Ultrastable Low-Noise Current Amplifiers With Extended Range and Improved Accuracy

(Ultrastable Low-Noise Current Amplifier → ULCA)

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Thanks to ...

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EMPIR EURAMET
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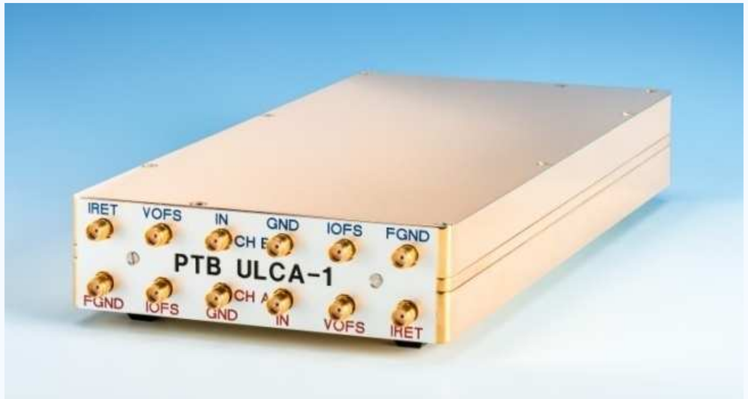
Outline:
- Introduction
- The “standard 3 GΩ ULCA”
- Second ULCA generation
- Conclusions



2012: Motivation for ULCA development

- Realization of ampere based on single-electron transport (SET) current sources
  $\rightarrow$ **I_{SET} = 100 pA**

- Goal: Measure **100 pA** with **10^{-7}** total uncertainty (k = 1, including type B)
  $\rightarrow$ Total uncertainty: **10^{-17} A = 10 aA = 62 e/s**

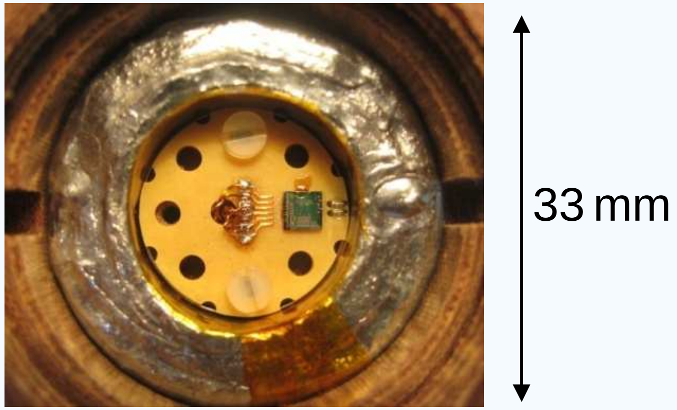
- PTB's CMC entry: **10 ppm** standard uncertainty at 100 pA (capacitor charging)

- 1 GΩ standard resistor calibrated with NPL CCC: **≈1 ppm** standard uncertainty

- Initial approach: **CCC** with **>10^4 turns** used as current amplifier

- SQUID serves as null detector

- Two limitations expected:
  SQUID nonlinearity & low-frequency noise

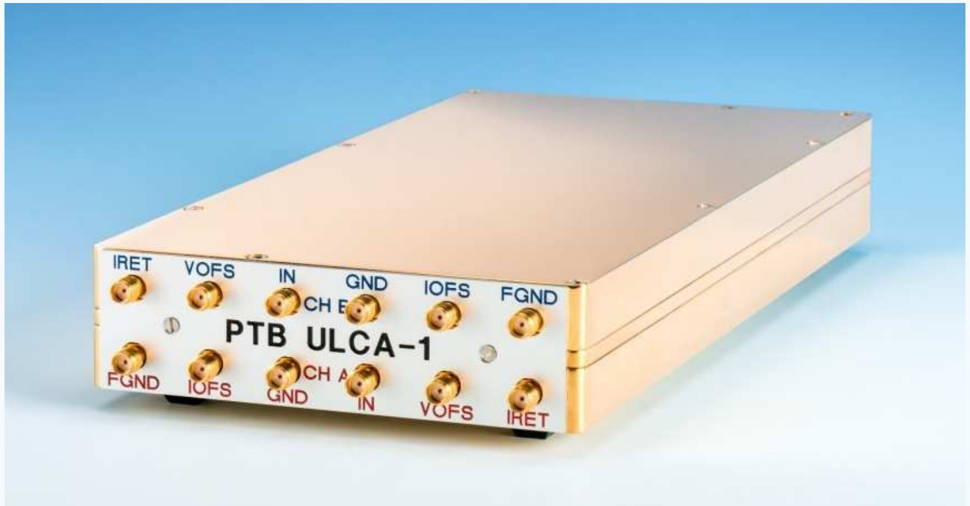


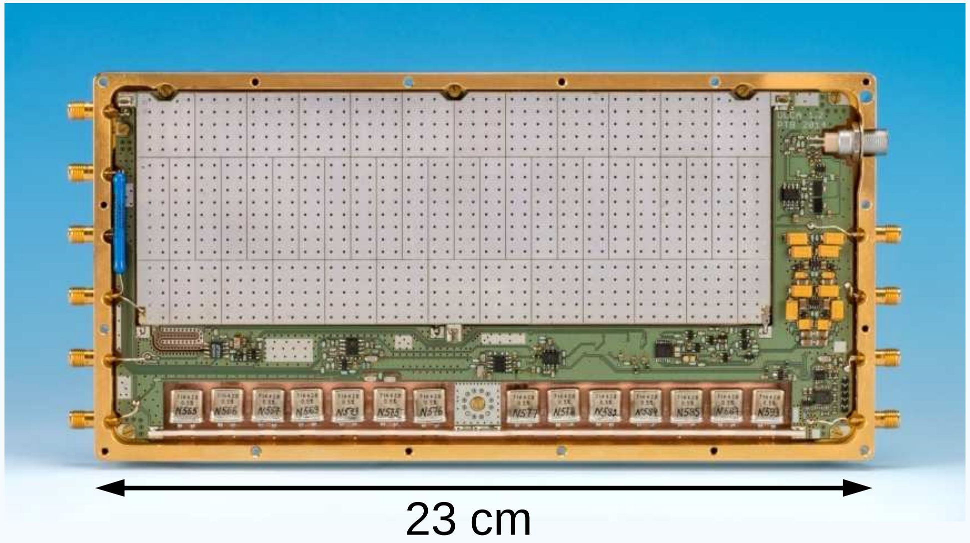
PTB 14-bit CCC
(18276 turns)

New Approach: The ULCA

Basic idea:

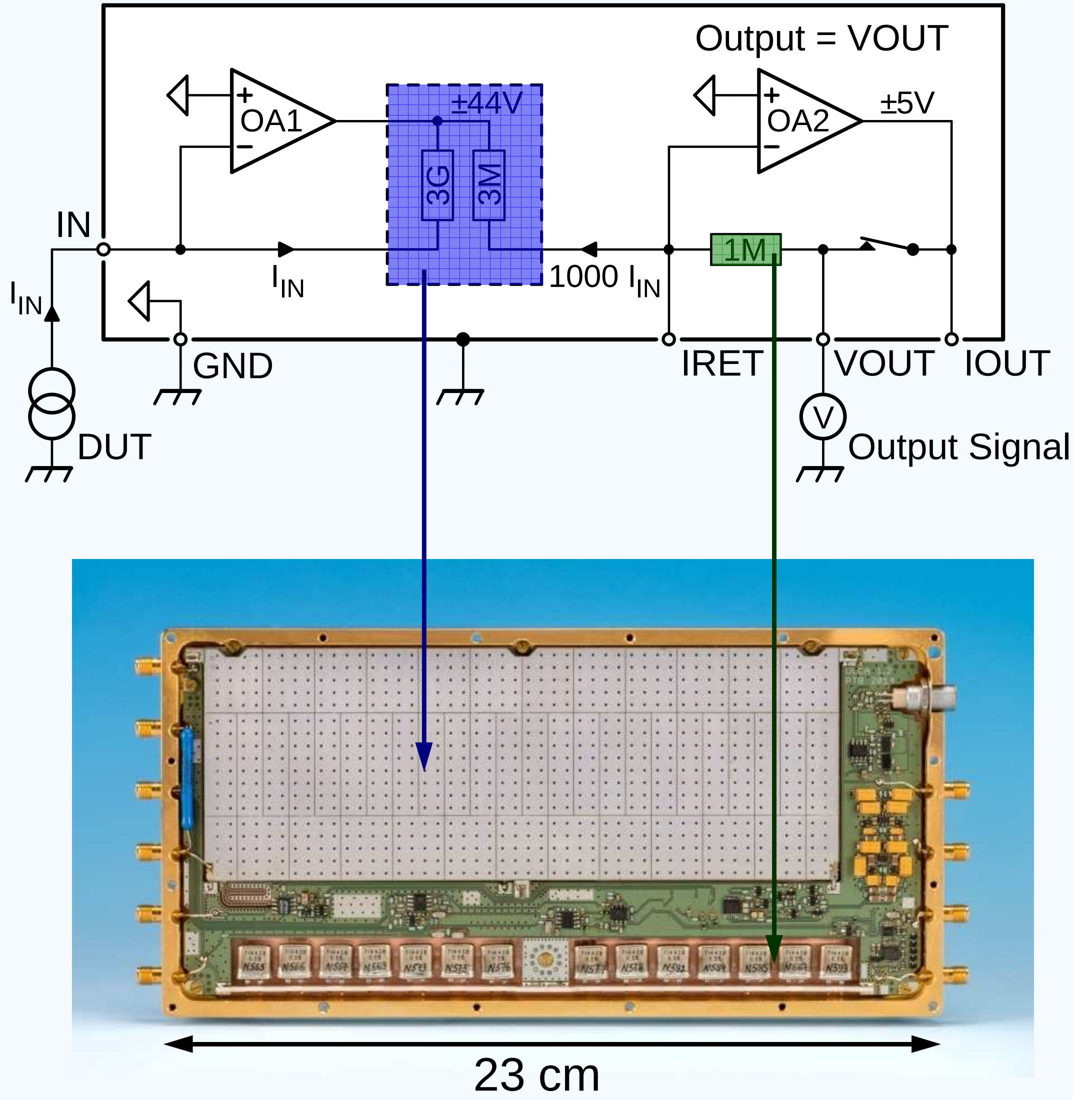
- Combine advantages of two technologies: CCC / semiconductor amplifier
- Use CCC for calibration at high current **≈10 nA** → **highest accuracy**
- Use semiconductor amplifier for measurement at **≈100 pA** → **lowest 1/*f* noise** → **highest user-friendliness** → **series production possible**





Basic ULCA Concept

(a) Voltage Output



- Input stage OA1 provides **1000-fold** current gain
- Thin-film resistor network with ≈ **3000** chip resistors (much better than thick-film)
- Output stage OA2 performs current-to-voltage conversion
- Voltage output: internal 1 MΩ metal-foil resistor
  → $\boldsymbol{A_{TR} = V_{OUT} / I_{IN} = 1\ \mathrm{G\Omega}}$

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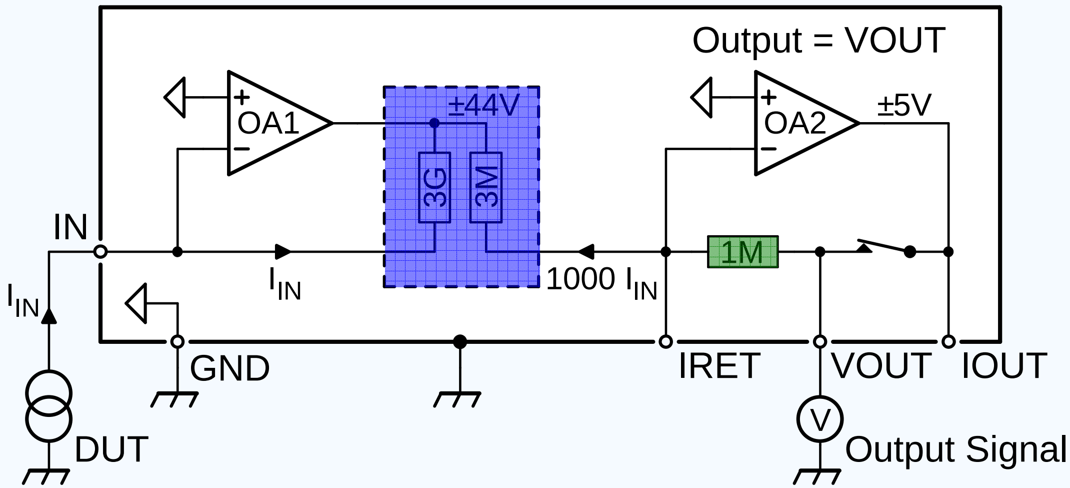
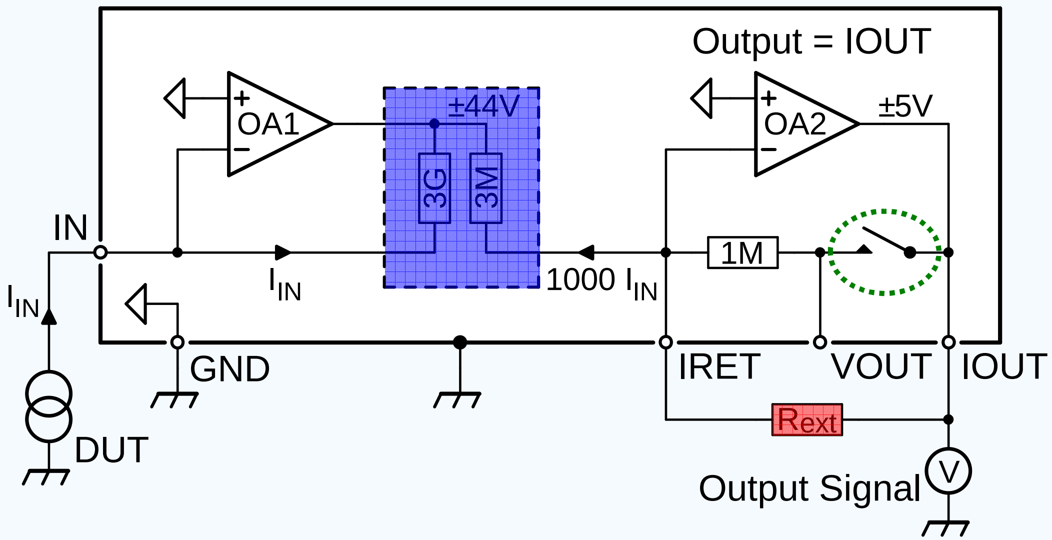


(b) Current Output



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- Current output: external resistor $\boldsymbol{R_{ext} = 0 - 100\,\mathrm{M\Omega}}$ (CCC coil or QHR possible)

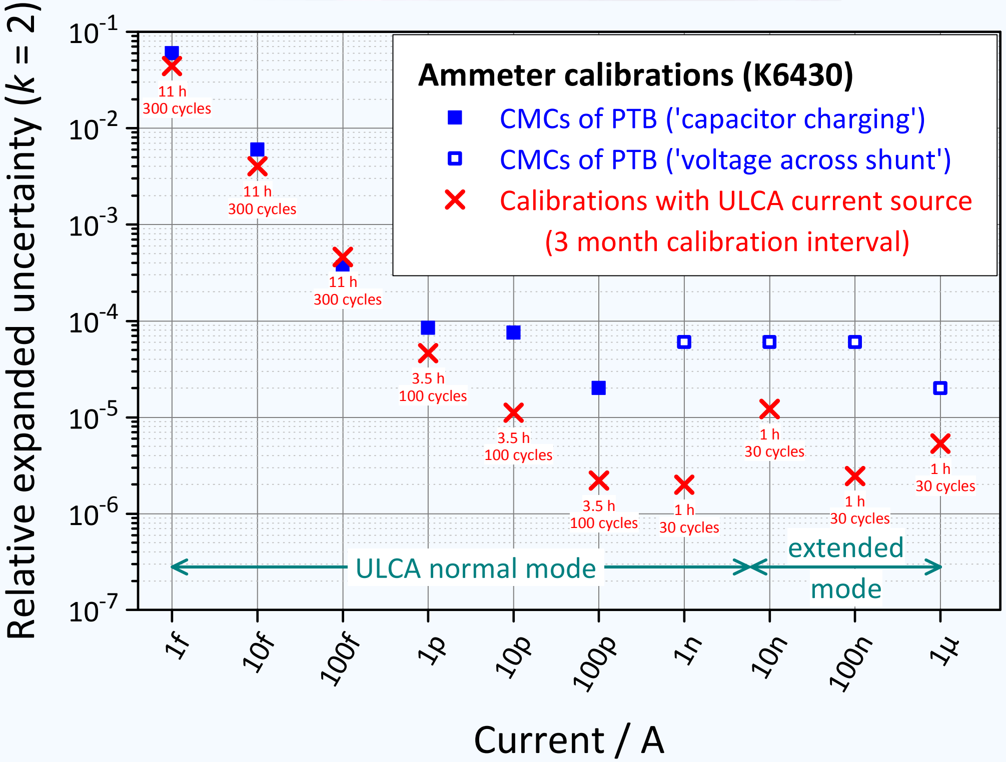
The “Standard 3 GΩ ULCA”

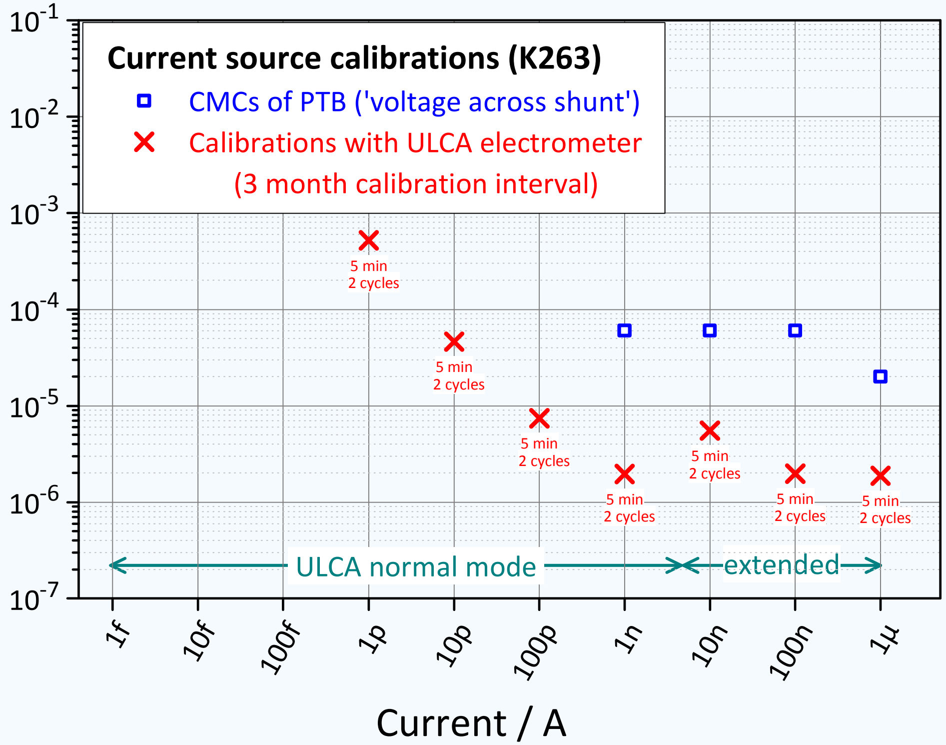
- Powered by two batteries (one charged while the other used for ULCA supply)
  → **uninterruptible earth-free battery operation**
- Well suited for current measurement & generation or resistance calibration
  → **Improved instrument for applications with fA to nA currents**
- Current range: **±5 nA** @ “normal” mode
  ±5 μA @ “extended” mode (output stage only)
- Excellent accuracy: **< 0.1 ppm** @ on-site calibration with PTB CCC
  < 1 ppm @ inter-lab comparisons
- Long-term stability: **≈ 2 ppm/yr** @ one year after assembling
  ≈ 1 ppm/yr @ two years after assembling
- Applications: Calibration of current sources and meters
  Calibration of high-value resistors
  Small-current travelling standard
  High-accuracy measurements of SET pumps

Calibration of Picoammeter and Source

Keithley 6430 picoammeter

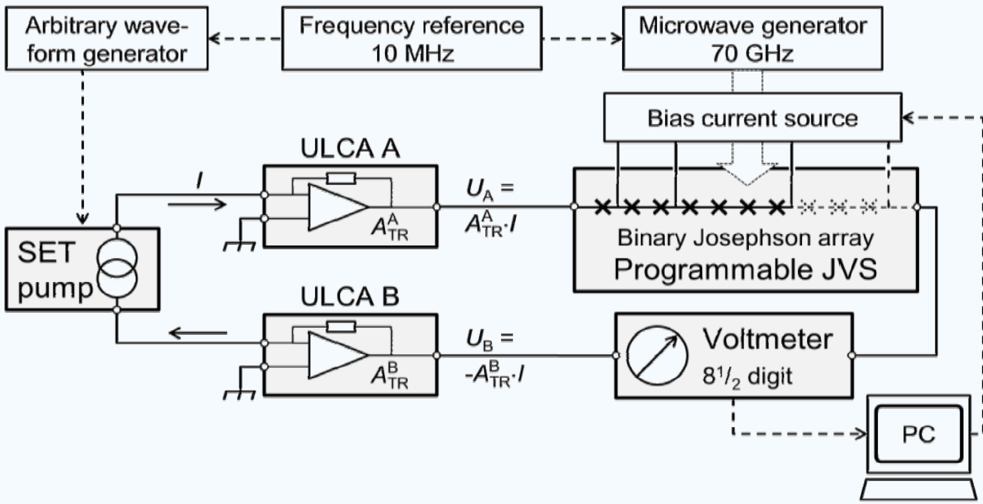
Keithley 263 current source

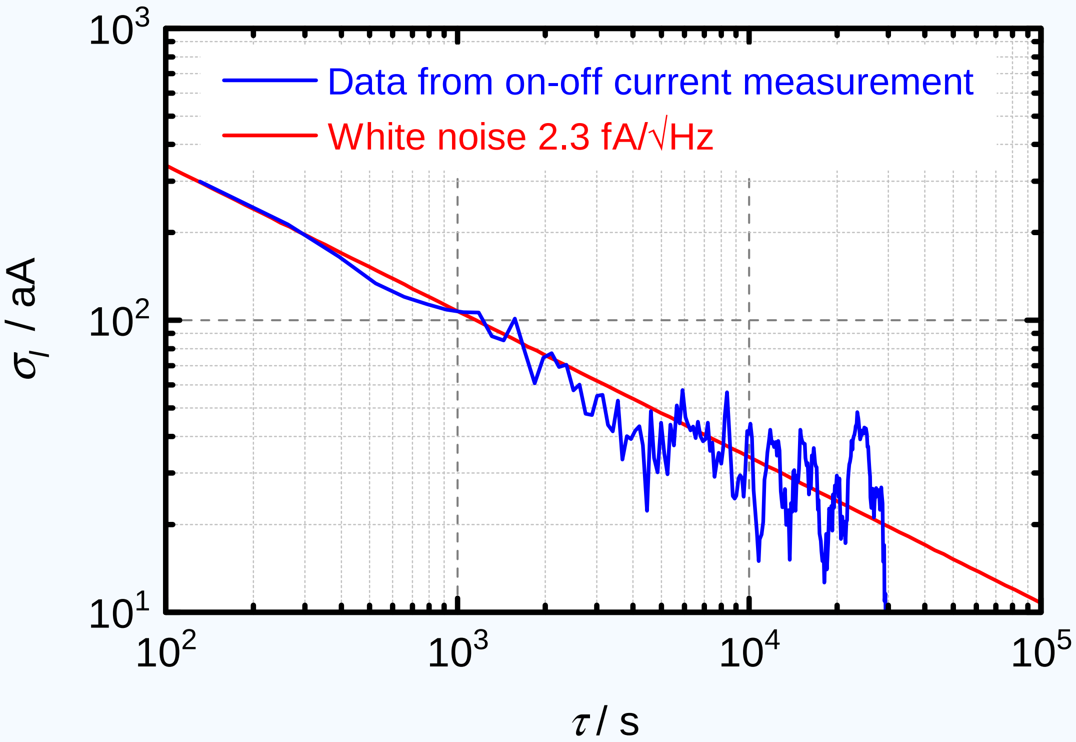




→ **Poster Tu-P20 by H. Scherer (Tuesday 15:00 - 16:00)**

High-Accuracy Measurements on SET Pumps





- Two 3 GΩ ULCAs measure $\pm I_{SET}$
- ΔV_{OUT} measured against JVS
  - → **Noise reduced by factor √2**
  - → **Influence of DVM negligible**
- Uncertainty **0.16 ppm** in 21 hours (combined type A & B uncertainty)
- Cable noise ≈ ULCA noise

→ **Talk by F. Hohls (We-1 Quantum Standards III on Wednesday 10:30)**

Commercial 3 GΩ Variant ULCA-1

- Available from MAGNICON GmbH
  http://www.magnicon.com/metrology/
- Delivered in solid transport box
  with diverse accessory parts
  (100 MΩ, filter, divider, data logger)
- Includes PTB calibration certificate

Single-channel variant

Dual-channel variant

Battery box

Second ULCA Generation

The second ULCA generation addresses the following issues:

Improved accuracy at “high” currents

- **780 MΩ ULCA** with ±**50nA** range, **0.02 ppm** uncertainty → **4.7 fA/√Hz**
- Secondary standard for ULCA gain calibrations (“CCC replacement”)
- High-accuracy ampere realization for currents below the QHE/CCC range

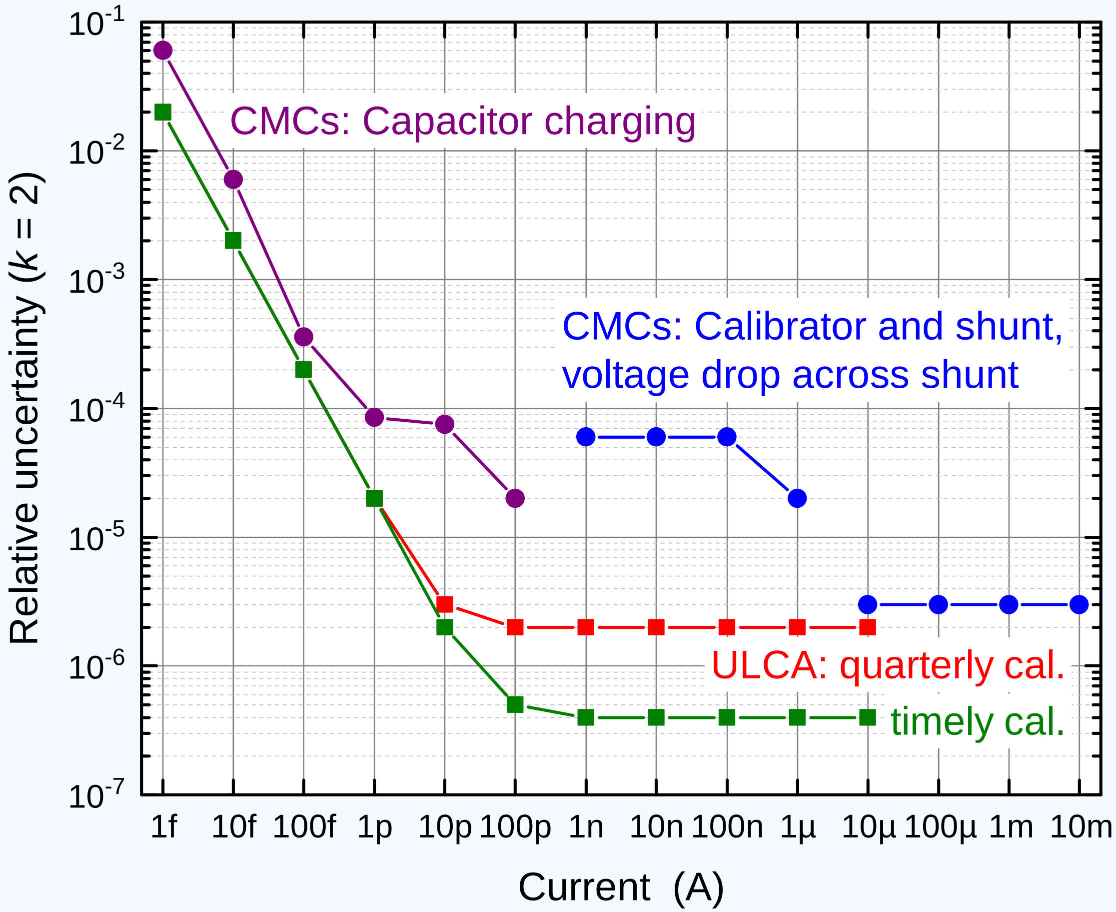
Improved noise at “low” currents

- **12 GΩ ULCA** with ±**3.6 nA** range, **< 0.1 ppm** uncertainty → **1.3 fA/√Hz**
- **60 GΩ ULCA** with ±**0.5 nA** range, ≈ **1 ppm** uncertainty → **0.7 fA/√Hz**
- Reduced measurement time / lower uncertainty

Minimum noise and input bias current at “ultralow” currents

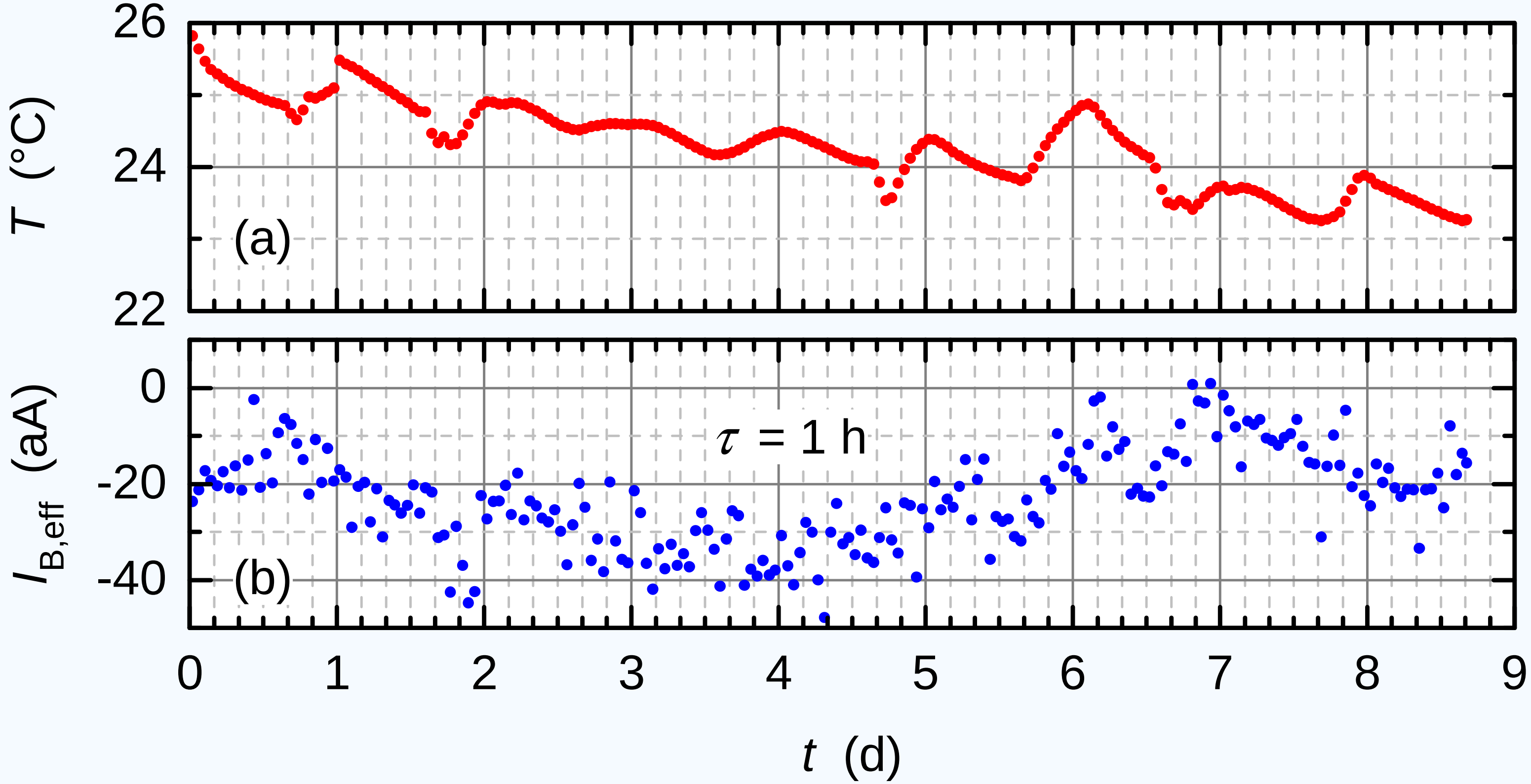
- **175 GΩ ULCA** with ±**5 pA** range, ≈ **10 ppm** uncertainty → **0.43 fA/√Hz**
- **10 aA** uncertainty in 17 minutes, **< 100 aA** input bias current
- Optimized for applications that do not allow current reversal or on/off switching

Improved Direct Current Standard



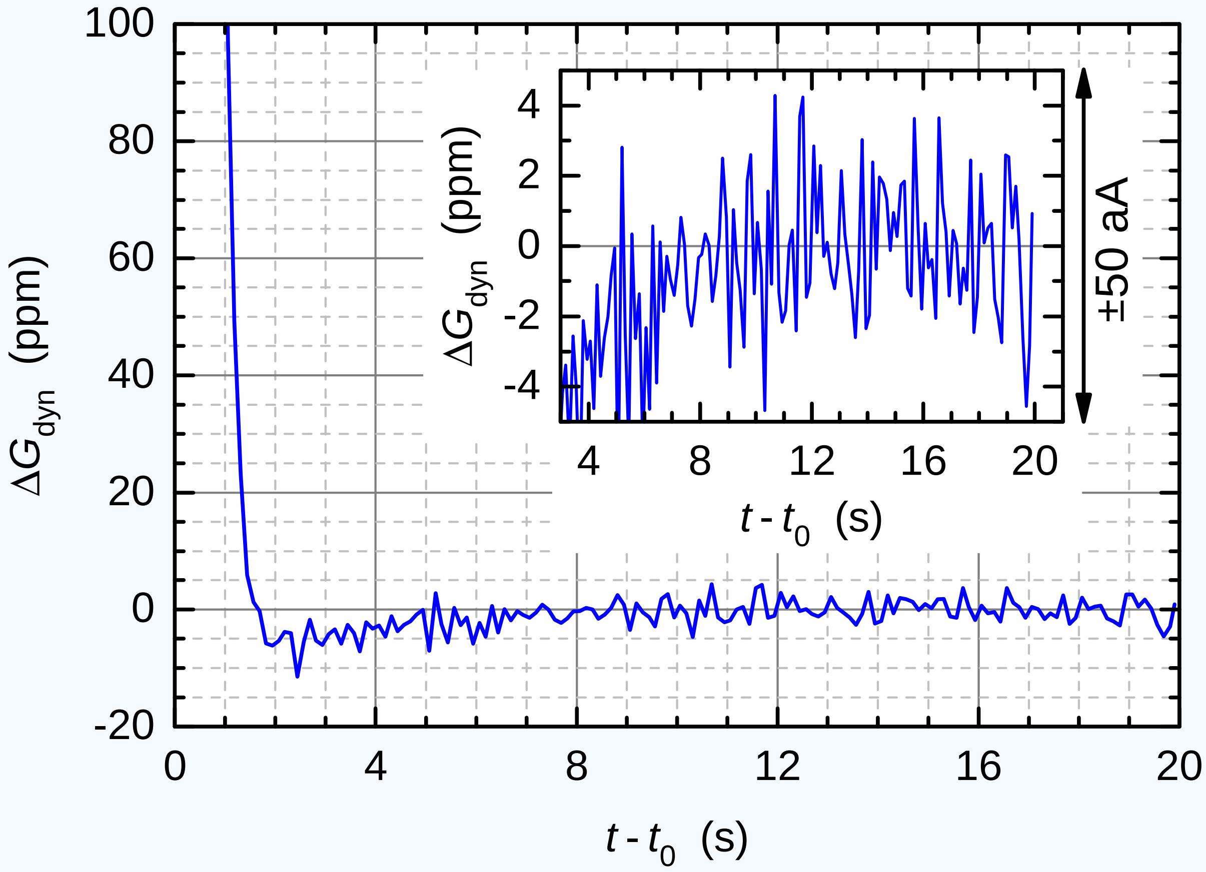
- Current range **< 50 µA**
- Two different ULCAs applied
  → **12 GΩ & 780 MΩ**
- Below 50 pA: ULCA cascade
  → $\boldsymbol{A_{TR}}$ **= 1000×100 MΩ = 100 GΩ**
- Above 50 nA: Extended mode
- Reduced uncertainties compared to present CMCs of PTB
- Performs better than 3 GΩ ULCA

Low-Bias ULCA: Input Bias Stability



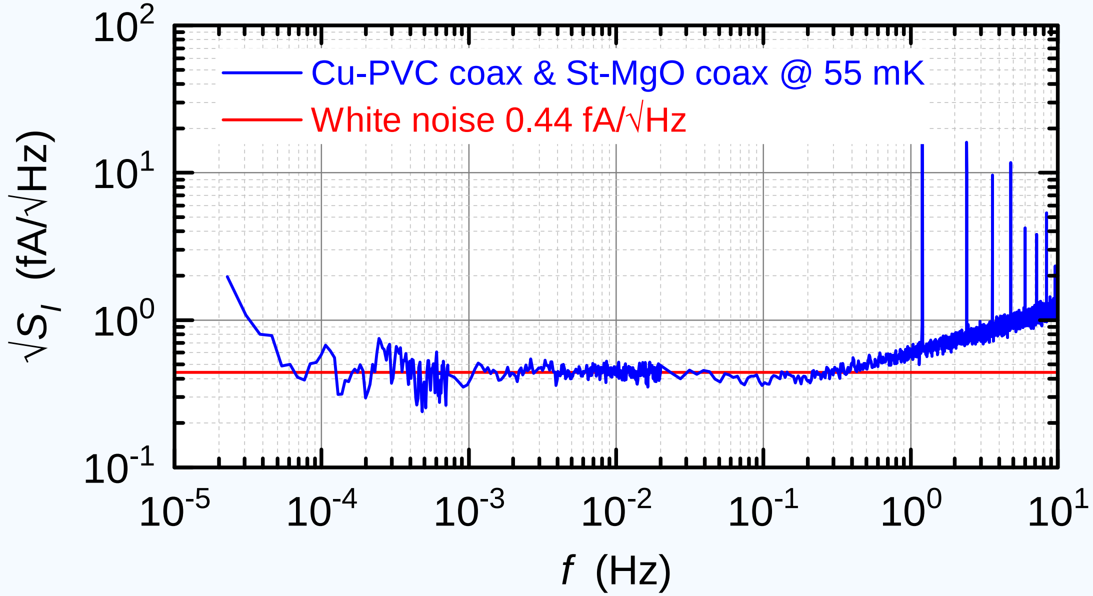
- No noticeable correlation between $I_{B,eff}$ and T at **10 aA level**
- True “attoampere performance”

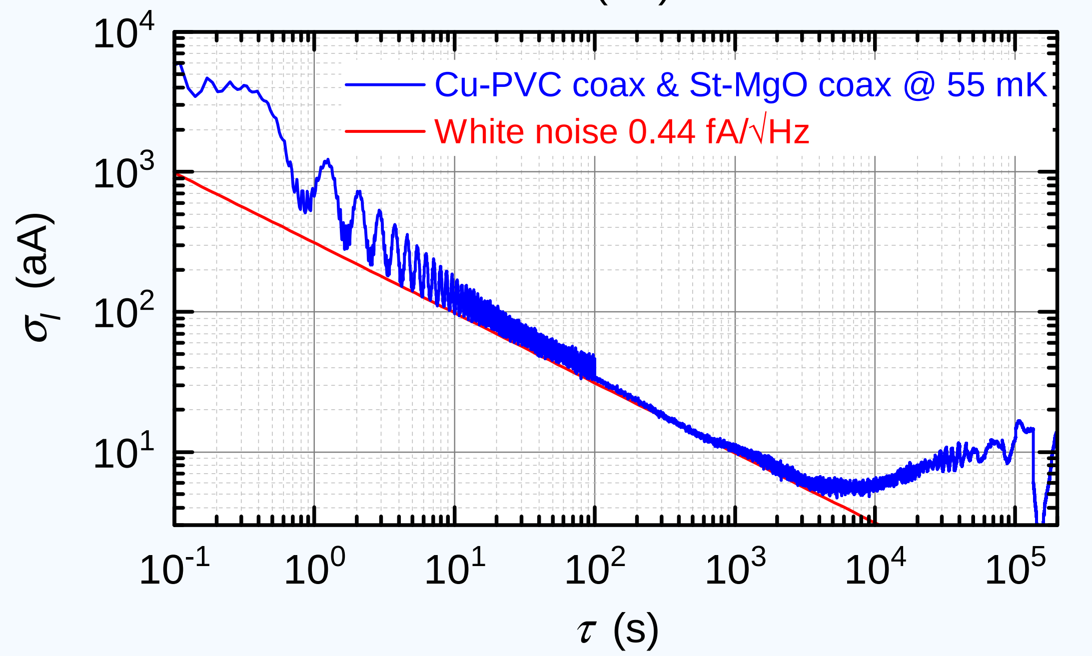
Low-Bias ULCA: Settling

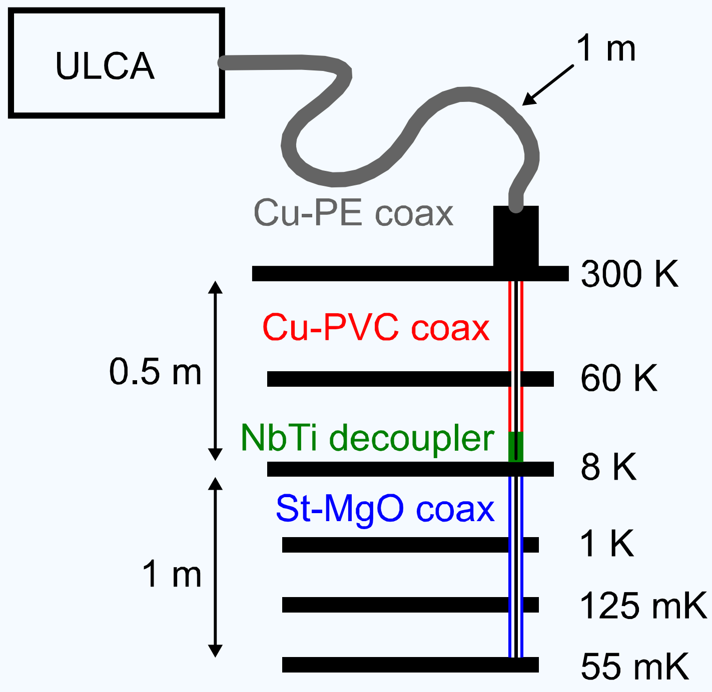


- **±5 pA** test current generated via 10 GΩ resistor
- Output settles to within **±5 ppm** or **±50 aA** after ≈ **4 s**

Low-Bias ULCA: Cable Noise Measurements







- Cable combination mounted in dilution fridge with pulse tube
- Total noise **0.44 fA/√Hz @ 55 mK**

→ **Poster Tu-P19 by C. Krause (Tuesday 14:00 - 15:00)**

Conclusions

- ULCA optimized for characterization of SET devices
  → **100 pA with 0.1 ppm uncertainty in 7 hours (two 12 GΩ ULCAs)**

- Well suited for highly-accurate, traceable current measurement & generation and for resistance calibration
  → **Improved solution for applications with direct currents below 50 μA**

- Non-cryogenic and easy-to-use instrument with excellent long-term stability

- Sets new accuracy benchmarks in small-current regime
  → **Improves state-of-the-art by up to two orders of magnitude**

- 3 GΩ ULCA commercially available, 2nd generation scheduled for early 2017
  MAGNICON GmbH http://www.magnicon.com/metrology/

- More information: Drung et al., *Rev. Sci. Instrum.* **86**, 024703 (2015)
  Drung et al., *IEEE Trans. Instrum. Meas.* **64**, 3021 (2015)
  Drung et al., *Metrologia* **52**, 756 (2015)
  Stein et al., *Appl. Phys. Lett.* **107**, 103501 (2015)