Noname manuscript No.
(will be inserted by the editor)

New evaluation of $T - T_{2000}$ from 0.02 K to 1 K by independent thermodynamic methods

J. Engert · A. Kirste · A. Shibahara ·
A. Casey · L. V. Levitin · J. Saunders ·
O. Hahtela · A. Kemppinen · E. Mykkänen ·
M. Prunnila · D. Gunnarsson · L. Roschier ·
M. Meschke · J. Pekola

Received: date / Accepted: date

Abstract This paper reports on the results achieved within the European Metrology Research Programme project ¨Implementing the new kelvin - InK¨ in the low-temperature range below 1 K. One of the main objectives of the InK project was the determination of new thermodynamic temperature data for comparison with the Provisional Low Temperature Scale 2000 (PLTS-2000), to provide reliable $T - T_{2000}$ values.
To this end, we have investigated three different types of primary thermometers: the current sensing noise thermometer (CSNT), the primary magnetic field fluctuation thermometer (pMFFT) and the Coulomb blockade thermometer (CBT). Based on a thorough investigation of the thermometers detailed uncertainty budgets were established for the measurement of thermodynamic temperatures. Direct comparison measurements between all thermometers demonstrate the agreement of temperature measurements within less than 1%. Our new $T - T_{2000}$ data confirm the correctness of the PLTS-2000 in the temperature range from 20 mK up to about 700 mK with relative combined standard uncertainties better than 0.64%.

Keywords primary thermometry · temperature scale · PLTS-2000 · *mise en pratique* of the kelvin (MeP-K)

J. Engert · A. Kirste
Physikalisch-Technische Bundesanstalt (PTB), 10587 Berlin, Abbestr. 2-12, Germany
E-mail: jost.engert@ptb.de

A. Shibahara · A. Casey · L.V. Levitin · J. Saunders
Department of Physics, Royal Holloway University of London, Egham, TW20 0EX, UK

O. Hahtela · A. Kemppinen · E. Mykkänen · M. Prunnila · D. Gunnarsson
VTT Technical Research Centre of Finland, P.O. Box 1000, 02044 VTT Espoo, Finland

L. Roschier
Aivon Oy, Valimotie 13A, 00380 Helsinki, Finland
(current address: BlueFors Cryogenics Oy Ltd, Arinatie 10, 00370 Helsinki, Finland)

M. Meschke · J. Pekola
Low Temperature Laboratory, Department of Applied Physics, Aalto University School of Science, P.O. Box 13500, 00076 Aalto, Finland

1 Introduction

The unit of temperature in the International System of Units (SI), the kelvin, as well as the units of the mass, the amount of substance and the electrical current, are expected to be redefined on the basis of fundamental constants by the general Conference of Weights and Measures (Conférence Générale des Poids et Mesures) in 2018 [1]. The kelvin will be defined in terms of the Boltzmann constant superseding the definition through temperature of the triple point of water, a material property. The corresponding methods for the practical realization of the kelvin in accordance with the SI are documented in the *mise en pratique* for the definition of the kelvin (MeP-K) [2]. In its current version the MeP-K refers only to the actual international temperature scales in force, the ITS-90 [3] and the PLTS-2000 [4]. After the redefinition of the kelvin, an updated version of the MeP-K will also allow primary methods for realization and dissemination of the kelvin. To support this process and prepare the implementation of the new MeP-K, the InK project was established within the European Metrology Research Programme [5]. The research reported here was part of the InK project.

For low temperatures below 1 K, the PLTS-2000 was adopted in 2000 on a provisional basis because of the still unresolved discrepancy in the input data. From 1 K down to about 20 mK the agreement between the input data of the PLTS-2000 is better than 1%. Below 20 mK, however, the discrepancies between the input data increase with decreasing temperature up to a value that is six times higher than the individual uncertainties, reaching about 6% at 1 mK [6]. To obtain new information about the relation between the PLTS-2000 and thermodynamic temperature, we have built and tested several novel designs of primary thermometers, which will also provide the necessary equipment for a future direct dissemination of the kelvin in the low-temperature region below 1 K. The paper is organized as follows. In Section 2 we shortly describe the primary thermometers developed and provide uncertainty budgets for the measurement of thermodynamic temperature. Section 3 gives some information about the comparison experiments between the thermometers and the PLTS-2000. The results are presented in Section 4. A short summary concludes the paper.

2 Primary thermometers and uncertainty budgets for thermodynamic temperature measurements

According to the definition of the *CCT Task Group for the Realization of the Kelvin* a primary thermometer is a thermometer based on a well-understood physical system, which can be described by an explicit relation between thermodynamic temperature T and independent quantities without unknown or significantly temperature-dependent constants [2]. In absolute primary thermometry the thermodynamic temperature is directly measured in terms of the Boltzmann constant without any reference to a temperature fixed point. In relative primary thermometry the thermodynamic temperature is measured indirectly by a primary thermometer but the values of key parameters are determined from a temperature fixed point [2].

The primary thermometers we have used are based on different working principles to allow checks for possible systematic effects in the determination of thermodynamic temperatures. Specifically, new designs of a current sensing noise thermometer (CSNT) [7], a new primary magnetic field fluctuation thermometer (pMFFT) [8] and a Coulomb blockade thermometer (CBT) [9] have been developed. Both the CSNT and pMFFT are different variants of noise thermometers, which rely on a fundamental law of physics, the so-called Nyquist relation, connecting the voltage fluctuations of thermally excited electrons in a (noise) resistor to absolute temperature. At low temperatures below 1 K the noise signals are so tiny that special equipment, namely dc Superconducting Quantum Interference Devices (dc SQUIDs), is necessary to measure them. The CBT exploits a completely different measurement principle. Here, the temperature dependent conductivity of tunnel junction arrays, which can be calculated explicitly once the junction parameters are known, is employed for temperature measurement.

The Current Sensing Noise Thermometer In the CSNT the fluctuations of the noise currents in the temperature sensing noise resistor are measured directly by connecting the noise resistor to the input coil of the SQUID. The SQUID is operated in flux-locked loop and read out by the SQUID electronics. The noise current I_N through the noise resistor is converted to a noise voltage $V_\mathrm{N} = I_\mathrm{N}(M_\mathrm{in} \cdot R_\mathrm{f})/M_\mathrm{f}$ at the output of the SQUID electronics.Then, the noise voltage V_N is digitized and Fourier transformed to obtain the power spectral density (PSD) of the noise spectrum. Finally, the noise temperature T_CSNT is computed from the PSD. A detailed description of the CSNT measurement set-up can be found in [7] and the references cited within. Besides the value of the noise resistor R the parameters of the SQUID readout such as the value of the feedback resistor R_f, the mutual inductances between the SQUID and the input coil M_in as well as the feedback coil M_f and the non-thermal noise components from the SQUID itself mainly determine the uncertainty of the measured noise temperature T_CSNT. The equation for calculating the temperature T_CSNT is:

$$T_\mathrm{CSNT} = \frac{R}{4k_\mathrm{B}} \left(\langle S_{V,\mathrm{N}} \rangle - \langle S_{V,\mathrm{SQ}} \rangle \right) \left(\frac{M_\mathrm{f}}{M_\mathrm{i} R_\mathrm{f}} \right)^2 , \tag{1}$$

where $\langle S_{V,\mathrm{N}} \rangle$ is the averaged PSD of the measured noise voltage in the limit of zero frequency obtained from a fit to the PSD, $\langle S_{V,\mathrm{SQ}} \rangle$ is the averaged PSD of the noise contribution from the SQUID and the SQUID electronics, and k_B is the Boltzmann constant. Equation 1 is slightly modified from that given in [7] as the temperature gradients are omitted here and considered in the uncertainty of the differences between T_CSNT and T_{2000} in Figure 1. Table 1 gives the uncertainty budget for the measurement of thermodynamic temperature with the CSNT at about 20 mK.

The Primary Magnetic Field Fluctuation Thermometer In the pMFFT, the thermally activated noise currents in the noise resistor cause fluctuating magnetic fields above the surface of the resistor. These magnetic field fluctuations are measured using a SQUID-based gradiometer, i.e. the noise resistor is not directly coupled to the input coil of the SQUID. In contrast to the CSNT where only a single SQUID channel

Table 1 Uncertainty budget for thermodynamic temperature T_{CSNT} measured with a CSNT at 20 mK using a noise resistor of approximately 2 mΩ. $u(x_i)$ are the standard uncertainties of the different input quantities, $u_{\mathrm{rel}}(x_i)$ are the corresponding relative values (coverage factor $k = 1$).

No.	Uncertainty contribution	$u(x_i)$ / mK	$u_{\mathrm{rel}}(x_i)$ / %	rel. contribution / %
1	noise resistor R	0.137	0.68	20.55
2	PSD of thermal noise $\langle S_{V,\mathrm{N}} \rangle$	0.040	0.20	1.76
3	PSD of SQUID noise $\langle S_{V,\mathrm{SQ}} \rangle$	0.000	0.30	0.00
4	mutual inductance of input coil M_{in}	0.118	0.30	15.28
5	mutual inductance of feedback coil M_{f}	0.234	1.17	60.07
6	feedback resistor R_{f}	0.023	0.12	0.59
7	fit of PSD $\langle S_{V,\mathrm{N}} \rangle$	0.040	0.20	1.75

T_{CSNT} / mK	$u(T_{\mathrm{CSNT}})$ / mK	$u_{\mathrm{rel}}(T_{\mathrm{CSNT}})$ / %
20.00	0.30	1.51

is used for the noise measurements, the pMFFT employs two SQUID channels and a cross-correlation technique for the noise measurement to minimize uncorrelated non-thermal noise contributions. For the calculation of the temperature, not only the transfer functions of the two SQUID channels have to be determined, as in the case of the CSNT, but also the geometric dimensions of the gradiometers and their distances to the noise resistor. The pMFFT, its working principle, a detailed uncertainty budget and measurements of thermodynamic temperature are described in [8]. The pMFFT was applied in absolute primary [8] and relative primary mode as presented in this paper, with resulting temperatures values T_{pMFFT} and T_{rpMFFT}, respectively. For the measurements in relative primary mode, we have calibrated the pMFFT at a known temperature T_{2000} realized according to the PLTS-2000. As the uncertainty of this calibration temperature in relation to thermodynamic temperature is known [6], we can derive a thermodynamic temperature T_{rpMFFT} from the relation of the PSDs for the noise signals measured at the unknown and the calibration temperature T_{cal} according to the procedure described in [10]:

$$T_{\mathrm{rpMFFT}} = T_{\mathrm{cal}} \left\langle \frac{\mathrm{Re}(\mathrm{PSD}(f, T_{\mathrm{rpMFFT}}))}{\mathrm{Re}(\mathrm{PSD}(f, T_{\mathrm{cal}}))} \right\rangle , \tag{2}$$

where Re denotes the real part of the complex PSDs, f represents the frequencies considered and T_{cal} was provided by a superconductive reference point with a transition temperature of 0.51863(10) K calibrated against the PLTS-2000. The corresponding uncertainty budget for T_{rpMFFT} is given in Table 2, that for T_{pMFFT} in [8].

The Coulomb Blockade Thermometer In arrays of normal metal islands connected with tunnel junctions the temperature dependent conductance is mainly governed by single electron charging effects [11]. The magnitude of the temperature effect depends on the relation between thermal energy $k_{\mathrm{B}}T$ and Coulomb charging energy E_{c} of the interacting electrons. The temperature measurement with the CBT consists of the determination of the differential conductance of such an array of tunnel junctions in dependence on bias voltage V_{dc}. The differential conductance ΔG normalized against the asymptotic conductance G_{a} at high bias voltages exhibits a dip around zero bias, in which the full width at half minimum $V_{1/2}$ value of the dip is directly

Table 2 Uncertainty budget for thermodynamic temperature T_{rpMFFT} measured with a pMFFT operated in relative primary mode at 20.697 mK. $u(x_i)$ are the standard uncertainties of the different input quantities, $u_{\mathrm{rel}}(x_i)$ are the corresponding relative values (coverage factor $k = 1$).

No.	Uncertainty contribution	$u(x_i)$ / mK	$u_{\mathrm{rel}}(x_i)$ / %	rel. contribution / %
1	calibration temperature T_{cal} in thermodynamic terms	$2.00 \cdot 10^{-2}$	0.096	3.33
2	calibration of the pMFFT at T_{cal}	$4.00 \cdot 10^{-3}$	0.019	0.13
3	feedback resistor R_{f} at calibration	$2.40 \cdot 10^{-2}$	0.005	4.79
4	feedback resistor R_{f}	$9.57 \cdot 10^{-4}$	0.005	0.01
5	change of mutual inductance M_{f} of feedback coil between T_{cal} and T measurement	$9.57 \cdot 10^{-3}$	0.046	0.76
6	timing accuracy of AD converter at calibration	$4.57 \cdot 10^{-3}$	0.001	0.17
7	timing accuracy of AD converter	$1.88 \cdot 10^{-4}$	0.001	0.00
8	signal to noise ratio of cross-correlation PSD at calibration	$7.27 \cdot 10^{-5}$	0.000	0.00
9	signal to noise ratio of cross-correlation PSD	$3.24 \cdot 10^{-4}$	0.002	0.00
10	ac voltage measurement at calibration	$1.04 \cdot 10^{-1}$	0.020	90.59
11	ac voltage measurement	$4.17 \cdot 10^{-3}$	0.020	0.14
12	number of averages at calibration	$1.93 \cdot 10^{-3}$	0.009	0.03
13	number of averages at T measurement	$1.96 \cdot 10^{-3}$	0.009	0.03

T_{rpMFFT} / mK	$u(T_{\mathrm{rpMFFT}})$ / mK	$u_{\mathrm{rel}}(T_{\mathrm{rpMFFT}})$ / %
20.697	0.109	0.53

proportional to thermodynamic temperature T in the limit of small charging energy $E_{\mathrm{c}} << k_{\mathrm{B}}T$ [11]:

$$V_{1/2} = \frac{5.439 N k_{\mathrm{B}} T}{e}, \tag{3}$$

where N is the number of tunnel junctions in the array in series and e is the elementary charge of the electron. Alternatively, the temperature can be derived from a calculation explicitly describing the whole conductance curve including such effects as heating of the tunneling electrons by the measurement current [12]. Two CBTs were provided for the comparison measurements. CBT99 and CBT33 samples contain 99 and 33 tunnel junctions in series, respectively. A description of the CBT sample fabrication is given in [13] and [14]. An investigation of the uncertainty components is discussed in [15] and a traceable CBT measurement scheme is described in [9]. The uncertainty budget for thermodynamic temperature measurements with the CBT99 is given in Table 3. The junction design of the CBT33 sample was originally optimized for lower temperatures than that of CBT99. Therefore, CBT33 produces a lower measurement signal level and higher uncertainty in the temperature range covered in this work.

3 Experiments

The basic idea of the investigations was to compare directly, for the first time, different primary low-temperature thermometers with each other and with T_{2000} temperatures according to the PLTS-2000.

Table 3 Uncertainty budget for thermodynamic temperature T_{CBT99} measured with a CBT with an array of 99 tunnel junctions at 20.83 mK. $u(x_i)$ are the standard uncertainties of the different input quantities, $u_{\mathrm{rel}}(x_i)$ are the corresponding relative values (coverage factor $k = 1$).

No.	Uncertainty contribution	$u(x_i)$ / mK	$u_{\mathrm{rel}}(x_i)$ / %	rel. contribution / %
1	dc bias voltage V_{dc} due to preamplifier calibration	0.002	0.008	0.05
2	dc bias voltage V_{dc} due to preamplifier temperature dependence	0.001	0.003	0.01
3	deviation in tunnel junction resistances	0.012	0.060	2.43
4	determination of normalised differential conductance $\Delta G/G_{\mathrm{a}}$	0.029	0.139	13.1
5	fit of charging energy E_{c}	0.052	0.250	42.21
6	Repeatability of T_{CBT99} measurements	0.052	0.250	42.21

T_{CBT99} / mK	$u(T_{\mathrm{CBT99}})$ / mK	$u_{\mathrm{rel}}(T_{\mathrm{CBT99}})$ / %
20.83	0.082	0.40

The realization of the PLTS-2000 requires special experience, is expensive, time consuming and was not available at each of the partners laboratories. Therefore, a superconductive reference point device SRD-1000 (SRD) [16] with 5 transition points at 21 mK, 65 mK, 93 mK, 155 mK, and 208 mK was supplied by PTB to provide a common basis and ensure the consistency of the temperature realization in the different experimental environments at the partners laboratories. The SRD carries a calibration according to the PLTS-2000 with relative combined standard uncertainties ranging from $4 \cdot 10^{-4}$ to $2 \cdot 10^{-3}$.

Initially, comparison measurements at all laboratories were planned but finally realized up to date only at VTT-MIKES and PTB. The first series of comparison experiments was carried out at VTT-MIKES in a dry dilution refrigerator equipped with commercial cryocables [17] for the SQUIDs of the noise thermometers and Thermocoax cables [18] for the CBT. The thermometers and the SRD were mounted on a temperature controlled platform attached to the mixing chamber of the dilution refrigerator. The temperature stabilization was realised by using the output signal of the transition midpoint of the superconductive transitions of the SRD as setpoints for a PID controller. Because of the limited number of wires installed in the cryostat, two cool downs were performed with different configurations of thermometers installed. In the first cool down the pMFFT and the CBT99 were compared with the T_{2000} temperatures provided by SRD, whereas in a second cool down the CSNT and the CBT33 were compared with the SRD. In the second cool down the minimum temperature reached was above the lowest transition temperature of the SRD. Therefore, for these thermometers the measurements of thermodynamic temperature were carried out only at four T_{2000} reference temperatures.

The second series of comparison measurements was conducted at PTB solely between a second pMFFT operated in absolute primary mode and T_{2000} reference temperatures [8]. These measurements were also carried out in a dry dilution refrigerator. In this second setup, the reference temperatures T_{2000} were provided by another MFFT operated in relative primary mode relying on a calibration according to the

PLTS-2000 with an relative combined standard uncertainty of $4 \cdot 10^{-4}$. For details of these measurements we refer to [8].

4 Results

The main results of measurements at VTT-MIKES are given in Table 4 and shown in Figure 1. From Figure 1, one can see that the relative deviations from the T_{2000} values of the thermodynamic temperatures measured by the CSNT, the CBTs and the pMFFT, operated in relative primary mode, are not randomly distributed around the corresponding reference temperature but have systematic offsets between each other. Therefore, to represent the measurement results in a coherent form for evaluation of the thermodynamic consistency of the PLTS-2000, we have combined them according to the procedure described in [19] and applying the formulas given therein in appendix 4. Firstly, we have calculated the weighted mean values for the measurements at each T_{2000} reference temperature provided by the SRD. The weighting was proportional to $1/u^2(x_i)/\sum_i(1/u^2(x_i))$, where $u(x_i)$ are the combined standard uncertainties of the individual measurement results. Secondly, a correction for the weighted mean and its associated uncertainty were calculated accounting for the systematic differences between the input data.The deviation of the individual temperature values from the simple arithmetic mean at each reference temperature are larger for data with larger individual uncertainties. Therefore, a triangular distribution for the calculation of the correction is used. This accounts for the fact that values near the mean are more likely than those near the end of the interval spanned by the measured temperatures and that the number of averaged values is small [19]. Finally, the corrected weighted mean T_{cwm} and its uncertainty $u(T_{\mathrm{cwm}})$ were calculated. Table 4 gives the values for the individual temperature measurements obtained by each of the primary thermometers at the reference temperatures T_{2000}, the corrected weighted means T_{cwm} as well as the differences $T_{\mathrm{cwm}} - T_{2000}$ together with the associated combined standard uncertainties for a coverage factor $k = 1$. The relative combined standard uncertainties for the corrected weighted means range from 0.34% to 0.58% between 20 mK and 207 mK. The corresponding uncertainties for the relative deviations $(T_{\mathrm{cwm}} - T_{2000})/T_{2000}$ range from 0.50% to 0.64%.

For a complete picture of the determinations of thermodynamic temperatures below 1 K obtained within the InK project, the results of the comparison measurements at VTT-MIKES and those of the independent measurements at PTB using a second pMFFT [8] are combined in Figure 2. All thermodynamic temperatures obtained by using the different primary thermometers, CSNT, CBT and pMFFT agree very well within their expanded uncertainties (coverage factor $k = 2$). The corrected weighted means of the thermodynamic temperatures obtained at VTT-MIKES are in very close agreement with independent measurements with the pMFFT at PTB and deviate from the PLTS-2000 by less than 0.53% in the temperature range from 20 mK to 207 mK. At higher temperatures up to 700 mK data sets for $T - T_{2000}$ obtained with pMFFTs operated in relative primary mode [8, 10] are in even better agreement with the PLTS-2000 within less than ±0.28%. All results taken together strongly confirm the thermodynamic correctness of the PLTS-2000 in the temperature range from 20 mK to

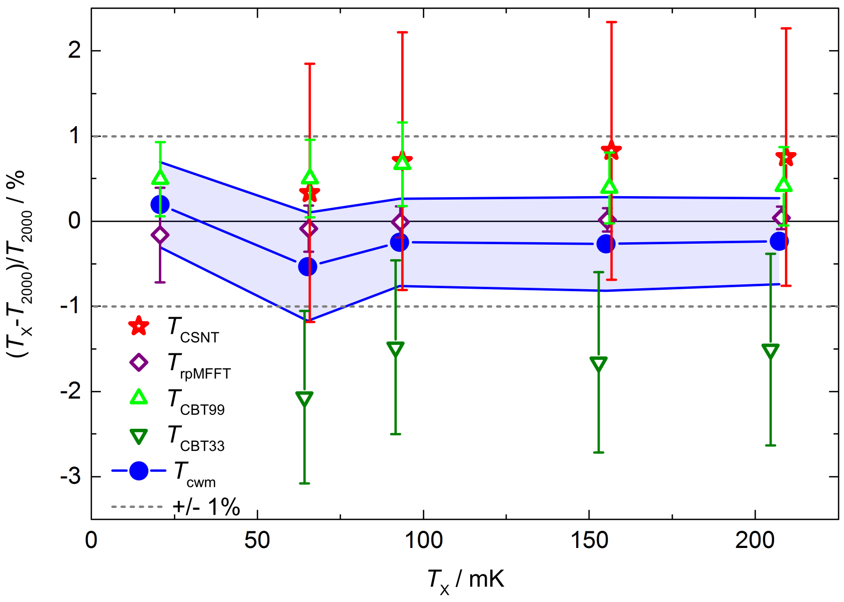

Fig. 1 Relative deviations of thermodynamic temperatures T_X measured with primary thermometers CSNT (T_{CSNT}), CBT (T_{CBT99}, T_{CBT33}) and pMFFT operated in relative primary mode (T_{rpMFFT}, calibration at 518 mK) from reference temperatures T_{2000} according to the PLTS-2000 (open symbols). The blue full dots correspond to corrected weighted mean values of the thermodynamic temperatures T_{cwm}. The corresponding combined standard uncertainty (coverage factor $k = 1$) is marked by the light-blue shadowed area. A ± 1% deviation band from T_{2000} is show by dashed grey lines. Error bars denote combined standard uncertainties ($k = 1$). For more information see text.

700 mK. The PLTS-2000 can be considered an excellent temperature scale, which is correct in thermodynamic terms with low uncertainty over a large temperature range usually covered by dilution refrigerators. Nevertheless, the region at the lower end of the PLTS-2000 from 20 mK down to 0.902 mK, where the discrepancies in the background data grow up to 6%, has to be explored further. Such experiments are currently under way.

5 Conclusion

For the first time direct comparison measurements have been carried out between different primary thermometers and the PLTS-2000. The measurements of thermodynamic temperature were conducted at two partner laboratories and agree well with each other within the expanded uncertainties (coverage factor $k = 2$). The deviation between the new thermodynamic temperature data and the PLTS-2000 is less than 0.53% for the corrected weighted mean of the temperature measurements with the CSNT, two CBTs and the pMFFT in the temperature range from 20 mK up to 207 mK. In a wider range from 20 mK to 700 mK, the deviation of the thermodynamic data of another pMFFT from the PLTS-2000 is less than 0.28%. This is an excellent confir-

Table 4 Thermodynamic temperature data obtained from measurements at VTT-MIKES using a CSNT, two CBTs and a pMFFT with the corrected weighted means T_{cwm} at defined reference temperatures T_{2000} and the corresponding differences $\Delta T = T_{\mathrm{cwm}} - T_{2000}$ and $\Delta T/T = (T_{\mathrm{cwm}} - T_{2000})/T_{2000}$. The uncertainties $u(T)$ are combined standard uncertainties (coverage factor $k = 1$).

No.	T_{2000} mK	$u(T_{2000})$ mK	T_{cwm} mK	$u(T_{\mathrm{cwm}})$ mK	$u_{\mathrm{rel}}(T_{\mathrm{cwm}})$ %	ΔT mK	$\Delta T/T$ %	$u(\Delta T/T)$ %
1	20.73	0.069	20.77	0.07	0.34	0.04	0.20	0.50
2	65.58	0.243	65.23	0.38	0.58	-0.35	-0.53	0.64
3	93.08	0.164	92.85	0.45	0.48	-0.23	-0.25	0.51
4	155.47	0.125	155.06	0.83	0.53	-0.41	-0.26	0.55
5	207.78	0.203	207.30	1.01	0.49	-0.48	-0.23	0.50

No.	T_{CSNT} mK	$u(T_{\mathrm{CSNT}})$ mK	T_{rpMFFT} mK	$u(T_{\mathrm{rpMFFT}})$ mK	T_{CBT99} mK	$u(T_{\mathrm{CBT99}})$ mK	T_{CBT33} mK	$u(T_{\mathrm{CBT33}})$ mK
1	-	-	20.70	0.11	20.83	0.08	-	-
2	65.08	1.01	65.53	0.13	65.91	0.27	64.23	0.65
3	93.74	1.43	93.07	0.15	93.71	0.45	91.70	0.95
4	156.76	2.40	155.49	0.20	156.08	0.64	152.90	1.65
5	209.35	3.20	207.87	0.26	208.64	0.95	204.65	2.34

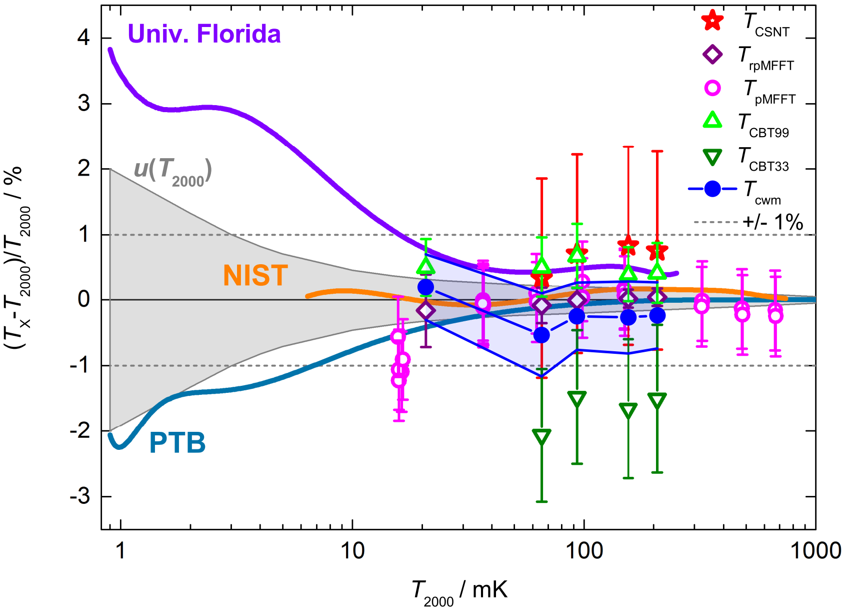

Fig. 2 Compilation of thermodynamic temperature determinations obtained in the InK project using different primary thermometers, a CSNT (T_{CSNT}), two CBTs ($T_{\mathrm{CBT99}}, T_{\mathrm{CBT33}}$) and a pMFFT ($T_{\mathrm{rpMFFT}}$), as relative deviations from the PLTS-2000. Shown are the same data as in Figure 1, plus measurements at PTB with a pMFFT operated in absolute primary mode (T_{pMFFT}). In addition, the relative deviations are shown of the background data of the PLTS-2000 obtained by NIST, the University of Florida and PTB [6]. The grey shadowed area depicts the uncertainty of the PLTS-2000 in thermodynamic terms (coverage factor $k = 1$). The dashed grey lines mark a ±1% deviation band from the PLTS-2000. Error bars denote combined standard uncertainties ($k = 1$).

mation of the thermodynamic correctness of the PLTS-2000 in the temperature range from 20 mK to 700 mK. Currently experiments are under way to extend the measurements down to the lower end of the PLTS-2000 at 1 mK.

Acknowledgements The research was carried out within the EURAMET project ”InK - Implementing the new kelvin” (JRP number: SIB01) [5]. Funding is gratefully acknowledged from the European Community´s 7th Framework Programme, ERA-NET Plus, Grant Agreement No. 217257. J. E. and A. K. thank D. Heyer, M. Fleischer-Bartsch, M. Regin and C. Aßmann for technical support and assistance during the experiments. The SQUID sensors were kindly provided by the PTB department ”Cryophysics and Spectrometry” [20]. J. E. and A. K. are also deeply grateful to the PTBs Berlin Institute workshop for fabricating the high-precision main copper bodies for the pMFFTs.

References

1. J. Fischer and J. Ullrich, The new system of units, *Nature Physics*, **12**, 4-6 (2016)
2. Fellmuth B. et al., The kelvin redefinition and its mise en pratique, Phil. Trans. R. Soc. A **374**, 20150037 (2016)
3. Preston-Thomas H., The International Temperature Scale of 1990 (ITS-90), Metrologia **27**, 3-10 (1990)
4. Comité International des Poids et Mesures (CIPM), The Provisional Low Temperature Scale from 0.9 mK to 1 K, PLTS-2000, Appendix to Recommendation C1 (2000), see http://www.bipm.org/utils/en/pdf/PLTS-2000.pdf and http://www.bipm.org/en/committees/cc/cct/guide-plts2000.html
5. Machin G., Engert J., Gavioso R. M., Sadli M., Woolliams E. R., The Euramet Metrology Research Programme Project Implementing the New Kelvin (InK). *Int. J. Thermophys.* **35**, 405 (2014)
6. Rusby R. L., Durieux M., Reesink A. L., Hudson R. P., Schuster G., Khne M., Fogle W. E., Soulen R. J., Adams E. D., The Provisional Low Temperature Scale from 0.9 mK to 1 K, PLTS-2000, *J. Low Temp. Phys.* **126** N 1/2, 633-642 (2002)
7. Shibahara A., Hahtela O., Engert J., van der Vliet H., Levitin L. V., Casey A., Lusher C. P., Saunders J., Drung D., Schurig Th., Primary current-sensing noise thermometry in the millikelvin regime, *Phil. Trans R. Soc.* **A 374**, 20150054 (2016)
8. Kirste A., Engert J., A SQUID-based primary noise thermometer for low temperature metrology, *Phil. Trans R. Soc.* **A 374**, 20150050 (2016)
9. Hahtela O. et al., Traceable Coulomb blockade thermometry, in preparation
10. Kirste A., Regin M., Engert J., Drung D., Schurig Th., A calculable and correlation-based magnetic field fluctuation thermometer, *J. Phys.: Conf. Ser.* **568**, 032012 (2014)
11. Pekola J., Hirvi K. P., Kauppinen J. P., Paalanen M. A., Thermometry by arrays of tunnel junctions, *Phys. Rev.Lett.* **73**, 2903 (1994)
12. Meschke M., Pekola J. P., Gay F., Rapp R. E., Godfrin H., Electron Thermalization in Metallic Islands Probed by Coulomb Blockade Thermometry, *J. Low Temp. Phys.* **134** No. 5/6, 1119 (2004)
13. Bradley D. I., George R. E., Gunnarson D., Haley R. P., Heikkinen H., Pashkin Yu. A., Penttilä J., Prance J. R., Prunnila M., Roschier L., Sarsby M., Nanoelectronic primary thermometry below 4 mK, *Nature Comm.* **7**, 10455 (2016)
14. Prunnila M., meschke M., Gunnarson D., Enouz-Vedrenne S., Kivioja J. M., Pekola J. P., Ex situ tunnel junction process technique characterized by Coulomb blockade thermometry, *J. Vac. Sci. Technol.* **B28** No. 5,1026 (2010)
15. Hahtela O., Meschke M., Savin A., Gunnarson D., Prunnila M., Penttilä J. S., Roschier L., Heinonen M., Manninen A., Pekola J. P., Investigation of uncertainty components in Coulomb blockade thermometry, *AIP Conf. Proc.* **1552**, 142 (2013)
16. Hightech Development Leiden, P.O. Box 691, 2300 AR Leiden, The Netherlands, https://hdleiden.home.xs4all.nl/srd1000/
17. Magnicon GmbH, Barkhausenweg 11, 22339 Hamburg, Germany, http://www.magnicon.com
18. Zorin A. B., The thermocoax cable as the microwave frequency filter for single electron circuits, *Rev. Sci. Instrum.* **66**, 4296 (1995)
19. Kacker R., Datla R., Parr A., Combined result and associated uncertainty from interlaboratory evaluations based on the ISO Guide, *Metrologia* **39**, 279 (2002)
20. http://www.ptb.de/cms/en/ptb/fachabteilungen/abt7/fb-72.html