IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January 2016.
KRYO 2015 tutorial presentation. Not submitted for publication.

Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
National Metrology Institute

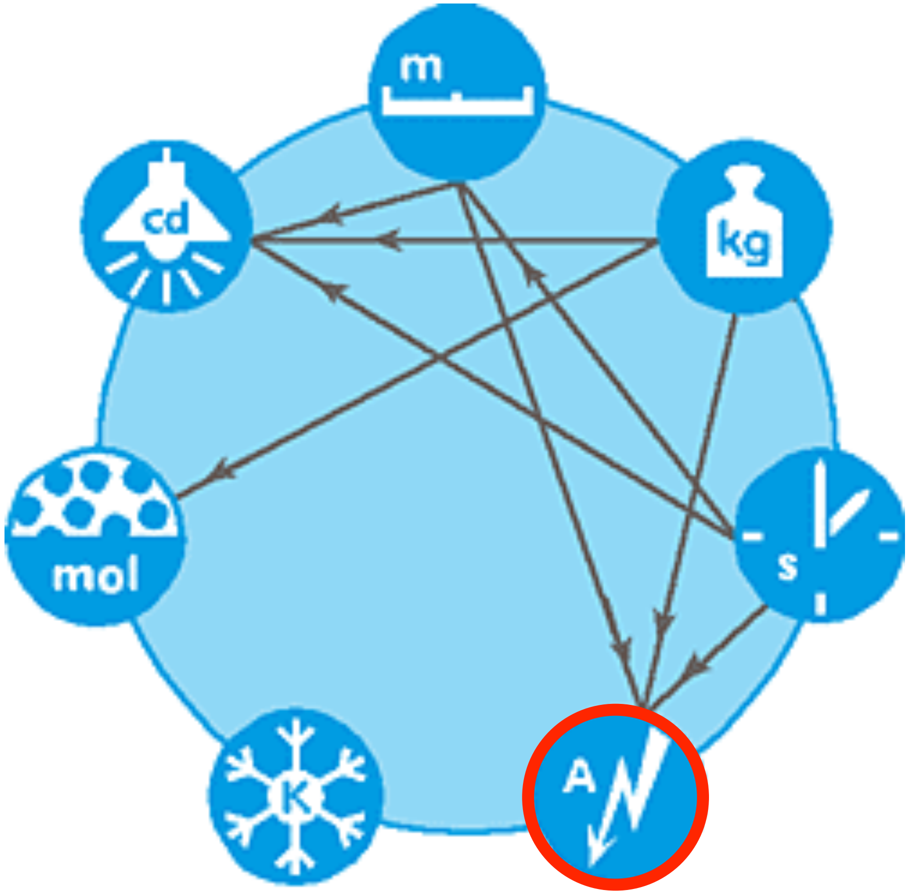
Single-electron transport and the new standard for electrical current

Hansjörg Scherer
PTB department 2.6 „Electrical quantum metrology“

Talk outline

- SI unit system and the ampere
- Single-electron current sources in general ('classical' and 'modern' devices....)
- Future "quantum ampere" realisation based on single-electron devices: Concepts and challenges
- Recent developments and advances
- Conclusions & outlook

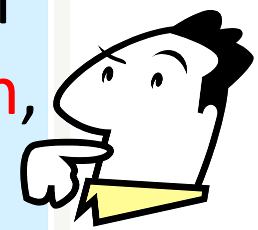
Système International d' Unités (SI) - since 1960



The ampere is the SI unit of electric current and is <u>the electrical base unit.</u>

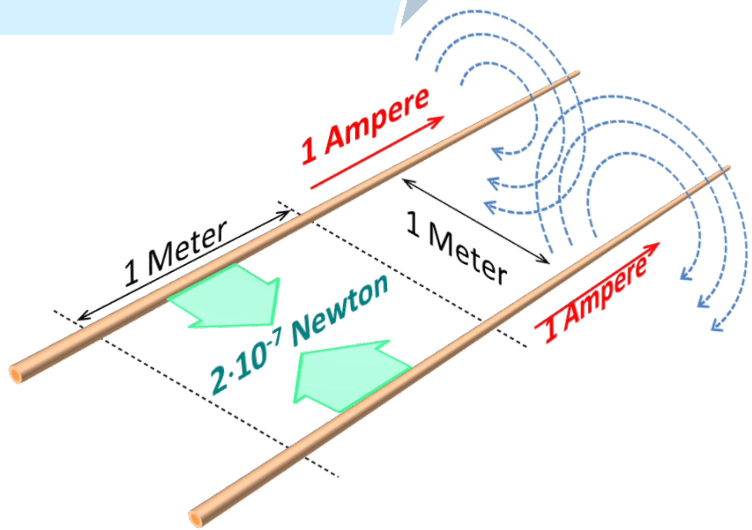
SI definition of the ampere

The ampere is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 metre apart in vacuum, would produce between these conductors a force equal to 2 x 10^{-7} newton per metre of length.



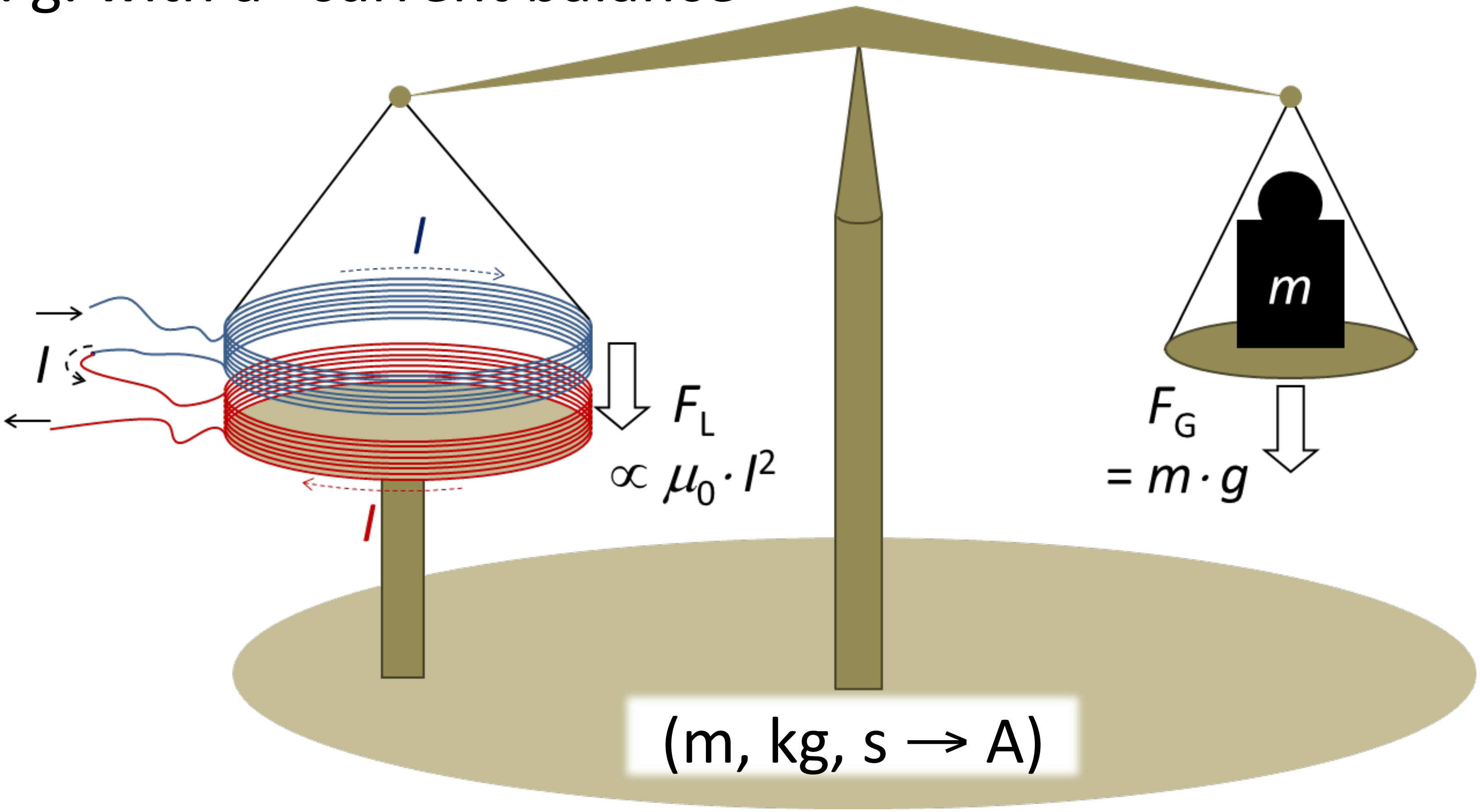
This definition

- **defines the values for the magnetic constant ($\mu_0 \equiv 4\pi \cdot 10^{-7}$ N/A^2) and for the electric constant $\varepsilon_0 = 1/\mu_0 c_0^2$**
- uses the action of force from electrical currents (m, kg, s → A)



Realisation of the SI ampere

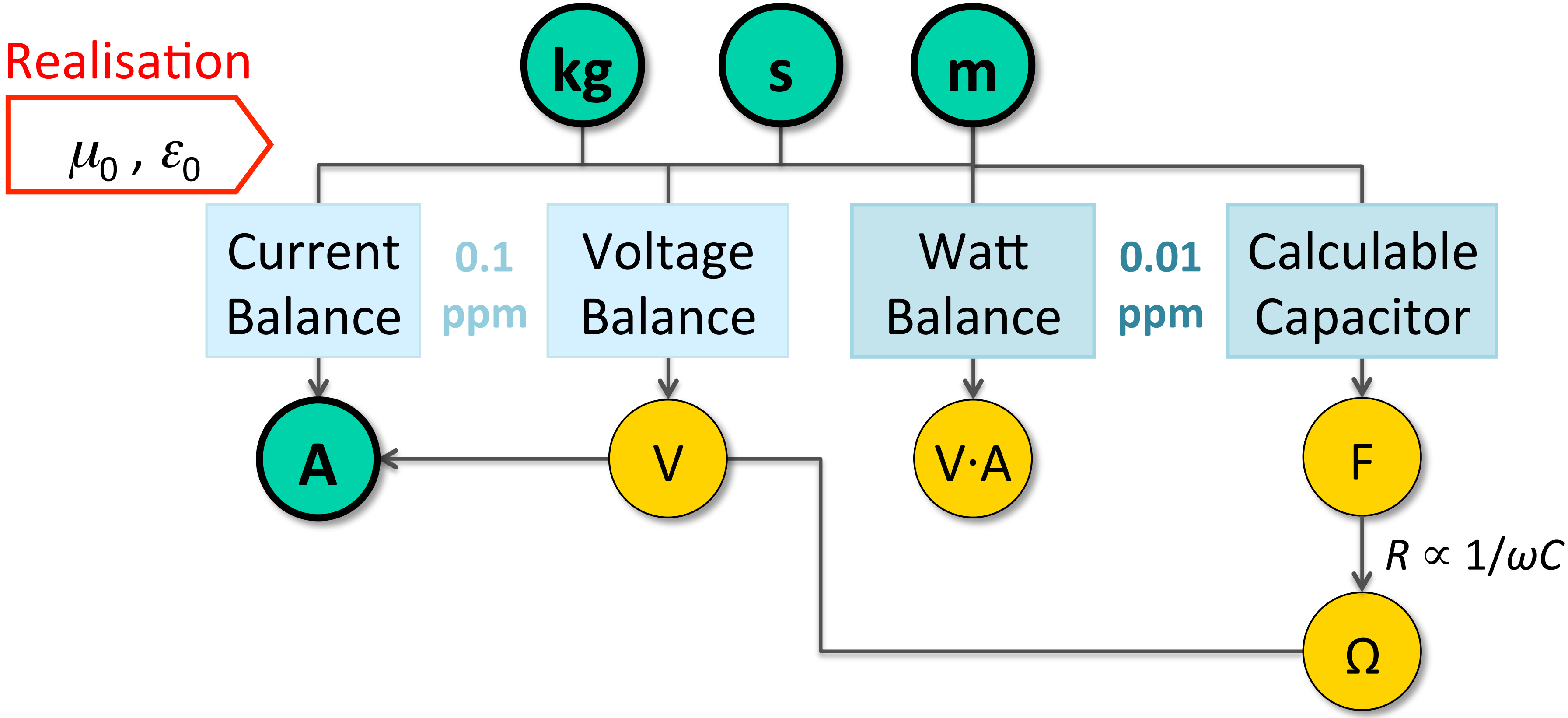
e. g. with a "current balance"



(m, kg, s → A)

Relative uncertainty ~ 10^{-7} (0.1 ppm)

Electrical units: Formerly ...



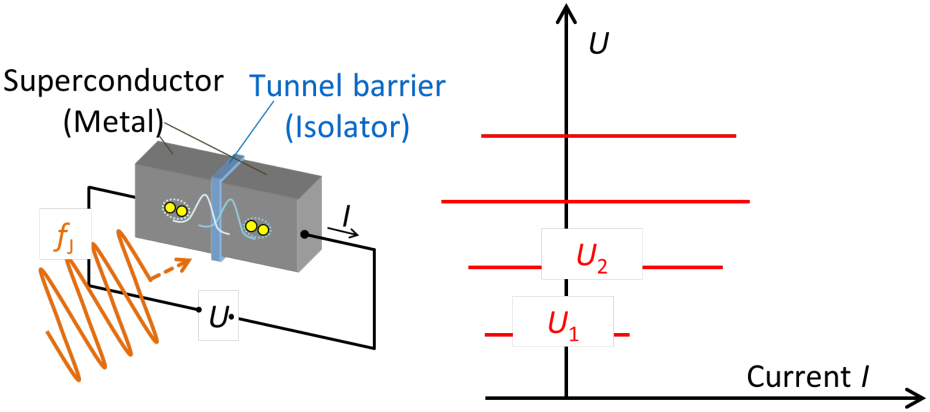
Electrical quantum effects (since 1990)

Josephson Effect, discovered 1962 by Brian D. Josephson

$$U_n = n \cdot f_J \cdot \frac{h}{2e}$$

Josephson constant $K_J = 2e/h$

$$K_{J\text{-}90} = 483\,597.9\ \text{GHz/V}$$

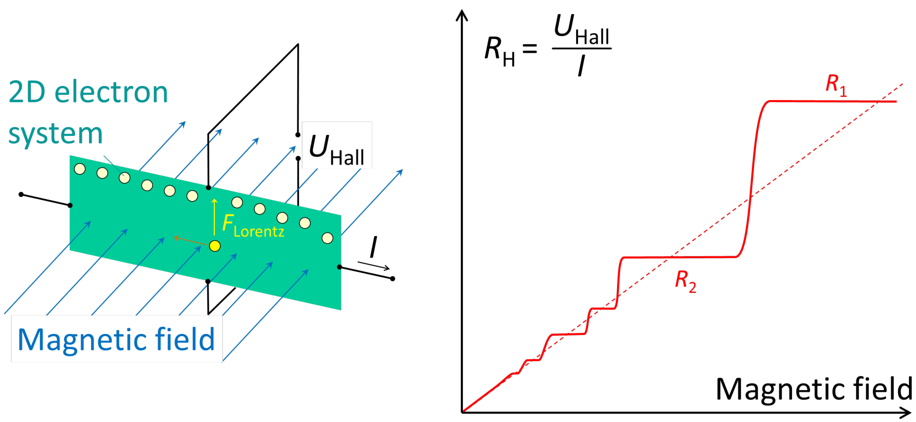


Quantum-Hall Effect, discovered 1980 by Klaus von Klitzing

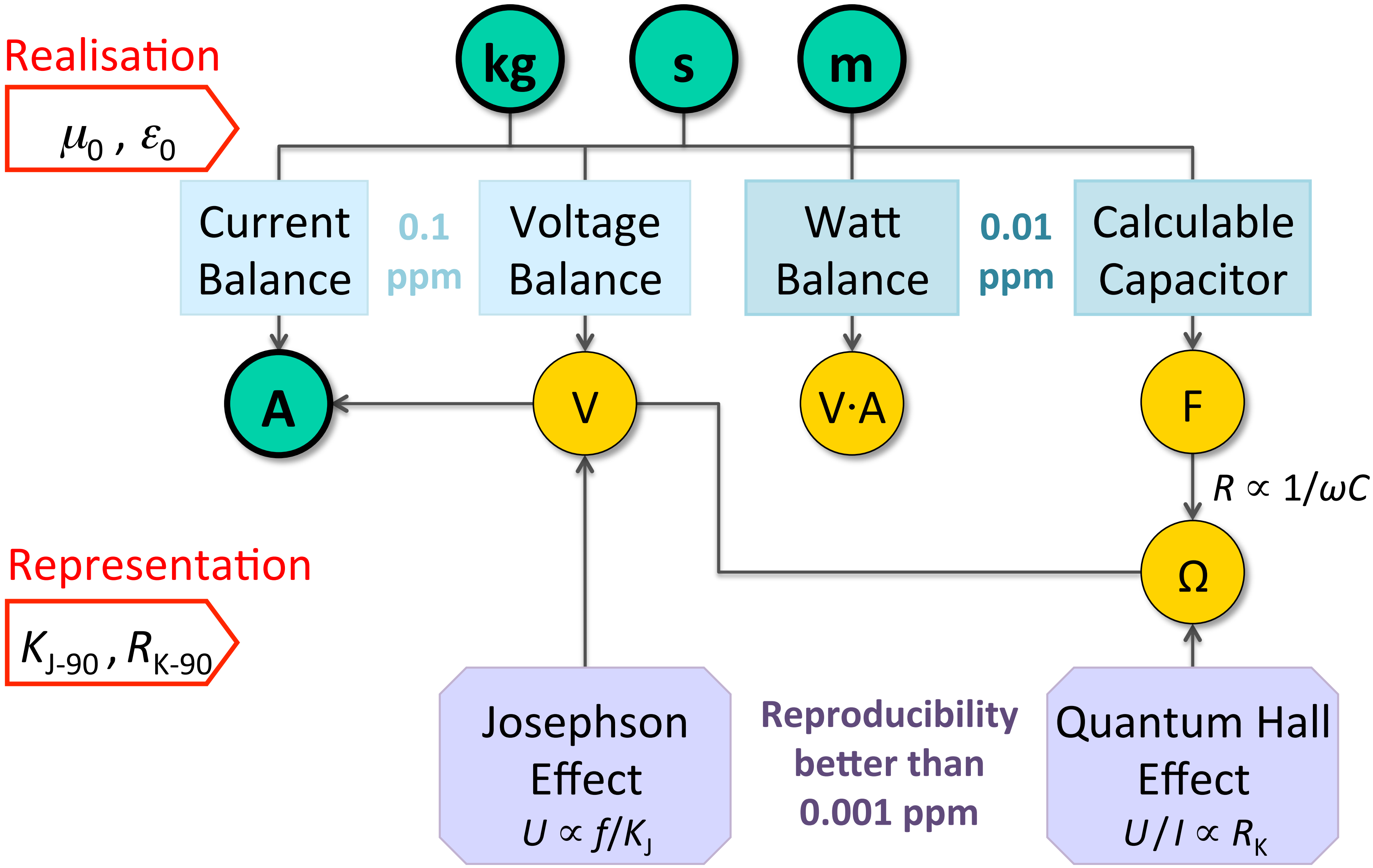
$$R_i = \frac{1}{i} \cdot \frac{h}{e^2}$$

von-Klitzing constant $R_K = h/e^2$

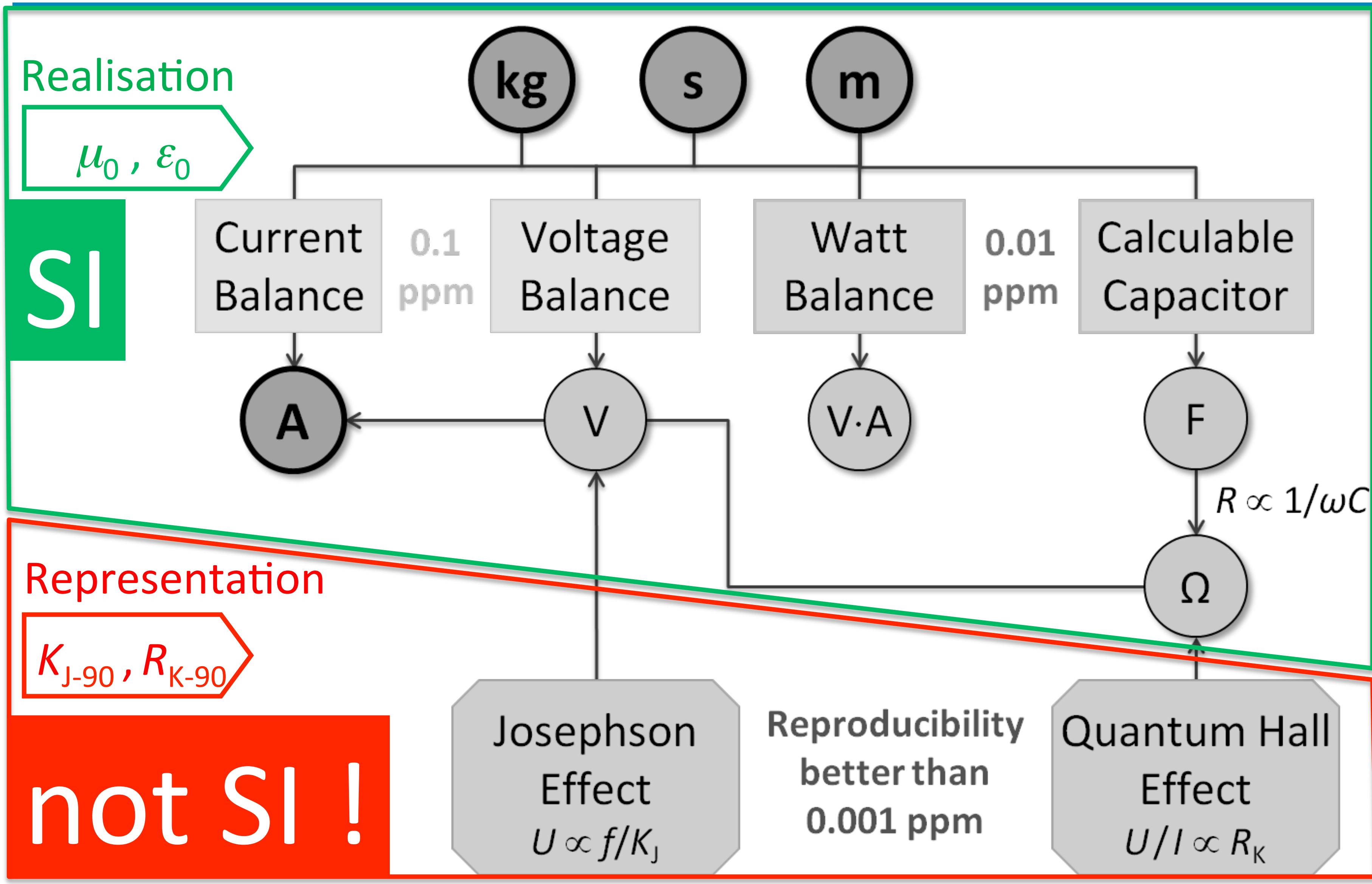
$$R_{K\text{-}90} = 25\,812.807\ \Omega$$



Electrical units: Formerly and today



Electrical units: Formerly and today



Revision of the SI: Redefinition of the units

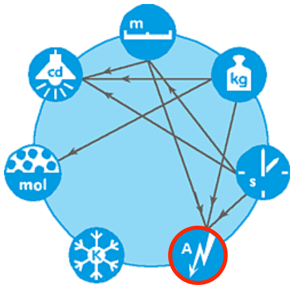
Planned by the "Conférence Générale des Poids et Mesures" and impending for 2018:

Definitions for all SI base units will entirely be based on **fixed numerical values for fundamental constants** (h, e, k_B, N_A, c, ...)

→ This will restore coherence between the "conventional" electrical units and the SI

Redefinition of the SI ampere

Resolution 1 of the 24th CGPM (2011):



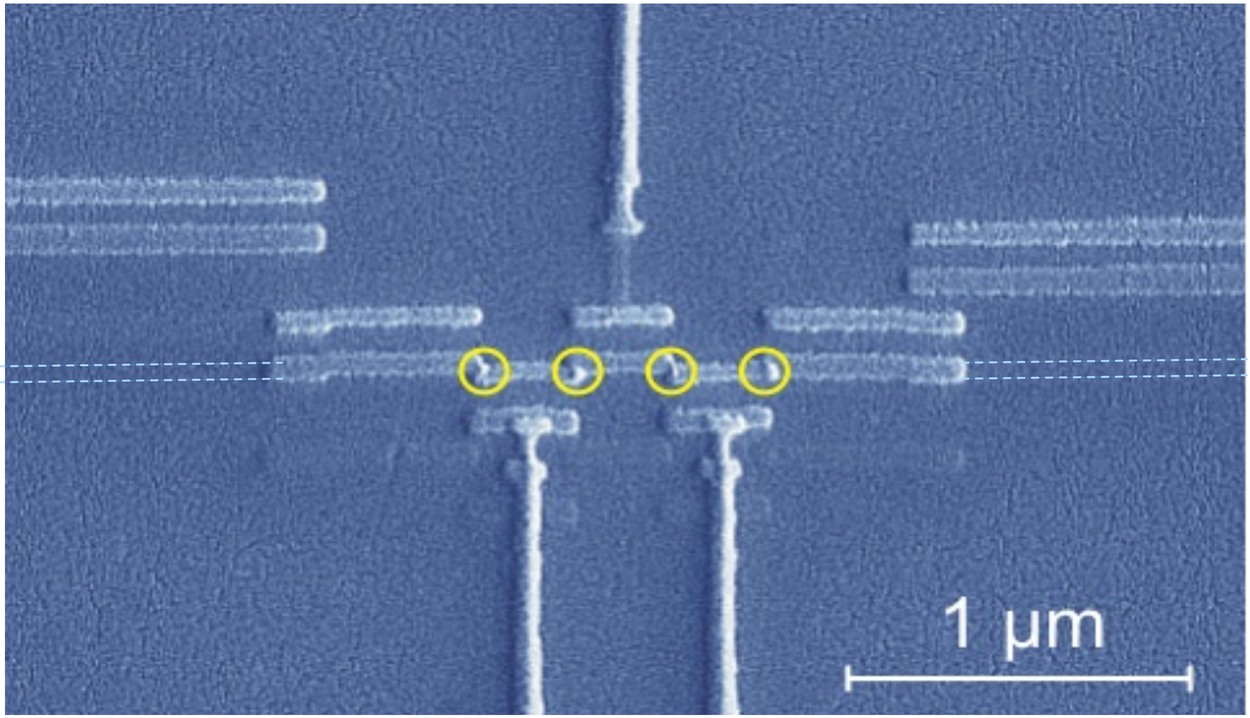
> "The International System of Units, the SI, will be the system of units in which... **the elementary charge *e* is exactly 1.602 17X ×10^{-19} coulomb...**"

Single-electron transport (SET) devices are considered the 'silver bullet' solution for the realisation the new ampere:

- it allows the **most direct unit realisation** using the physical definition of current **I = dq/dt**, exploiting the simple and evident relation $I_{SET} = e \cdot f$
- it involves **only one fundamental constant (*e*)**, not two (*e* & *h*), as Josephson-/QHE-based realizations do.

SET current sources

"Classical" devices: SET pumps made from **ultra-small tunnel junctions (metal)**



- J. Pekola *et al.*, *"Single-electron current sources: Toward a refined definition of the ampere"*, Rev. Mod. Phys. 85, 1421-1472 (2013)

SET current sources

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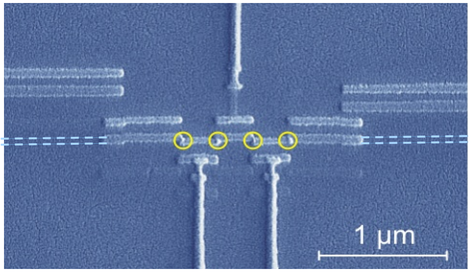
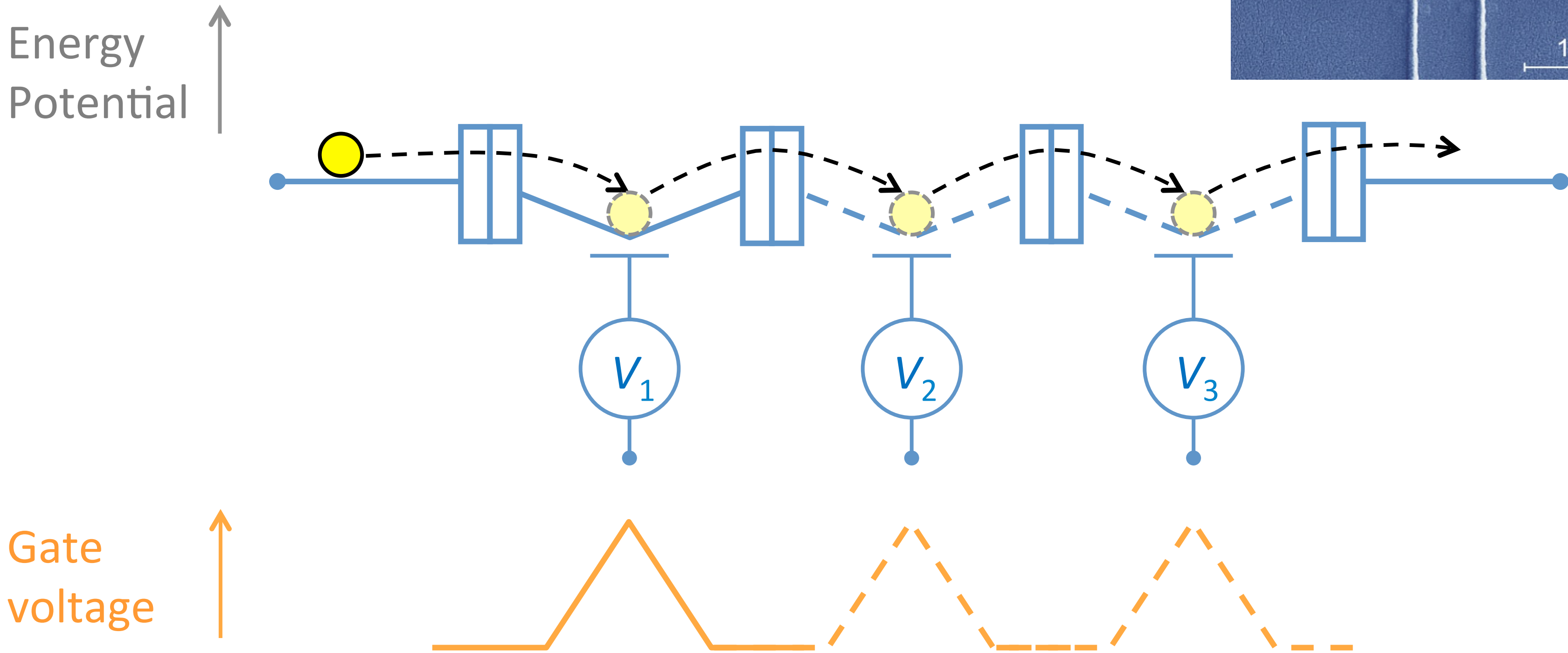


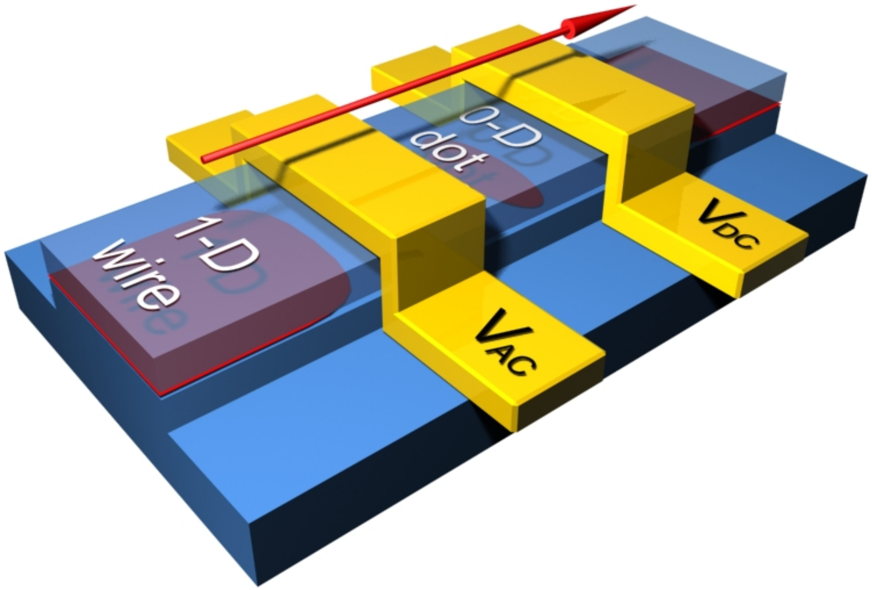


RC time constant of tunnel junctions:

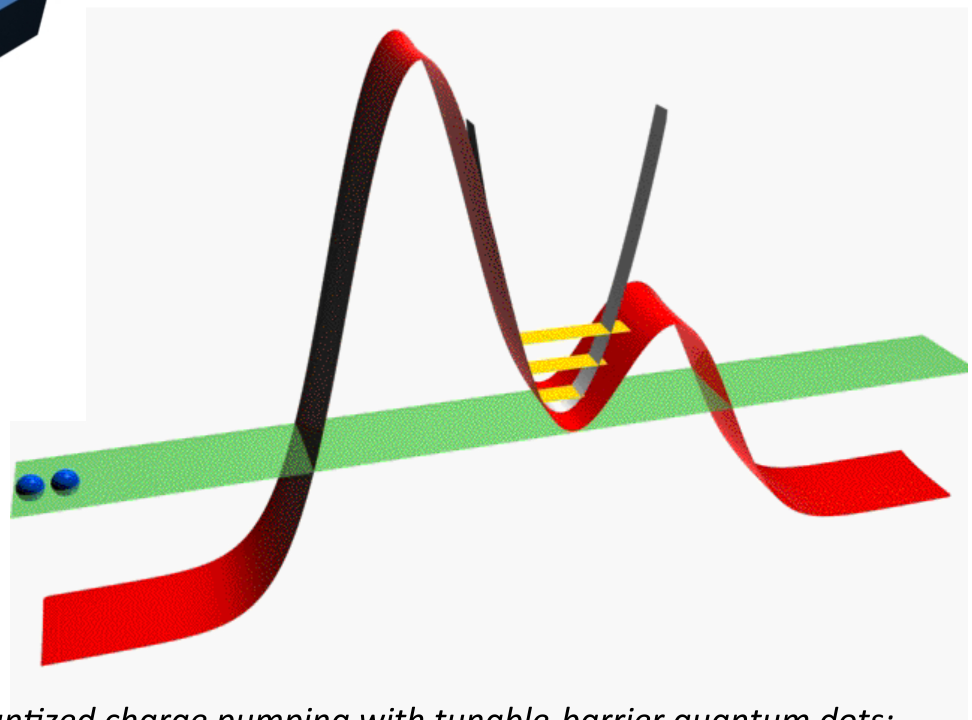
$f \leq 100$ MHz $\Rightarrow I = e \cdot f \leq$ 16 pA ($1.6 \cdot 10^{-11}$ A)

SET current sources

"Modern" devices: SET pumps made from **'dynamic quantum dots' (semiconductor)**



GaAs hetero structure
+ Schottky contacts (gates)



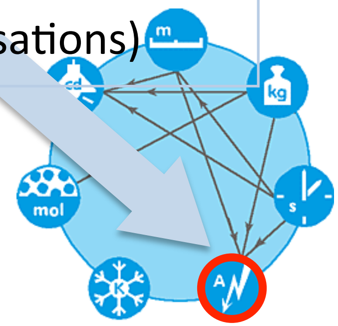
$f \sim 1$ GHz

$\Rightarrow I = e \cdot f \sim$ 160 pA

- B. Kaestner and V. Kashcheyevs, *"Non-adiabatic quantized charge pumping with tunable-barrier quantum dots: a review of current progress"*, Rep. Prog. Phys. 78, 103901 (2015)

Future SET-based "quantum ampere" realisation

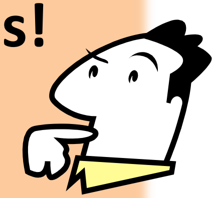
Electrical current	SET current sources (state-of-the-art)	Metrology needs
Level	$f_{max} \sim 1$ GHz $\Rightarrow$ **$I_{max} \sim 160$ pA**	**$I \sim 1$ µA**
Accuracy	Dominated by (statistical) single-electron **transfer errors!**	**Uncertainty ~ 0.1 ppm** or better (cf. 'old' electromechanical SI ampere realisations)



Future SET-based “quantum ampere” realisation

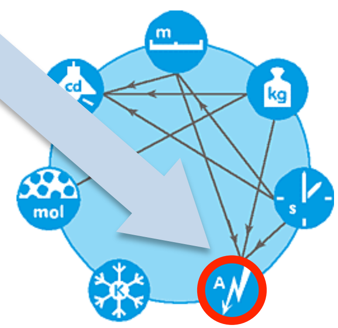
SET current sources generate **small currents!**

⇒ **Required: Current amplification and measurement methods** (highly accurate)

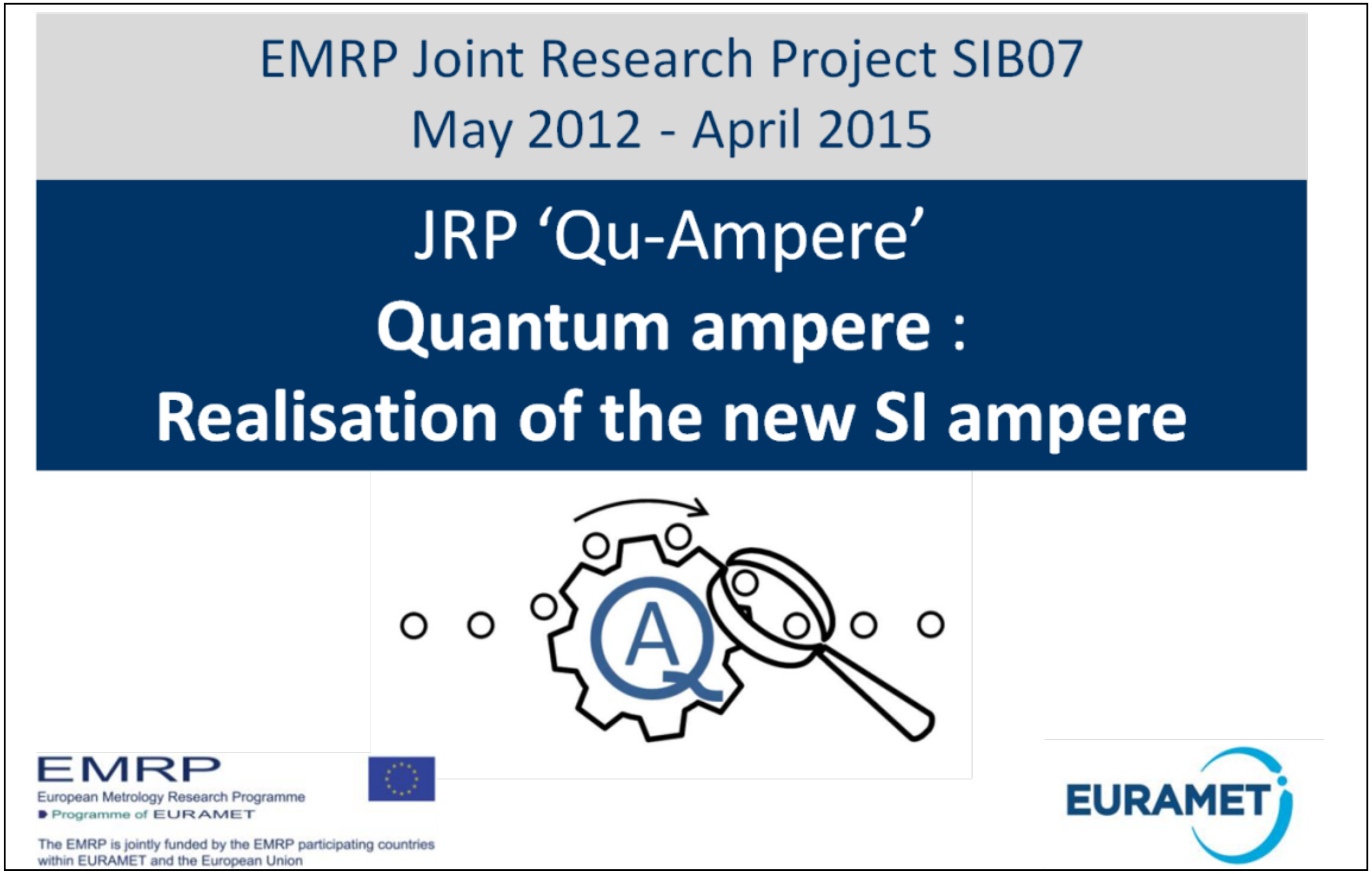


SET current sources are subject to single-electron **transfer errors!**

⇒ **Required: Error (ac)counting schemes**



Future SET-based "quantum ampere" realisation



For details see:
http://www.ptb.de/emrp/qu_ampere.html

Future SET-based quantum current standards

SET current sources generate small currents!

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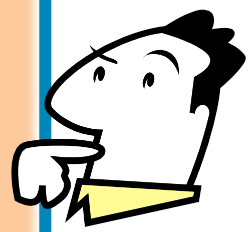


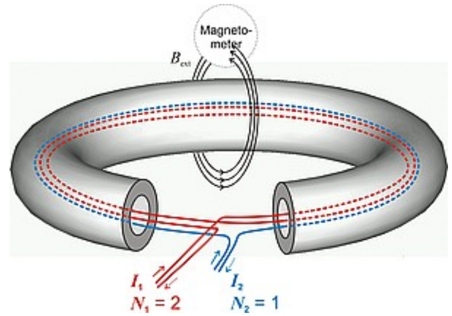
SET current sources are subject to single-electron transfer errors!

⇒**Required: SET error (ac)counting schemes**

State-of-the-art in 100 pA measurements

- **Commercial pAmmeters**
  offer accuracies of not better than 10 ppm, limited by gain instabilities

- **Cryogenic Current Comparators** (CCCs)
  are alternative high-accuracy current amplification techniques,
  but in the low-flux (small current) regime they suffer from noise rectification effects



⇒ **Novel concepts and instrumentation are necessary!**

Wanted: A handy (mobile), non-cryogenic, single-box tabletop electrometer with superior accuracy!

'Ultrastable low-noise current amplifier' (ULCA)

ULCA key specifications (standard variant)	
Effective transresistance A_{TR}	1 GΩ (1000 × 1 MΩ)
Temperature coefficient of A_{TR}	< 0.2 ppm/K
Long-term stability of A_{TR}	< 5 ppm/year
Fluctuations of A_{TR} in 1 week	0.1 ppm typical
Input current range	±5 nA
Input impedance	1 Ω
Effective input noise	2.4 fA/√Hz (f < 1 Hz)
1/f-noise corner	1 mHz

Further ULCA features:

- Modular design with one or two independent channels
- Uninterrupted power supply via two intermittently charging/powering 12 V batteries in external box
- Low operating current (11 mA maximum) → negligible self-heating effects
- Temperature sensors in each channel for correction of temperature effects (only necessary for applications requiring highest accuracy)

Measures 100 pA with 0.1 ppm total uncertainty in about 10 hours!

➢ D. Drung *et al.*, "*Ultrastable low-noise current amplifier: a novel device for measuring small electric currents with high accuracy*", Rev. Sci. Instrum. 86, 024703 (2015)
➢ D. Drung *et al.*,"*Improving the traceable measurement and generation of small direct currents*", IEEE Trans. Instrum. Meas. 64, 3021 – 3030 (2015), open-access http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=7132759

CCC system for calibration of the ULCA

SQUID electronics

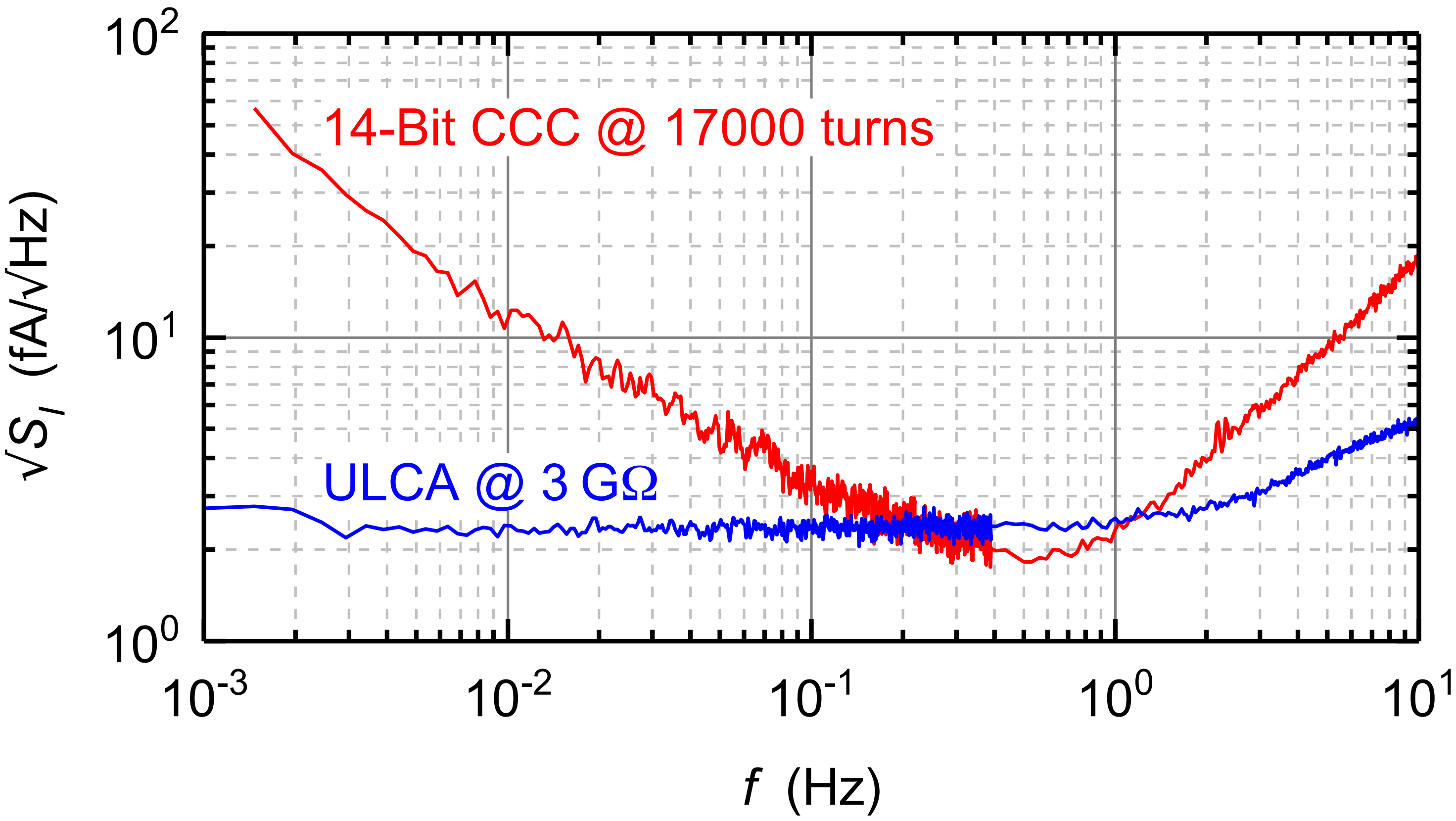
Digital dual channel current source and bridge voltmeter

Comparator with binary winding arrangement (12- bit or 14-bit) and SQUID null detector, in superconducting screen

PTB developments, commercially available

- D. Drung *et al.*, *"Ultrastable low-noise current amplifier: a novel device for measuring small electric currents with high accuracy"*, Rev. Sci. Instrum. 86, 024703 (2015)
- D. Drung *et al.*,*"Improving the traceable measurement and generation of small direct currents"*, IEEE Trans. Instrum. Meas. 64, 3021 – 3030 (2015), open-access http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=7132759

CCC and ULCA: Effective input current noise



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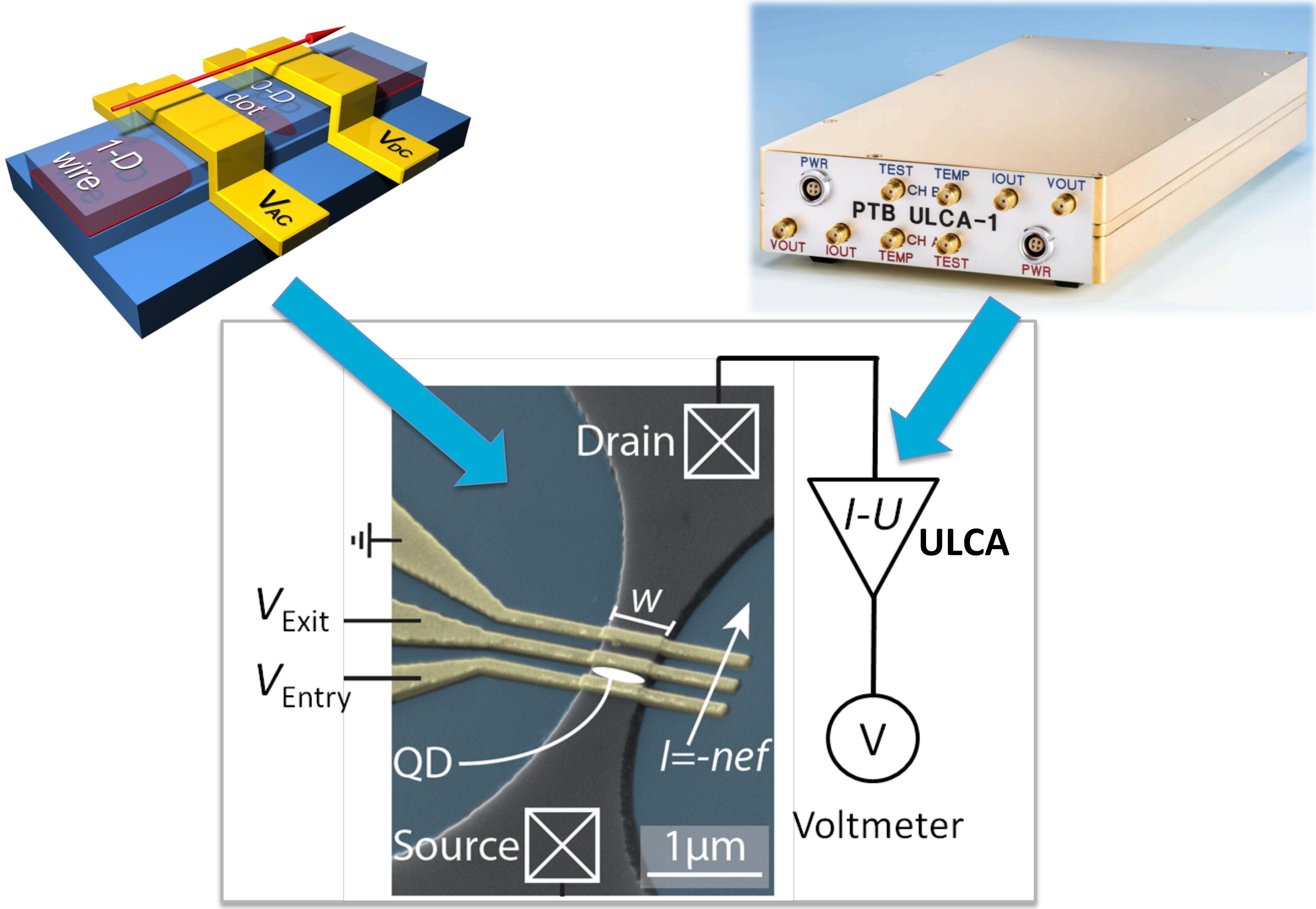
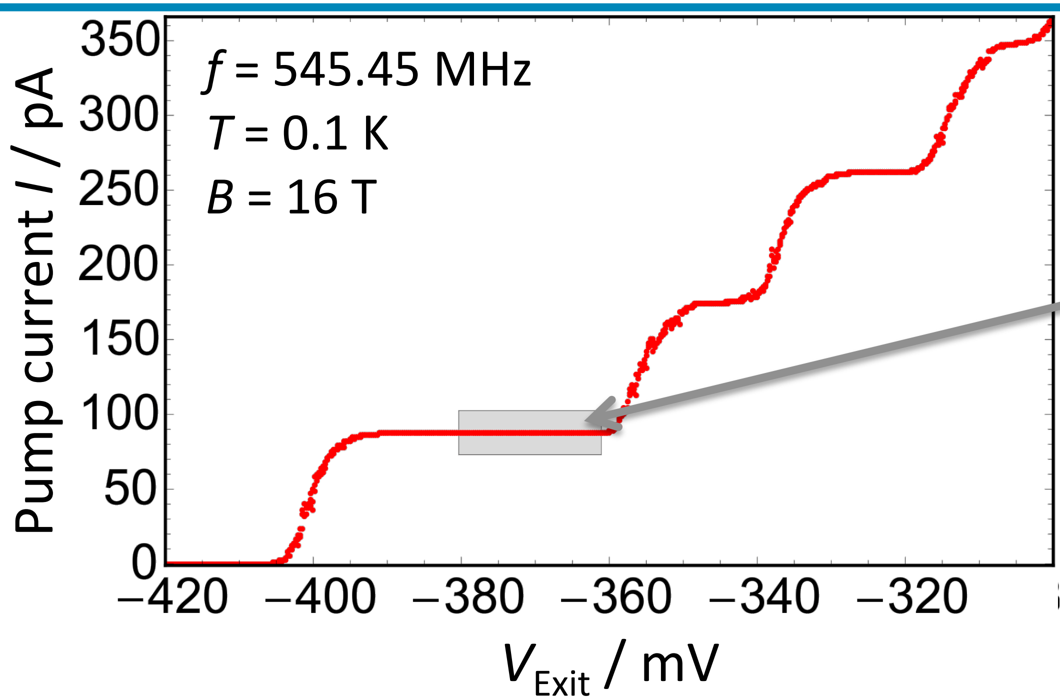
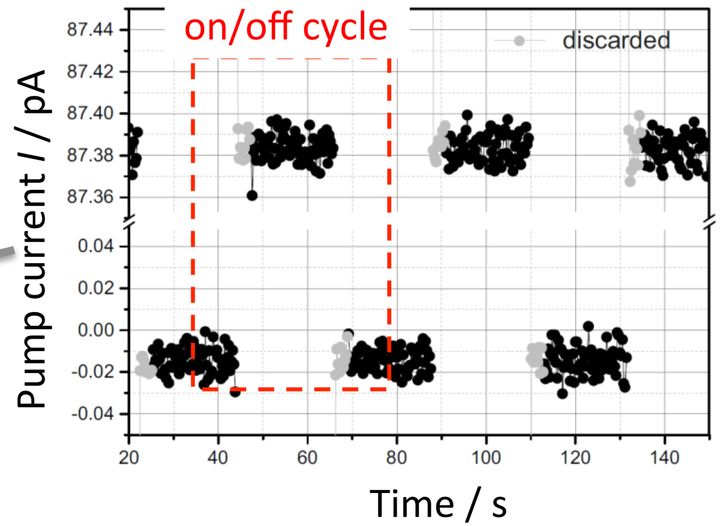
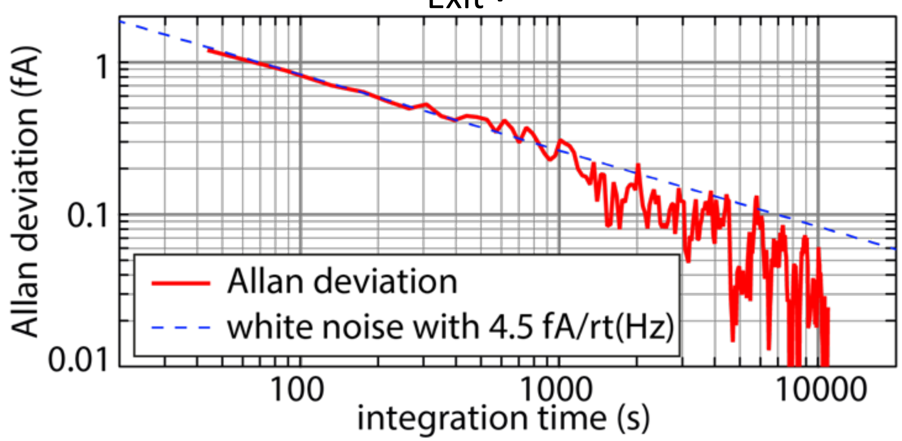
High-accuracy SET current measurements

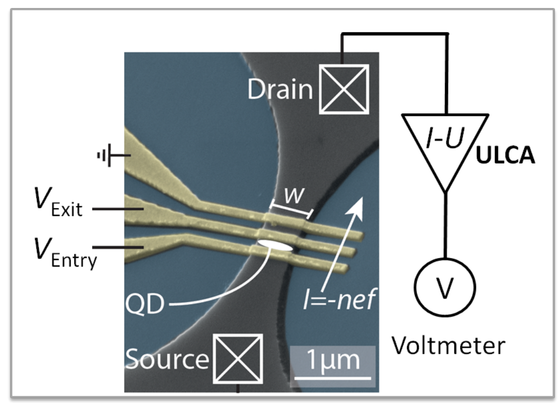


High-accuracy SET current measurements



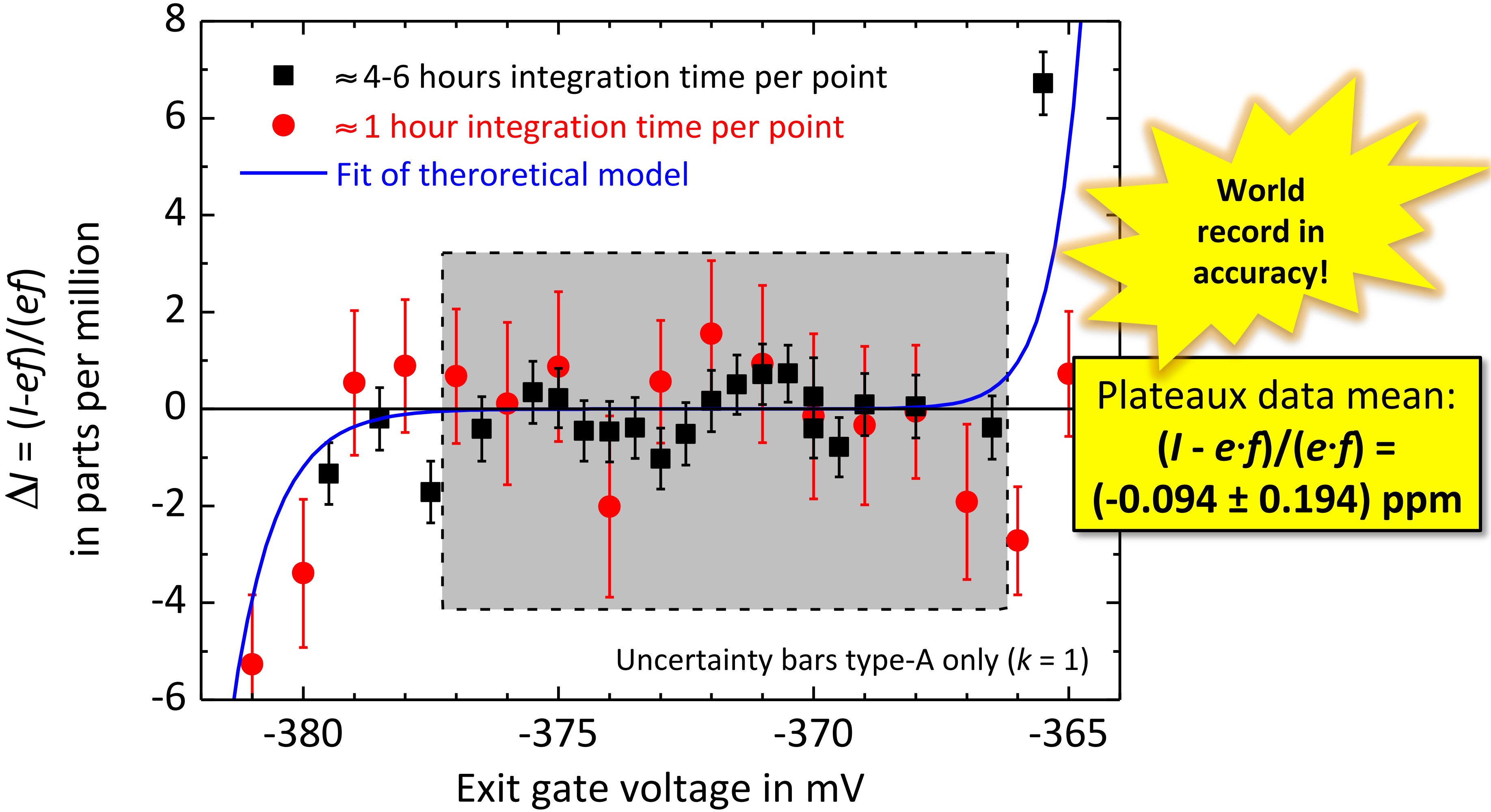






➢ F. Stein *et al.*, "*Validation of a quantized-current source with 0.2 ppm uncertainty*", APL 107, 103501 (2015)

High-accuracy SET current measurements



- F. Stein *et al.*, "*Validation of a quantized-current source with 0.2 ppm uncertainty*", APL 107, 103501 (2015)

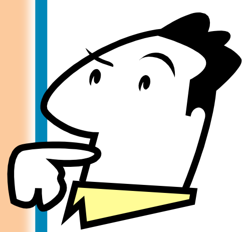
Future SET-based quantum current standards

SET current sources generate small currents!

⇒ **Required: Current amplification and measurement methods**

SET current sources are subject to single-electron transfer errors!

⇒ **Required: SET error (ac)counting schemes**



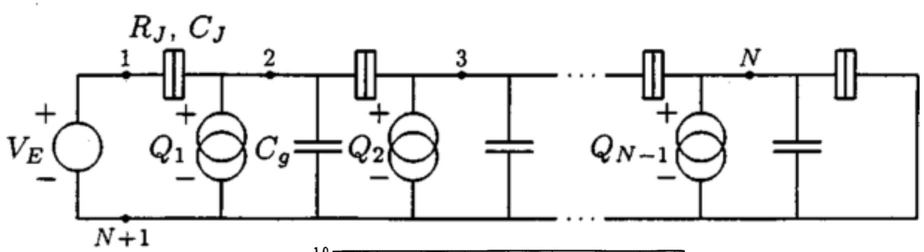
Transfer errors in SET pumps

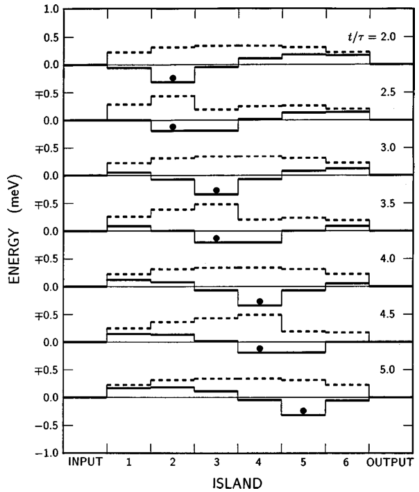
Example: SET pumps based on tunnel junctions

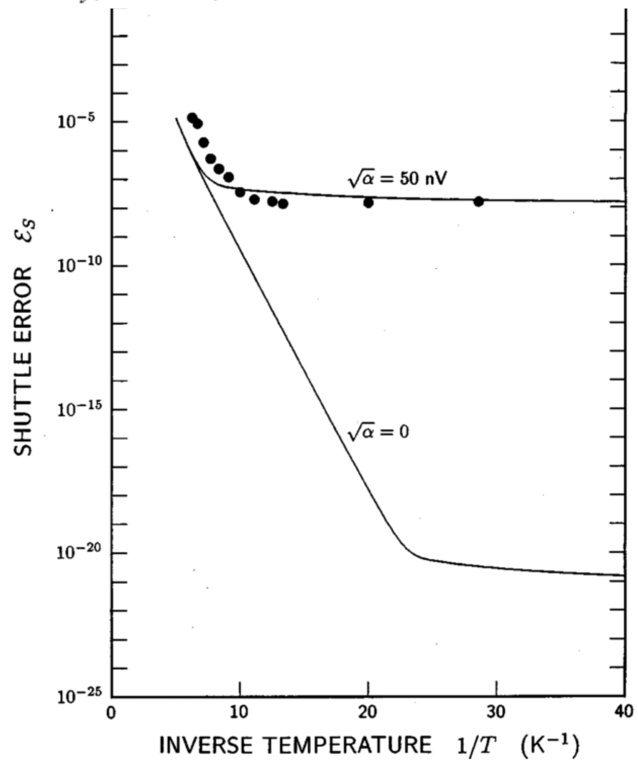
PHYSICAL REVIEW B   VOLUME 62, NUMBER 23   15 DECEMBER 2000-I

Noise-induced leakage and counting errors in the electron pump

R. L. Kautz, Mark W. Keller, and John M. Martinis
National Institute of Standards and Technology, 325 Broadway, Boulder, Colorado 80305







Transfer errors in SET pumps

Example: SET pumps based on dynamical quantum dots

PRL **104,** 186805 (2010) PHYSICAL REVIEW LETTERS week ending 7 MAY 2010

Universal Decay Cascade Model for Dynamic Quantum Dot Initialization

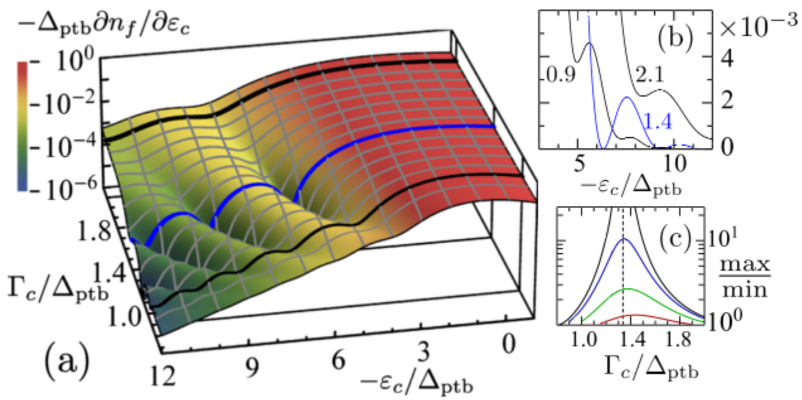
Vyacheslavs Kashcheyevs[1,2] and Bernd Kaestner[3]
[1]*Faculty of Computing, University of Latvia, Riga LV-1586, Latvia*
[2]*Faculty of*
[3]*Physikalisch-Te*

Error $<n-<n>>^2$

PRL **109,** 216801 (2012) PHYSICAL REVIEW LETTERS week ending 21 NOVEMBER 2012

Quantum Fluctuations and Coherence in High-Precision Single-Electron Capture

Vyacheslavs Kashcheyevs and Janis Timoshenko
Faculty of Computing and Faculty of Physics and Mathematics, University of Latvia, LV-1586, Riga, Latvia



Counting single-electron transfer errors

SET pump + SET detector

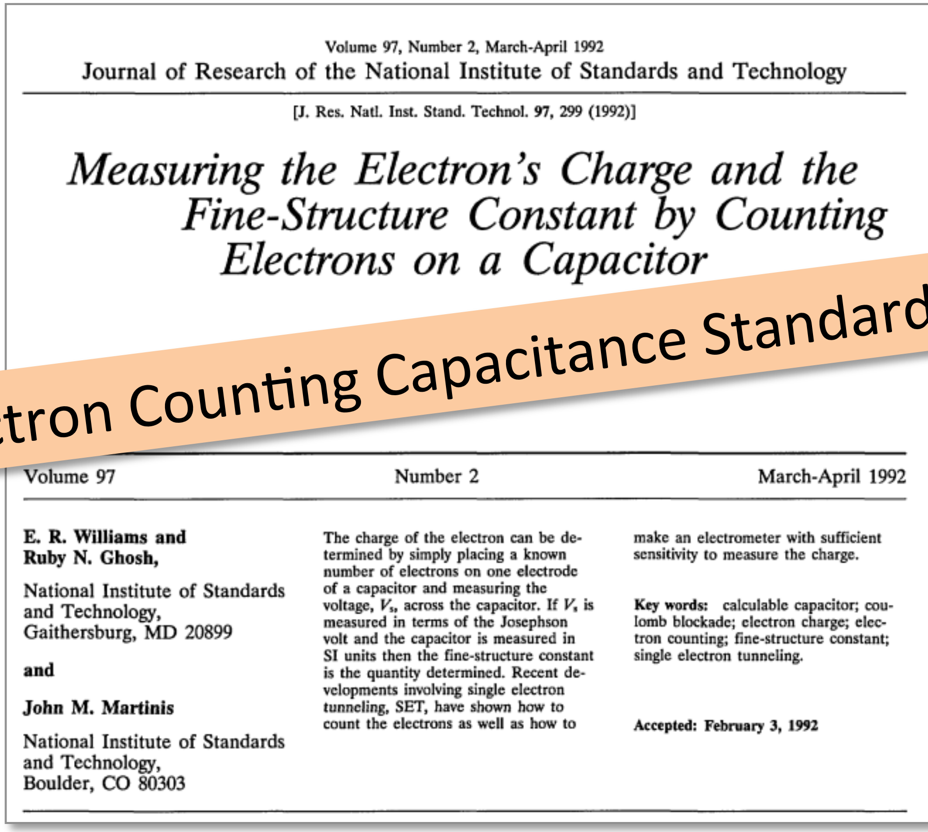
$I_{SET} = \langle n \rangle \cdot e \cdot f$ with $\langle n \rangle \approx 1$

$\langle n \rangle$ incl. uncertainty (!) must be quantified for any metrological application/experiment! (Quantum Metrology Triangle, SET current standard, ...)

Key idea:
To count not every electron (way too fast!), but just count the errors (much more rare)!

Counting single-electron transfer errors

Idea (1992) and first pioneering experiments (1994) by NIST:



Volume 97, Number 2, March-April 1992
Journal of Research of the National Institute of Standards and Technology

[J. Res. Natl. Inst. Stand. Technol. 97, 299 (1992)]

Measuring the Electron's Charge and the Fine-Structure Constant by Counting Electrons on a Capacitor

Volume 97 | Number 2 | March-April 1992

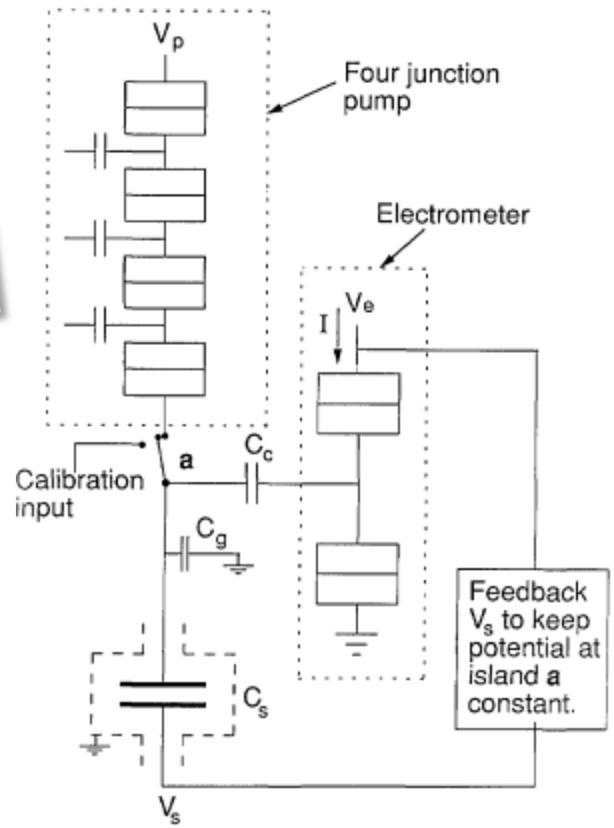
E. R. Williams and Ruby N. Ghosh,
National Institute of Standards and Technology, Gaithersburg, MD 20899
and
John M. Martinis
National Institute of Standards and Technology, Boulder, CO 80303

The charge of the electron can be determined by simply placing a known number of electrons on one electrode of a capacitor and measuring the voltage, V_s, across the capacitor. If V_s is measured in terms of the Josephson volt and the capacitor is measured in SI units then the fine-structure constant is the quantity determined. Recent developments involving single electron tunneling, SET, have shown how to count the electrons as well as how to make an electrometer with sufficient sensitivity to measure the charge.

Key words: calculable capacitor; coulomb blockade; electron charge; electron counting; fine-structure constant; single electron tunneling.

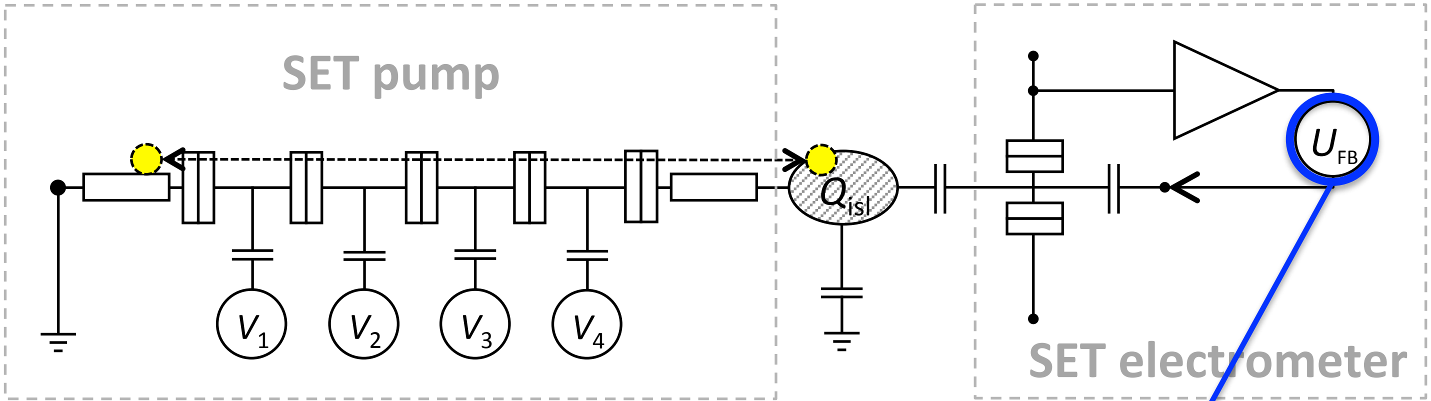
Accepted: February 3, 1992

"Electron Counting Capacitance Standard"



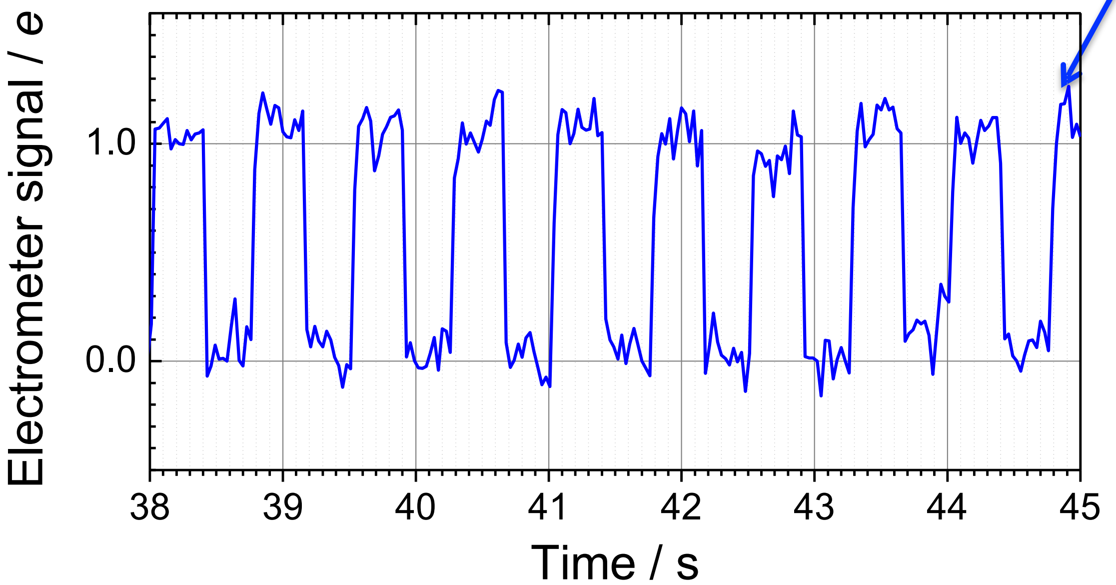
Counting single-electron transfer errors

... in the "Electron Counting Capacitance Standard" by PTB



"shuttle pumping"

slow @ 2.5 Hz

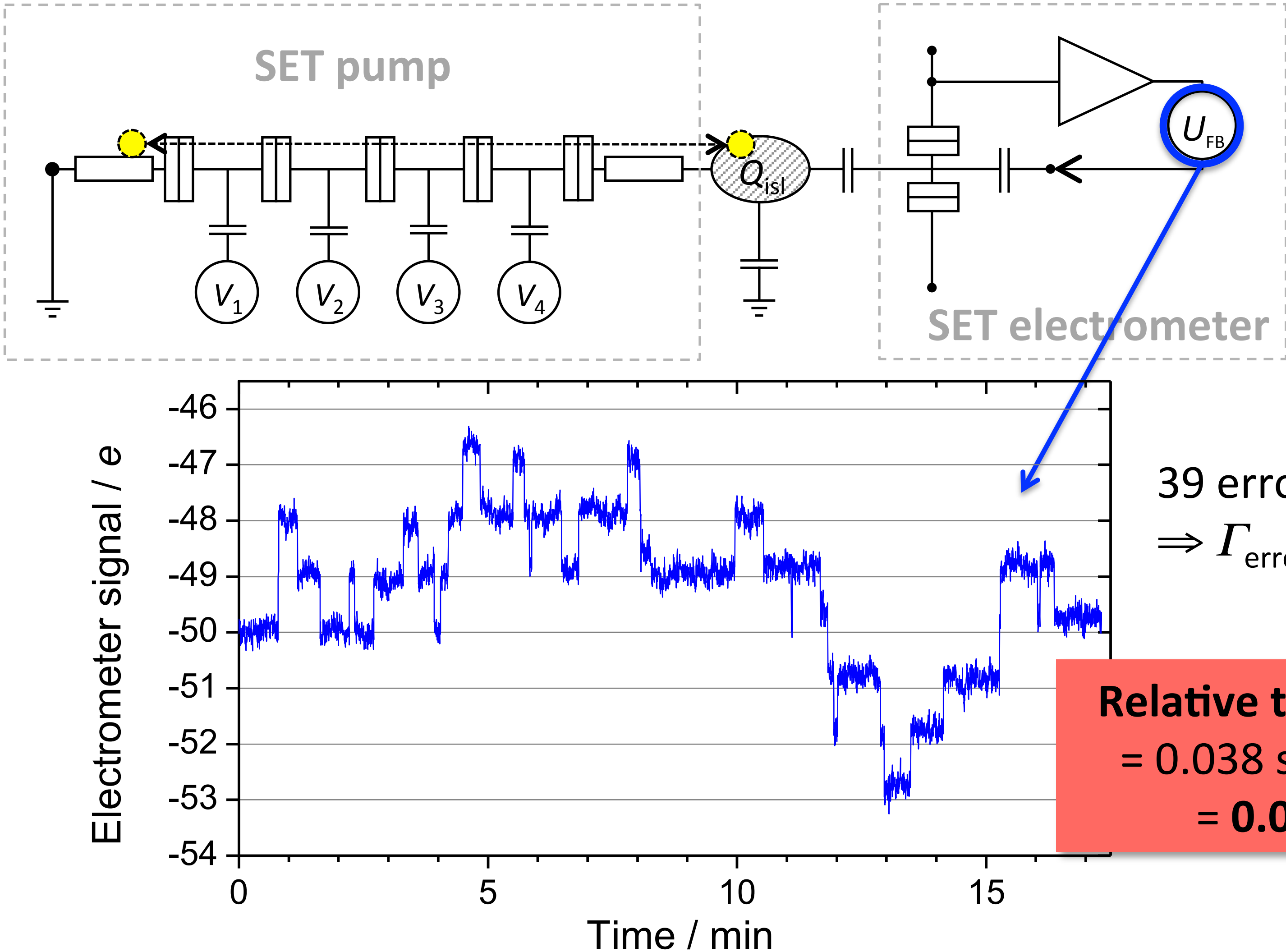


Fidelity test on the SET pump

- B. Camarota *et al.*, "*Electron Counting Capacitance Standard with an improved five-junction R-pump*", Metrologia 49, 8-14 (2012)

Counting single-electron transfer errors

... in the "Electron Counting Capacitance Standard" by PTB



"shuttle pumping"

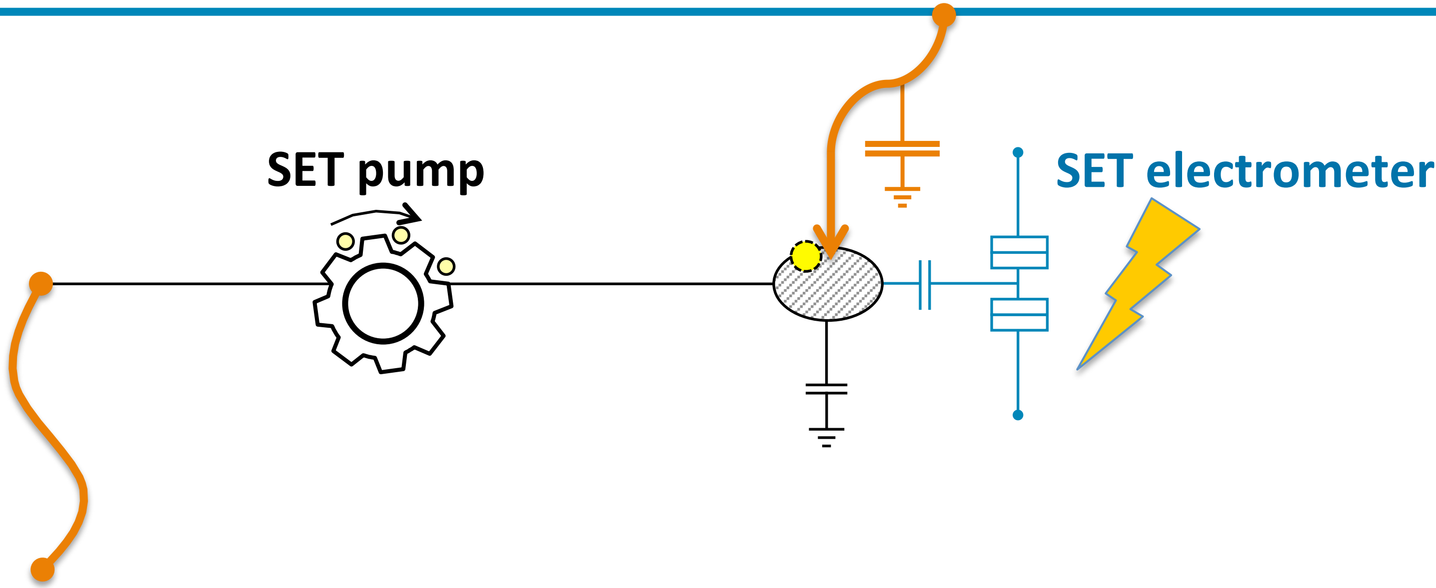
fast @ 2.5 MHz

39 errors in 1049 s

$\Rightarrow \Gamma_{error} = 0.038\ s^{-1}$

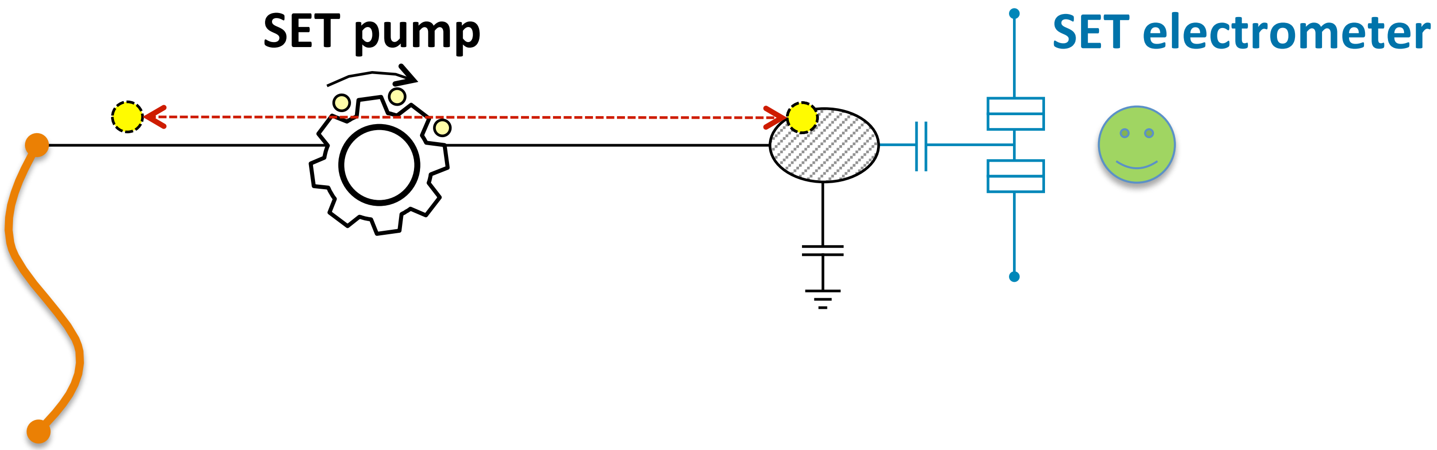
Relative transfer error
$= 0.038\ s^{-1} / 2.5\ MHz$
$=$ **0.015 ppm**

BUT... not suitable for SET current standard



Scheme does not allow to contact pump drain side by current lines because high stray capacitance of 'drain wire' deteriorates single-electron resolution of detector (SET electrometer = SET transistor)

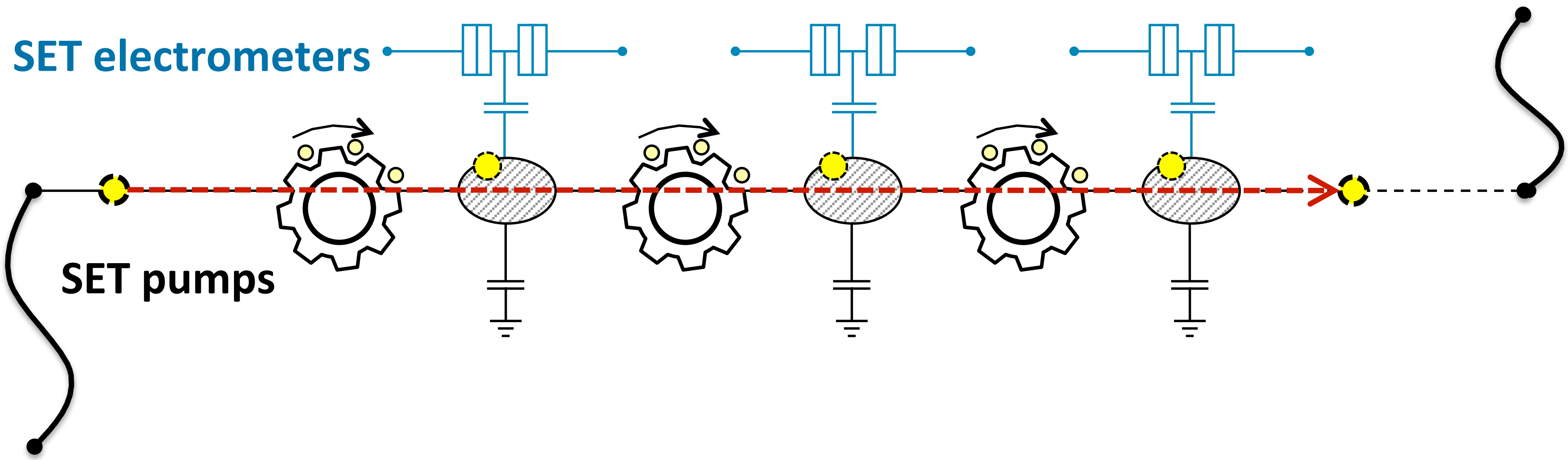
BUT... not suitable for SET current standard



Scheme does not allow to contact pump drain side by current lines because high stray capacitance of 'drain wire' deteriorates single-electron resolution of detector (SET electrometer = SET transistor)

⇒ Counting single-electron transfer errors must be done in a separate evaluation phase, which is different from the 'current sourcing' operation mode!

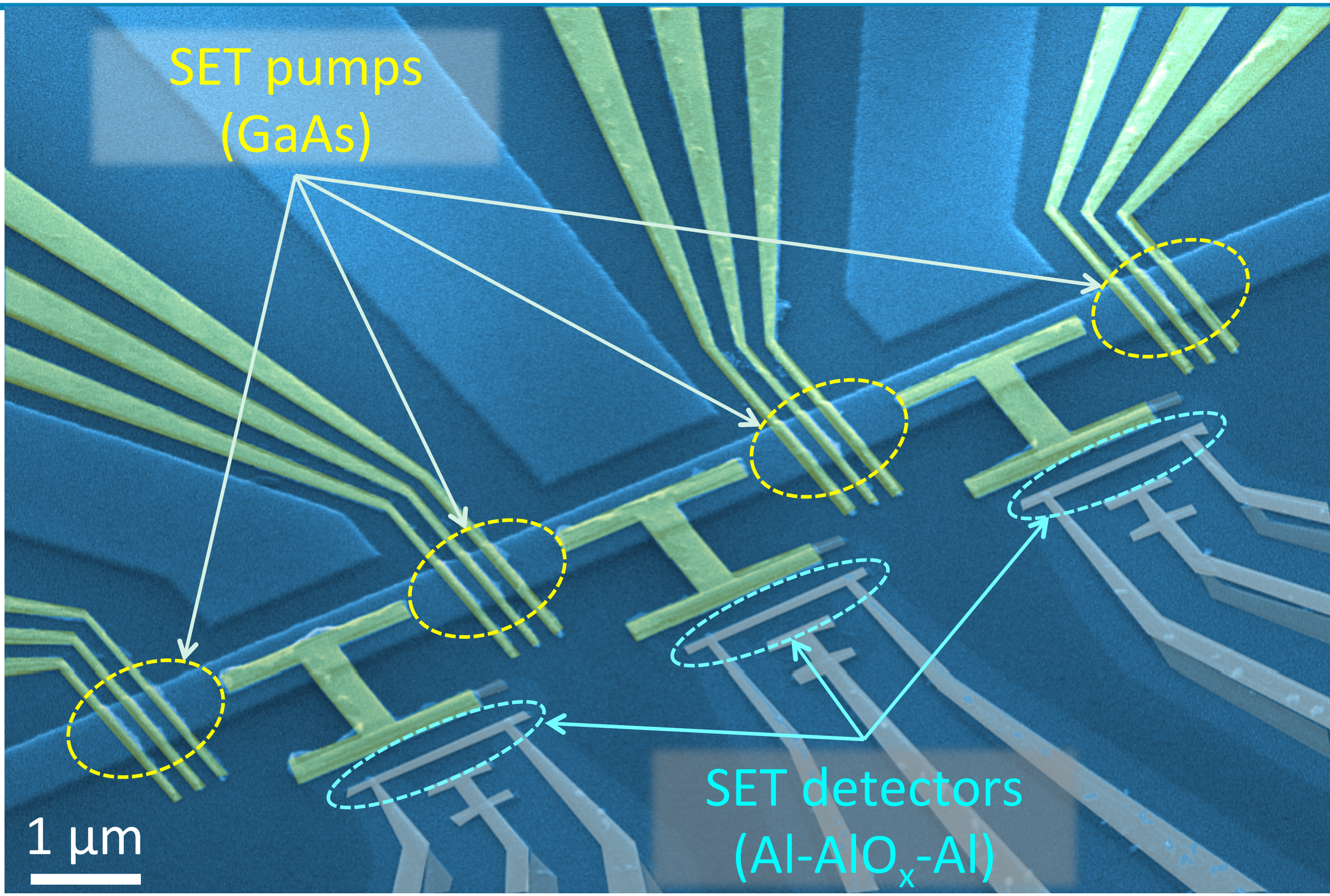
Advanced SET error accounting scheme



- Allows contacting the circuit without impairing single-electron resolution of the detectors
- Allows to count SET errors while pumping unidirectionally: **'*in situ*' error accounting** **'Self-referenced' SET current source**
- **Further advantages by correlation analysis of detector signals!**

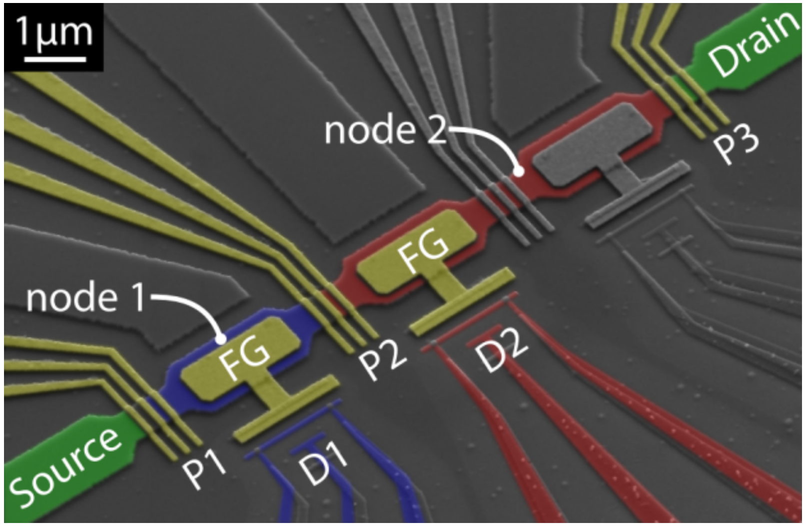
➢ M. Wulf, "*Error accounting algorithm for electron counting experiments*", PRB 87, 035312 (2013)

'Self-referenced' SET current source: device

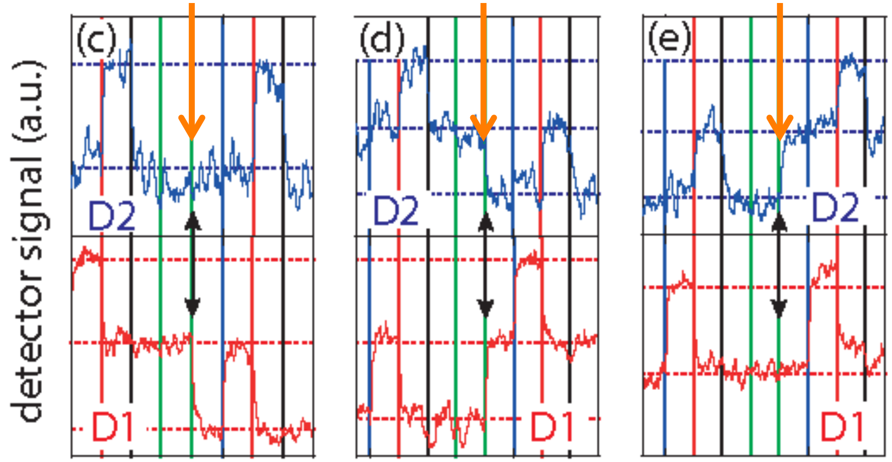


- L. Fricke *et al.*, "*Counting Statistics for Electron Capture in a Dynamic Quantum Dot*", PRL 110, 126803 (2013)
- L. Fricke *et al.*, "*Self-referenced single-electron quantized current source*", PRL 112, 226803 (2014)

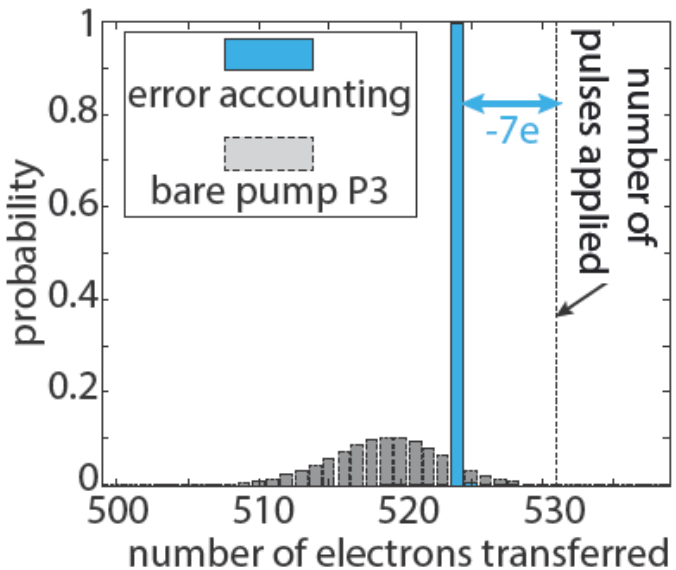
'Self-referenced' SET current source: first results



Signatures of missed-cycle events



50-fold accuracy enhancement by error accounting (but: $f \sim 30$ Hz)



➢ L. Fricke *et al.*, "*Self-referenced single-electron quantized current source*", PRL 112, 226803 (2014)

Conclusions & outlook

... on the challenges regarding
"future SET-based quantum current standards":

- **SET-generated current level and accuracy:**
  100 pA with ~ 0.1 ppm within reach,
  1 nA with < 0.1 ppm envisaged (silicon-based SET pumps?)

- **SET error accounting:**
  ... is mandatory for metrology! Schemes for solutions exist (demonstrated & validated), but need optimized implementations (high-speed operation, using rf-SET detectors, ...)

- **Small-current measurement and amplification:**
  The novel ULCA instrument is superior to CCC-based systems, offering unparalleled performance for applications in small-current metrology (SET, and more!)

... thanks to all involved colleagues from four PTB departments in Braunschweig and Berlin!

- **Quantum Electronics** (PTB department 2.4)
- **Semiconductor Physics and Magnetism** (PTB department 2.5)
- **Electrical Quantum Metrology** (PTB department 2.6)
- **Cryophysics and Spectrometry** (PTB department 7.2)

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