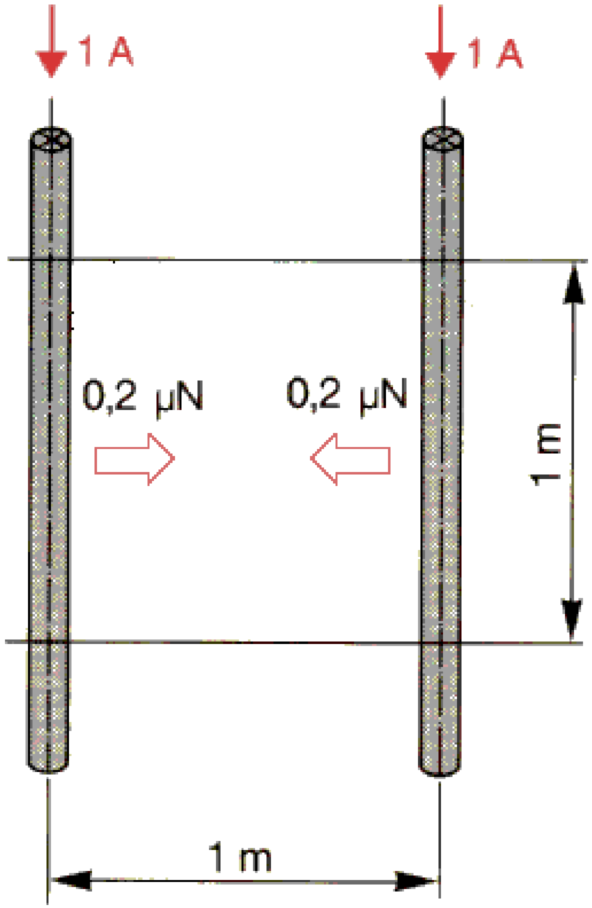
Investigation of dynamic quantum dot initialization by electron counting

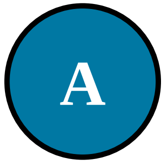
Lukas Fricke

Overview

- Introduction to dynamic quantum dots → electron pumping
- Characterization of a dynamic dot by charge detection
- Series operation of 3 pumps with charge detectors

Electrical units





SI base unit: Ampere (A)

- present definition: force between wires
- not used for realisation

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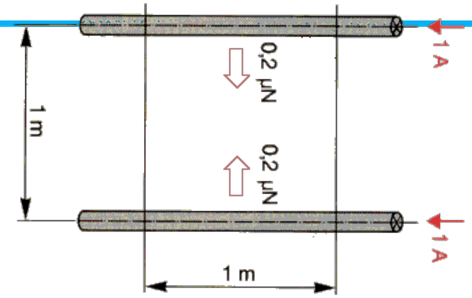

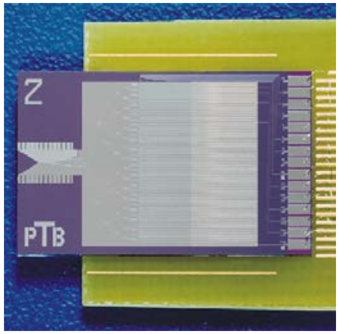

$$U = n \cdot \frac{h}{2e} \cdot f$$

A

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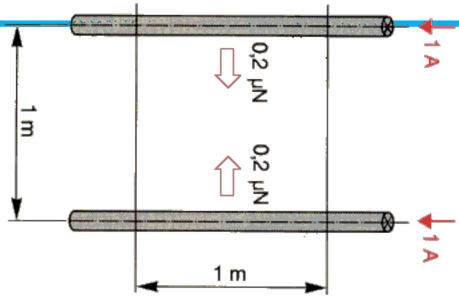
V

Volt (V)

- realised by Josephson effect
- fixed proportionality:
  2e/h = 483 597.9X GHz/V

Electrical units



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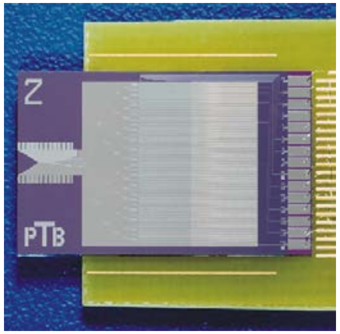

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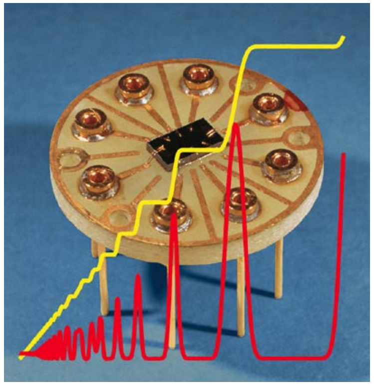


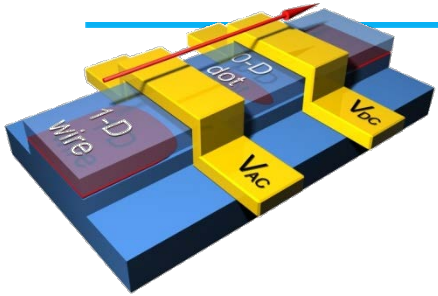
$$R_H = \frac{1}{n}\frac{h}{e^2}$$

Ω

Ohm (Ω)

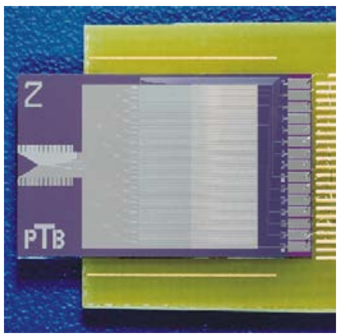
- quantum Hall effect
- h/e^2 = 25 712.807X Ω

Electrical units



$$I = n \cdot e \cdot f$$

A



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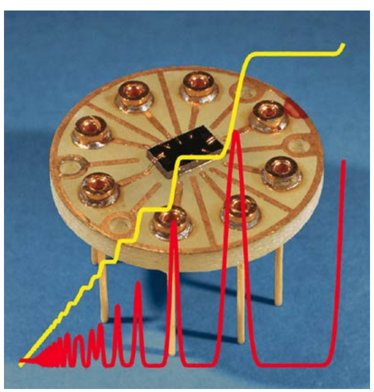

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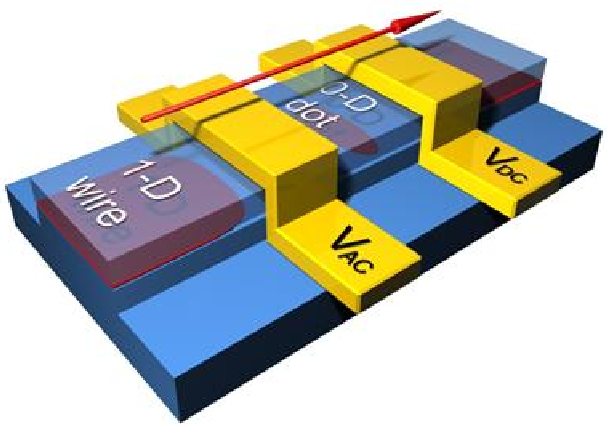
new Ampere (A):
1 A = 6.24150X·10^{18} e / 1s

- fix elementary charge e
- quantised electron pumping

Non-adiabatic quantum dot



- GaAs/AlGaAs 2D electron gas channel
- Top gates define quantum dot
- Modulation of entrance barrier
- Capture electrons from source
- Lift electrons over exit barrier
- Directed pumping without bias
- Quantized current: $I = e \cdot f$

- Advantages:
- GHz frequencies

  → high currents
- Prospect for high precision
- Simple device & operation

  → Parallelization

Phys. Rev. B **77**, 153301 (2008)

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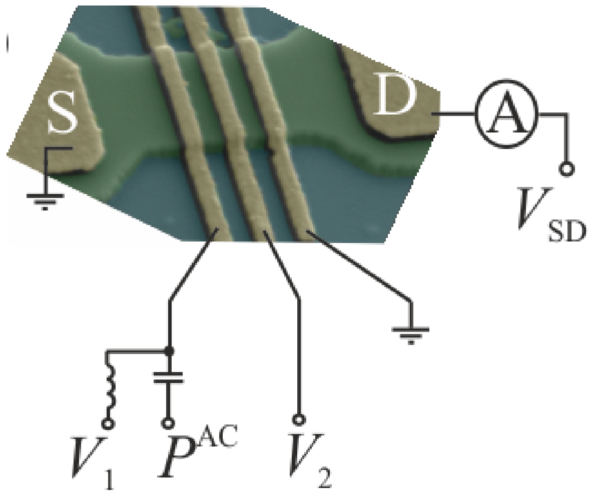

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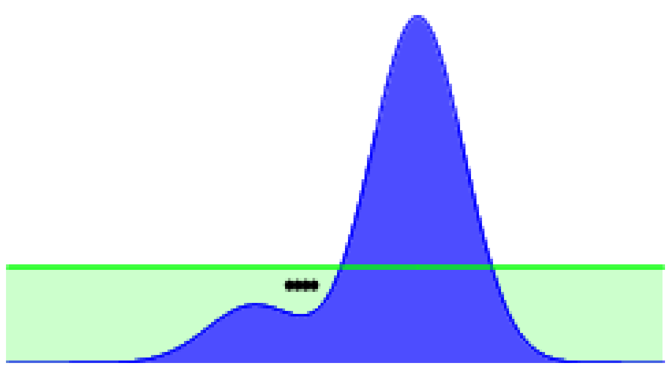

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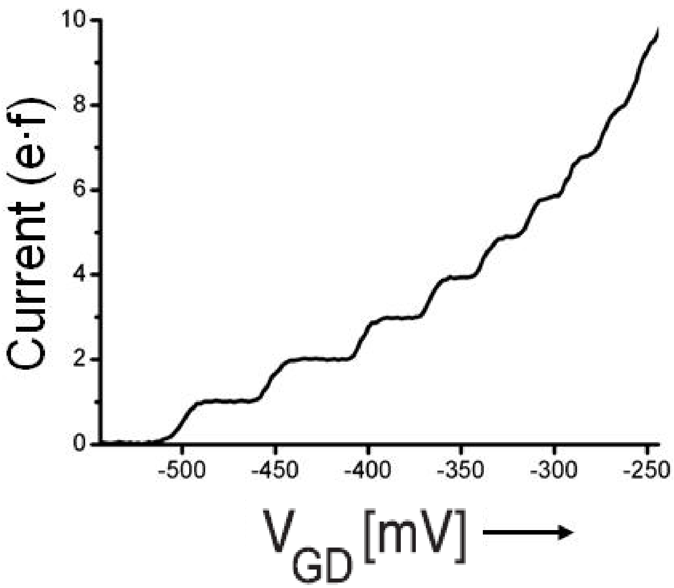

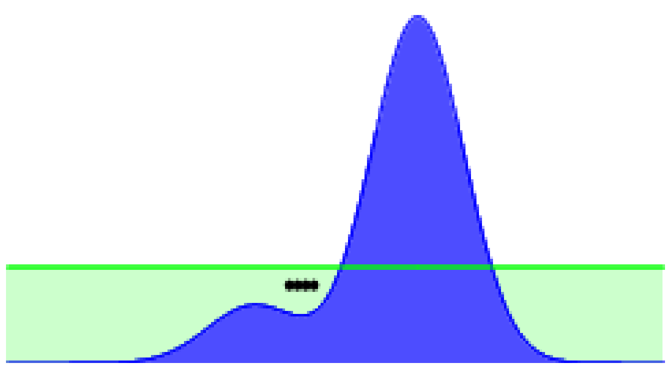

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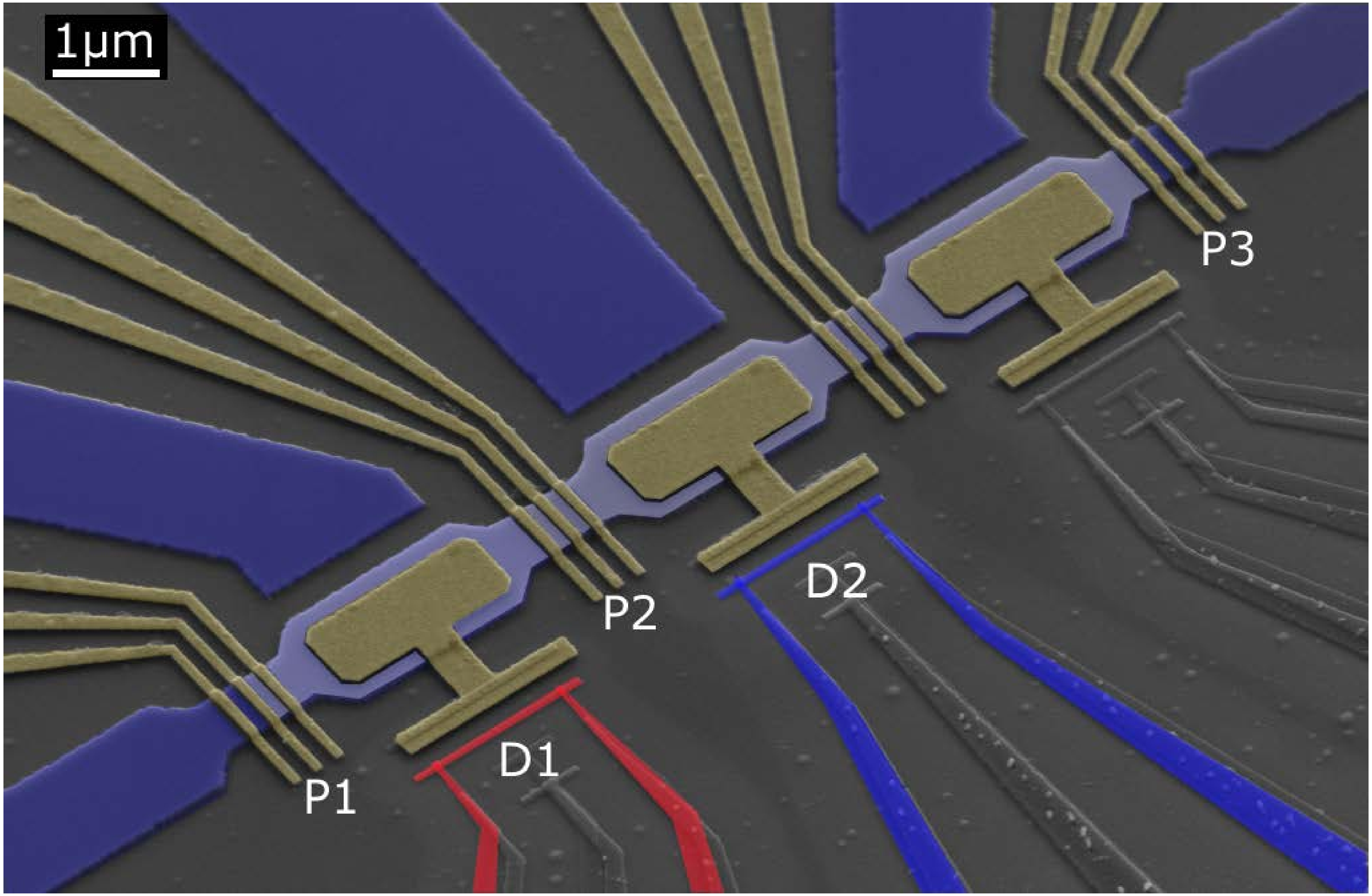

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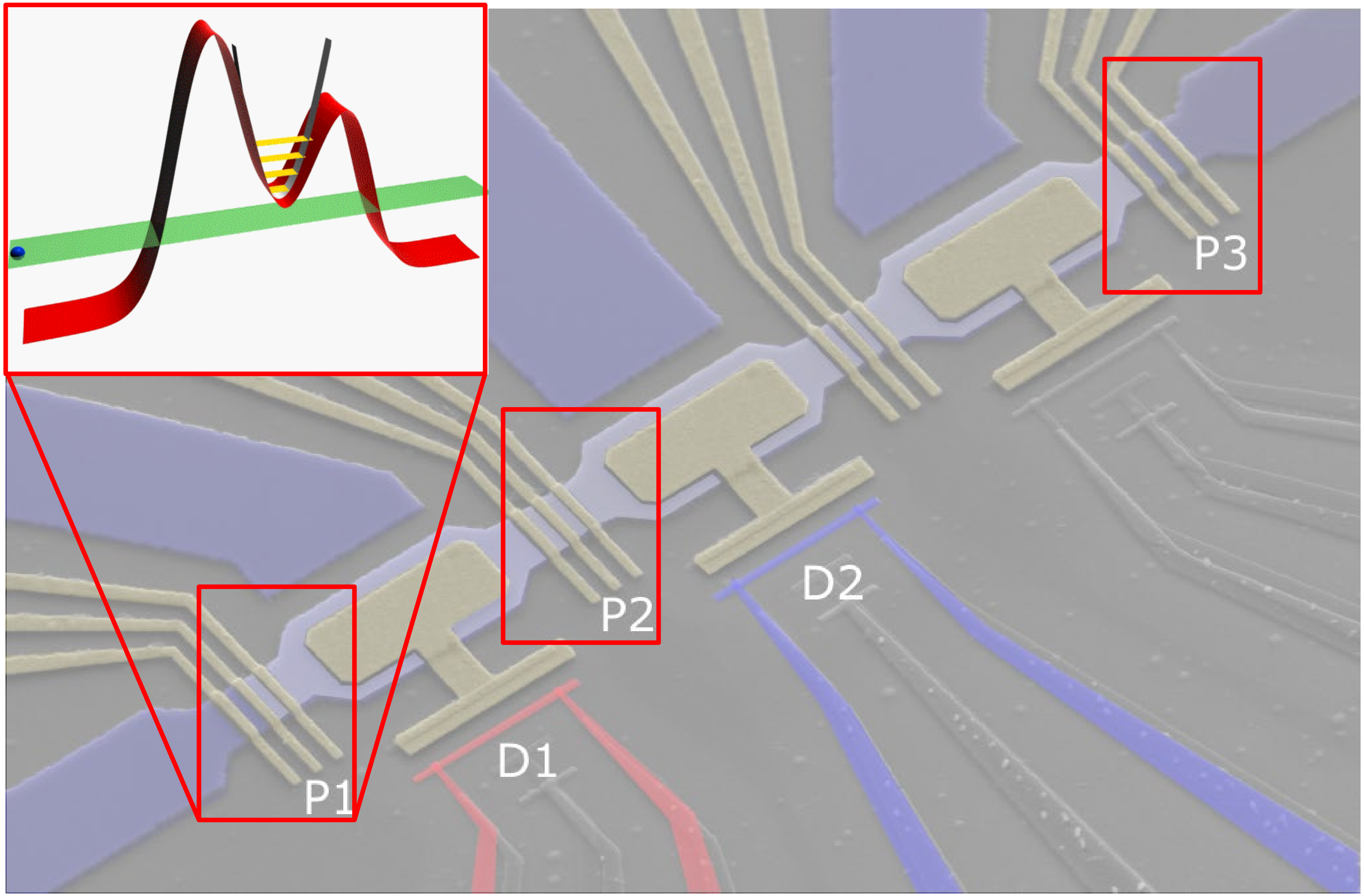

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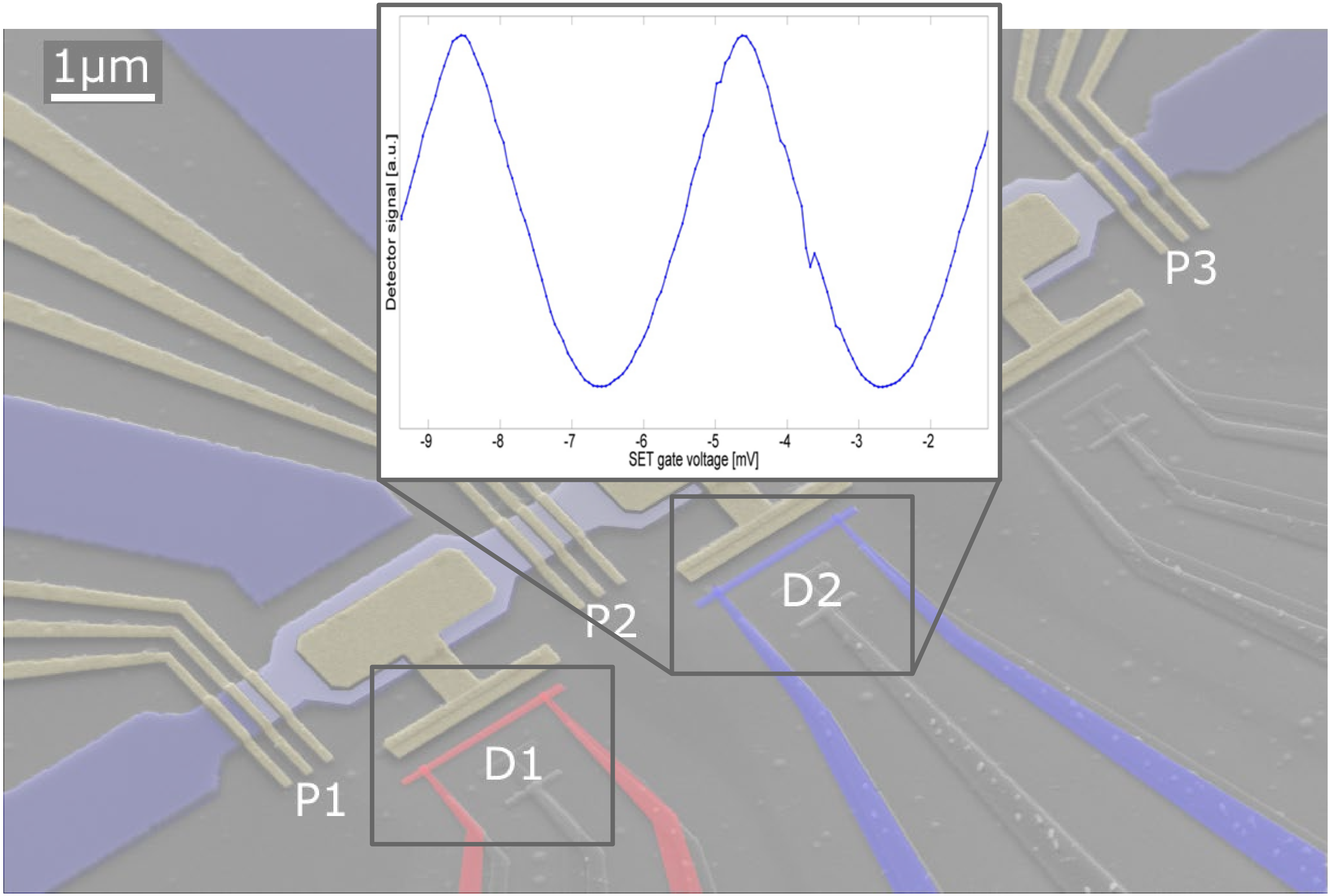

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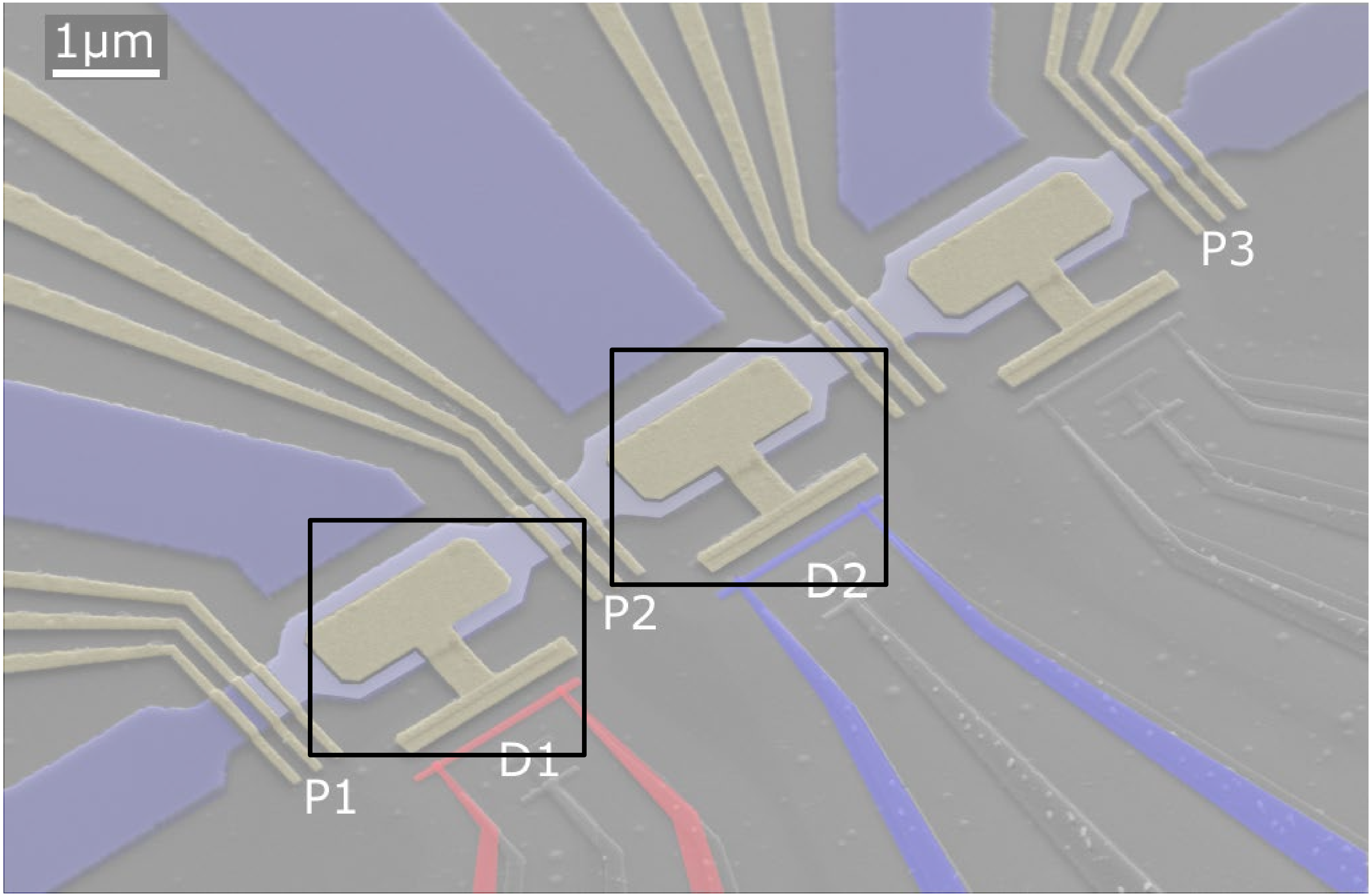

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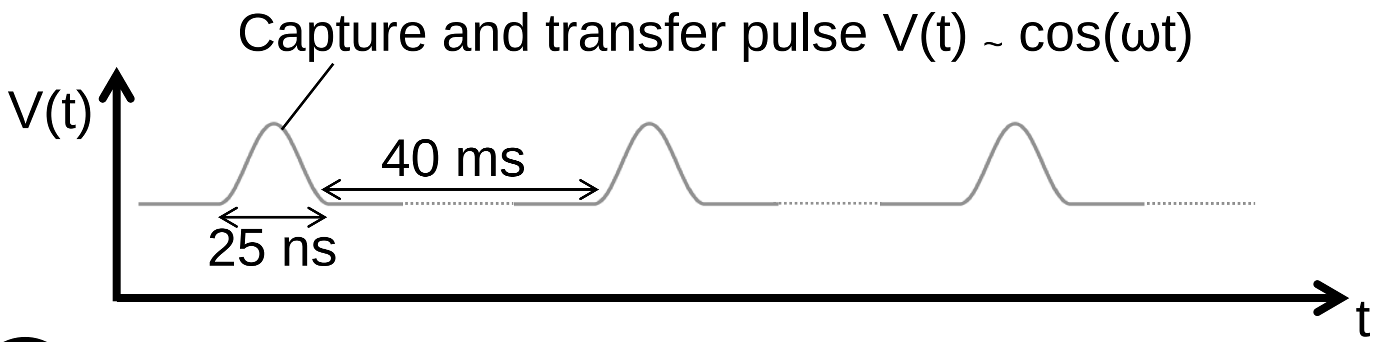
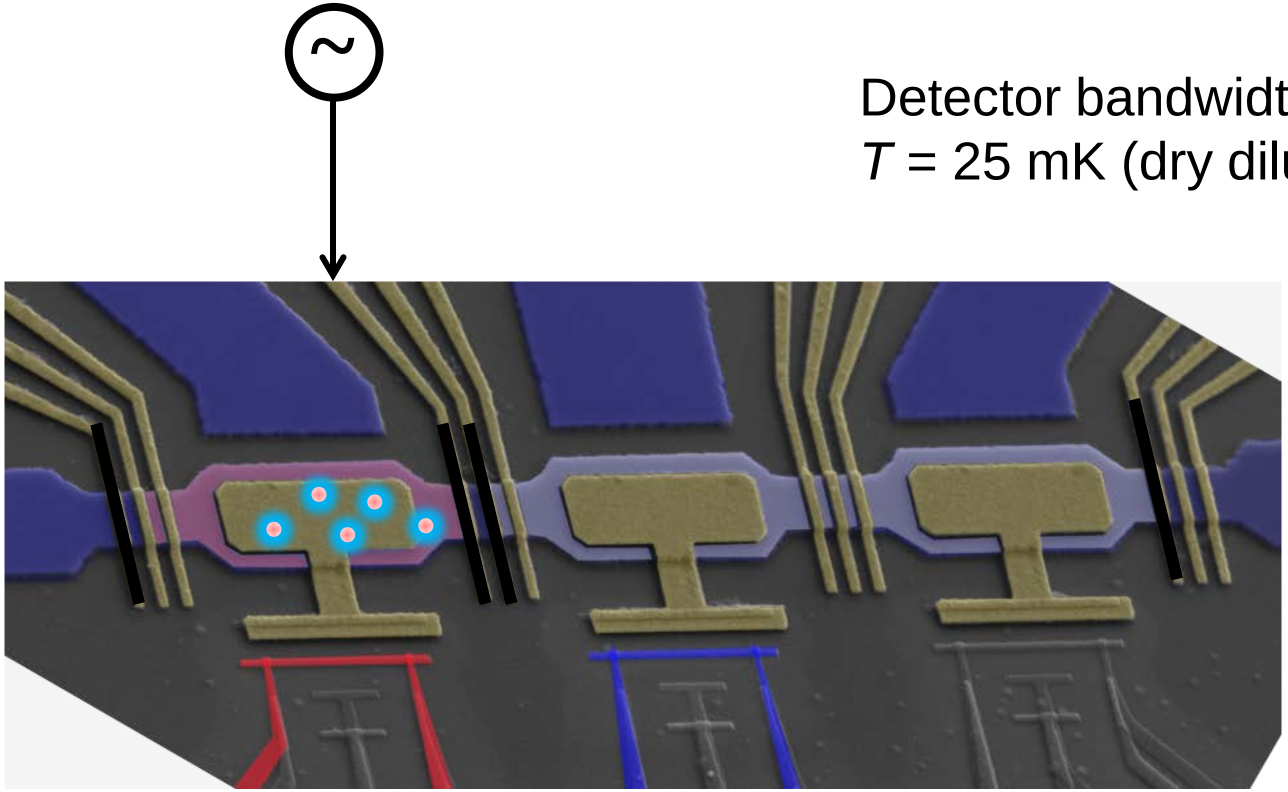
Single-charge transfer between nodes



Detector bandwidth: ~ 1 kHz

T = 25 mK (dry dilution fridge)



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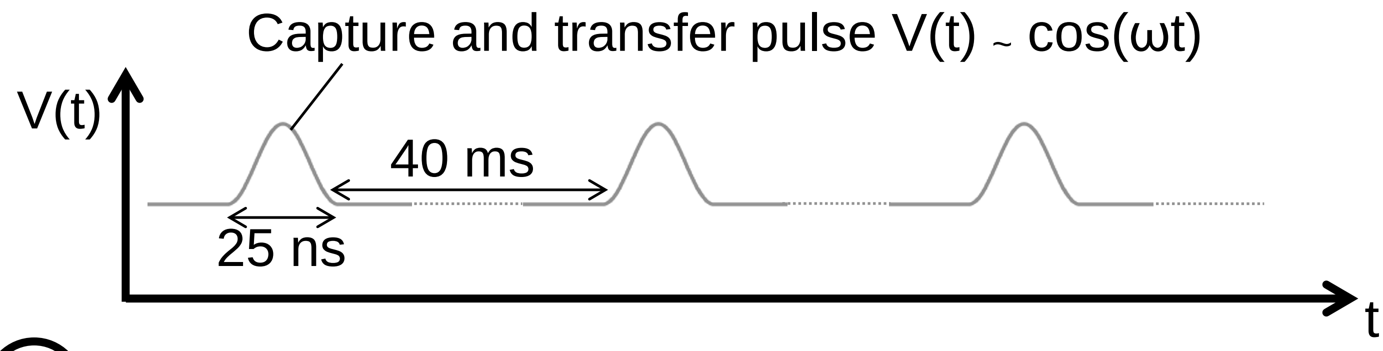

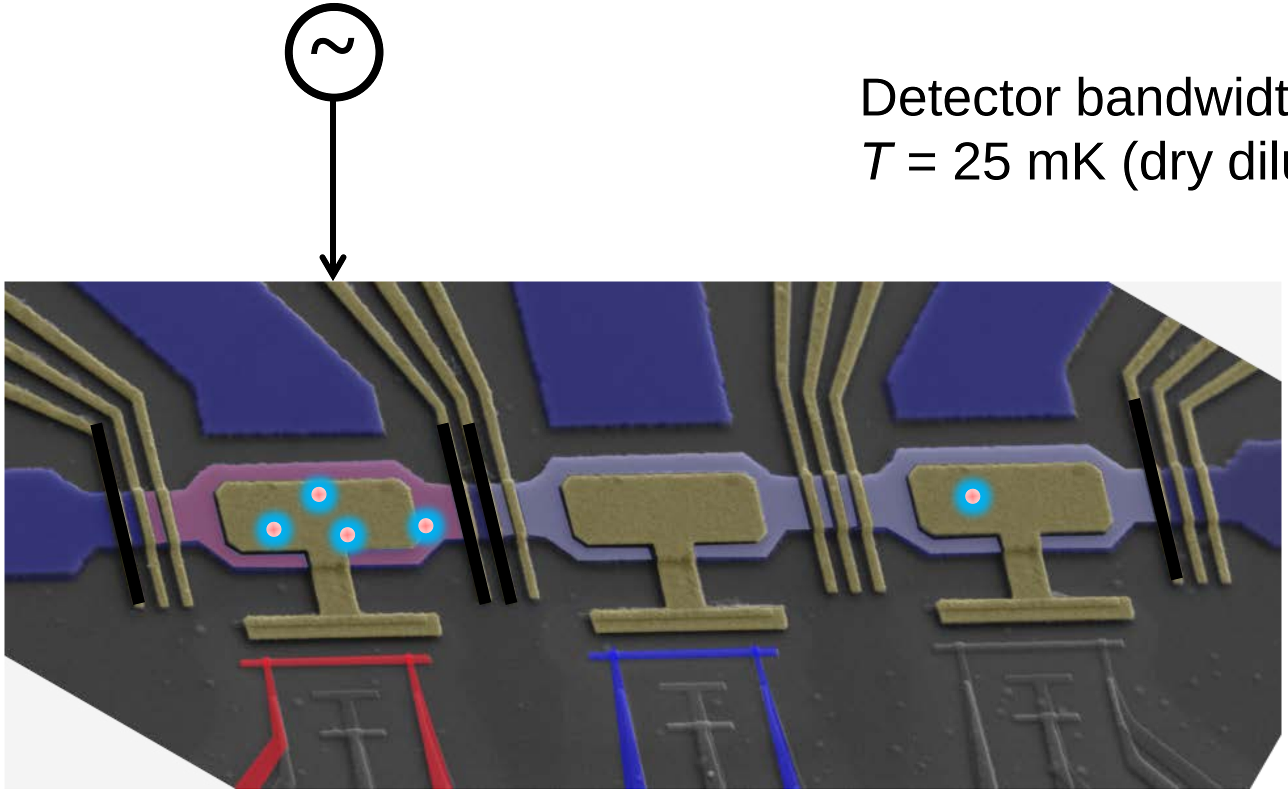

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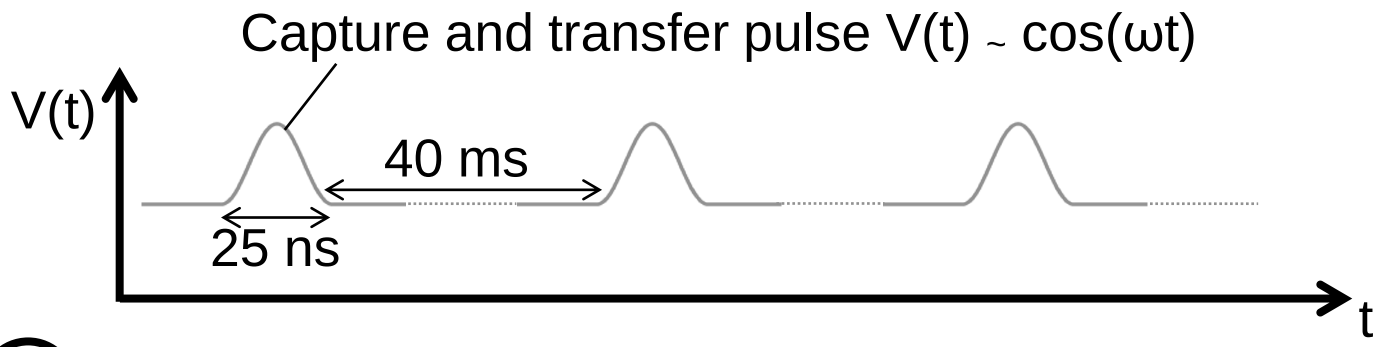

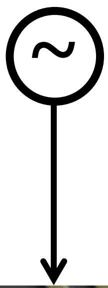

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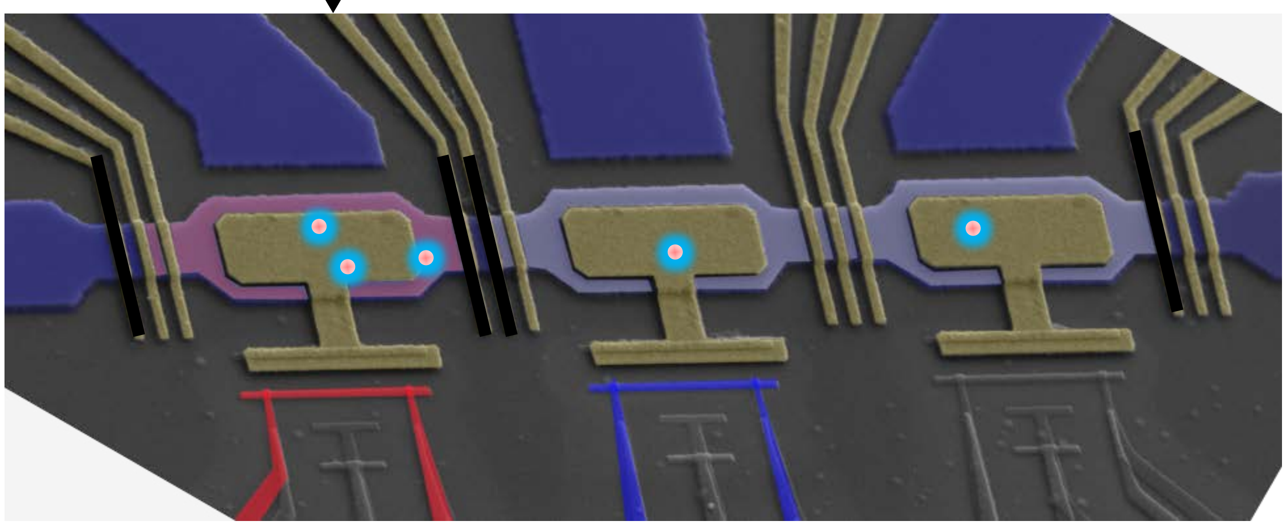

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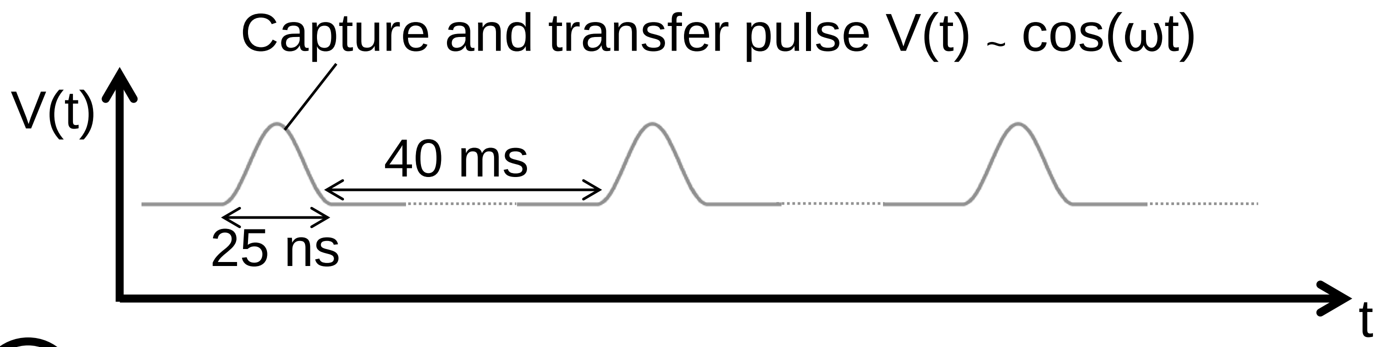

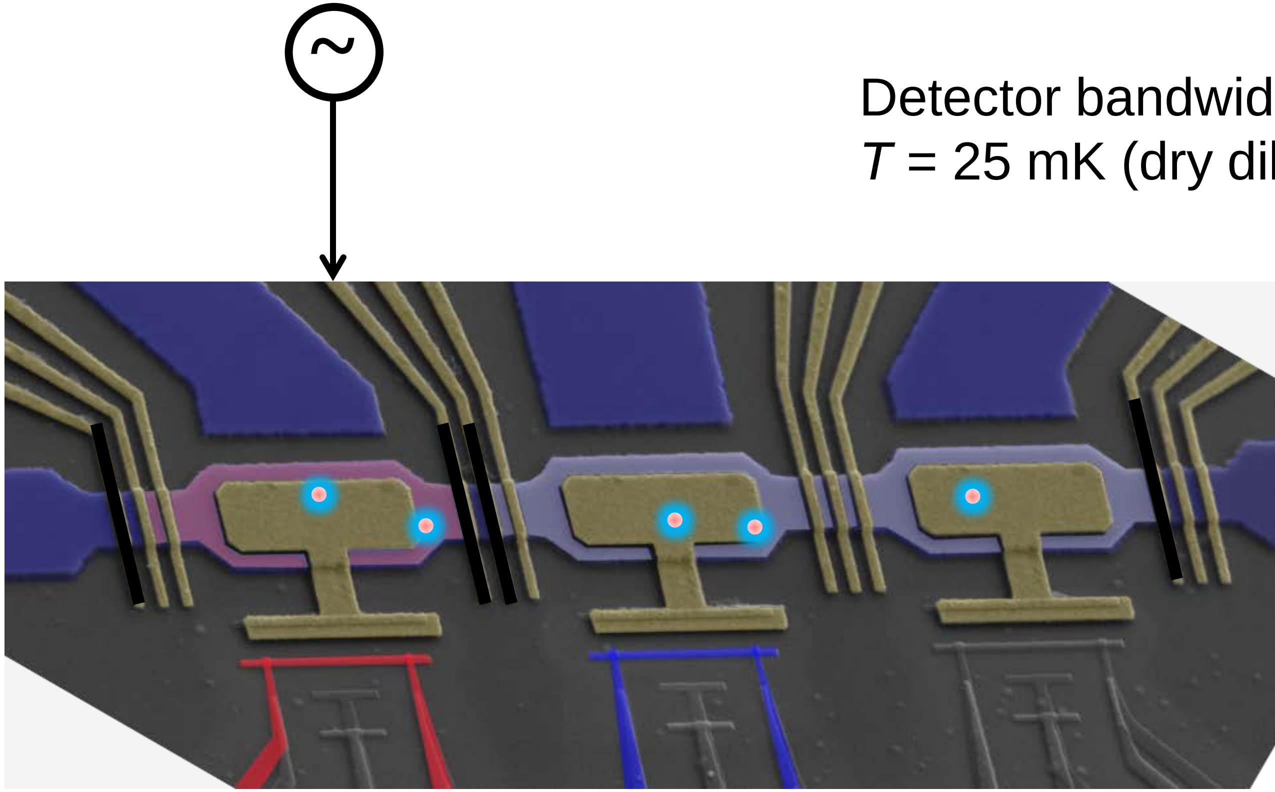

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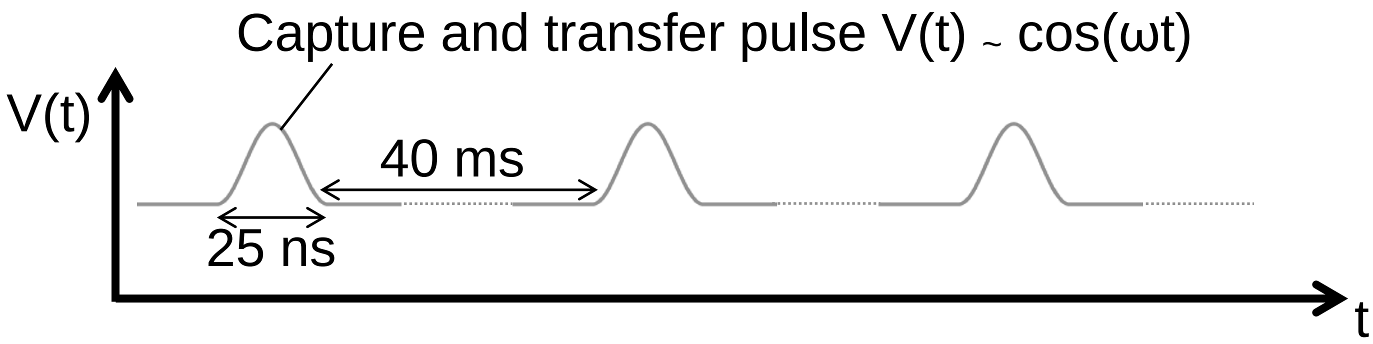

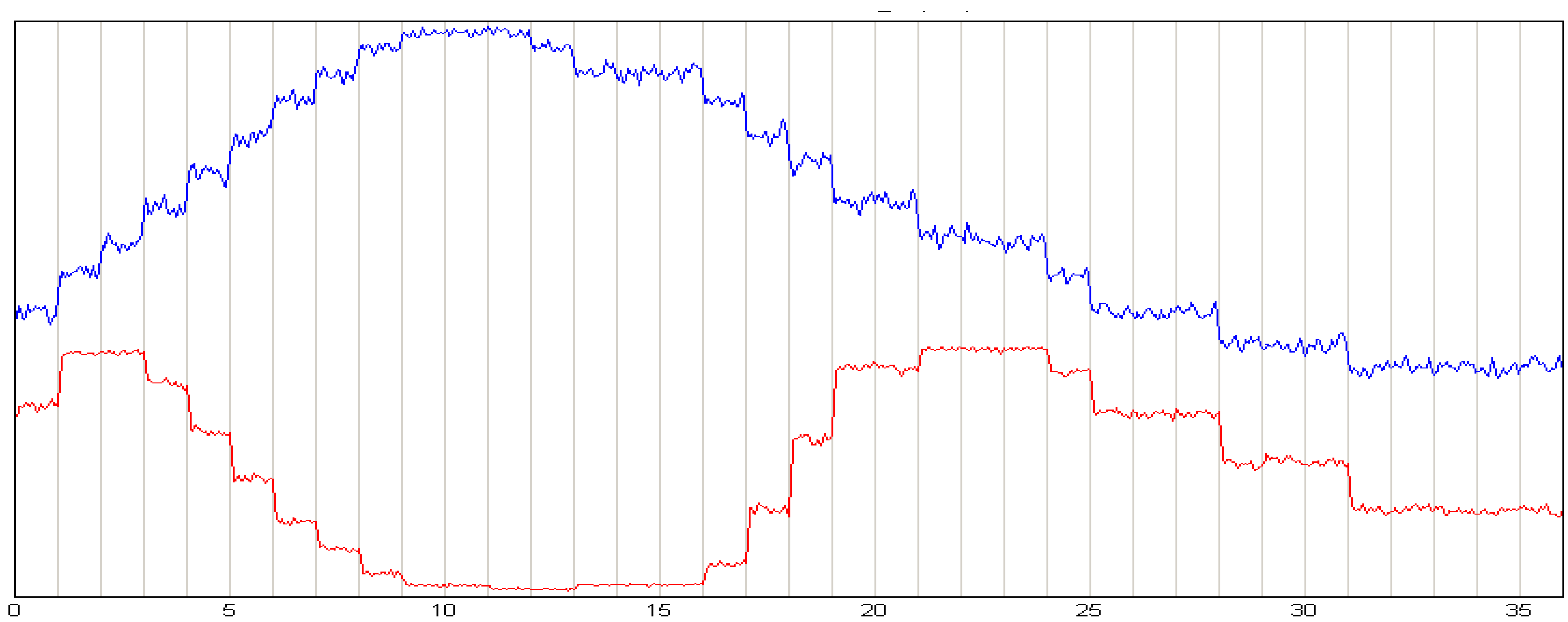

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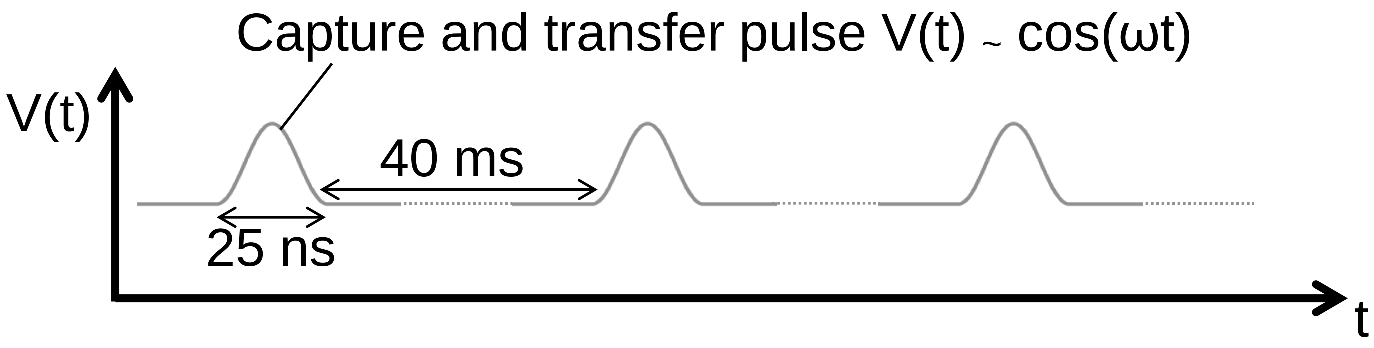

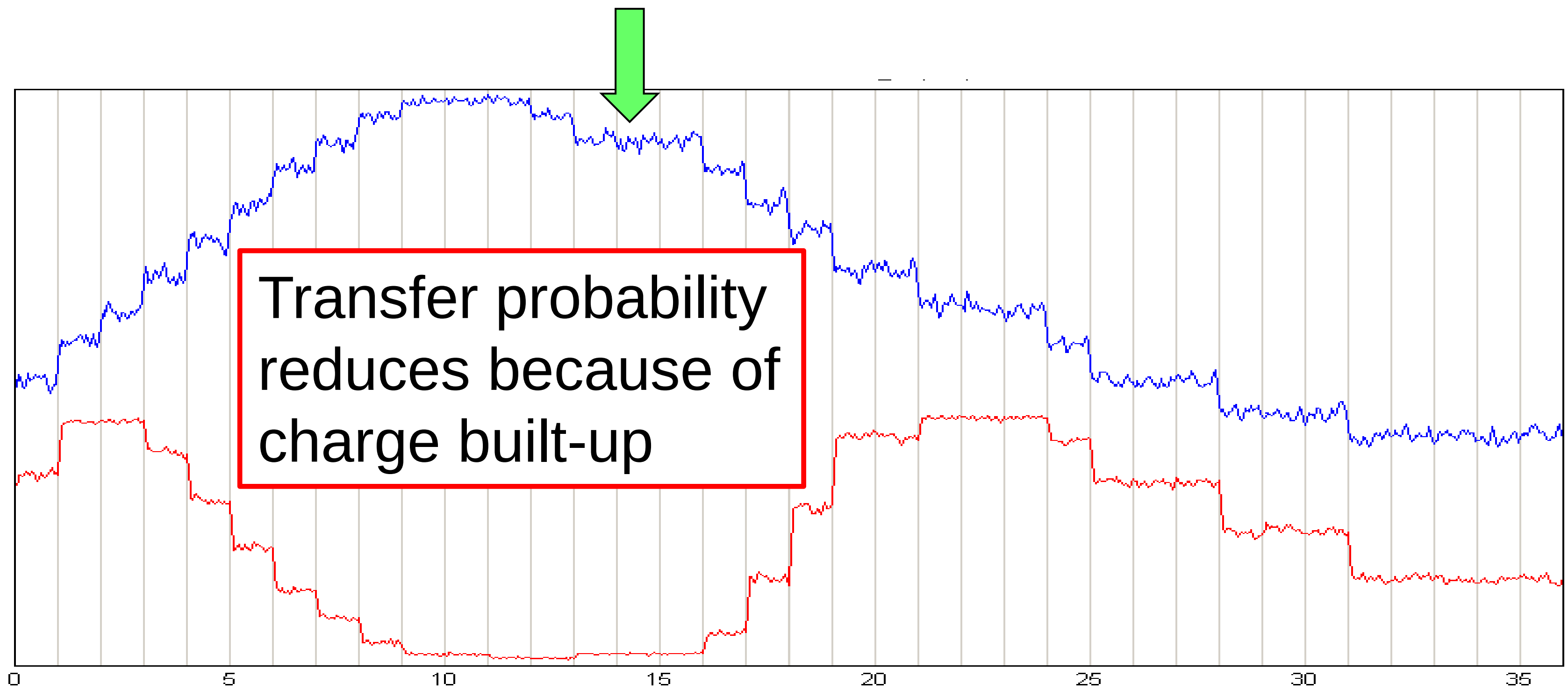

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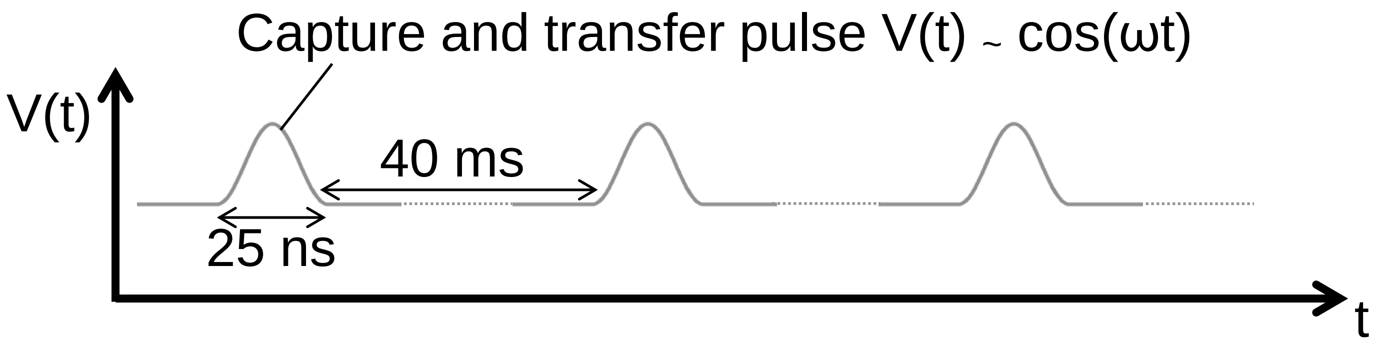
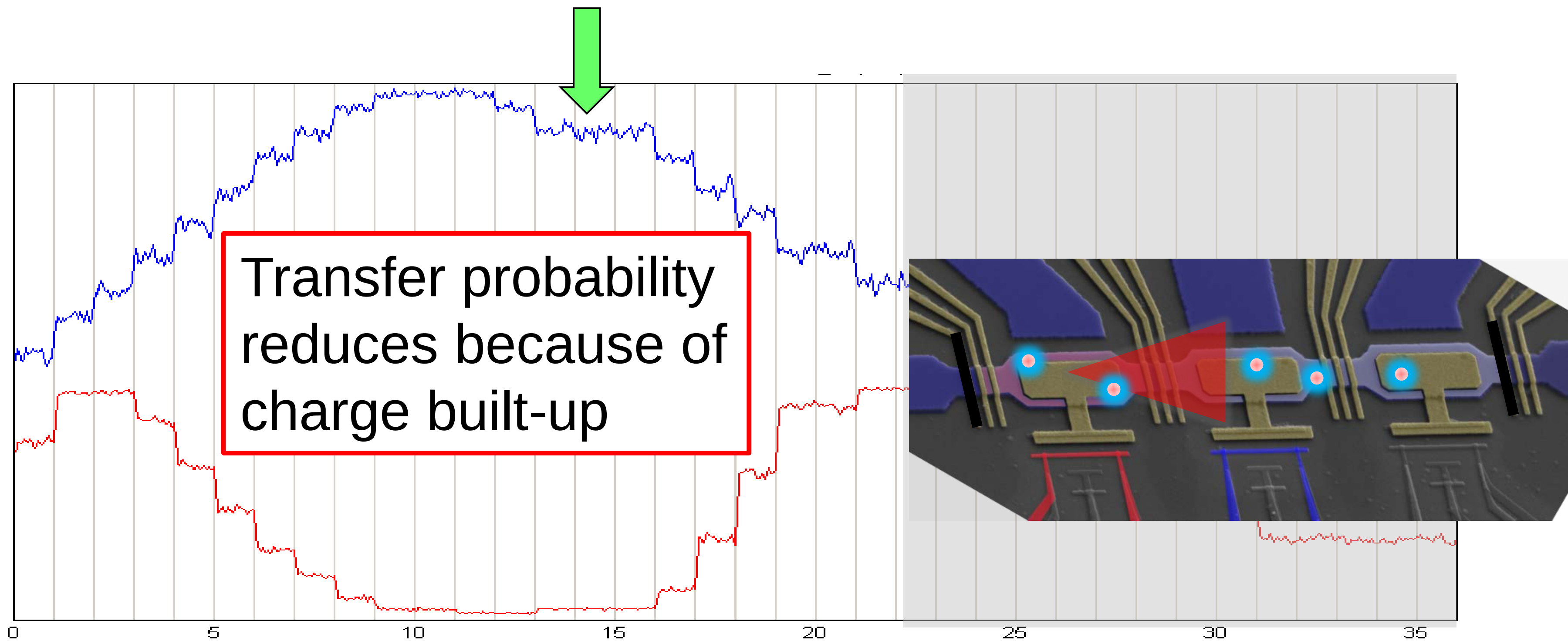
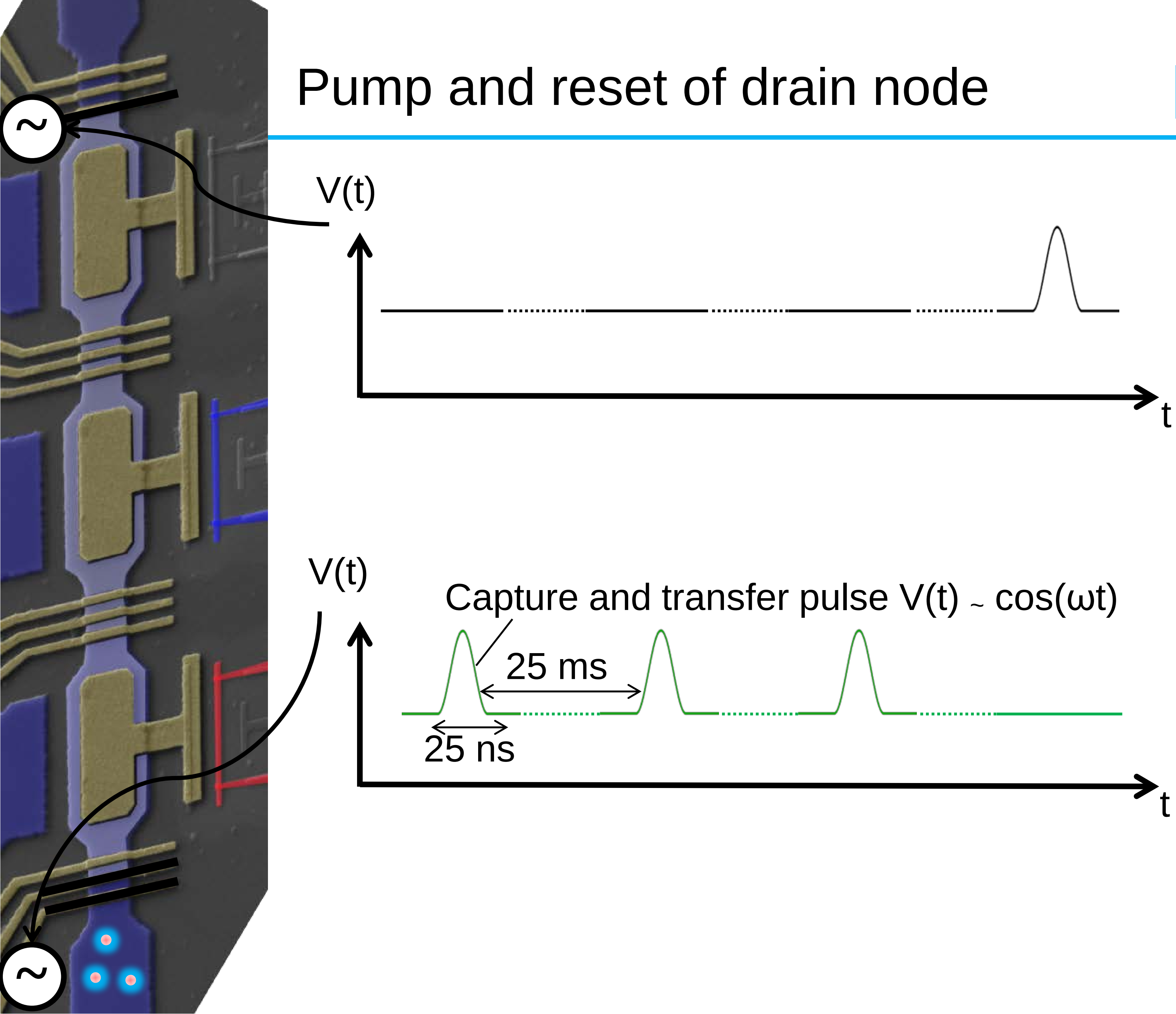




Pump and reset of drain node



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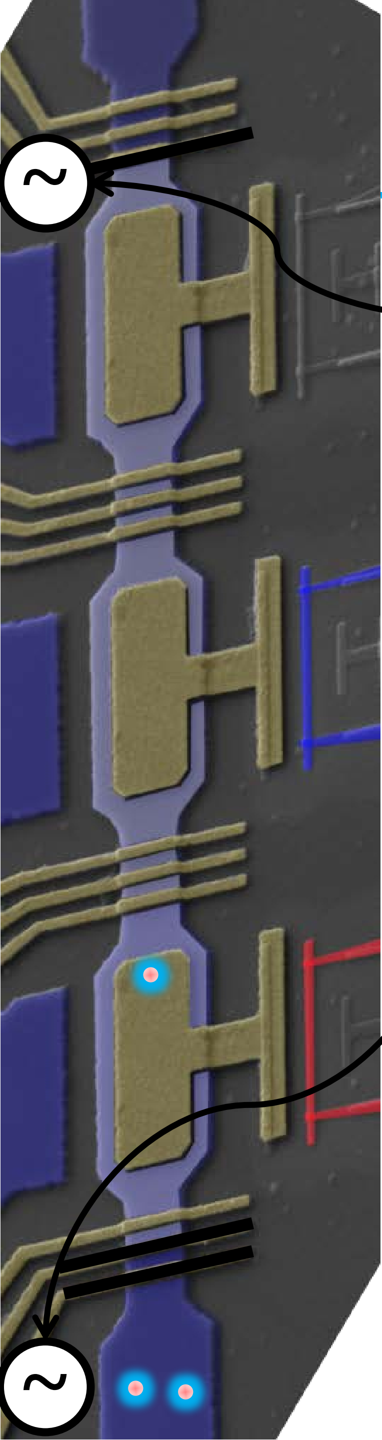

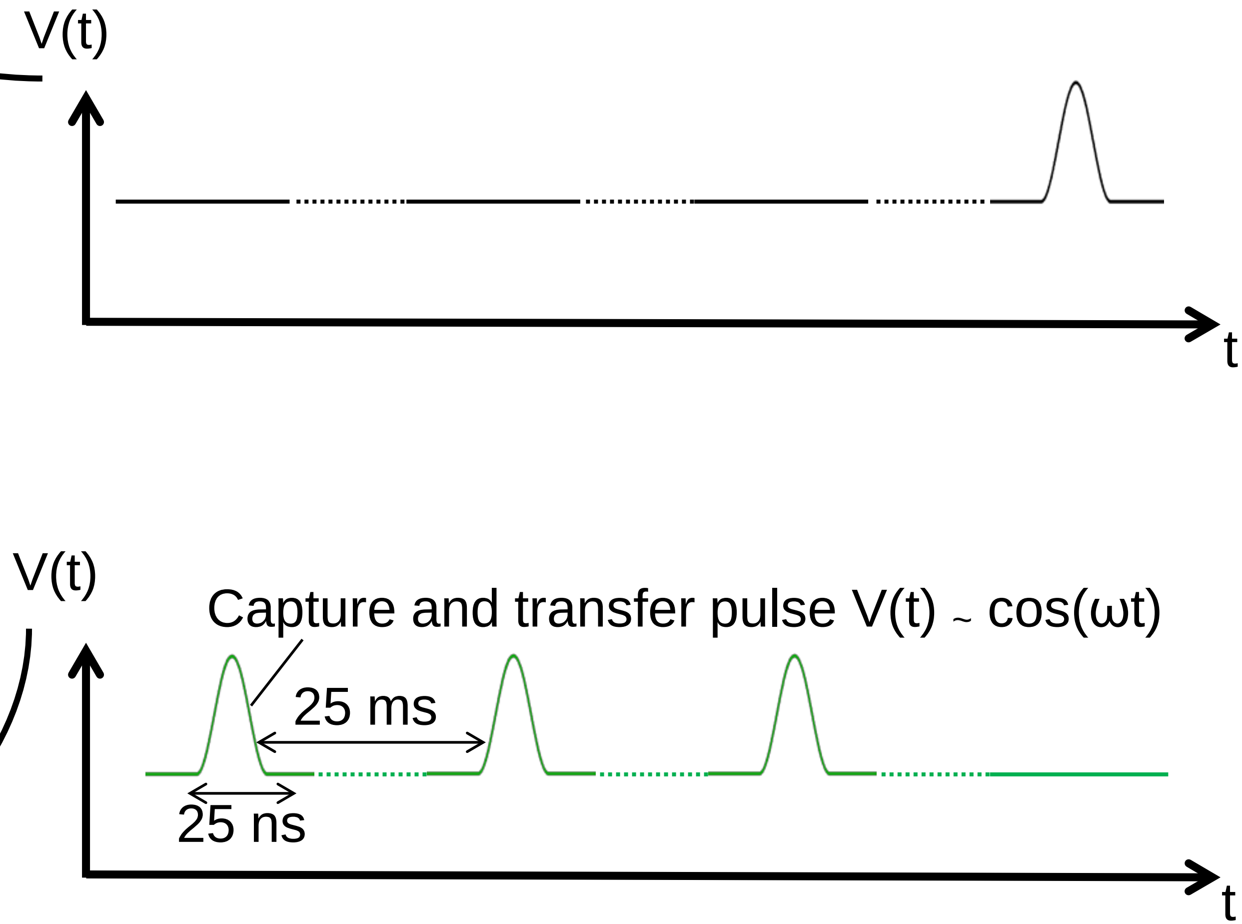

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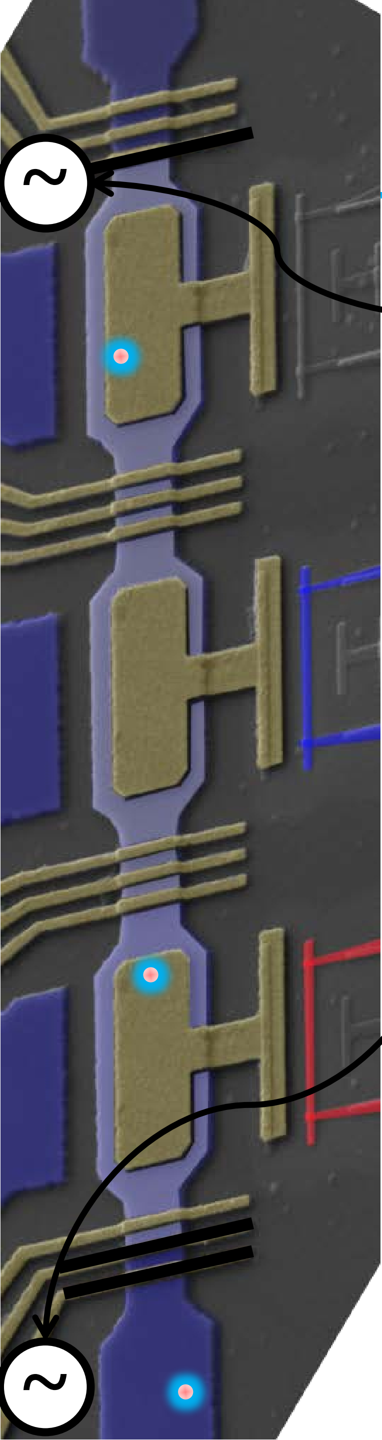

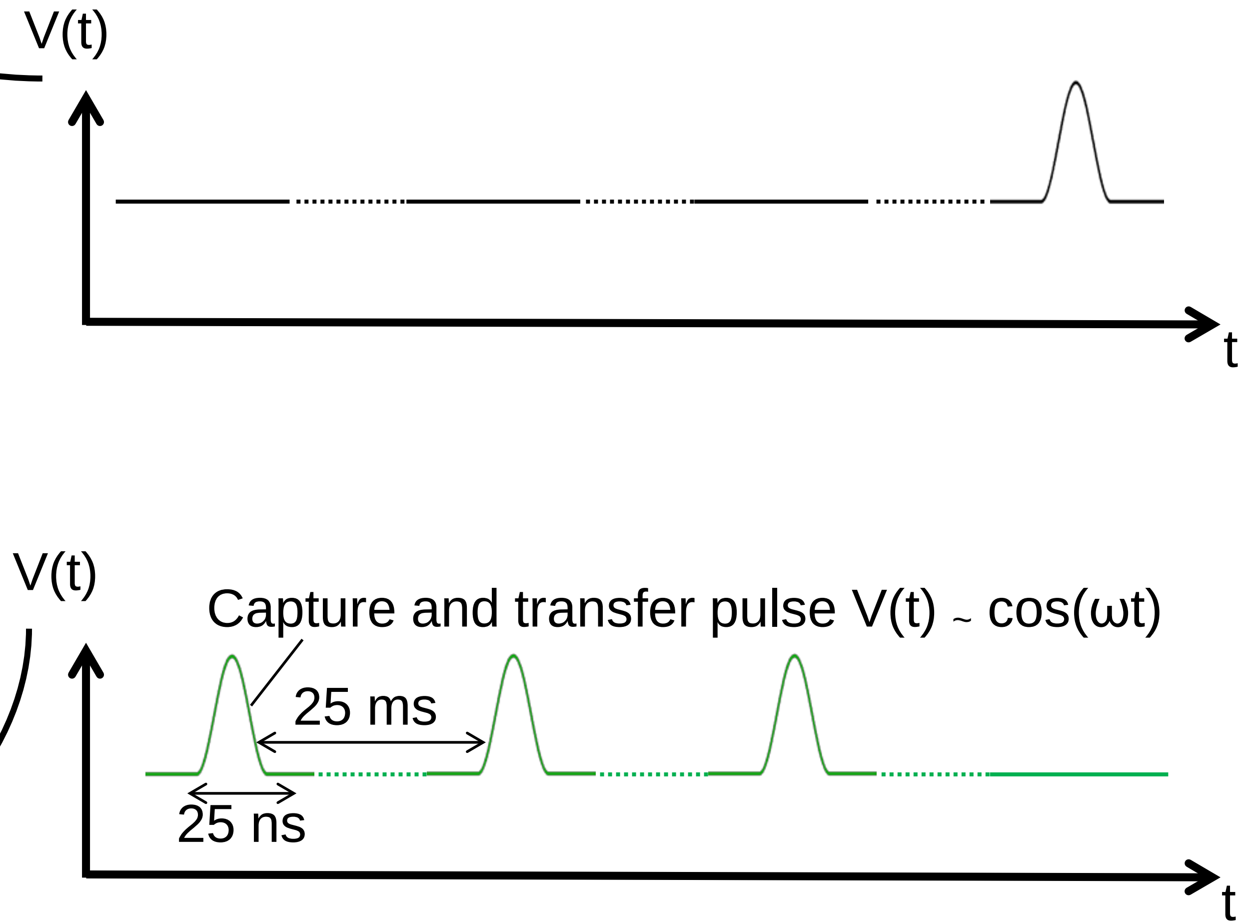

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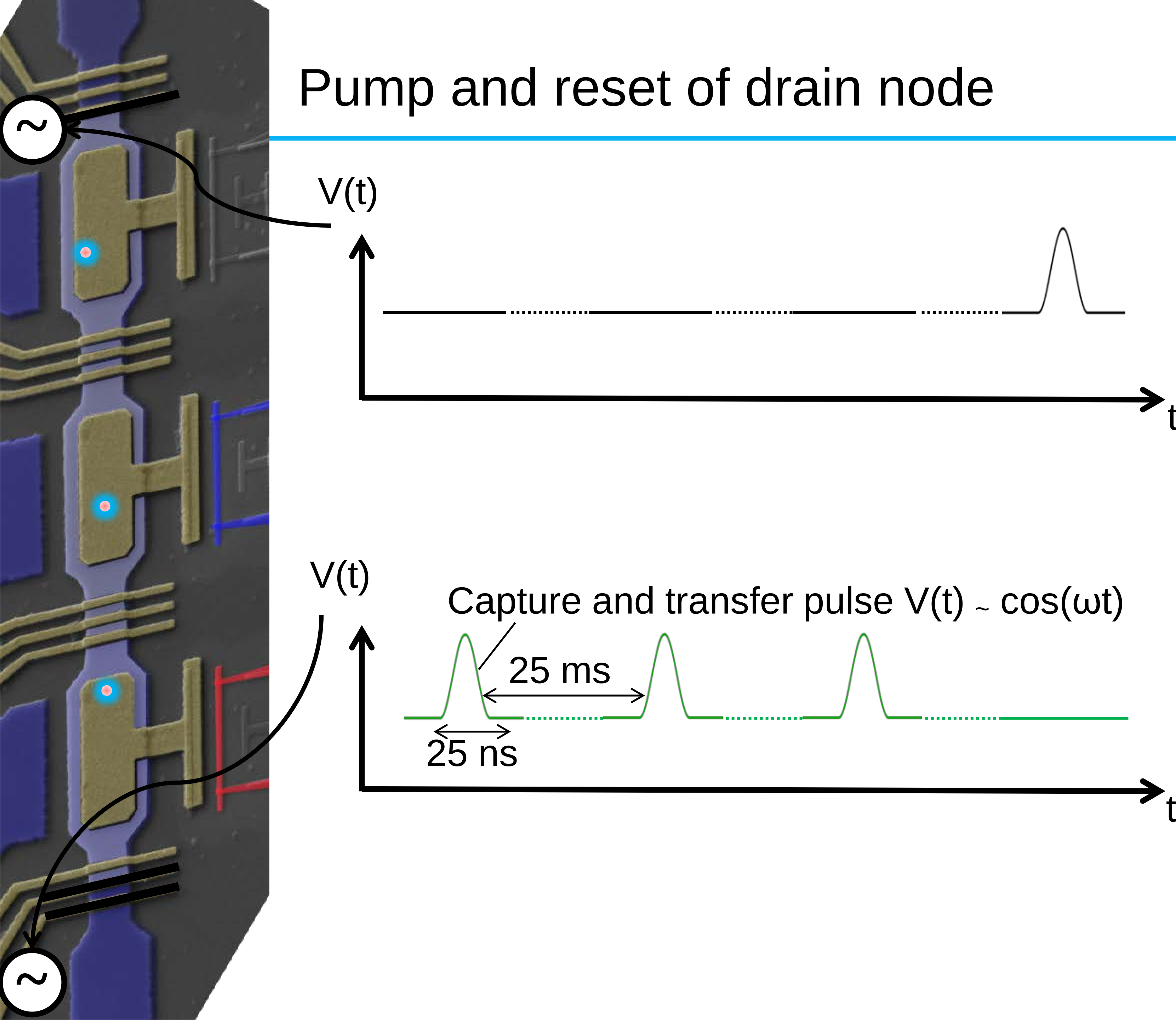

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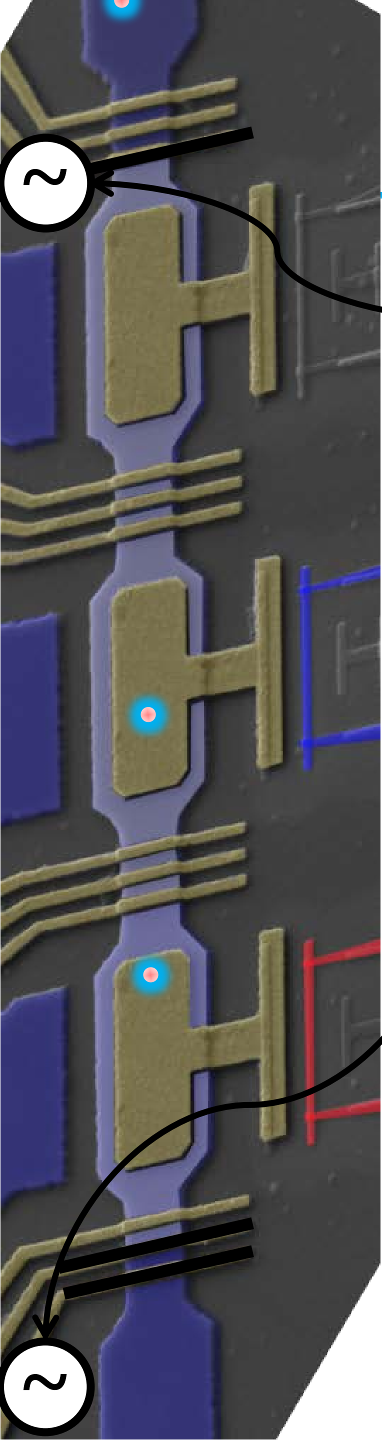

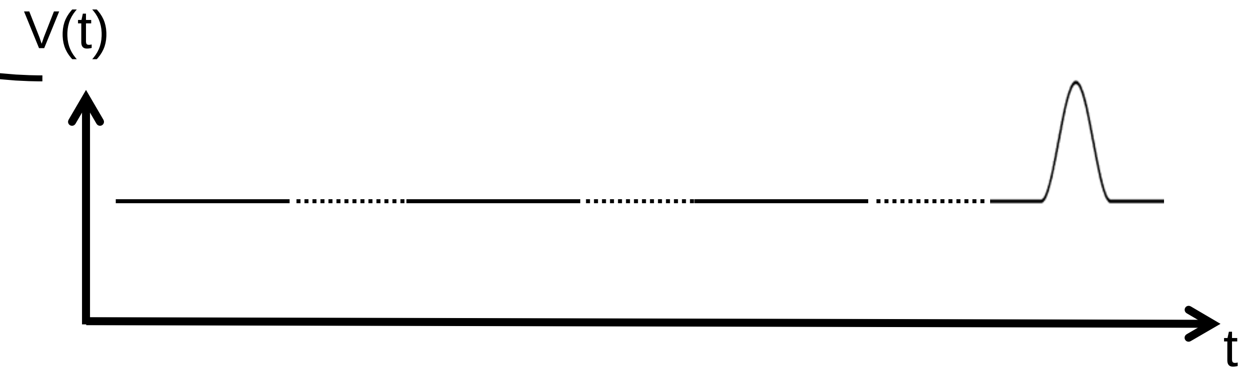

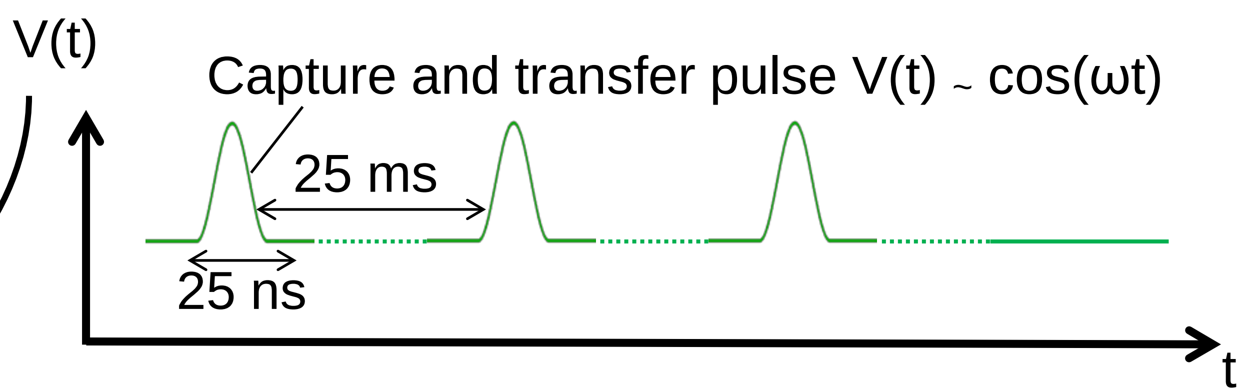

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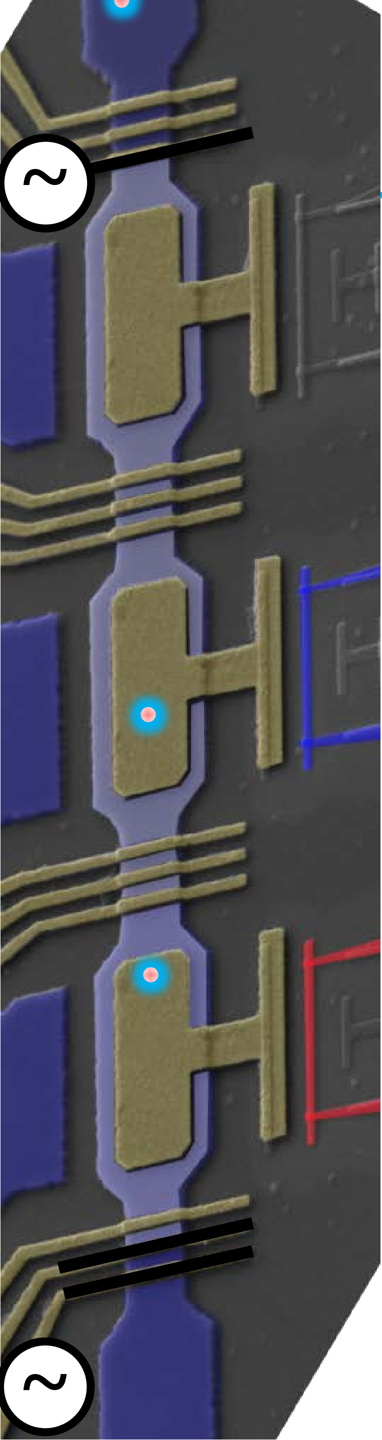

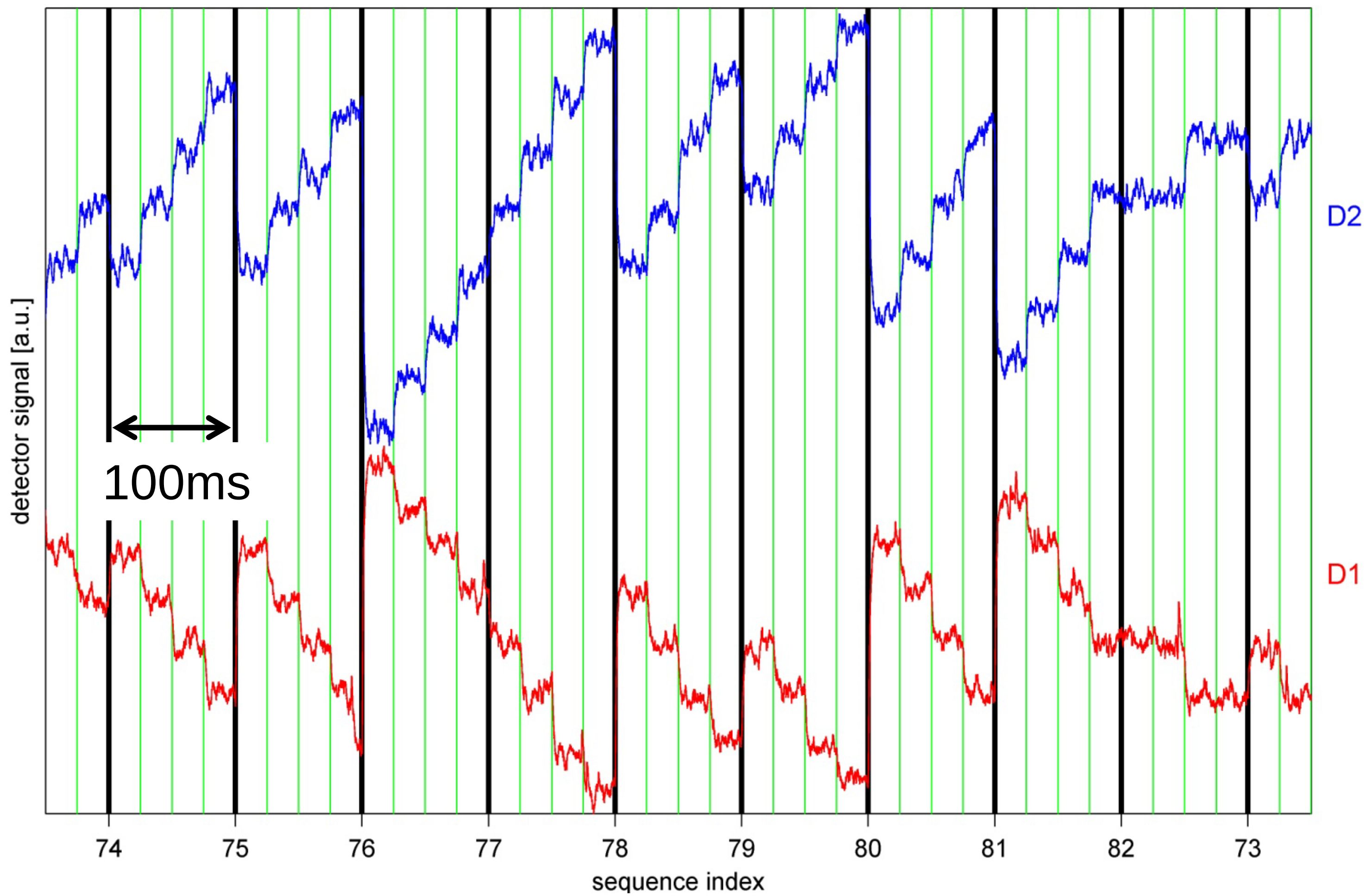

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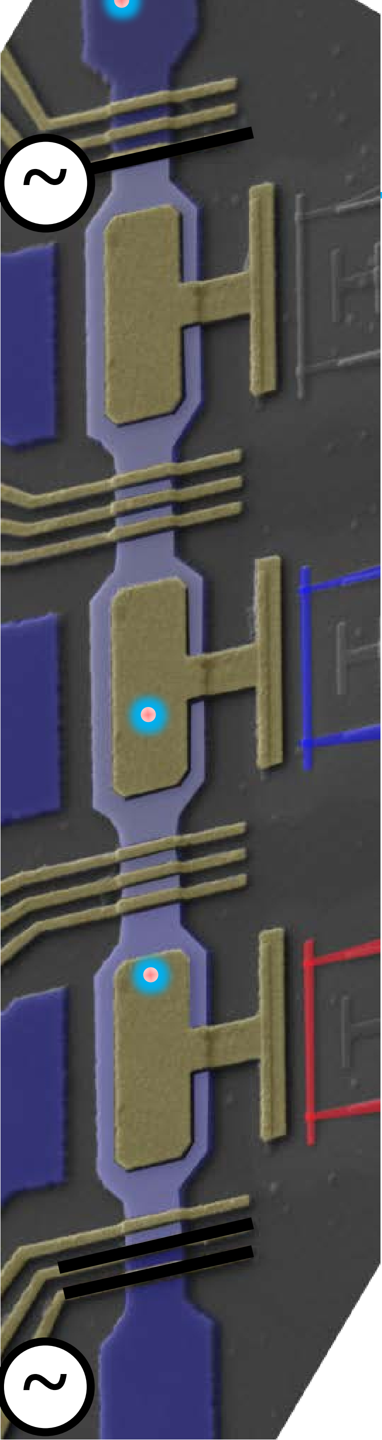
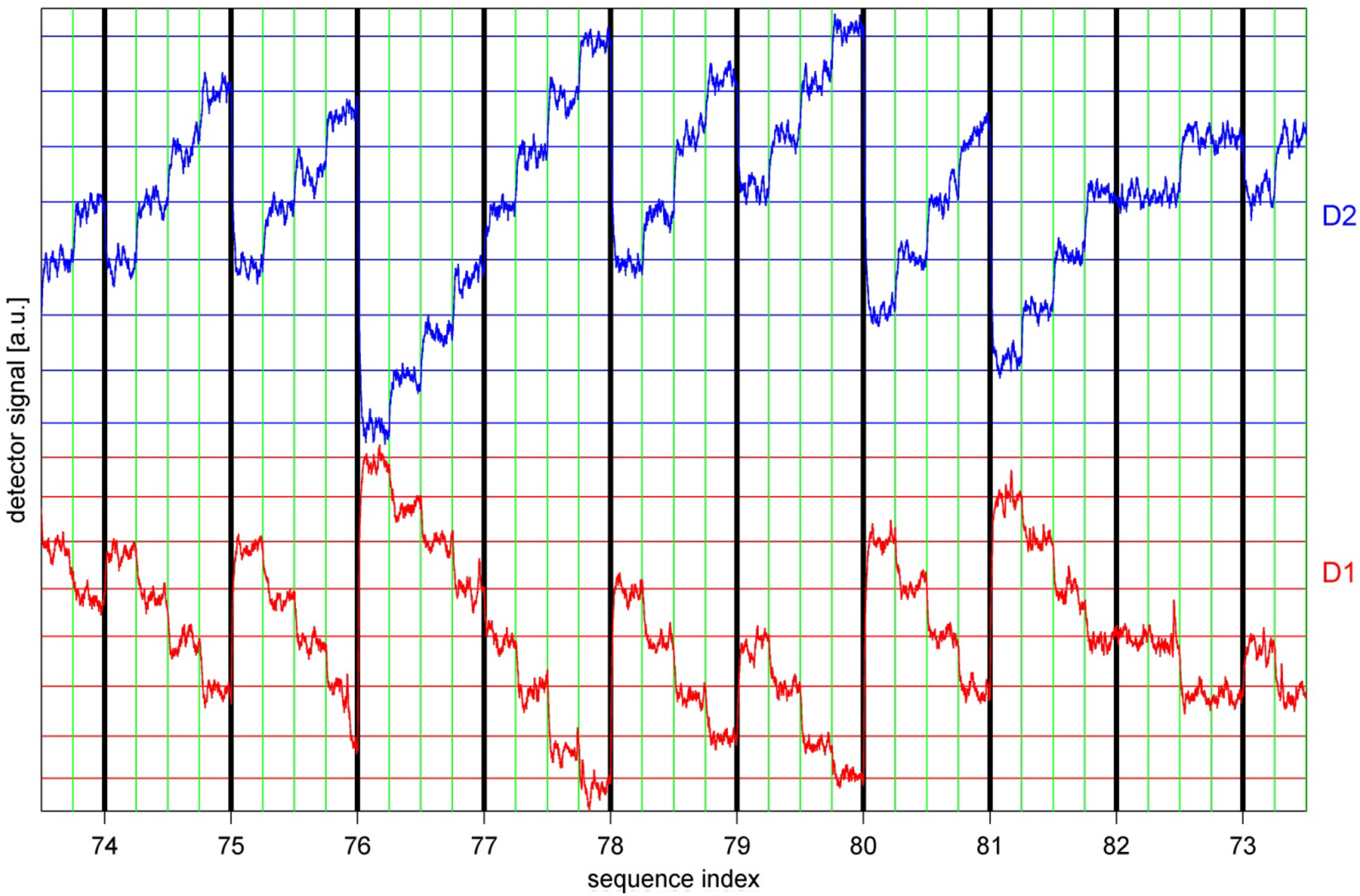
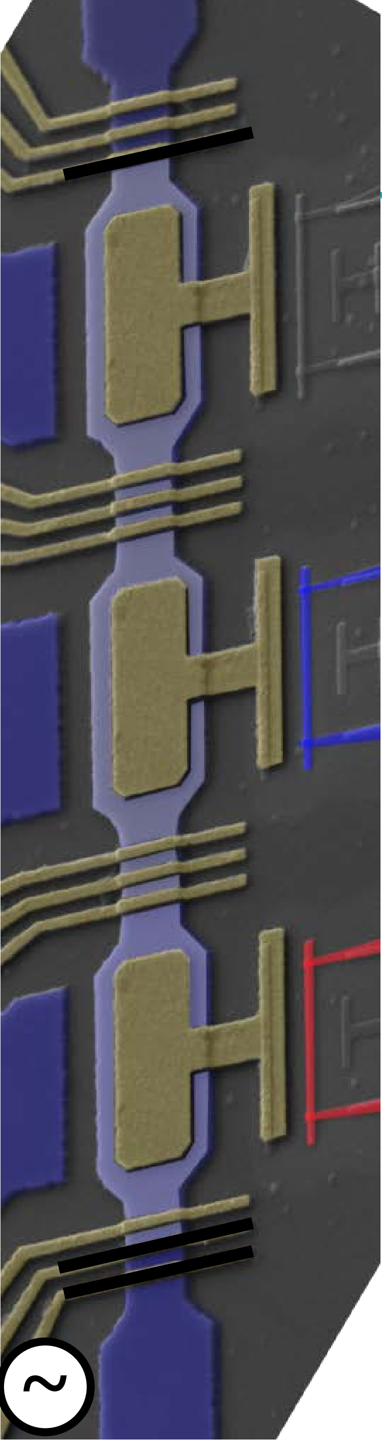
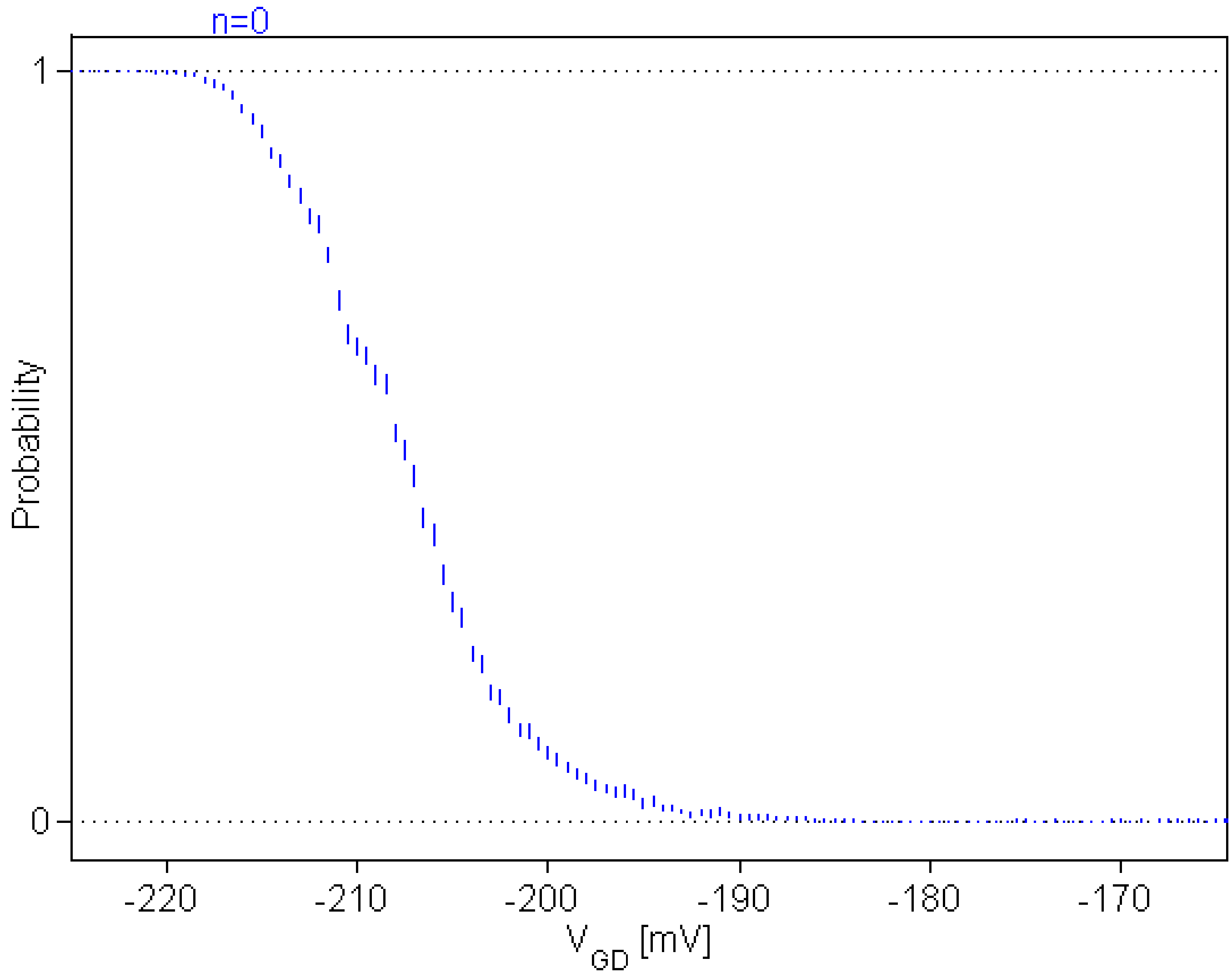




Capture probability





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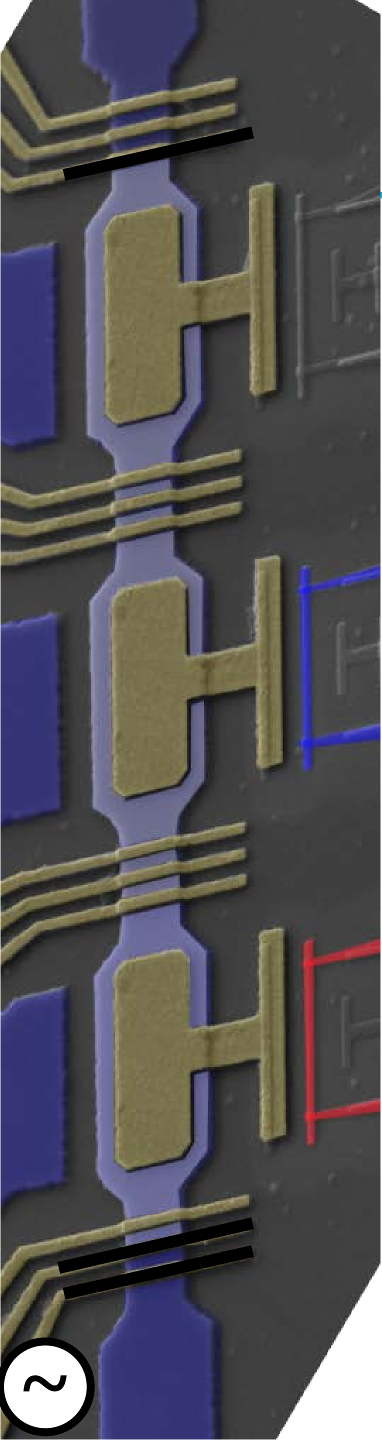

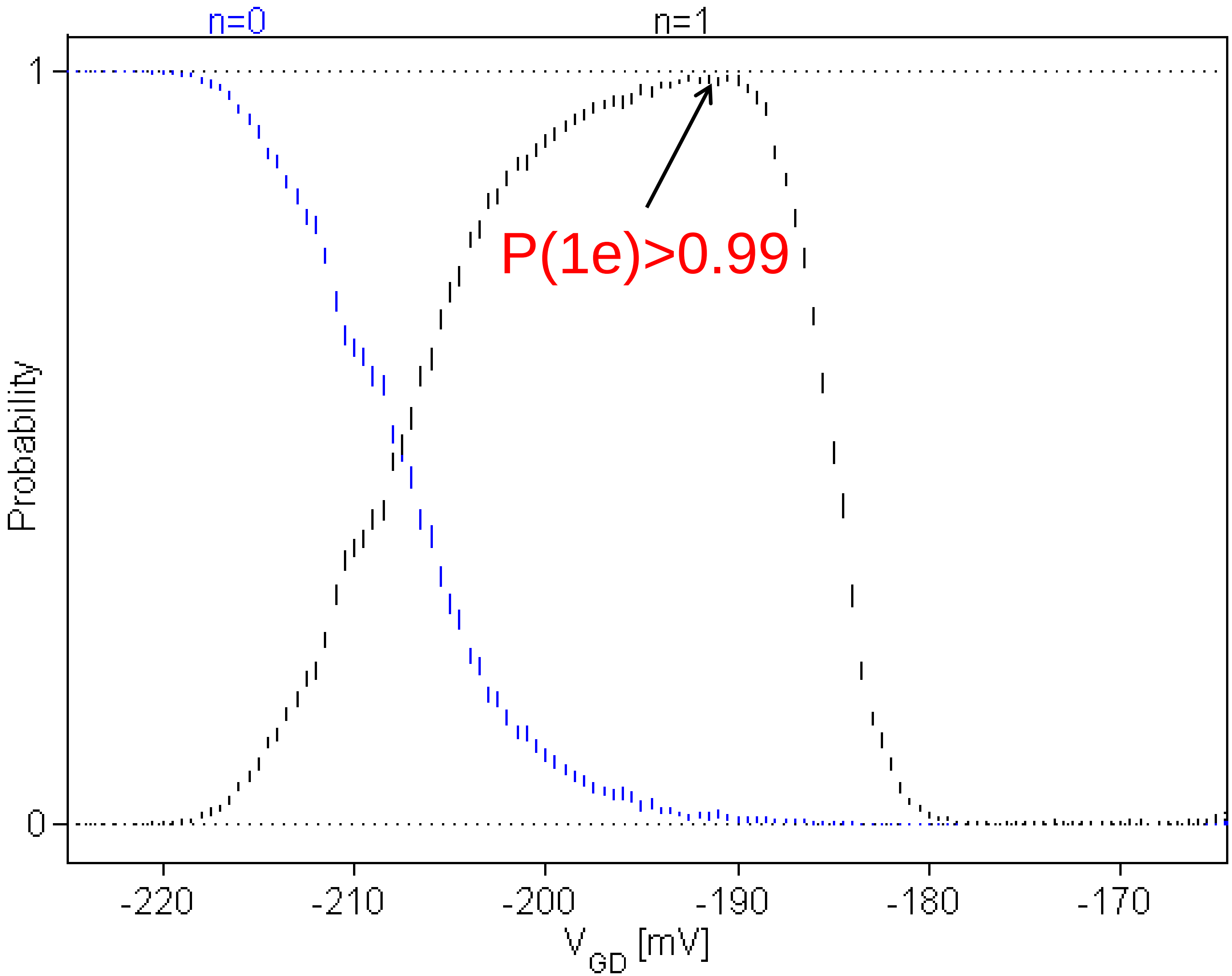

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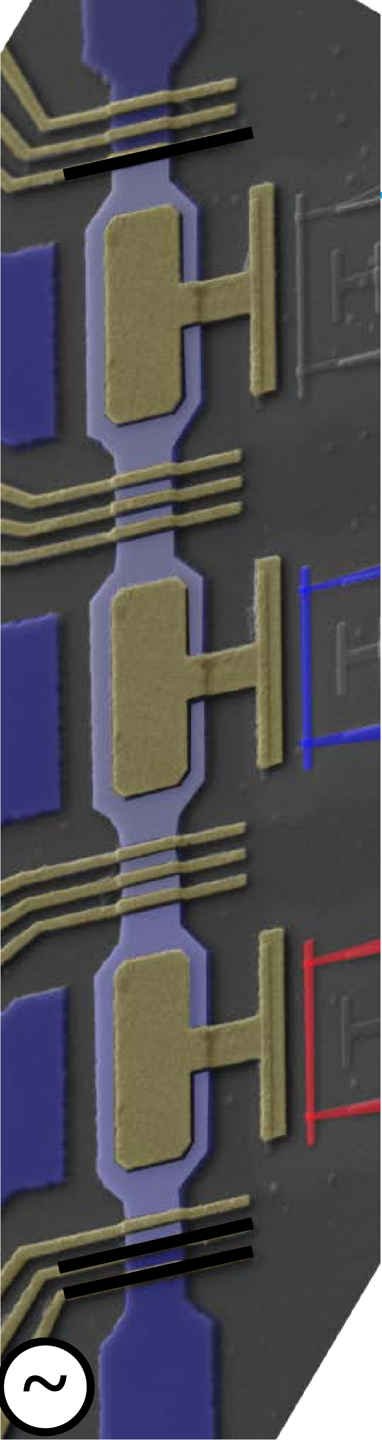
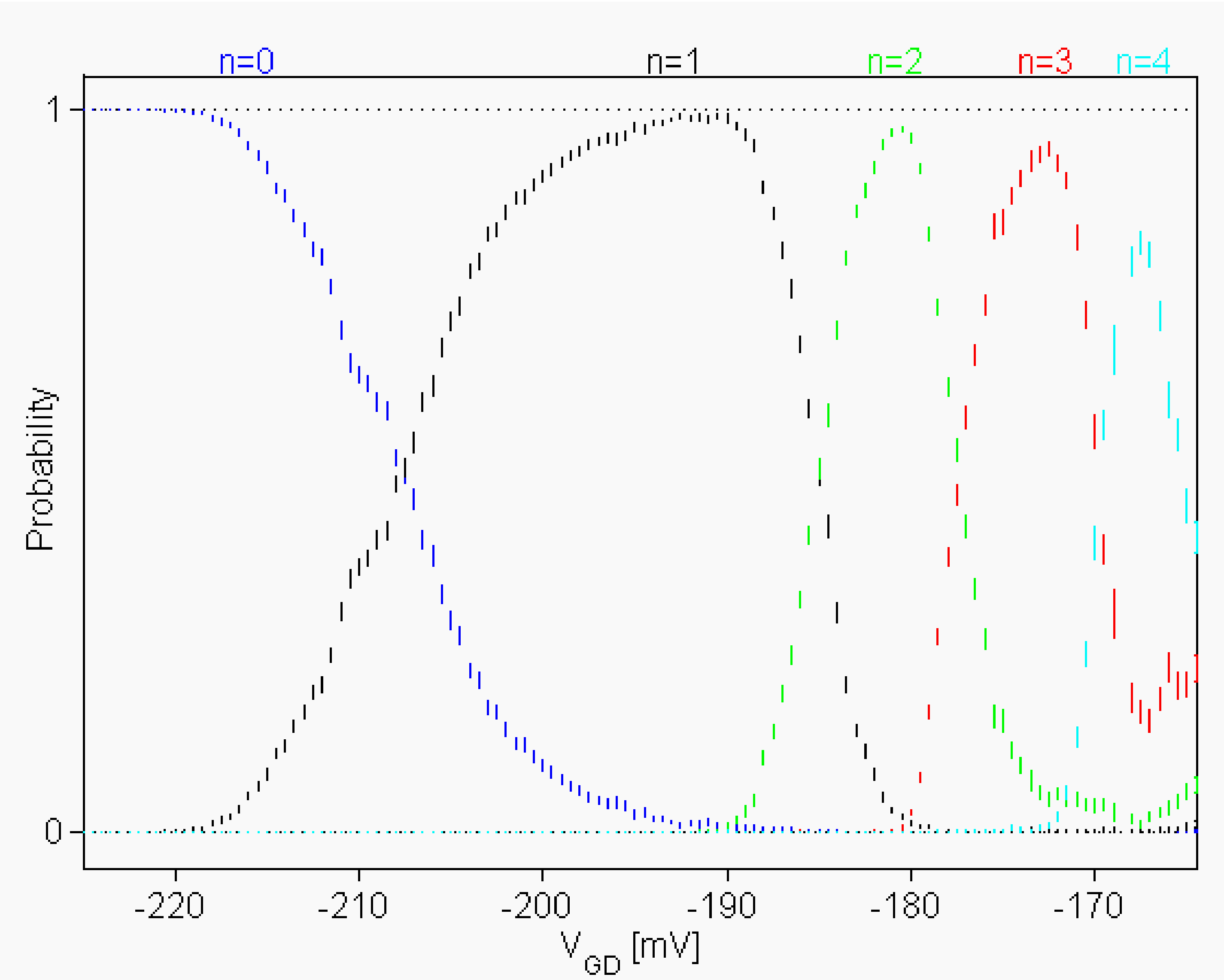
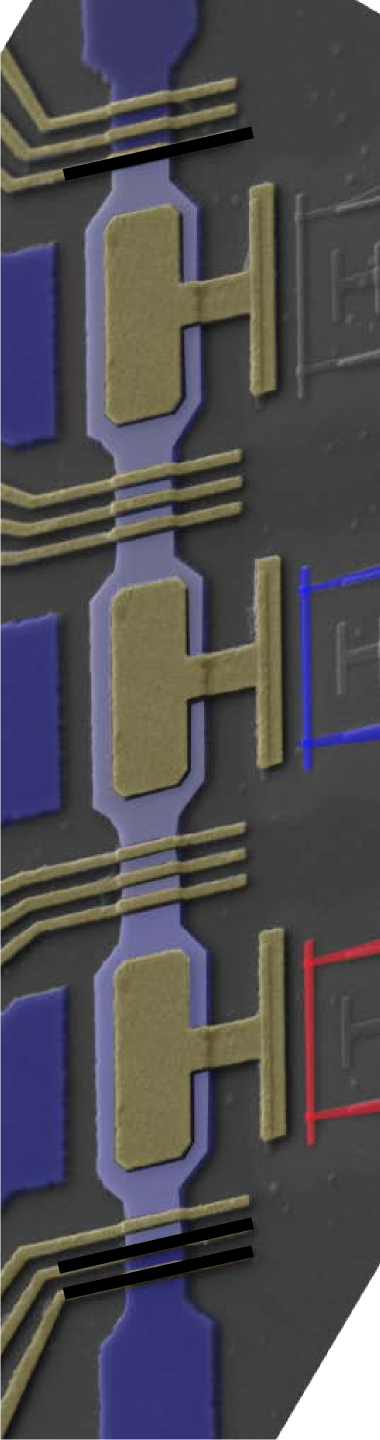
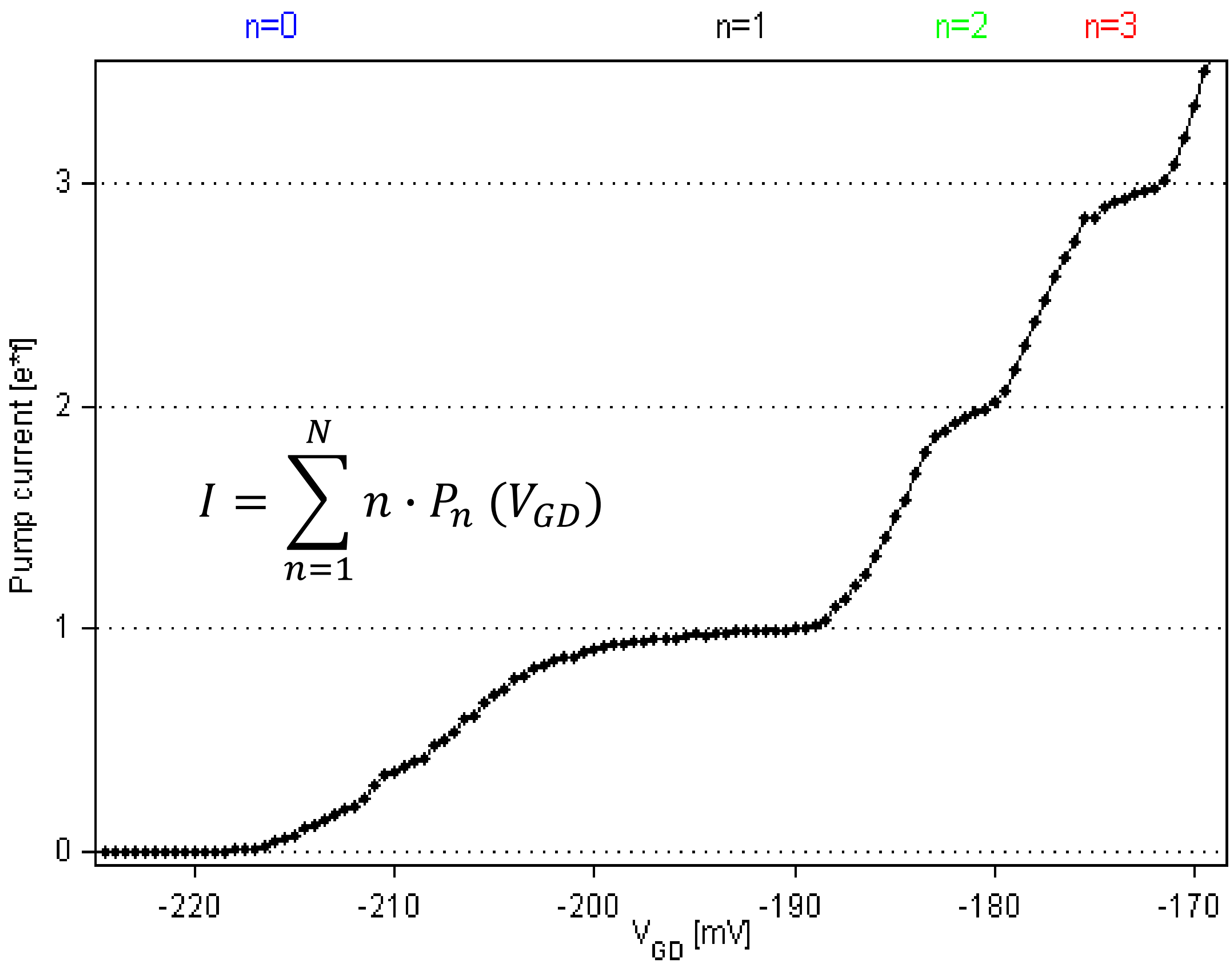




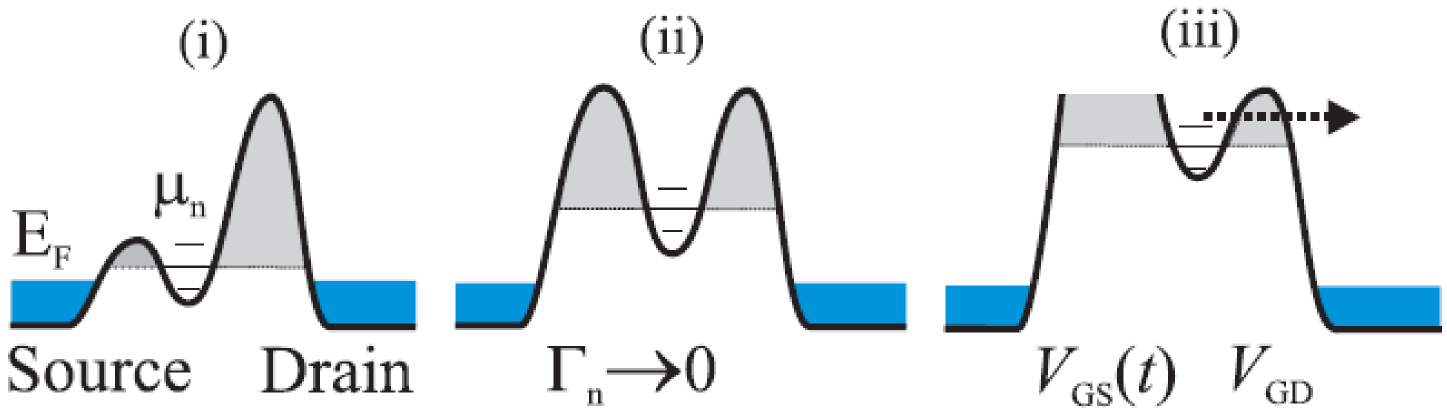
Calculated current





$$I = \sum_{n=1}^{N} n \cdot P_n\,(V_{GD})$$

Model calculation



Time-dependent potential on left gate affects

- Barrier between source and dot (Tunneling rate Γ_n)
- Chemical potential of the dot μ_n

Phys. Rev. Lett. **110**, 126803 (2013)

Model calculation

Thermal model

• Population of the dot follows adiabatically the lead‘s thermal distribution

• Then sudden decoupling freezes the states of the dot

Decay cascade model

• At low temperatures, $f(\mu_n)$ may go to zero much faster than Γ_n

• Gradual decoupling limit

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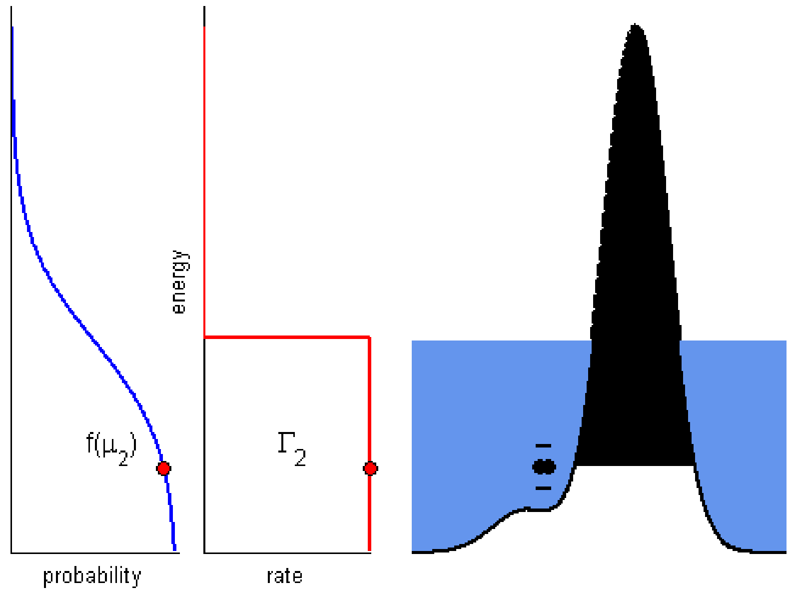

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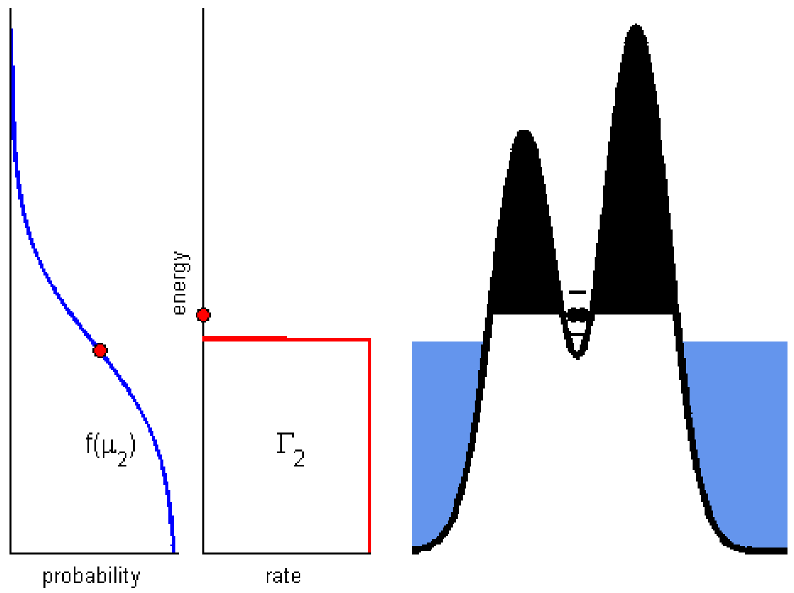

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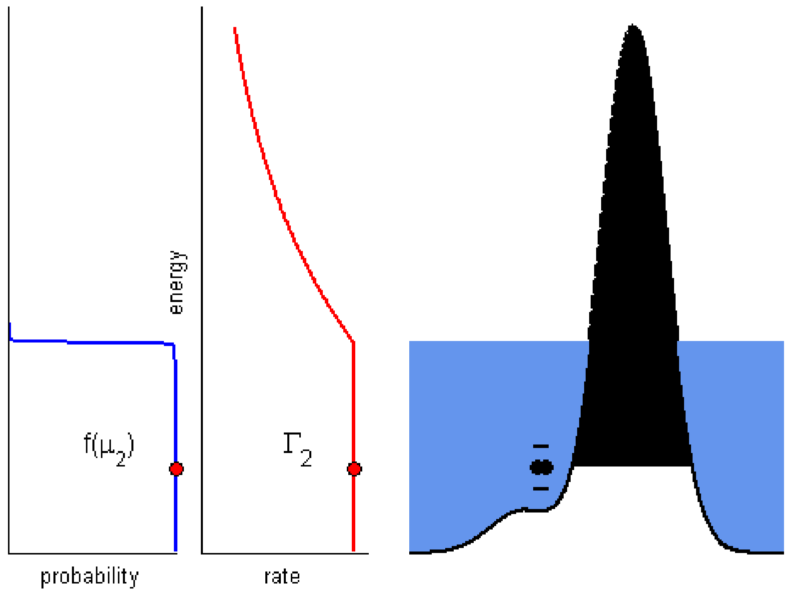

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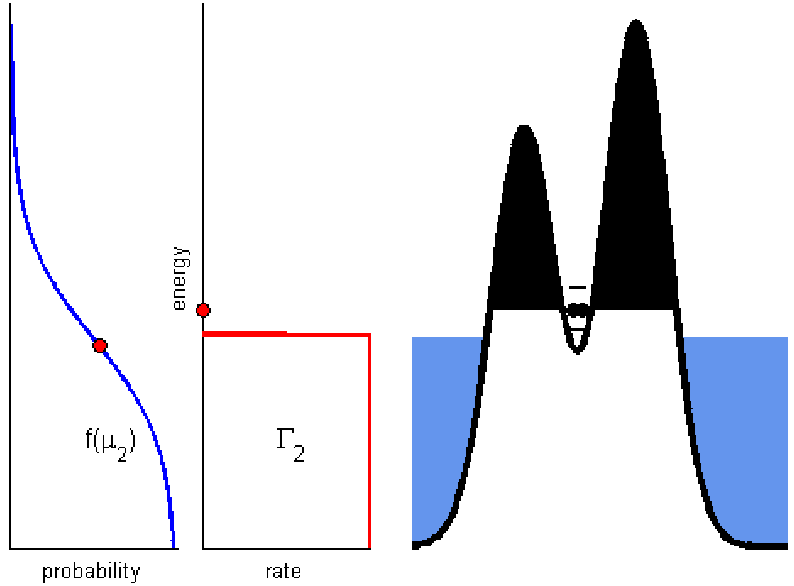

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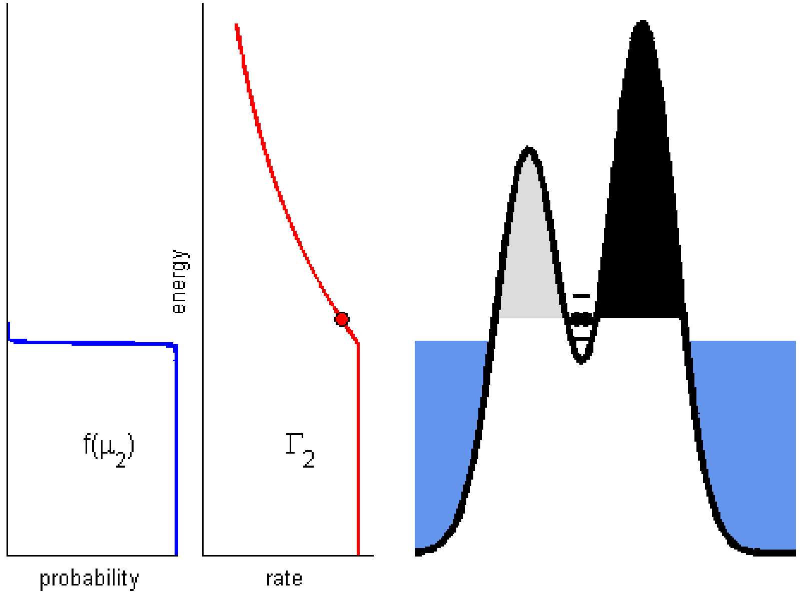

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- Then sudden decoupling freezes the states of the dot

Decay cascade model

- At low temperatures, $f(\mu_n)$ may go to zero much faster than Γ_n
- Gradual decoupling limit

$$P_n = \left(1 - f\left[\mu_{n+1}(t^c_{n+1})\right]\right) \prod_{m=1}^{n} f\left[\mu_m(t^c_m)\right]$$

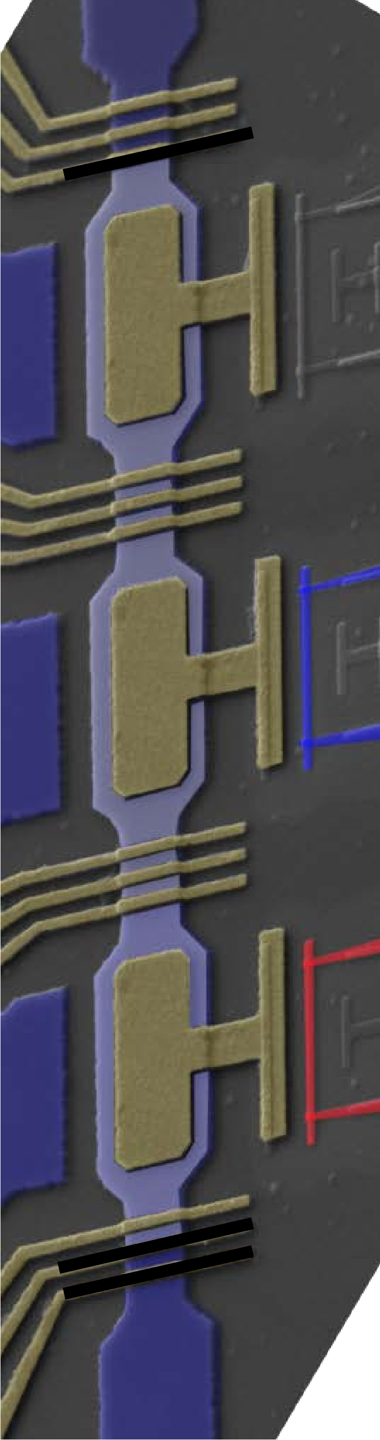
$$f(\mu_n) \equiv \frac{1}{1 + e^{(\mu_n - \mu)/k_\mathrm{B}T}}$$

$$P_n = e^{-X_n} \prod_{j=n+1}^{N} \left(1 - e^{-X_j}\right)$$

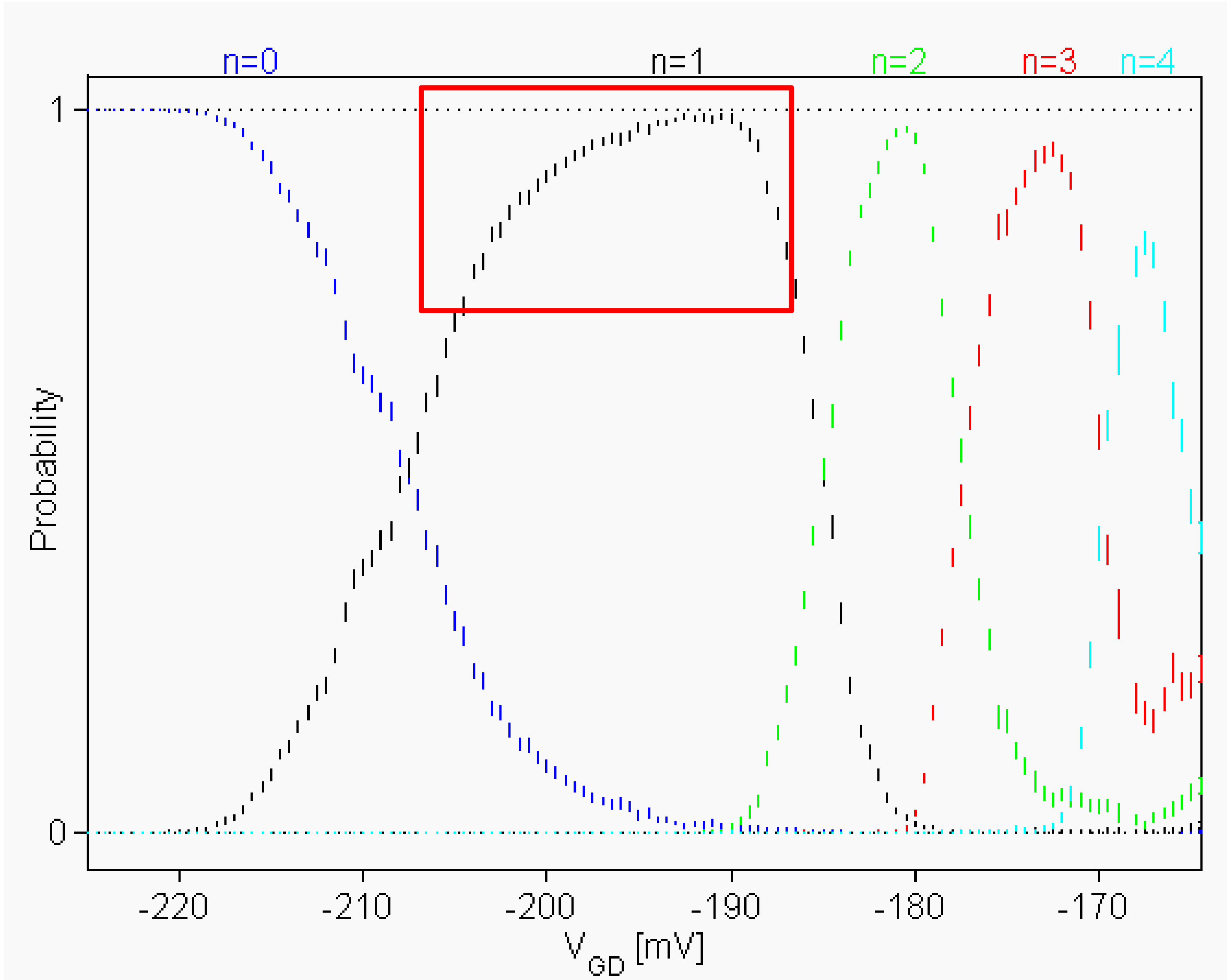
$$X_n \equiv \int_{t_b}^{\infty} \Gamma_n(t')dt'$$

Ansatz:

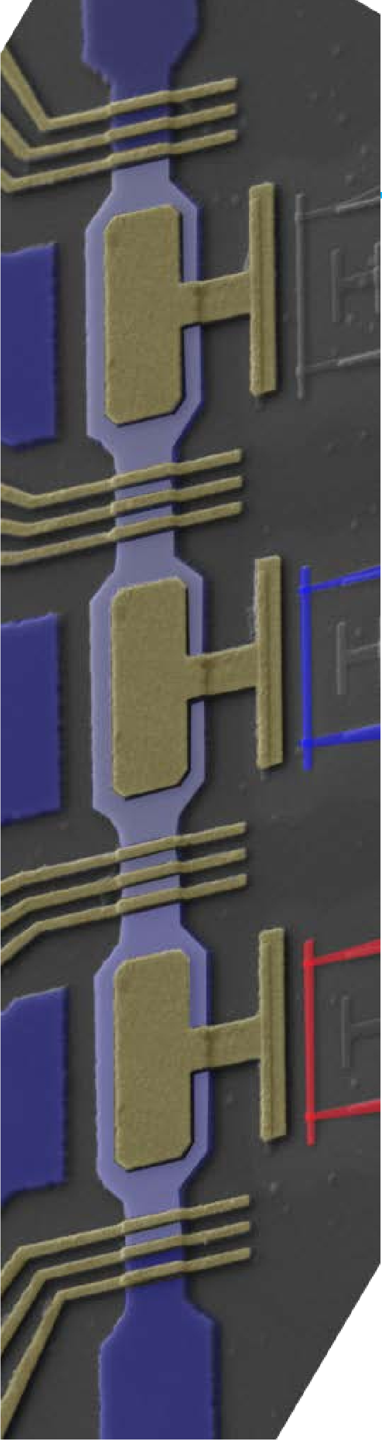
$$\mu_m(t^c_m)/k_\mathrm{B}T = -\alpha_{\mu,n} V_\mathrm{GD} + \Delta_{\mu,n}$$
$$\ln X_n = -\alpha_{X,n} V_\mathrm{GD} + \Delta_{X,n}$$

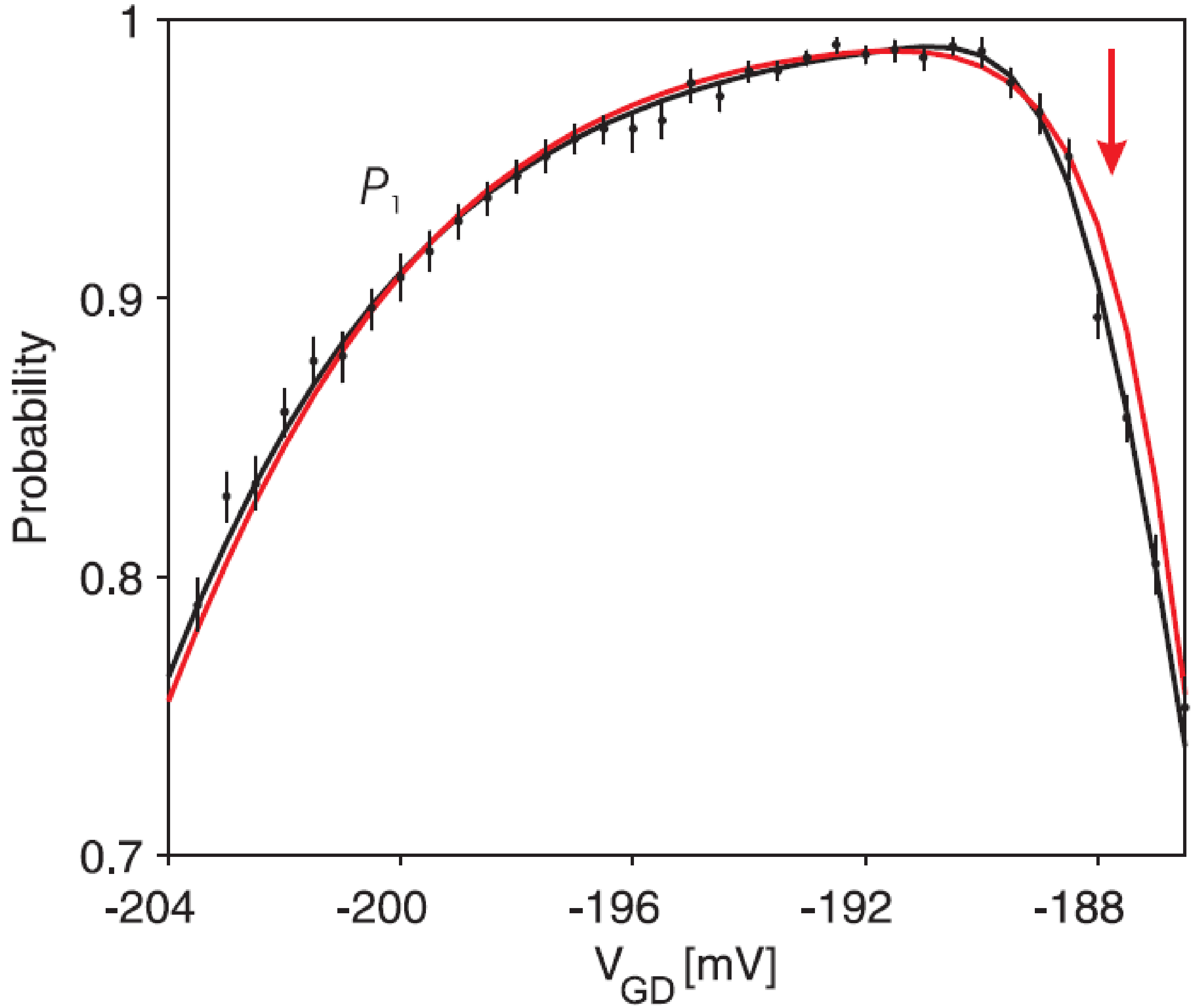


Capture probabilities



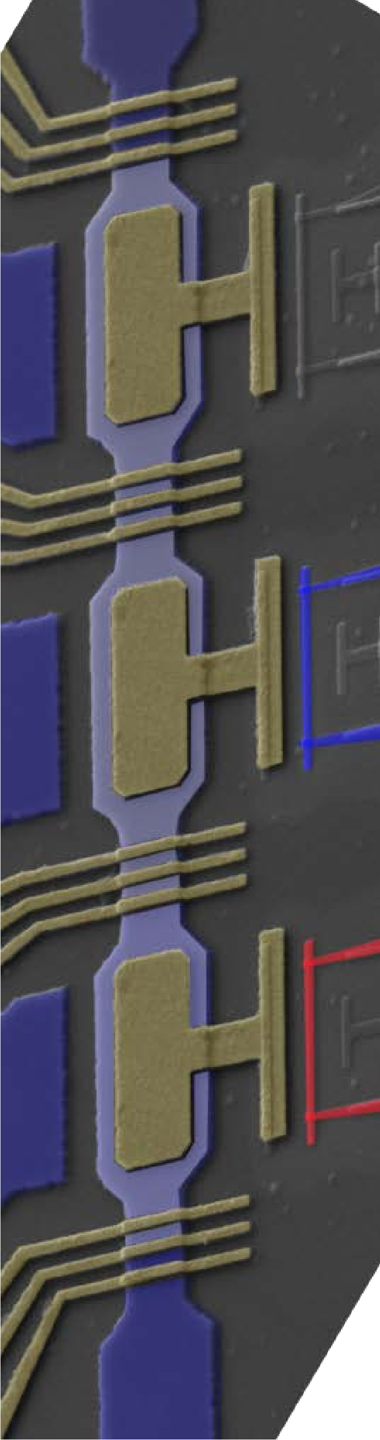
Model fits

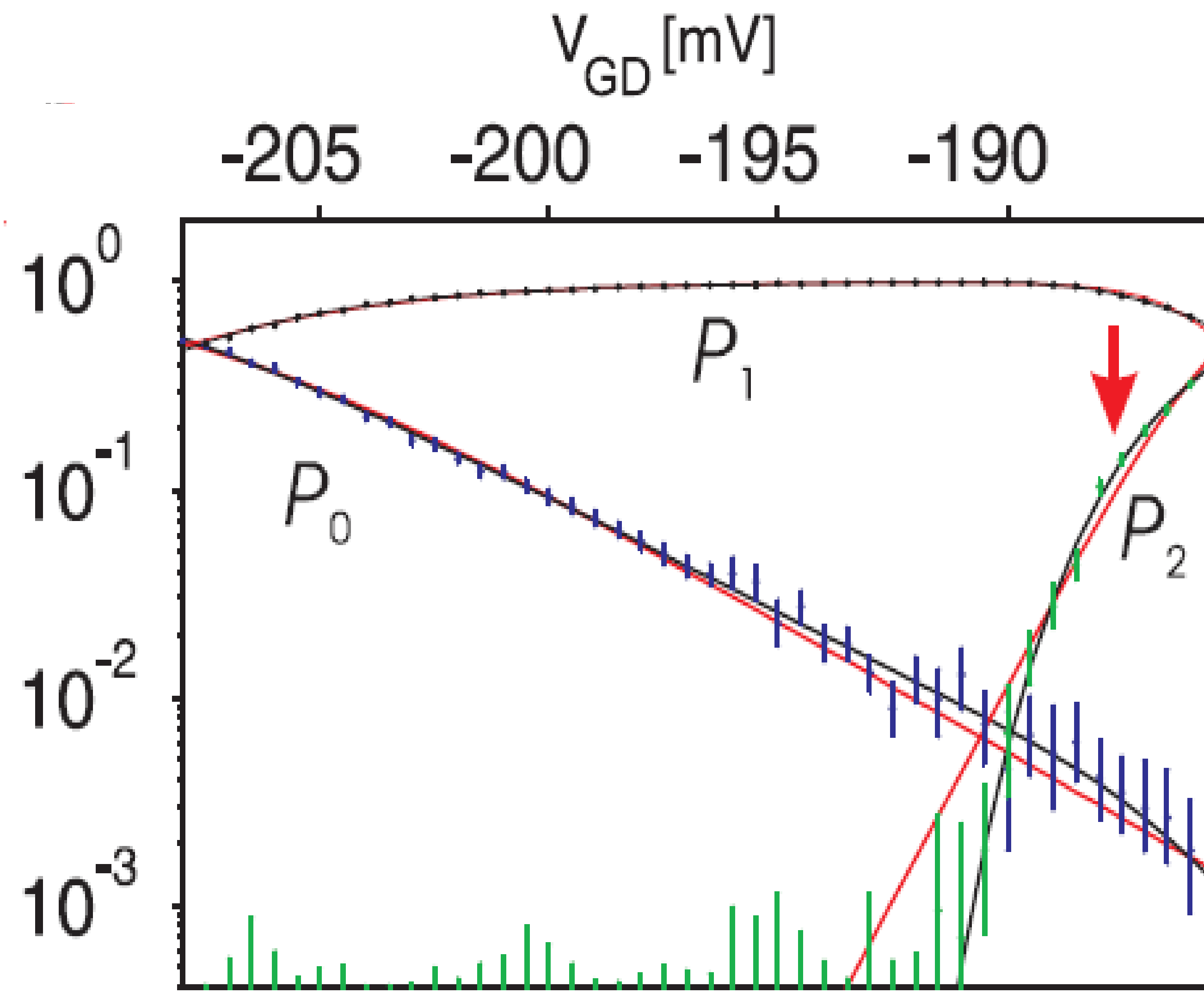




Phys. Rev. Lett. **110**, 126803 (2013)

Model fits





Phys. Rev. Lett. **110**, 126803 (2013)

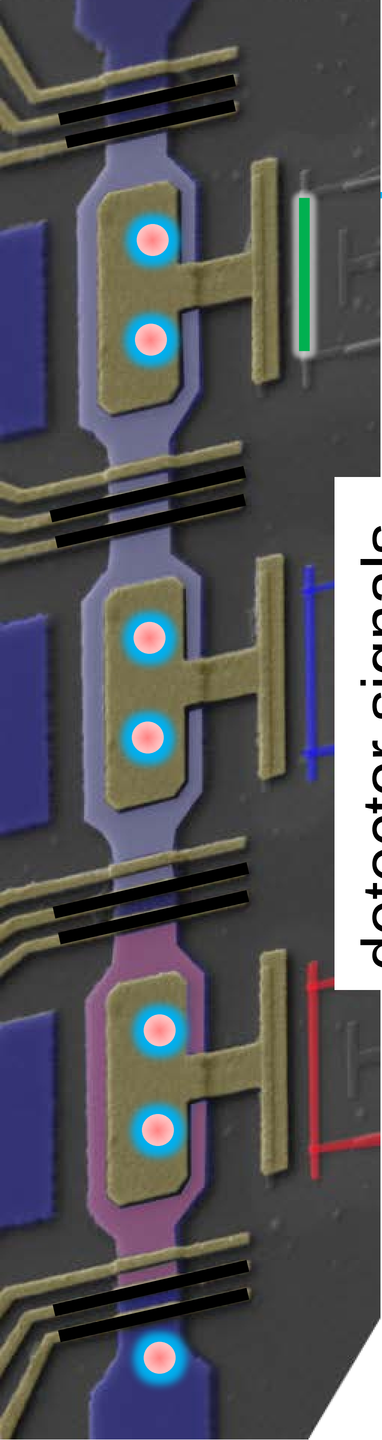
Optimization strategies

Thermal model	Decay cascade model
Pump fidelity may profit from further lowering of temperature Reduced coupling between barrier and plunger necessary May be achieved by applying compensation pulses onto the 2nd gate	Lowering the temperature will not increase fidelity Instead increase the separation of decay steps by • Large ratio of tunneling rates • Large energy separation for different n

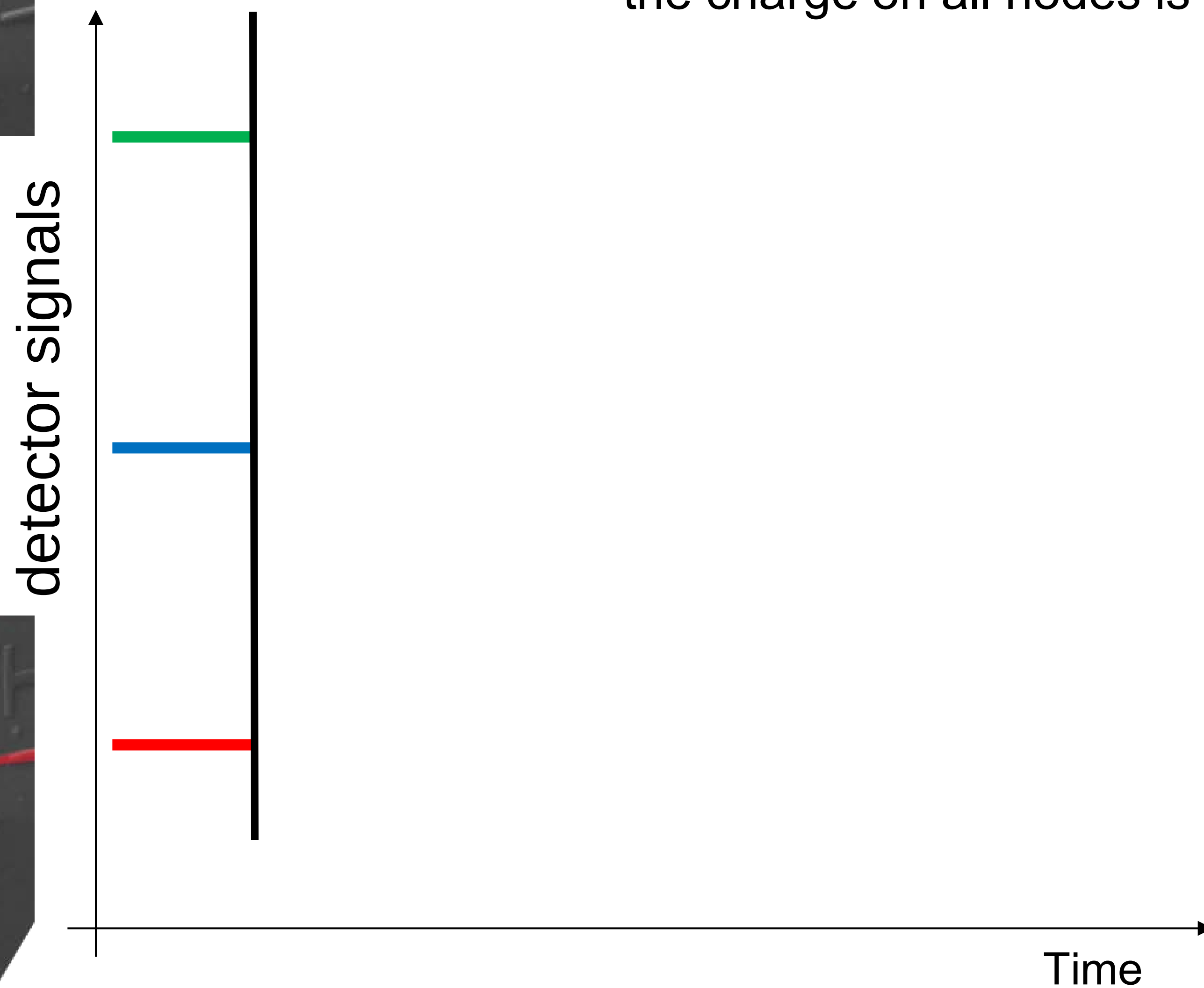
Overview

- Introduction to dynamic quantum dots → electron pumping
- Characterization of a dynamic dot by charge detection
- Series operation of 3 pumps with charge detectors

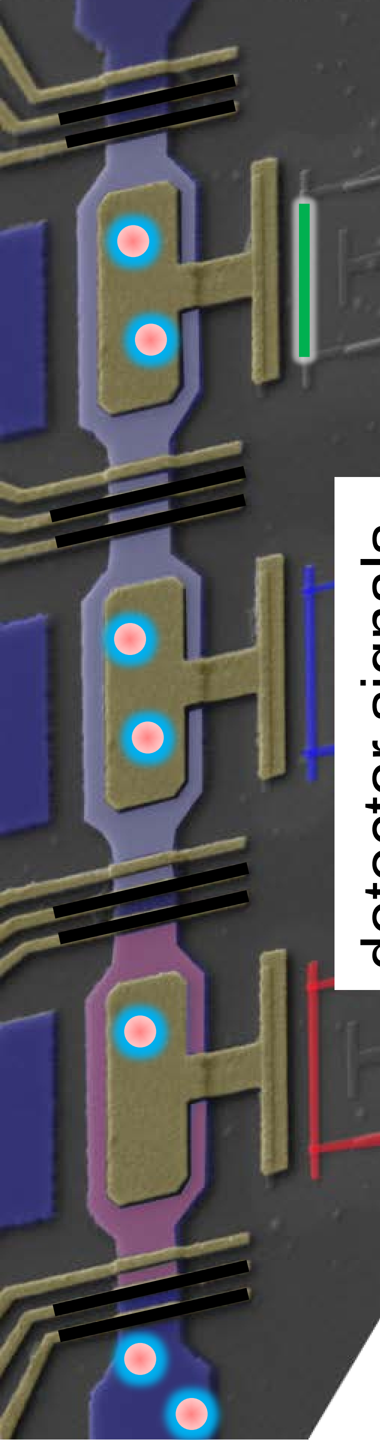
No errors: Constant node signals



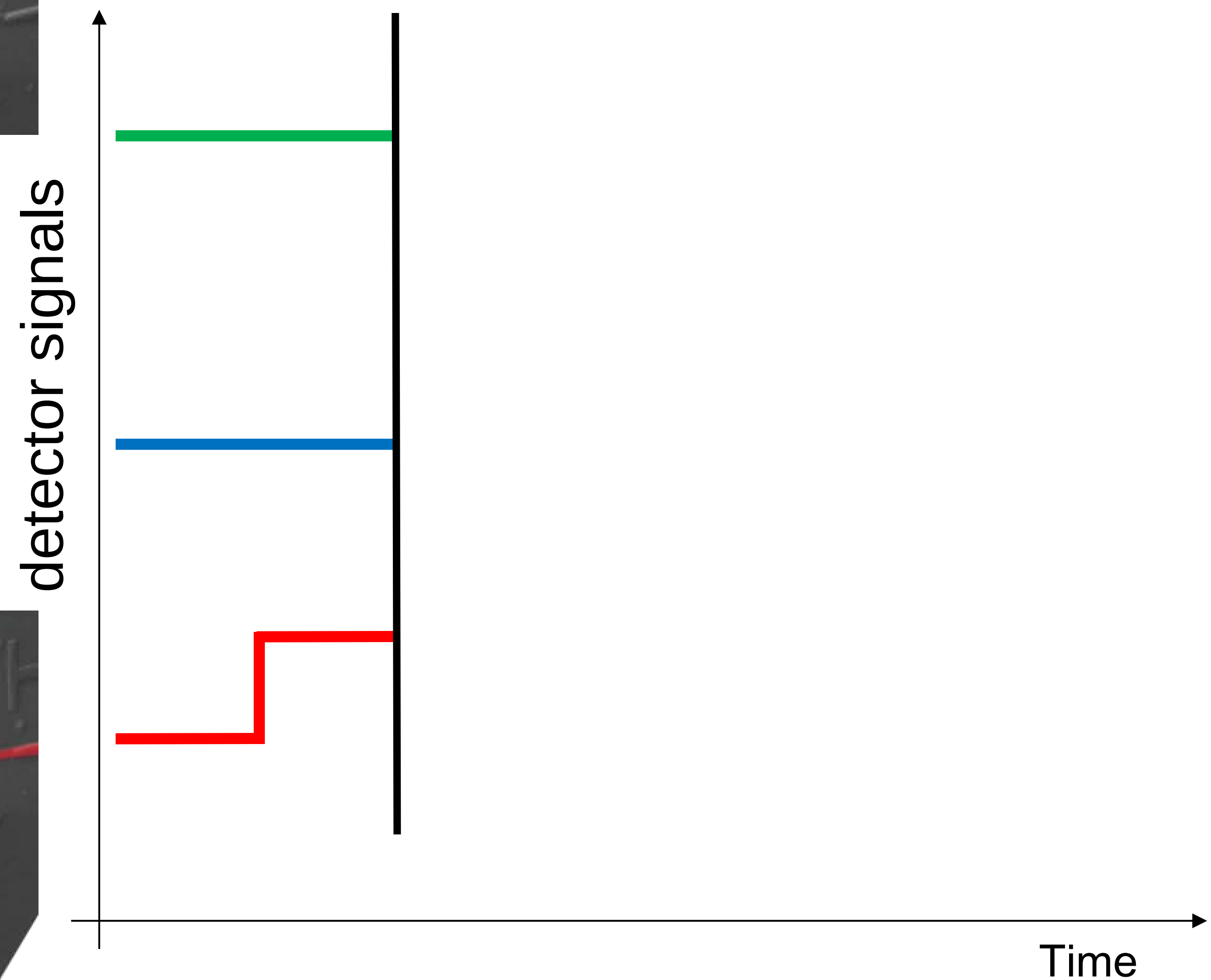
If all pumps work without errors,
the charge on all nodes is constant



Transfer error by first pump

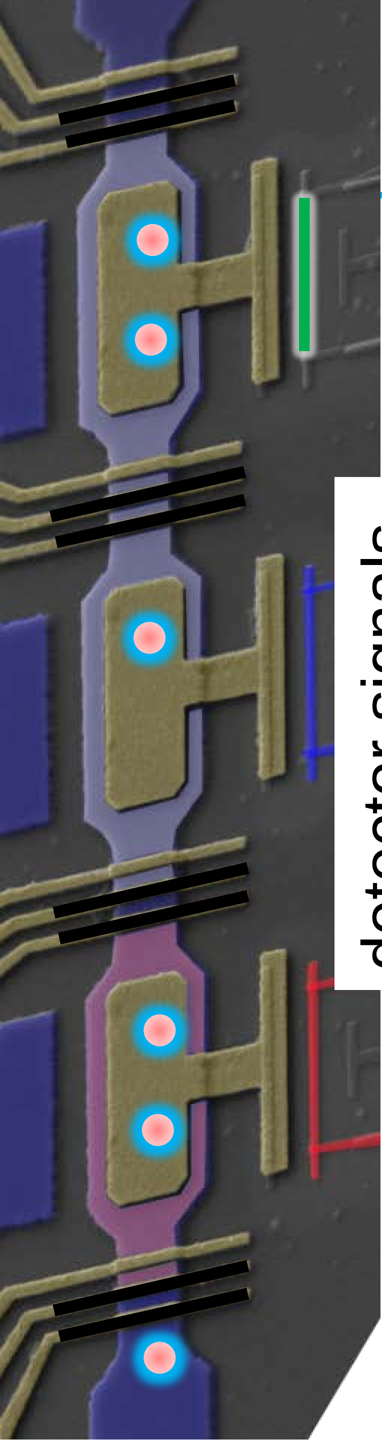


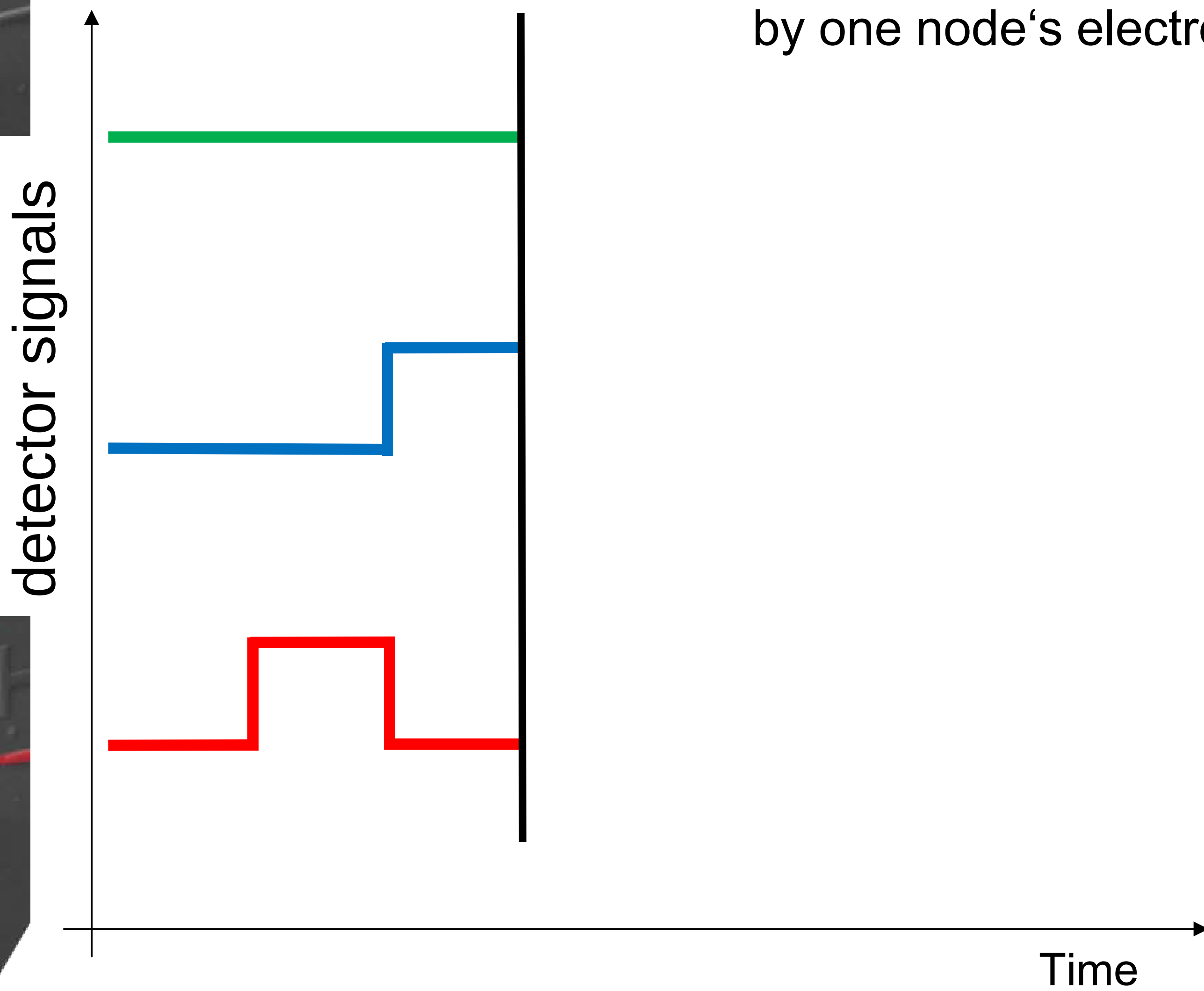
Red detector monitors change in the first island's charge state



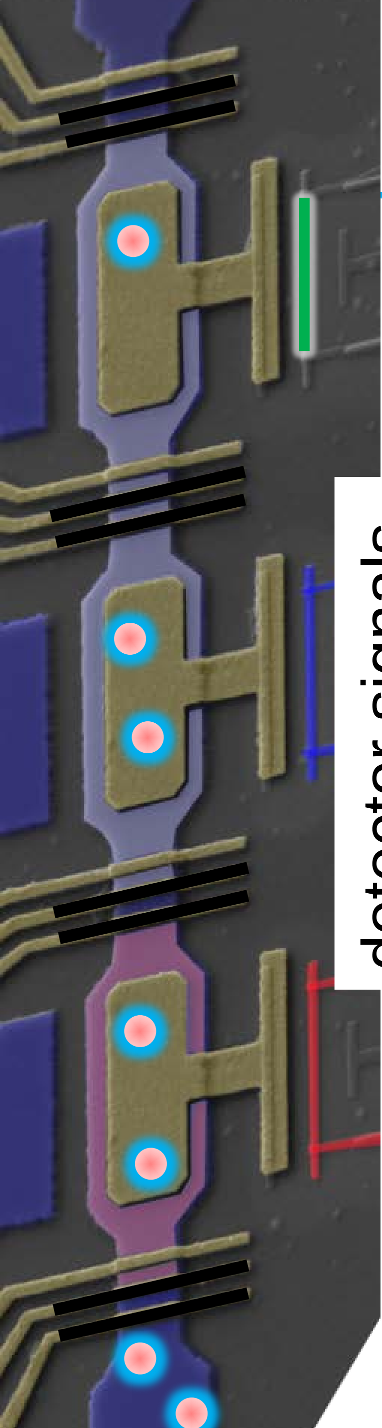
Consecutive error by second pump

Red detector switches back to initial state, blue detector changes by one node‘s electron

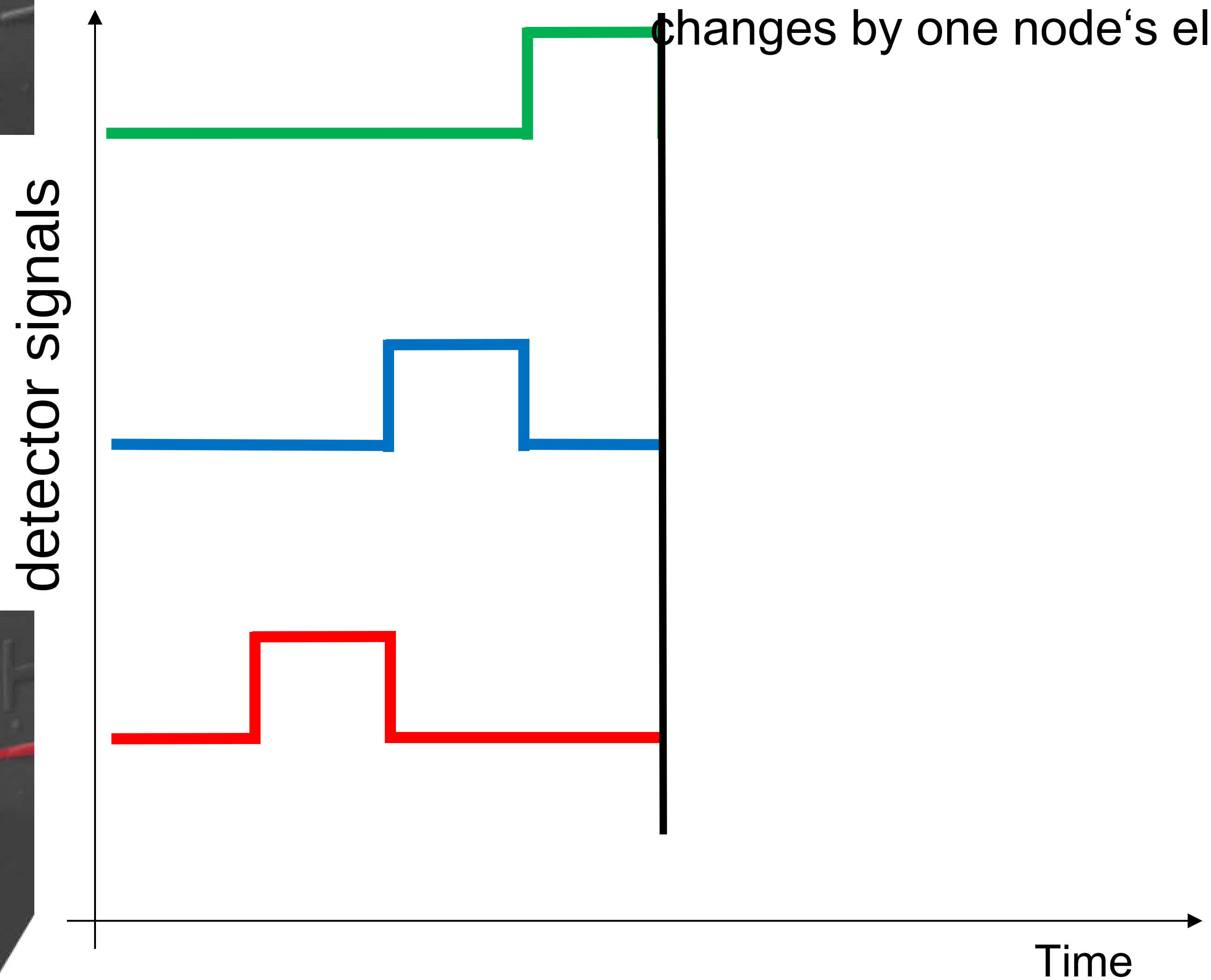




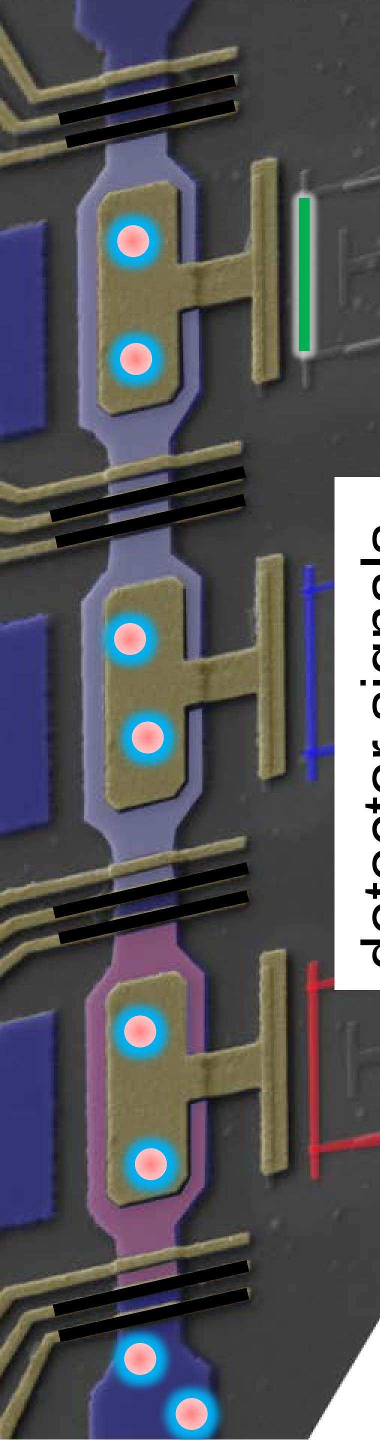
Consecutive error by third pump



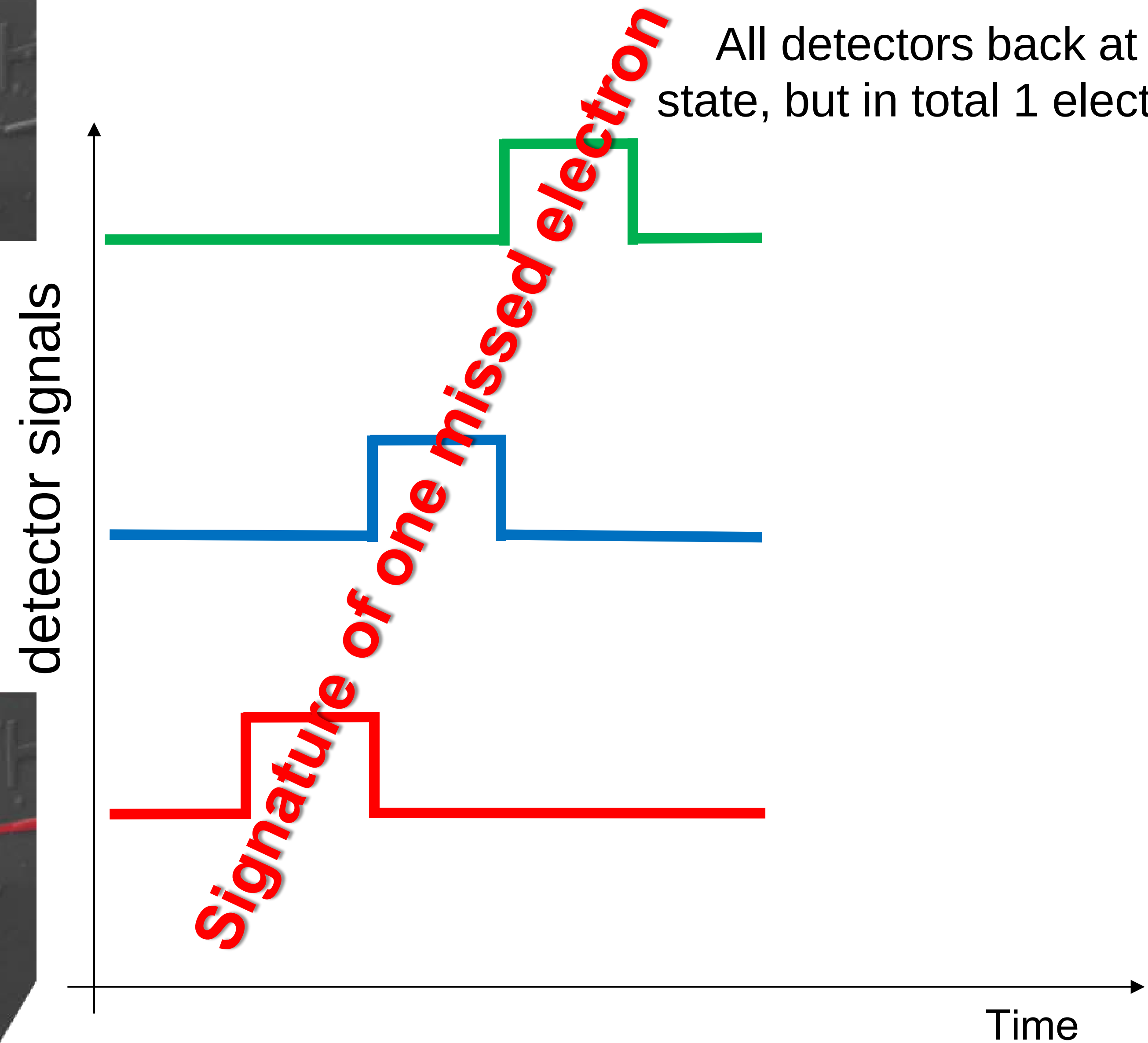
Blue detector switches back to initial state, green detector changes by one node‘s electron



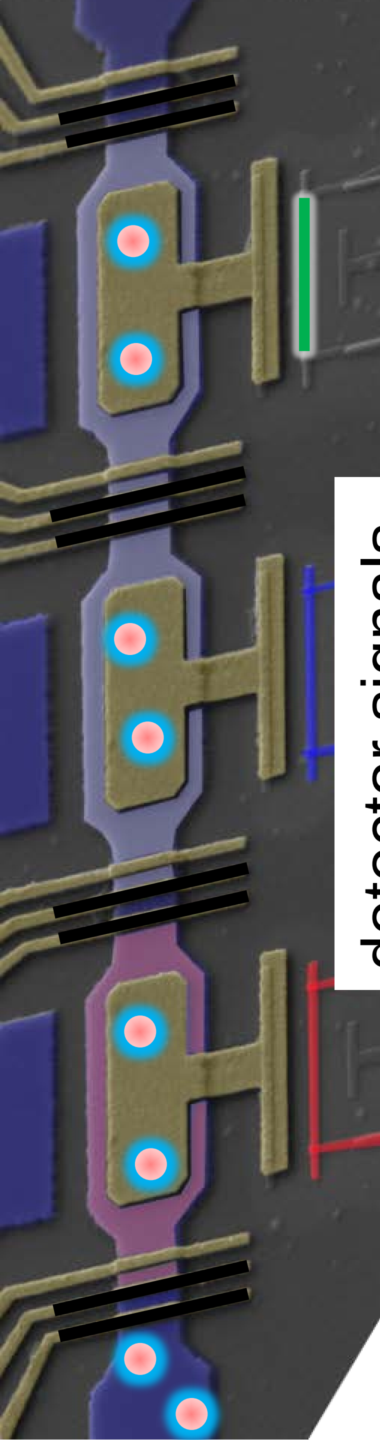
Consecutive error by fourth pump

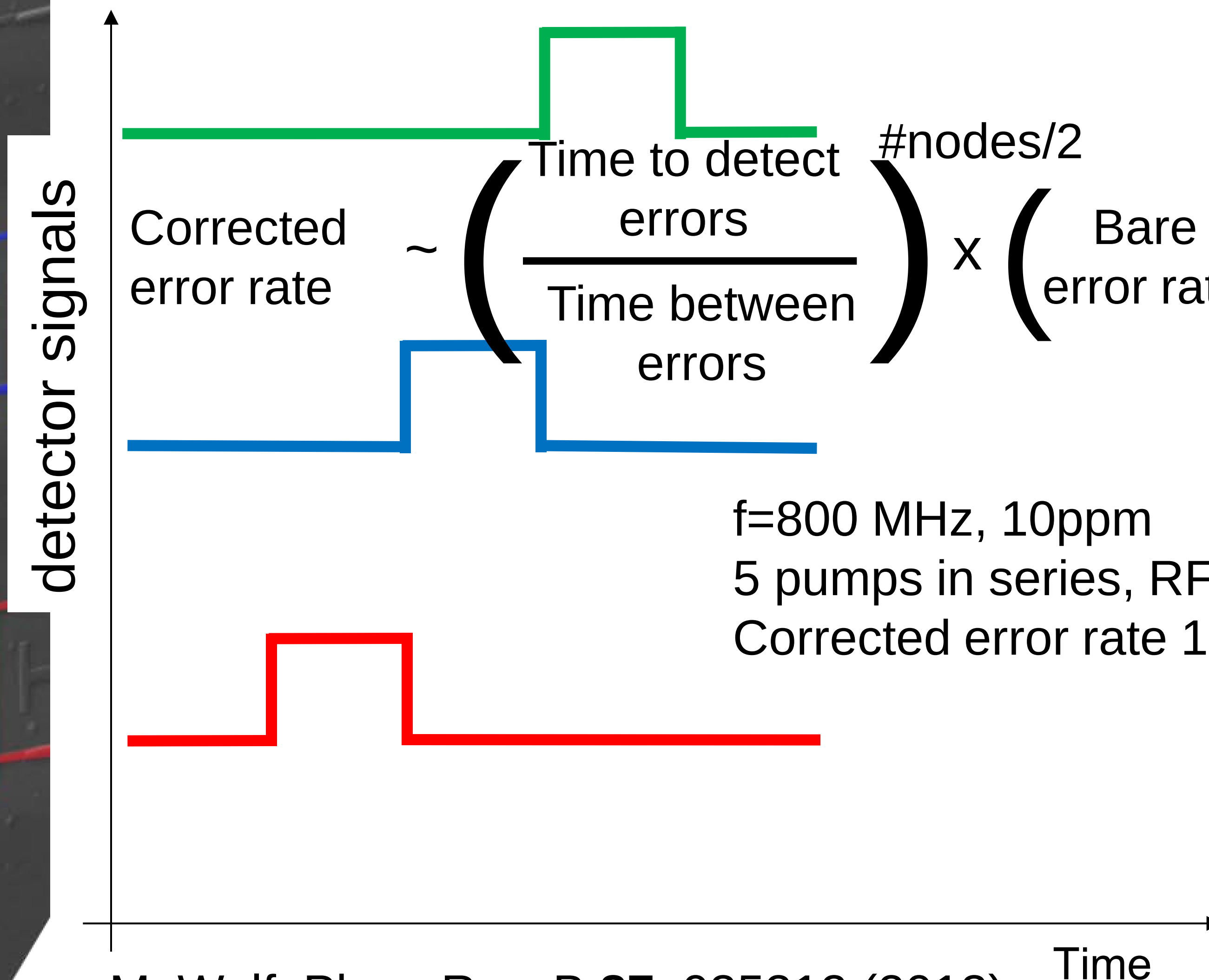


All detectors back at the initial state, but in total 1 electron missed!



Consecutive error by fourth pump



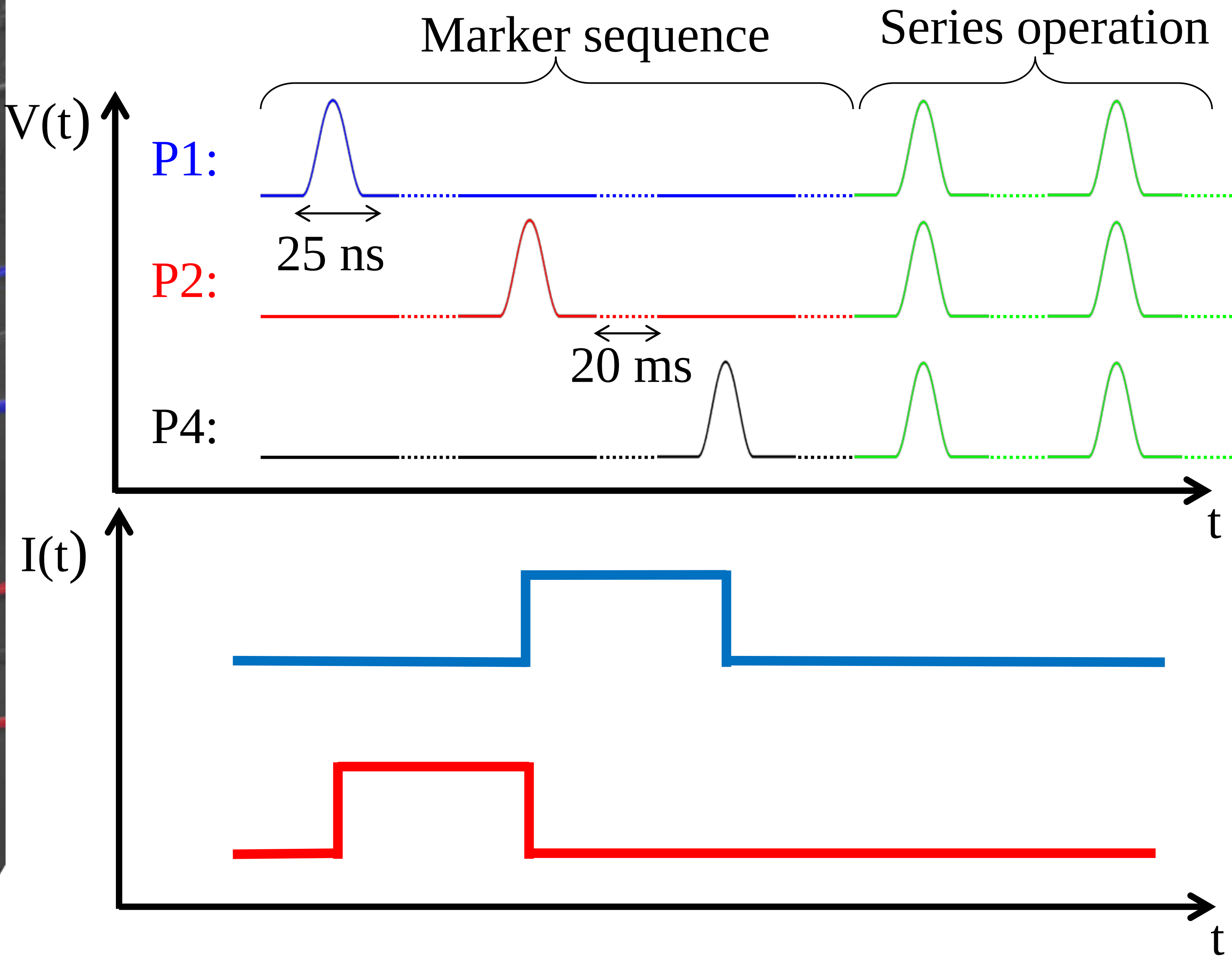


$$\text{Corrected error rate} \sim \left(\frac{\text{Time to detect errors}}{\text{Time between errors}}\right)^{\#\text{nodes}/2} \times \left(\text{Bare error rate}\right)^{\#\text{nodes}/2+1}$$

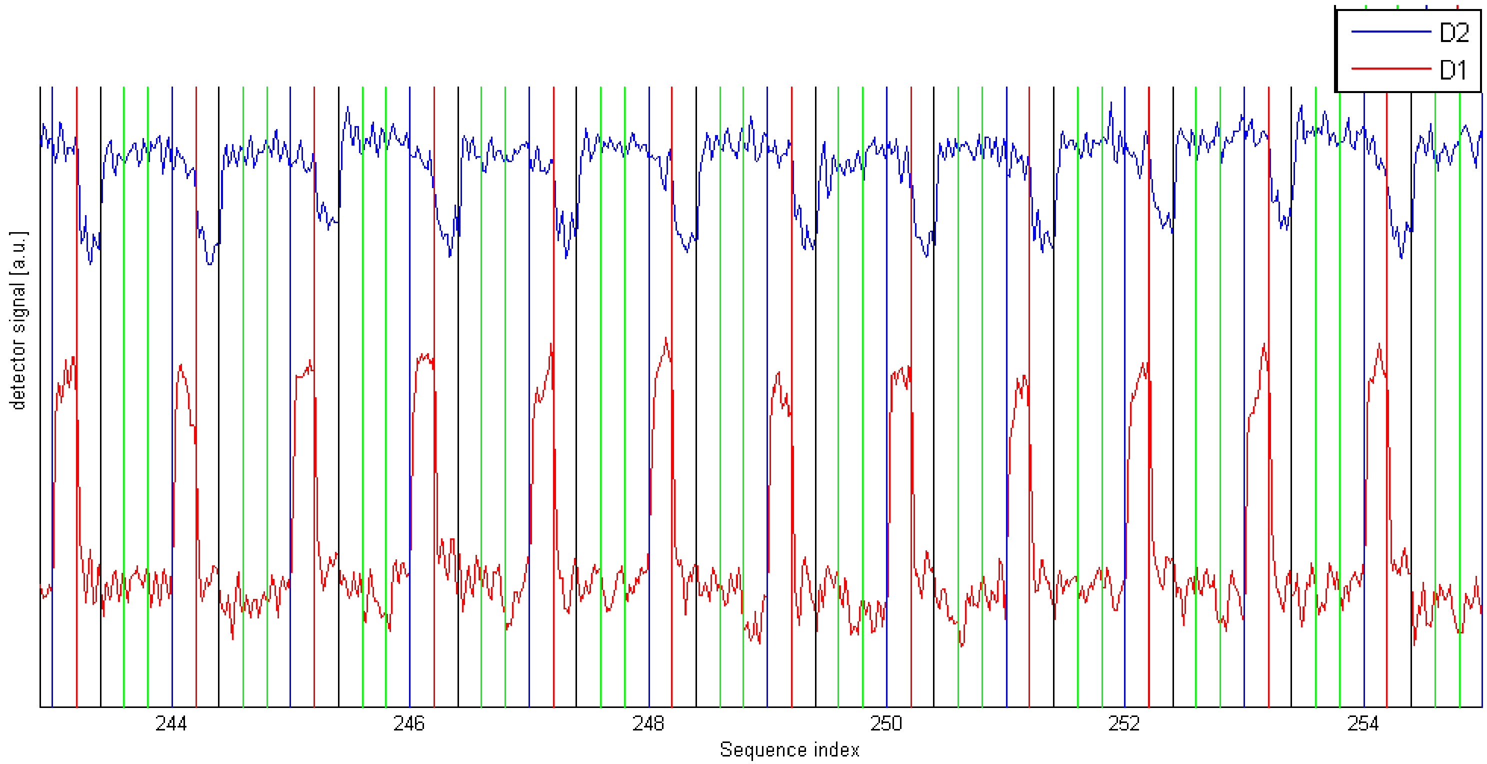
f=800 MHz, 10ppm
5 pumps in series, RF-SETs
Corrected error rate 10ppb

M. Wulf, Phys. Rev. B **87**, 035312 (2013)

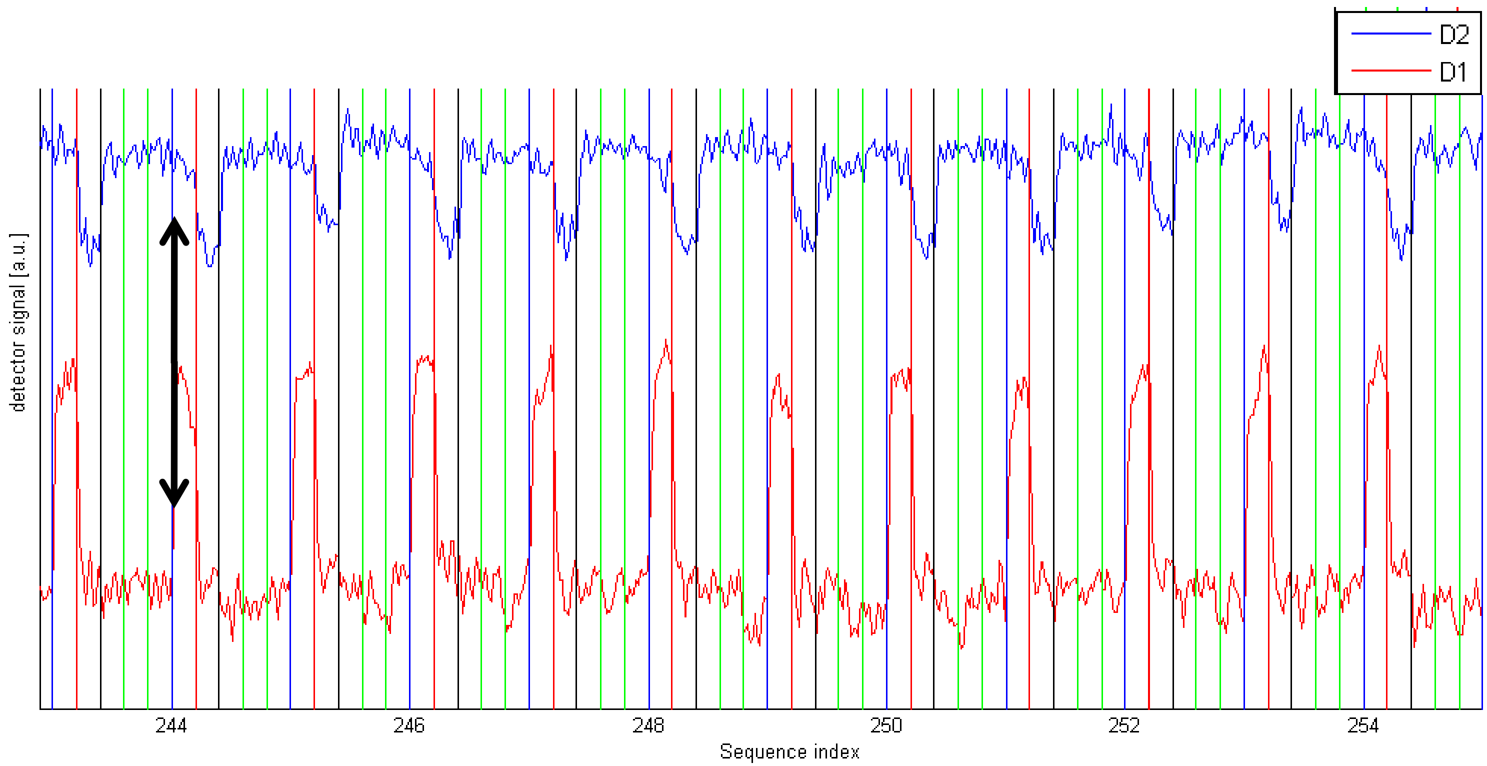
Simultaneous series pumping



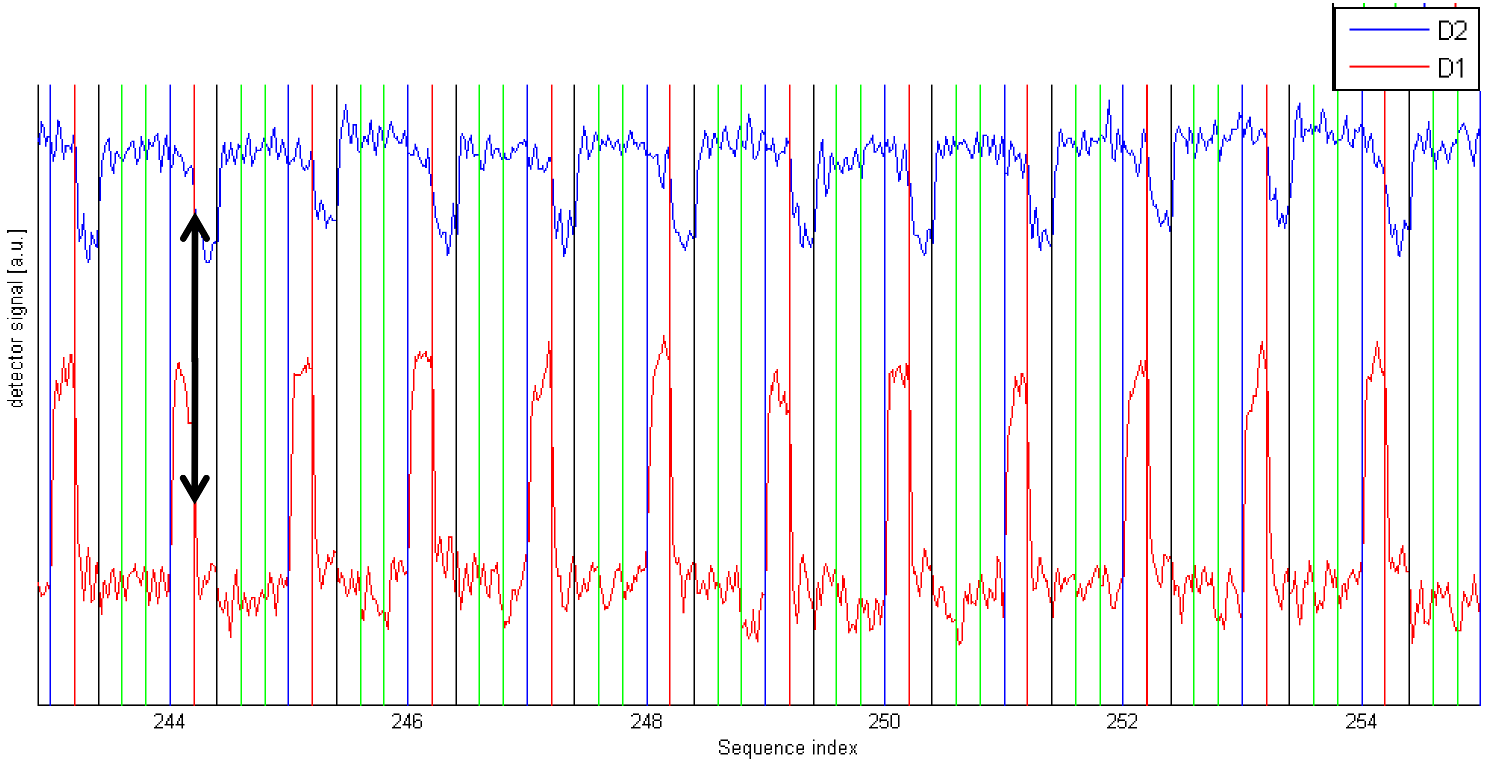
Simultaneous series pumping



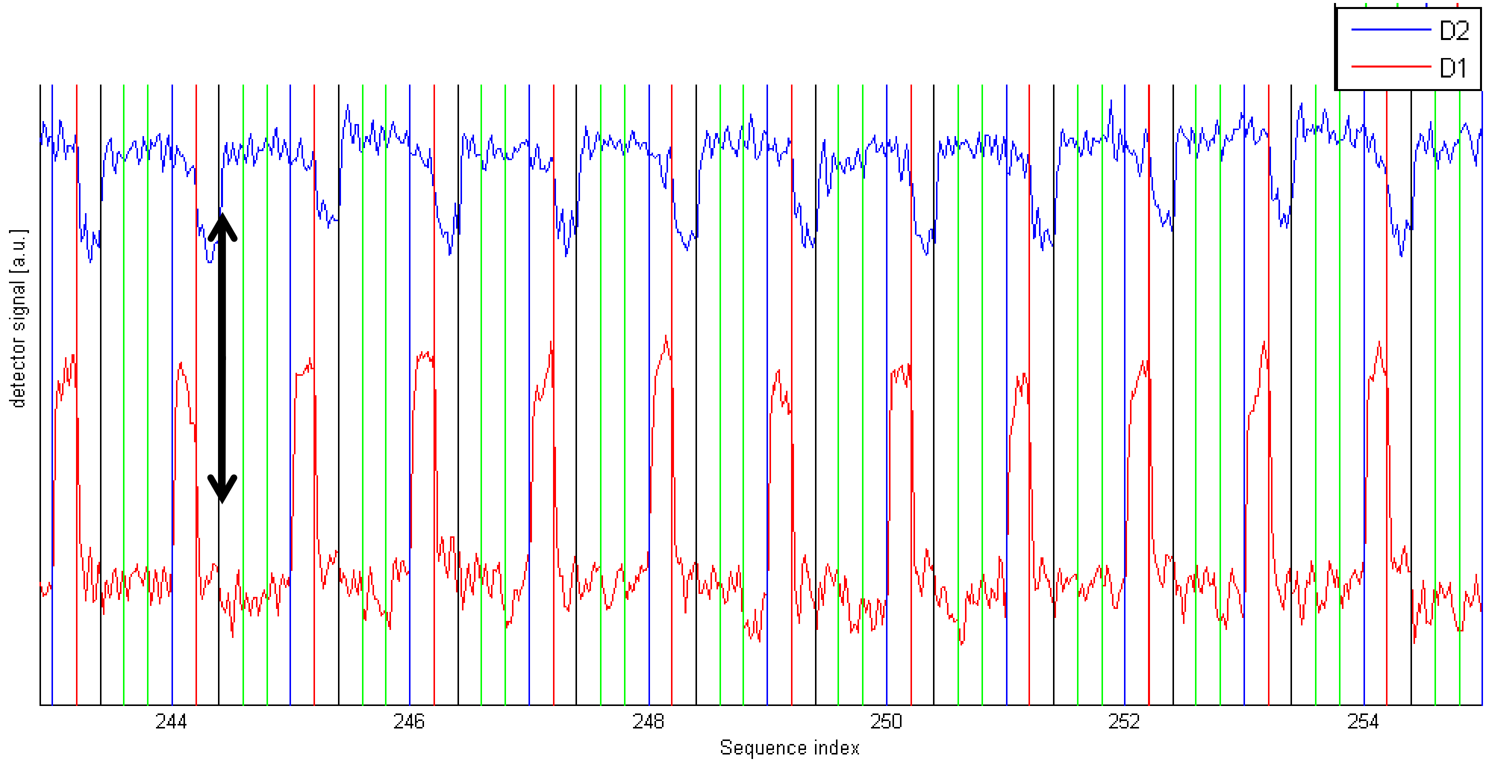
Simultaneous series pumping



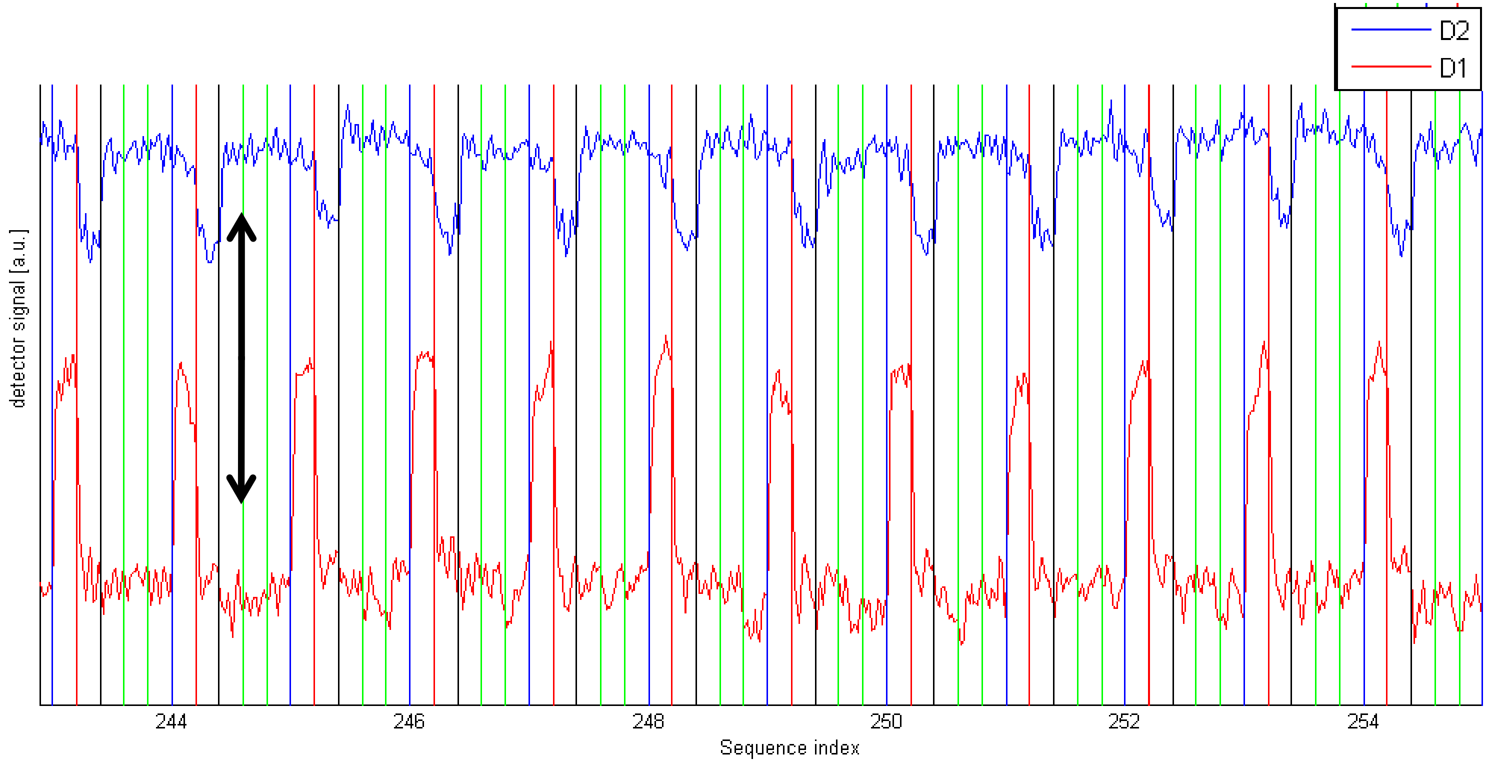
Simultaneous series pumping



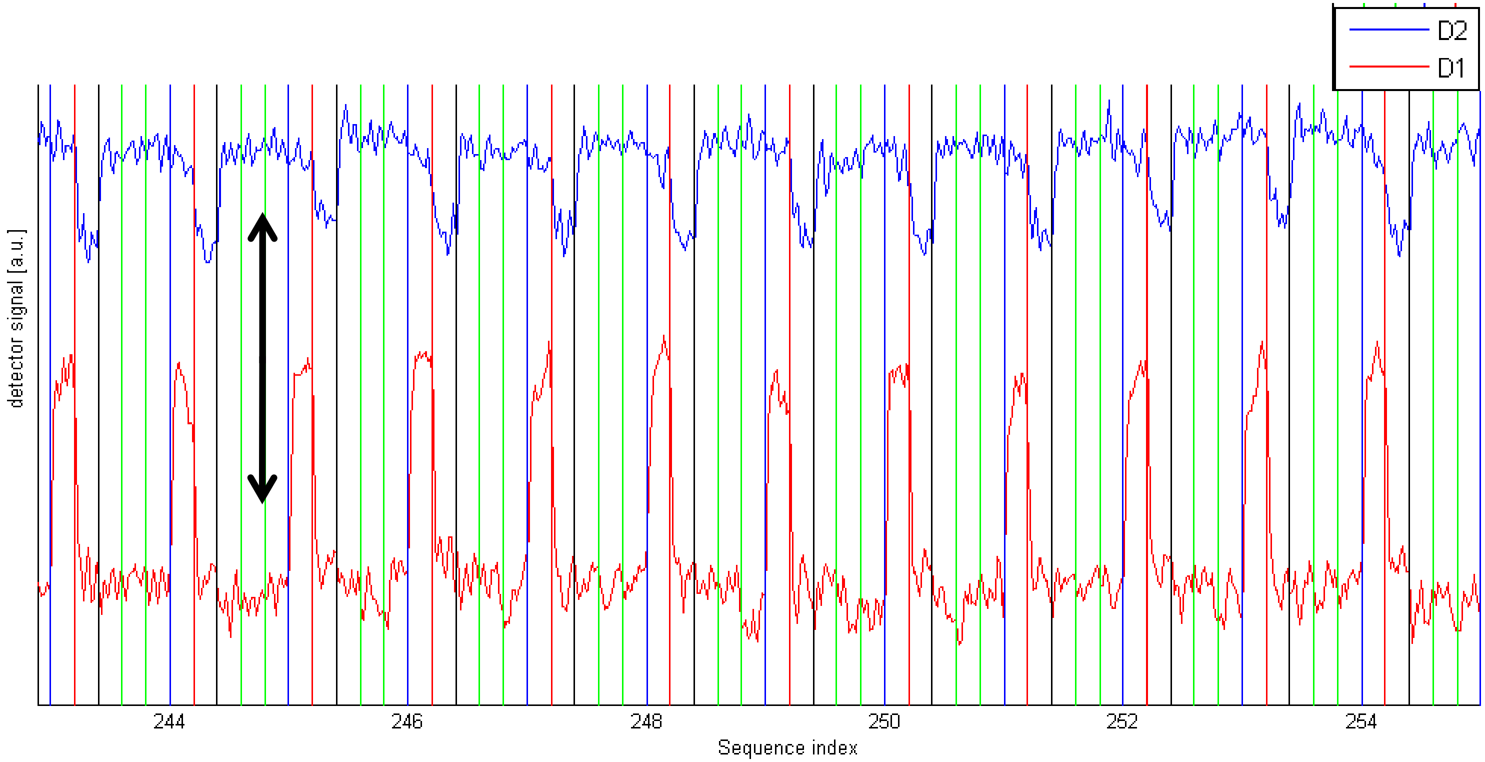
Simultaneous series pumping



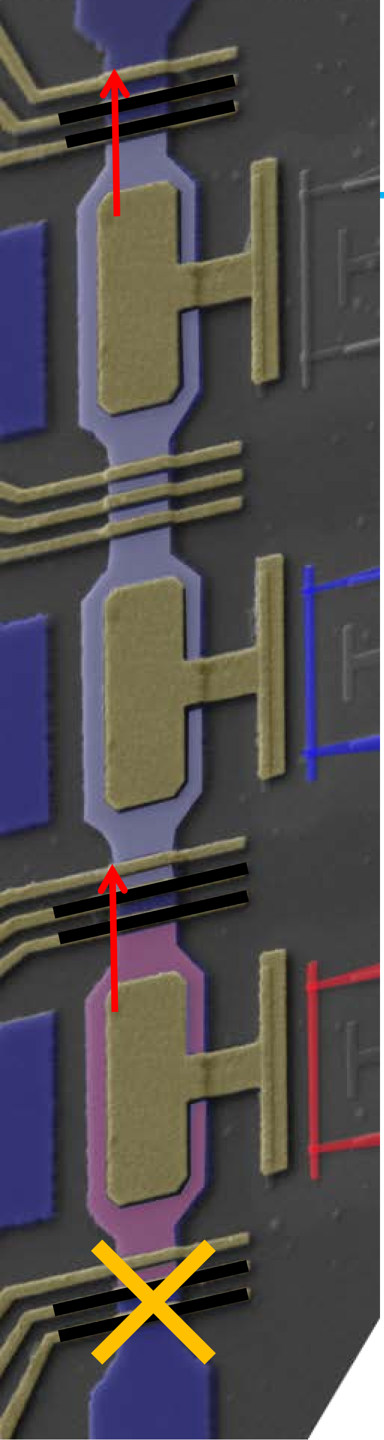
Simultaneous series pumping

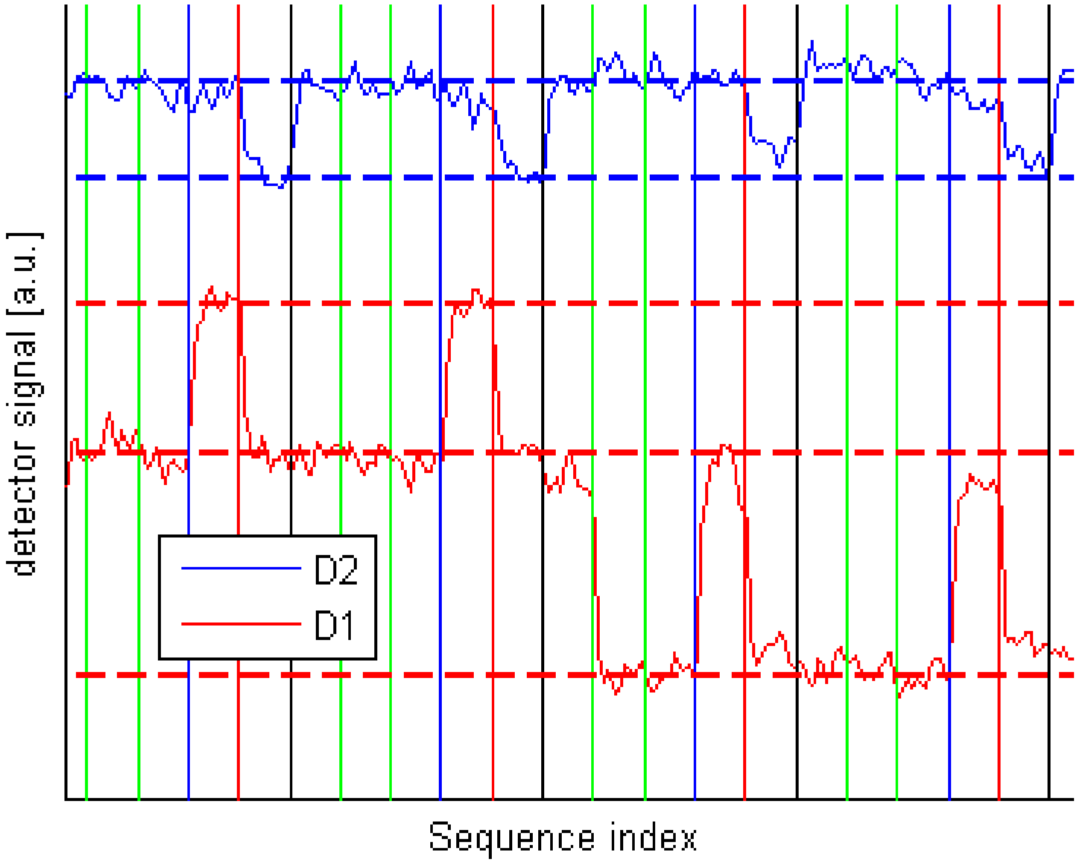


Simultaneous series pumping



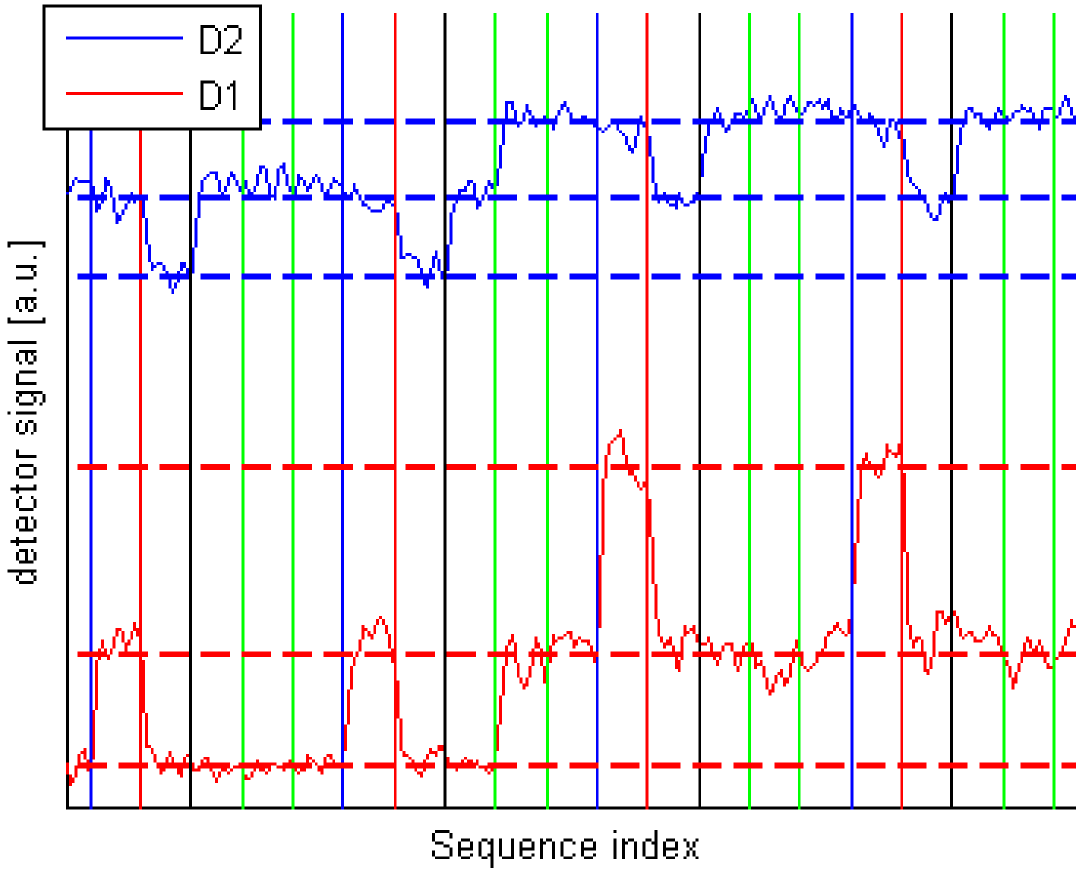
Identification of pump errors





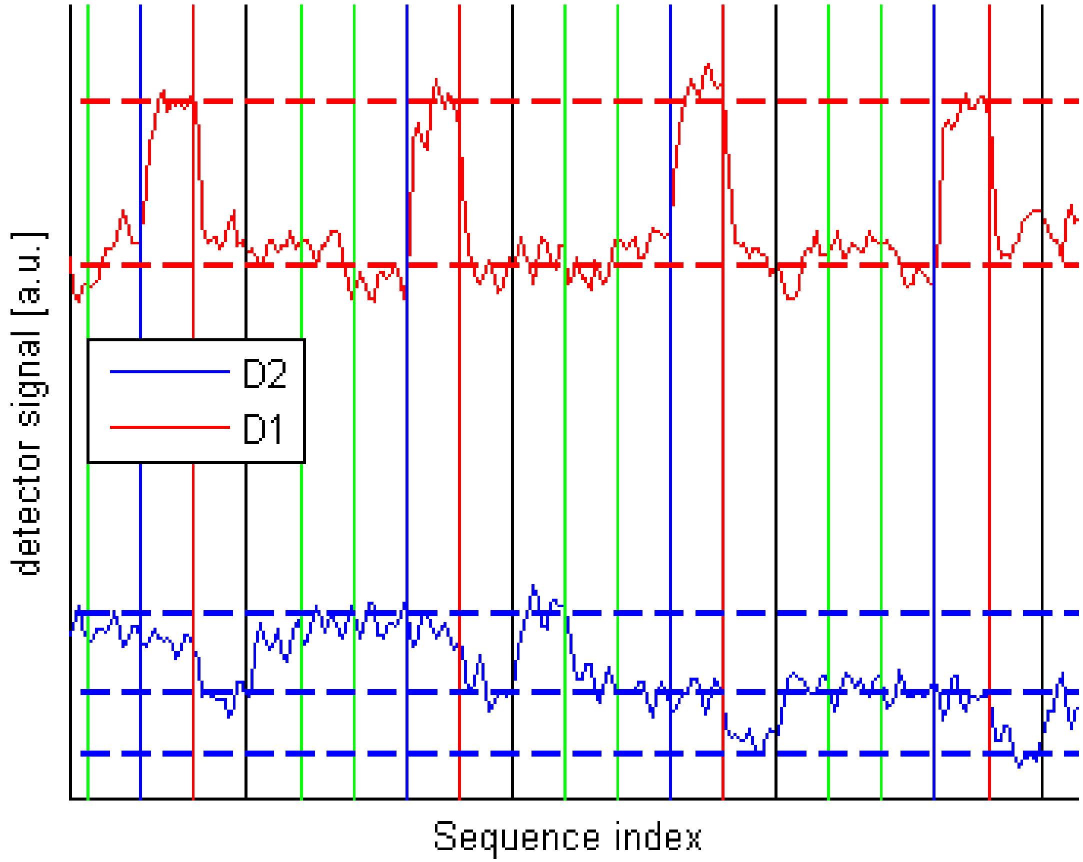
Pump error by P1: Only red SET affected

Identification of pump errors



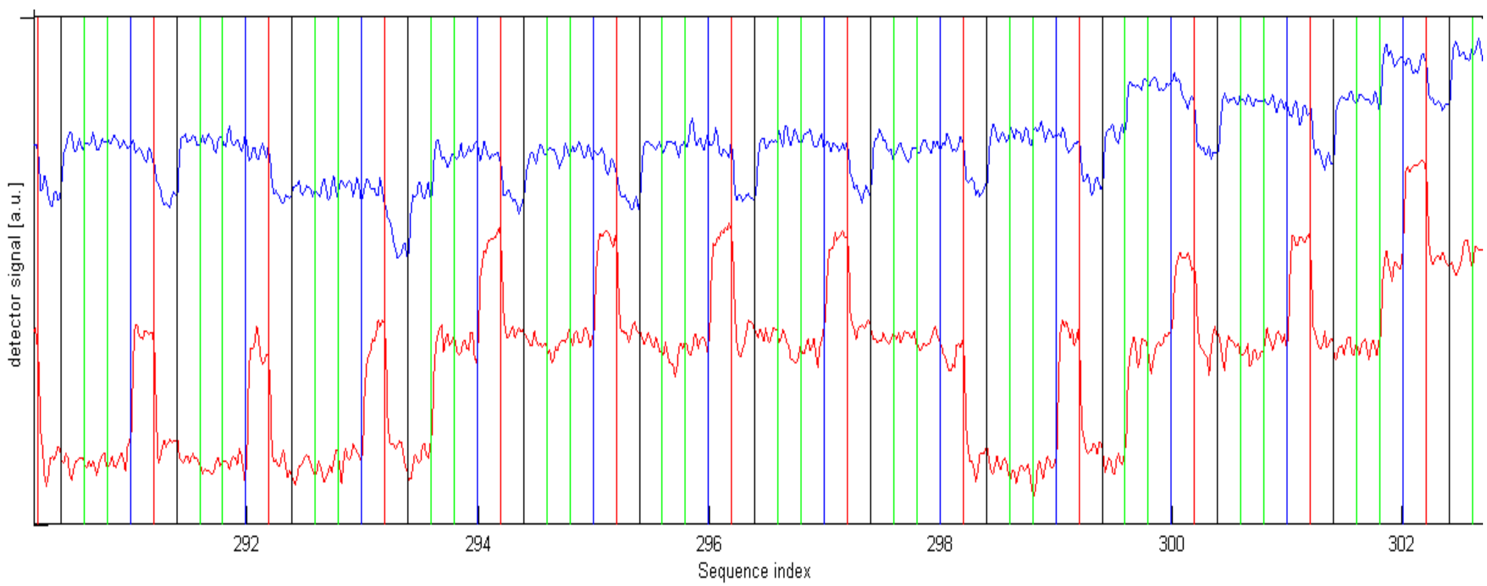
Pump error by P2: Both SETs affected

Identification of pump errors

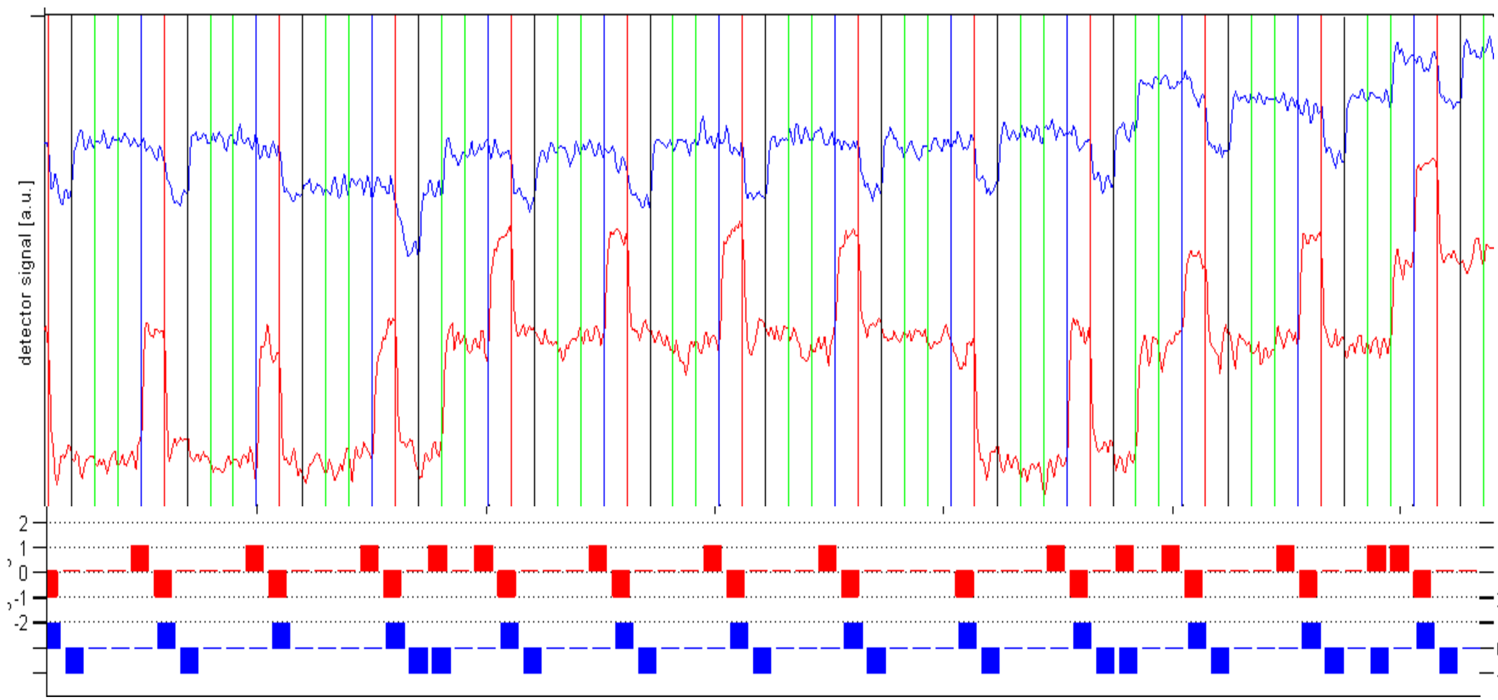


Pump error by P4: Only blue SET affected

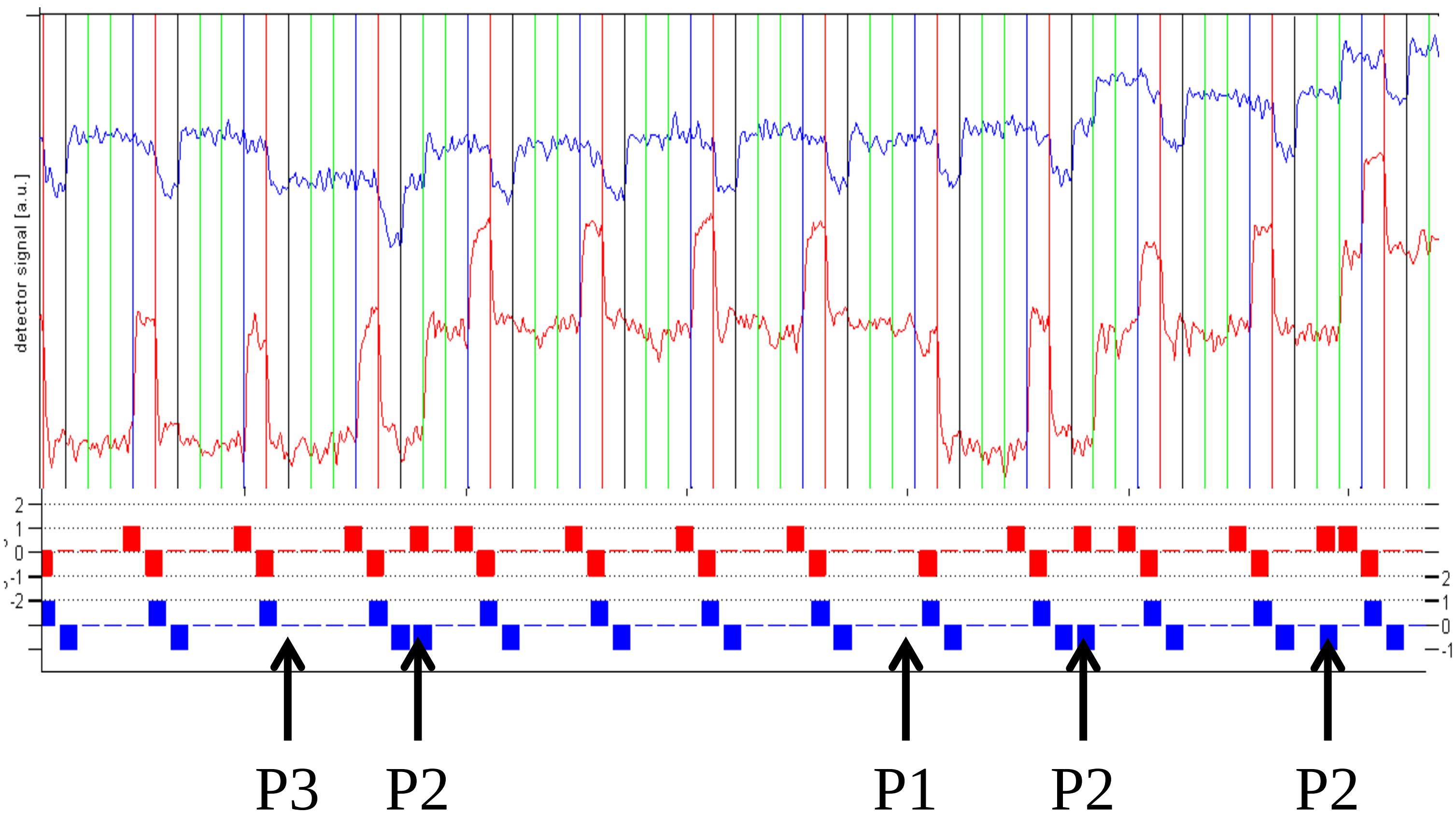
Identification of pump errors



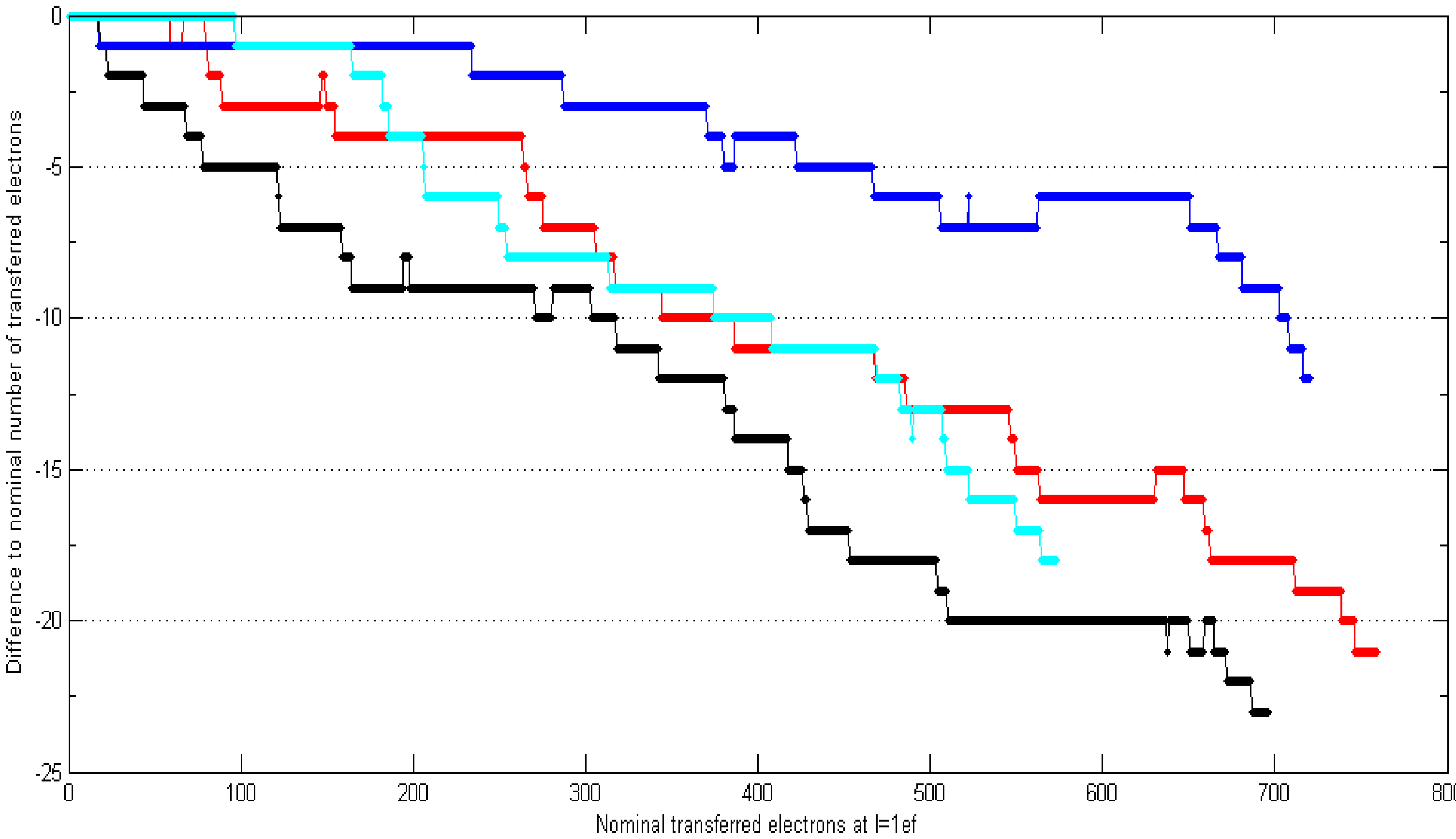
Identification of pump errors



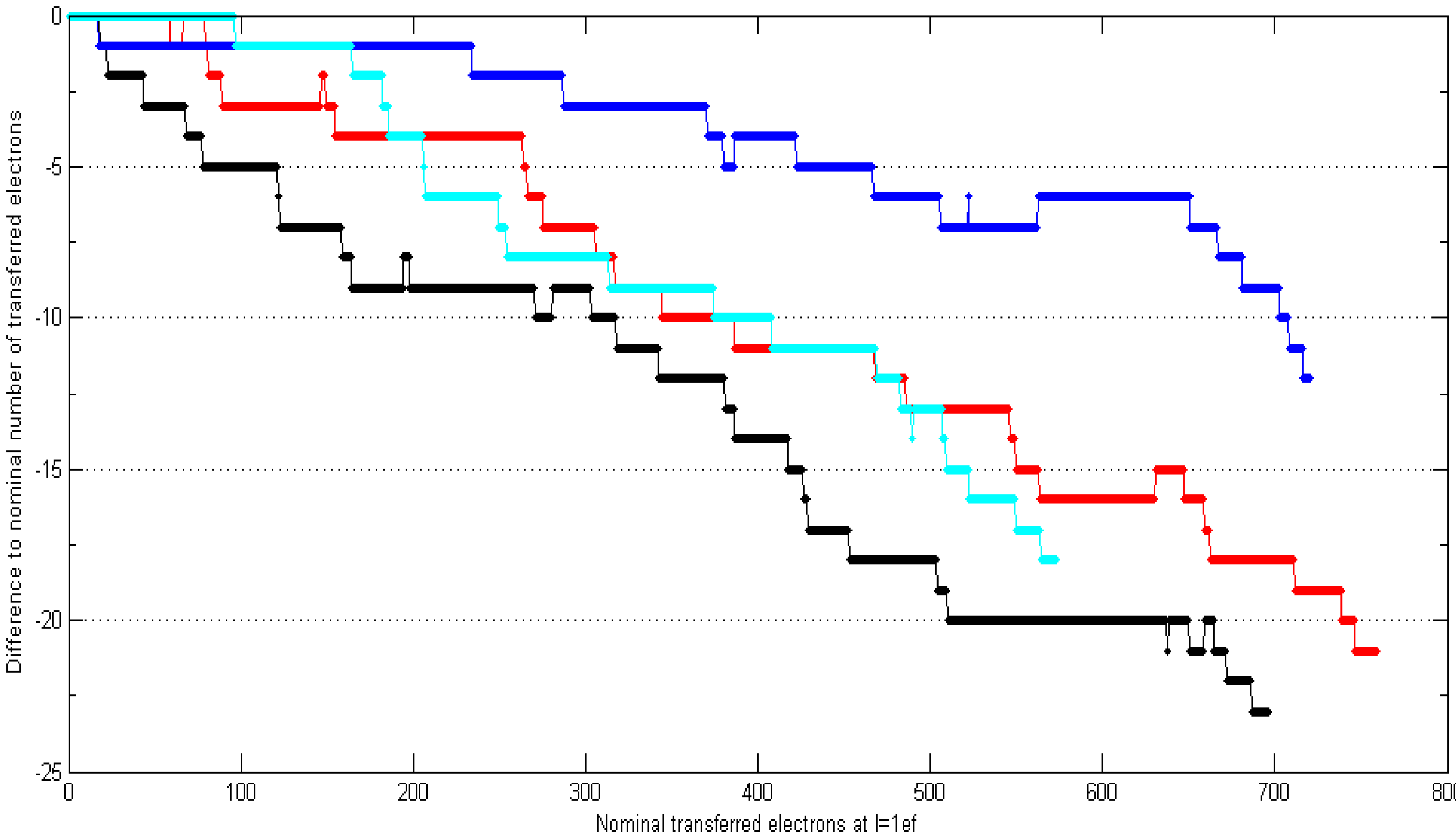
Identification of pump errors



Identification of pump errors

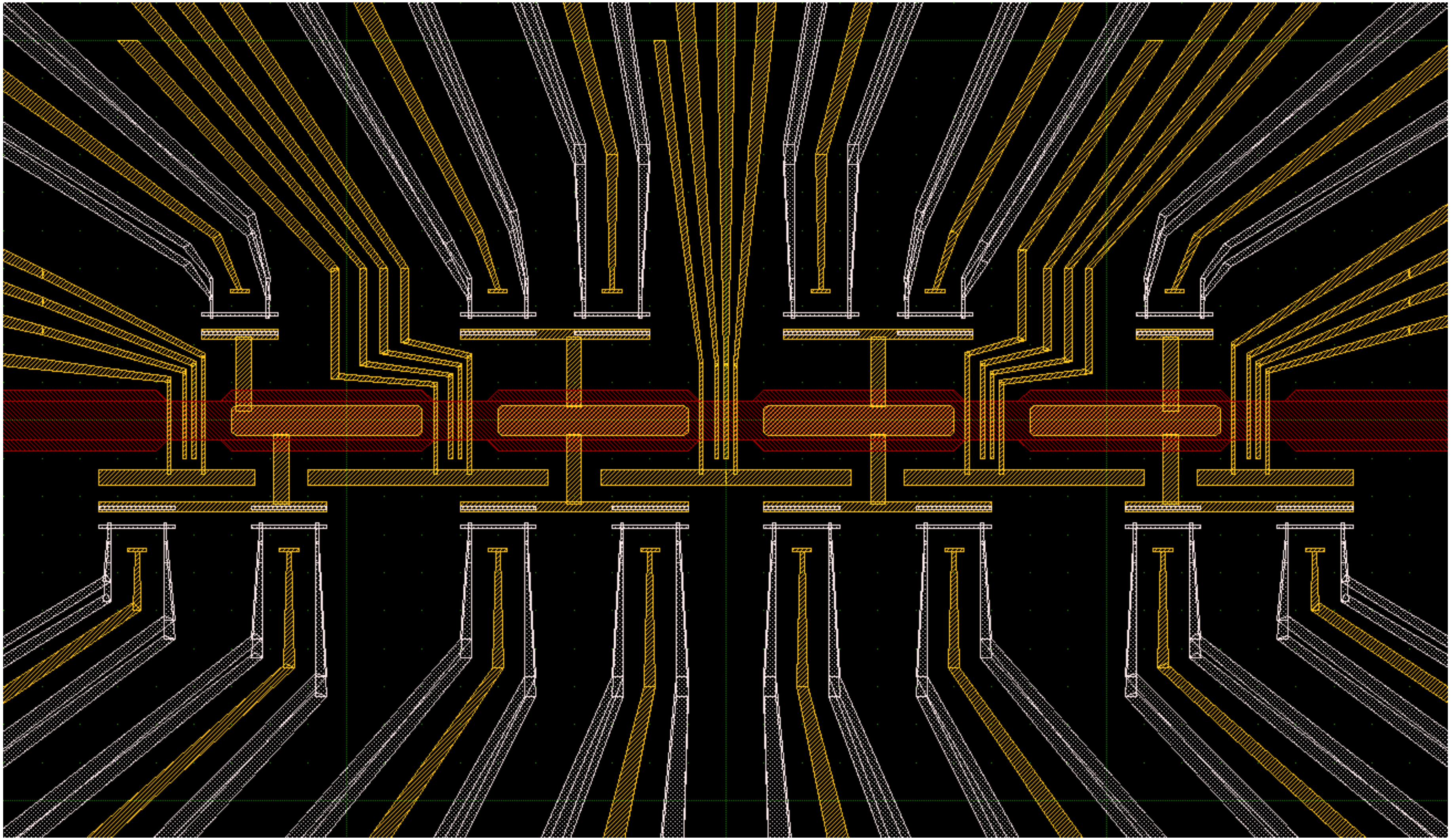


Identification of pump errors



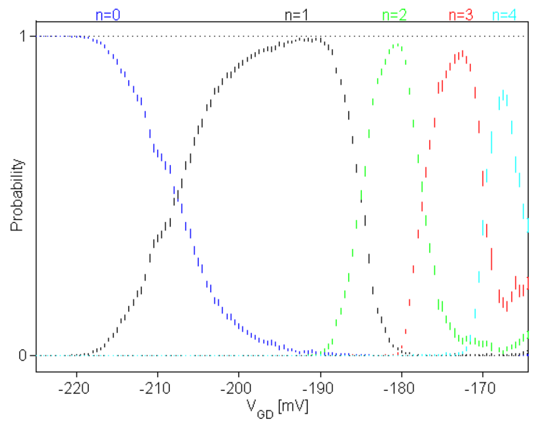
The charge transfer error is reduced by ~2 orders of magnitude by error accounting

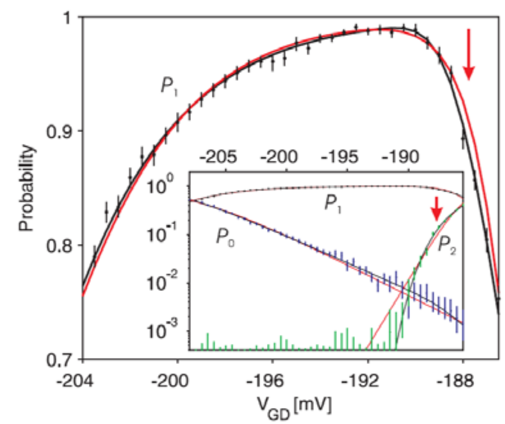
New design



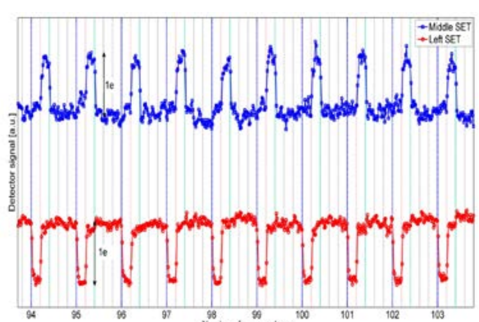
Summary

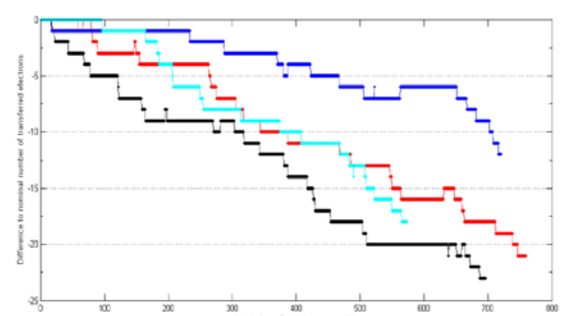
- **Counting measurements on the non-adiabatic electron pump**
  - Microscopic insights into the dynamics of electron capture





- **First demonstration of a self-referenced current source**
  - Road towards error reduction by accounting for (rare) errors





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Theoretical treatment of error accounting:

Error accounting algorithm for electron counting experiments

Phys. Rev. B 87, 035312 (2013)

Experiments on counting statistics :

Counting statistics for electron capture in a dynamic quantum dot

Phys. Rev. Lett. 110, 126803 (2013)

Experiments on serial pumps with error detection:

Series Operation of Single-Electron Sources with Charge Detection

CPEM (2012)

Thank you for your attention