times 10^2$	
						type A	type B
Air attenuation k_a †	1.122 2	1.027 4	1.020 0	1.005 9	1.003 0	0.03	0.01 ‡
Scattered radiation k_{sc}	0.994 3	0.995 0	0.994 7	0.996 7	0.997 1	-	0.1
Electron loss k_e	1.000	1.000	1.000	1.000	1.000	-	0.1
Ion recombination k_s	1.000 5	1.000 9	1.000 6	1.000 7	1.000 5	-	0.05
Field distortion k_d	1.000	1.000	1.000	1.000	1.000	-	0.1
Aperture edge transmission k_l	1.000 0	1.000 0	1.000 0	1.000 0	1.000 0	-	0.05
Wall transmission k_p	1.000 0	1.000 0	1.000 0	1.000 0	1.000 0	-	0.05
Humidity k_h	0.998 0	0.998 0	0.998 0	0.998 0	0.998 0	-	0.03
$1 - g_{air}$	1.000 0	1.000 0	1.000 0	1.000 0	1.000 0	-	0.01

† These are nominal values for 293.15 K and 100 000 Pa; each measurement is corrected using the air temperature and pressure measured at the time.
‡ This value is derived from the uncertainty of μ_{air} at the BIPM. The value for $s \times 10^2$ used at the ENEA-INMRI is 0.2.

3.3 *Chamber positioning and measurement procedure*

The ENEA-INMRI 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 0.2 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

[2] Except for the 50 kV(a) quality, for which the calculated value is 1.000 5 and the measured value 1.001 0. The calculated value is used in this report.

correction is applied for the radial non-uniformity of the beam. The reference plane for each chamber was positioned at 500 mm from the radiation source for all qualities up to 50 kV and at 750 mm for the 80 kV quality. 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 kV and 68 mm for the 80 kV quality.

The air temperature for the ENEA-INMRI chamber was measured using a BIPM mercury thermometer calibrated to 0.02 K and positioned in the holder of the ENEA-INMRI 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 was less than 0.05 % of the ionization current and for the ENEA-INMRI chamber less than 0.01 %. Each series consisted of five measurements. The relative standard uncertainty of the mean of a series of five measurements was typically less than 2×10^{-4}. Taking into account the relative standard uncertainty of 4×10^{-4} arising from the repeatability over the duration of a comparison of current measurements using the ENEA-INMRI standard, a type A relative standard uncertainty of 5×10^{-4} is taken for current measurements using this chamber. For both chambers, measurements were made at both polarities to correct for any polarity effect. The measured difference was typically 0.11 % for the BIPM chamber and less than 0.02 % for the ENEA-INMRI chamber.

4. Supporting measurements

4.1 Comparison of apertures

The ENEA-INMRI aperture of diameter 8.014 mm was positioned in the BIPM chamber, replacing the BIPM aperture of diameter 9.941 mm. The current measured at 30 kV by the BIPM standard under these conditions was corrected for the decrease in aperture diameter and for the decrease in ion recombination using [5]. The resulting air-kerma rate determination was 0.09 % less than that determined using the BIPM aperture (measured with a relative standard uncertainty of 2×10^{-4}).

4.2 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 decrease in the ionization current, μ_{air} is determined for an air path length of 100 mm. For the 10 kV radiation quality, additional measurements are made over a range of air pressures to determine μ_{air} for other air path lengths, from which the correction factor 1.0009 for the ENEA-INMRI air path length of 65.12 mm is derived. Note that the thin beryllium windows of the tube are included in the stated inherent filtration (2.9 mm beryllium).

The ENEA-INMRI method for determining μ_{air} is by the addition of an aluminium tube of internal diameter 25 mm to the front of the chamber, which moves the aperture towards the radiation source by a known distance. The source must be moved back by this distance. The decrease in the ionization current is a measure of the air attenuation arising from the additional air path between the aperture and the collecting volume.

Two sets of measurements were performed at 10 kV. In the first set, a tube of length 50.4 mm was added to the ENEA-INMRI standard and the radiation source moved back by this amount. From the measured decrease in current, the air-attenuation coefficient was evaluated as $\mu_{air} = 1.706 \times 10^{-3}$ mm^{-1} (at 293.15 K and 100 kPa). For the second set of measurements a tube of length 95.0 mm was used, giving $\mu_{air} = 1.687 \times 10^{-3}$ mm^{-1}. From these results one can interpolate (linearly) the value $\mu_{air} = 1.700 \times 10^{-3}$ mm^{-1} for an air path length of 65 mm. Using this value rather than the BIPM value yields an air-kerma rate determination which is smaller by 0.37 % for the ENEA-INMRI standard and by 0.57 % for the BIPM standard.

4.3 Measurements at 80 kV

Although the ENEA-INMRI standard is not designed for use above 50 kV, the opportunity was taken to compare the two standards at 80 kV. This allows an experimental determination of the electron-loss correction k_e for the ENEA-INMRI standard at this quality, on the assumption that all other correction factors are known. Those for the BIPM standard are given in Table 4. The value for k_e is derived from measurements at the BIPM using the magnetic field technique and has been verified by comparison with the BIPM medium-energy free-air chamber standard and by recent Monte Carlo calculations [6]. For the ENEA-INMRI standard, k_{sc} was taken to be the same as for the BIPM standard (their values at 50 kV are very similar), k_s was calculated using [5], k_d was taken to be the same as at lower energies and $1 - g_{air}$ was taken to be unity. This leaves only the corrections for aperture-edge transmission k_l and wall transmission k_p for the ENEA-INMRI standard, which were measured.

Aperture-edge transmission was measured using a dummy 'aperture' of the same material and thickness as the real aperture but without the hole. At 80 kV no transmission was measurable at the 0.02 % level. Wall transmission was measured using a large lead stopper. At 80 kV the wall-transmission correction $k_p = 0.995\,2$ was determined with an estimated relative standard uncertainty of 0.02 %.

5. Uncertainties

The uncertainties associated with the primary standards and with the results of the comparison are listed in Table 6. In general, the quoted uncertainties are representative of those associated with routine air-kerma rate determinations at both institutions. The uncertainty of μ_{air} is that of the BIPM determination and is significantly less than that quoted for determinations at the ENEA-INMRI (see Table 5 and footnote). The uncertainties associated with the measurement of the ionization current and with chamber positioning are those which apply to measurements at the BIPM.

The uncertainties of the ratios $\dot{K}_{\text{ENEA-INMRI}}/\dot{K}_{\text{BIPM}}$ take into account correlations in the type B uncertainties associated with the determination of the ionization current, the humidity correction and the physical constants. Correlations between the values for k_{sc} are not taken into account, although these are derived from the same basic data.

6. Results and discussion

The comparison results are given in Table 7. General agreement at the level of 0.3 % to 0.4 % is observed, which is approximately 1.5 times the relative standard uncertainty. The result of the aperture comparison accounts for almost 0.1 % of the difference and so the standards can be considered to be in acceptable agreement. No significant trend with radiation quality is observed

The result of the comparison at 80 kV is $\dot{K}_{\text{ENEA-INMRI}}/\dot{K}_{\text{BIPM}} = 0.969\,1$, with a relative standard uncertainty of 0.27 % (including the 0.10 % uncertainty of k_e for the BIPM standard). Comparing this with the mean result obtained in the range from 10 kV to 50 kV, one can deduce the value $k_e = 1.028$ for the ENEA-INMRI standard at this quality. Using this method, many correlated uncertainties cancel and the relative standard uncertainty of this value for k_e is estimated to be 0.12 %. This result will be used for comparison with Monte Carlo calculations.

Of particular concern is the difference in the BIPM and the ENEA-INMRI determinations of the air-attenuation coefficient μ_{air} for the 10 kV quality at the BIPM. This difference is very much larger than the estimated uncertainty of the measurement techniques. Using the ENEA-INMRI value yields an air-kerma rate determination which is smaller by 0.37 % for the ENEA-INMRI standard. Around 0.1 % of this difference may be explained by a change in the photon-scatter correction k_{sc} when using the ENEA-INMRI technique, which is not taken into account. The use of the ENEA-INMRI value for μ_{air} for the BIPM standard at 10 kV yields an air-kerma rate determination which is smaller by 0.57 %. The net effect of these changes is an increase in the comparison result at 10 kV by 0.20 % which worsens the consistency of the results as a function of beam quality. From this evidence one might deduce that the BIPM determination of μ_{air} is the closer estimate.

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

Table 6. Uncertainties associated with the comparison results

Standard	BIPM		ENEA-INMRI	
$s \times 10^2$	type A	type B	type A	type B
Ionization current	0.02	0.02	0.05	0.02
Volume	0.03	0.05	-	0.05
Positioning	0.01	0.01	0.01	0.06
Correction factors (excl. k_h)	0.04	0.10	0.03	0.19
Humidity k_h	-	0.03	-	0.03
Physical constants	-	0.15	-	0.15
$\dot{K}_{Standard}$	0.06	0.19	0.06	0.26
	0.20		0.27	
$\dot{K}_{ENEA-INMRI}/\dot{K}_{BIPM}$	0.25†			

† Takes account of correlations in Type B uncertainties.

Table 7. Comparison results

Generating potential / kV	10	30	25	50(b)	50(a)
$\dot{K}_{ENEA-INMRI}/\dot{K}_{BIPM}$	0.9972	0.9958	0.9956	0.9966	0.9966

References

[1] BIPM, Qualités de rayonnements, CCEMRI (Section I), 1972, 2, R15.

[2] BOUTILLON M., HENRY W.H. and LAMPERTI P.J., Comparison of exposure standards in the 10-50 kV x-ray region, *Metrologia*, 1969, 5, 1-11.

[3] BOUTILLON M., Measurement conditions used for the calibration of ionization chambers at the BIPM, 1996, *Rapport BIPM*-96/1.

[4] MORETTI C.J., HEATON J.A., LAITANO R.F. AND TONI M.P., Intercomparison of low-energy primary standards for x-ray exposure of NPL and ENEA, 1991, *NPL Report RSA (EXT)* 19.

[5] BOUTILLON M., Volume recombination parameter in ionization chambers, *Physics in Medicine and Biology*, 1998, 43, 2061-2072.

[6] BURNS D.T., Consistent set of calculated values for electron-loss and photon-scatter corrections for parallel-plate free-air chambers, 1999, CCRI(I)/99-4, 14 p.

Annex A

The results of BIPM comparisons of air-kerma standards for low-energy x-rays are presented in Table A.1. For laboratories which have compared more than once at the BIPM, only the results of the most recent comparison are included. The same data are presented in graphical form in Figure A.1.

Table A.1 Results of BIPM low-energy x-ray comparisons, expressed as $\dot{K}_{\mathrm{NMI}}/\dot{K}_{\mathrm{BIPM}}$.

NMI	Country	Date	Generating potential / kV				
			10 kV	30 kV	25 kV	50 kV(b)	50 kV(a)
NRC	Canada	1966	1.000 7	1.000 3	-	-	0.999 5
ETL	Japan	1972	0.996 3	0.996 3	-	-	1.003 2
CIEMAT	Spain	1979	1.002 1	1.001 1	1.001 3	1.001 8	1.002 5
OMH	Hungary	1988	0.997 3	-	0.999 4	1.001 0	1.002 0
GUM	Poland	1994	0.996 3	0.997 3	-	0.996 8	0.997 7
NMi	Netherlands	1996	0.997 2	0.998 4	-	0.998 4	0.996 3
NPL†	UK	1997	0.998 3	0.998 0	0.999 5	-	0.997 7
NIST	USA	1998	0.995 0	0.994 3	0.994 9	0.993 8	0.995 6
OFMET	Switzerland	1998	0.999 4	0.999 3	0.999 4	0.998 4	0.998 5
ENEA	Italy	1998	0.997 2	0.995 8	0.995 6	0.996 6	0.996 6

† The results for this laboratory are provisional; BIPM report still in preparation.

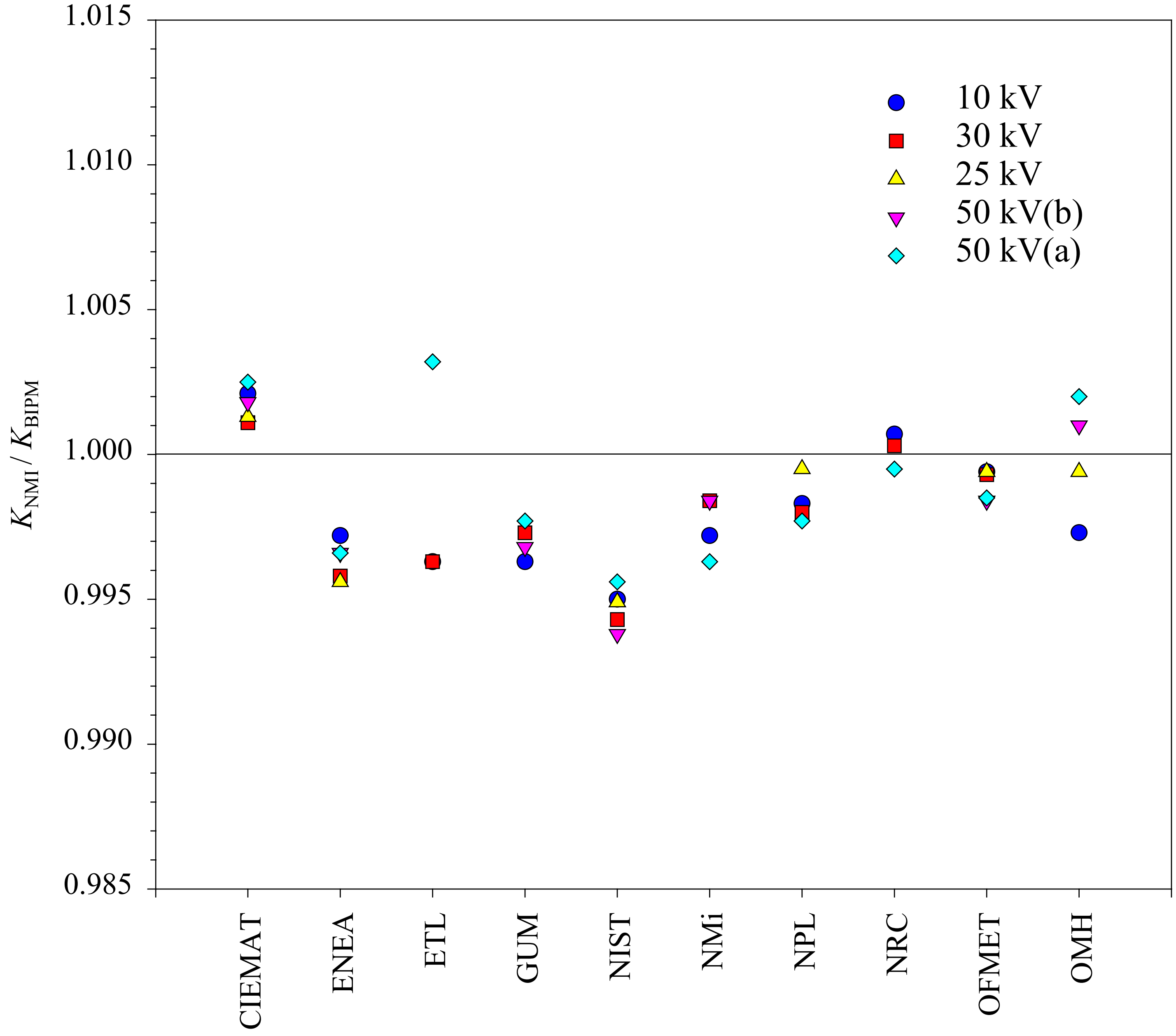

Figure A.1. Results of BIPM low-energy x-ray comparisons, expressed as the ratio of the air-kerma rate determined by the NMI standard to that determined by the BIPM standard. The results for the NPL are provisional.