Physikalisch-Technische Bundesanstalt
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Counting Electrons for Metrology of Electrical Currents

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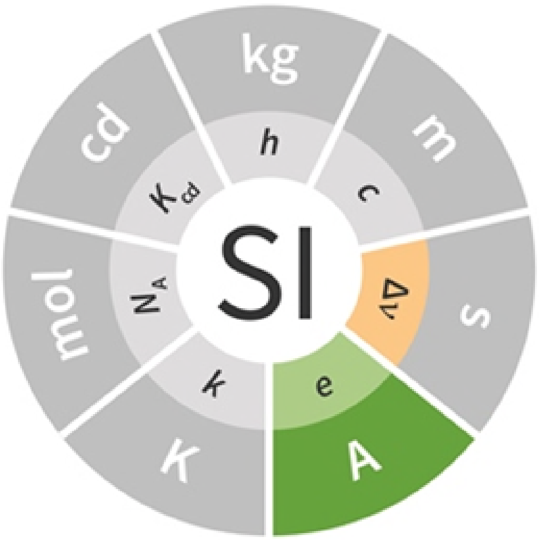
SI base unit: ampere (A)

The ampere, is the SI unit of electric current.
It is defined by taking the **fixed numerical value of the elementary charge *e* = 1.602 176 634 x 10^{-19} C** …

All electrons carry the same charge.

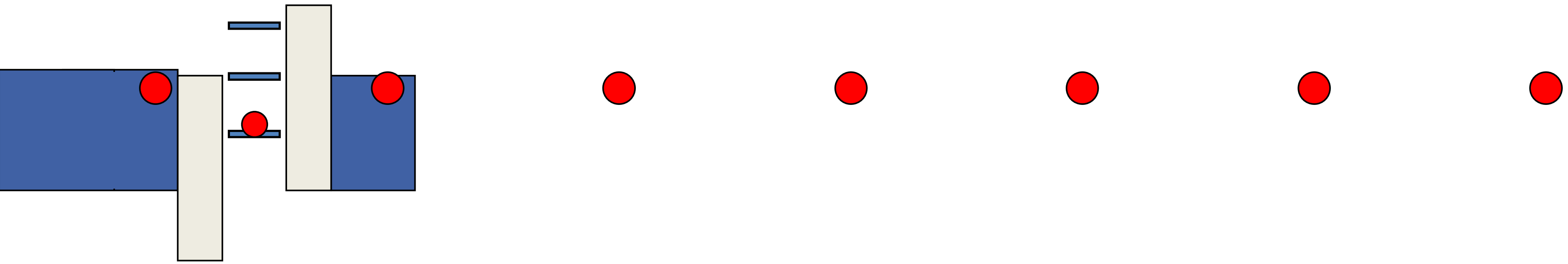


Mise en pratique:
The Ampere can be realized by…
using a single electron transport (SET)
or similar device...

➔ **Count electrons to measure current.**

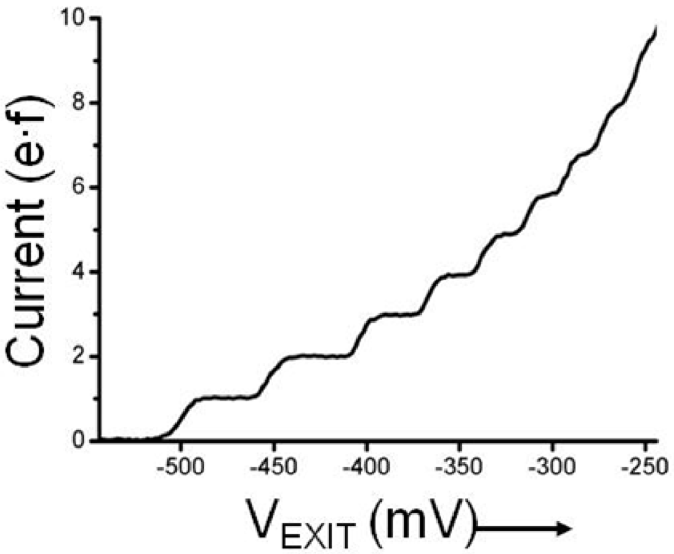
Single Electron Pumps (SEP)

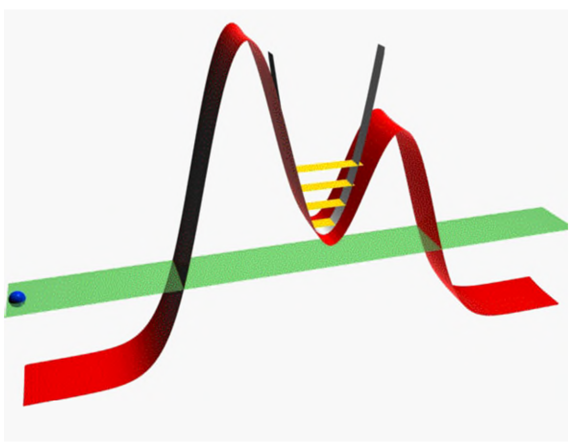
$$I = nef$$



- Direct realization of the SI ampere
- Challenges:
  - Frequency as large as possible, e.g., f = 1 GHz, I = 160 pA (for n= 1)
  - Low uncertainty, at least smaller than the uncertainty of the ampere realization in the old SI ($\approx 3 \times 10^{-7}$)

Semiconductor single electron pumps





- GaAs/AlGaAs quantum dot
- Charging energy E_C ~ meV
- Modulation of entrance barrier
- Capture electron from source
- Eject to drain
- Quantised current: $I = e \cdot f$

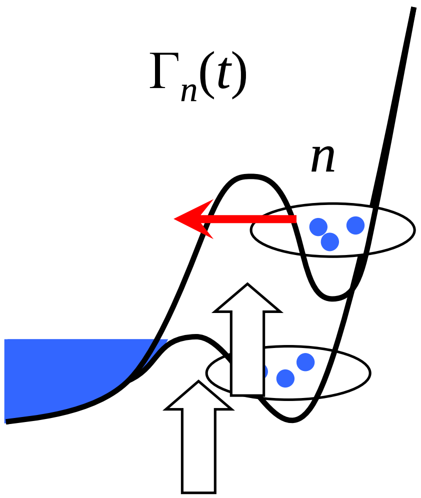
- Advantage:
- High frequency → high currents
- Simple fabrication
- Low error rate

But:

- Tunnelling is stochastic
- Rare pump errors need to be controlled or counted

Decay cascade model

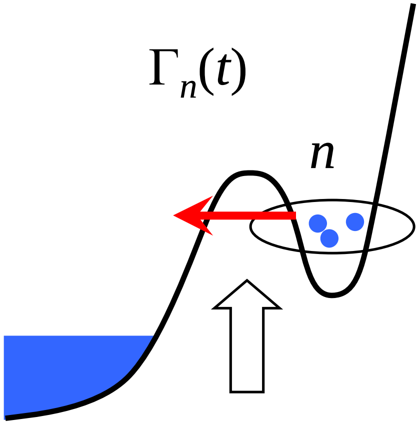
- What happens when the barrier is raised?
- Barrier *and* dot rise
  → excess electrons tunnel back

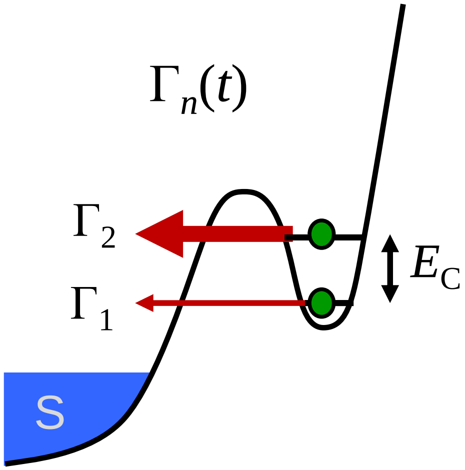


Decay cascade model

- What happens when the barrier is raised?
- Barrier *and* dot rise
  → excess electrons tunnel back
- Barrier more transparent for higher electron number
- Higher electrons tunnel back faster than lower electrons
- Predicts double exponential curve for each level

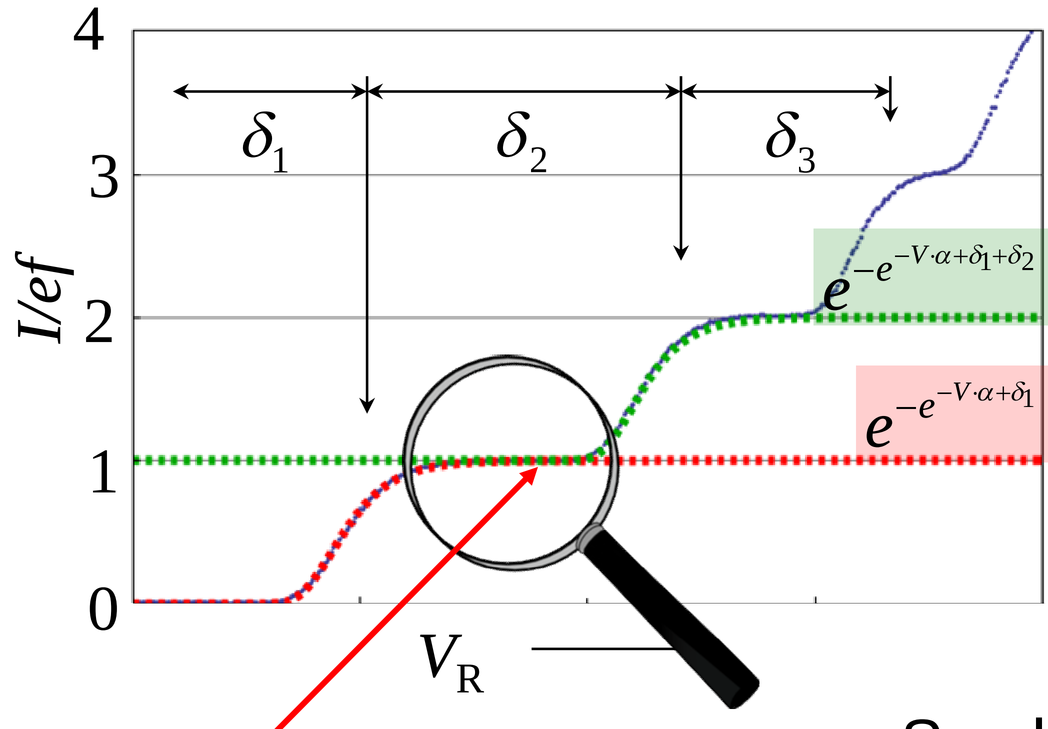
$$\boxed{I(V) = e^{-e^{-V\cdot\alpha+\delta}}}$$

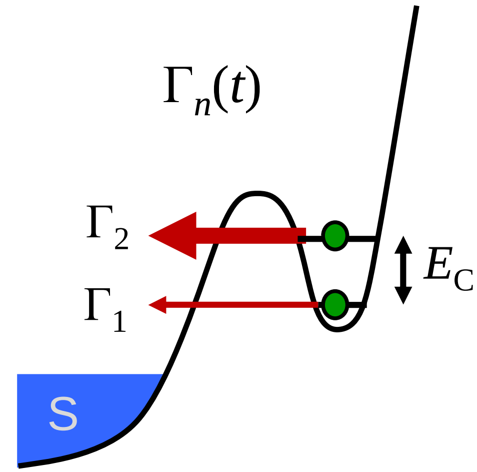




How go get a good pump?

Decay cascade model predicts error rate P_{err} at sweet spot



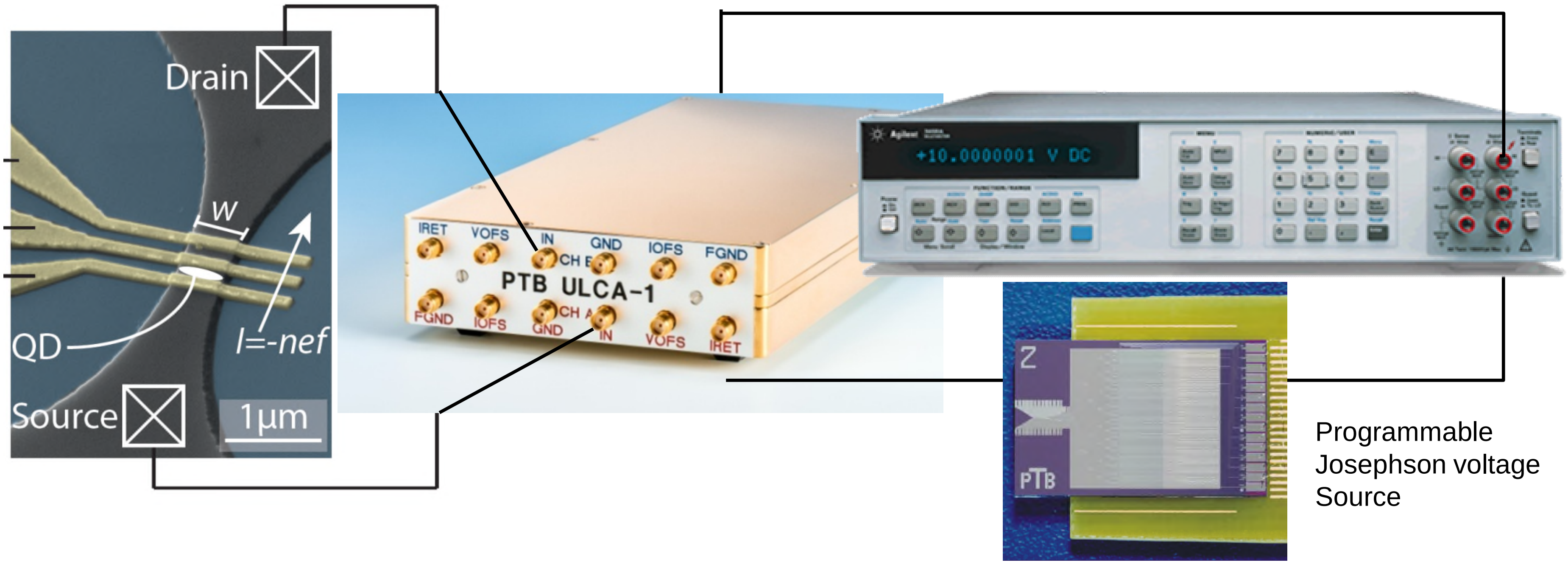


$$P_{err} \sim \exp\left(-\left[\ln\frac{\Gamma_2}{\Gamma_1}\right]\right)$$

Smaller dot → larger E_C

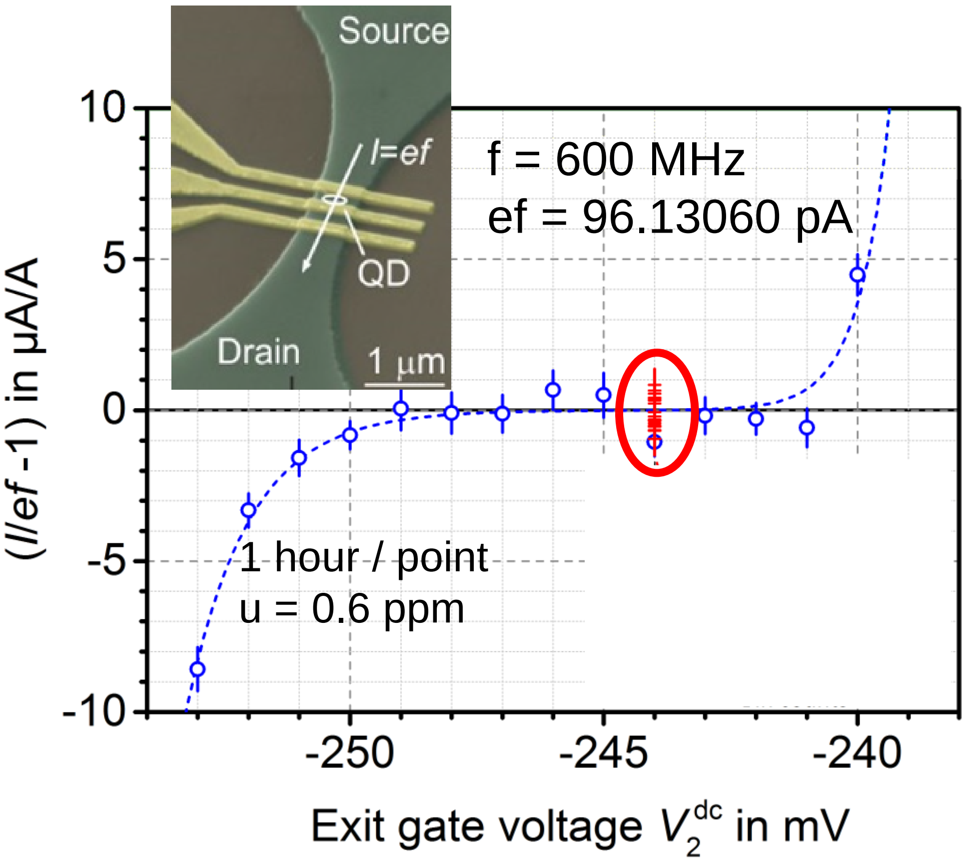
→ larger $\frac{\Gamma_2}{\Gamma_1}$ → better pump!

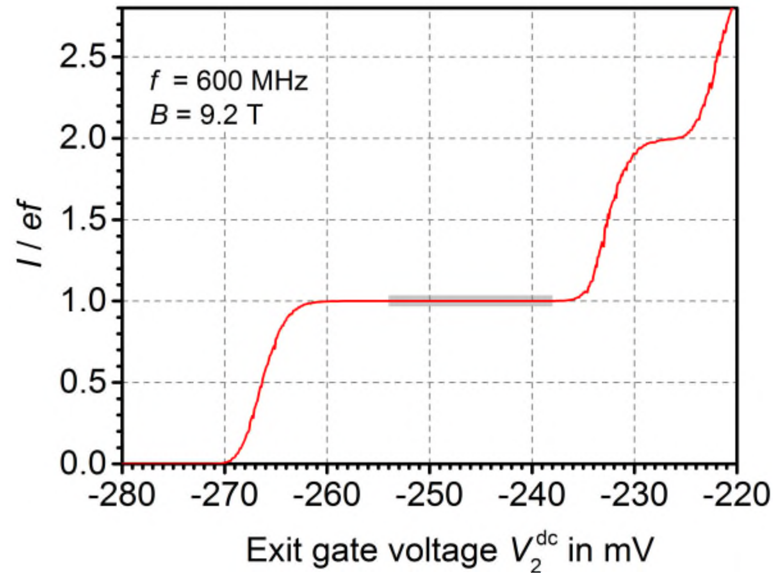
Traceable measurement of SEP output current



Programmable Josephson voltage Source

Single-electron pump verification





21 hour measurement at working point V_2 = -244 mV

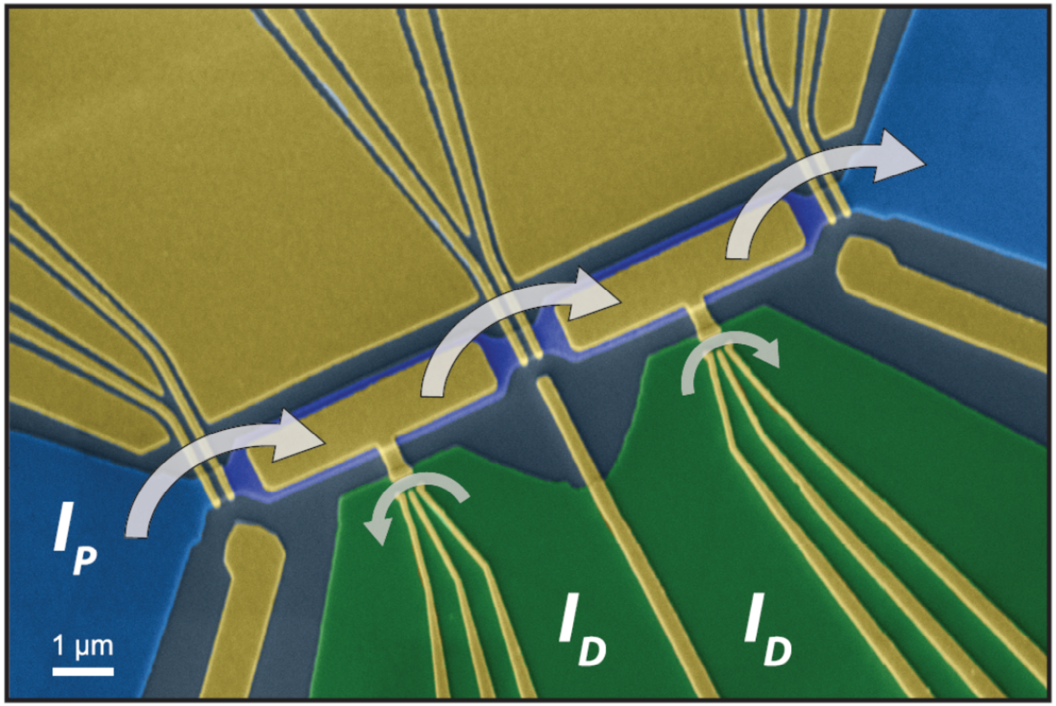
Deviation from ef:
0.10 ± 0.16 ppm
(total uncertainty)
< 100 electrons/s

SEP quantization **verified** with better **accuracy than Ampere realization in the old SI**

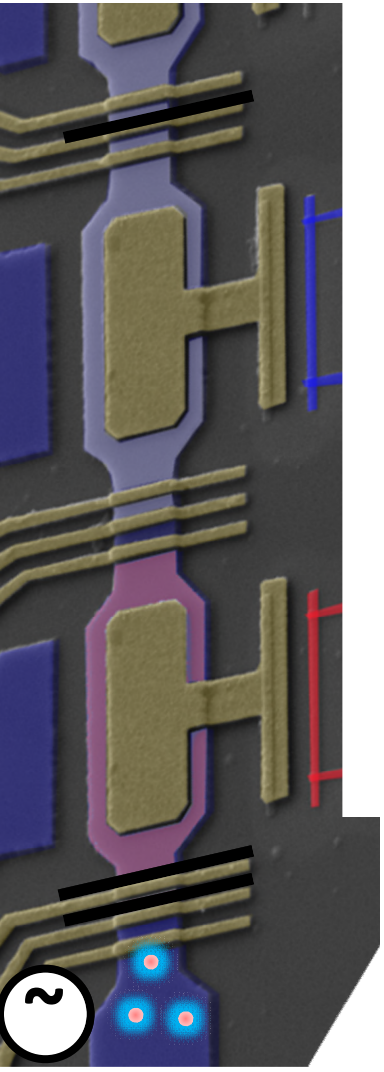
F. Stein et al. APL 2015
ibid. Metrologia 2016

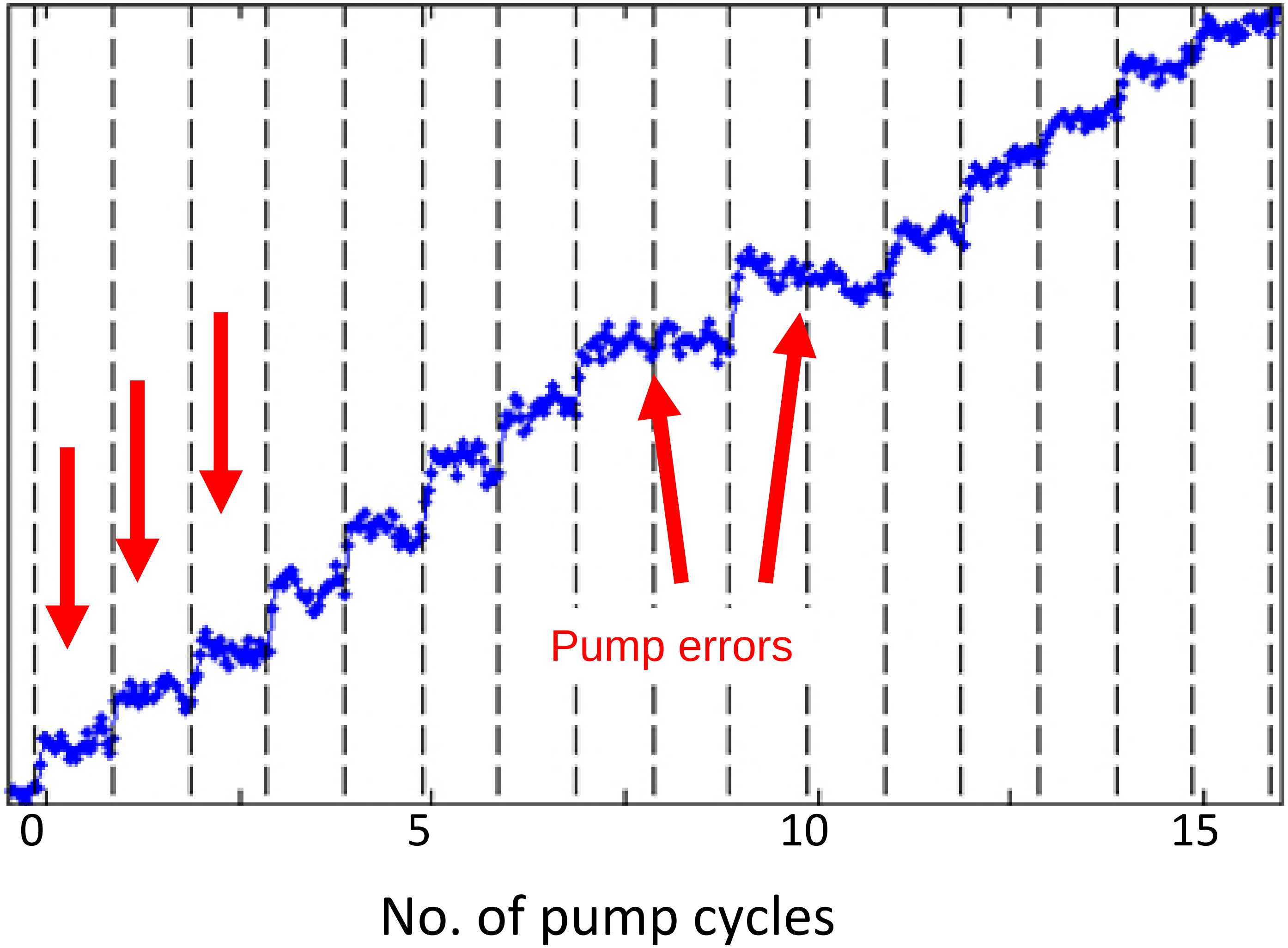
Detection of pumping errors

- Serial connection of single electron pumps
- Single charge detection on connecting nodes

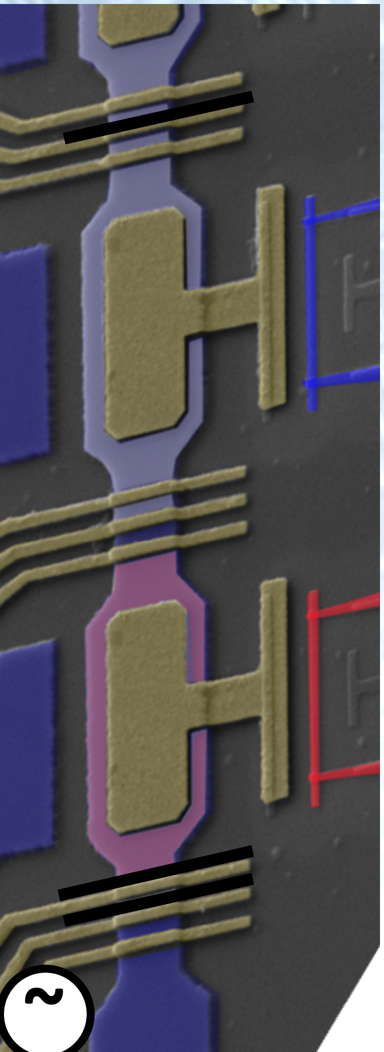


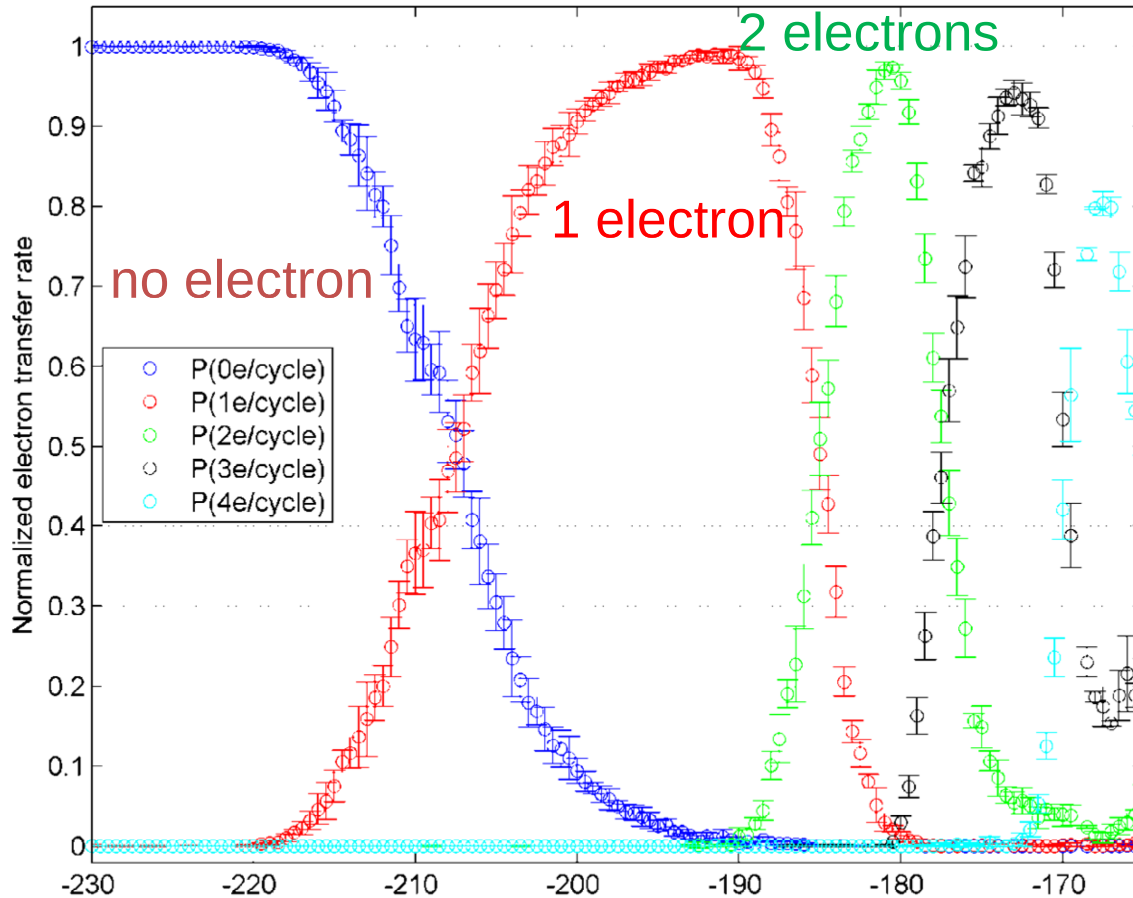
Single electron detection





Counting statistics of pumping





Exit gate voltage V [mV]

Fricke et al PRL 2012

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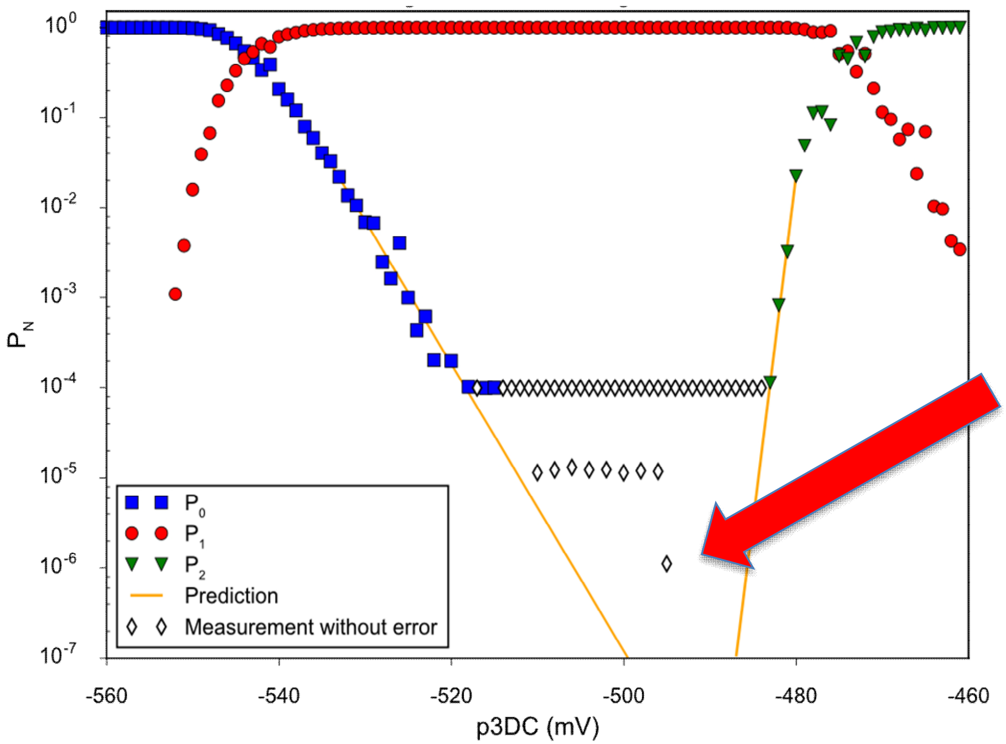
Error limit from single charge detection

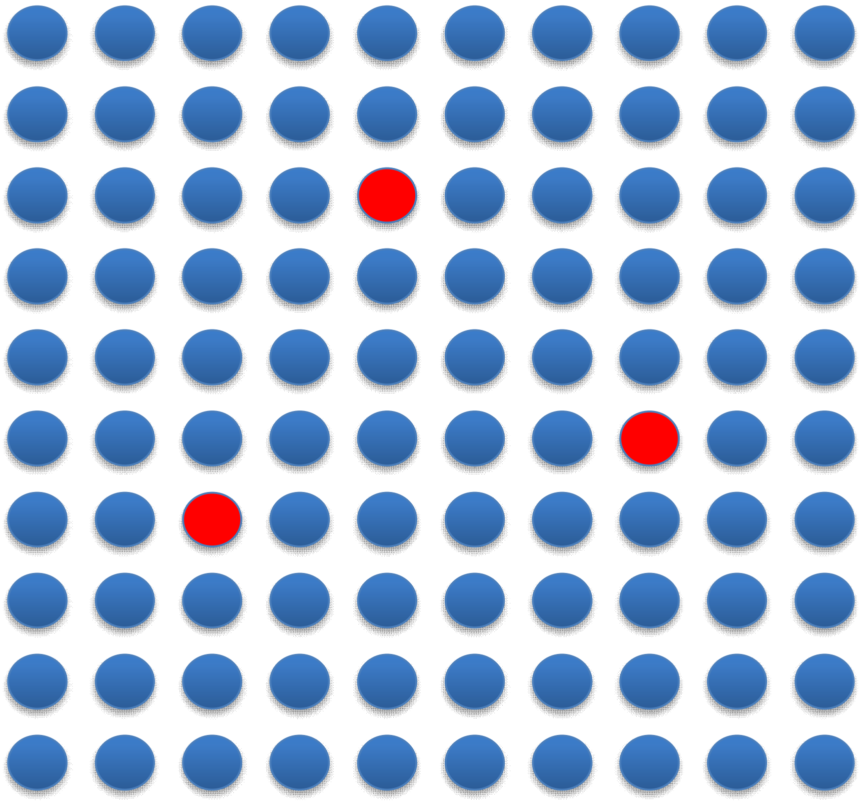
B=10T, QD-Detector



- No error after 10^6 pump cycles at B = 10T; *f* = 50 MHz
- Measurement limited by slow acquisition (1-2 days for 10^6)
- ➢ Ongoing: develop faster RF-SET detectors → better validation

PTB In situ validation: counting strategies

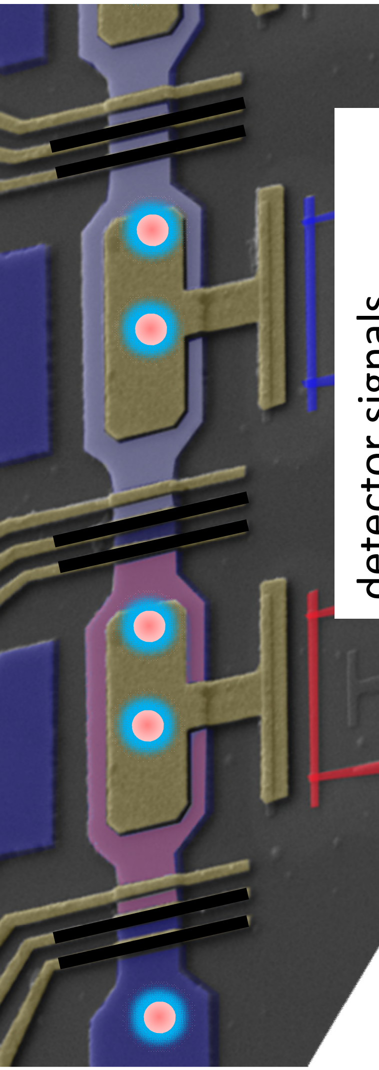
- Validate single electron current by single-electron detectors
  - about 5 x 10^8 electrons/s
  - about 100 - 1000 errors/s
  - what to count?

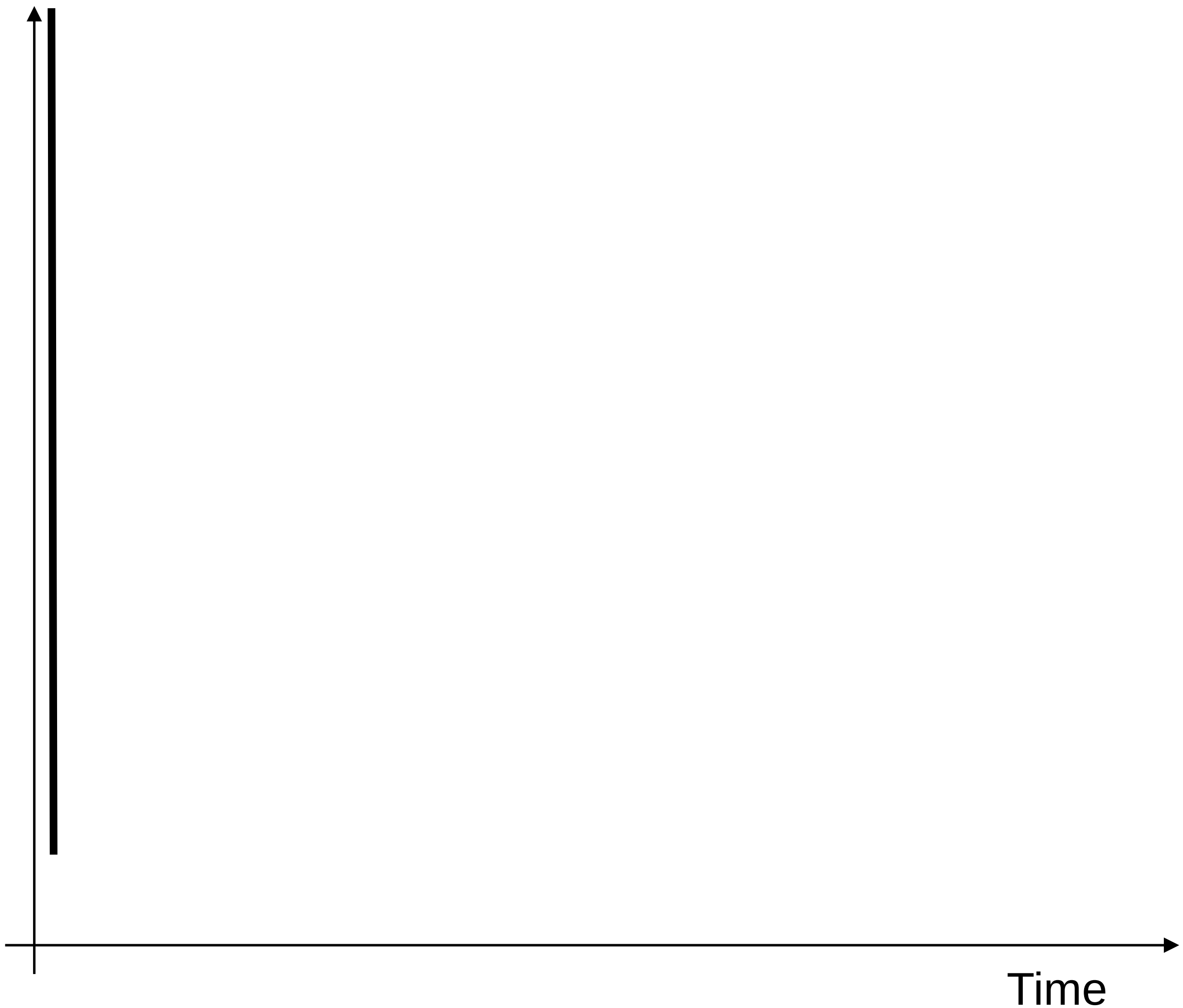


- **Count the errors!**

In-situ error detection

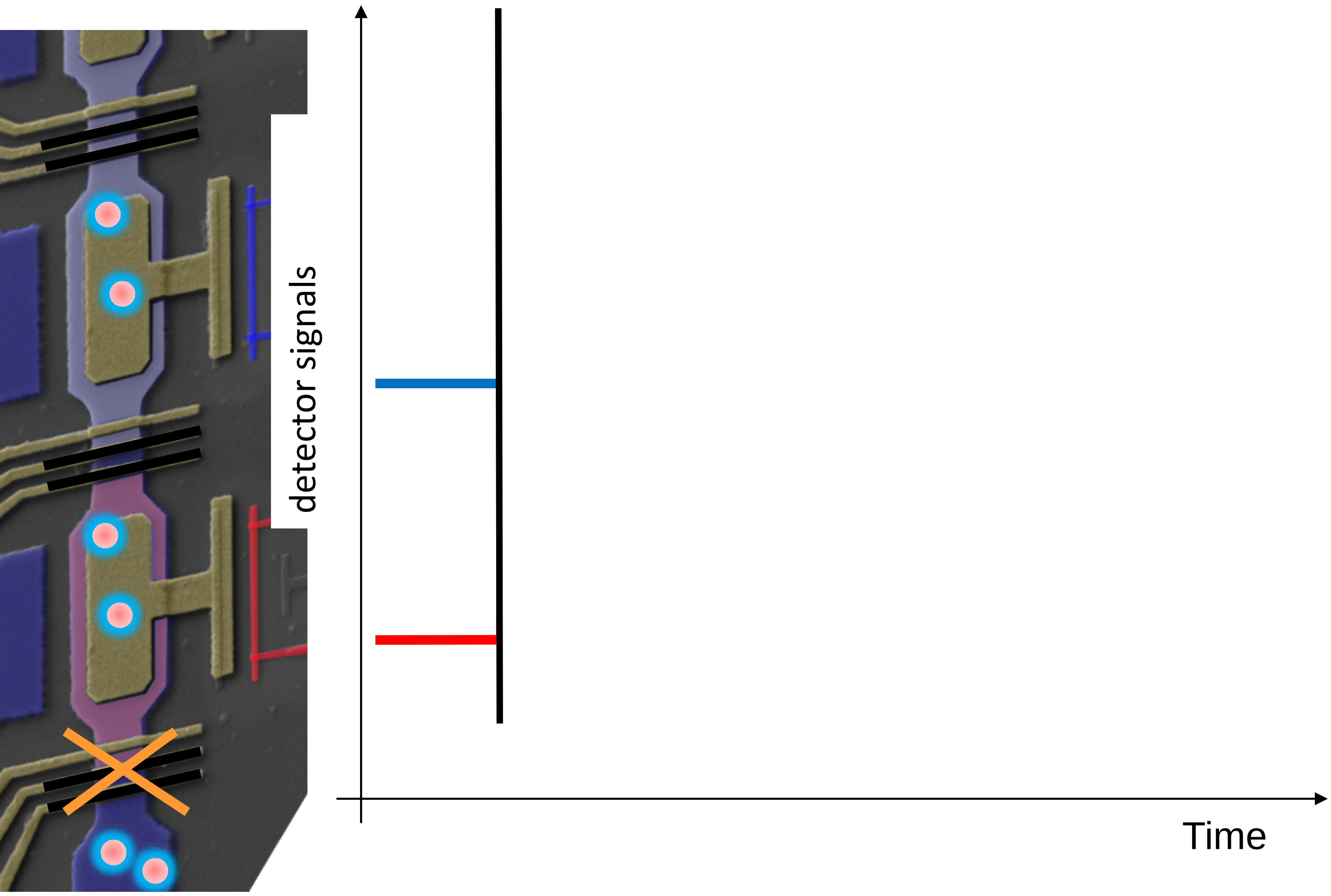
No errors: Constant detector signal





In-situ error detection

Fehler P1: D1: 1 one electron less

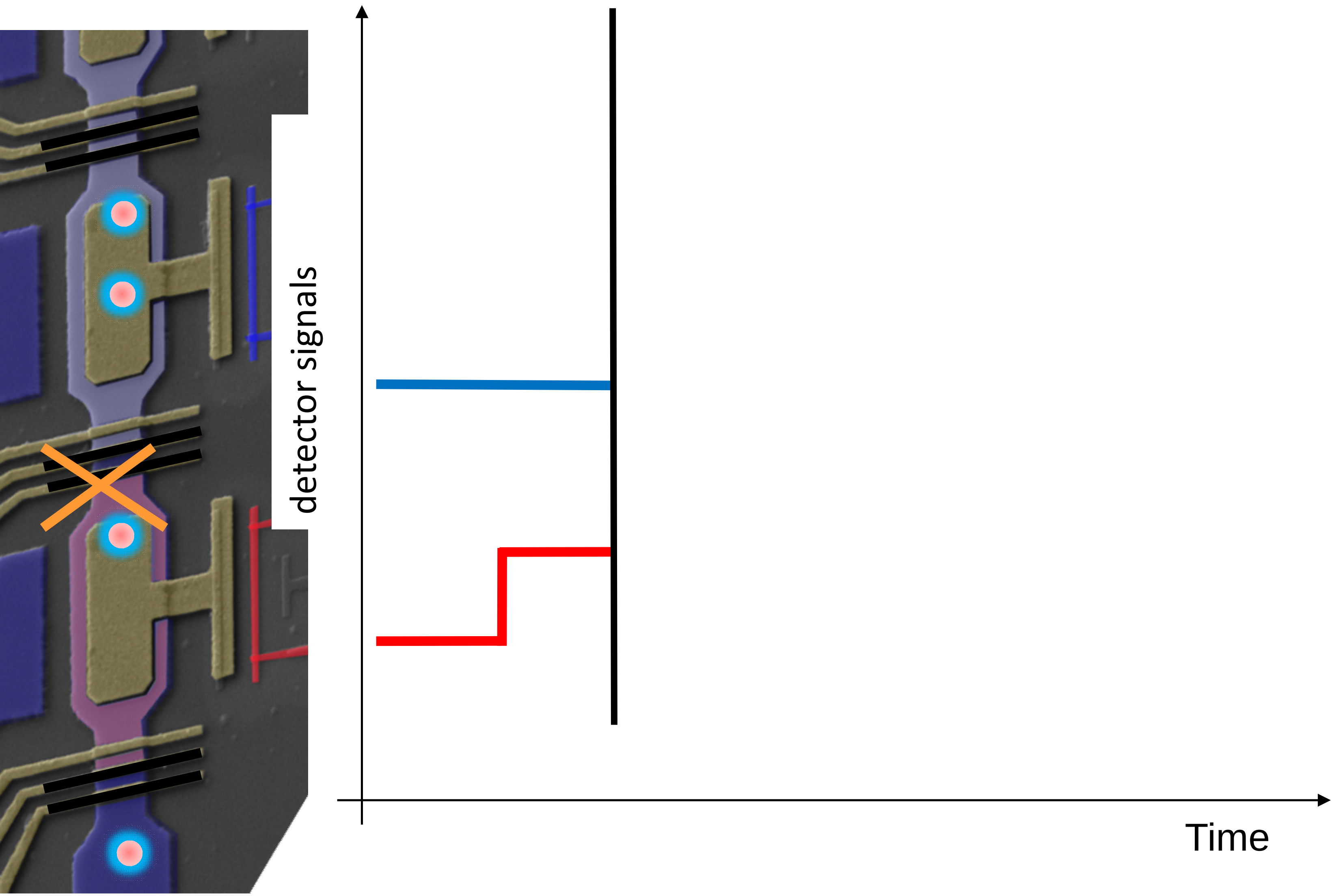


In-situ error detection

Error P2:

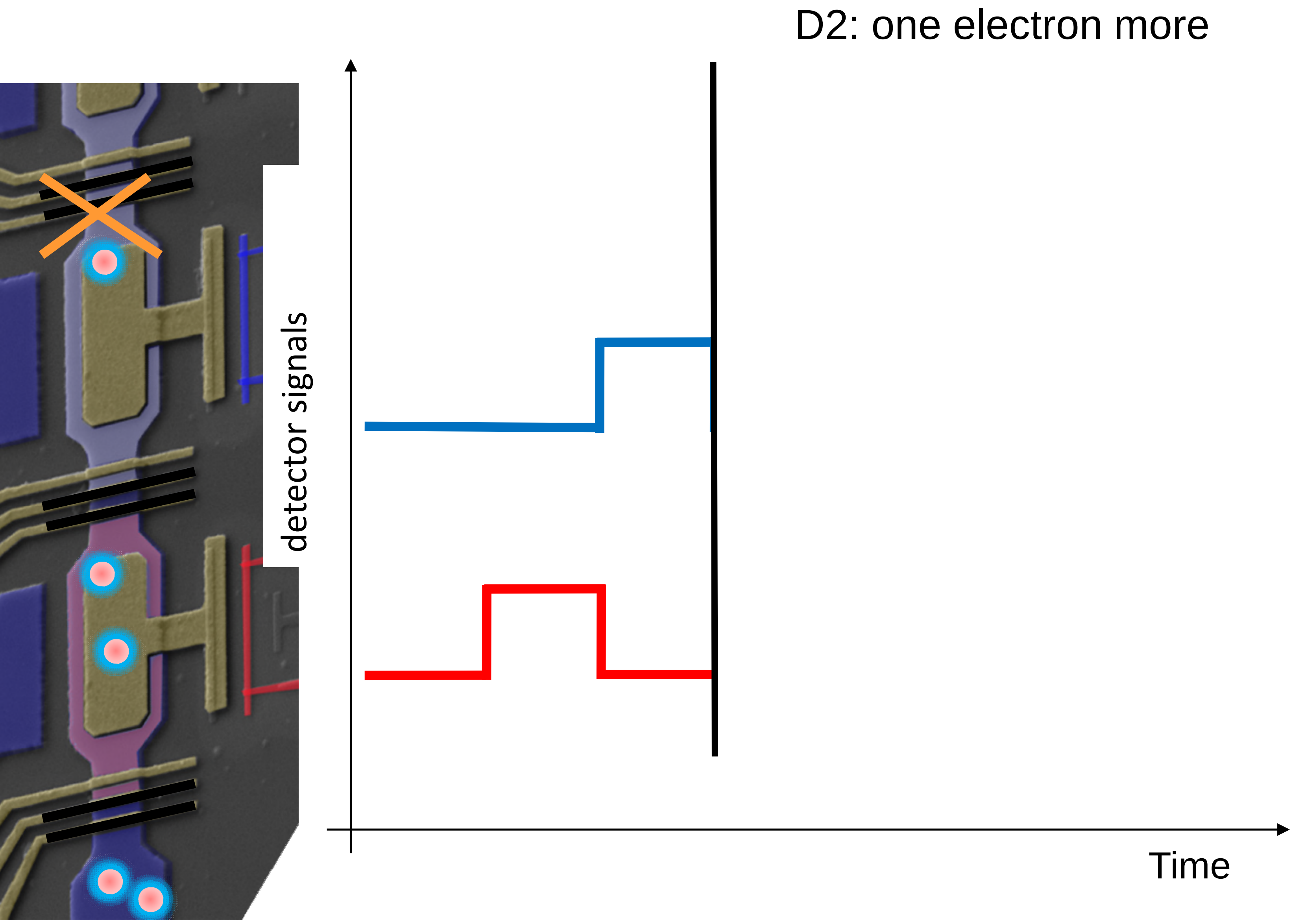
D1: one electron more

D2: one electron less

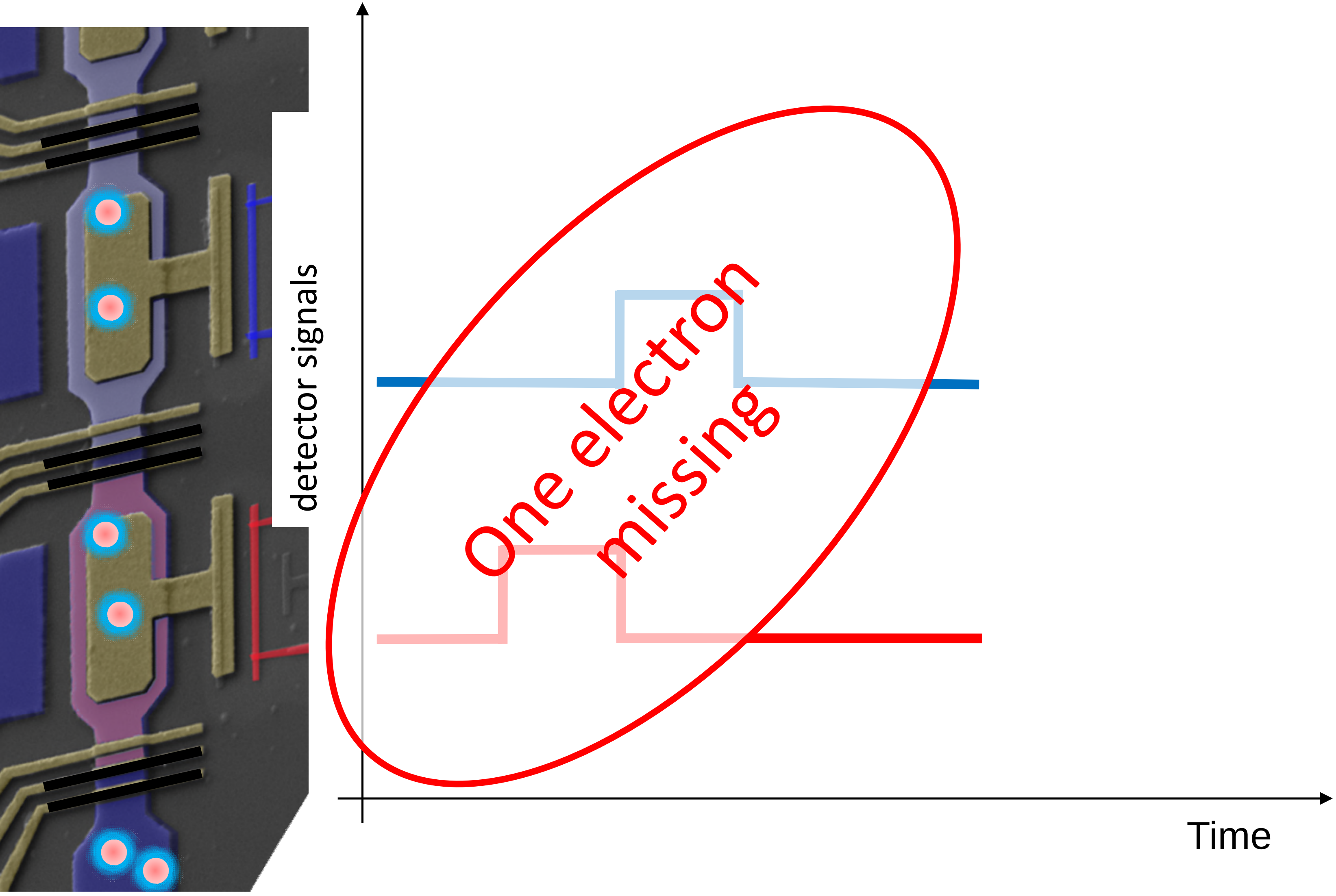


In-situ error detection

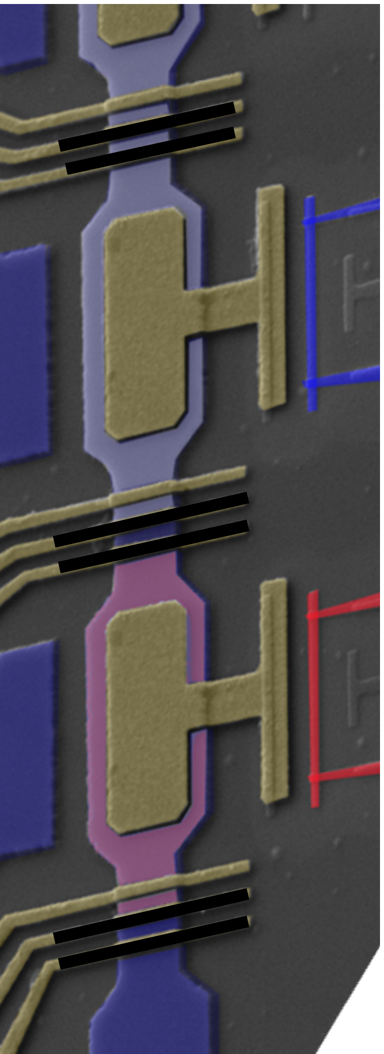
Error P3:

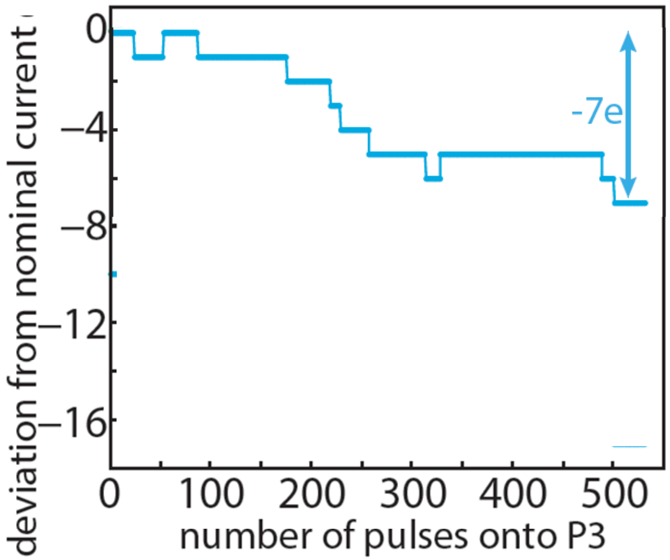


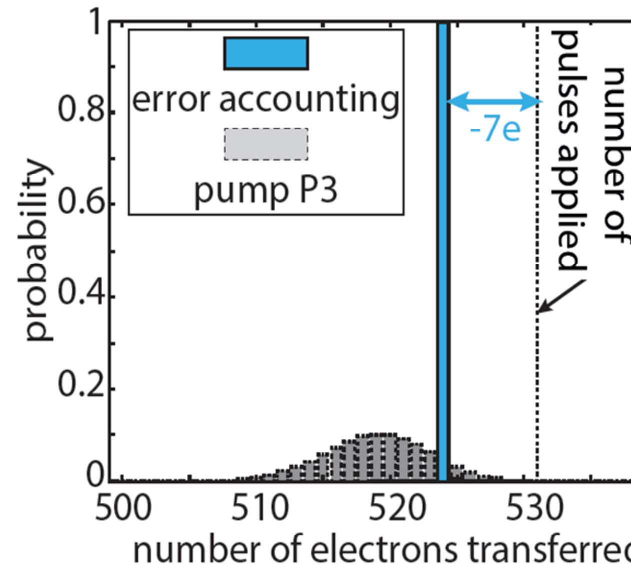
In-situ error detection



Statistic analysis of current uncertainty



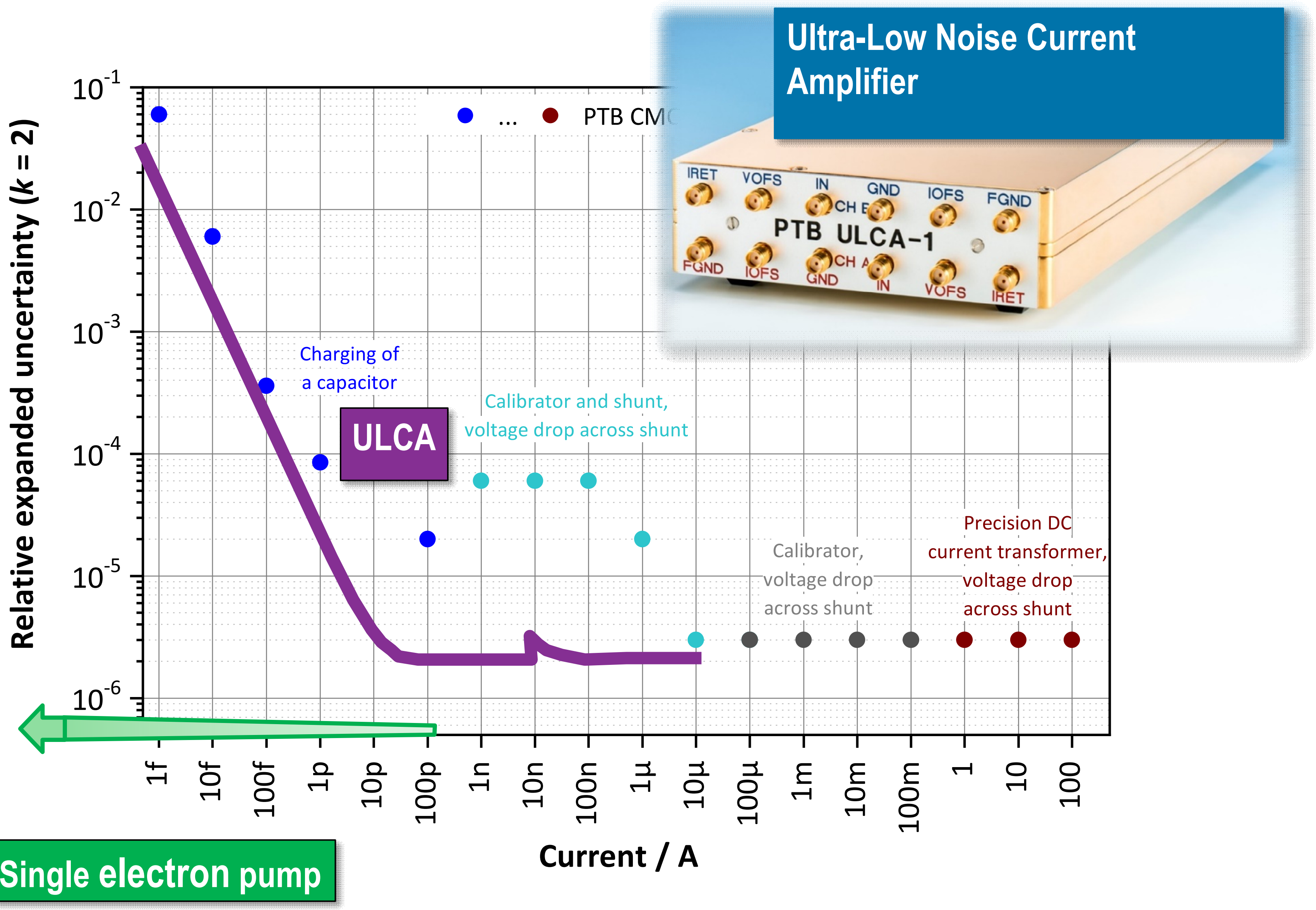




- Self referenced quantized current source
- Uncertainty reduced by factor of 50
- At few aA current amplitudes

Phys. Rev. Lett. ***112****, 126803* (2014)

DC Current Metrology: Present & Future



Conclusions

- Realization of the ampere by pumping electrons

  $u = 1.6\ 10^{-7}$ at 100 pA

- Single electron detection

  ➔ single electron counting

- In situ validation of single electron pumps

- Counting electrons is a tool for ultimate low current metrology

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Thanks to

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