

Report on Comparison EUROMET.EM-S14 (EUROMET PROJECT 495)

MEASUREMENTS UP TO 100 KV DC

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1. Introduction

The purpose of the project is to compare the measurement systems of various European National Measurement Institutes (NMI) who make DC voltage measurements up to 100 kV. A similar comparison was carried out between 1981 and 1983 [2]. The transfer standard is a resistive voltage divider provided by NPL and the participants were asked to measure the scale factor for various ratios at specified voltages up to a maximum applied voltage of 100 kV. The scale factor is defined as (IEC 60060-2, High-voltage test techniques, clause 3.5.2) ‘The scale factor is the factor by which the output of the converting device is to be multiplied to obtain the value of the input quantity.’

The ratios to be measured are:

100 000/1

100 000/10

100 000/100

at voltages of 10 kV, 50 kV and 100 kV. The 100 000/100 ratio was also measured at 1 kV

The divider has another ratio of 100 000/2 which can be measured as an optional ratio.

The instructions to participants are given in Appendix 3.

The participating laboratories are (in order of measurement):

(The full names and addresses of the all the participants are given in Appendix 4).

National Physical Laboratory (NPL) UK,

Physikalisch-Technische Bundesanstalt (PTB) Germany,

Istituto Elettrotecnico Nazionale “Galileo Ferraris”(IEN) Italy,

SP Swedish National Testing and Research Institute (SP) Sweden,

Centre of Metrology and Accreditation - Helsinki University of Technology (MIKES-HUT) Finland, (NB This laboratory is now called (MIKES-TKK)

Swiss Federal Office of Metrology and Accreditation (METAS) Switzerland,

Bureau National de Metrologie - Laboratoire National d’Essais (BNM-LNE) France,

Nederlands Meetinstituut Van Swinden Laboratorium (NMI/VSL) Netherlands.

The original schedule was changed to suit the convenience of the participants and the actual measurement schedule was as shown below

NPL1	September 1999
PTB	November 1999
IEN	December 1999/January 2000
NPL2	March 2000
SP	May/June 2000
MIKES-HUT	June/July 2000
NPL3	August 2000
METAS	September/October 2000
BNM-LNE	November/December 2000
NMi-VSL	February/March 2001
NPL4	March 2001

The transfer standard is a conventional resistive divider composed of a chain of 10 MΩ wirewound resistors giving a total resistance of 1 GΩ. The best available resistors were used in groups of low temperature coefficients of mixed sign in order to minimise the overall influence of ambient temperature and dissipated power. These are arranged in 4 sections. In each section the resistors are arranged in a helical fashion around a central core. A large corona shield is fitted to the top of the structure and a smaller corona shield is fitted between each section of 25 resistors. The output resistors are 5 kΩ for 1 V, 2 kΩ for 2 V, 100 kΩ for 10 V and 1 MΩ for 100 V (for 100 kV input and 100 μA operating current). Further details are given in reference [1].

2. Reference Value.

There is no evidence for a systematic drift in the value of the standard so it is assumed to be constant over the period of the comparison.

2.1. Calculation of reference value

The approach taken here is:

1. Firstly to average the NPL results so as to give one value for NPL so as not to give undue weight to NPL in the calculation of the reference value. For BNM-LNE only the results from Divider 1 were used.

2. Take as the reference value (RV) the mean of all the results for a given measurement.

$$RV = \frac{1}{N} \sum_{i=1}^N V_i \quad (1)$$

where N is the number of measurements and V_i is the value from the i^{th} participant.

3. The expanded uncertainty of this value U_{RV} is given by (2) below.

$$U_{RV} = k \sqrt{\frac{1}{N(N-1)} \sum_{i=1}^N (V_i - RV)^2} \quad (2)$$

Where k is the Student's T factor (obtained from Student T tables) to give an uncertainty at the 95% confidence level. The number of effective degrees of freedom is taken to be the number of participants minus one. The uncertainties in the values of the scale factors provided by the participants are at the 95% confidence level. In the tables comparing the results of the different laboratories against the reference value the uncertainty U of the difference is calculated using equation (3) given below which takes into account the correlation between the reference value and each of the values used in calculating the reference value.

$$U = \sqrt{U_{RV}^2 + \left(1 - \frac{2}{N}\right) U_i^2} \quad (3)$$

where U_i is the expanded uncertainty associated with the individual value.

All the measurements have been corrected to 20 °C using a correction factor of $+2 \cdot 10^{-6}/^{\circ}\text{C}$. The uncertainty in the scale factor due to any uncertainty in this correction is considered to be negligible. The uncertainty used in the tables and figures in section 4 is the expanded uncertainty appropriate to a 95% confidence level.

Appendix 5 gives a weighted mean approach to calculating the reference value.

2.2 Calculation of pair-wise degrees of equivalence:

The degree of equivalence D_{ij} between the measured results provided by participants i and j is given by:

$$D_{ij} = V_i - V_j$$

Where V_i and V_j are the measurement results of participants i and j after correction for temperature. Since all participants measurements are independent of each other, the expanded uncertainty U_{ij} for D_{ij} is given by

$$U_{ij} = \sqrt{U_i^2 + U_j^2}$$

3. Methods

A brief description is given, for each laboratory, of the traceability chain, ie, the way in which the laboratory standard is calibrated, and of the method of measurement of the travelling standard. In each case the travelling standard is compared against the laboratory standard.

In this section R_{high} refers to the high voltage resistor and R_{low} refers to the output resistor.

3.1 NPL

3.1.1 Calibration of Laboratory Standard.

The standard is calibrated against a low voltage (1000 V) Resistive Voltage Divider which is itself calibrated by a self consistent build up.

3.1.2 Calibration of Travelling Standard.

The two dividers are calibrated by applying the same source to the dividers in parallel and reading the output voltages using a DVM.

The reported measurements were made 30 minutes after the application of the voltage.

Ambient conditions: Temperature (20±1) °C, Relative Humidity between 30 % and 60 %.

3.2 PTB

3.2.1 Calibration of Laboratory Standard.

(a) 100:1 ratio by applying 1000 V and measuring output using null detector and reference source,

(b) 10 000:1 by comparing at high voltage with 300 kV divider which was calibrated with reference to the standard at 100:1 ratio.

3.2.2 Calibration of Travelling Standard.

The two dividers are energised in parallel and the output voltages measured using two DVMs.

The reported measurements were made 30 minutes after the application of the voltage.

The 100 000:100 ratio was measured at 1 kV by applying a known voltage to the divider and measuring the output voltage using a DVM.

Ambient conditions: Temperature (21±1) °C, Relative Humidity between 40 % and 60 %.

3.3 IEN

3.3.1 Calibration of Laboratory Standard.

Using the Hamon principle the HV resistor elements are connected in parallel giving 20 kΩ. The ratio of R_{highP} (with resistors in parallel) to R_{low} is measured using a Kelvin Varley divider and null detector. The Kelvin Varley divider is a self-calibrating device. Using the Hamon principle the ratio of the divider when the resistors of R_{high} are connected in series can be calculated from the measured ratio of R_{highP} to R_{low} .

3.3.2 Calibration of Travelling Standard.

The two dividers are energised from the same source and the outputs are measured using DVMs.

For the 100 000:100 ratio a battery operated DVM is used to measure the difference between the output voltages from the two dividers.

Measurements were made at 75 kV instead of 100 kV.

The reported measurements were made 20 minutes after the application of the voltage.

Ambient conditions: Temperature (23±1) °C, Relative Humidity < 50 %.

3.4 SP

3.4.1 Calibration of Laboratory Standard.

After original NPL calibration 1994 at 100 kV the calibration has been maintained by calibration at 1 000 V.

3.4.2 Calibration of Travelling Standard.

The two dividers are energised in parallel and the output voltage measured using DVMs.

For 100 000:100 ratio the output voltage of the travelling standard is measured by comparing it with a standard voltage and using a DVM to measure the small difference voltage.

The reported measurements were made at least 60 minutes after the application of the voltage.

Ambient conditions: Temperature (22±1) °C.

3.5 MIKES-HUT

3.5.1 Calibration of Laboratory Standard.

The ratio was calibrated at low voltage (1000 V) by measuring the input and output voltages with two calibrated DVMs.

3.5.2 Calibration of Travelling Standard

At 1 kV the input and output voltages are measured using DVMs. Measurements were performed after 30 seconds of the onset of the voltage. Dividers were left unenergized for 10 minutes before next measurement. The travelling standard and the reference divider are energised in parallel and the outputs of the dividers are measured directly using two DVMs. Two different reference voltage dividers were used. One allowing measurements up to 200 kV (used for 100 kV measurements) and a second one of better accuracy allowing voltage measurements up to 50 kV only (10 kV and 50 kV).

The reported measurements were made 30 seconds after the application of the voltage.

Ambient conditions: Temperature (24±2)°C, Relative Humidity (65±3)%.

3.6 METAS

3.6.1 Calibration of Laboratory Standard.

The ratio of the standard was measured with the high resistance bridges developed at METAS.

3.6.2 Calibration of Travelling Standard.

The two dividers are energised in parallel and the outputs of the two dividers measured directly using a DVM. Alternatively the output voltage can be measured by comparing it against a voltage standard and measuring the small voltage difference using a DVM.

The reported measurements were made at a minimum of 30 minutes after the application of the voltage.

Ambient conditions: Temperature (20±0.5) °C, Relative Humidity (46±5) %

3.7 BNM-LNE

3.7.1 Calibration of Laboratory Standard.

Calibrated by direct measurement of the resistance of R_{high} and R_{low} .

3.7.2 Calibration of Travelling Standard.

The travelling and BNM-LNE standard dividers are energised in parallel and a null detector is used to sense the difference in the outputs of the two dividers. A third divider is used to guard the low voltage part of the measuring set-up.

Two different standard high voltage dividers from BNM-LNE were used during this comparison. One allowing measurements up to 250 kV (denoted divider 1 in the result tables of paragraphs 4 and 5) and a second one of better accuracy allowing voltage measurements up to 50 kV only (divider 2 in tables of paragraphs 4 and 5).

The reported measurements were made 30 minutes after the application of the voltage.

Ambient conditions: Temperature (23±1) °C, Relative Humidity between 30 % and 45 %.

3.8 NMI-VSL

3.8.1 Calibration of Laboratory Standard.

The scale factor of the standard is calculated from the measured values of all the resistors making up the divider. R_{high} is 200 M Ω (100 x 2 M Ω). R_{low} is 2 k Ω .

3.8.2 Calibration of Travelling Standard.

For 100 000:1 the output voltage is measured using a DVM and the input voltage measured using the standard reference divider and a calibrated DVM.

For 100 000: 10 and 100 000:100 the output voltage is measured by comparing it with a standard voltage using a null method.

The reported measurements were taken at 15 minutes after applying the voltage.

Ambient conditions: Temperature 22.5°C , Relative Humidity 40 %.

4 Results

The results of the comparison are given in two ways:

1. The Scale Factors are given after correcting all values to a common temperature of 20 °C. Values are given of Scale Factor (SF) and the expanded uncertainty U (95 % confidence). The expanded uncertainty associated with the Scale Factor values are given as absolute values.
2. The results are also presented as tables and graphs of difference from a reference value. The reference value is calculated as indicated in section 2. The expanded uncertainty is given for 95 % confidence level ($k = 2$)

Tables of the E_n value for 95 % confidence level are also given where
 $E_n = ((\text{difference from reference value})/(\text{expanded uncertainty of the difference}))$

The uncertainty of the difference is calculated as given in equation (3).

4.1 Ratio 100 000/1

Ratio	100 000/1					
	10 kV		50 kV		100 kV	
Applied voltage						
Laboratory	SF	U	SF	U	SF	U
NPL1	100 005.0	1.5	100 004.2	1.5	100 004.4	1.5
PTB	100 002.9	1.0	100 004.0	0.4	100 004.9	0.4
IEN(75kV)	100 003.2	1.6	100 003.3	1.4	100 003.5	1.4
NPL2	100 005.2	1.5	100 001.7	1.5	100 002.0	1.5
SP	100 003.2	1.5	100 004.3	1.4	100 004.6	1.4
MIKES-HUT	100 004.8	2.8	100 004.8	2.8	100 004.2	4.3
NPL3	100 003.0	1.5	100 003.4	1.5	100 004.0	1.5
METAS	100 003.1	2.3	100 005.4	2.6	100 010.1	4.5
BNM-LNE (divider 1)	100 003.1	1.75	100 003.9	1.75	100 006.0	1.75
BNM-LNE (divider 2)	100 002.9	1.1	100 003.9	1.2	-	-
NMi-VSL	100 006.7	4.44	100 005.9	4.60	100 004.4	4.93
NPL4	100 005.1	1.5	100 002.8	1.5	100 003.8	1.5
Reference value	100 003.95	1.15	100 004.3	0.88	100 005.1	1.87

Table 4.1.1. Values of Scale Factor for Ratio 100 000/1. corrected to 20 °C

En values for 95 % confidence for Ratio 100 000/1			
Laboratory	10 kV	50 kV	100 kV
NPL	0.36	-0.84	-0.71
PTB	-0.73	-0.36	-0.14
IEN	-0.41	-0.70	-0.74
SP	-0.43	-0.03	-0.25
MIKES-HUT	0.32	0.18	-0.23
METAS	-0.37	0.48	1.14
BNM-LNE	-0.44	-0.26	0.36
NMi-VSL	0.69	0.38	-0.16

Table 4.1.2 En values (95% confidence) for Ratio 100 000/1

Ratio 100 000/1 Difference from reference value ($\times 10^{-6}$)						
Laboratory	10 kV		50 kV		100 kV	
	Difference	Expanded uncertainty	Difference	Expanded uncertainty	Difference	Expanded uncertainty
NPL	6.3	17	-13.2	16	-16.1	23
PTB	-10.5	14	-3.4	9	-2.6	19
IEN	-7.5	18	-10.4	15	-16.6	22
SP	-7.5	17	-0.4	15	-5.6	22
MIKES-HUT	8.5	27	4.6	26	-9.6	42
METAS	-8.5	23	11.6	24	49.4	43
BNM-LNE	-8.5	19	-4.4	17	8.4	24
NMi-VSL	27.5	40	15.6	41	-7.6	47

Table 4.1.3 Difference from reference value ($\times 10^{-6}$) for Ratio 100 000/1

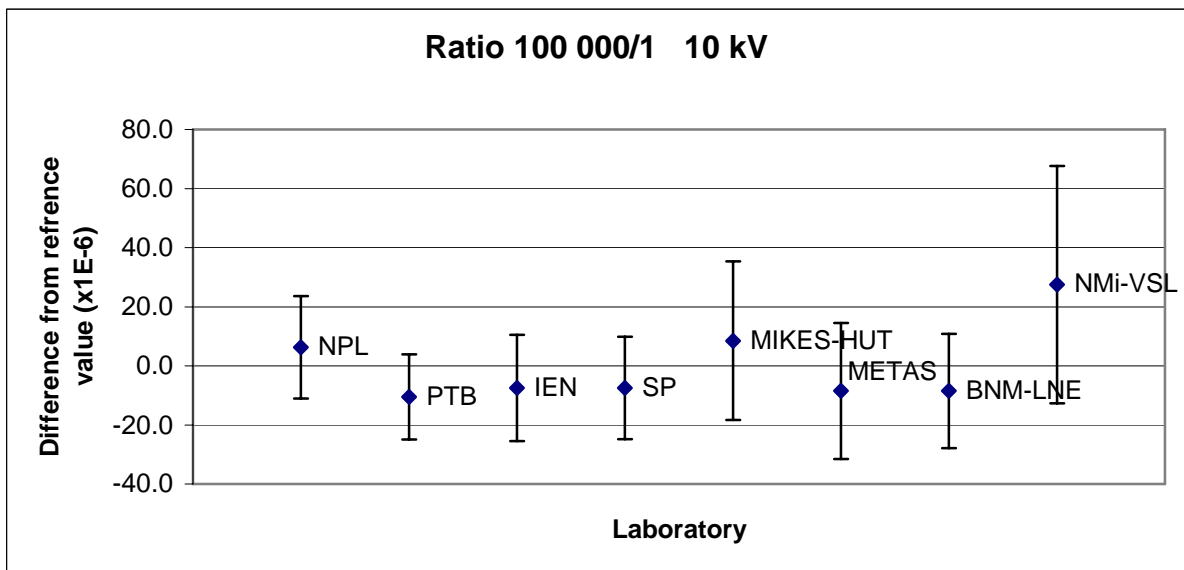


Figure 4.1.1 Difference from reference value ($\times 10^{-6}$) for Ratio 100 000/1 at 10 kV

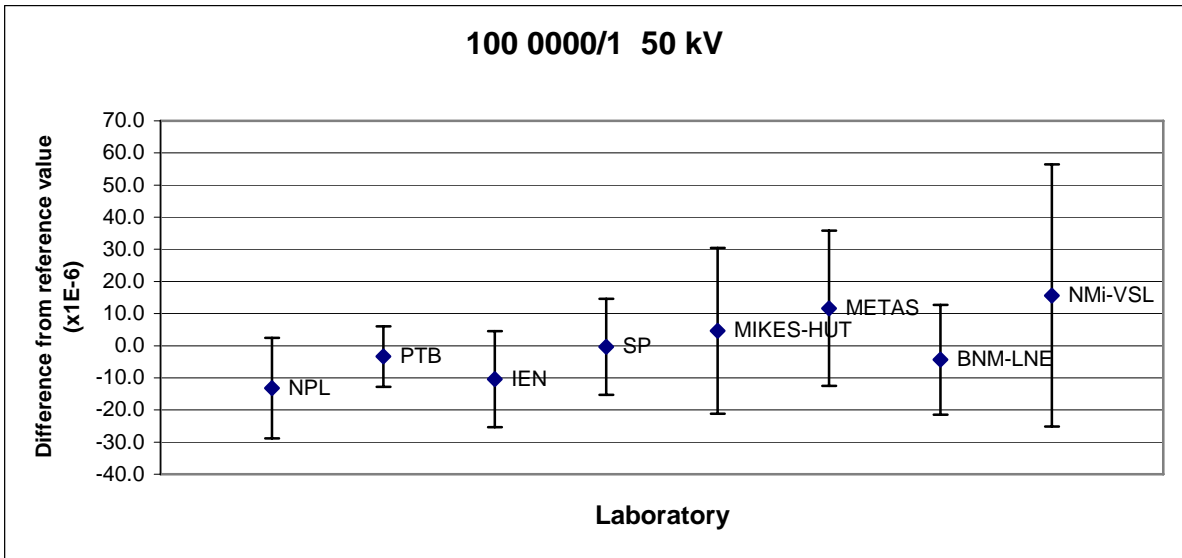


Figure 4.1.2 Difference from reference value ($\times 10^{-6}$) for Ratio 100 000/1 at 50 kV

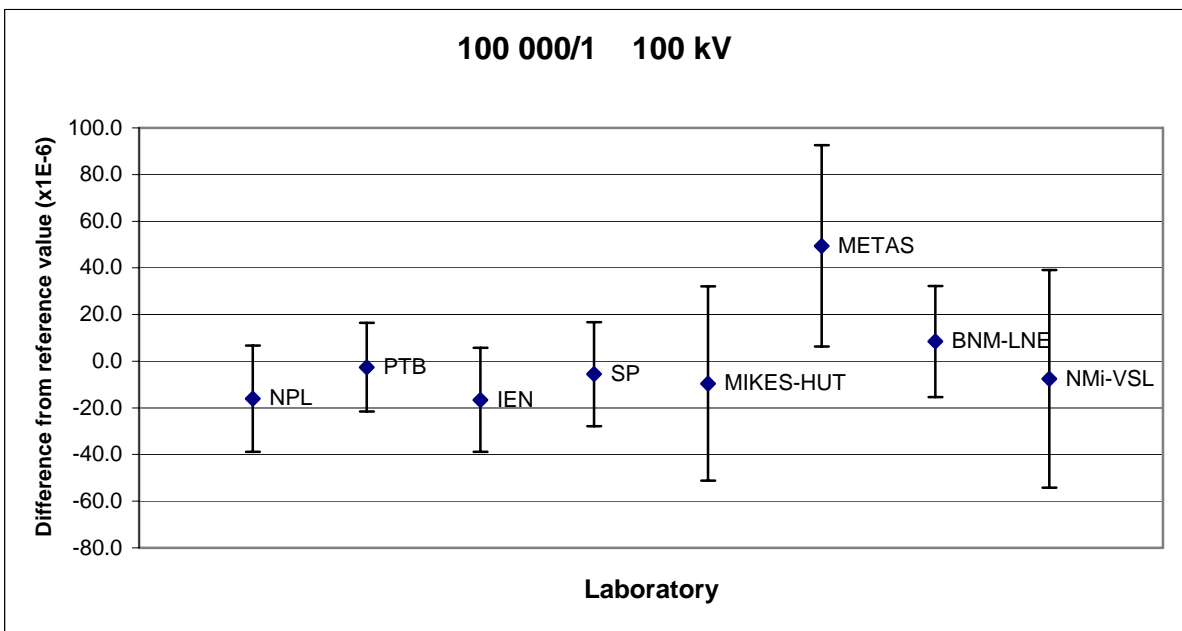


Figure 4.1.3 Difference from reference value ($\times 10^{-6}$) for Ratio 100 000/1 at 100 kV

4.2 Ratio 100 000/10

Ratio	100 000/10					
	10 kV		50 kV		100 kV	
Applied voltage						
Laboratory	SF	U	SF	U	SF	U
NPL1	10 000.39	0.15	10 000.26	0.15	10 000.28	0.15
PTB	10 000.19	0.04	10 000.25	0.03	10 000.31	0.03
IEN(75 kV)	10 000.18	0.07	10 000.20	0.065	10 000.24	0.065
NPL2	10 000.38	0.15	10 000.37	0.15	10 000.31	0.15
SP	10 000.32	0.14	10 000.32	0.14	10 000.38	0.14
MIKES-HUT	10 000.35	0.28	10 000.35	0.28	10 000.40	0.41
NPL3	10 000.29	0.15	10 000.35	0.15	10 000.42	0.15
METAS	10 000.28	0.23	10 000.48	0.26	10 000.95	0.45
BNM-LNE (divider 1)	10 000.17	0.174	10.000.28	0.174	10 000.46	0.174
BNM-LNE (divider 2)	10 000.13	0.11	10 000.18	0.12	-	-
NMi/VSL	10 000.38	0.458	10 000.35	0.455	10 000.24	0.492
NPL4	10 000.14	0.15	10 000.18	0.15	10 000.27	0.15
Reference value	10 000.27	0.07	10 000.31	0.07	10 000.41	0.20

Table 4.2.1. Values of Scale Factor for Ratio 100 000/10. corrected to 20 °C

En value for 95 % confidence for Ratio 100 000/10			
Laboratory	10 kV	50 kV	100 kV
NPL	0.19	-0.17	-0.39
PTB	-1.03	-0.84	-0.51
IEN	-0.98	-1.25	-0.83
SP	0.35	0.04	-0.14
MIKES-HUT	0.31	0.14	-0.03
METAS	0.04	0.70	1.23
BNM-LNE	-0.62	-0.21	0.19
NMi-VSL	0.27	0.09	-0.37

Table 4.2.2 En values (95 % confidence) for Ratio 100 000/10

Ratio 100 000/10 Difference from reference value ($\times 10^{-6}$)						
Laboratory	10 kV		50 kV		100 kV	
	Difference	Expanded uncertainty	Difference	Expanded uncertainty	Difference	Expanded uncertainty
NPL	2.9	15	-2.5	15	-9.3	24
PTB	-8.1	8	-6.5	8	-10.3	20
IEN	-9.1	9	-11.5	9	-17.3	21
SP	4.9	14	0.5	14	-3.3	23
MIKES-HUT	7.9	25	3.5	25	-1.3	41
METAS	0.9	21	16.5	24	53.8	44
BNM-LNE	-10.1	16	-3.5	16	4.8	25
NMI-VSL	10.9	40	3.5	40.1	-17.3	47

Table 4.2.3 Difference from reference value ($\times 10^{-6}$) for Ratio 100 000/10

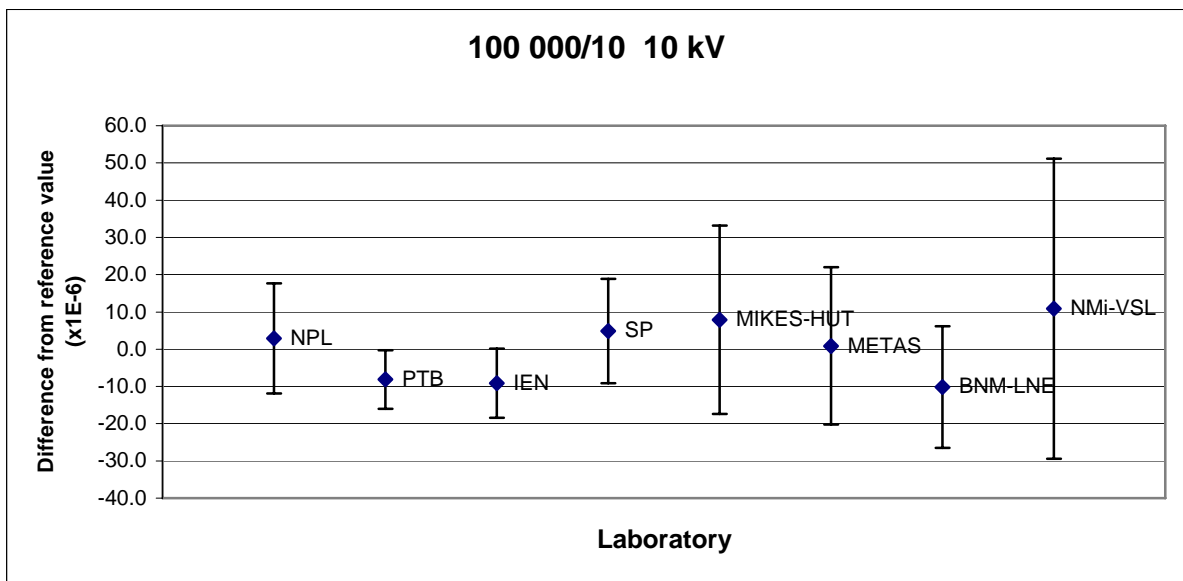


Figure 4.2.1 Difference from reference value ($\times 10^{-6}$) for Ratio 100 000/10 at 10 kV

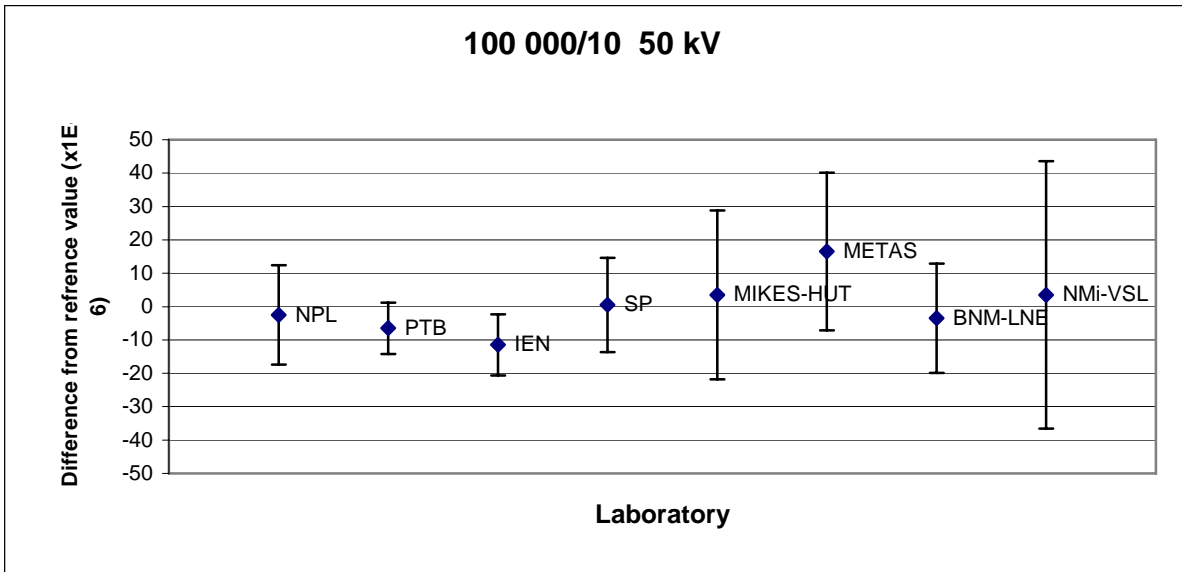


Figure 4.2.2 Difference from reference value ($\times 10^{-6}$) for Ratio 100 000/10 at 50 kV

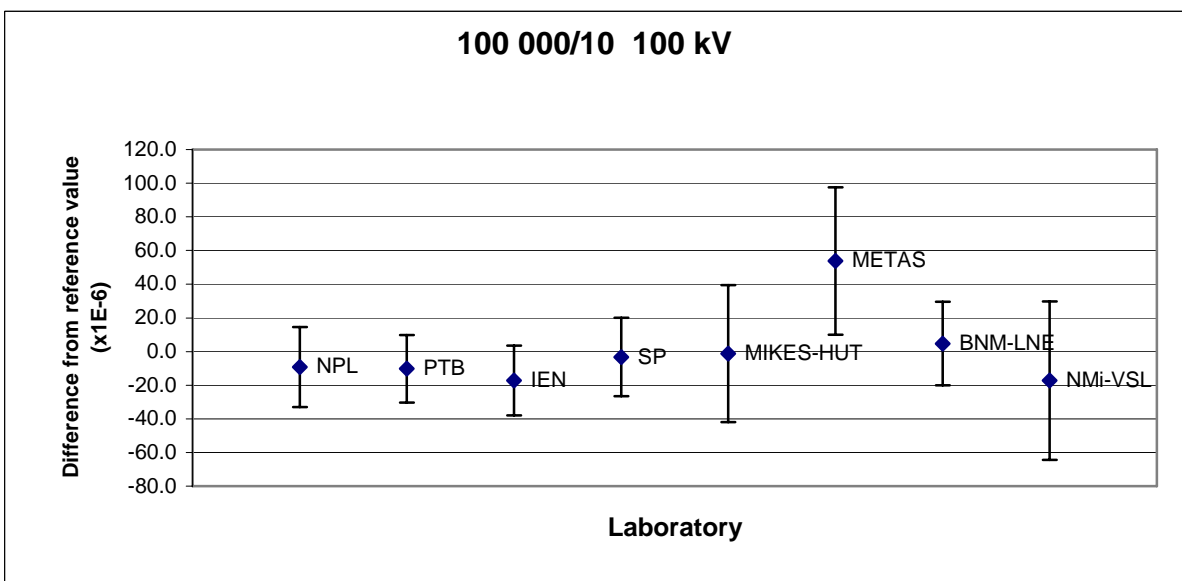


Figure 4.2.3 Difference from reference value ($\times 10^{-6}$) for Ratio 100 000/10 at 100 kV

4.3 Ratio 100 000/100

Ratio	100 000/100					
	10 kV		50 kV		100 kV	
Laboratory	SF	U	SF	U	SF	U
NPL1	999.983	0.015				
PTB	1000.002	0.004	1000.005	0.007	1000.014	0.004
IEN(75 kV)	1000.031	0.022	1000.041	0.022	1000.044	0.022
NPL2	999.997	0.015				
SP	1000.018	0.022	1000.005	0.014	1000.014	0.014
MIKES-HUT	1000.009	0.017	1000.006	0.029	999.997	0.040
NPL3	999.987	0.015				
METAS	999.988	0.024	1000.009	0.026	1000.065	0.045
BNM-LNE (divider 1)	999.992	0.018	1000.003	0.018	1000.023	0.017
BNM-LNE (divider 2)	999.991	0.011	999.995	0.012	-	-
NMi/VSL	1000.012	0.017	1000.000	0.045	1000.001	0.049
Reference value	1000.005	0.013	1000.0099	0.0126	1000.0226	0.021

Table 4.3.1. Values of Scale Factor for Ratio 100 000/100. corrected to 20 °C

En values for 95 % confidence for Ratio 100 000/100			
Laboratory	10 kV	50 kV	100 kV
NPL	-0.87		
PTB	-0.23	-0.35	-0.37
IEN	1.11	1.36	0.72
SP	0.72	-0.27	-0.33
MIKES-HUT	0.14	-0.14	-0.63
METAS	-0.70	-0.03	0.96
BNM-LNE	-0.64	-0.34	0.02
NMi-VSL	0.17	-0.24	-0.45

Table 4.3.2 En values (95 % confidence) for Ratio 100 000/100

Ratio 100 000/100		Difference from reference value ($\times 10^{-6}$)				
Laboratory	10 kV		50 kV		100 kV	
	Difference	Expanded uncertainty	Difference	Expanded uncertainty	Difference	Expanded uncertainty
NPL	-16	19				
PTB	-3	14	-4.9	14	-8.6	23
IEN	26	23	31.1	23	21.4	30
SP	13	18	-4.9	18	-8.6	26
MIKES-HUT	4	28	-3.9	28	-25.6	41
METAS	-17	25	-0.9	26	42.4	44
BNM-LNE	-13	20	-6.9	20	0.4	27
NMi-VSL	7	40	-9.9	40	-21.6	48

Table 4.3.3 Difference from reference value ($\times 10^{-6}$) for Ratio 100 000/100

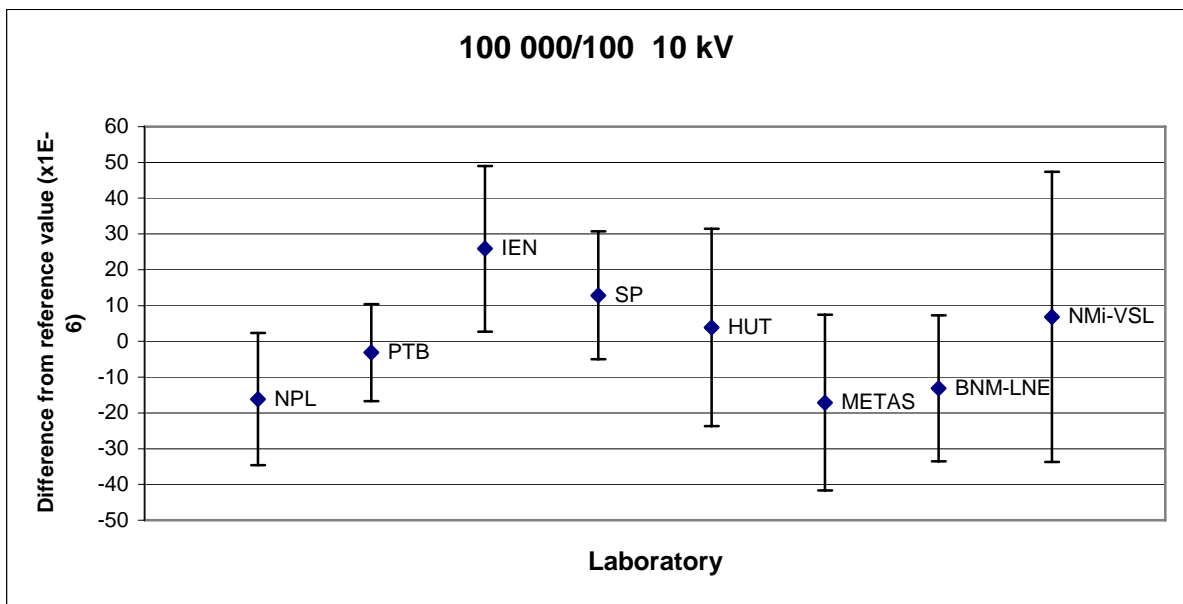


Figure 4.3.1 Difference from reference value ($\times 10^{-6}$) for Ratio 100 000/100 ratio at 10 kV

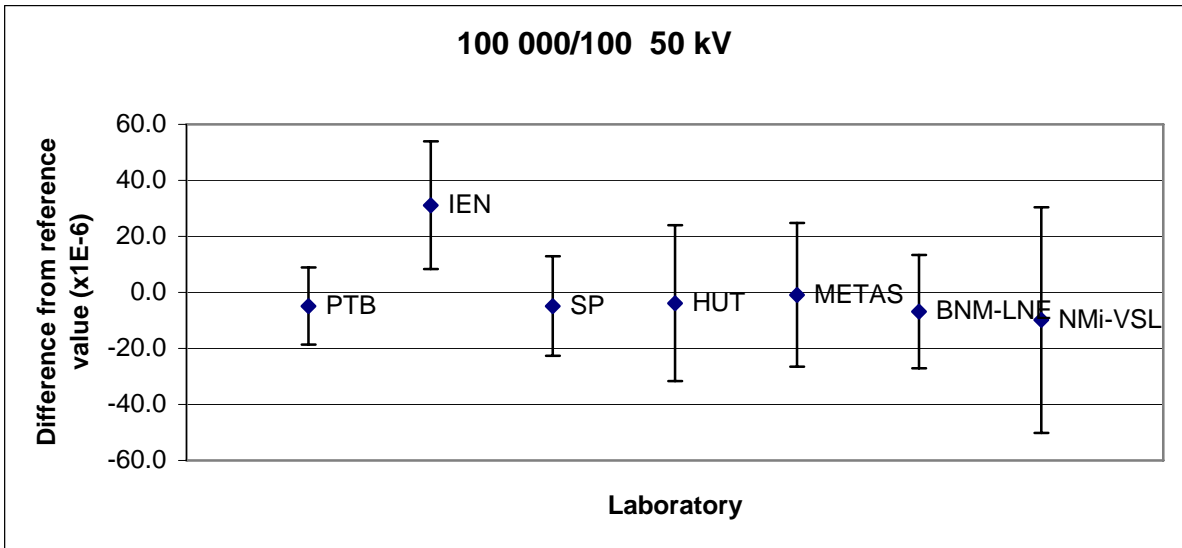


Figure 4.3.2 Difference from reference value ($\times 10^{-6}$) for Ratio 100 000/100 ratio at 50 kV

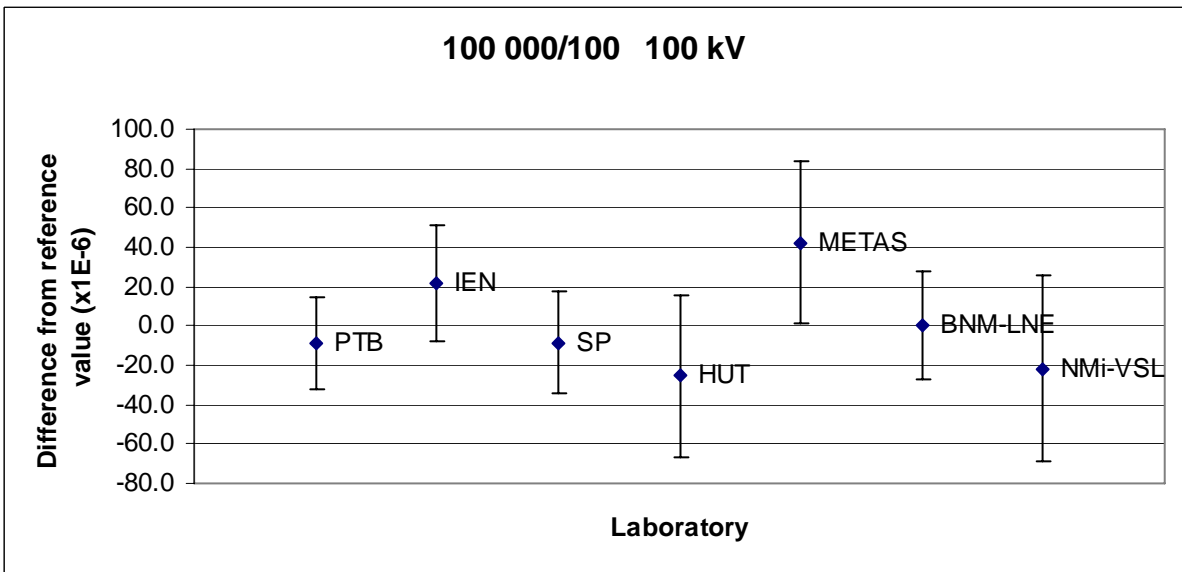


Figure 4.3.3 Difference from reference value ($\times 10^{-6}$) for Ratio 100 000/100 ratio at 100 kV

4.4 Ratio 100 000/100 at 1 kV

Ratio	100 000/100	
Applied voltage	1 kV	
Laboratory	SF	U
NPL1	999.989	0.010
PTB	1000.005	0.004
IEN		
NPL2	999.992	0.010
SP	1000.001	0.006
MIKES-HUT	999.999	0.019
NPL3	999.986	0.010
METAS	999.973	0.009
BNM-LNE (divider 2)	999.992	0.010
NMi/VSL	999.991	0.006
NPL4	999.995	0.010
Reference value	999.9931	0.0091

Table 4.4.1. Values of Scale Factor for Ratio 100 000/100 corrected to 20 °C

En values for ratio 100 000/100 at 1 kV	
Laboratory	En
NPL	-0.20
PTB	1.14
SP	0.71
MIKES-HUT	0.31
METAS	-1.61
BNM-LNE	-0.08
NMi-VSL	-0.19

Table 4.4.2 En values (95 % confidence) for Ratio 100 000/100

Ratio 100 000/100 Difference from reference value ($\times 10^{-6}$)		
Applied voltage	1 kV	
Laboratory	Difference	Expanded uncertainty
NPL	-2.6	13.0
PTB	11.9	10.5
SP	7.9	11.1
MIKES-HUT	5.9	18.8
METAS	-20.1	12.5
BNM-LNE	-1.1	13.1
NMi-VSL	-2.1	11.1

Table 4.4.3 Difference from reference value ($\times 10^{-6}$) for Ratio 100 00/100

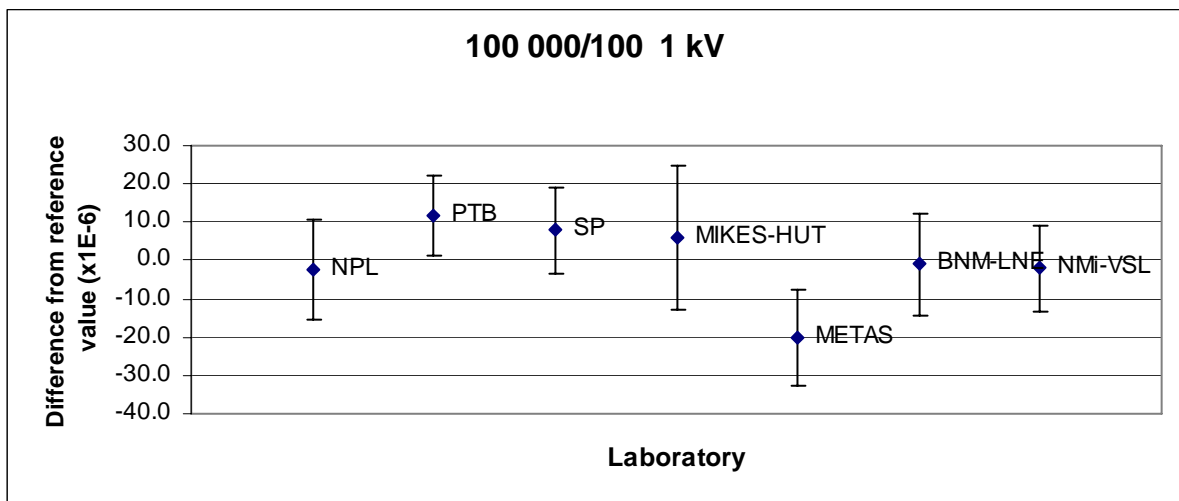


Figure 4.4.1 Difference from reference value ($\times 10^{-6}$) for 100 000/100 ratio at 1 kV

5. Discussion of results

In general the laboratories are in agreement within the expanded uncertainties quoted. The En ratios which were calculated by dividing the difference from the reference value by the expanded uncertainty associated with this difference, are with a few exceptions, less than 1. In some cases the uncertainty in the difference comes mainly from the uncertainty in the reference value. As this is calculated from equation 1, ie relative to the unweighted mean, it is a reflection of the scatter in the results from the various laboratories. It is not possible to differentiate between what might be due to variations in the value of the travelling standard and genuine variations in the results obtained by the participating laboratories.

For the results of measurements of ratio 100 000/100 at 1 kV it is noted that the variation in the results and the uncertainties quoted by the participants are considerably higher than for the EUROMET 449 comparison of dc voltage ratio. The latter comparison used a precision divider designed for such measurements whereas the travelling standard used in the present comparison 495 was designed as a high voltage divider and may not be as stable under the conditions encountered in transporting around Europe. The NPL measurements made during the comparison show a spread of 9 ppm. In addition the methods used in the present comparison were not aimed at the sub ppm uncertainties obtained in the 449 comparison.

6. Conclusions

The measurements by the various laboratories have a wide range of uncertainties. In general the measurements are in agreement with the reference value taking the uncertainties into account

7. References

- [1] A high voltage divider having an uncertainty of 5 ppm at 100 kV.
R B D Knight and P Martin, IEEE Trans. Instrum. Meas. 42 568-560 (1993).
- [2] Intercomparison measurement of the ratios of the ratios of a 100 kilovolt dc voltage divider.
T A Deacon, Commission of the European Communities BCR Applied Metrology Report EUR 10178 EN

Appendix 1 Optional 100 000/2 measurements

The results of the measurements on the optional ratio of 100 000/2 is described in this appendix

Ratio 100 000/2 (Optional)

Ratio	100 000:2					
	10 kV		50 kV		100 kV	
Applied voltage						
Laboratory	SF	u	SF	u	SF	u
IEN(75 kV)	50 001.35	0.6	50 001.35	0.5	50 001.5	0.5
NPL1	50 001.05	0.75	50 001.0	0.75	50 001.0	0.75
MIKES-HUT	50 002,05	1.4	50 002.1	1.4	50 002,01	2.15
NPL2	50 002.65	0.75	50 001.4	0.75	50 002.05	0.75
BNM-LNE (divider 1)	50 001.25	0.87	50 001.8	0.87	50 002.8	0.87
BNM-LNE (divider 2)	50 001.26	0.55	50 001.42	0.61	-	-
NPL3	50 001.70	0.75	50 001.3	0.75	50 001.65	0.75
Reference value	50 001.54	0.75	50 001.58	0.6	50 001.9	1.7

Table A2.1 Values of Scale Factor for 100 000/2. corrected to 20 °C

En value for 95 % confidence for Ratio 100 000/2			
Laboratory	10 kV	50 kV	100 kV
NPL	0.21	-0.37	-0.33
IEN	-0.31	-0.35	-0.39
MIKES-HUT	0.36	0.38	0.02
BNM-LNE	-0.38	0.17	0.64

Table A2.2 En values (95 % confidence) for Ratio 100 000/2

Ratio 100 000:2 Difference from reference value ($\times 10^{-6}$)						
Applied voltage	10 kV		50 kV		100 kV	
Laboratory	Difference	Expanded uncertainty	Difference	Expanded uncertainty	Difference	Expanded uncertainty
NPL	3.8	16	-7.7	18.0	-8.3	25.4
IEN	-5.2	15	-5.4	16.2	-9.3	24.1
MIKES-HUT	8.8	23	9.6	24.6	0.9	38.1
BNM-LNE (divider 1)	-7.2	18	3.6	19.1	16.7	26.1

Table A2.3 Difference from reference value ($\times 10^{-6}$) for Ratio 100 000/2

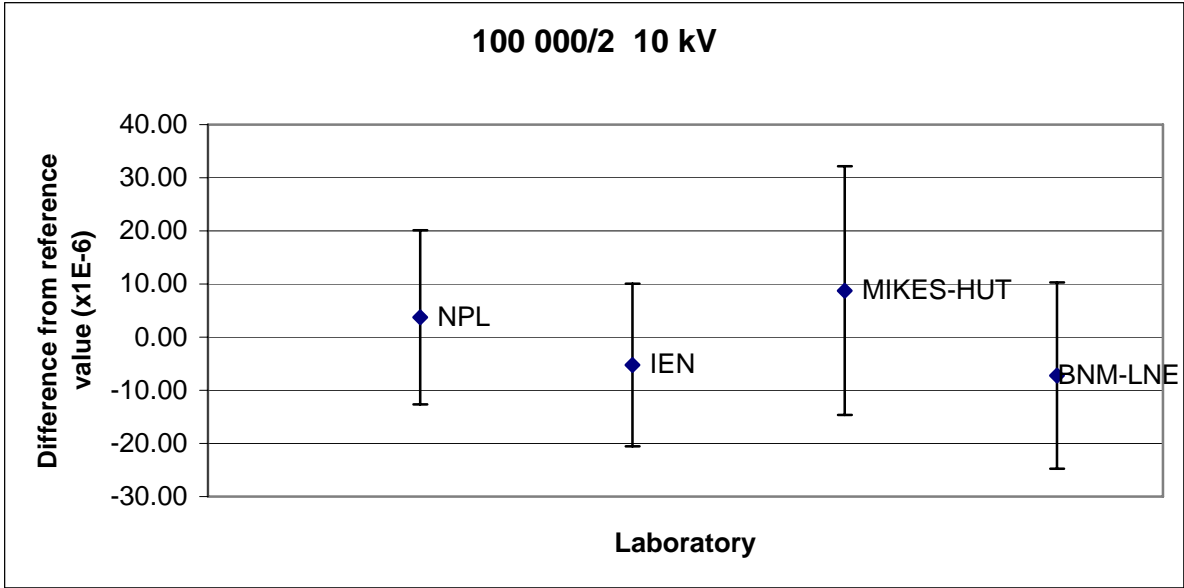


Figure A2.1 Difference from reference value ($\times 10^{-6}$) for 100 000/2 ratio at 10 kV

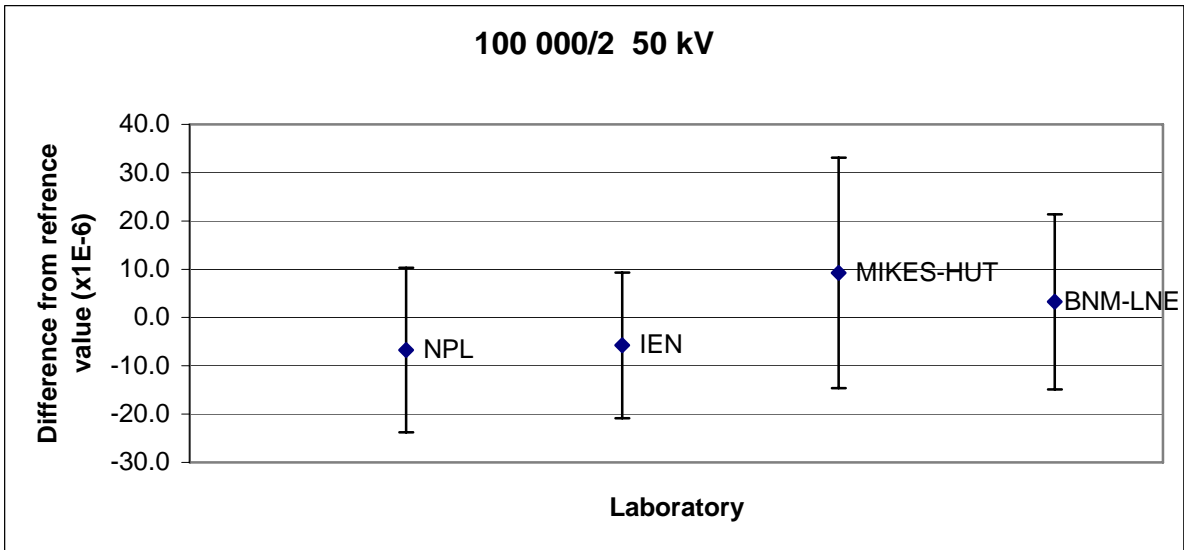


Figure A2.2 Difference from reference value ($\times 10^{-6}$) for 100 000/2 ratio at 50 kV

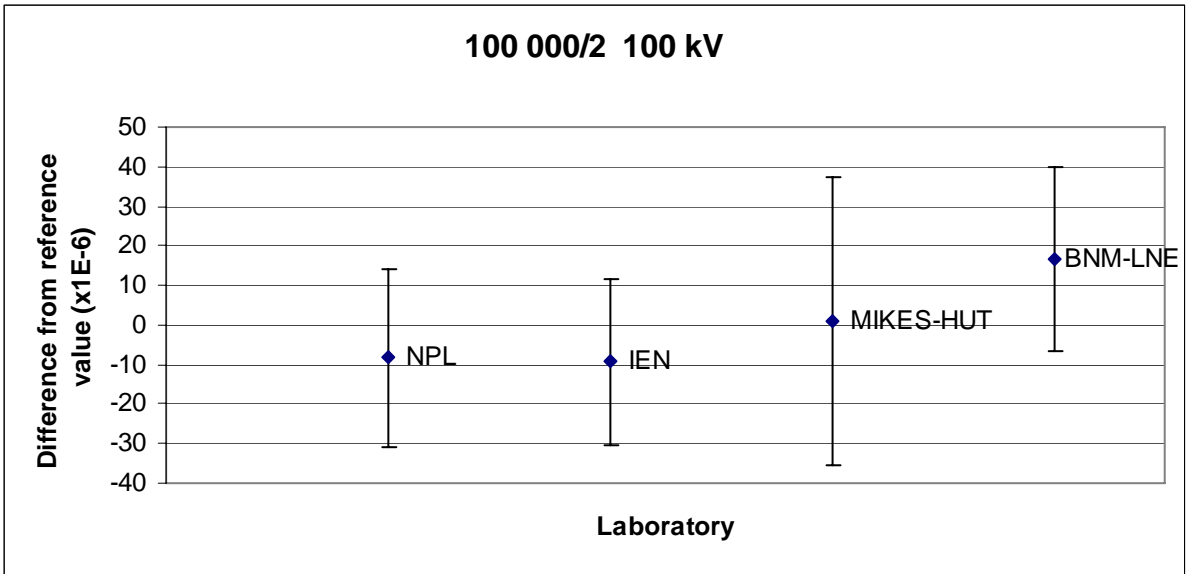


Figure A2.3 Difference from reference value ($\times 10^{-6}$) for 100 000/2 ratio at 100 kV

Appendix 2 Uncertainty tables

A3.1 NPL

<u>Calibration of Test High Voltage Dividers V < 100 kV</u>					
Source of Uncertainty	Reference	Value (ppm)	Probability Distribution	Divisor	Uncertainty (ppm)
Calibration of NPL standard divider	Calibration	5.9	normal	1.00	5.9
Linearity	Assessed	0.5	rectangular	1.73	0.3
Linearity	Assessed	0.5	rectangular	1.73	0.3
Noise	Assessed	0.3	rectangular	1.73	0.2
Noise	Assessed	0.3	rectangular	1.73	0.2
Quantisation	Assessed	0.2	rectangular	1.73	0.1
Quantisation	Assessed	0.2	rectangular	1.73	0.1
Loading (1 kΩ outputs)	Assessed	0.2	rectangular	1.73	0.1
Loading (1 kΩ outputs)	Assessed	0.2	rectangular	1.73	0.1
Relative error and scaling	Assessed	3.5	rectangular	1.73	2.0
Self heating of test divider	Assessed	3.5	rectangular	1.73	2.0
Temperature coefficient of test divider	Assessed	2.5	rectangular	1.73	1.4
Stability of NPL divider	Assessed	3.5	rectangular	1.73	2.0
Random measurements	Typical	2.0	normal	1.00	2.0
Combined standard uncertainty					7.3
Expanded uncertainty					14.6

<u>Calibration of Test Dividers at 1 kV</u>					
Source of Uncertainty	Reference	Value (ppm)	Probability Distribution	Divisor	Uncertainty (ppm)
Calibration of NPL standard low voltage divider	Calibration	3.5	normal	1.00	3.5
Comparison with test divider	Assessed	4	rectangular	1.73	2.3
Combined standard uncertainty					4.2
Expanded uncertainty					8.4

A3.2 PTB

Ratio	100 000:1			100 000:10			100 000:100		
	Standard uncertainty			Standard uncertainty			Standard uncertainty		
Applied Voltage	10kV	50kV	100kV	10kV	50kV	100kV	10kV	50kV	100kV
Contribution									
Uncertainty in standard	1.0	1.0	1.0	1.0	1.0	1.0	1	1	1
Ratio of voltage readings of two DVMs	2.0	1.0	0.5	0.3	0.7	0.6	1	0.5	0.8
Reading of DVM on standard	1.2	0.35	0.32	1.2	0.35	0.32	1.2	0.35	0.32
Reading of DVM on transfer standard	4.3	1.4	1.2	1.2	0.35	0.32	0.32	1.15	1.15
Effect of temperature on transfer standard	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Self heating of transfer standard	0.12	0.06	0.06	0.12	0.06	0.06	0.29	0.17	0.06
Combined standard uncertainty	5	2	1.8	2	1.4	1.3	1.9	1.7	1.8
Expanded uncertainty	10	4	4	4	3	3	4	4	4

Ratio	100 000/100
	Standard Uncertainty
Applied Voltage	1kV
Contribution	
Uncertainty in standard	0.5
Ratio of voltage readings of two DVMs	1.4
Reading of DVM on standard	0.32
Reading of DVM on transfer standard	0.87
Effect of temperature on transfer standard	0.35
Combined standard uncertainty	1.8
Expanded uncertainty	3.6

A3.3 IEN

Ratio	100 000:1			100 000:10			100 000:2		
	Standard uncertainty			Standard uncertainty			Standard uncertainty		
Applied Voltage	10kV	50kV	75kV	10kV	50kV	75kV	10kV	50kV	75kV
Contribution									
Uncertainty in standard	6.3	6.3	6.3	3.1	3.1	3.1	4.6	4.6	4.6
Calibration of DVM on standard	3	1.3	1.2	0.9	0.5	0.4	2	1.1	0.7
Calibration of DVM on transfer standard	3	1.3	1.2	0.9	0.5	0.4	2	1.1	0.7
Type A uncertainty in ratio of DVM readings	0.7	0.07	0.35	0.7	0.3	0.5	2.5	0.8	0.2
Combined standard uncertainty	7.8	6.6	6.6	3.5	3.2	3.2	6	4.9	4.7
Expanded uncertainty	16	14	14	7	6.5	6.5	13	10	10

Ratio	100 000:100		
	Standard uncertainty		
Applied Voltage	10kV	50kV	75kV
Contribution			
Uncertainty in standard	0.010	0.010	0.010
Uncertainty in differential voltage on high side	$3 \cdot 10^{-5}$	$3 \cdot 10^{-5}$	$3 \cdot 10^{-5}$
Uncertainty in differential voltage on low side	$1 \cdot 10^{-5}$	$1 \cdot 10^{-5}$	$1 \cdot 10^{-5}$
Uncertainty in output voltage of IEN divider	0.4	2	3
Type A uncertainty in ratio of DVM readings	$1.3 \cdot 10^{-3}$	$1.5 \cdot 10^{-3}$	$2.1 \cdot 10^{-3}$
Combined standard uncertainty	0.011	0.011	0.011
Expanded uncertainty	0.022	0.022	0.022

A3.4 SP

Ratio	100 000:1			100 000:10			100 000:100		
Contribution	Standard uncertainty			Standard uncertainty			Standard uncertainty		
Uncertainty in standard	5			5			5		
Stability of standard	2.3			2.3			2.3		
Temperature dependence of standard	0.58			0.58			0.58		
Calibration of DMM (100 000:1 at 10 kV)	3			3			3		
Calibration of DMM on DUT	2			2			2		
Calibration of DMM on Voltage reference	2			2			2		
Stability of DMM	2.3			2.3			2.3		
	10kV	50kV	100kV	10kV	50kV	100kV	10kV	50kV	100kV
Type A uncertainty	0.2	0.2	0.1	0.2	0.2	1.2	0.3	0.3	0.1
Combined Standard uncertainty									
Expanded Uncertainty	15	14	14	14	14	14	14	14	14

Ratio	100 000/100
Applied Voltage	1 kV
Contribution	Standard Uncertainty
Calibration of Datron 4708	1.5
Calibration of Datron 4000 A	1.5
Calibration of Datron 1281	1.5
Type A uncertainty	0.17
Combined Standard Uncertainty	2.6
Expanded Uncertainty	5.2

A3.5 MIKES-HUT

Uncertainty calculation for 40 kV

Quantity	Value	Standard uncertainty	Degrees of freedom	Sensitivity coefficient	Uncertainty contribution	Index
Ratio of voltmeter readings	19.8817917	$62.8 \cdot 10^{-6} \%$	5	5030	0.0628	0.2 %
Effect of different gains of voltmeters	1.0	$1.00 \cdot 10^{-3} \%$	50	100000	1.0	49.7 %
Scale factor of standard	5029.9950	$1.00 \cdot 10^{-3} \%$	50	19.9	1.0	49.7
Ambient temperature	23.1 °C	5.0 %	∞	0.06	0.0693	0.2 %
Temperature coefficient	$6.0 \cdot 10^{-7} / ^\circ\text{C}$	10.0 %	50	10000	$600 \cdot 10^{-6}$	0.0 %
Effect of self heating	$2.0 \cdot 10^{-6}$	28.9 %	∞	100000	0.0577	0.2 %
High voltage applied to divider	40.0 kV					
Voltage coefficient	0.0/kV	$5.0 \cdot 10^{-9} / \text{kV}$	50	$4.0 \cdot 10^{-6}$	0.02	0.0 %
Scale factor of travelling standard	1.00005.52	$1.42 \cdot 10^{-3} \%$	101			
Expanded uncertainty		$2.8 \cdot 10^{-3} \%$				

Uncertainty calculation for 100 kV

Quantity	Value	Standard uncertainty	Degrees of freedom	Sensitivity coefficient	Uncertainty contribution	Index
Ratio of voltmeter readings	5.0059932	$1.06 \cdot 10^{-3} \%$	5	20000	1.06	24.4 %
Effect of different gains of voltmeters	1.0	$1.00 \cdot 10^{-3} \%$	50	100000	1.0	21.9 %
Scale factor of standard	19981.800	$1.00 \cdot 10^{-3} \%$	50	5.0	1.0	21.9 %
Ambient temperature	23.1 °C	5.0 %	∞	0.06	0.0693	0.1 %
Temperature coefficient	$6.0 \cdot 10^{-7} / ^\circ\text{C}$	10.0 %	50	10000	$600 \cdot 10^{-6}$	0.0 %
Effect of self heating	$2.0 \cdot 10^{-6}$	28.9 %	∞	100000	0.0577	0.1 %
Voltage coefficient	$239.8 \cdot 10^{-6}$	5 %				
Linear term in voltage coefficient	0.745302/kV					
Voltage applied to divider	100 kV					
Quadratic term in voltage coefficient	$0.016526 / \text{kV}^2$					
Uncertainty for voltage non-linearity correction	1.0	5.0 %	50	-24.0	-1.20	31.5 %
Scale factor of travelling standard	1.00004.97	$2.14 \cdot 10^{-3} \%$				
Expanded uncertainty		$\pm 43 \cdot 10^{-6}$	63			

A3.6 METAS

Ratio	100 000:1			100 000:10			100 000:100		
	Standard uncertainty X 10			Standard uncertainty			Standard uncertainty		
Contribution	10kV	50kV	100kV	10kV	50kV	100kV	10kV	50kV	100kV
Reproducibility of voltage measurements	2.4	2.6	2.0	1.8	3.1	3.4	3.9	2.4	3.2
Calibration of DVM	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Input impedance of DVM on 100 V range							1.0	1.0	1.0
Value of standard divider	1.0	3.0	7.0	1.0	3.0	7.0	1.0	3.0	7.0
Corona effect	2.0	3.0	5.0	2.0	3.0	5.0	2.0	3.0	5.0
Temperature effects	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2	9.2
Reproducibility of resistance measurements	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8
Calibration of resistance bridge	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Temperature coefficient of reference divider	2.0	2.0	2.0	2.0	2.0	2.0	0.2	4.2	17
Power coefficient of reference divider	0.2	4.2	17	0.2	4.2	17	0.1	2.0	5.6
Combined standard uncertainty	11	13	22	11	13	22	12	13	22
k value	2.01	2.00	2.03	3.01	2.00	2.03	2.00	2.00	2.03
Expanded uncertainty	23	26	45	23	26	45	24	26	45

Ratio	100 000/100
Applied Voltage	1 kV
Contribution	Standard Uncertainty
Measurement reproducibility	0.1
DVM gain	0.5
Temperature	3.6
Temperature coefficient	2.0
Power coefficient	0.1
Combined Standard Uncertainty	4.2
Expanded Uncertainty	9

A3.7 BNM-LNE

Uncertainty parts	Uncertainty values (1σ)		Degrees of freedom
	<i>Divider1</i> (divider 250 kV)	<i>Divider2</i> (divider 50 kV)	
Type A uncertainty u_A (repeatability of measurements)	5.10^{-7} to $1,6.10^{-6}$	5.10^{-7} to 1.10^{-6}	4
• $u(R_{hvo})$: Calibration of R_{hv}	4.10^{-6}	$2,1.10^{-6}$	50
• $u(R_{lvo})$: Calibration of R_{lv}	6.10^{-7}	6.10^{-7}	50
• $u(\mathcal{E}_1)$: Temperature difference between calibration of R_{lv} and comparison measurements	$3,2.10^{-6}$	$3,1.10^{-6}$	> 40 for R_{hv1} > 1000 for R_{hv2}
• $u(\mathcal{E}_2)$: Self heating of high voltage arm R_{hv}	$2,8.10^{-6}$	5.10^{-7} to 3.10^{-6} depending on applied voltage	50
• $u(\mathcal{E}_3)$: Absorption current	$1,2.10^{-6}$	0	200
• u_1 : Knowledge of R_{lv} at the working temperature	$1,7.10^{-6}$	$1,7.10^{-6}$	∞
• u_2 : Self heating of R_{lv} during measurements	1.10^{-6} to 3.10^{-6} depending on ratio and applied voltage	1.10^{-6} to 3.10^{-6} depending on ratio and applied voltage	>50
• u_3 : Leakage currents of the high voltage arm	5.10^{-6}	2.10^{-6}	200
• u_4 : Corona effects	Negligible ($\leq 1.10^{-7}$)	Negligible ($\leq 1.10^{-7}$)	∞
• u_5 : Drift of R_{hv} since last calibration	1.10^{-6}	2.10^{-7}	≥ 200
• u_6 : Drift of R_{lv} since last calibration	Negligible ($\leq 1.10^{-7}$)	Negligible ($\leq 1.10^{-7}$)	≥ 200
Uncertainty due to the imperfection of the BNM-LNE standard divider (at the most)	$8,5.10^{-6}$	$5,7.10^{-6}$	≥ 150 for R_{hv1} ≥ 450 for R_{hv2}
• u_7 : Imperfection of the null detector	1.10^{-6}	1.10^{-6}	200
• u_8 : Sensitivity of the bridge set-up	4.10^{-7} to 1.10^{-6} depending on ratio and applied voltage	4.10^{-7} to 1.10^{-6} depending on ratio and applied voltage	> 200
• u_9 : Null detector resolution	2.10^{-7}	2.10^{-7}	∞
• u_{10} : Residual electromotive forces	$\leq 1.10^{-6}$	$\leq 1.10^{-6}$	> 50
• u_{11} : Leakage current in the measuring cables	Negligible ($\leq 1.10^{-7}$)	Negligible ($\leq 1.10^{-7}$)	> 50
• u_{12} : Electromagnetic perturbations	5.10^{-7}	5.10^{-7}	∞
Uncertainty due to the imperfection of the calibration set-up (at the most)	$1,7.10^{-6}$	$1,7.10^{-6}$	≥ 280
1σ Combined uncertainty	$\approx 9.10^{-6}$ (10 to 100 kV)	$5,1.10^{-6}$ (at 1 kV) $5,4.10^{-6}$ (at 10 kV) $6,1.10^{-6}$ (at 50 kV)	≥ 350 for both divider

Expanded uncertainty with a coverage factor $k=2$	$\approx 18.10^{-6}$	$\approx 10.10^{-6}$ (at 1 kV) $\approx 12.10^{-6}$ (at 50 kV)
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A3.8 NMi/VSL

Ratio	100 000:1			100 000:10			100 000:100		
	Standard uncertainty			Standard uncertainty			Standard uncertainty		
Contribution	10kV	50kV	100kV	10kV	50kV	100kV	10kV	50kV	100kV
Uncertainty in standard	21.8	22.3	24.0	21.8	22.3	24.0	21.8	22.3	24.0
Calibration of DVM on standard	1	1	1	1	1	1	1	1	1
Calibration of DVM on transfer standard	2.5	1.5	1						
Calibration of calibrator				1	1	1	1	1.5	2.5
Null detector uncertainty				0.3	0.3	0.3	0.25	0.25	0.25
Type A uncertainty in ratio of DVM readings	3.1	5.1	5.5	6.8	4.1	5.3	3.5	2.3	5.3
Combined standard uncertainty	22.2	23.0	24.6	22.9	22.8	24.6	22.1	22.5	24.7
Expanded uncertainty	44.4	46.0	49.3	45.8	45.5	49.2	44.3	45.1	49.4

100 000/1 ratio at 1 kV	
Contribution	Standard uncertainty x 10 ⁻⁶
Calibration of 1 kV source	2.5
Calibration of DVM on DUT	
Calibration of calibrator used to null DUT output	1.5
Null detector uncertainty	.25
Type A uncertainty	.18
Combined type A uncertainty	2.9
Expanded uncertainty	5.9

Appendix 3. Comparison Protocol

Comparison of Voltage measurement at DC voltages up to 100 kV EUROMET PROJECT

Instructions for participants

1. OBJECTIVES

The purpose of the comparison is to compare the reference standards and measurement techniques of the participants in the area of high voltages up to 100 kV

2. TRANSFER STANDARD

The transfer standard is a resistive divider provided by NPL. It is contained in a packing case and will be conveyed by courier from NPL to each participant in turn. NPL will arrange for a courier to collect the standard from each participant and return it to NPL.

The output impedance of the divider at the various ratios is given below. The input impedance is 1 G Ω

3. MEASUREMENTS

The measurements to be made are as given below

1. Measurements of the scale factor

(IEC 60060-2, High-voltage test techniques, clause 3.5.2)

“The scale factor is the factor by which the output of the converting device is to be multiplied to obtain the value of the input quantity.”

100 000/1

100 000/10

100 000/100

at voltages of 10 kV, 50 kV and 100 kV.

The divider has another ratio of 100 000/2 which can be measured as an optional ratio.

2. Measurement at 1000 V on 100 000/100 ratio. This voltage can be obtained from a calibrator.

At least 5 measurements should be made at each voltage and ratio

Because of the effect of self heating the measurements should be made at a known time after applying the voltage.

Measurements have shown that the time required for the transfer standard to reach equilibrium at the various voltages is (VALUE TO BE SUPPLIED BY NPL)

Participants are asked to follow their usual measurement procedure. The suggested ambient temperature is 20°C. The calibrations at NPL are usually done at 20°C but if a laboratory wishes to make a measurement at another temperature then NPL can also make measurements to check if there is any variation in the ratio values with temperature.

4. REPORT AND ANALYSIS OF RESULTS

Following the EUROMET guidelines it is requested that the report contain

4.1 the results of the measurements

4.2 the combined uncertainty with a coverage factor $k=2$

4.3 the number of degrees of freedom

4.4 a complete uncertainty budget indicating the uncertainty of the laboratory reference standard and the uncertainty in comparing the traveling standard with the laboratory standard.

5. SCHEDULE

5.1 NPL

5.2 LAB 1

5.3 NPL

5.4 LAB 2

5.5 LAB 3

5.6 NPL

5.7 LAB 4

5.8 NPL

6. REPORT

NPL will collate the results and write the report.

Appendix 4. Names and addresses of participants

Full list of names and addresses of participants

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Appendix 5. Results compared using weighted mean calculation of reference value

In the original report the reference value is calculated using an arithmetic mean. In this appendix the results are recalculated with the reference value determined as the weighted mean of the values given by the participants. The results are calculated in two ways.

- a) using the weighted mean [1] of the values given by **all** the participants
- b) using the method developed by Cox [2] of determining the Largest Consistent Subset (LCS). This means that in some cases one or two of the values are excluded as not being consistent with the remainder. In four cases out of 13 one of the values is excluded and in one case two values are excluded.

The results of the comparison are given in two ways:

1. The Scale Factors are given after correcting all values to a common temperature of 20 °C. Values are given of Scale Factor (SF) and the expanded uncertainty U (at the 95 % level of confidence). The expanded uncertainties for the Scale Factor values are given as absolute values.
2. The results are also presented as tables and graphs of difference from the reference value. The reference value as weighted mean and the standard deviation of this mean are calculated as indicated below where x_i is the value and u_i is the associated standard uncertainty.

$$\text{Weighted mean} = \frac{\sum_1^n (x_i / u_i^2)}{\sum_1^n 1 / u_i^2}$$

$$\text{Standard deviation of weighted mean} = \frac{1}{\sum_1^n 1 / u_i^2}$$

Tables of the En value for a 95 % coverage interval are also given where

En = ((difference from reference value)/(uncertainty of the difference for a coverage probability of 95 %))

For measured values that were not excluded from the determination of the reference value the uncertainty of the difference of a value from the reference value is calculated from the equation given below

$$u^2(\text{difference}) = u^2(\text{value}) - u^2(\text{reference value})$$

This equation (equation (5) in ref. [1]) takes into account the correlation between the reference value and the individual value resulting from the reference value being formed from the measured values.

For measured values that were excluded from the determination of the reference value, the uncertainty of the difference of a value from the reference value is calculated from

$$u^2(\text{difference}) = u^2(\text{value}) + u^2(\text{reference value})$$

The plus sign in this expression (rather than a minus sign in that above) is a consequence of the reference value being independent of the measured value.

In each case an assessment has been made of the Largest Consistent Subset (LCS) [2]. This method excludes from the weighted mean values that are not statistically consistent with the body of the results. In most cases (eight from 13) all the values are included in the LCS. In the cases where some values are excluded, these are indicated in the tables in bold font. In the tables of Scale Factor both the reference values are given, i.e. that calculated using all values and that using the LCS. In the "En" and "Difference from reference value" tables values are also given for both cases. Only the LCS results are used in the figures. The results for all measured values are visually indistinguishable from these.

The largest consistent subset

Consider the circulation of a stable travelling standard around the national measurement institutes (NMIs) participating in a key comparison. Consider the set of data consisting of a measurement result, comprising a measured value and the associated standard uncertainty, provided by each such NMI. Each measurement result is the corresponding NMI's best estimate of the value of a stipulated property of the standard. Consider the case where these results have been obtained independently. The weighted mean (WM) of these measurement results can be formed, the weights being inversely proportional to the squared standard uncertainties.

If this WM is consistent with the measurement results according to a chi-squared measure, it can be accepted as a key comparison reference value (KCRV) for the comparison. Otherwise, as an alternative, a largest consistent subset (LCS) of the measurement results, i.e., a subset of the measurement results from the complete set that corresponds to as many participating NMIs as possible and that is consistent with the WM of the subset, can be determined. This subset is not in general equal to that which would be obtained by successively excluding the most discrepant measurement result. Reference [2] in this appendix describes an efficient approach, based on the properties of the chi-squared function, for determining the LCS having smallest chi-squared value, and applies it to measurement results from several key comparisons.

The results for 100 000/100

The results for 100 000/100 deserve comment.

For 10 kV and 100 kV, the values provided by IEN are inconsistent according to a chi-squared measure with those of the other participants. However, for 50 kV, the complete set of measured values are statistically consistent, even though the *En* value for IEN of 1.61 lies outside the interval -1 to 1 . (The *En* values for IEN for 10 kV and 100 kV were 1.31 and 1.32, respectively.) The reason for this apparent anomaly is that all the other measured values for the 50 kV comparison are sufficiently close to the reference value that statistically the measured values, *as a set*, including that of IEN, are consistent. This occurrence is unusual and has happened by chance. If the other measured values had departed just a little more from the reference value, but were still consistent with it, the IEN value would have been identified as discrepant.

The fact that all three IEN values for 100 000/100 exceed unity is a strong indication that its measuring system “reads high” (taking its declared uncertainties into account).

Acknowledgment

The results contained in this appendix were provided by Maurice Cox, NPL, based on the determination of the weighted mean [1] and the largest consistent subset [2]

- [1] M. G. Cox. The evaluation of key comparison data. *Metrologia*, **39**:589–595, 2002.
- [2] M. G. Cox, The evaluation of key comparison data: determining the largest consistent subset, *Proceedings of International Workshop on Key Comparison Data Evaluation*, Tsukuba, Japan, 16 May 2005. Paper in preparation for submission to *Metrologia*.

A5.1 Ratio 100 000/1

Ratio	100 000/1					
	10 kV		50 kV		100 kV	
Applied voltage						
Laboratory	SF	U	SF	U	SF	U
NPL1	100 005.0	1.5	100 004.2	1.5	100 004.4	1.5
PTB	100 002.9	1.0	100 004.0	0.4	100 004.9	0.4
IEN(75kV)	100 003.2	1.6	100 003.3	1.4	100 003.5	1.4
NPL2	100 005.2	1.5	100 001.7	1.5	100 002.0	1.5
SP	100 003.2	1.5	100 004.3	1.4	100 004.6	1.4
MIKES-HUT	100 004.8	2.8	100 004.8	2.8	100 004.2	4.3
NPL3	100 003.0	1.5	100 003.4	1.5	100 004.0	1.5
METAS	100 003.1	2.3	100 005.4	2.6	100 010.1	4.5
BNM-LNE (divider 1)	100 003.1	1.75	100 003.9	1.75	100 006.0	1.75
BNM-LNE (divider 2)	100 002.9	1.1	100 003.9	1.2	-	-
NMi-VSL	100 006.7	4.44	100 005.9	4.60	100 004.4	4.93
NPL4	100 005.1	1.5	100 002.8	1.5	100 003.8	1.5
Reference value (All values)	100 003.42	0.29	100 003.97	0.17	100 004.79	0.17
Reference value (LCS)					100 004.76	0.18

Table A5.1.1. Values of Scale Factor for Ratio 100 000/1. corrected to 20 °C

En values for 95 % confidence for Ratio 100 000/1					
Laboratory	10 kV	50 kV	100 kV		
			All values	LCS	
NPL	0.84	-0.65	-0.85	-0.83	
PTB	-0.64	0.15	0.55	0.73	
IEN	-0.15	-0.49	-0.95	-0.93	
SP	-0.16	0.24	-0.14	-0.12	
MIKES-HUT	0.50	0.30	-0.14	-0.13	
METAS	-0.14	0.59	1.18	1.18	
BNM-LNE	-0.19	-0.04	0.73	0.75	
NMi-VSL	0.75	0.42	-0.08	-0.07	

Table A5.1.2 En values (95% confidence) for Ratio 100 000/1

Ratio 100 000/1 Difference from reference value ($\times 10^{-6}$)								
Laboratory	10 kV		50 kV		100 kV			
	Difference	Expanded uncertainty	Difference	Expanded uncertainty	All values		LCS	
					Difference	Expanded uncertainty	Difference	Expanded uncertainty
NPL	11.6	13.8	-9.4	14.6	-12.4	14.6	-12.1	14.6
PTB	-5.2	8.1	0.3	2.0	1.1	2.0	1.4	1.9
IEN	-2.2	14.9	-6.7	13.6	-12.9	13.6	-12.6	13.6
SP	-2.2	13.8	3.3	13.6	-1.9	13.6	-1.6	13.6
MIKES-HUT	13.8	27.4	8.3	27.8	-5.9	42.9	-5.6	42.9
METAS	-3.2	22.3	15.3	25.8	53.1	44.9	53.4	45.1
BNM-LNE	-3.2	17.0	-0.7	16.6	12.1	16.6	12.4	16.6
NMi-VSL	32.8	44.0	19.3	45.9	-3.9	49.1	-3.6	49.1

Table A5.1.3 Difference from reference value ($\times 10^{-6}$) and 95% coverage interval values for Ratio 100 000/1

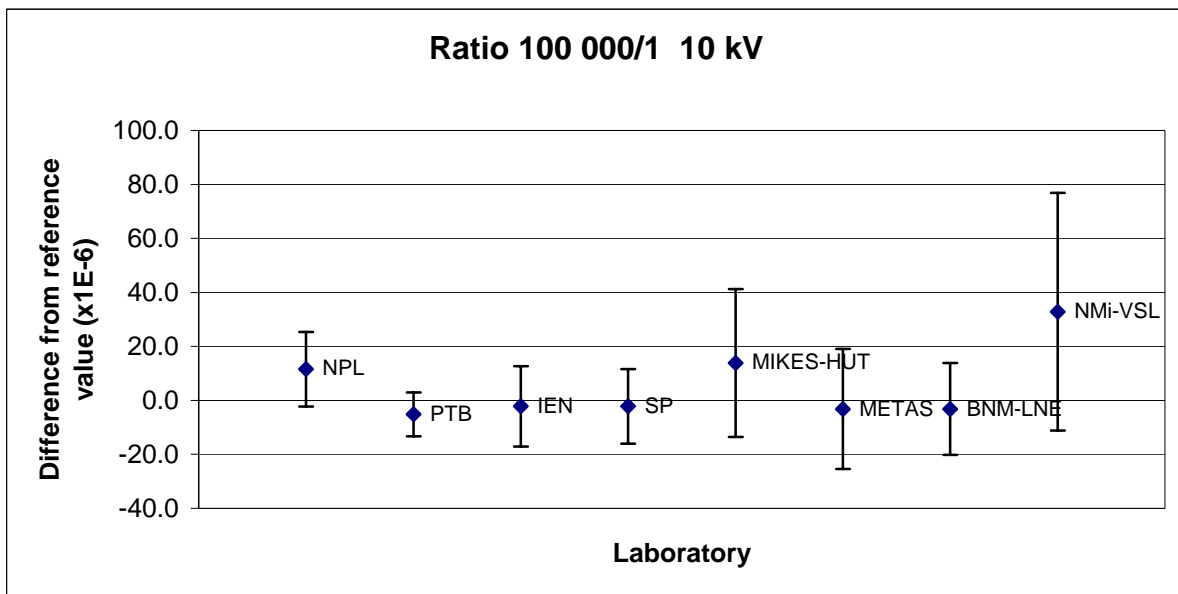


Figure A5.1.1 Difference from reference value ($\times 10^{-6}$) and 95% coverage interval values for Ratio 100 000/1 at 10 kV

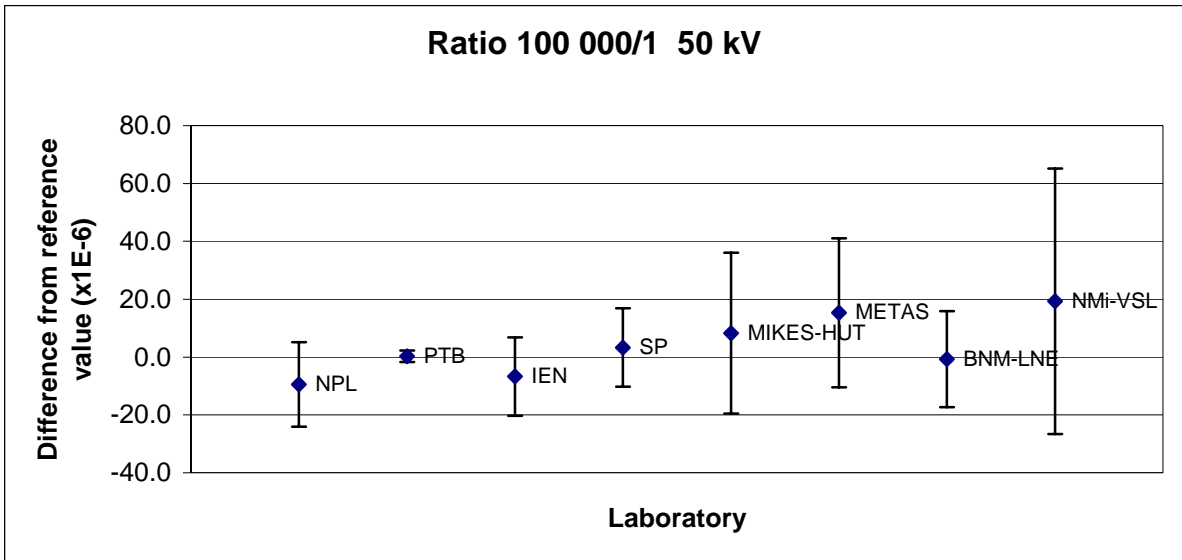


Figure A5.1.2 Difference from reference value ($\times 10^{-6}$) and 95% coverage interval values for Ratio 100 000/1 at 50 kV

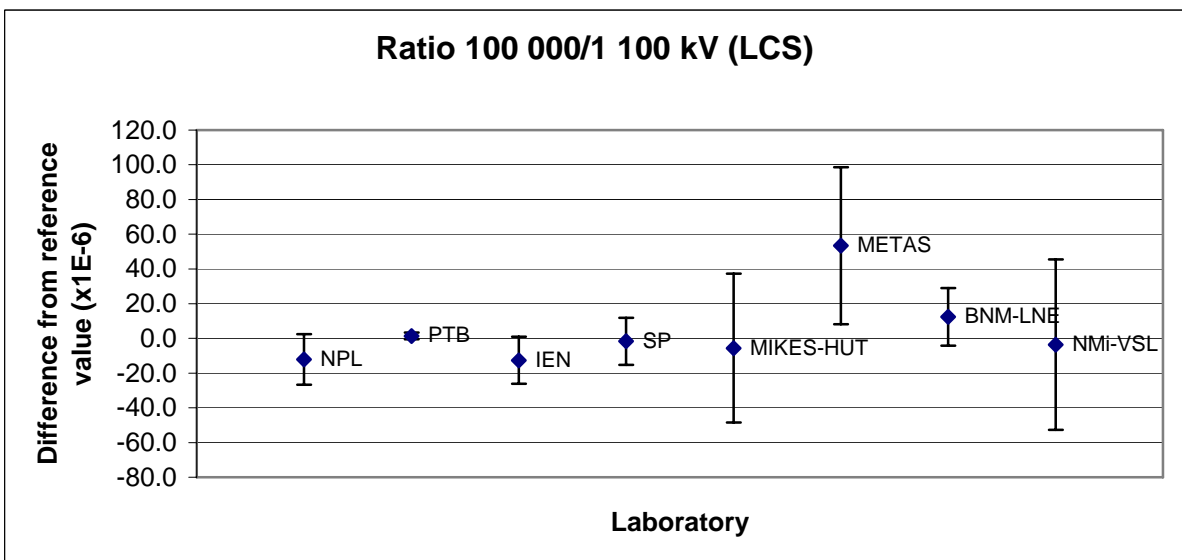


Figure A5.1.3 Difference from reference value ($\times 10^{-6}$) and 95% coverage interval values for Ratio 100 000/1 at 100 kV

A5.2 Ratio 100 000/10

Ratio	100 000/10					
	10 kV		50 kV		100 kV	
Laboratory	SF	U	SF	U	SF	U
NPL1	10 000.39	0.15	10 000.26	0.15	10 000.28	0.15
PTB	10 000.19	0.04	10 000.25	0.03	10 000.31	0.03
IEN(75 kV)	10 000.18	0.07	10 000.20	0.065	10 000.24	0.065
NPL2	10 000.38	0.15	10 000.37	0.15	10 000.31	0.15
SP	10 000.32	0.14	10 000.32	0.14	10 000.38	0.14
MIKES-HUT	10 000.35	0.28	10 000.35	0.28	10 000.40	0.41
NPL3	10 000.29	0.15	10 000.35	0.15	10 000.42	0.15
METAS	10 000.28	0.23	10 000.48	0.26	10 000.95	0.45
BNM-LNE (divider 1)	10 000.17	0.174	10.000.28	0.174	10 000.46	0.174
BNM-LNE (divider 2)	10 000.13	0.11	10 000.18	0.12	-	-
NMi/VSL	10 000.38	0.458	10 000.35	0.455	10 000.24	0.492
NPL4	10 000.14	0.15	10 000.18	0.15	10 000.27	0.15
Reference value (All values)	10 000.20	0.02	10 000.25	0.01	10 000.307	0.013
Reference value (LCS)					10 000.305	0.013

Table A5.2.1. Values of Scale Factor for Ratio 100 000/10. corrected to 20 °C

En value for 95 % confidence for Ratio 100 000/10					
Laboratory	10 kV	50 kV	100 kV		
			All values	LCS	
NPL	0.66	0.27	0.09	0.10	
PTB	-0.55	0.01	0.17	0.32	
IEN	-0.38	-0.83	-1.13	-1.09	
SP	0.85	0.51	0.53	0.54	
MIKES-HUT	0.53	0.36	0.23	0.23	
METAS	0.34	0.89	1.43	1.43	
BNM-LNE	-0.20	0.18	0.91	0.92	
NMi-VSL	0.39	0.22	-0.14	-0.13	

Table A5.2.2 En values (95 % confidence) for Ratio 100 000/10

		Ratio 100 000/10 Difference from reference value ($\times 10^{-6}$)						
Laboratory	10 kV		50 kV		100 kV			
	Difference	Expanded uncertainty	Difference	Expanded uncertainty	All values		LCS	
					Difference	Expanded uncertainty	Difference	Expanded uncertainty
NPL	9.7	14.7	4.0	14.8	1.3	14.8	1.5	14.8
PTB	-1.4	2.4	0.0	1.5	0.3	1.5	0.5	1.5
IEN	-2.4	6.2	-5.0	6.0	-6.7	6.0	-6.5	6.0
SP	11.7	13.6	7.0	13.8	7.3	13.8	7.5	13.8
MIKES-HUT	14.7	27.8	10.0	27.9	9.3	40.9	9.5	40.9
METAS	7.7	22.8	23.0	25.9	64.3	44.9	64.5	45.1
BNM-LNE	-3.4	16.7	3.0	16.8	15.3	16.8	15.5	16.8
NMi-VSL	17.7	45.7	10.0	45.4	-6.7	49.1	-6.5	49.1

Table A5.2.3 Difference from reference value ($\times 10^{-6}$) and 95% coverage interval values for Ratio 100 000/10

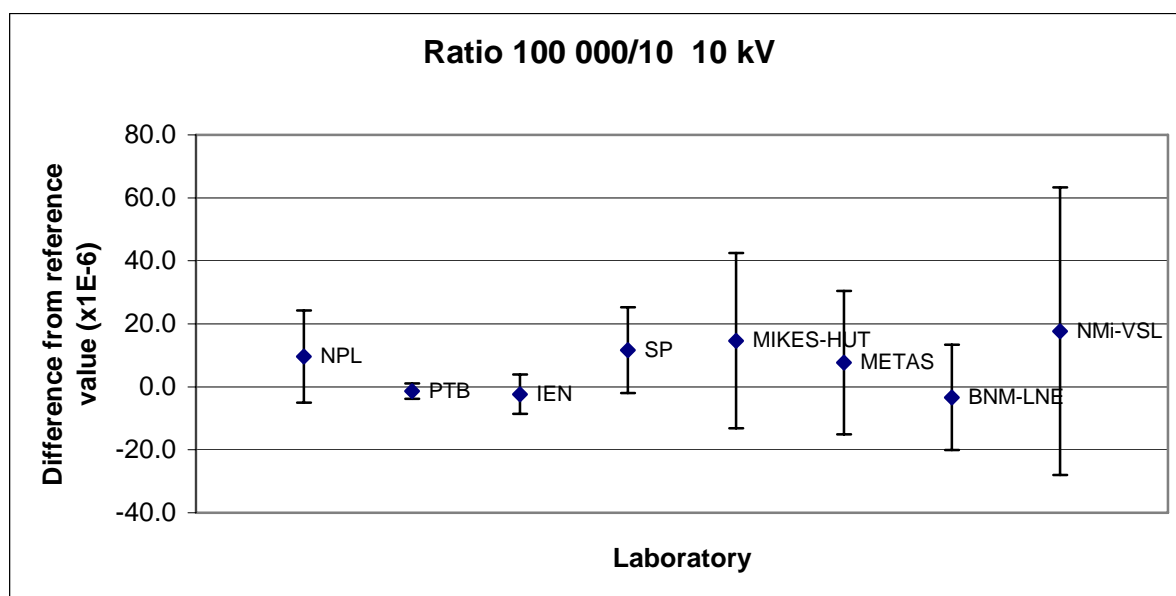


Figure A5.2.1 Difference from reference value ($\times 10^{-6}$) and 95% coverage interval values for Ratio 100 000/10 at 10 kV

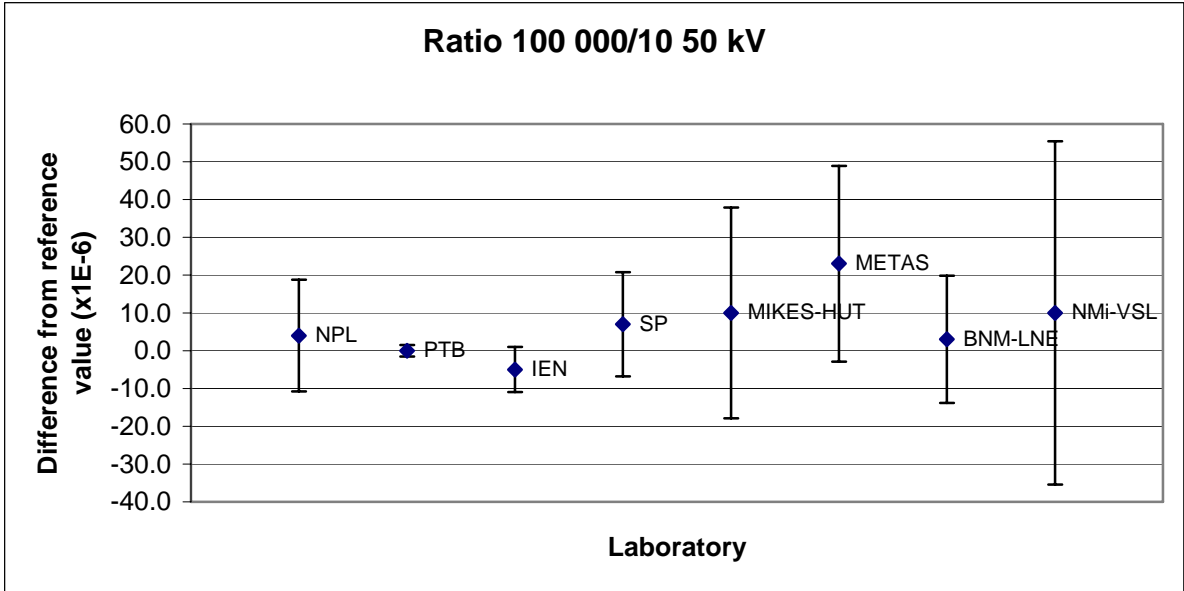


Figure A5.2.2 Difference from reference value ($\times 10^{-6}$) and 95% coverage interval values for Ratio 100 000/10 at 50 kV

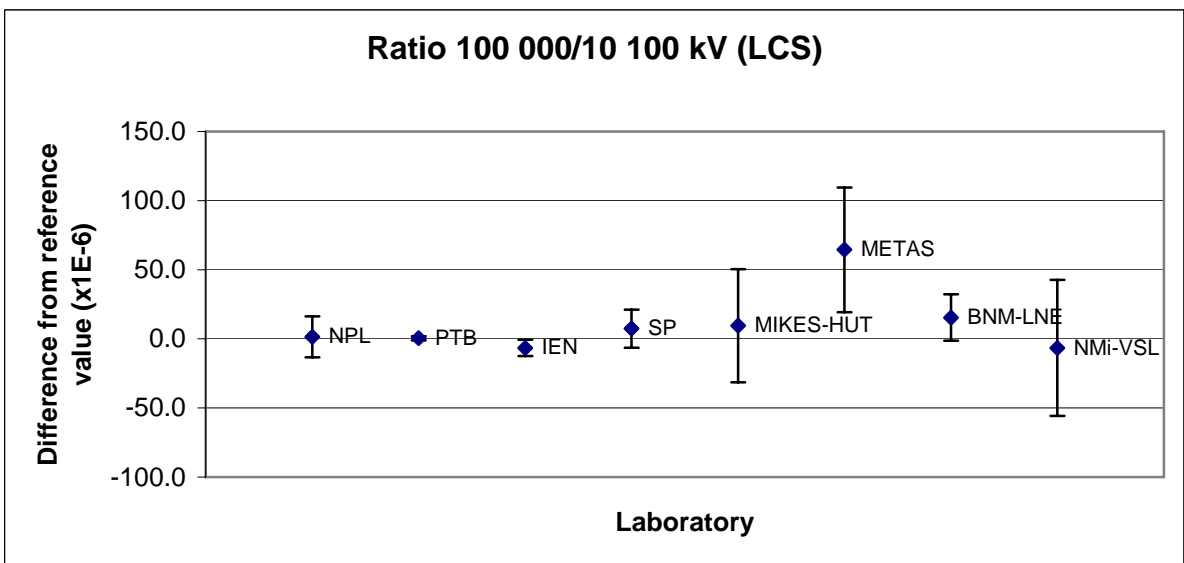


Figure A5.2.3 Difference from reference value ($\times 10^{-6}$) and 95% coverage interval values for Ratio 100 000/10 at 100 kV

A5.3 Ratio 100 000/100

Ratio	100 000/100					
	10 kV		50 kV		100 kV	
Laboratory	SF	U	SF	U	SF	U
NPL1	999.983	0.015				
PTB	1000.002	0.004	1000.005	0.007	1000.014	0.004
IEN(75 kV)	1000.031	0.022	1000.041	0.022	1000.044	0.022
NPL2	999.997	0.015				
SP	1000.018	0.022	1000.005	0.014	1000.014	0.014
MIKES-HUT	1000.009	0.017	1000.006	0.029	999.997	0.040
NPL3	999.987	0.015				
METAS	999.988	0.024	1000.009	0.026	1000.065	0.045
BNM-LNE (divider 1)	999.992	0.018	1000.003	0.018	1000.023	0.017
BNM-LNE (divider 2)	999.991	0.011	999.995	0.012	-	-
NMi/VSL	1000.012	0.017	1000.000	0.045	1000.001	0.049
Reference value (All values)	1000.00253	0.00176	1000.006	0.0018	1000.0154	0.00183
Reference value (LCS)	1000 00178	0.00178			1000 0146	0.00186

Table A5.3.1. Values of Scale Factor for Ratio 100 000/100. corrected to 20 °C

En values for 95 % confidence for Ratio 100 000/100						
Laboratory	10 kV		50 kV	100 kV		
	All Values	LCS		All values	LCS	
NPL	-0.93	-0.88				
PTB	-0.28	0.12	-0.57	-0.85	-0.37	
IEN	1.31	1.31	1.61	1.32	1.32	
SP	1.14	1.20	-0.07	-0.10	-0.04	
MIKES-HUT	0.23	0.26	0.00	-0.46	-0.44	
METAS	-0.61	-0.58	0.12	1.11	1.13	
BNM-LNE	-0.60	-0.55	-0.17	0.46	0.51	
NMi-VSL	0.21	0.23	-0.13	-0.29	-0.28	

Table A5.3.2 En values (95 % confidence) for Ratio 100 000/100

Ratio 100 000/100 Difference from reference value ($\times 10^{-6}$)										
Laboratory	10 kV				50 kV		100 kV			
	Difference		Expanded uncertainty		Difference	Expanded uncertainty	Difference		Expanded uncertainty	
	All values	LCS	All values	LCS			All values	LCS	All values	LCS
NPL	-13.5	-12.8	14.6	14.6						
PTB	-0.5	0.2	1.9	1.8	-1.0	1.7	-1.4	-0.6	1.6	1.5
IEN	28.5	29.2	21.7	22.3	35.0	21.7	28.6	29.4	21.7	22.3
SP	15.5	16.2	13.6	13.5	-1.0	13.5	-1.4	-0.6	13.5	13.5
MIKES-HUT	6.5	7.2	27.8	27.8	0.0	28.8	-18.4	-17.6	39.8	39.8
METAS	-14.5	-13.8	23.7	23.7	3.0	25.7	49.6	50.4	44.9	44.8
BNM-LNE	-10.5	-9.8	17.7	17.6	-3.0	17.6	7.6	8.4	16.6	16.6
NMi-VSL	9.5	10.2	44.2	44.2	-6.0	45.0	-14.4	-13.6	49.3	49.3

Table A5.3.3 Difference from reference value ($\times 10^{-6}$) and 95% coverage interval values for Ratio 100 000/100 (LCS)

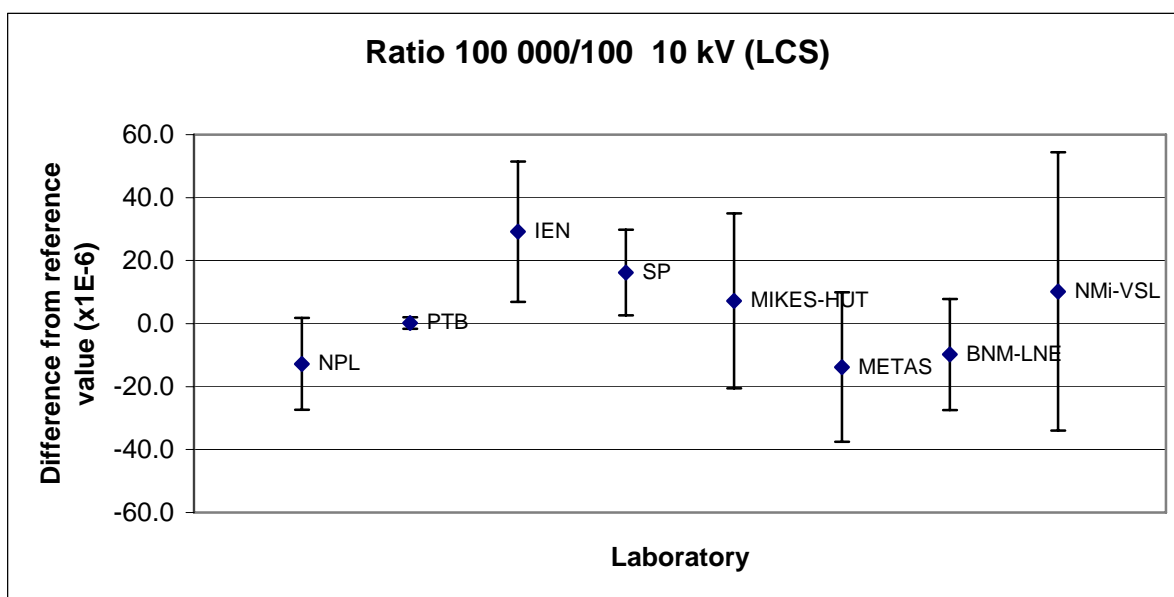


Figure A5.3.1 Difference from reference value ($\times 10^{-6}$) and 95% coverage interval values for Ratio 100 000/100 ratio at 10 kV

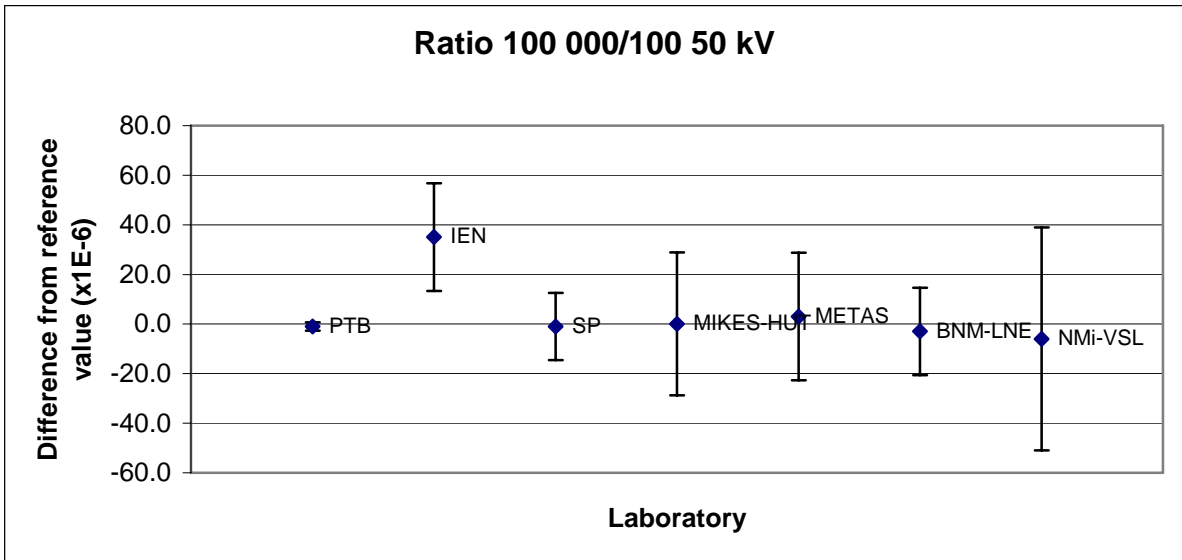


Figure A5.3.2 Difference from reference value ($\times 10^{-6}$) and 95% coverage interval values for Ratio 100 000/100 ratio at 50 kV

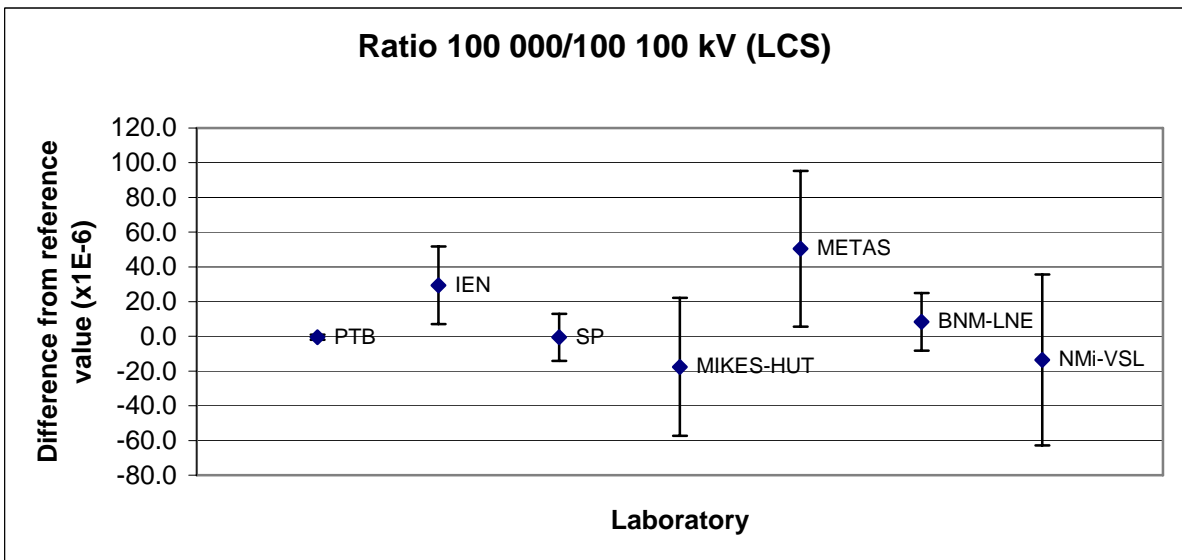


Figure A5.3.3 Difference from reference value ($\times 10^{-6}$) and 95% coverage interval values for Ratio 100 000/100 ratio at 100 kV

A5.4 Ratio 100 000/100 at 1 kV

Ratio	100 000/100	
Applied voltage	1 kV	
Laboratory	SF	U
NPL1	999.989	0.010
PTB	1000.005	0.004
IEN		
NPL2	999.992	0.010
SP	1000.001	0.006
MIKES-HUT	999.999	0.019
NPL3	999.986	0.010
METAS	999.973	0.009
BNM-LNE (divider 2)	999.992	0.010
NMi/VSL	999.991	0.006
NPL4	999.995	0.010
Reference value (All values)	999.99723	0.000128
Reference value (LCS)	999.99486	0.000178

Table A5.4.1. Values of Scale Factor for Ratio 100 000/100 corrected to 20 °C

En values for ratio 100 000/100 at 1 kV		
Laboratory	En	
	All values	LCS
NPL	-0.70	-0.47
PTB	2.52	1.89
SP	0.70	1.27
MIKES-HUT	0.09	0.22
METAS	-2.81	-2.26
BNM-LNE	-0.53	-0.30
NMi-VSL	-1.17	-0.82

Table A5.4.2 En values (95 % confidence) for Ratio 100 000/100

Ratio 100 000/100 Difference from reference value ($\times 10^{-6}$)				
Applied voltage	1 kV			
Laboratory	Difference		Expanded uncertainty	
	All values	LCS	All values	LCS
NPL	-6.7	-4.4	9.7	9.3
PTB	7.8	10.1	3.1	5.4
SP	3.8	6.1	4.4	4.8
MIKES-HUT	1.8	4.1	18.8	18.7
METAS	-24.2	-21.9	8.6	9.7
BNM-LNE	-5.2	-2.9	9.9	9.6
NMi-VSL	-6.2	-3.9	5.3	4.7

Table A5.4.3 Difference from reference value ($\times 10^{-6}$) and 95% coverage interval values for Ratio 100 00/100

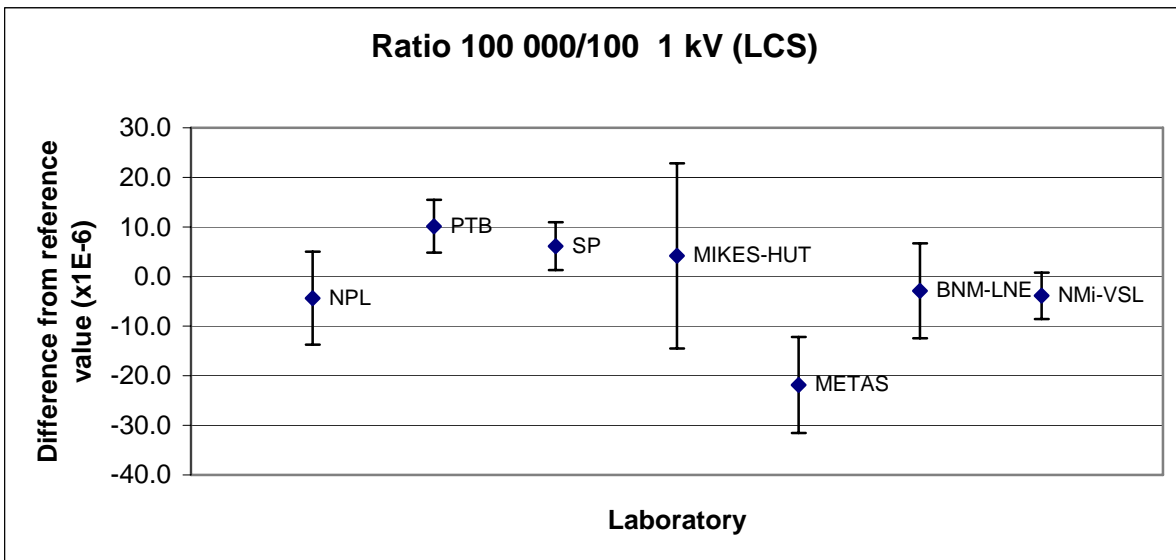


Figure A5.4.1 Difference from reference value ($\times 10^{-6}$) and 95% coverage interval values for 100 000/100 ratio at 1 kV

A5.5 Ratio 100 000/2 (Optional)

Ratio	100 000:2					
	10 kV		50 kV		100 kV	
Applied voltage						
Laboratory	SF	u	SF	u	SF	u
IEN(75 kV)	50 001.35	0.6	50 001.35	0.5	50 001.5	0.5
NPL1	50 001.05	0.75	50 001.0	0.75	50 001.0	0.75
MIKES-HUT	50 002,05	1.4	50 002.1	1.4	50 002,01	2.15
NPL2	50 002.65	0.75	50 001.4	0.75	50 002.05	0.75
BNM-LNE (divider 1)	50 001.25	0.87	50 001.8	0.87	50 002.8	0.87
BNM-LNE (divider 2)	50 001.26	0.55	50 001.42	0.61	-	-
NPL3	50 001.70	0.75	50 001.3	0.75	50 001.65	0.75
Reference value	50 001.52	0.20	50 001.47	0.18	50 001.77	0.18

Table A5.5.1 Values of Scale Factor for 100 000/2. corrected to 20 °C

En value for 95 % confidence for Ratio 100 000/2			
Laboratory	10 kV	50 kV	100 kV
NPL	0.45	-0.21	-0.31
IEN	-0.35	-0.36	-0.79
MIKES-HUT	0.40	0.46	0.12
BNM-LNE	-0.35	0.41	1.31

Table A5.5.2 En values (95 % confidence) for Ratio 100 000/2

Ratio 100 000:2 Difference from reference value ($\times 10^{-6}$)						
Applied voltage	10 kV		50 kV		100 kV	
	Difference	Expanded uncertainty	Difference	Expanded uncertainty	Difference	Expanded uncertainty
NPL	5.7	12.7	-2.8	13.1	-4.0	13.1
IEN	-3.3	9.6	-2.5	6.9	-5.3	6.7
MIKES-HUT	10.7	26.8	12.5	27.0	4.9	42.4
BNM-LNE (divider 1)	-5.3	15.4	6.5	15.8	20.7	15.8

Table A5.5.3 Difference from reference value ($\times 10^{-6}$) and 95% coverage interval values for Ratio 100 000/2

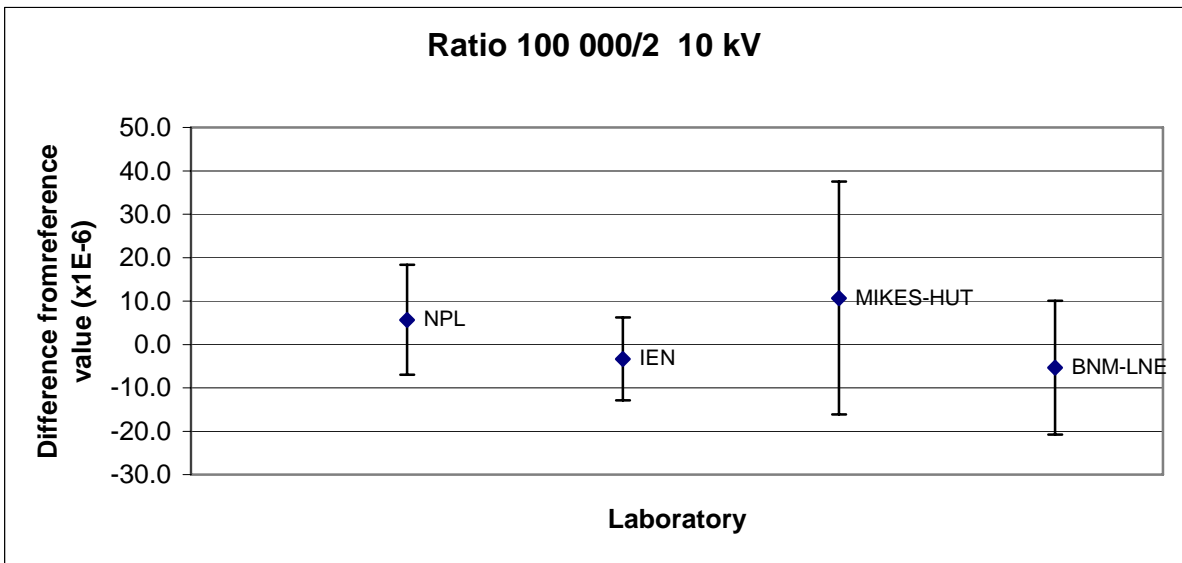


Figure A5.5.1 Difference from reference value ($\times 10^{-6}$) and 95% coverage interval values for 100 000/2 ratio at 10 kV

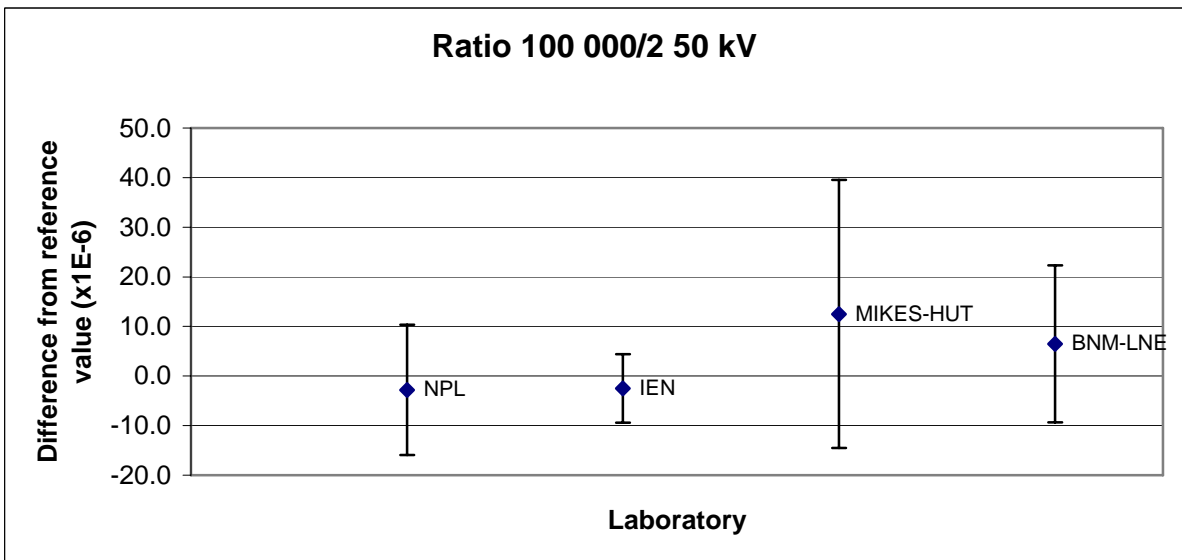


Figure A5.5.2 Difference from reference value ($\times 10^{-6}$) and 95% coverage interval values for 100 000/2 ratio at 50 kV

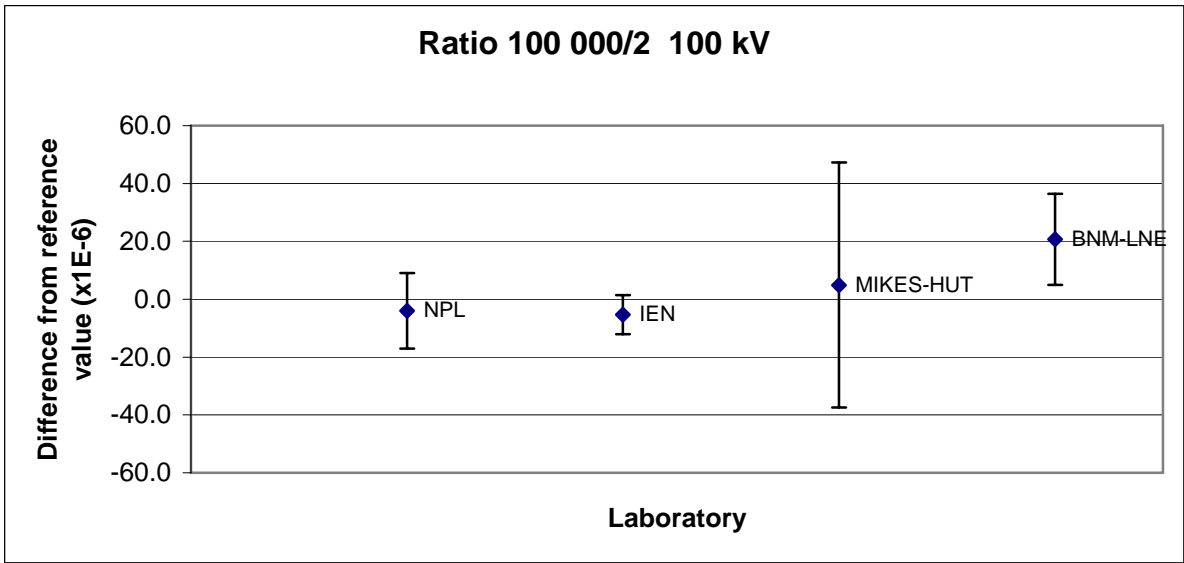


Figure A5.5.3 Difference from reference value ($\times 10^{-6}$) and 95% coverage interval values for 100 000/2 ratio at 100 kV