https://doi.org/10.5194/ar-2026-33
Preprint. Discussion started: 25 September 2026

A metrological calibration facility for particle number counters used in emission measurements

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Abstract. A metrological calibration facility for particle number counters (PNCs) has been developed at the Physikalisch-Technische Bundesanstalt (PTB) as a primary reference standard for this metric required in the quantification of solid soot emission as described in national and European regulatory frameworks. This study describes the calibration of a Condensation Particle Counter (CPC) using PTB's primary aerosol number standard, a Faraday Cup Aerosol Electrometer (FCAE). The calibration facility enables high accuracy determination of CPC counting efficiency for particles with mobility diameters between 17 and 200 nm, as well as linearity measurements of particle number concentrations ranging from 1 cm^{-3} to 20 000 cm^{-3}. Soot aerosol particles were generated using a miniCAST 5303 and subsequently treating them in a Catalytic Stripper to remove volatile components before homogenisation in an integrated mixing unit. The aerosol flow was distributed via a ten-port manifold, allowing simultaneous evaluation of up to eight CPCs and a FCAE connected to two different ports simultaneously. The results demonstrate that the facility provides state-of-the-art metrological capabilities for CPC calibration, supporting improved reliability and comparability of particle number measurements in emission control applications.

1 Introduction

Airborne particulate matter (PM) is an atmospheric pollutant with well documented impacts on human health, agricultural productivity, natural ecosystems and the climate. Traditionally, PM has been monitored using mass-based metrics PM10, PM2.5 and PM1 which correspond to the mass concentration of particles with aerodynamic diameters below 10 µm, 2.5 µm and 1.0 µm, respectively. However, recent regulatory frameworks have begun to incorporate particle number (PN) based metrics, particularly in automotive emission control (Giechaskiel et al., 2012). PN provides significantly more information on fine and ultrafine aerosols, as these particles dominate number concentrations while contributing only minimally to particulate mass.

The introduction of PN as a regulatory metric necessitates the development of SI-traceable calibration methods and primary standard instruments. The Faraday Cup Aerosol Electrometer (FCAE) has been established as the primary standard for PN determination (Molzahn et al., 2025) . It measures the electrical current carried by a stream of charged particles providing direct SI traceability through current and volumetric flow measurements (Molzahn et al., 2025). A metrological

https://doi.org/10.5194/ar-2026-33
Preprint. Discussion started: 25 September 2026

intercomparison of FCAE instruments among national metrology institutes (NMIs) has demonstrated consistent performance, and several NMIs now offer FCAE-based calibration facility services for particle counters (Högström et al., 2014) (Brown et al., 2023). The achievable concentration range and uncertainty of SI-traceable PN measurements are therefore fundamentally limited by the actual calibration of the FCAE itself, which is in the range of 1000 fA resulting in 125 000 cm^{-3} – 375 000 cm^{-3} particles with different flows which is required for higher atmospheric or emission level concentrations.

Within the PN traceability chain, reference condensation particle counters (CPCs) serve mostly as secondary standards in accredited calibration laboratories here in Germany (International Organization for Standardization, 2020). Whereas aerosol generators produce test aerosols of controlled particle size. The choice of the aerosol generator depends on the regulatory framework, for example: calibration of particle counter for emissions measurement requires thermally stable soot like particles (United Nations Economic Commission for Europe, 2013). Other regulations permit alternative aerosol sources, such as salt nebulisers, spark discharge generators, or electrospray generators, depending on application, desired measurement uncertainty and instrument type (Bundesministerium für Verkehr und digitale Infrastruktur, 2021; PTB-Anforderungen PTB-A 12.16, 2021).

Several particle loss mechanisms must be considered in calibration facility for PN traceability, including diffusion and thermophoretic losses. These corrections are standardised in ISO 15900:2020 (International Organization for Standardization, 2020) and are strongly size dependent. In this paper, we present a harmonised procedure for operating a robust calibration facility for particle number (PN) measurements. The proposed methodology addresses the generation of suitable test aerosols, the characterisation and correction of particle losses, and the implementation of traceable measurement procedures. Most importantly, ensuring metrological traceability, minimising measurement uncertainty and improving the calibration methods in our laboratory setups.

2 Methods

2.1 Stability of reference aerosol generator

Stability of the reference aerosol generator is crucial to PN determination, to minimize the statistical error of repeated observations to achieve lower measurement uncertainties. Particle generators are usually optimized to sustain a particle diameter and concentration output for a couple of hours. Thus, measurement also needs quality control routines include periodic checks of particulate properties of the generators and the conditioning system (Pratzler et al., 2026).

https://doi.org/10.5194/ar-2026-33
Preprint. Discussion started: 25 September 2026

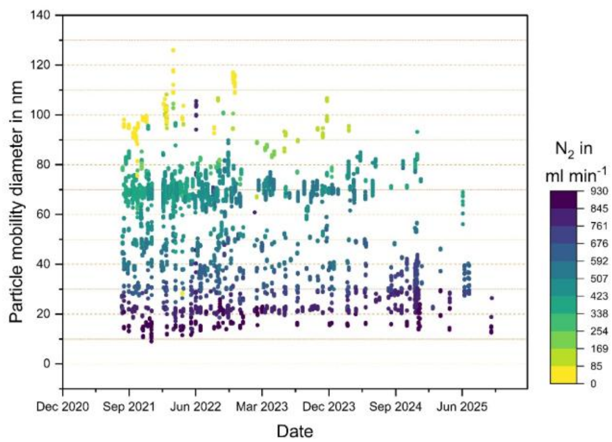

Figure 1 Multi-year time series of particle mobility diameter of miniCAST soot. The colour code indicates nitrogen flow rate in the gas mixing of the miniCAST. Horizontal lines indicate the regular operation points.

At the PTB calibration facility, a diffusion flame generator (miniCAST 5303C) is used continuously for more than 4 years to produce an output of thermo-stable soot particles from 17 nm up to 100 nm in mobility diameter. Larger particles, about 200 nm are usually selected from a set point with geometric mean diameter of about 100 nm (polydisperse). To better understand the stability of the PTB conditioning setup, a multi-year analysis of the stability of the generator indicates that the operation points (OPs) are repeatable within a certain range of dilution of the propane flow rate with nitrogen (see Figure 1). By fixing the propane and oxidation air flows at a stoichiometric ratio ($\Phi = 1$), the different OPs can be finetuned by adjusting N_2 flow rates. Figure 2 provides a comprehensive overview of these conditions. The variation in N_2 flow rate for the different OPs, shown in Figure 2, spans from a ±30 mL min^{-1} (inter-quartile range) for the 17 nm OP to ±150 mL min^{-1} for the 100 nm OP.

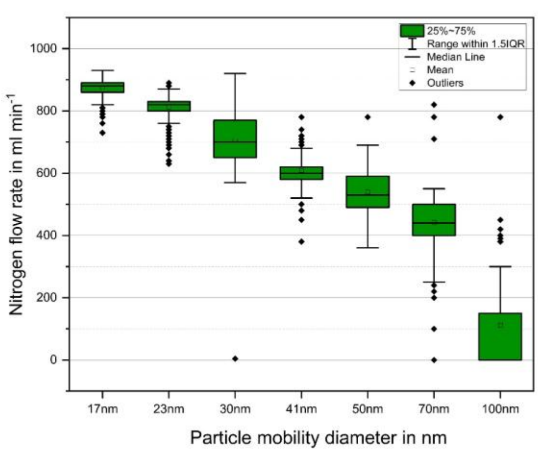

Figure 2 Descriptive statistics of nitrogen flow rate used to adjust size of the target operation points.

https://doi.org/10.5194/ar-2026-33
Preprint. Discussion started: 25 September 2026

In terms of dilution, various technologies are used including rotating disk diluters, venturi effect and critical orifices. The dilution factor should be characterised prior and after a PN measurement experiment. Particles with different sizes penetrate the measurement system in different ratios. Therefore, the dilution factor for aerosol particles is known as particle concentration dilution factor. Some regulations go beyond this approach and consider the particle penetration efficiency, which includes the gas dilution factor in consideration and therefore provide more information about the effects of particle in the overall dilution of the system (Giechaskiel et al., 2019).

2.2 PTB-calibration facility of PN-counters up to 200 nm

Figure 3 presents a schematic overview of the experimental setup used for the calibration of multiple CPCs in terms of polydisperse and monodisperse particle number concentration. Soot particles are generated using a miniCAST soot generator, which are then mixed with particle-free compressed air at a flow rate ranging from 48 - 100 L min^{-1}. A rotating disk diluter is used to adjust the number concentration of soot aerosol, which is then passed through a catalytic stripper to remove/oxidize any semi volatile particles from the aerosol sample. Particle size was measured using a mobility particle size spectrometer with a Krypton source. Aerosols are injected into the gas distributor using an Aerosol Gas Mixing Unit (AGMU). The reference instrument in this setup is a FCAE, which provides SI traceable particle number concentration measurements against which the CPCs are calibrated. The aerosol soot output produced by the miniCAST is subsequently diluted with aerosol rotational disk dilutor to achieve the particle number concentration at levels required for CPC calibration.

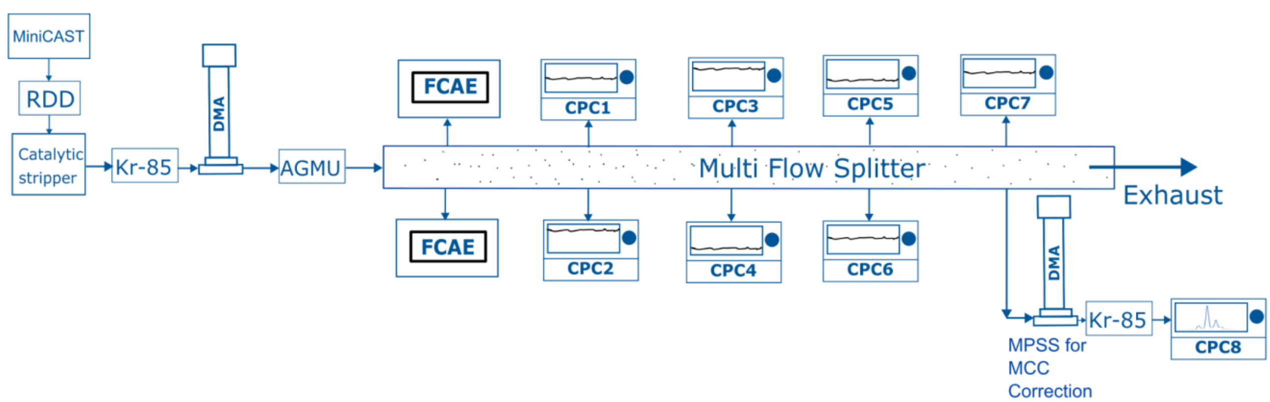

Figure 3 Schematic scheme of the PTB's calibration facility including reference device

The polydisperse soot aerosol is directed through a Catalytic Stripper (CS) model CS015, Catalytic Instruments Germany, to remove volatile and semi volatile material, ensuring that only the solid particle fraction was introduced into the measurement system. The use of the CS minimizes artifacts associated with volatile condensation within the CPC saturator–condenser region and enhances the reproducibility and comparability of calibration results.

https://doi.org/10.5194/ar-2026-33
Preprint. Discussion started: 25 September 2026

Following the removal of volatile components by a catalytic stripper (CS 015), particle size classification was performed using a Differential Mobility Analyzer (DMA), enabling the selection of monodisperse aerosol with a well-defined electrical mobility diameter. The operating conditions (sheath to aerosol flow ratio 1:10) of the DMA were optimized by a strict standard operation procedure (SOP) to ensure stable and reproducible output, which is essential for determining CPC detection efficiency as a function of particle size. The monodisperse aerosol flow was then divided using a characterised multi-flow splitter, which provided uniform aerosol distribution and ensured identical sampling conditions for the FCAE and all CPCs operating in parallel, for more details see sec. 3.

The detection efficiencies for particle number counters of tailpipe emission were evaluated for electrical mobility diameters from 17 nm to 200 nm. Linearity tests were additionally performed at particle number concentrations of approximately 5 000 cm^{-3} and 500 000 cm^{-3} to assess CPC response across the operational measurement range. All calibration measurements were performed under stable laboratory conditions to ensure the reliability and reproducibility of the measurements. The long-term environmental conditions of the laboratory are logged through OPUS 20 device and summarized in Figure 4 which demonstrates the stability of key parameters such as temperature, pressure, and relative humidity over a period of three years. To maintain stable ambient conditions is essential to minimize systematic uncertainties and external influences on the measurement results.

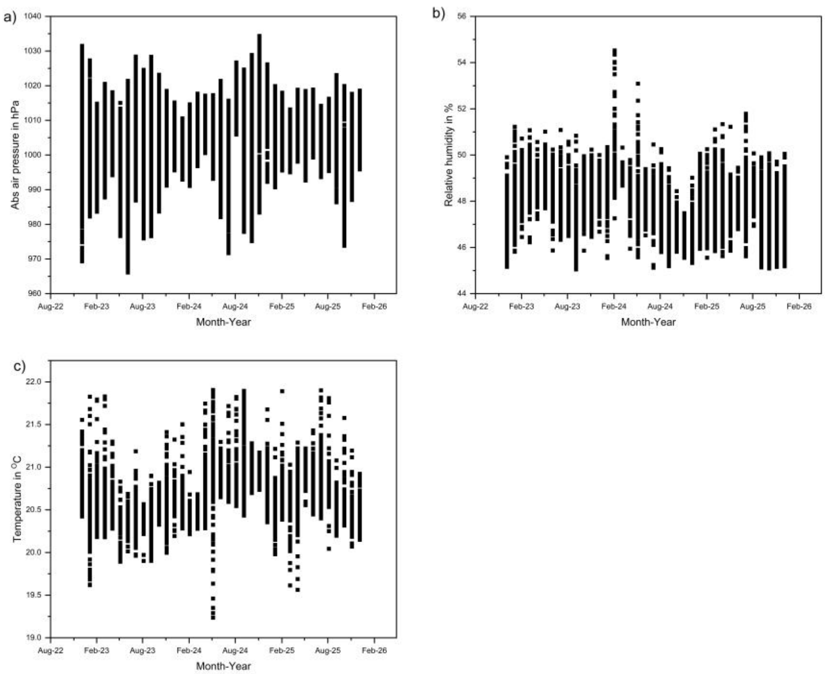

Figure 4 Long-term stability of laboratory a) Air pressure in hPa, b) Relative humidity in % and c) Temperature in ^{O}C

https://doi.org/10.5194/ar-2026-33
Preprint. Discussion started: 25 September 2026

2.3 New Multiflow splitter for monodisperse injection

Figure 5 shows the self-made aerosol multi-flow splitter (MFS) used for distributing the monodisperse aerosol to the reference instrument and the devices under test (DUT). The splitter consists of up to ten outlet ports (designated 1a/1b through 5a/5b) and enables simultaneous assessment of particle linearity and detection efficiency for multiple aerosol measuring devices. Each port of the splitter was characterised and validated using monodisperse aerosol particles with mobility diameters between 17 nm and 100 nm at a particle number concentration of approximately 10 000 cm^{-3}. This characterisation ensured uniform aerosol distribution across all outlets and confirmed that each sampling port provided equivalent and reproducible particle number concentrations for calibration purposes.

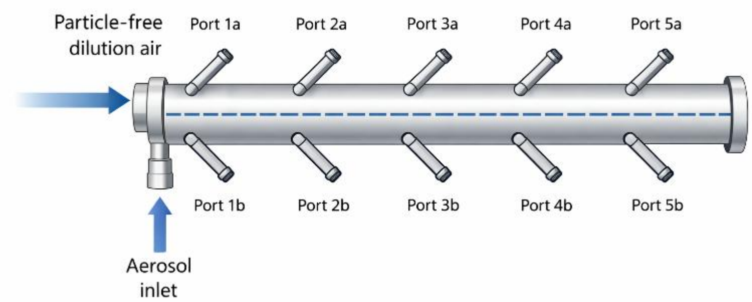

Figure 5 Schematic of PTBs- Multi flow splitter (MFS) with 10 Ports

Figure 6 illustrates the aerosol gas mixing unit (AGMU), which incorporates PTB's in house aerosol injection system (Patent No. DE 10 2017 123 379 B3). In this setup, the monodisperse aerosol is mixed with pressurized air controlled via a pressure-regulated flow sensor, typically operated between 1 and 2 L min^{-1}. Additional dilution is achieved by introducing pressurized air at flow rates between 10 and 130 L min^{-1}, allowing precise adjustment of the aerosol particle concentration for calibration purposes.

To evaluate the splitter bias between two ports of the aerosol gas distributor, two nominally identical particle counters (A and B) were operated at equal and constant volumetric flow rates. The counters were sequentially connected to ports 1a and 1b following a three-step protocol:

A→1a and B→1b

A→1b and B→1a (swapped configuration)

A→1a and B→1b (return to the initial configuration)

https://doi.org/10.5194/ar-2026-33
Preprint. Discussion started: 25 September 2026

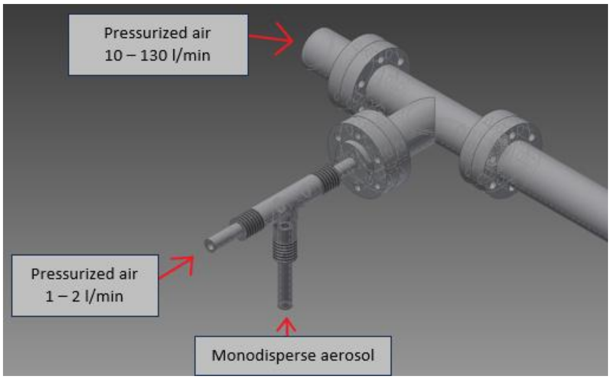

Figure 6 PTB's own developed aerosol gas mixing unit

For each configuration, mean particle number concentrations were determined and evaluated. The splitter bias correction factor (ß) is defined as a correction factor for the concentration ratio between ports 1a and 1b and β was determined following the procedure described in Annex G of ISO 27891 (International Organization for Standardization, 2020), ensuring proper correction for any systematic deviations introduced by the splitter.

The inlet flow to the MFS was adjusted to achieve the desired particle number concentration in a range of 15 – 170 L min^{-1}. Two ultrafine condensation particle counters (UCPCs), each operating at a flow rate of 1.5 L min^{-1}, were connected to ports 1a and 1b, while two condensation particle counters (CPCs), each operating at 1.0 L min^{-1}, were attached to ports 2a and 2b, respectively [6].

Figure 7 presents the results of β evaluation conducted for the MFS measurements were performed under full load conditions to assess the performance and uniformity of all outlet ports, which is always recommended to have optimal performance of such MFS. Symmetric flow ratios were employed, as recommended, to minimize measurement uncertainty. The results indicate that ports 2a and 2b exhibited the lowest splitter bias and therefore represent the most suitable connection points for high-grade CPC calibration. Ports 1a and 1b showed significantly higher bias values of approximately 6%, whereas the remaining ports demonstrated deviations within 3%. These findings suggest that ports 2a/2b onwards provide more reliable and consistent aerosol sampling which is an important consideration for applications requiring high accuracy in particle number concentration measurements. Therefore, this behaviour of ports 1a/1b will be further validated through extended investigations involving additional optimisation steps of the MFS.

https://doi.org/10.5194/ar-2026-33
Preprint. Discussion started: 25 September 2026

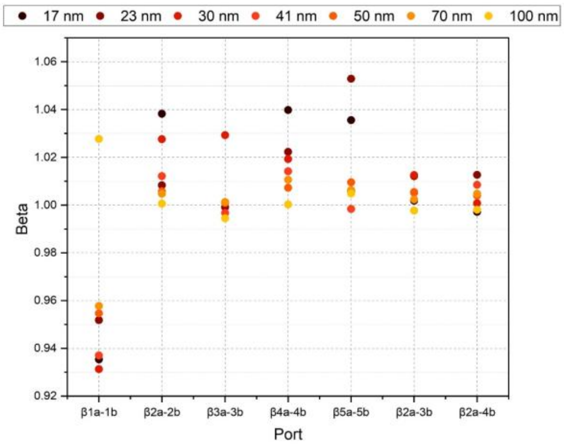

Figure 7 Splitter bias β measurement and evaluation for different ports combination

2.4 Multiple charge correction using a tandem DMA system

For the determination of multiply charge particles, especially for larger diameter ≥ 70 nm, a tandem DMA setup is used at PTB calibration facility for non-spherical particles such as solid soot. Differential Mobility Analyzer (DMA) classifies aerosol particles according to their electrical mobility. Since electrical mobility is a function of both particle size and charge, particles carrying multiple elementary charges may overlap in main mobility spectra with singly charged particles. This overlap introduces systematic bias in the retrieved particle size distribution. A tandem DMA system offers an alternative approach by enabling experimental discrimination of charge states and thereby improving the accuracy of multiple-charge corrections by modifying the setup. In a tandem DMA configuration, particles are first classified by a primary DMA (DMA1) and then the classified aerosol is subsequently passed through a neutralizer to re-establish a known charge distribution before entering a second DMA, where the mobility spectrum is re-analysed. A major advantage of the TDMA system is the ability to experimentally resolve the contributions of singly and multiply charged particles. To calculate the fraction of each charged particles, the total number concentration under each peak (i.e., the integral of that peak) must be considered rather than the number concentration at the peak (Annex D, ISO 27891) (International Organization for Standardization, 2020).

In comparing the MCC factor calculation approach discussed in ISO Annex G (International Organization for Standardization, 2020), the stepping measurement method is evaluated. Figure 8 shows the MCC measurements for 100nm. The stepping method is evaluated for three different voltages 1U, 2U and 3U.

https://doi.org/10.5194/ar-2026-33
Preprint. Discussion started: 25 September 2026

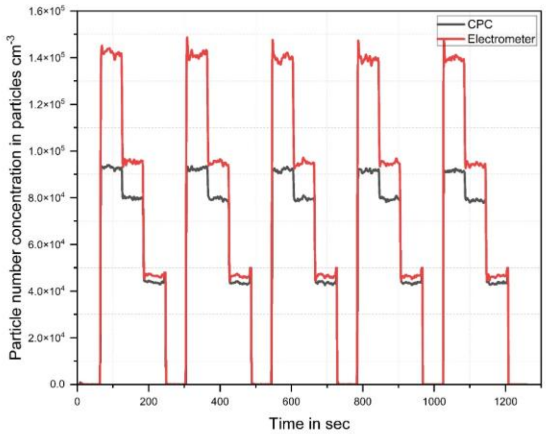

Figure 8 Stepping approach for MCC factor evaluation

Figure 9 shows an exemplary size distribution of polydisperse particles produced by the soot generator (black line) with a count mean diameter of around 100 nm. This figure also shows the distribution of particles size selected at 100 nm by the second DMA (red line).

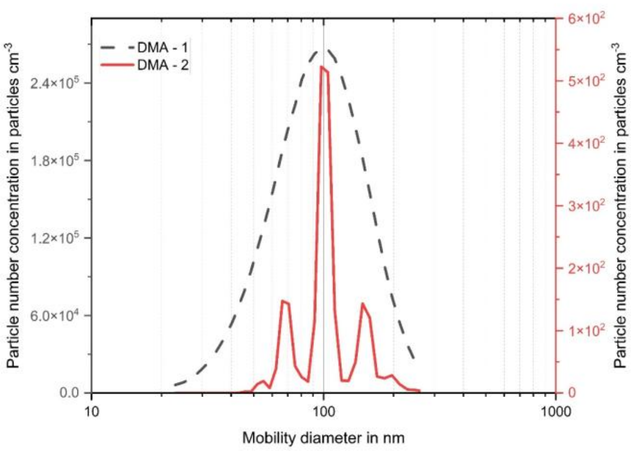

Figure 9 Size distributions of polydisperse 100 nm soot particles (black) and particles size selected at 100 nm using the first DMA (red).

To minimize the multiply charges present in the selected monodisperse size range of DMA 2, we modified the TDMA setup by shifting the DMA 1 peak to the left side. As shown in Figure 10 the polydisperse particle size distribution in DMA 1 is at 70 nm and the selected diameter size is at 100nm. With this approach, we minimize the effect of multiple charged particles fraction in the monodisperse spectra of DMA 2 to be closer on the theory like bipolar approximation (Mamakos, 2016). When

https://doi.org/10.5194/ar-2026-33
Preprint. Discussion started: 25 September 2026

compared with the method discussed in ISO-27891 (International Organization for Standardization, 2020), The proposed approach yields a multiply charge correction of less than 10%.

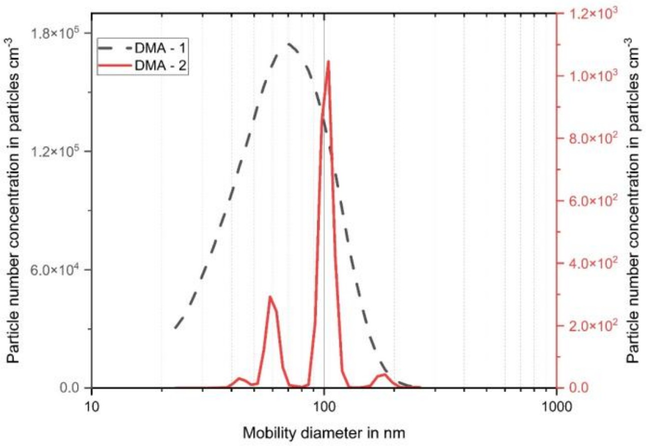

Figure 10 Size distributions of polydisperse 70 nm soot particles (black) and particles size selected at 100 nm using the first DMA (red).

Figure 11 illustrates graphical representative example of counting efficiency curves for the TSI Faraday Cup Aerosol Electrometer 3068B and TSI CPC 3750. The dashed line indicates the ideal counting efficiency, while the blue and yellow symbols show the counting efficiency after correction for flow and splitter bias, with and without correction scheme of the multiple charges.

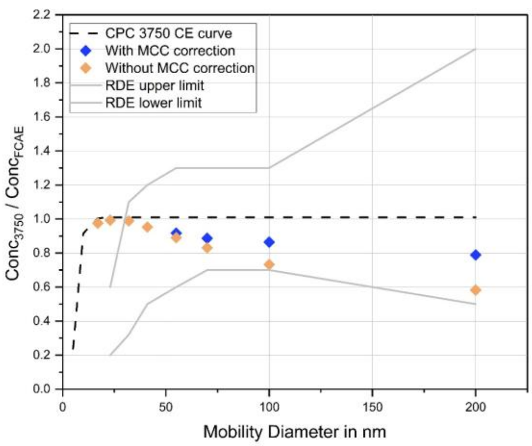

Figure 11 Graphical representation of counting efficiency for TSI FCAE and TSI CPC 3750 with different correction schemes for MCC

https://doi.org/10.5194/ar-2026-33
Preprint. Discussion started: 25 September 2026

Beside this, Table 1 shows the given standard operation points for determining multiply charge fractions for most of the soot measurements at PTB to perform calibration for counting efficiency of particle number counters.

Table 1 Polydisperse and monodisperse size-selected particles for SOPs at PTB TDMA to calculate fraction of multiply charged particles.

Mean diameter of polydisperse particles of DMA 1 in nm	Total concentration of polydisperse particles in particles cm^{-3}	Diameter of particles selected by DMA 2 in nm
50	$5\times10^6 – 7\times10^6$	70
50	$5\times10^6 – 7\times10^6$	100
70	$5\times10^6 – 7\times10^6$	200
115	$5\times10^6 – 7\times10^6$	250
115	$5\times10^6 – 7\times10^6$	300

3 Results and Discussion

The linearity and counting efficiency of the particle counters (including PN-PTI counters) were evaluated in accordance with the requirements of ISO 27891 (International Organization for Standardization, 2020). A calibrated aerosol electrometer was used as the reference instrument for determining the particle number concentration.

3.1 Calibration facility for particle counter with PTB Primary Standard

The primary standards are essential for ensuring a robust calibration infrastructure in aerosol measurements. The traceability of the FCAE is established through regular calibration at the Physikalisch-Technische Bundesanstalt (PTB). Since 2013, the PTB TSI 3068B FCAE has been calibrated annually over an electrical current range of 2 fA - 200 fA and a corresponding flow range of 1 - 4 L min^{-1}. In addition, PTB participates in international key comparisons to establish and validate its Calibration and Measurement Capabilities (CMCs) (Brown et al., 2023). These comparisons provide independent verification of measurement equivalence among national metrology institutes and support the mutual recognition of national standards. These activities ensure the accuracy and reliability of the FCAE and maintain a robust and internationally traceable measurement chain for aerosol measurements.

Figure 12 shows the long-term stability of the PTBs FCAE as a primary aerosol standard was evaluated by comparing its measured current to the PTB national standard (Brown et al., 2023). The relative deviation between the FCAE and the national standard was analysed, and a linear regression was applied to quantify any drift. These long-term results demonstrate that the FCAE maintains a stable relationship to the national standard over more than a decade, thereby confirming its suitability as a primary aerosol standard for measurements.

https://doi.org/10.5194/ar-2026-33
Preprint. Discussion started: 25 September 2026

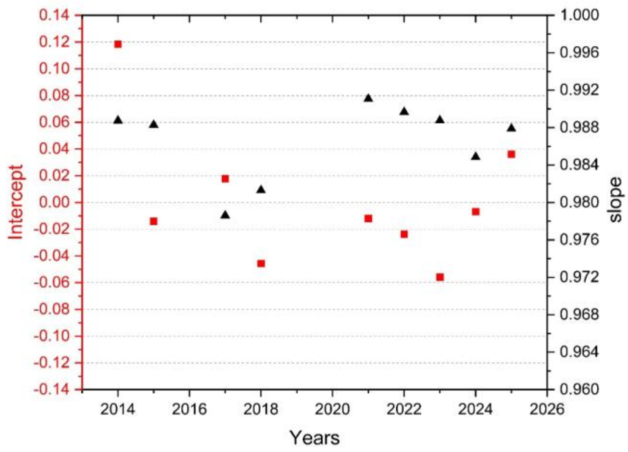

Figure 12 The long-term stability of the PTBs FCAE as a primary aerosol standard over the period from 2013 to 2025

In Figure 12, data is plotted using the linear regression equation which is defined as:

$$y= mx + b \quad (1)$$

Where,

y = FCAE (primary aerosol standard)

x = PTB national standard for current

m = slope

b = intercept

As shown in Figure 3, PTB calibration facility is mainly used for internal quality checks for reference counters as well as for DUTs, which can be PTI counters, Diffusion Chargers or CPC of customers. Firstly, linearity measurements were performed, followed by counting efficiency measurements.

3.1.1 Linearity Measurements of reference CPCs:

Linearity measurements were performed for a monodisperse solid soot particles at 70 nm with concentrations ranging from 1000 cm^{-3} to 20 000 cm^{-3}, where PTB is using the optimal range of current CMC (Brown et al., 2023). The measured data were evaluated by applying the following corrections:

1. Correction of reference particle counter concentration in accordance with calibration certificate
2. FCAE linearity fit correction against national norm of electric current
3. Device flow correction
4. Diffusion loss correction
5. Multiple charge correction (new approach)

https://doi.org/10.5194/ar-2026-33
Preprint. Discussion started: 25 September 2026

Figure 13 shows an example of linearity measurements and the corresponding evaluation for particles with a mobility diameter of 70 nm, obtained using a TSI Electrometer and a TSI 3750 CPC. The long term intercomparison for linearity measurements at 70 nm for TSI Electrometer and TSI CPC 3750 over past several years is shown in Figure 14.

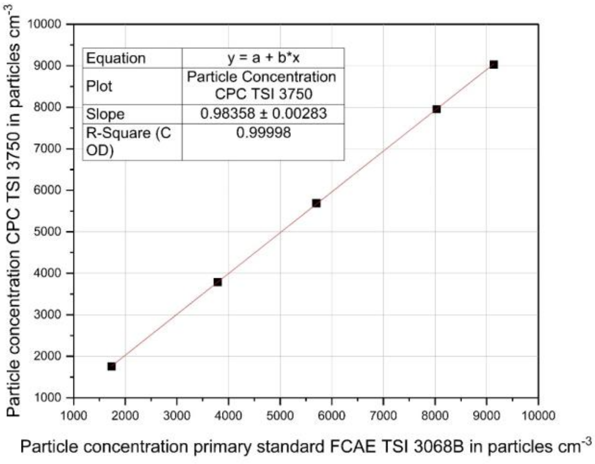

Figure 13 Linearity measurements at 70nm, TSI Electrometer and one example for TSI CPC 3750

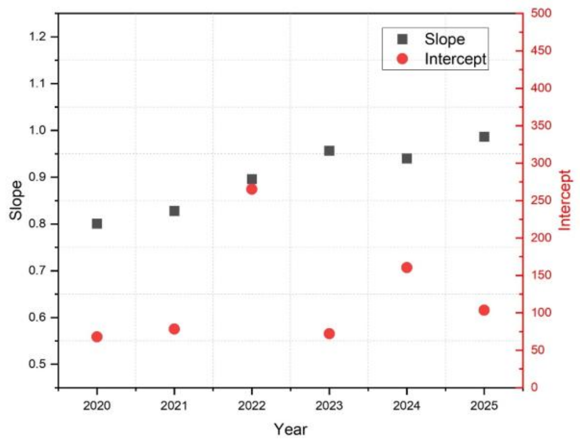

Figure 14 Long term intercomparison for linearity measurements at 70nm for TSI Electrometer and TSI CPC 3750 over past several years

3.1.2 Counting Efficiency Measurements for reference CPC

The counting efficiency was determined for particle sizes (17 nm, 23 nm, 30 nm, 50 nm, 70 nm, 100 nm, and 200 nm). The fraction of multiply charged particles at each particle size (> 50 nm) shall be measured and not exceed 10% as recommended

https://doi.org/10.5194/ar-2026-33
Preprint. Discussion started: 25 September 2026

by ISO 27891 (International Organization for Standardization, 2020), hence the modified setup was used. The procedure to ensure the requirement for multiply charged particles was explained in above sections.

CPC efficiency is defined as the ratio of the particle number concentration measured by the reference CPC to that measured by the primary FCAE during parallel measurements of a monodisperse aerosol with mobility diameter d_p with concentrations normalized to identical temperature and pressure conditions. Therefore, the counting efficiency of reference CPC is calculated as follows:

$$\eta(d_p) = Conc\ CPC(d_p)\ /\ Conc\ FCAE(d_p) \qquad (2)$$

Figure 15 presents the size dependent counting efficiency of FCAE - 3068B and CPC - 3750 using soot aerosol at different diameters.

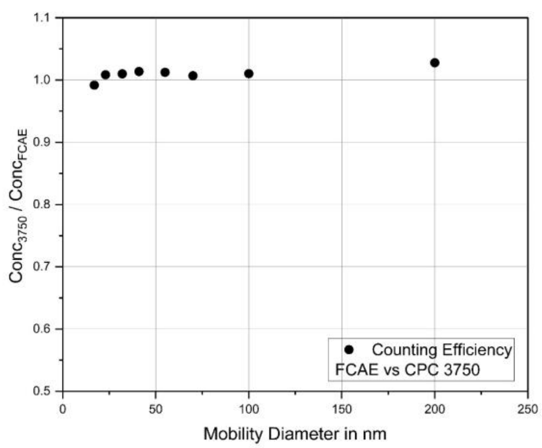

Figure 15 Counting efficiency TSI - Electrometer 3068B and TSI CPC 3750

3.2 Results for DUTs like PTI particle number counters

Several devices under test, including CPC-based and diffusion charger-based particle number counters, were evaluated using the PTB calibration facility.

The current regulations (RDE3_Regulation_2017-1154) require that the material used for counting efficiency tests should be thermally stable soot-like particles (such as miniCAST soot conditioned in a catalytic stripper). Counting efficiency measurements using soot particles with different monodisperse particle diameters ranging 23 nm – 190 nm are shown in Figure 16. Particle Number Concentrations (PNC) for the reference counter is in the range of 5 000 particles cm^{-3} to 20 000 particles cm^{-3} which is traceable via the particle number CMC of the PTB.

https://doi.org/10.5194/ar-2026-33
Preprint. Discussion started: 25 September 2026

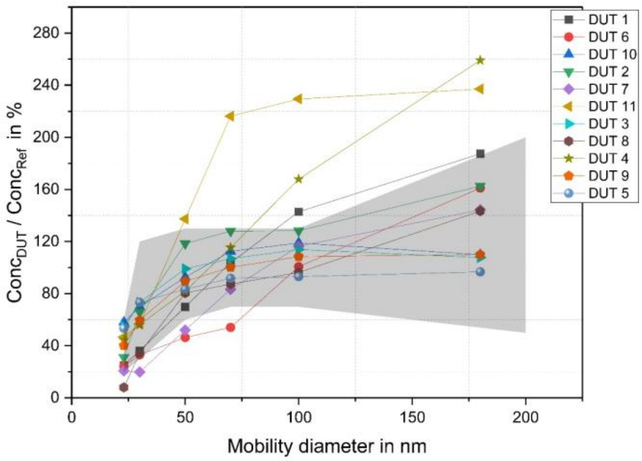

Figure 16 Counting efficiency curve with different Devices Under Test

Linearity measurements were conducted using a polydisperse salt aerosol with a particle diameter of approximately 70 nm. Particle number concentrations were varied between 1.5 × 10^4 particles cm^{-3} and 5.0 × 10^5 particles cm^{-3}. The response of multiple devices under test (DUTs) was evaluated relative to a reference condensation particle counter (TSI CPC 3750). The aerosol was distributed via a four-way flow splitter supplying the DUT, the reference CPC, and a mobility particle size spectrometer (MPSS) system. The MPSS was used to continuously monitor the particle size distribution during the measurements.

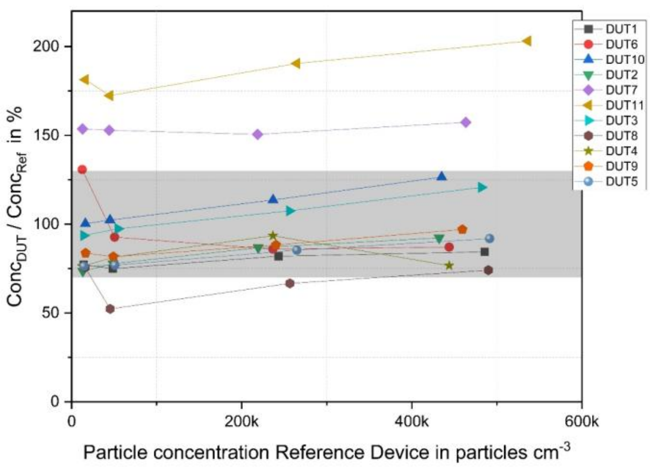

Figure 17 Linearity measurements with different Devices Under Test (DUT)

Figure 17 shows the measured linearity results for different DUTs participated. Most of the DUTs performed well and stayed within the specified range.

https://doi.org/10.5194/ar-2026-33
Preprint. Discussion started: 25 September 2026

4 Measurement uncertainties

Figure 18 presents the hierarchical traceability chain of the PTB's calibration facility for the metric PNC. As per standard documents (Molzahn et al., 2025),(DIN EN ISO/IEC 17025:2018-03, 2018), the combined standard uncertainty of a measurement is expressed as the combination of several individual uncertainty components, which are evaluated using either Type A or Type B methods. Type A uncertainty evaluation is based on the statistical evaluation of measurements results through repeated observations. The Type A uncertainty evaluation therefore reflects the intrinsic variability of the measurement and calibration process. Type B uncertainty covers all other known contributions, which are not evaluated by repetition but rather by prior knowledge or supporting literature evidence. At PTB also, the evaluation of uncertainties in PN measurements follows the same principle: the Type A component is first established from the variability of repetitive N measurements corresponding to calibration points (Diameter and PN) at each level, while the Type B component is determined based on the existing literature through internal investigations and knowledge gained from international (within NMIs) round robin exercises. Following is a framework developed for deriving the combined uncertainty in PN measurements at each calibration stage of the pyramid.

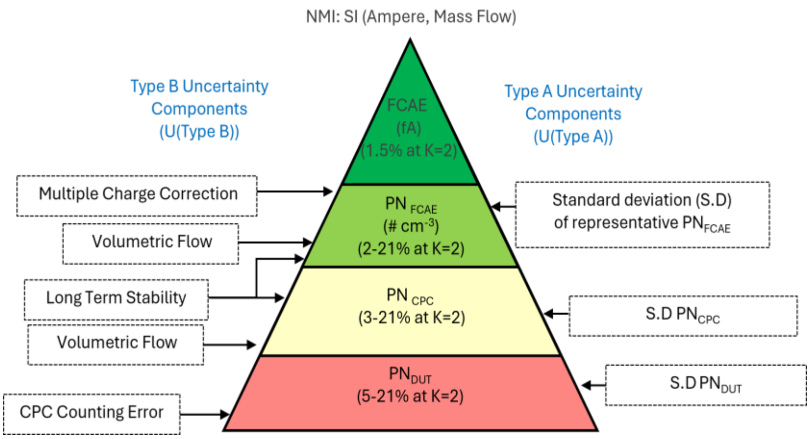

Figure 18 The hierarchical traceability chain of PNC metric for emission measurements in Germany. At each step, the combined uncertainty is calculated as the positive square root of the total combined variance. This total variance is the sum of the combined variance propagated from the previous level and the variances of all new uncertainty components introduced at the current level, properly weighted by their respective sensitivity coefficients.

As mentioned earlier, the PNC measurements are traceable to the FCAE, which is maintained at the PTB as the primary reference standard for the PN measurements (ISO 27891). Starting from the FCAE, that measures the electrical current i.e., the total charges passing through a given cross section per second. The current measurement of FCAE is traceable to primary electrical standards at NMIs, typically with an uncertainty of about 0.03 % (at 200 fA) to 2.5 % (at 2 fA). The current measured by FCAE is related to the number of particles per cm^3 as per following equation (Molzahn et al., 2025).

https://doi.org/10.5194/ar-2026-33
Preprint. Discussion started: 25 September 2026

$$N = \frac{I}{e \times n_p \times q} \tag{3}$$

Where,

N = Particle number concentration (particles cm^{-3})

I = Electrical current measured by FCAE (A)

n_p = Number of charges per particles

q = volumetric flow rate (cm^3 s^{-1})

e = elementary unit of charge (1.602 x 10^{-19} C)

Subsequently deriving the total particle concentration introduces additional Type B uncertainties, primarily from the mass flow meter (and subsequent conversion of mass flow into volume flow) and corrections for multiply charged particles, apart from these, other contributing factor are long-term stability of instrument, and stability (in terms of standard deviation) of calibration setup itself. Under well-controlled conditions, the combined expanded uncertainty (k=2) of PN measurements with the FCAE (U_c (PN_{FCAE})) is achievable to be below 2 % for PN ~20 000 particles cm^{-3} and can be as high as 21 % for PN ~1 000 particles cm^{-3}. However, the uncertainty limits are expected to be revised to a much lower values after acceptance of newly submitted CMCs. The derived combined uncertainty in PN_{FCAE} subsequently propagates as the type B relative uncertainty when FCAE is used as a reference device for subsequent calibration of CPCs. Furthermore, the new uncertainty components in the form of volumetric flow, and type A uncertainties of CPC are also introduced at this stage ((DIN EN 16976:2024-09, 2024)). Subsequently, the uncertainties in PN_{CPC} calibrated against reference CPC are a bit higher (3% for PN ~20 000 particles cm^{-3} and 21 % for PN ~1 000 particles cm^{-3}) than the FCAE. However, as mentioned this uncertainty limits are expected to be revised to much lower values after acceptance of newly submitted CMCs.

5. Summary and outlook

We presented a comprehensive metrological facility at the Physikalisch-Technische Bundesanstalt (PTB) for the calibration of particle number counters (PNCs) against an SI traceable Faraday Cup Aerosol Electrometer (FCAE) that is regularly used to calibrate reference particle number counters for end users in the field of automotive emission like homologation, RDE and PTI applications. The facility enables rigorous determination of counting efficiencies for particle number counters across electrical mobility particle diameter ranges from 17 nm to 200 nm and assesses linearity over controlled particle number concentrations representative for emission of soot particles by combustion engines. Thermally stable soot aerosol particles are generated by a diffusion flame generator and conditioned with a catalytic stripper to remove volatile components. The particles were size classified using differential mobility analysis and delivered via a well characterised multi flow splitter to both reference devices and devices under test (DUT) under identical sampling and laboratory conditions.

Systematic corrections for volumetric flow deviations, diffusion losses, splitter bias, and effects of multiple charging were applied to enhance traceability and reduce measurement uncertainty. The PTB facility provides an experimental platform for quantitative evaluation of aerosol instrument performance with traceable uncertainty quantification, addressing ongoing needs for intercomparison studies and calibration chains in aerosol metrology. Future work will focus on extending calibration capabilities to smaller particle diameters and broader concentration ranges, as well as further reducing overall measurement uncertainty in alignment with state-of-the-art aerosol instrument calibration studies.

Code availability

Software for data evaluations and laboratory setup are written internally using labview and excel which may not be provided but can be discussed openly.

Author Contributions

AW: measurement setup, data evaluation, validation, methodology, review and editing. JS: soot generator evaluation, AM: measurement uncertainty. JR: measurement setup, evaluation, validation, review and editing. SP: review and editing, AN: measurement setup, methodology, review and editing

Competing interest

Author declares to have no conflict of interest

Disclaimer

Acknowledgements

I am thankful to the working group airborne nano particles for their deep discussion for improvement of our calibration facility. PTB's internal calibration facility to provide all the necessary equipment. Figure 5 Schematic of PTBs- Multi flow splitter (MFS) with 10 Ports was created using an AI tool.

Financial support

PTB internal funding for PNC calibration laboratories.

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Review Statement

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