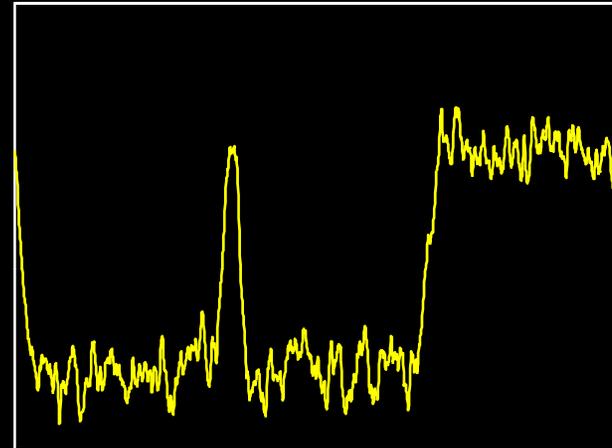
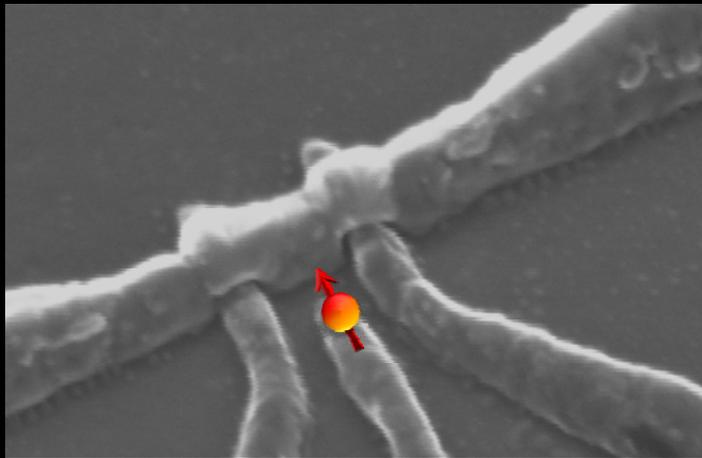


Single-shot Electron Spin Readout of Individual Implanted P Donors in Silicon

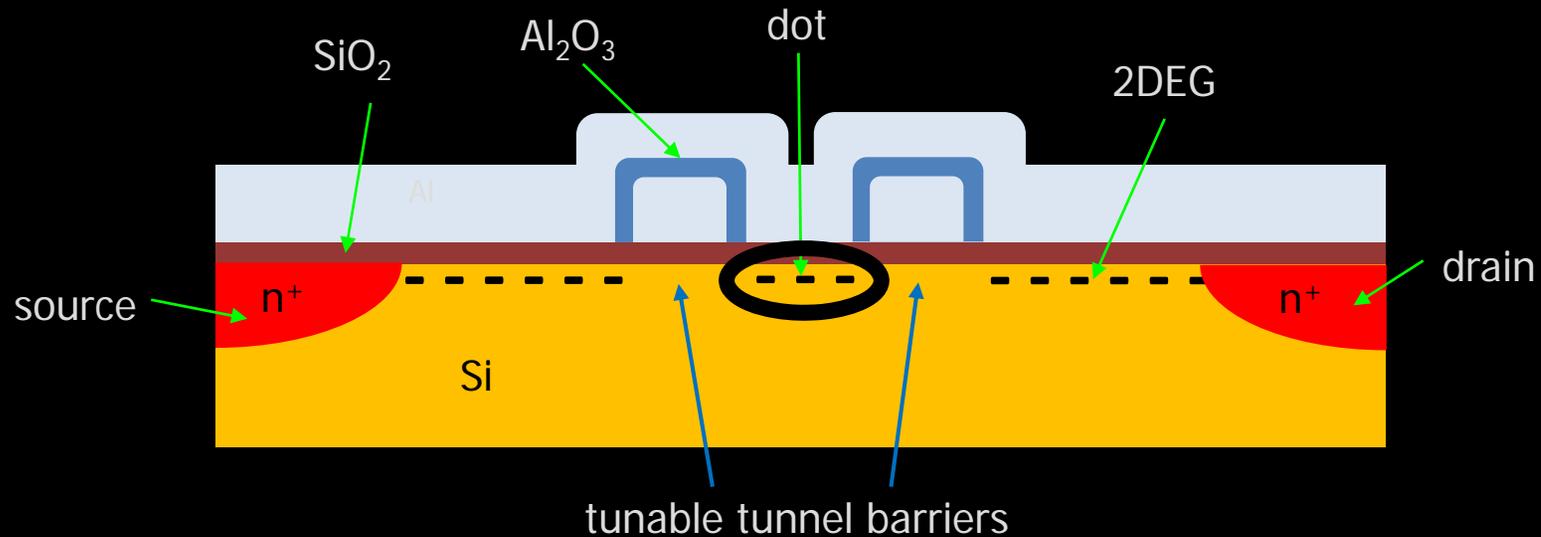
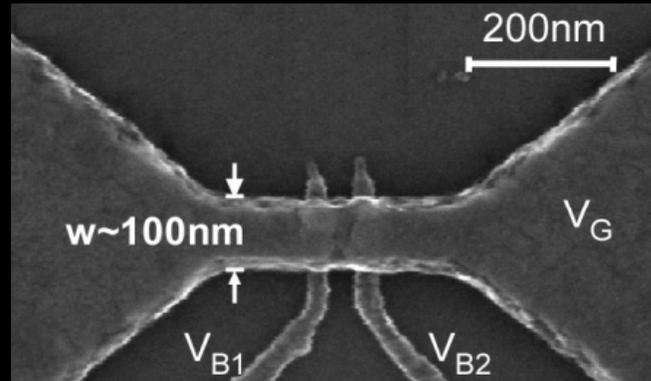


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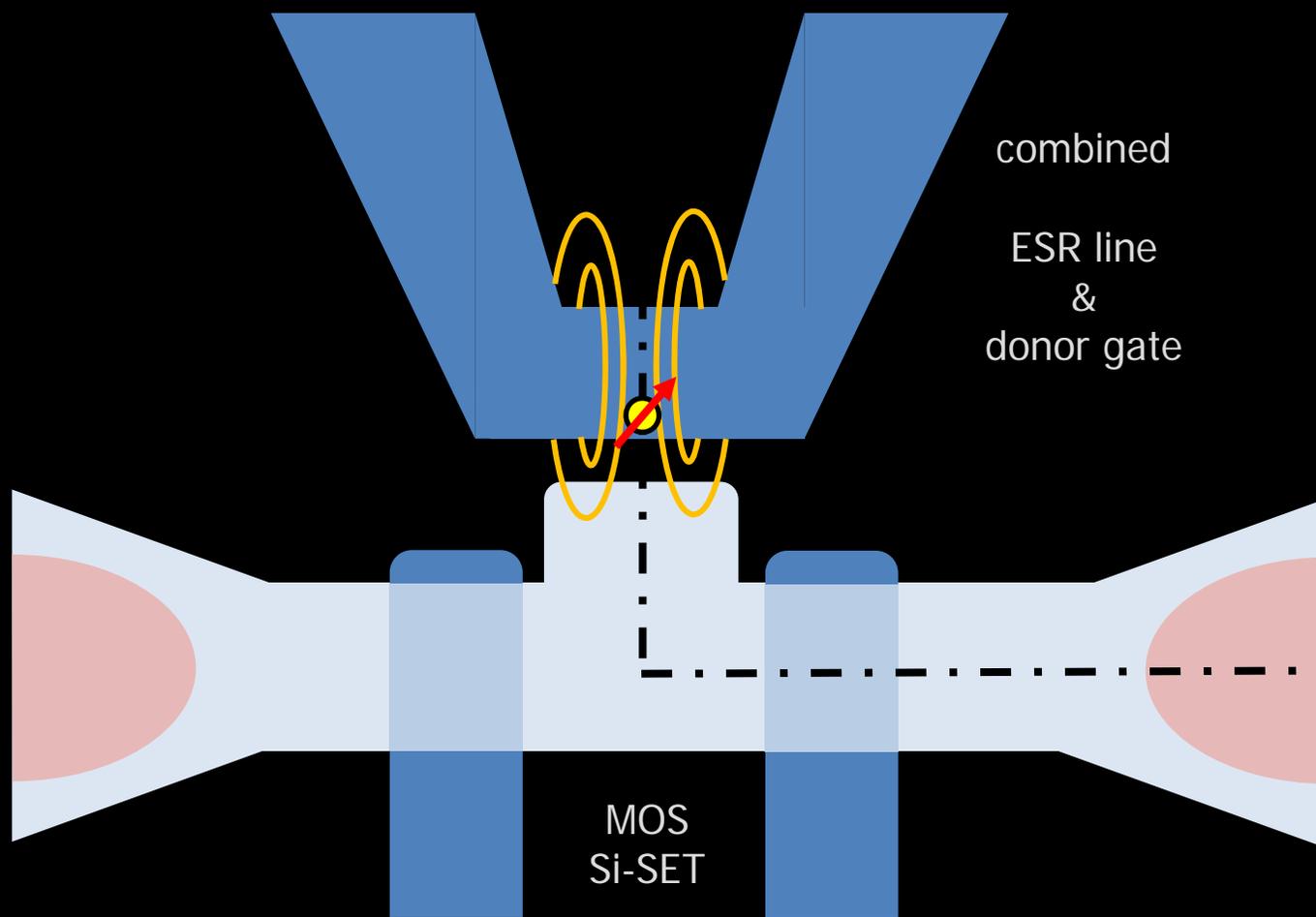


MOS Silicon SET



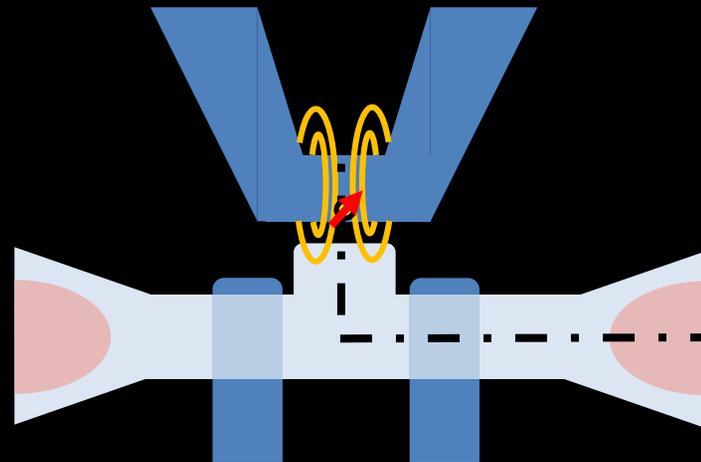
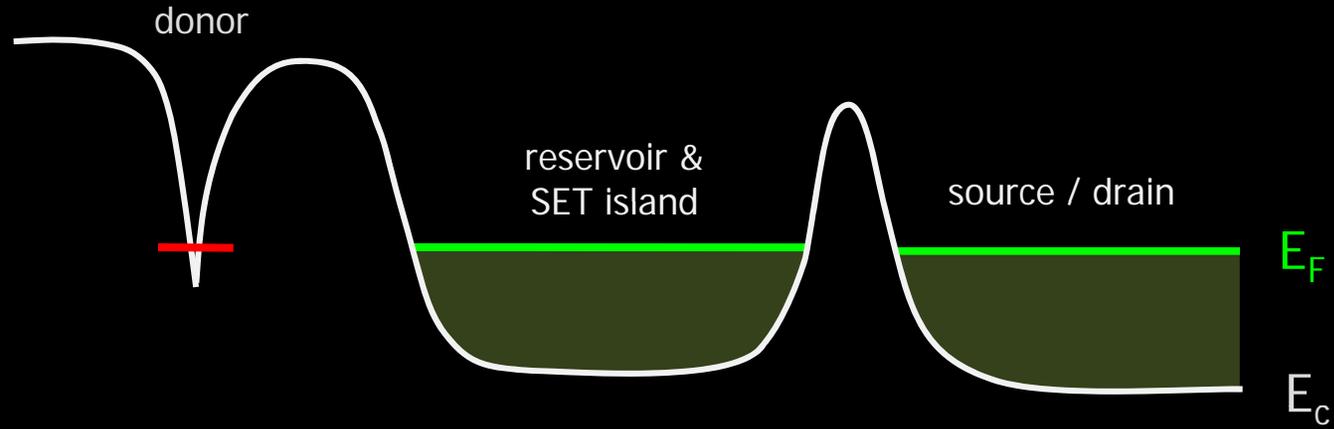
SET island underneath the SiO₂

MOS spin qubit !

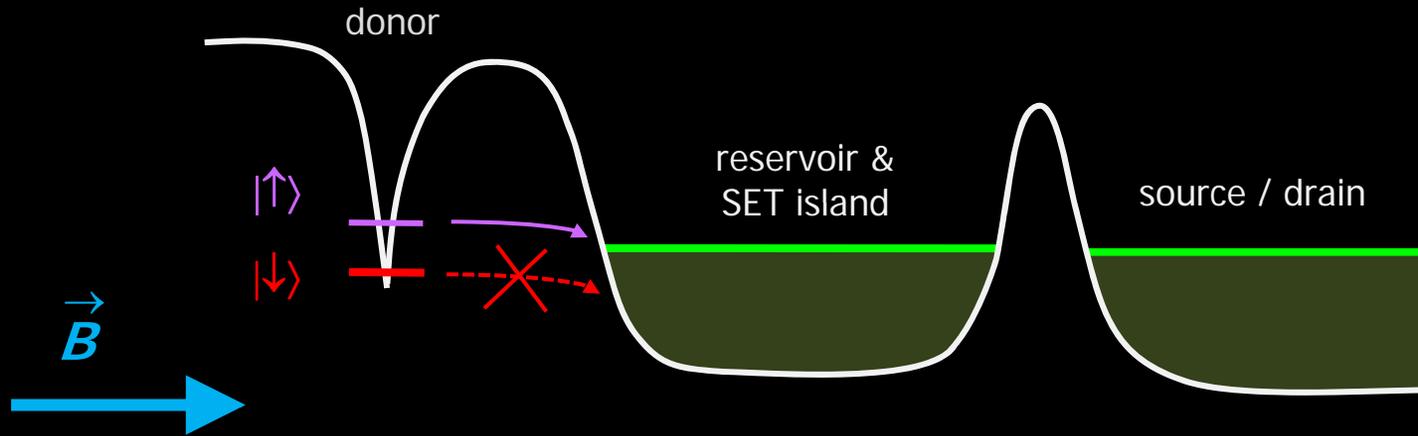
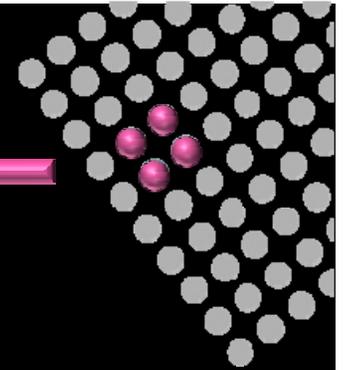


The SET island can act as reservoir for spin→charge conversion

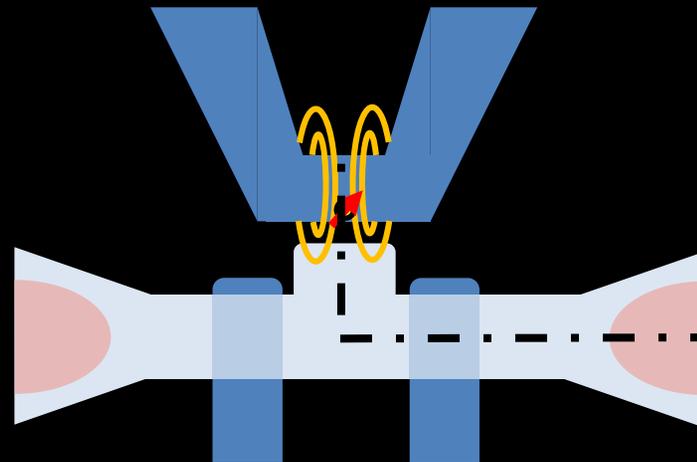
Energy landscape



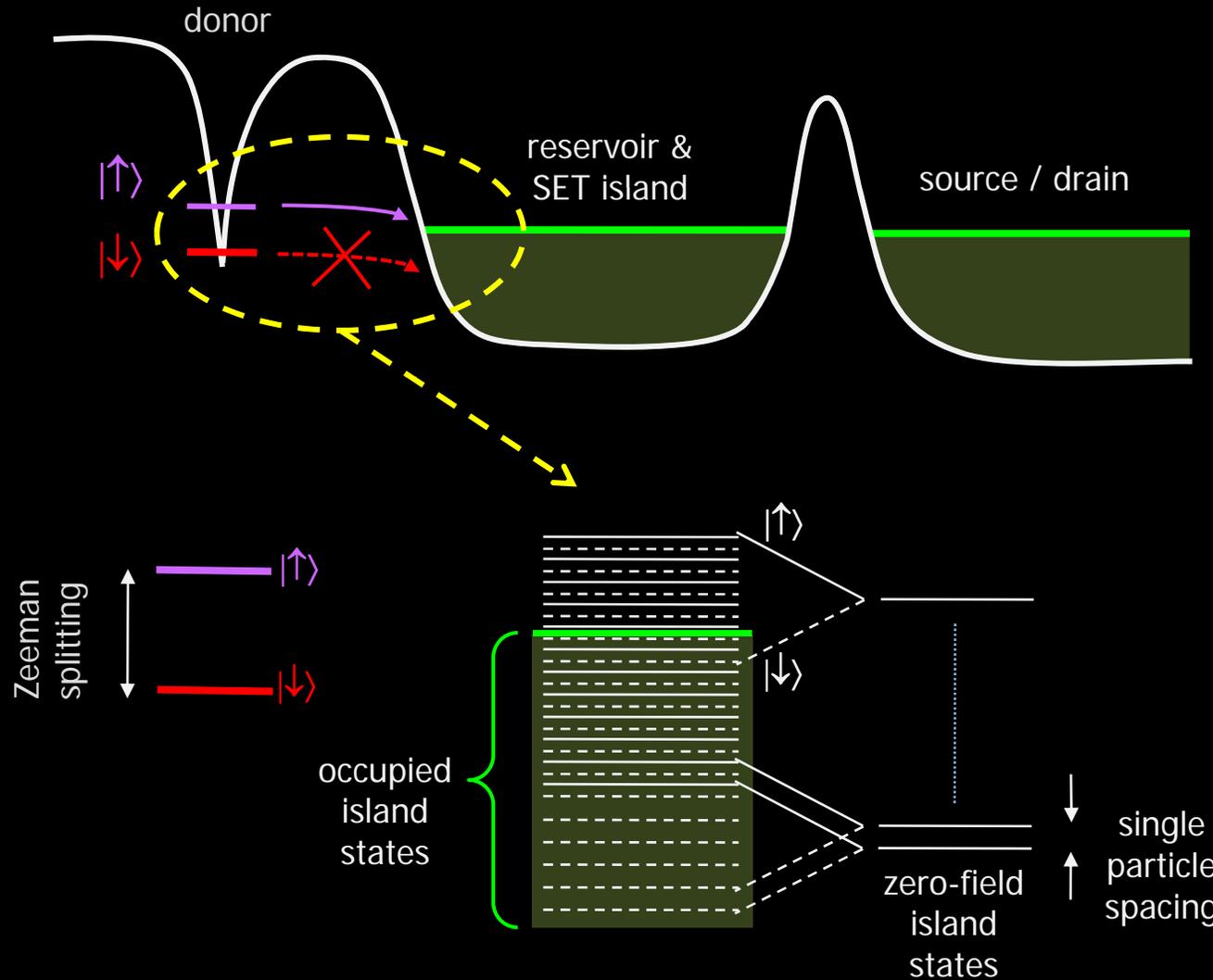
Spin to charge conversion



The electron can jump out of the donor only if it is in the **spin-up** state
⇒ detecting a charge transfer is equivalent to reading out the spin

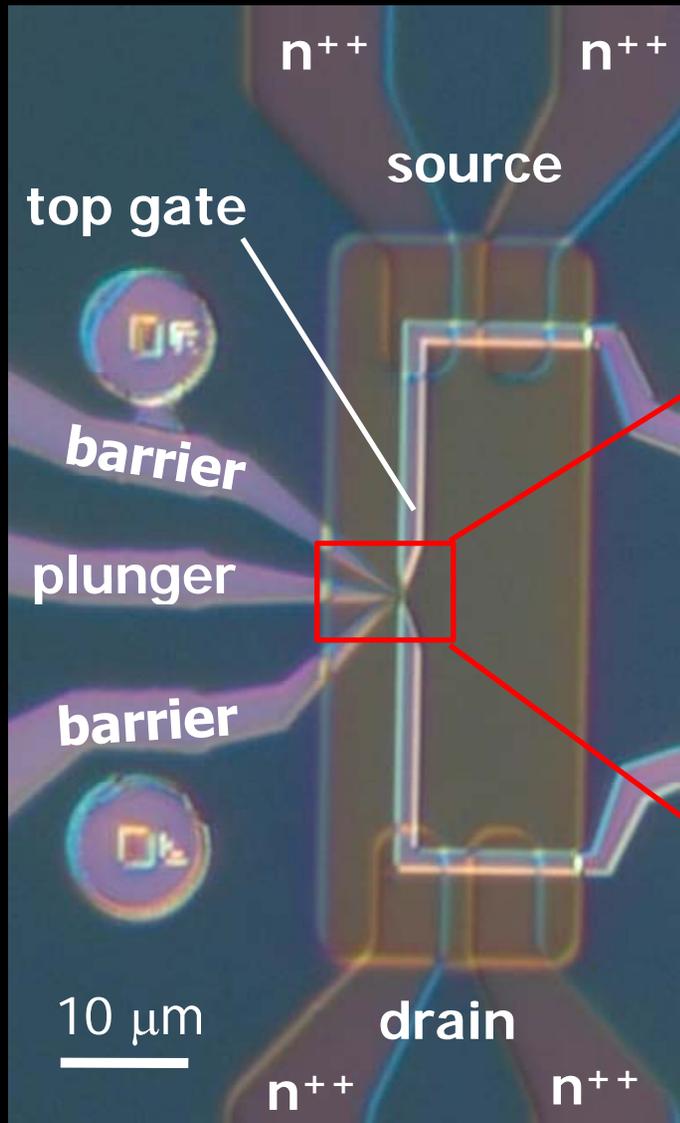
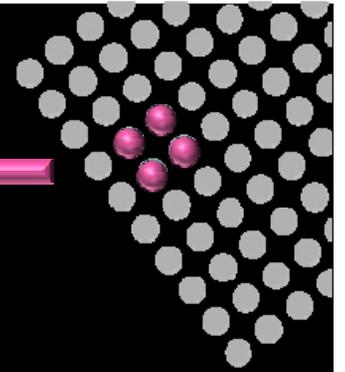


Zeeman splitting

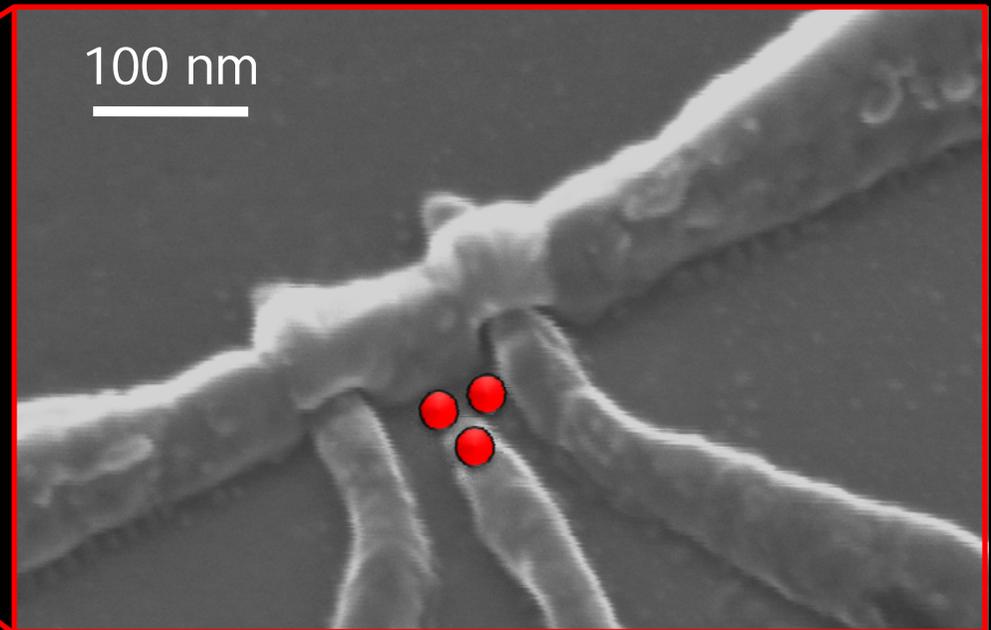


~ 100-electrons dot \rightarrow discreteness in the density of states?

Device for spin readout (no ESR)

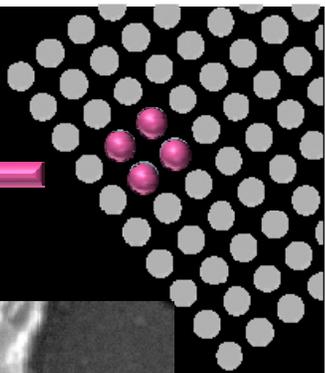


DC plunger instead of ESR line

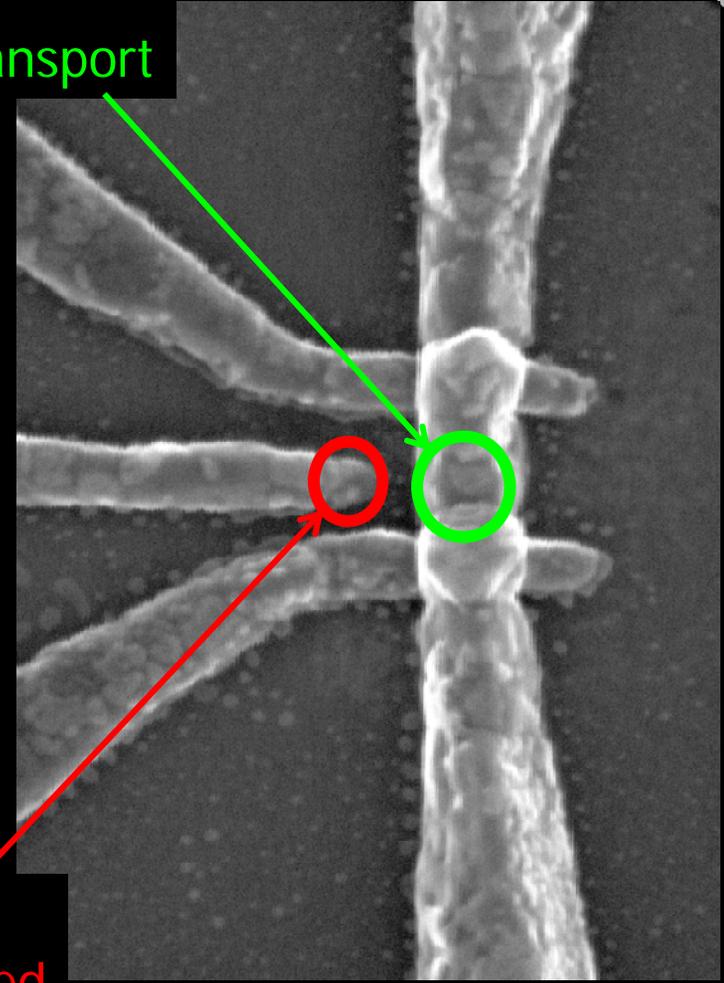
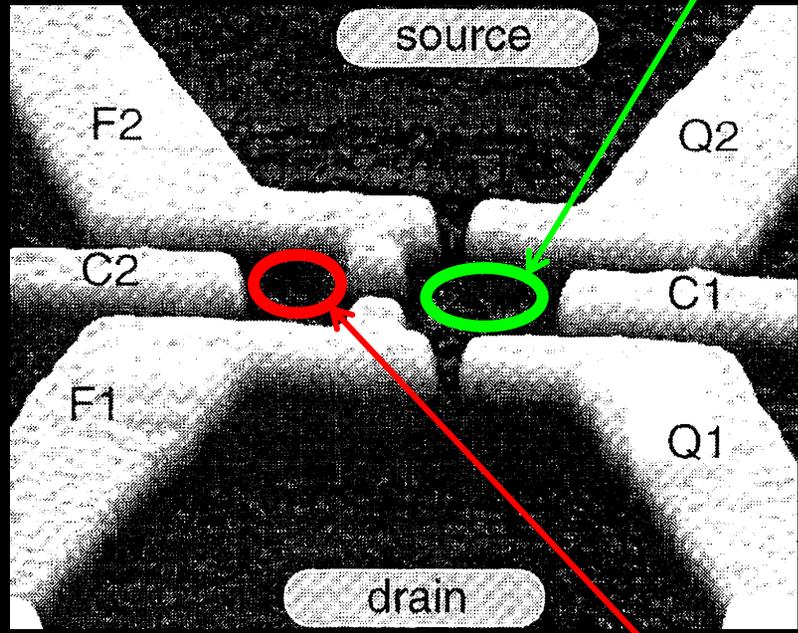


~ 3 donors in the 30×30 nm "active area"
~ 18 in total

"Parallel double-dot" analogy

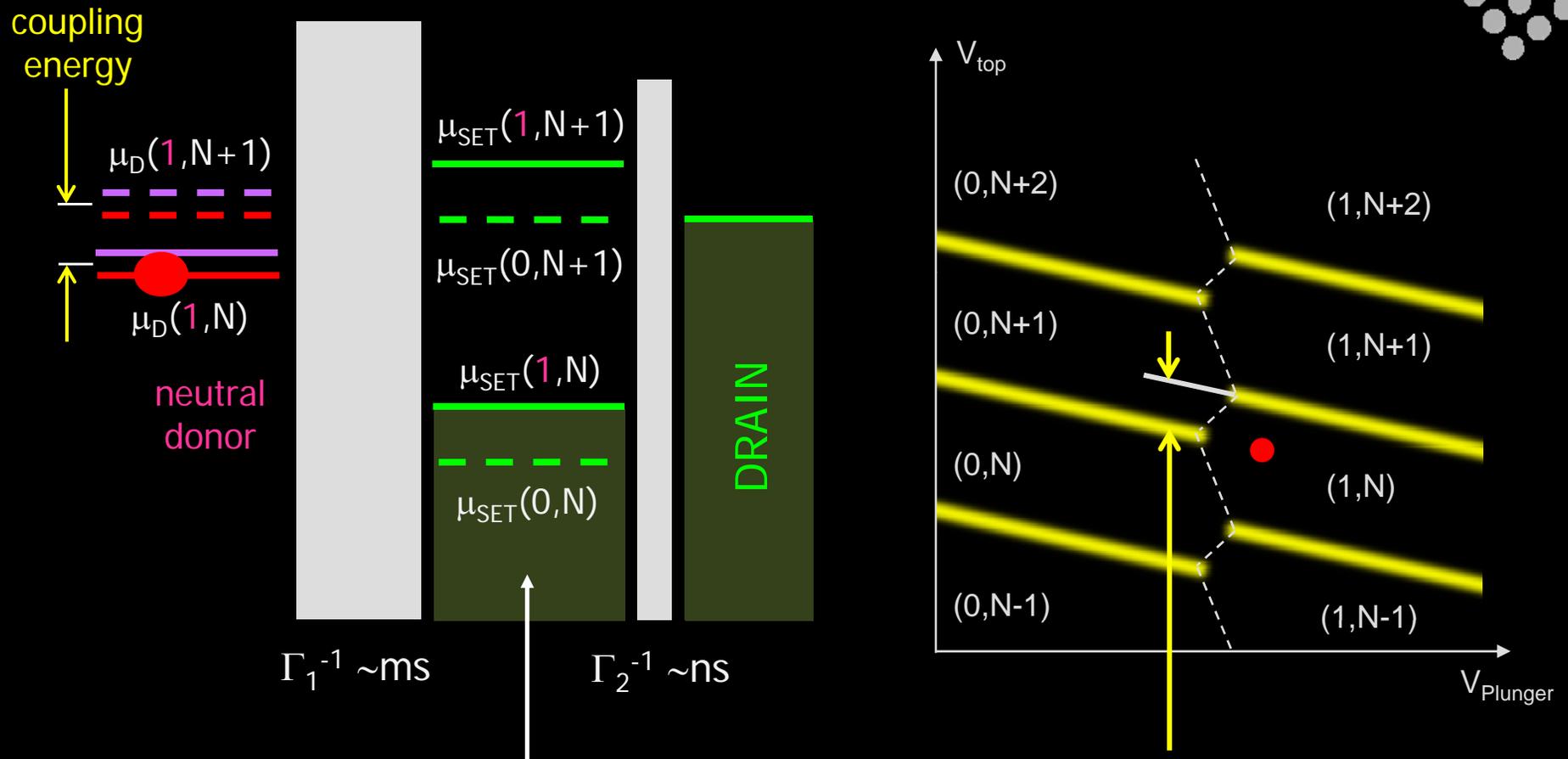


dot 1
measured in transport



dot 2
tunnel - coupled

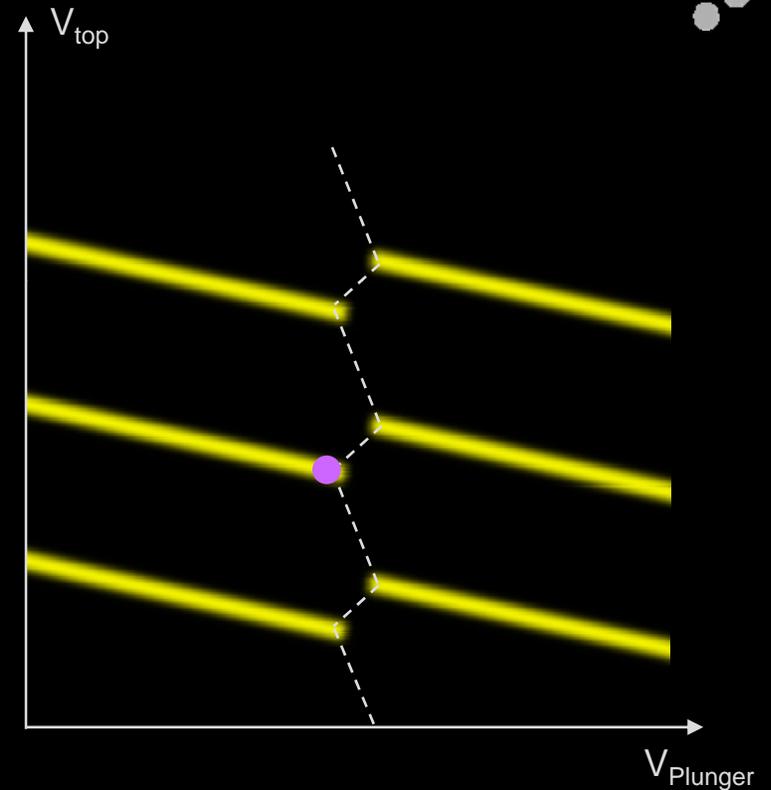
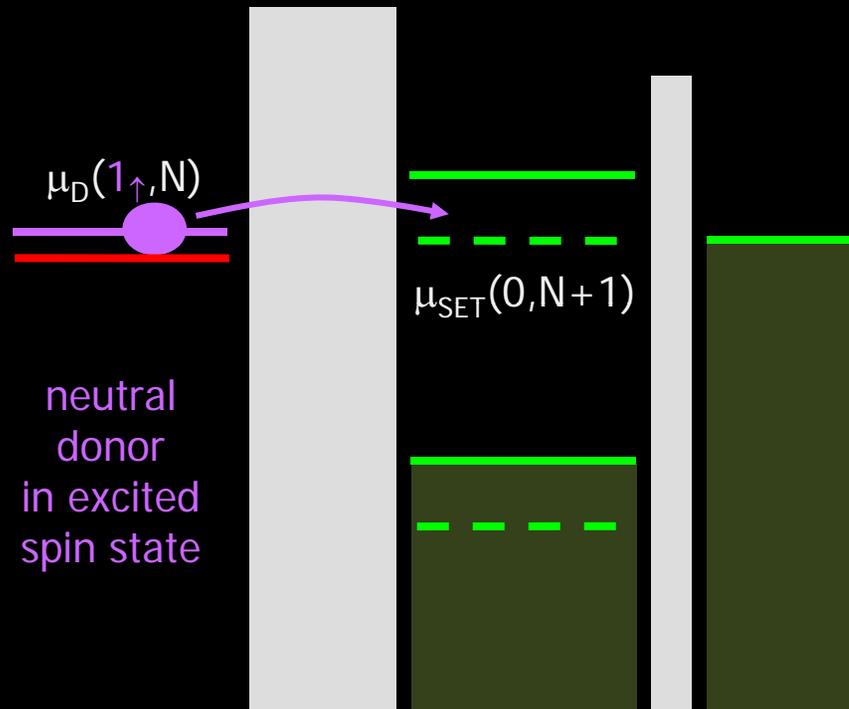
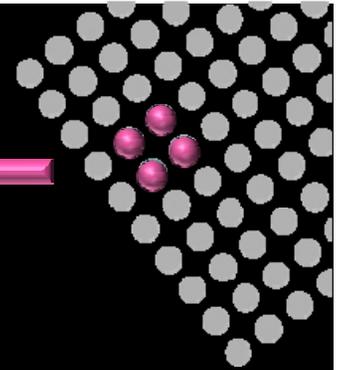
"Parallel double-dot" description



2 ladders of electrochemical potentials depending on the charge state of the donor

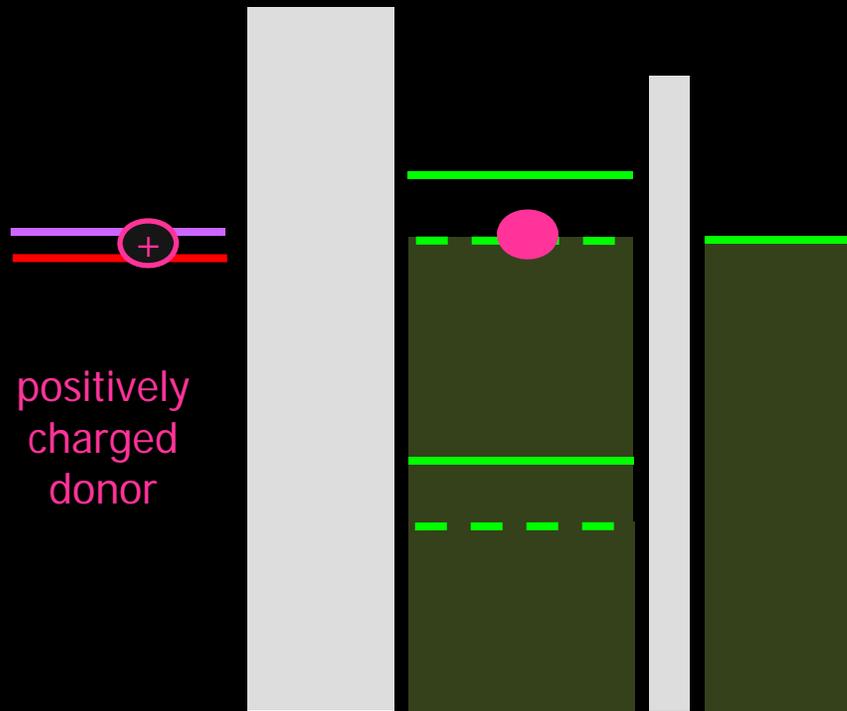
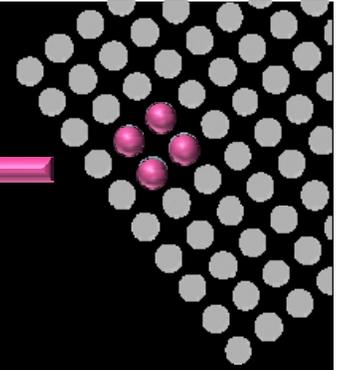
charge transfer signal $\Delta q / e$

"Parallel double-dot" description

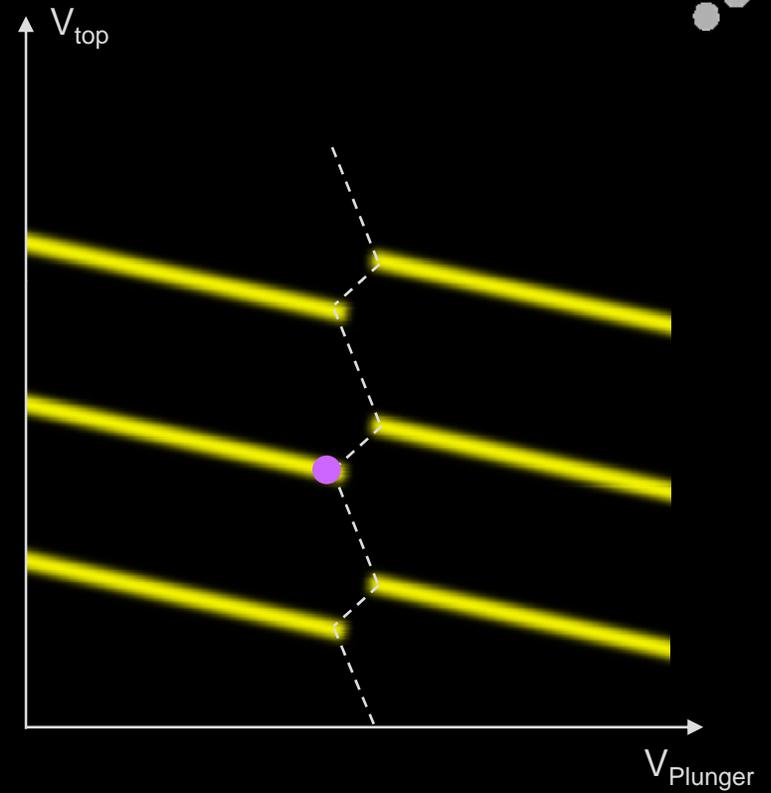


SET blocked when the donor is neutral

"Parallel double-dot" description

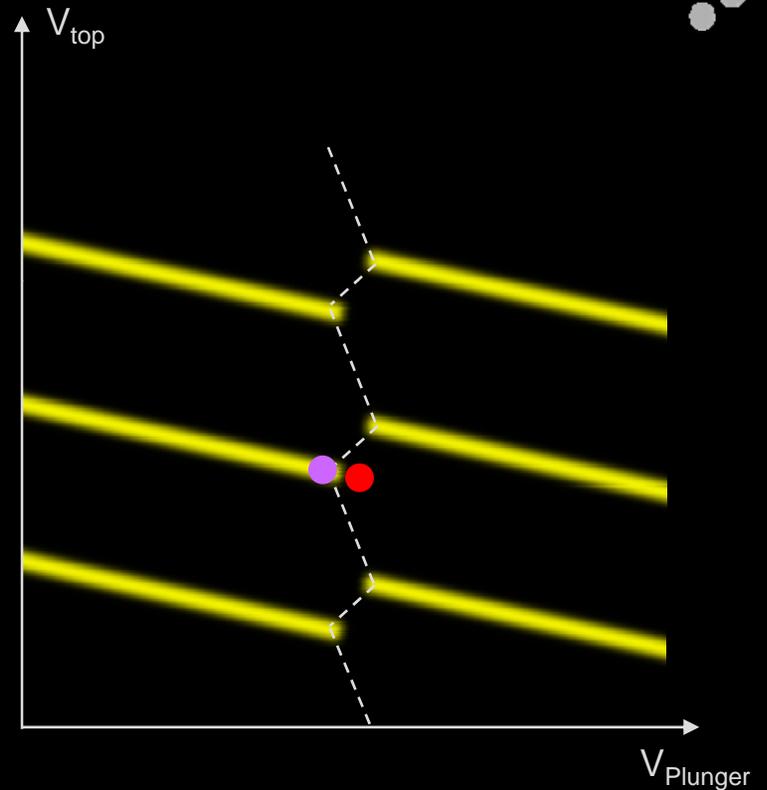
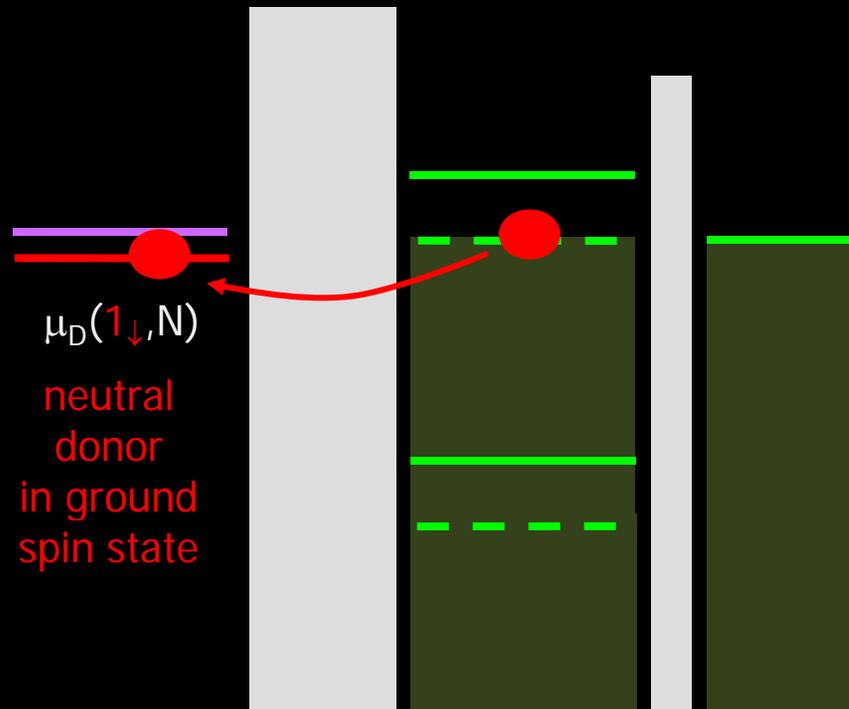


positively
charged
donor



Blockade lifted when the donor is ionized

"Parallel double-dot" description

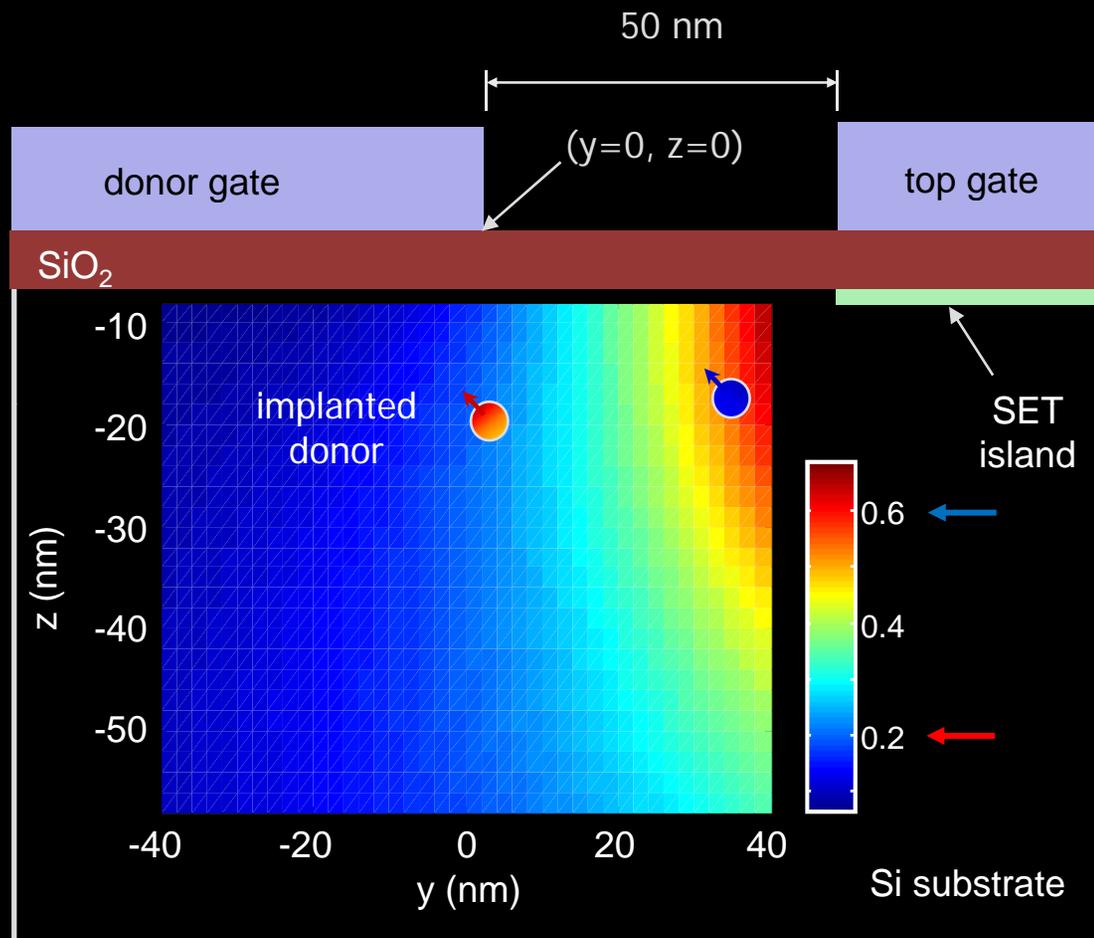


Blockade restored when the donor is neutralized

~ 100% on-off contrast if coupling energy $> 0.1 e$

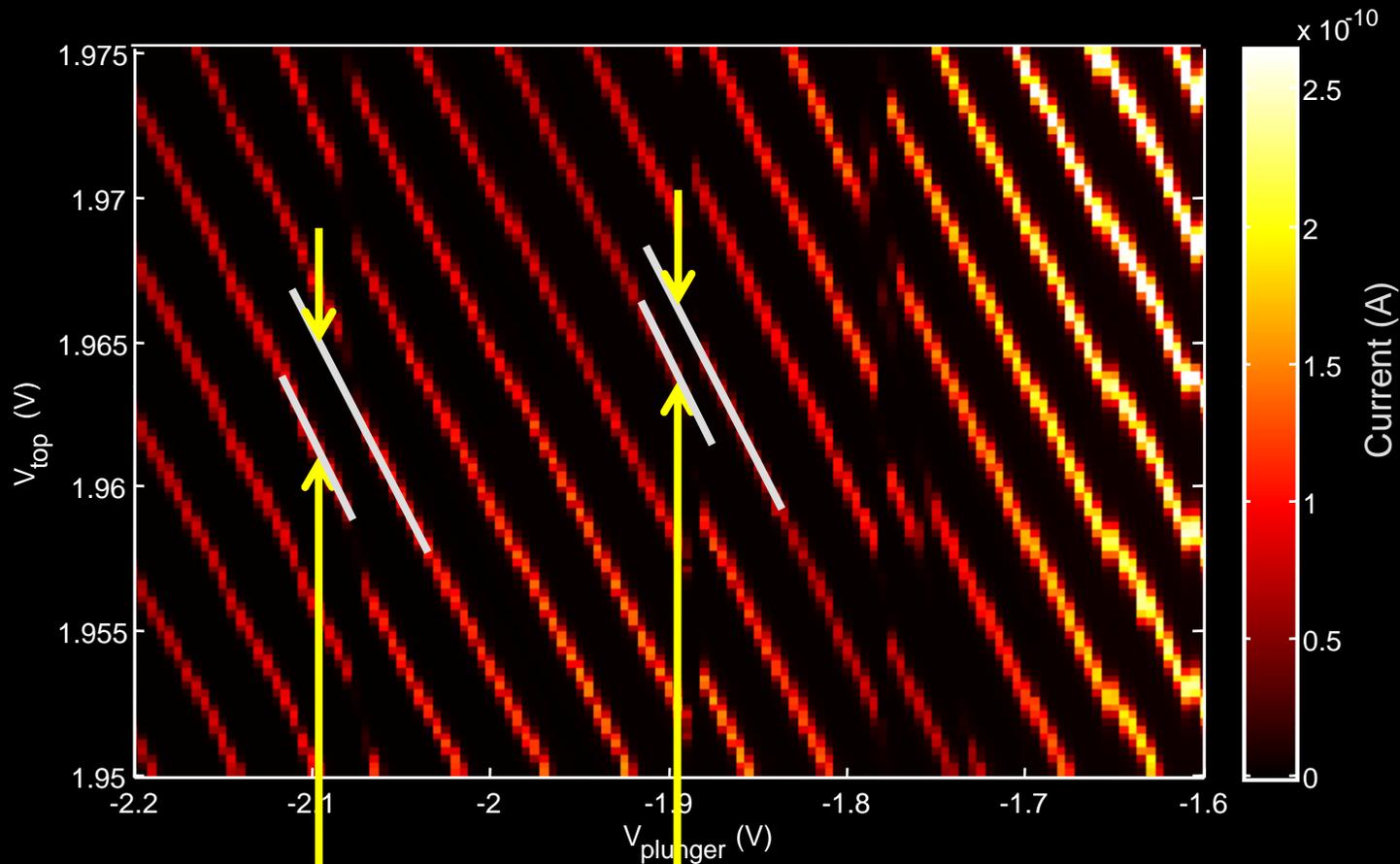
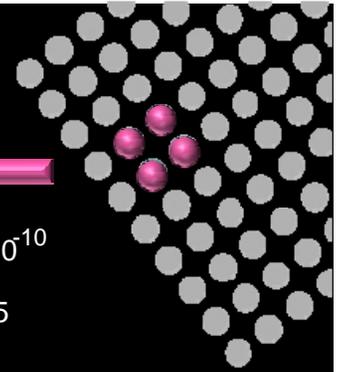
No current \Rightarrow no back-action before projective measurement

Charge transfer: modelling



Typical coupling $\sim 0.2 - 0.6 e$

Charge transfer: experiment



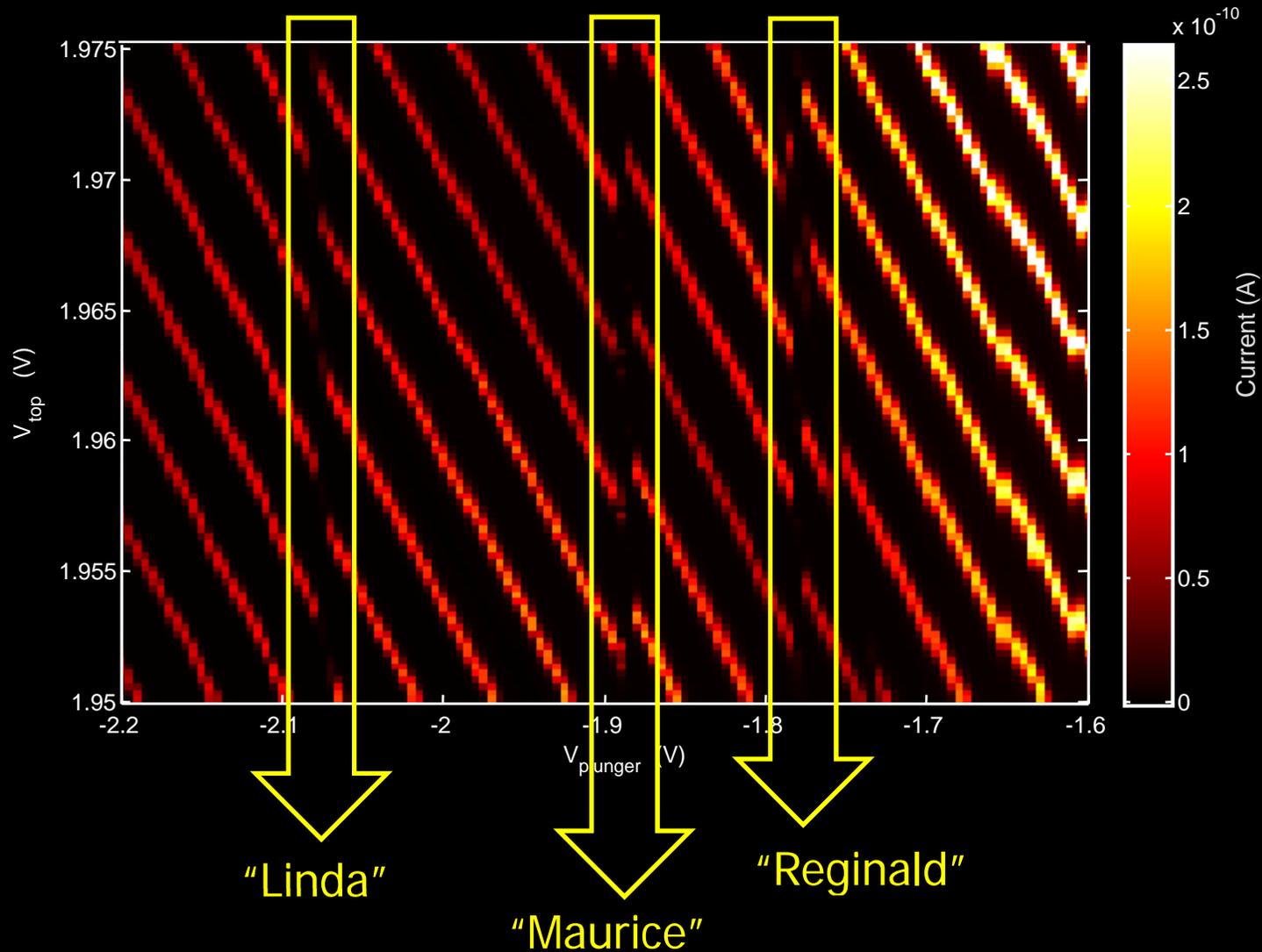
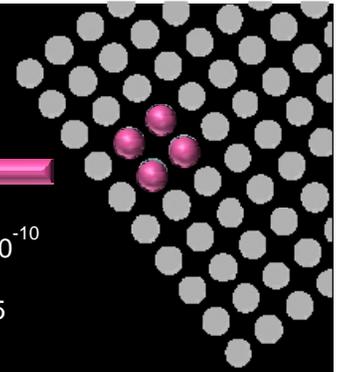
$$\Delta q / e \approx 0.7$$

Donor very close to SET
Fast tunnel rate $\approx 10 \mu\text{s}$

$$\Delta q / e \approx 0.3$$

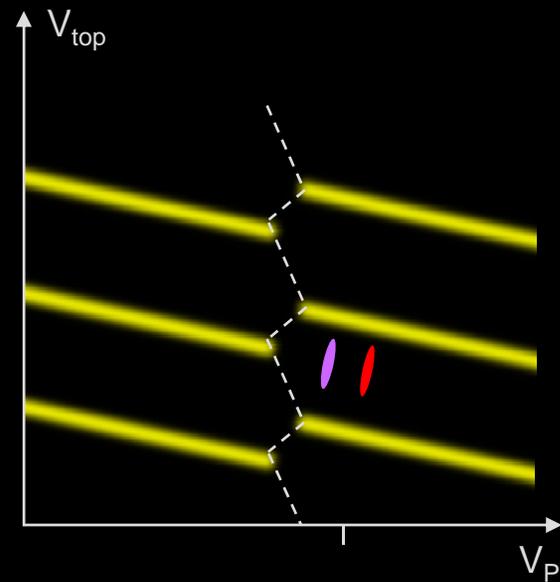
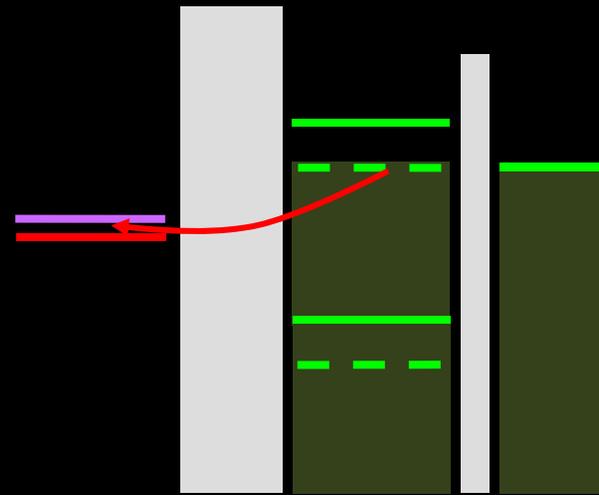
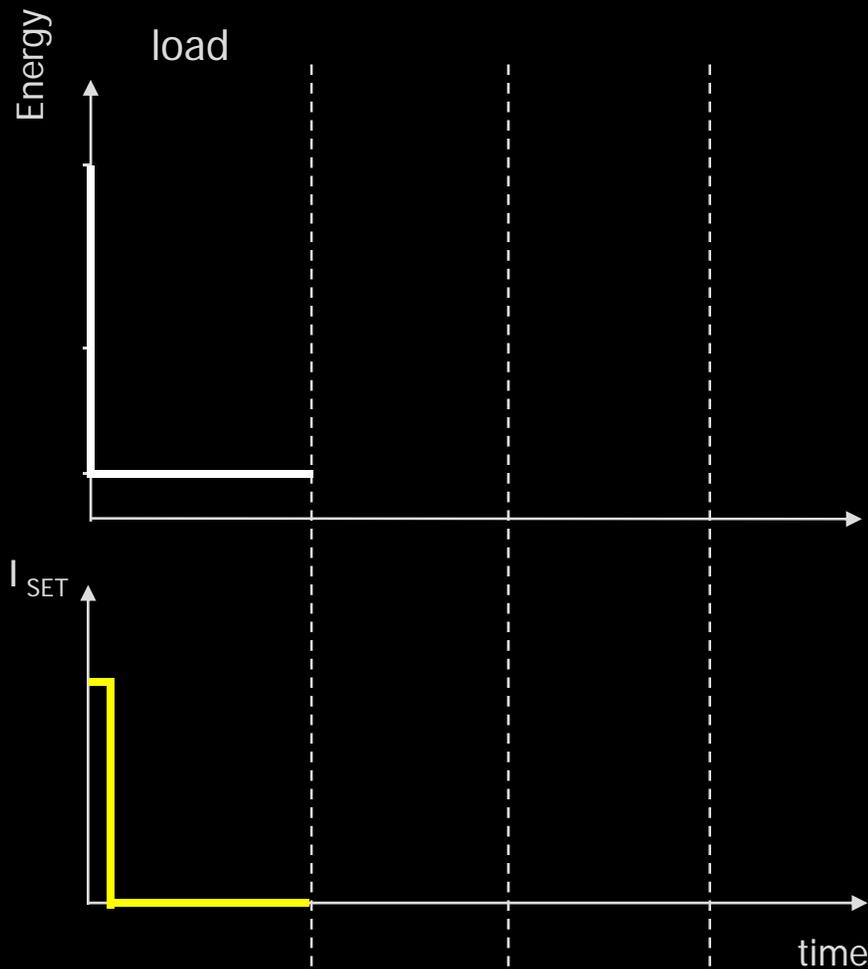
Donor far from SET
Slow tunnel rate $\approx 100 \text{ms}$

Charge transfer: experiment

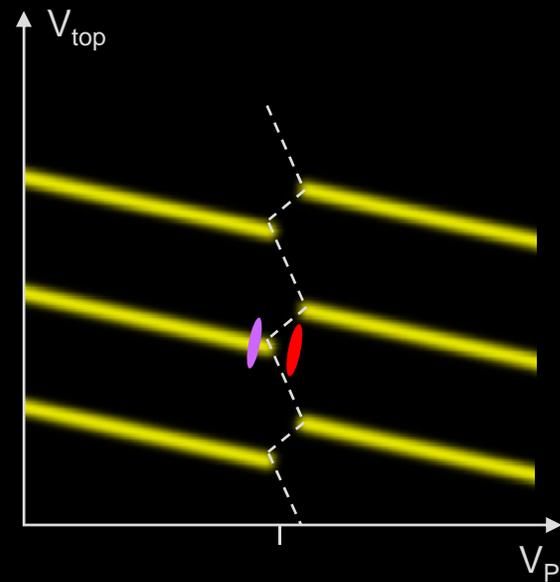
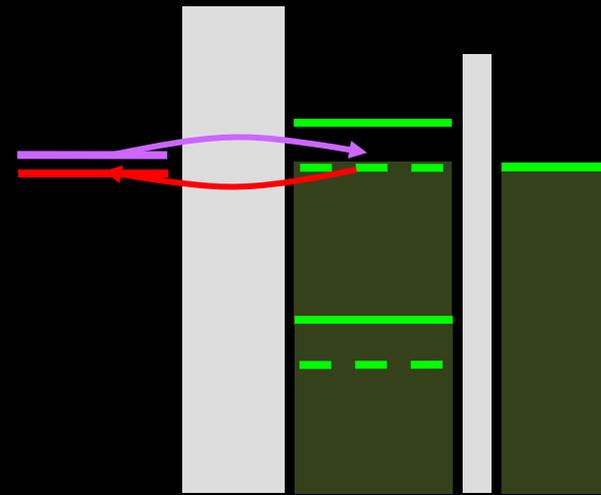
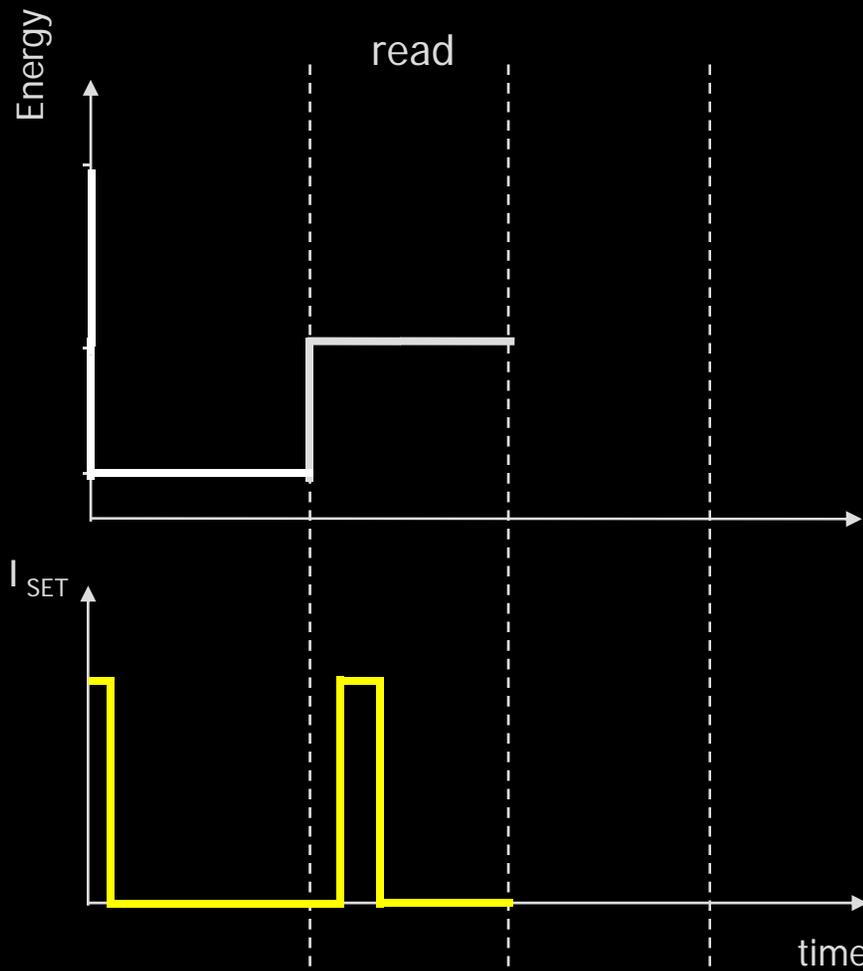


Reproducible and recognizable donor charge transfer events

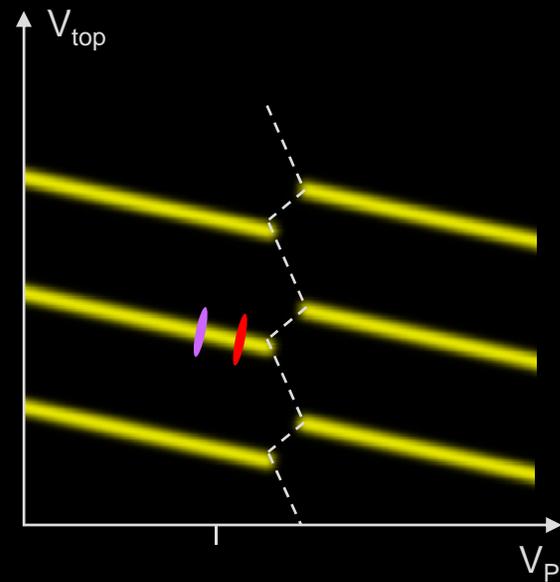
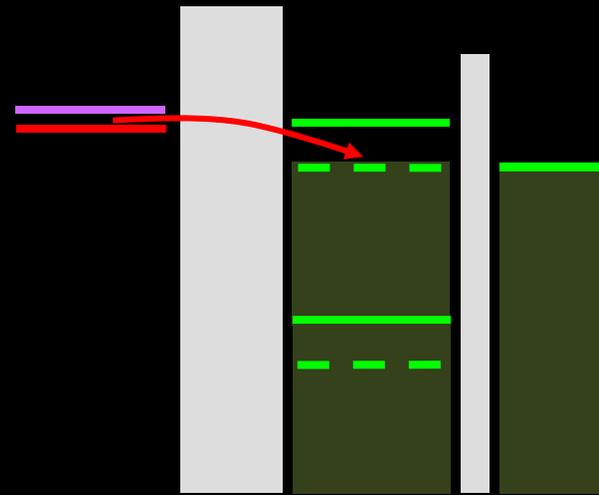
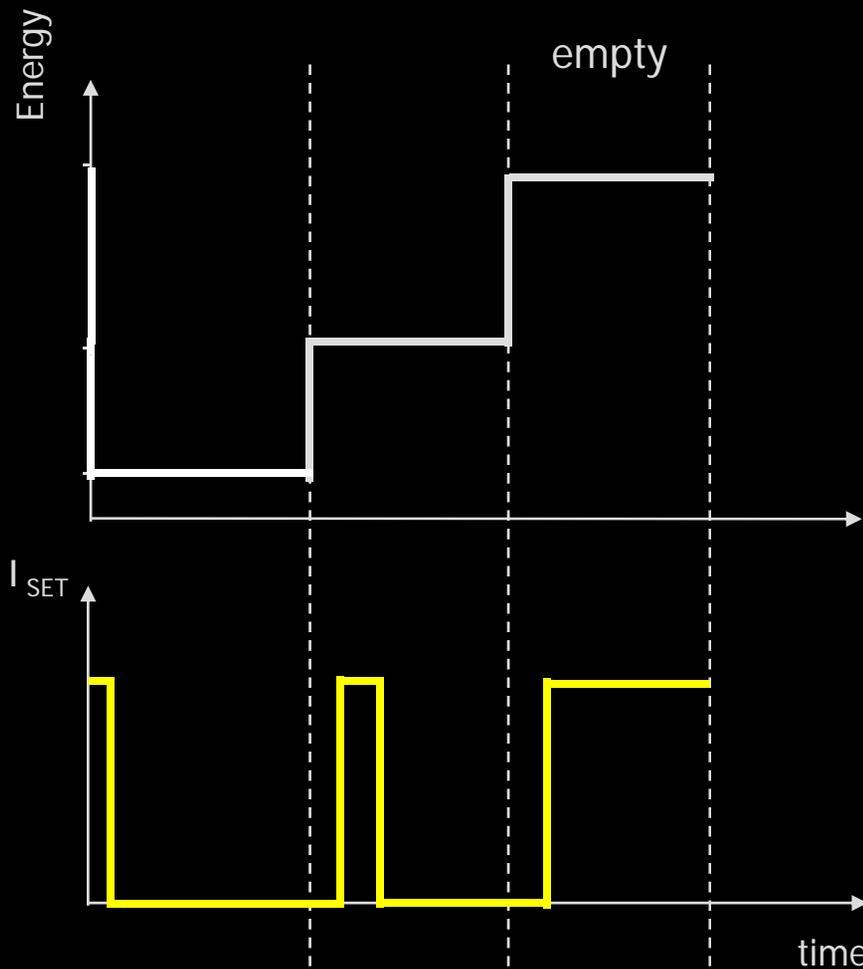
Spin readout protocol



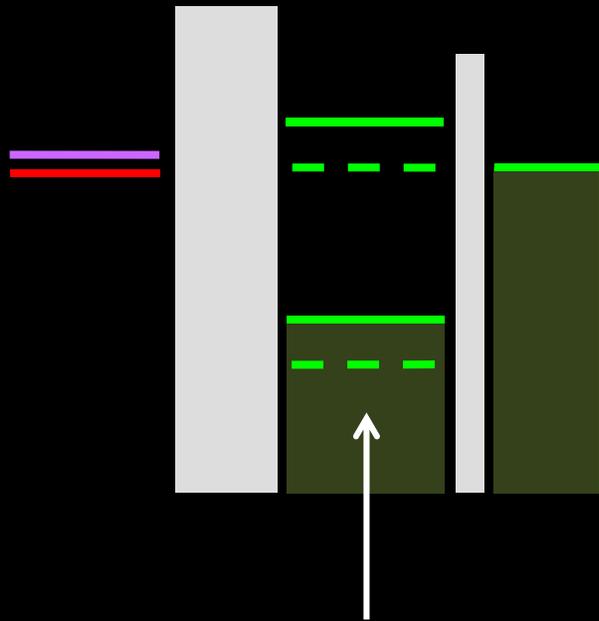
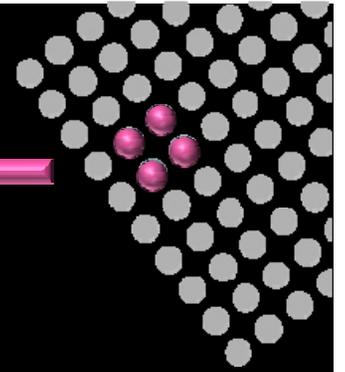
Spin readout protocol



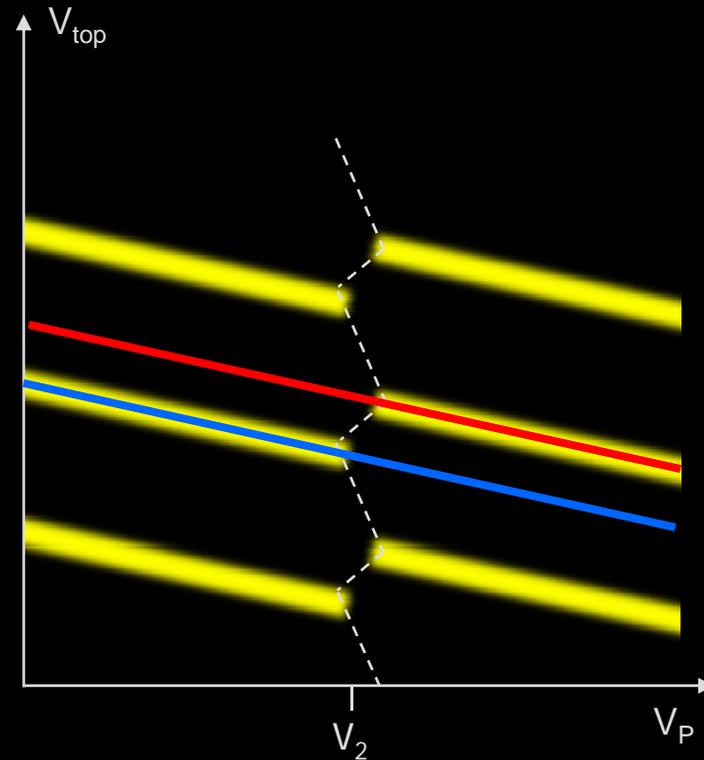
Spin readout protocol



Compensated pulses



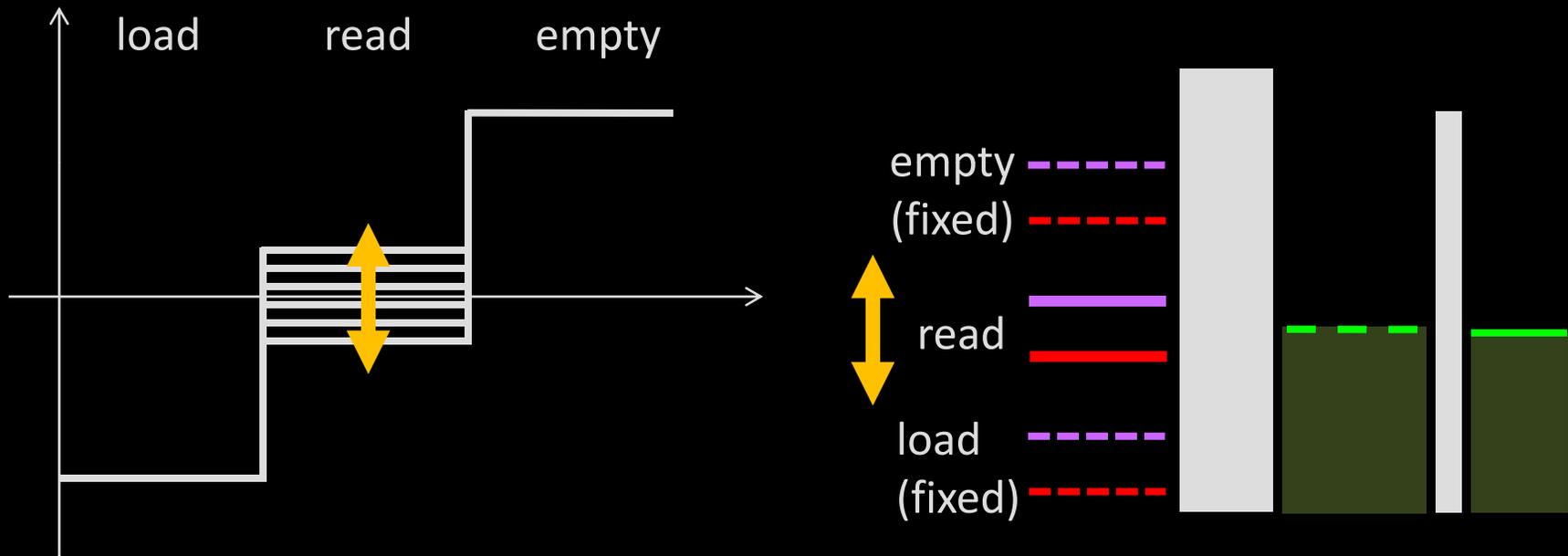
keep this ladder fixed
while pulsing the donor



compensate V_P with V_{top}

On the red line, there is current through the SET while the electron
is on the donor → test detector back-action!

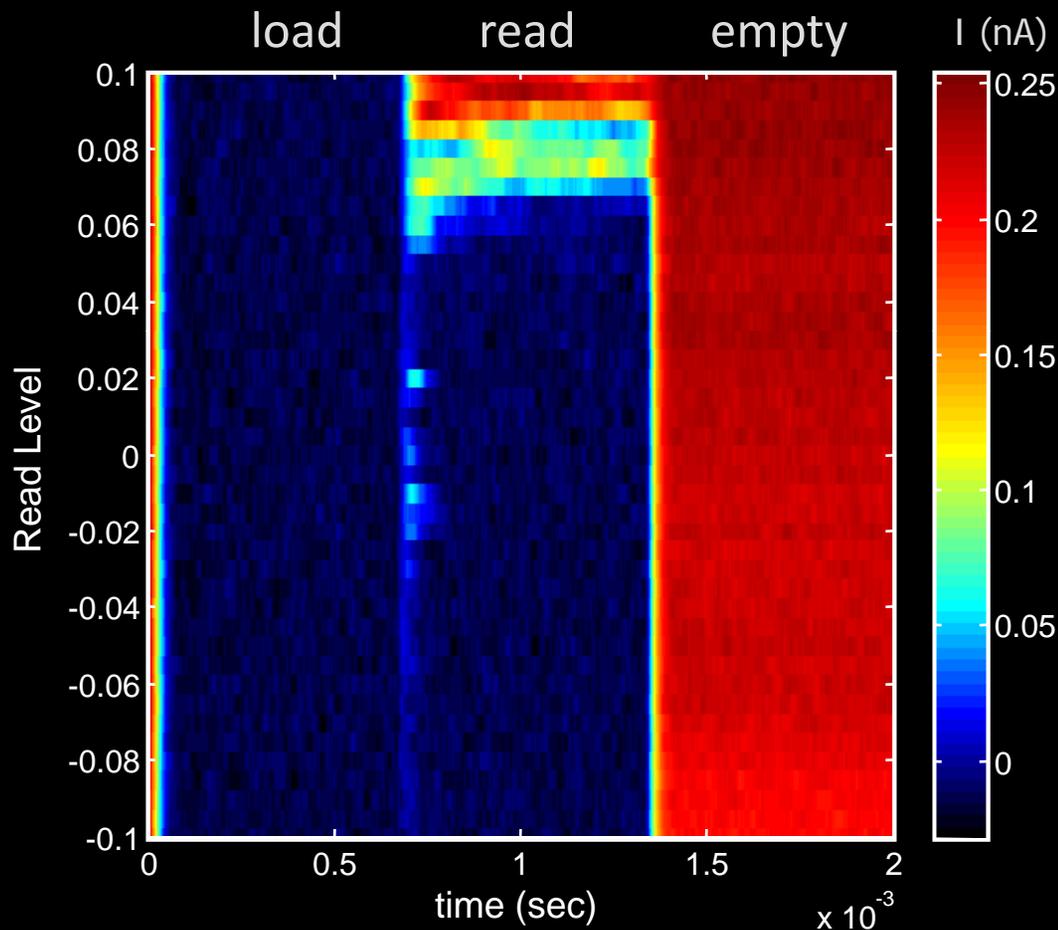
Finding the correct read level



"empty" and "load" levels kept fixed

"read" level varied

Averaged readout traces



Linda

$B = 5 \text{ T}$

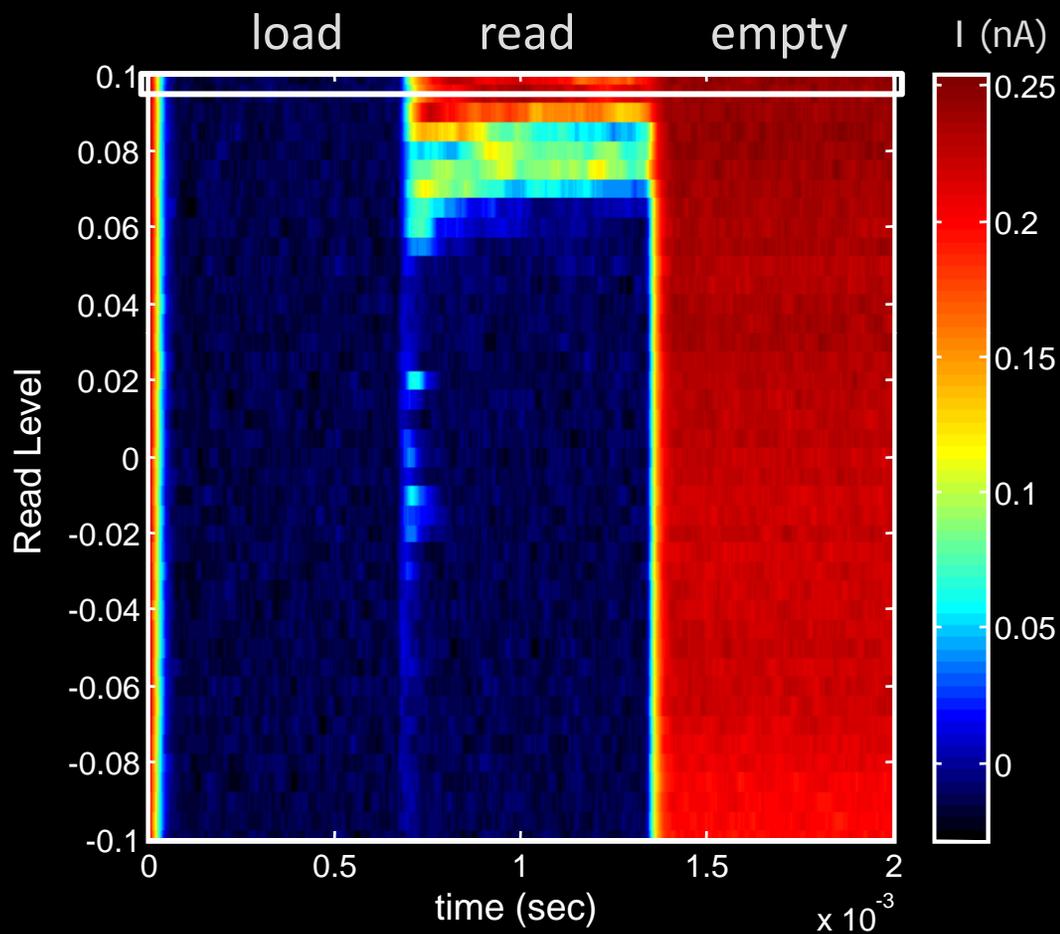
$T_{\text{el}} \approx 200 \text{ mK}$

$f = 500 \text{ Hz}$

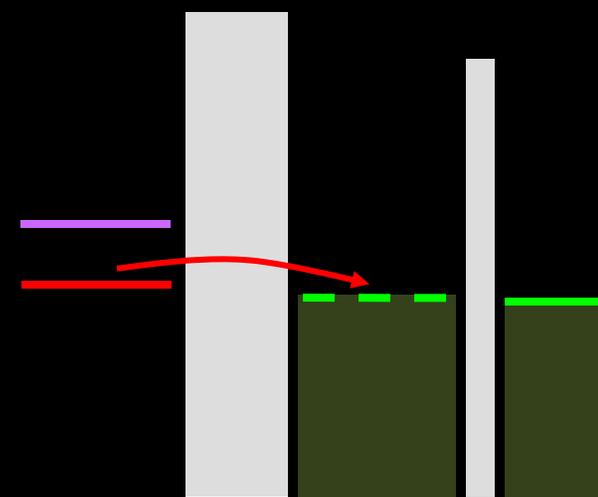
meas. BW = 10 kHz

32 averages, scanning the read pulse level

Read level too high

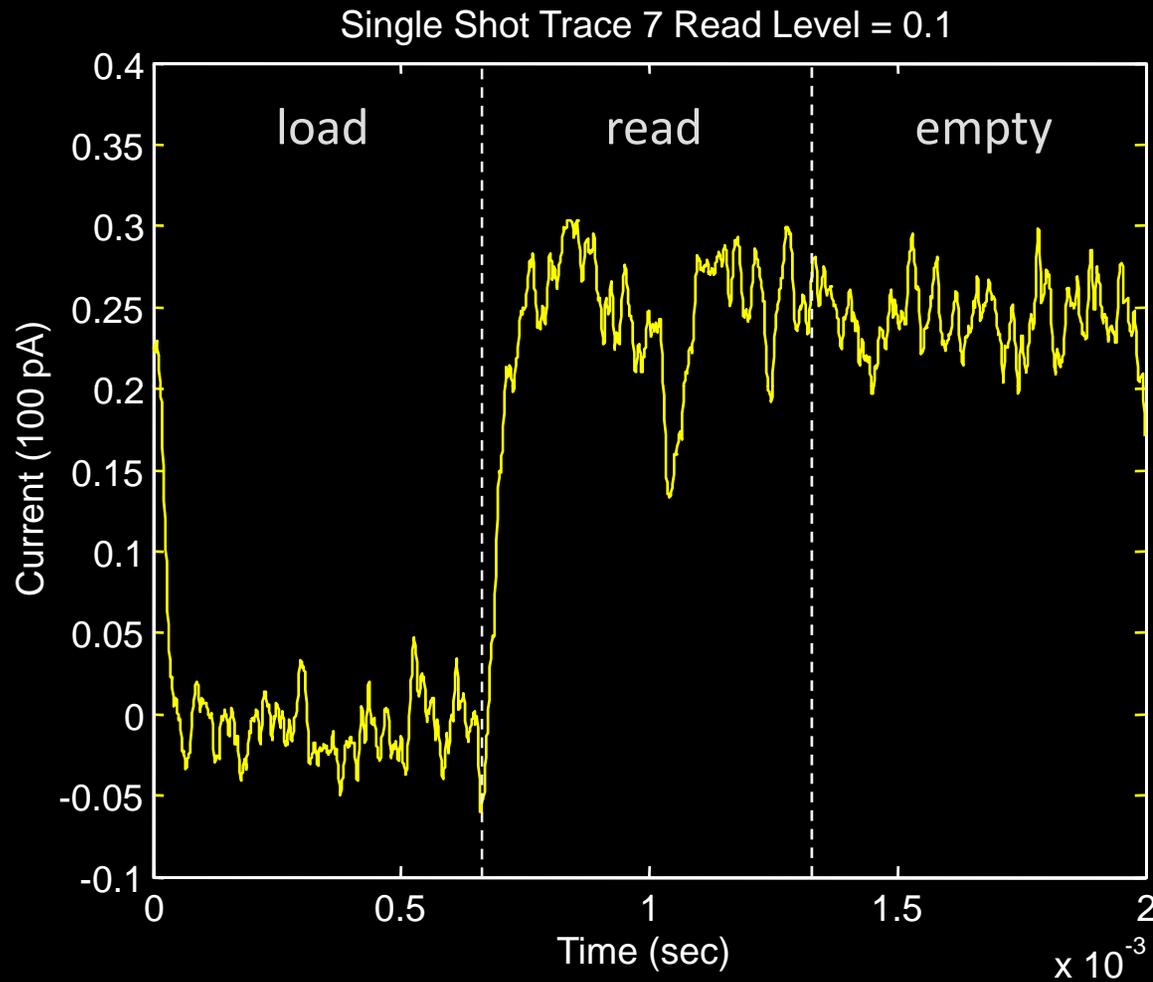
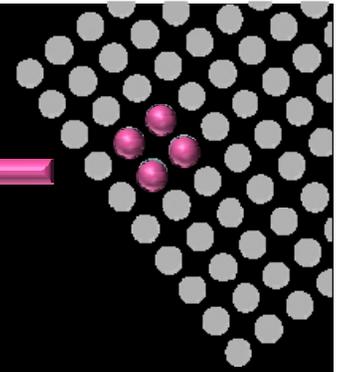


B = 5 T

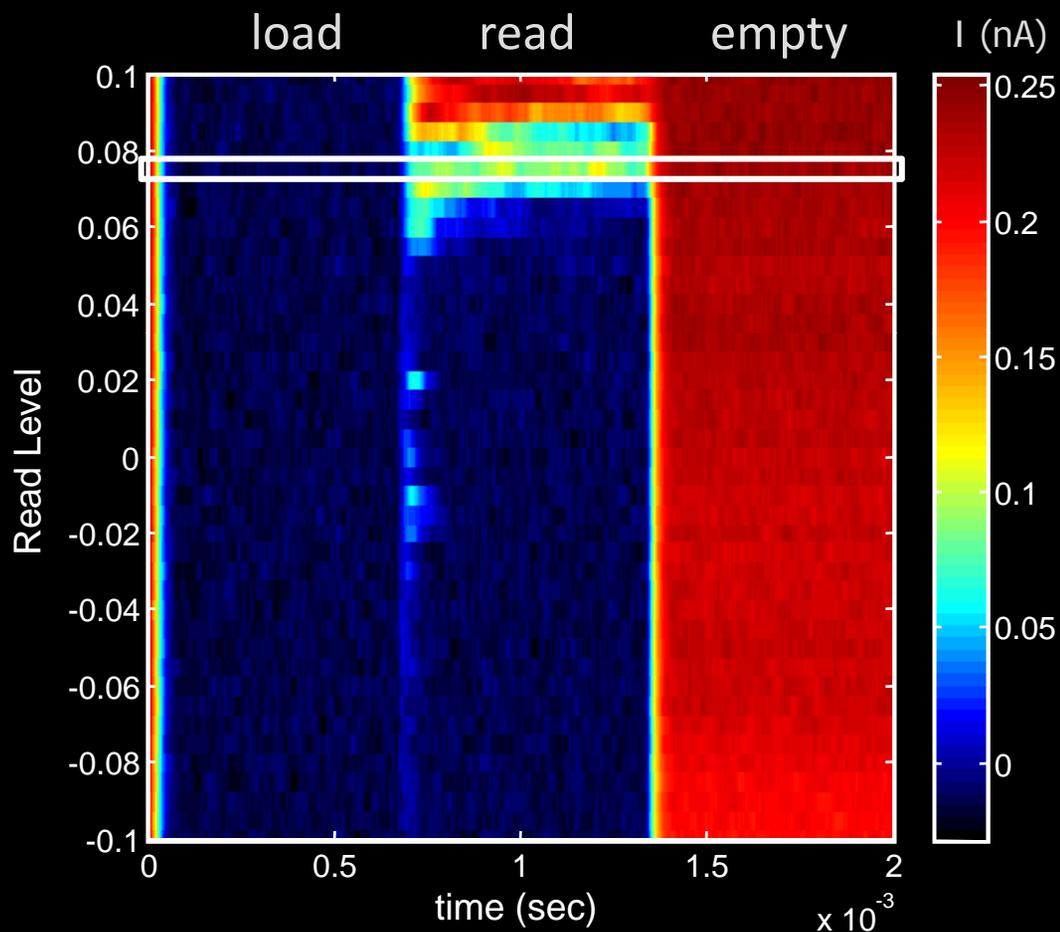


The electron mostly leaves the donor during the read pulse

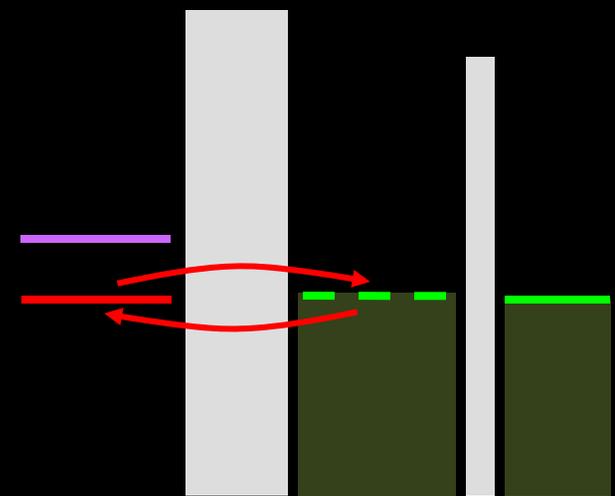
Read level too high



Ground state in resonance

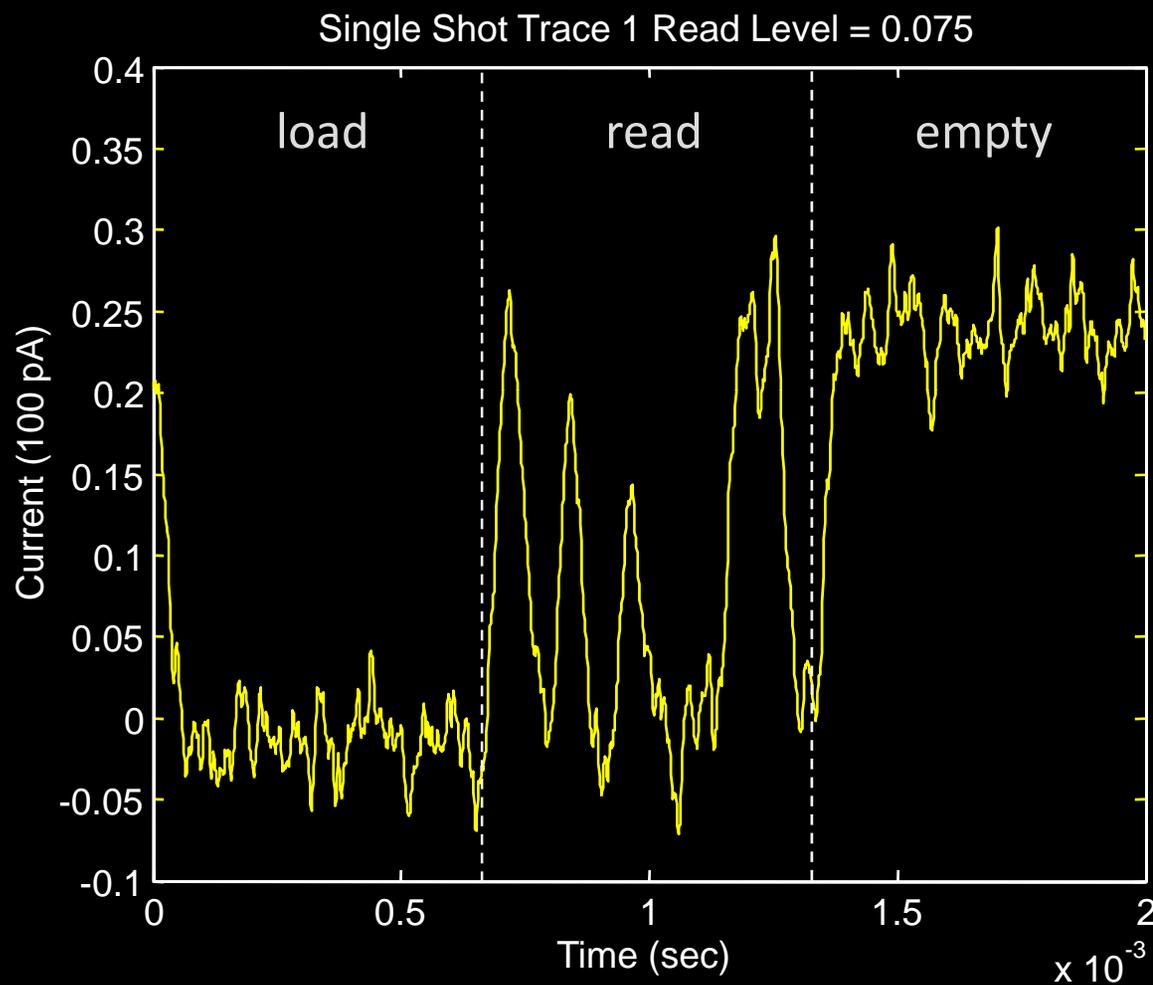
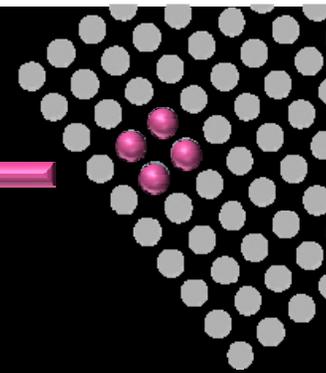


$B = 5 \text{ T}$



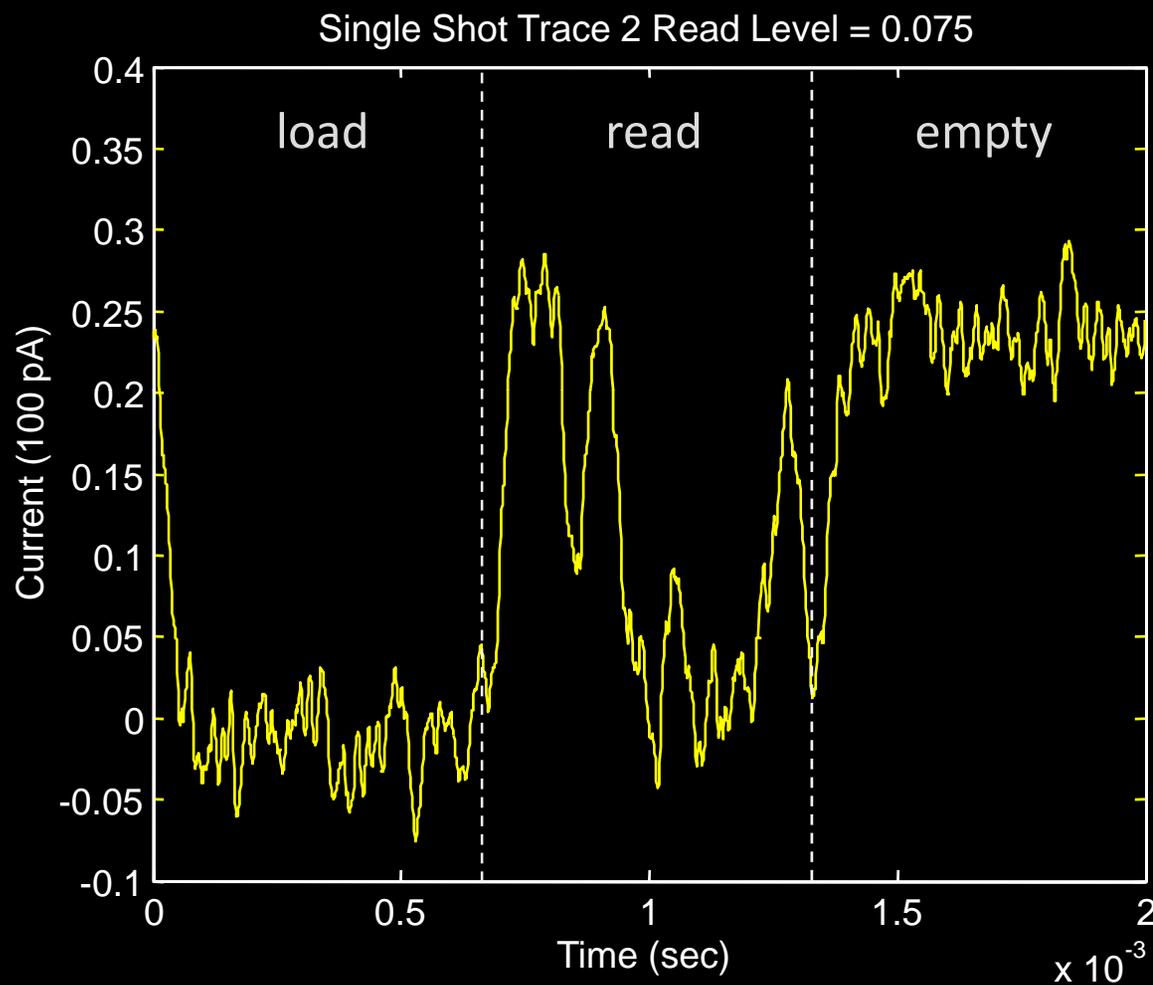
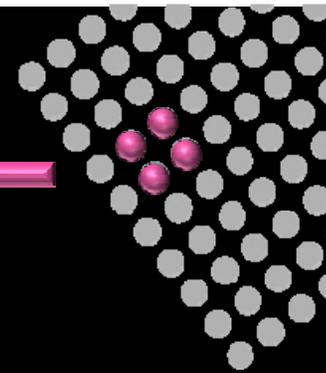
The electron switches randomly on and off the spin-down state

Ground state in resonance



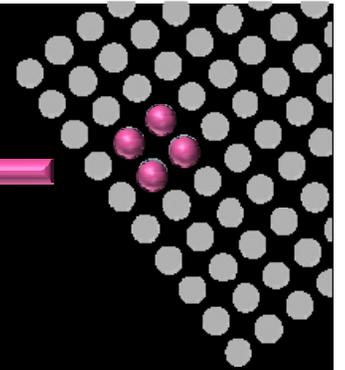
random telegraph signal

Ground state in resonance



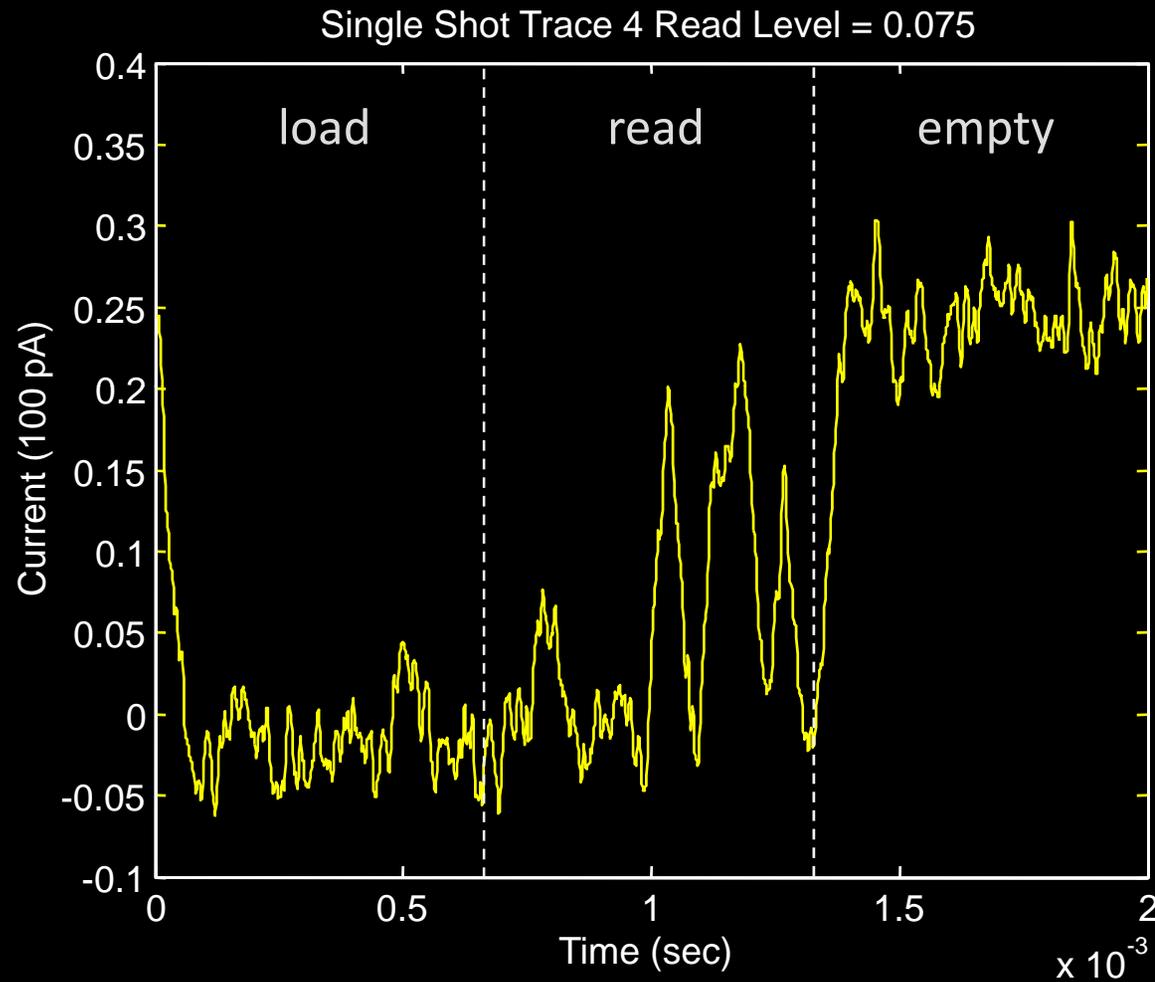
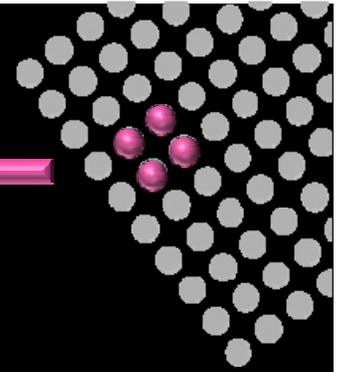
random telegraph signal

Ground state in resonance



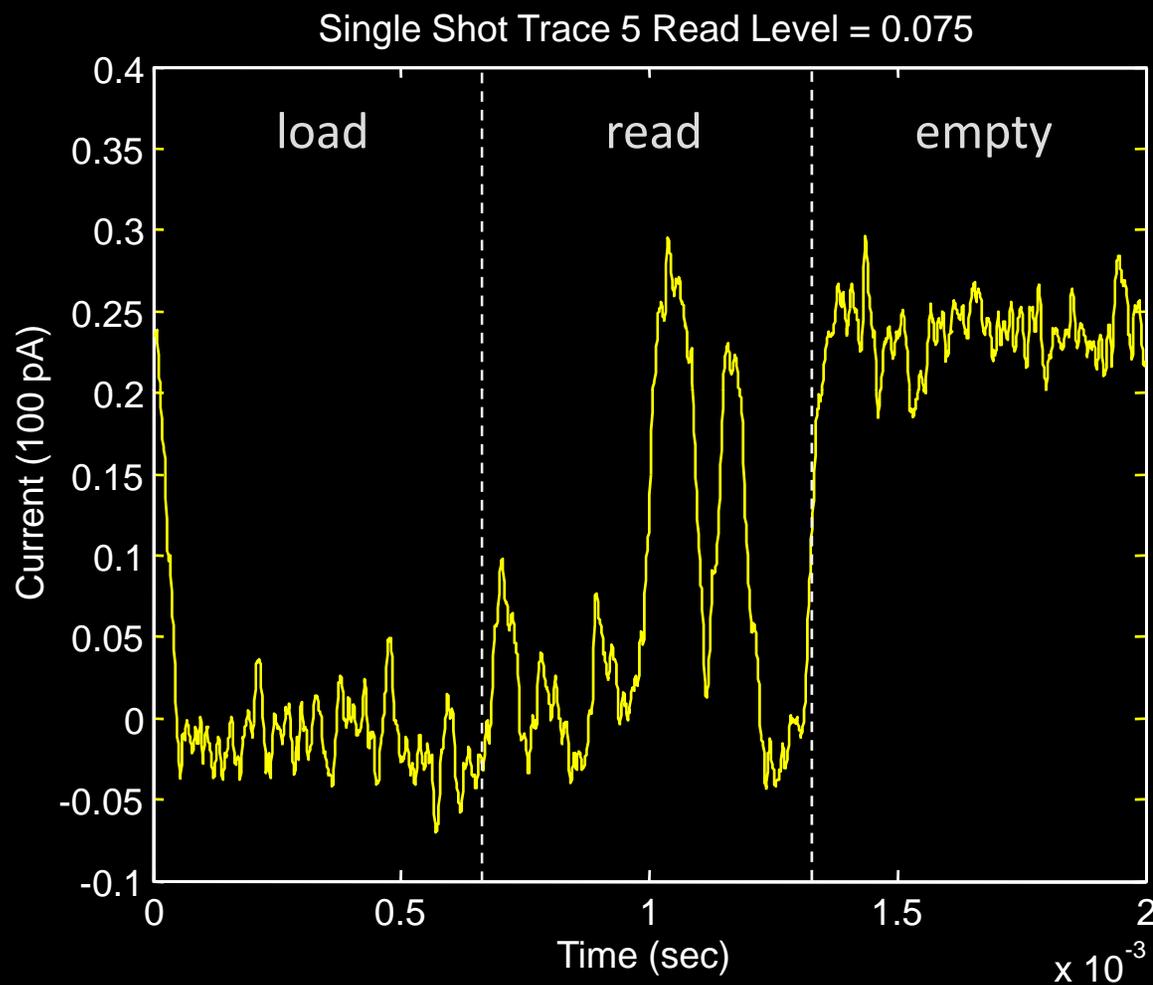
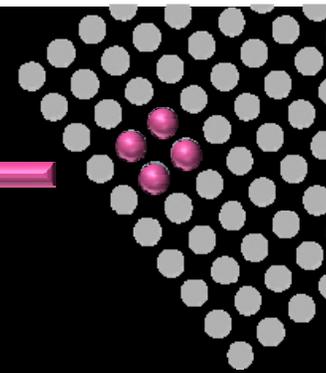
random telegraph signal

Ground state in resonance



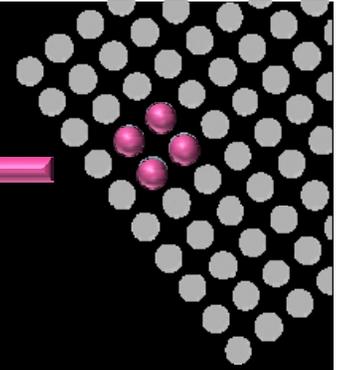
random telegraph signal

Ground state in resonance



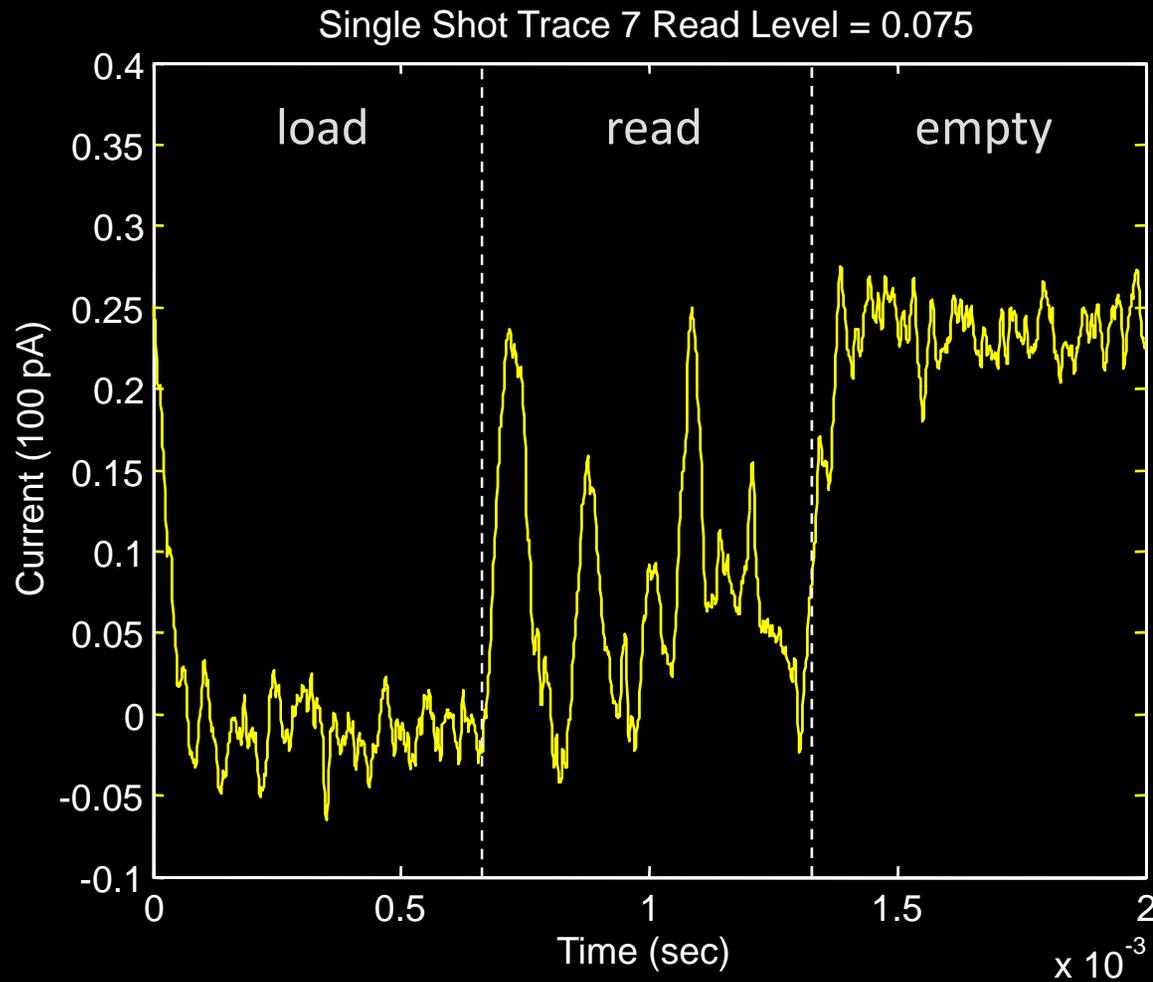
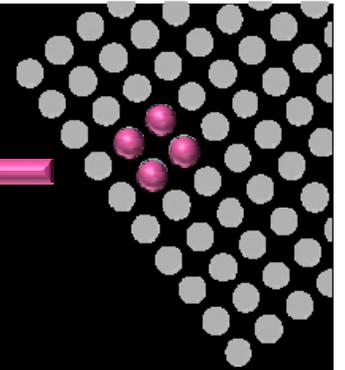
random telegraph signal

Ground state in resonance



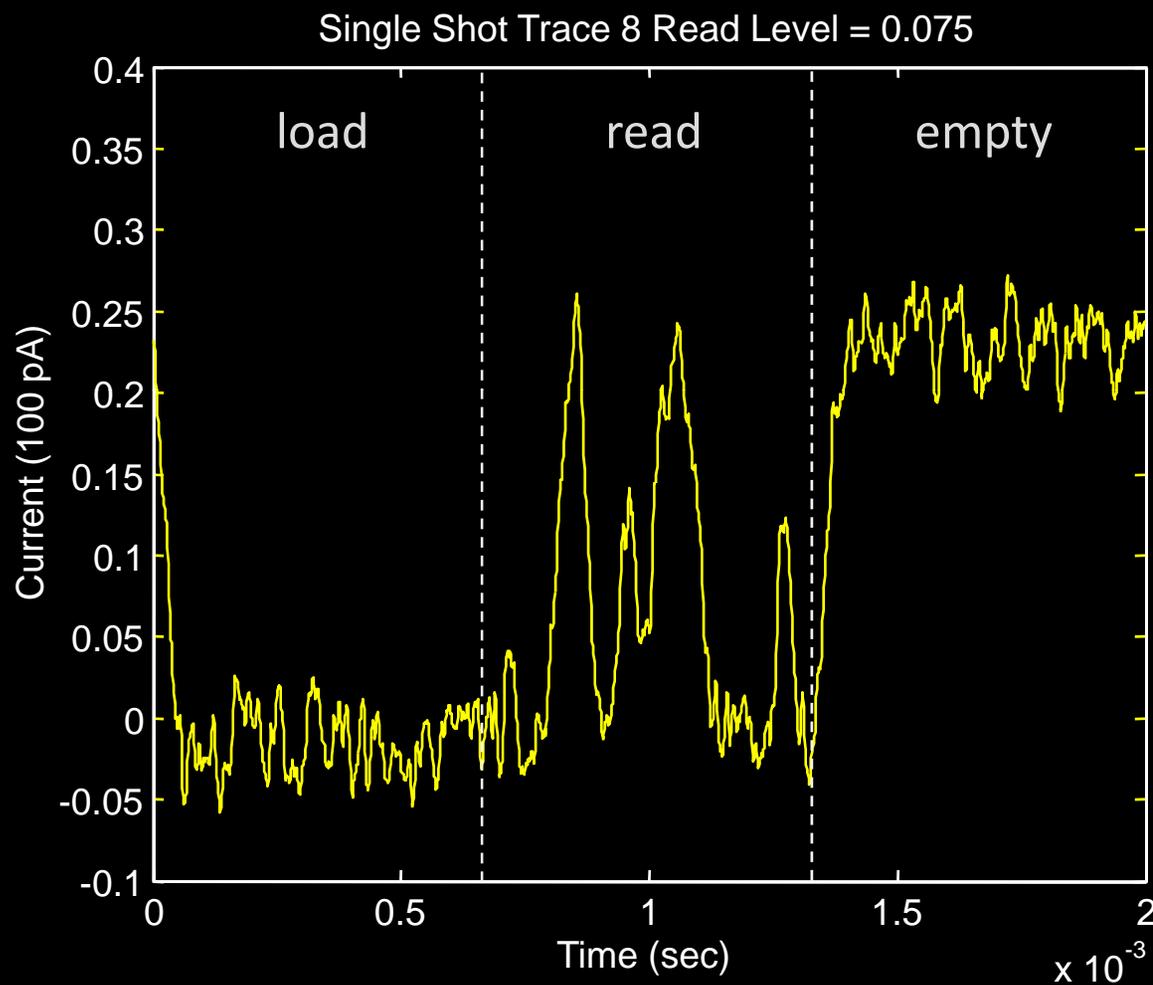
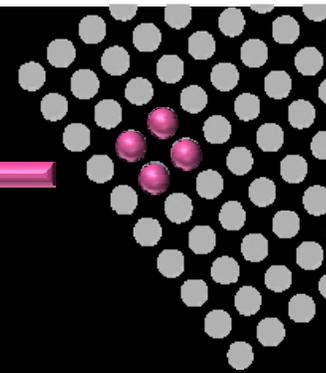
random telegraph signal

Ground state in resonance



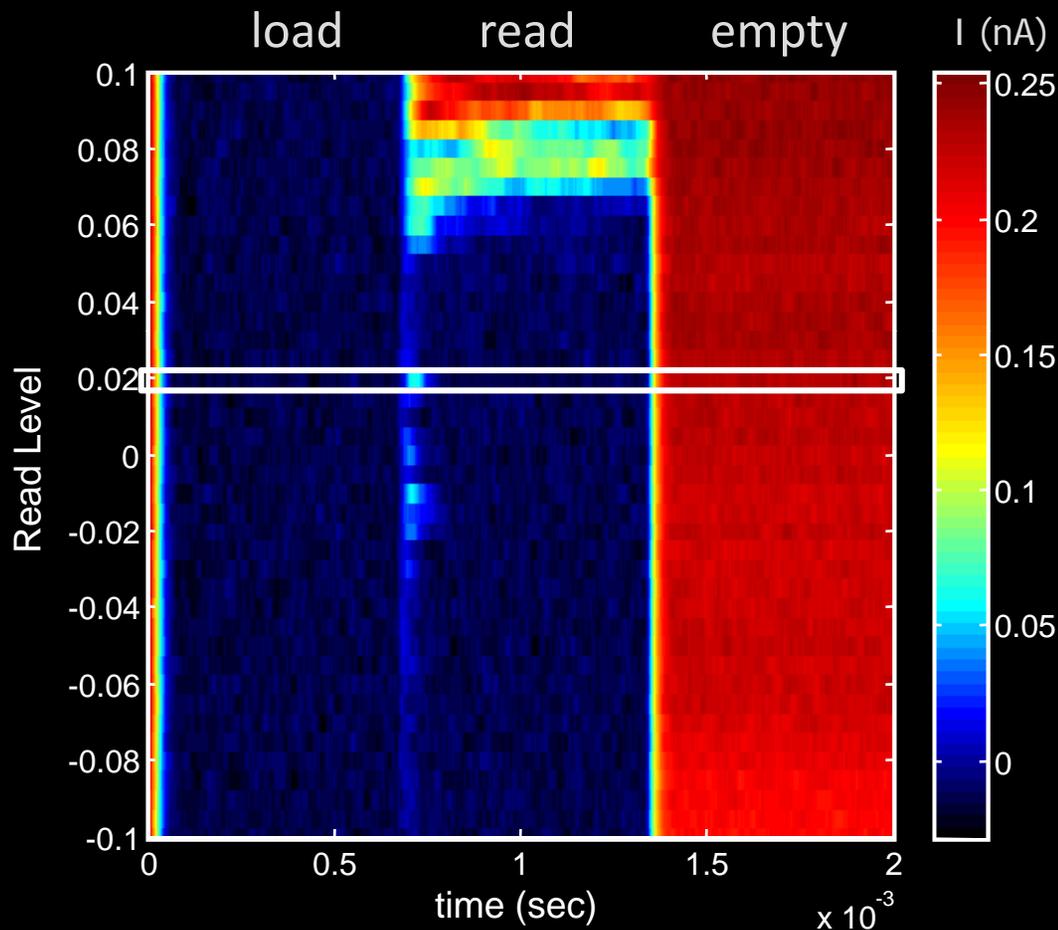
random telegraph signal

Ground state in resonance

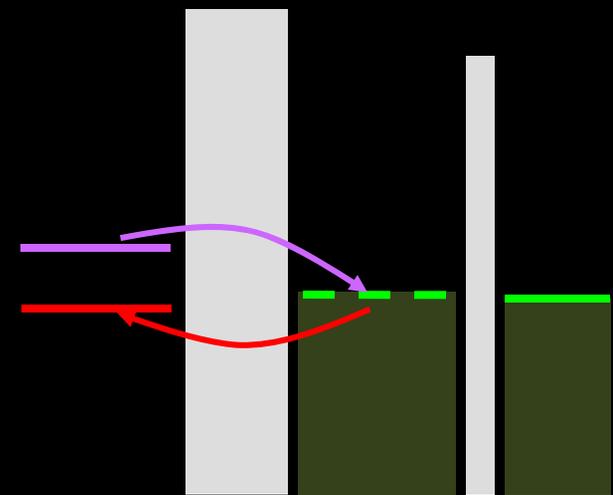


random telegraph signal

Correct read level

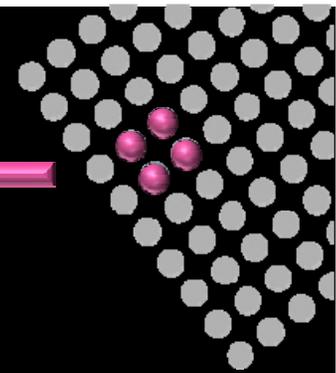


$B = 5 \text{ T}$

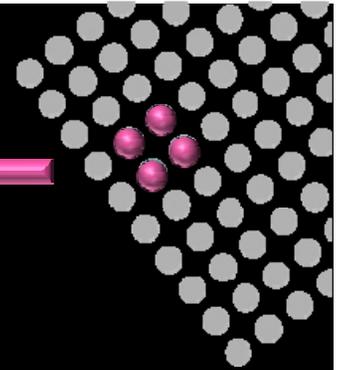


The averaged traces show a prominent occurrence of high current at the start of the read pulse

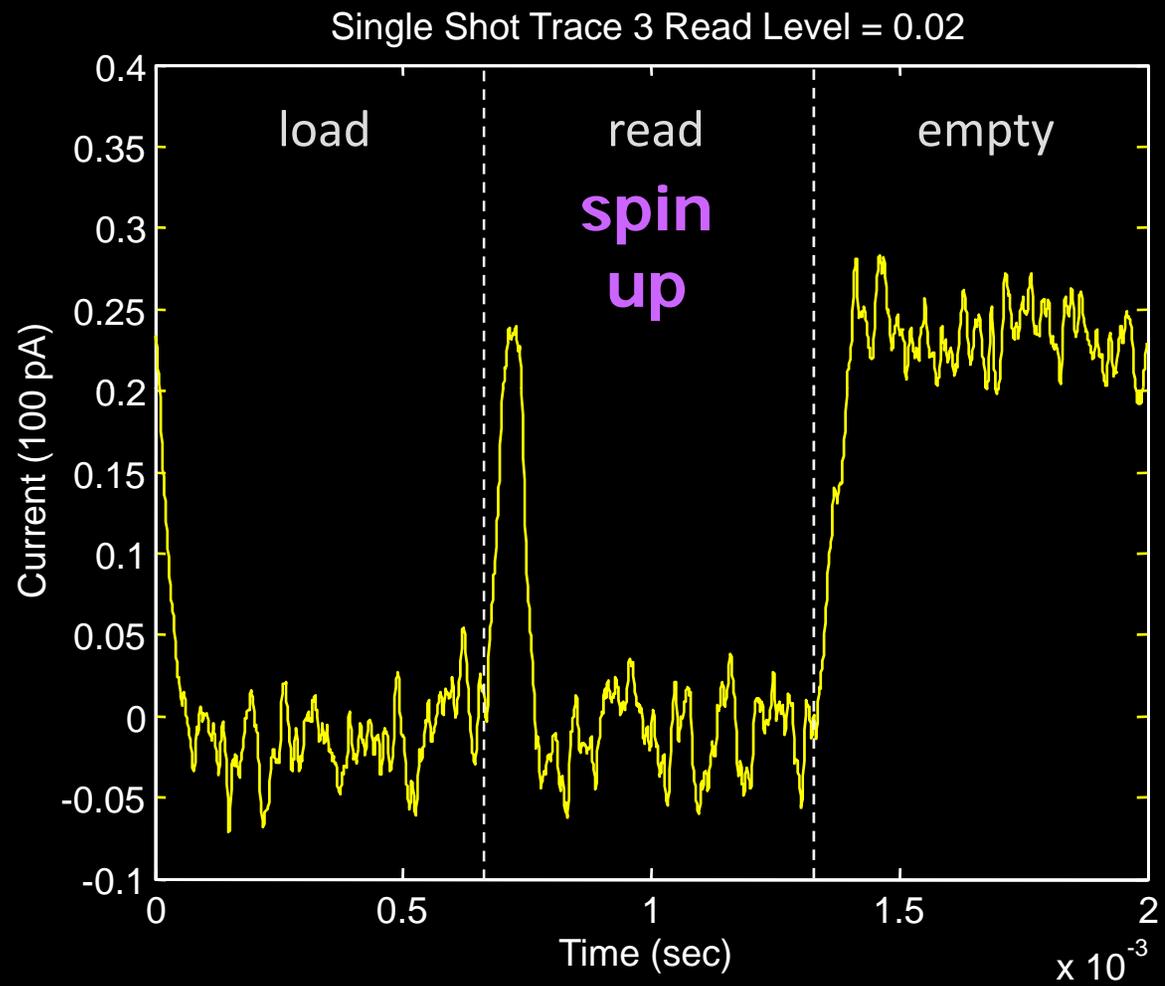
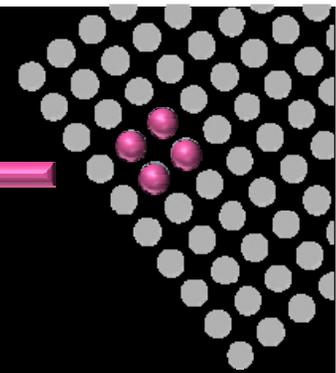
Correct read level



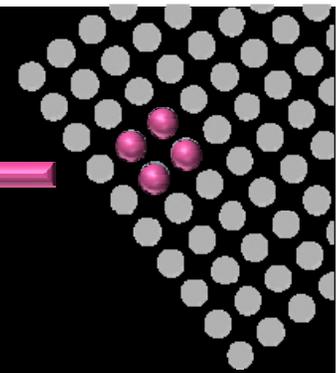
Correct read level



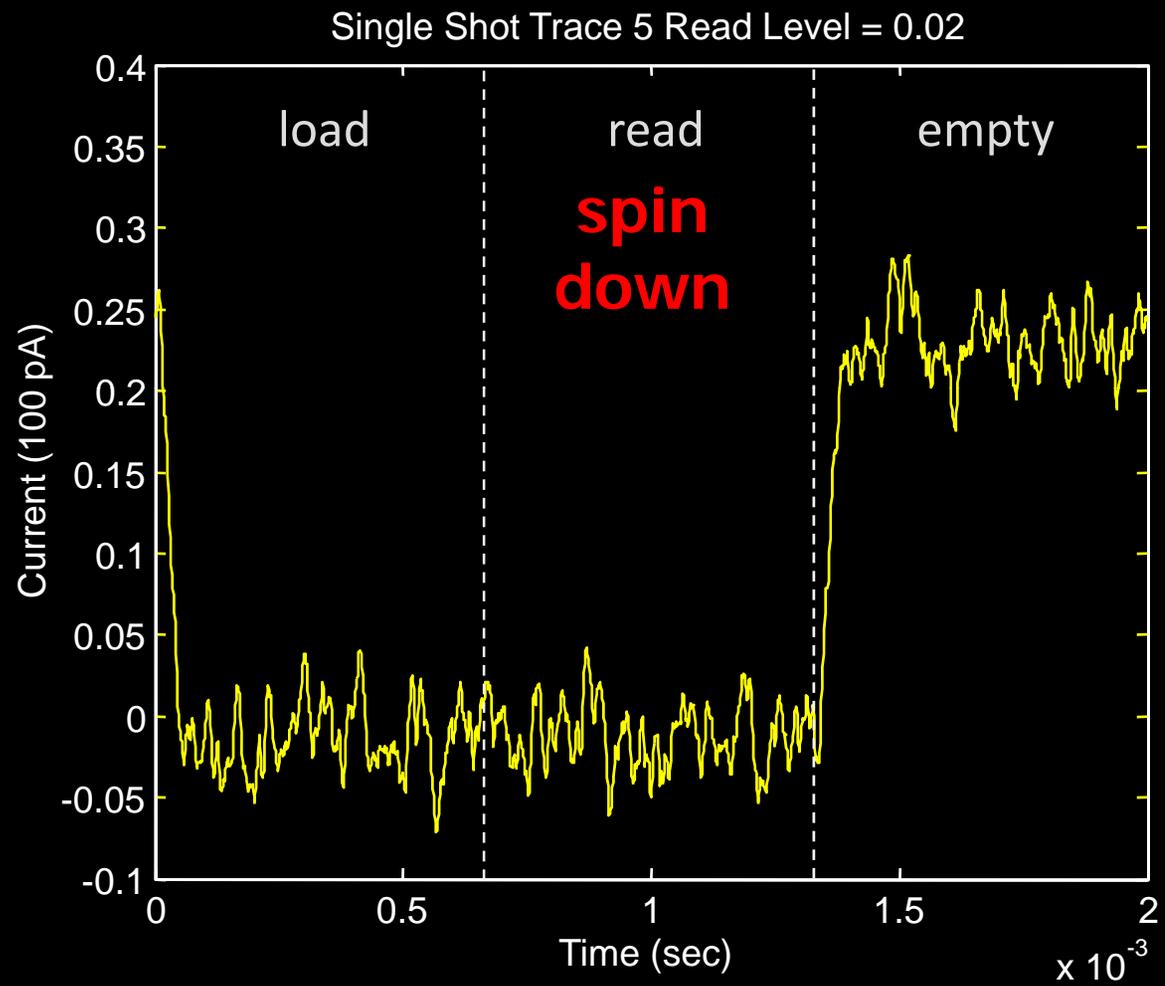
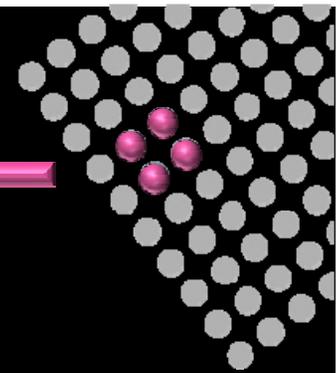
Correct read level



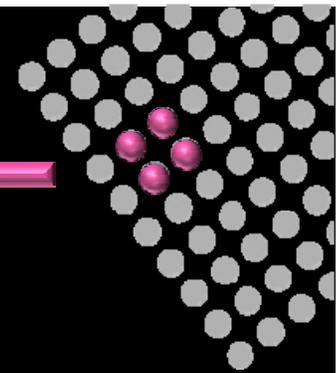
Correct read level



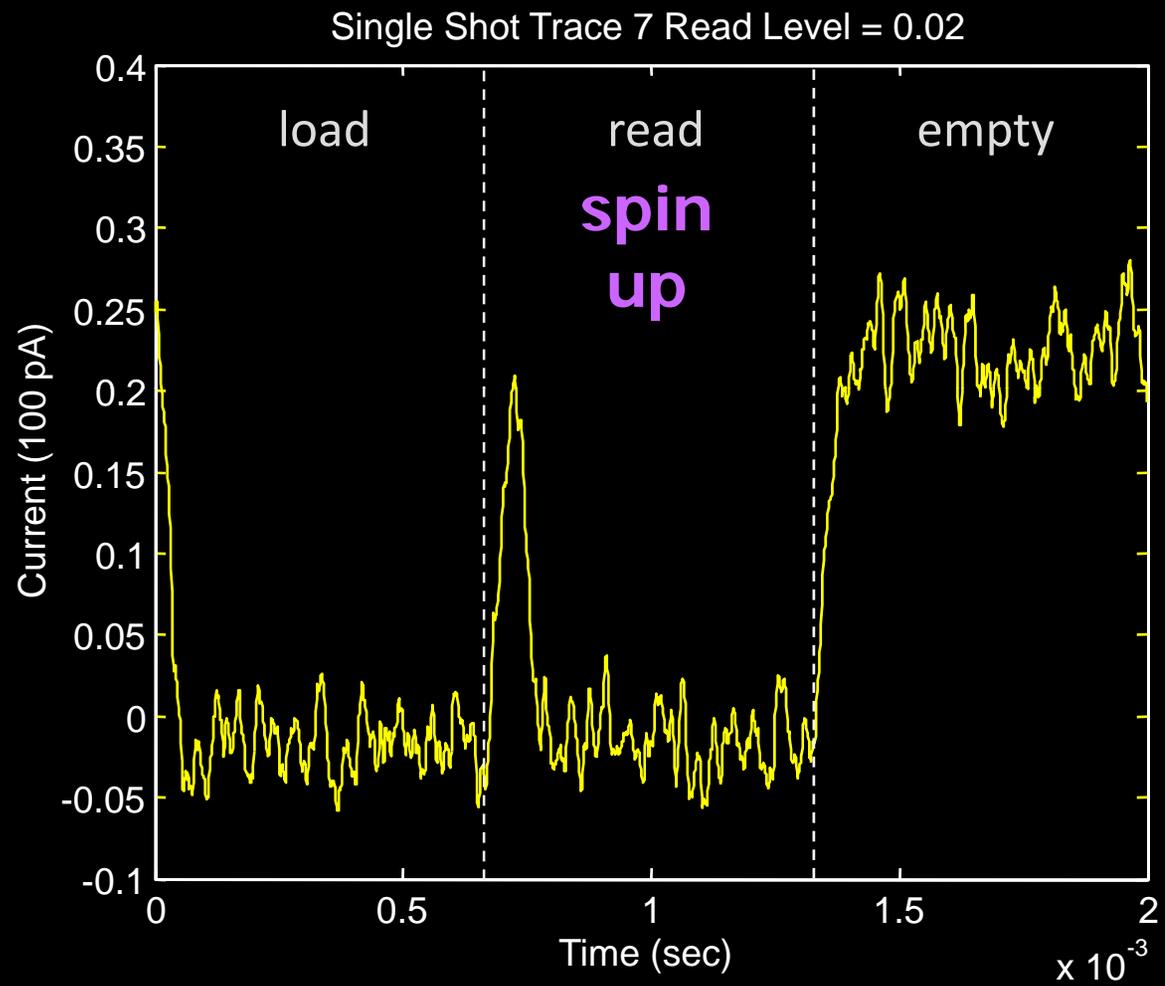
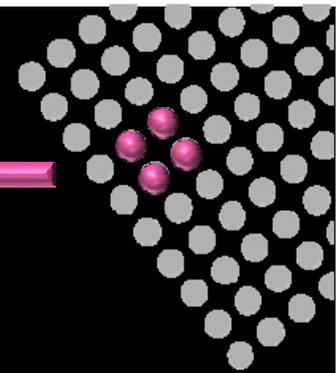
Correct read level



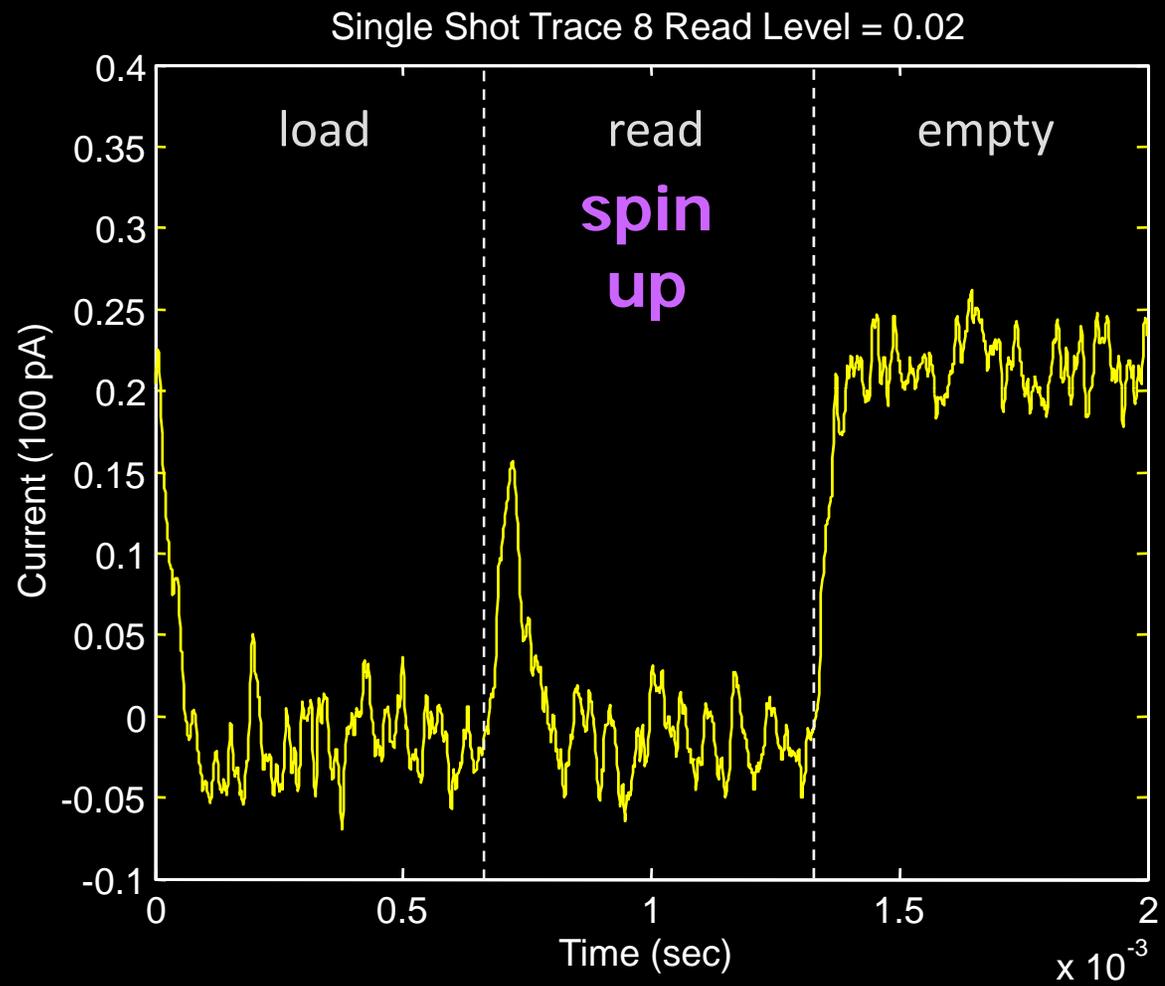
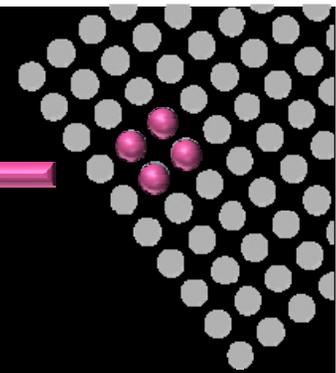
Correct read level



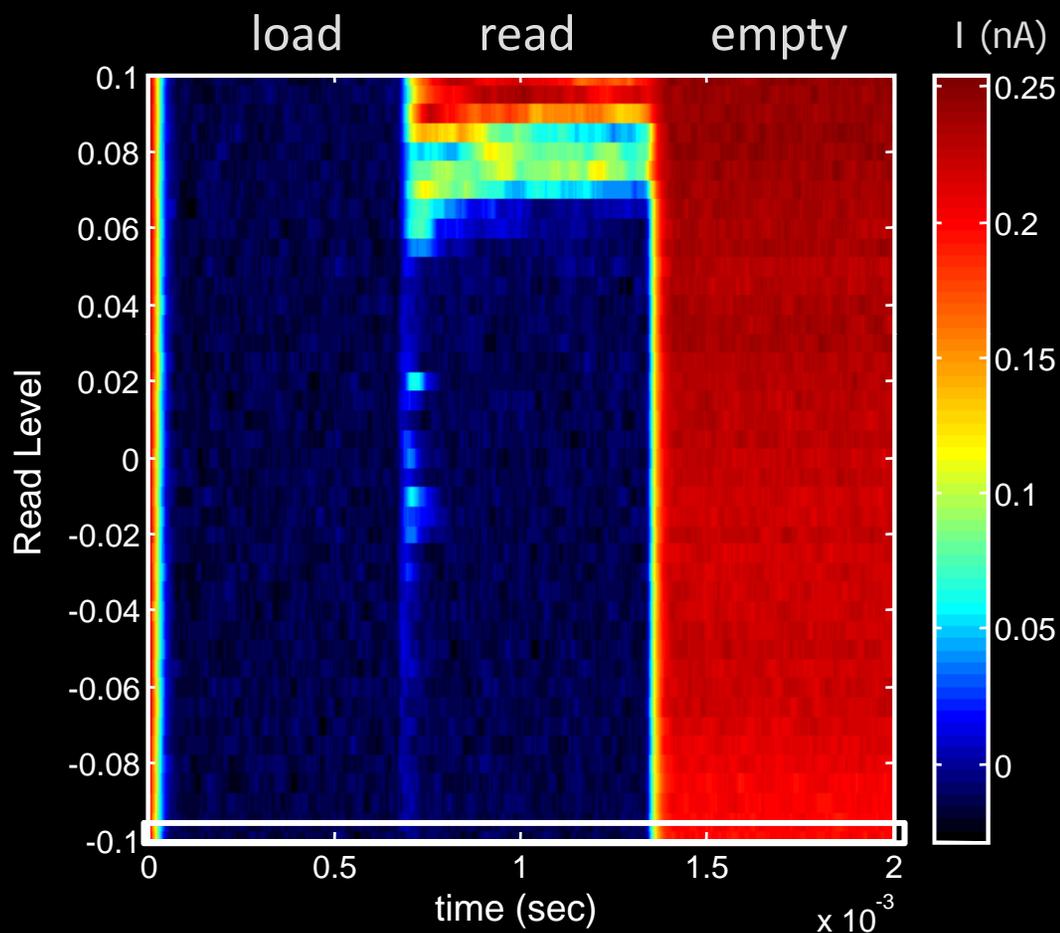
Correct read level



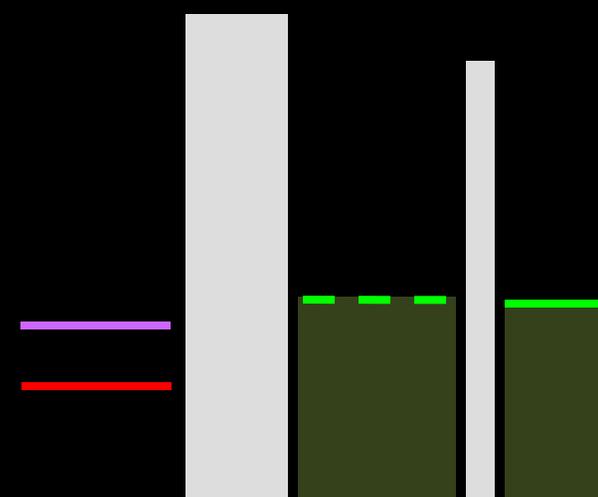
Correct read level



Read level too low

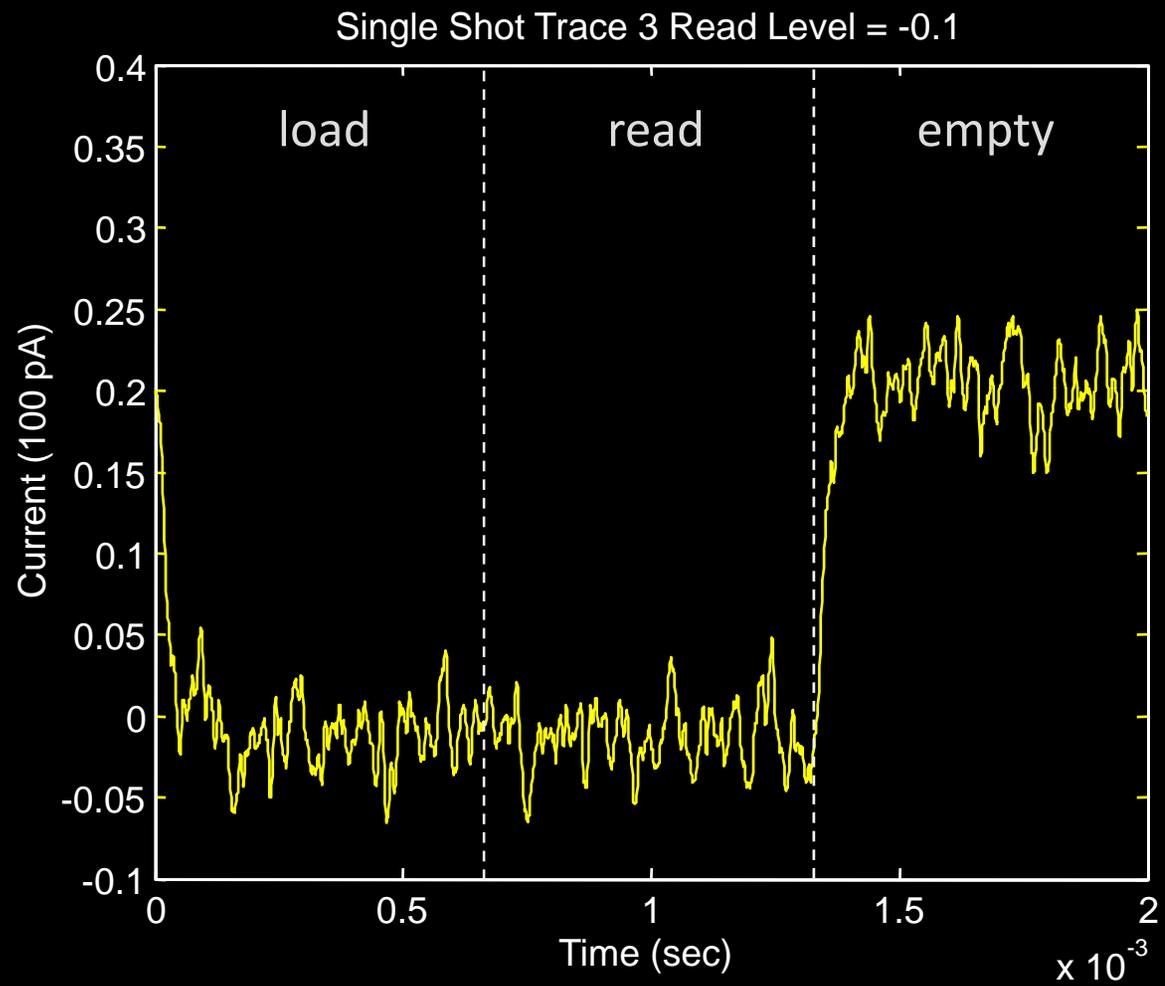
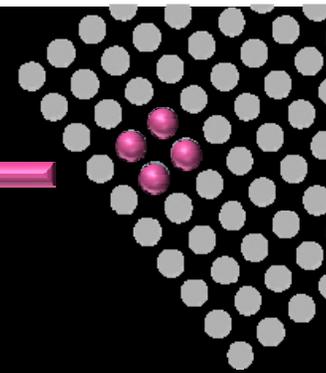


$B = 5 \text{ T}$

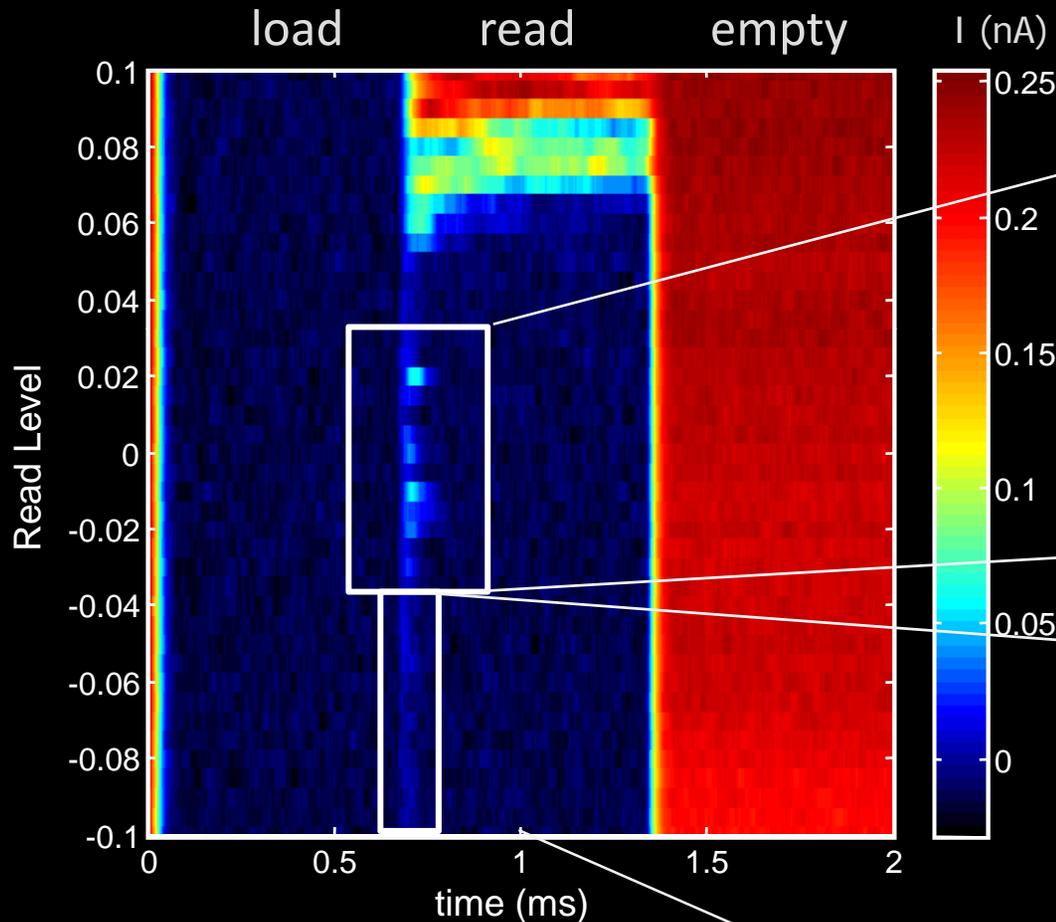
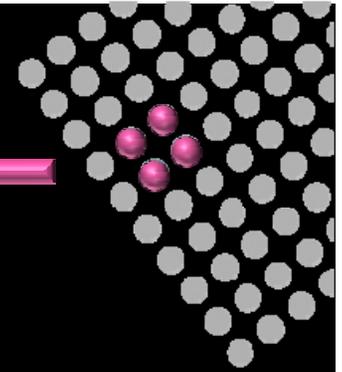


The electron never leaves the donor during the read pulse
no matter what the spin state is

Read level too low



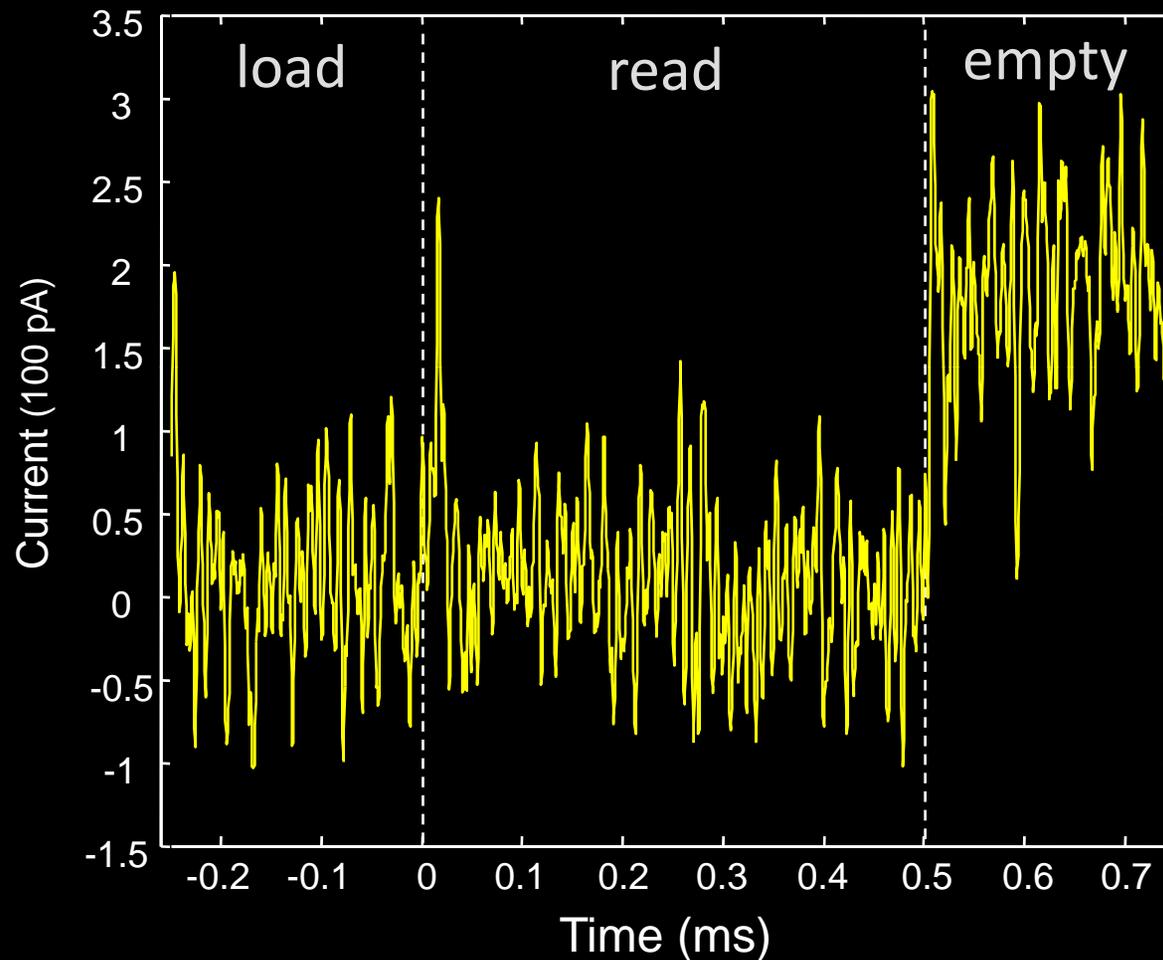
Interesting details



There is structure in the pattern of current peaks due to spin-up states
↓
discrete density of states in the SET?

Extra blip in the averaged signal due to induced charge by pulsing the top gate
↓
Too small to be visible in single-shot

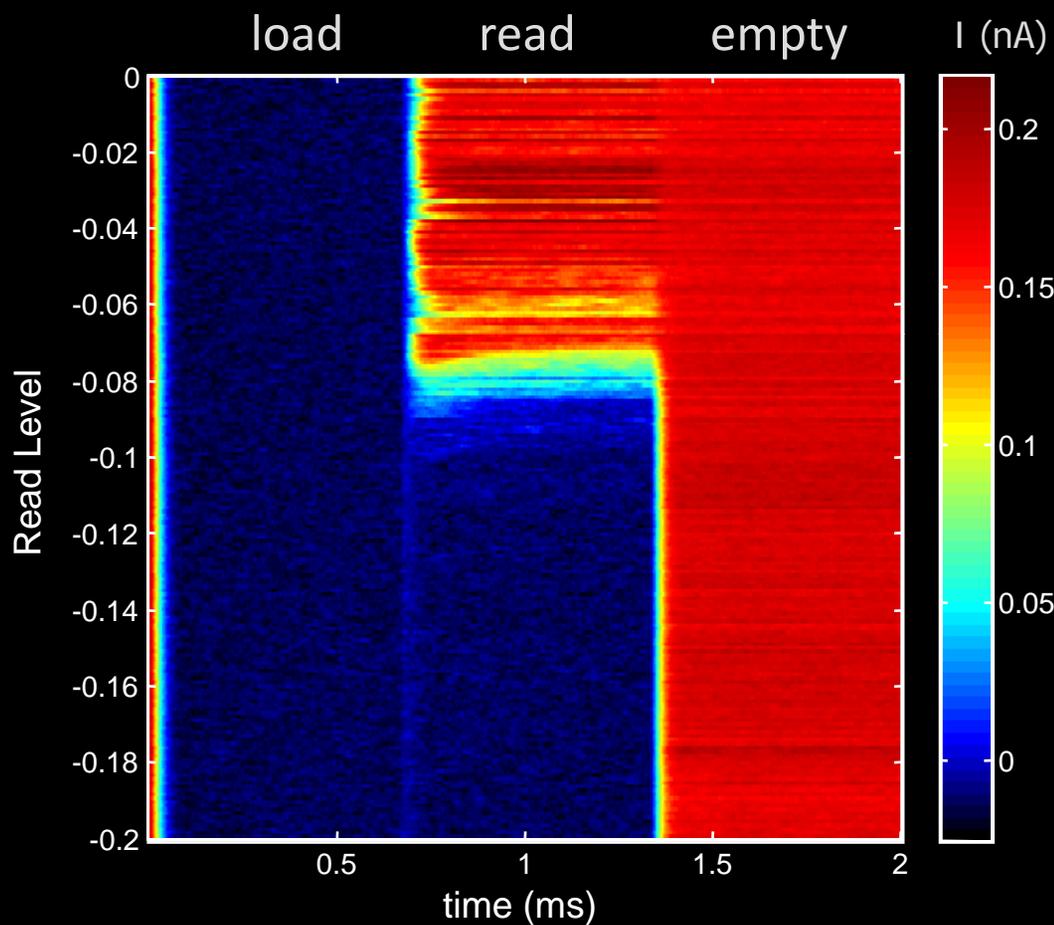
Pushing the bandwidth



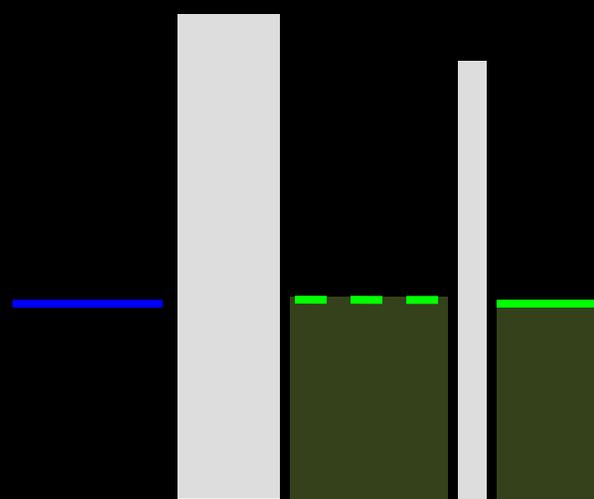
$S/N \sim 2$ at 100 kHz bandwidth \Rightarrow 4 μ s measurement time

Could be improved by low-T current comparator

Zero field

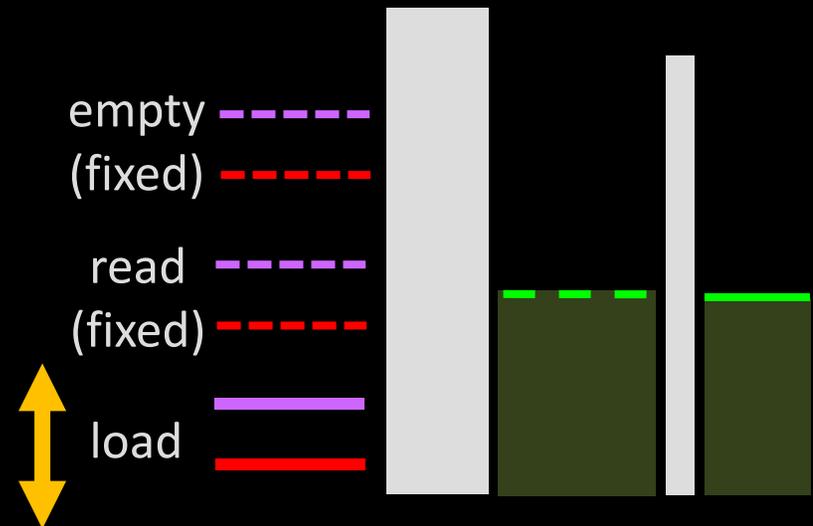
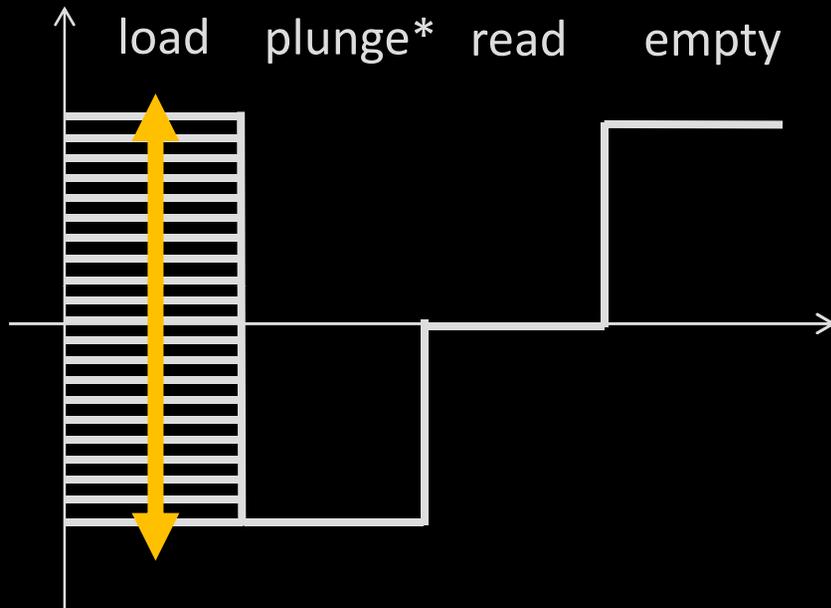
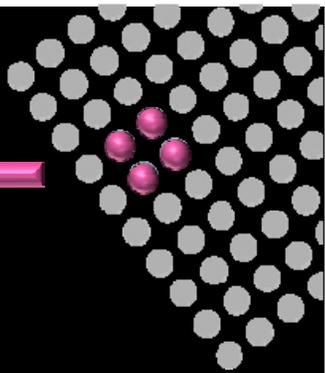


$B = 0$ T



No Zeeman splitting \Rightarrow no isolated blips in zero field

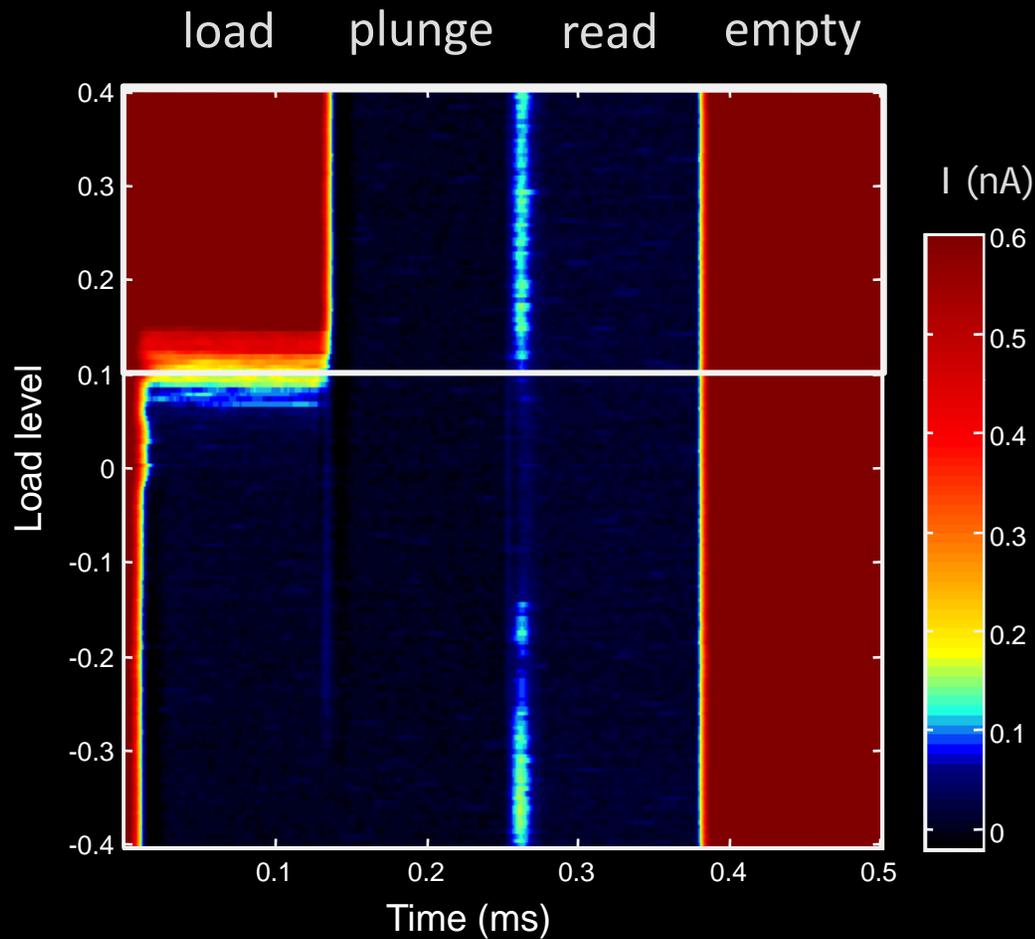
Scanning the load level



* Ensures that the voltage step before "read" is always the same

Having found the proper read level, we change the load
⇒ we have the choice to load ONLY spin-down

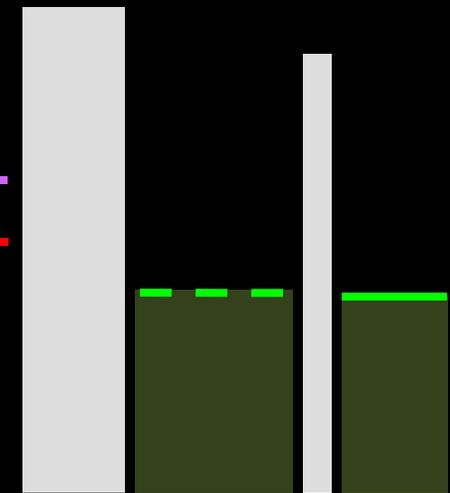
Scanning the load level



$B = 5 \text{ T}$

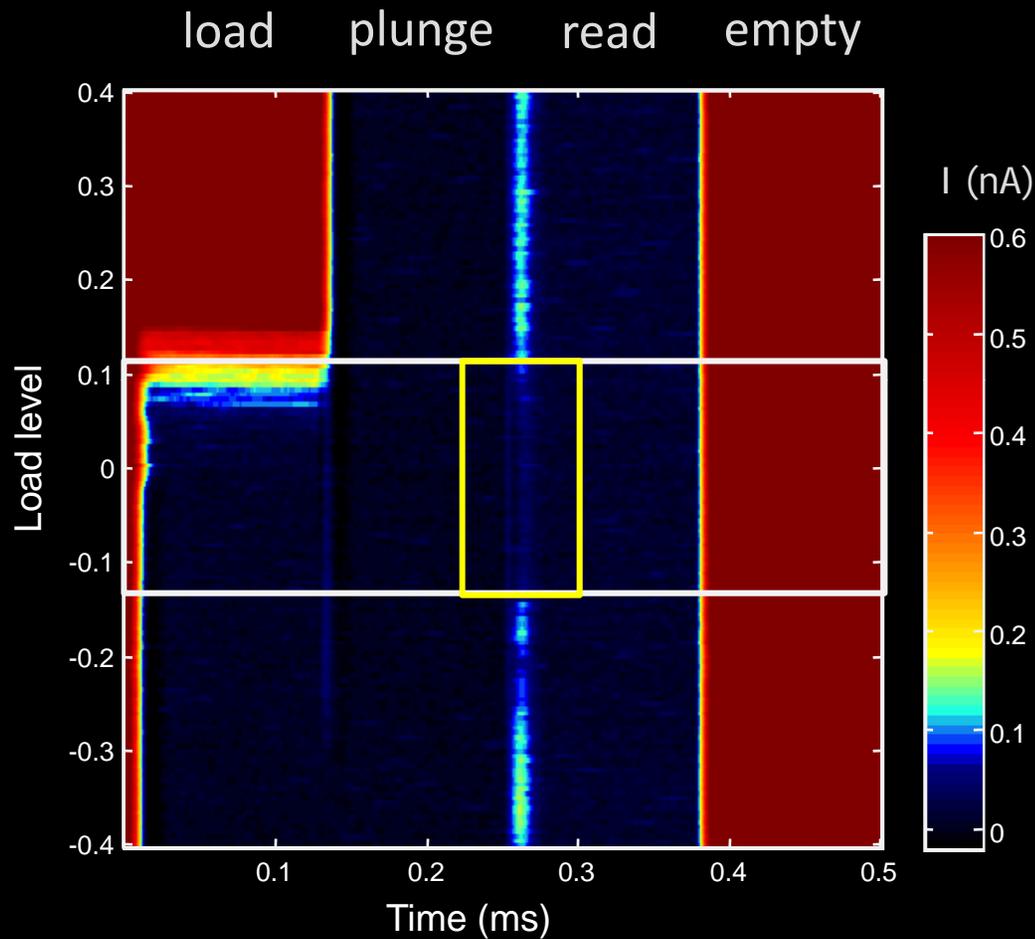
load pulse

—



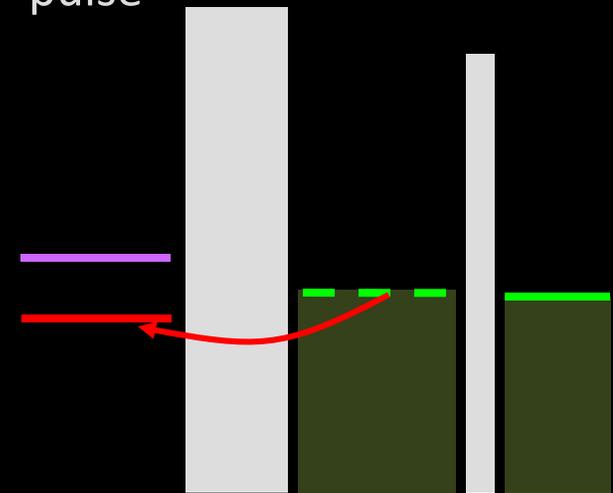
Load level higher than read: no electron loaded during “load”
→ loaded during “plunge” (\Rightarrow at fixed level)

Scanning the load level



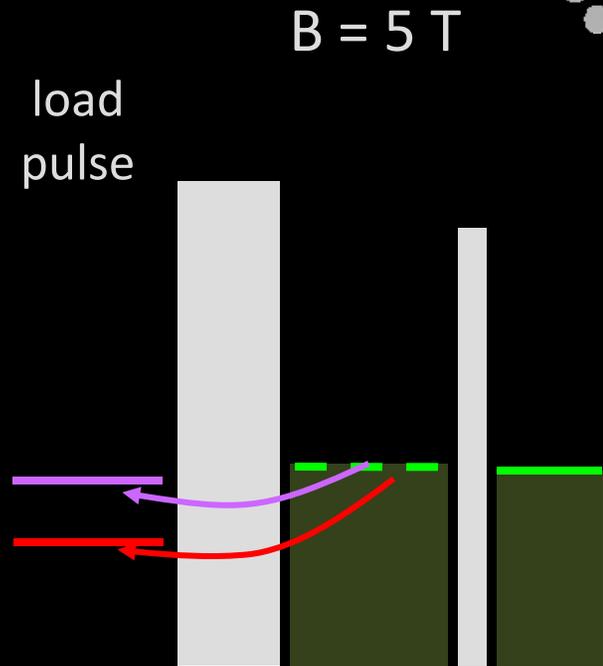
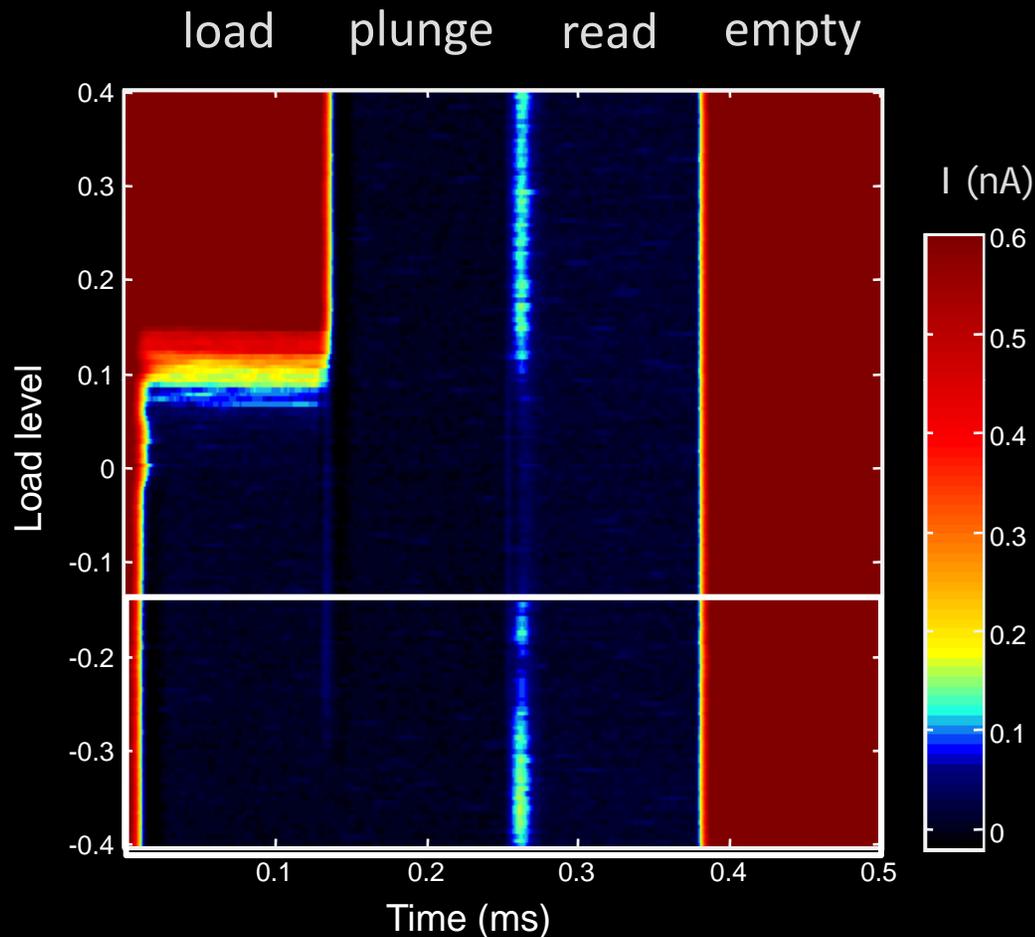
no spin-up states detected!

load
pulse



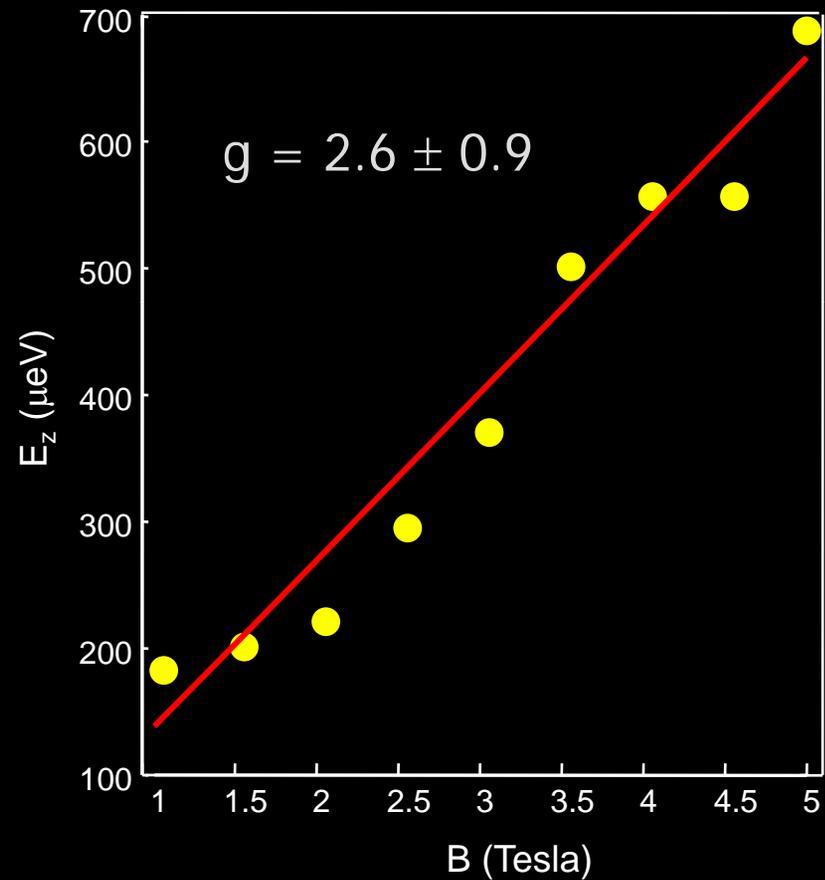
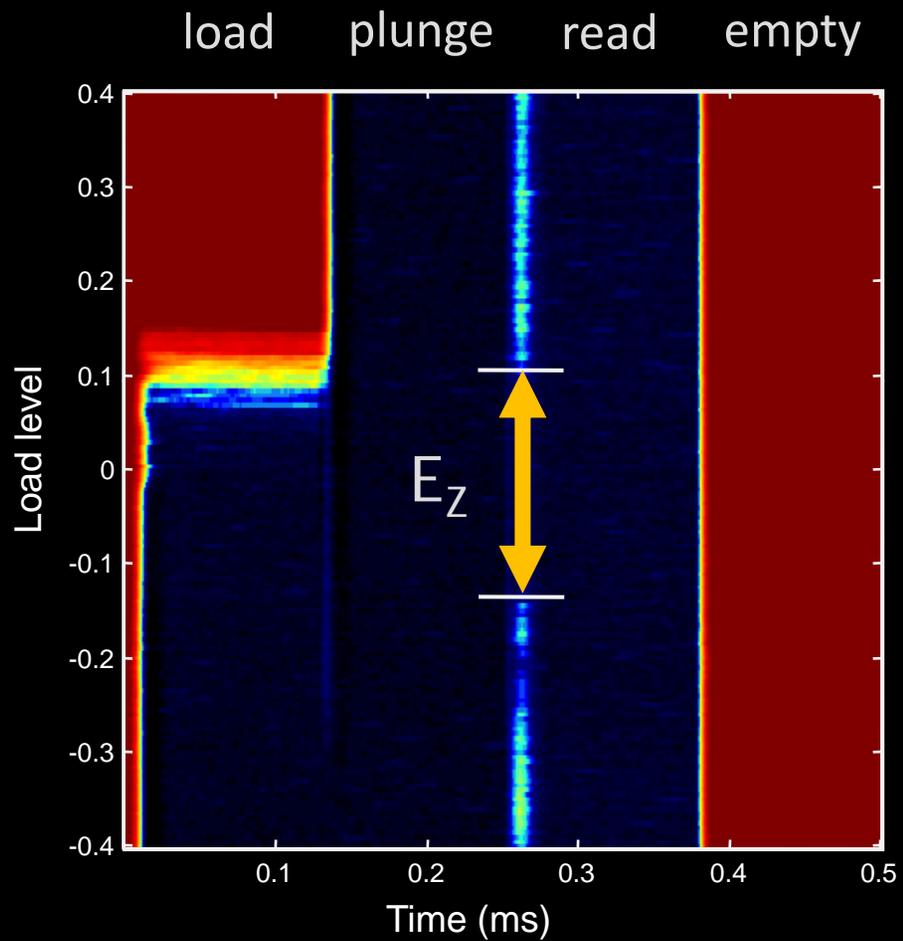
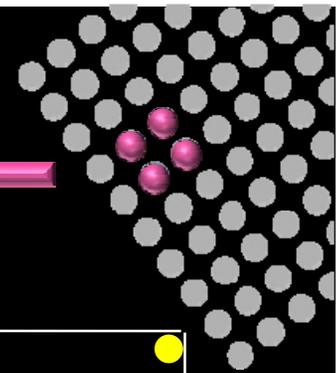
Load level close to read:
only spin down loaded

Scanning the load level

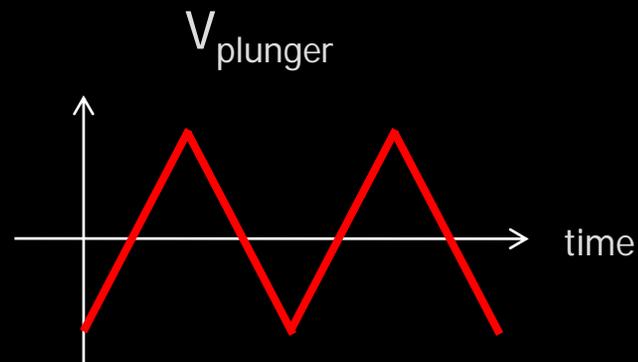
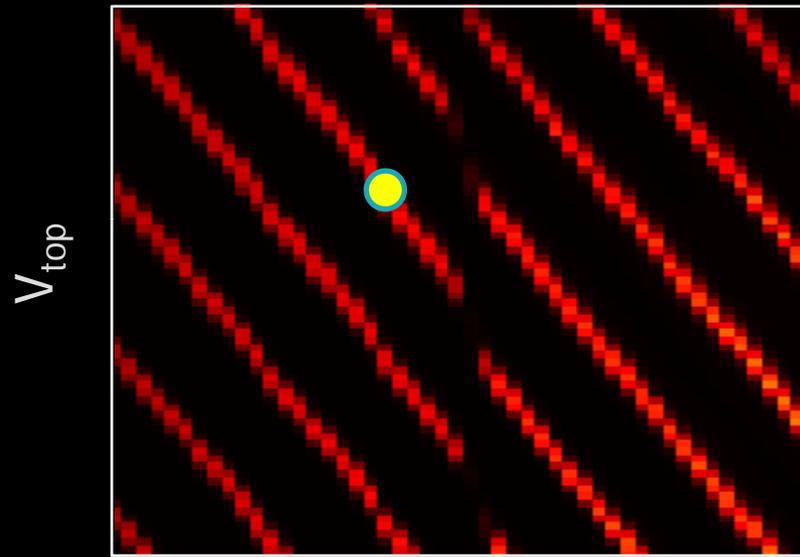
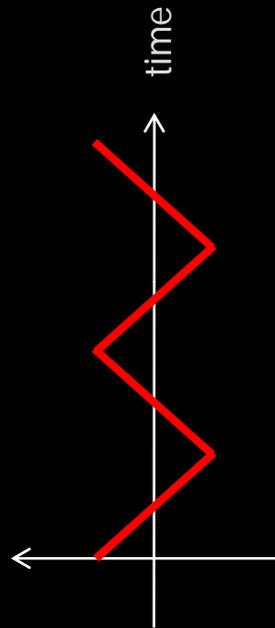
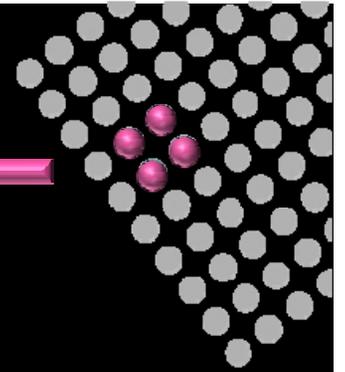


Load level lower than read: both spin states loaded during “load”
(\Rightarrow at variable level) and detected accordingly

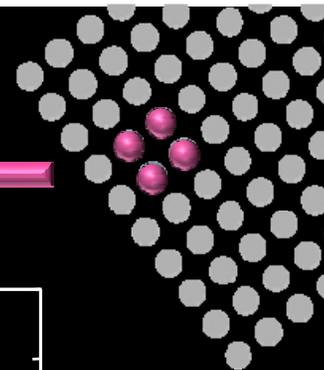
Zeeman splitting



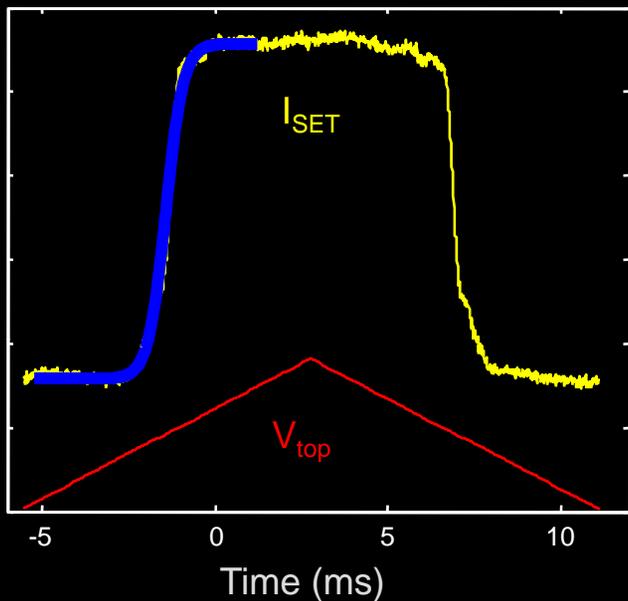
Lever arm calibration



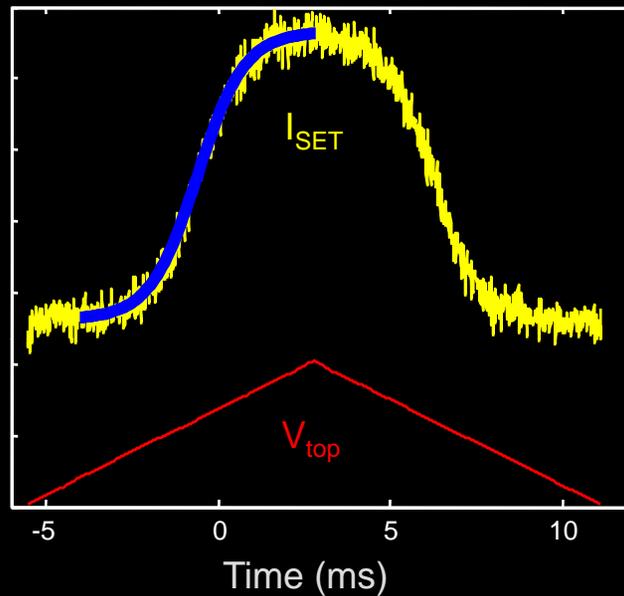
Lever arm calibration



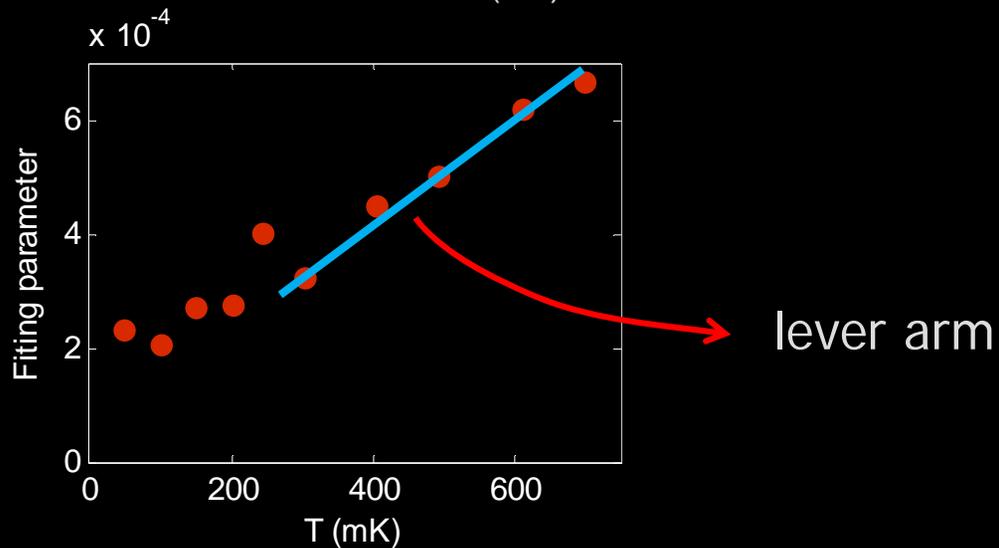
$T_{\text{fridge}} = 40 \text{ mK}$



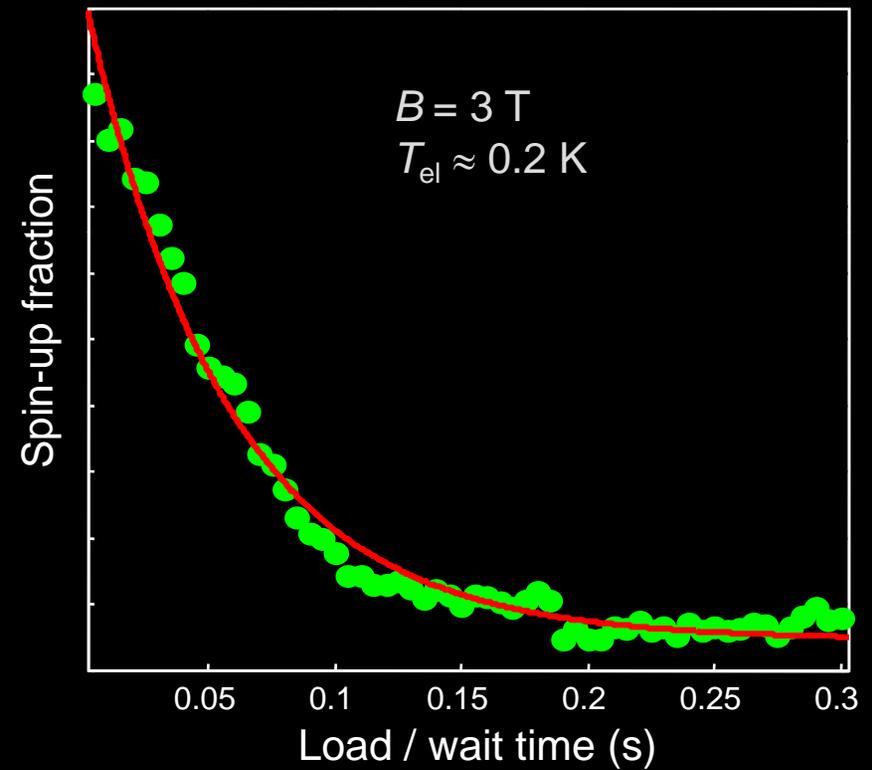
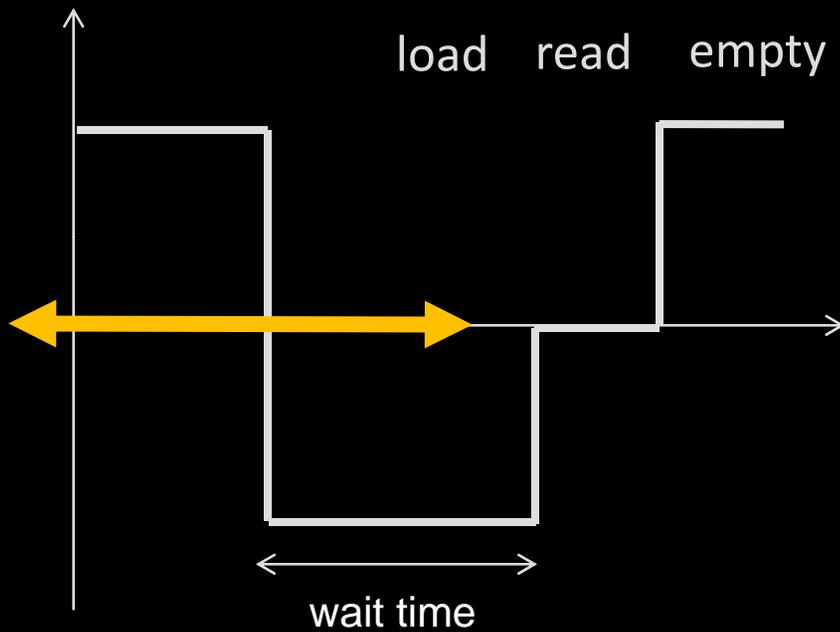
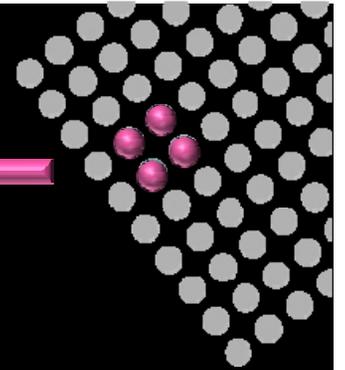
$T_{\text{fridge}} = 700 \text{ mK}$



fit Fermi distribution \rightarrow

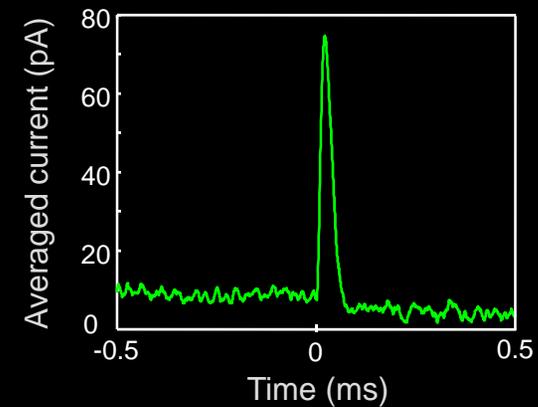
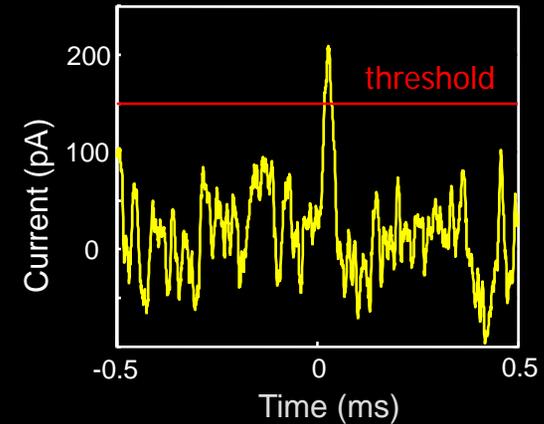
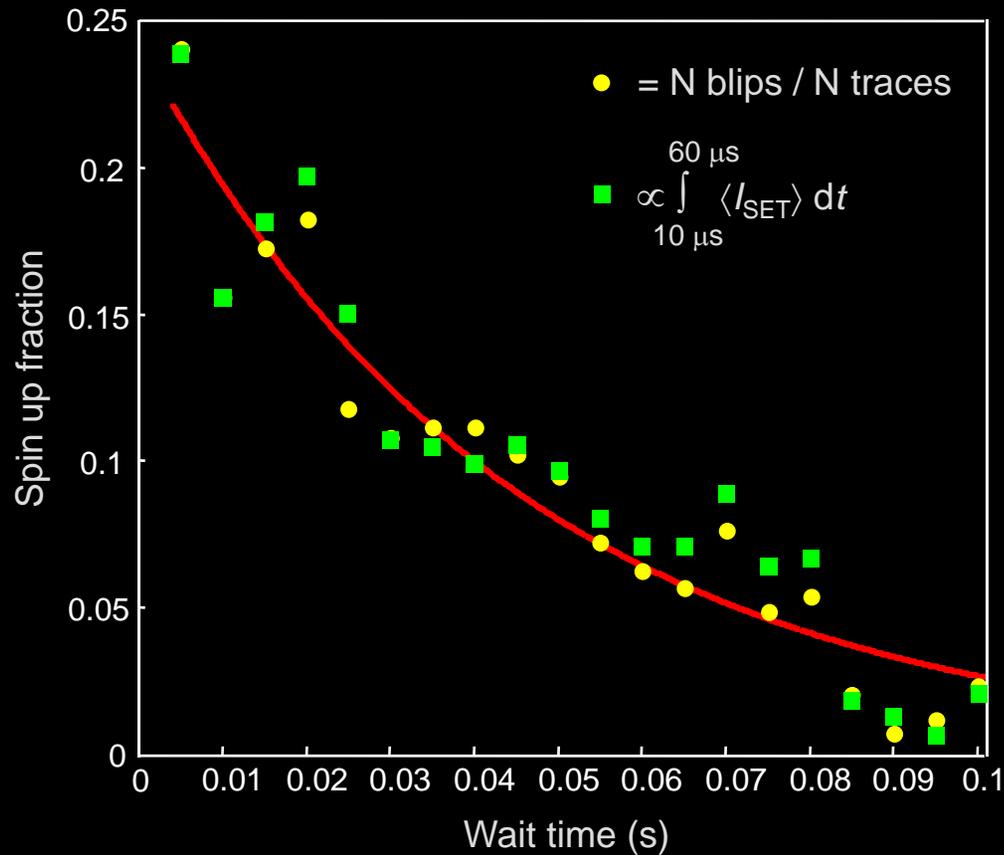


Spin lifetime measurement



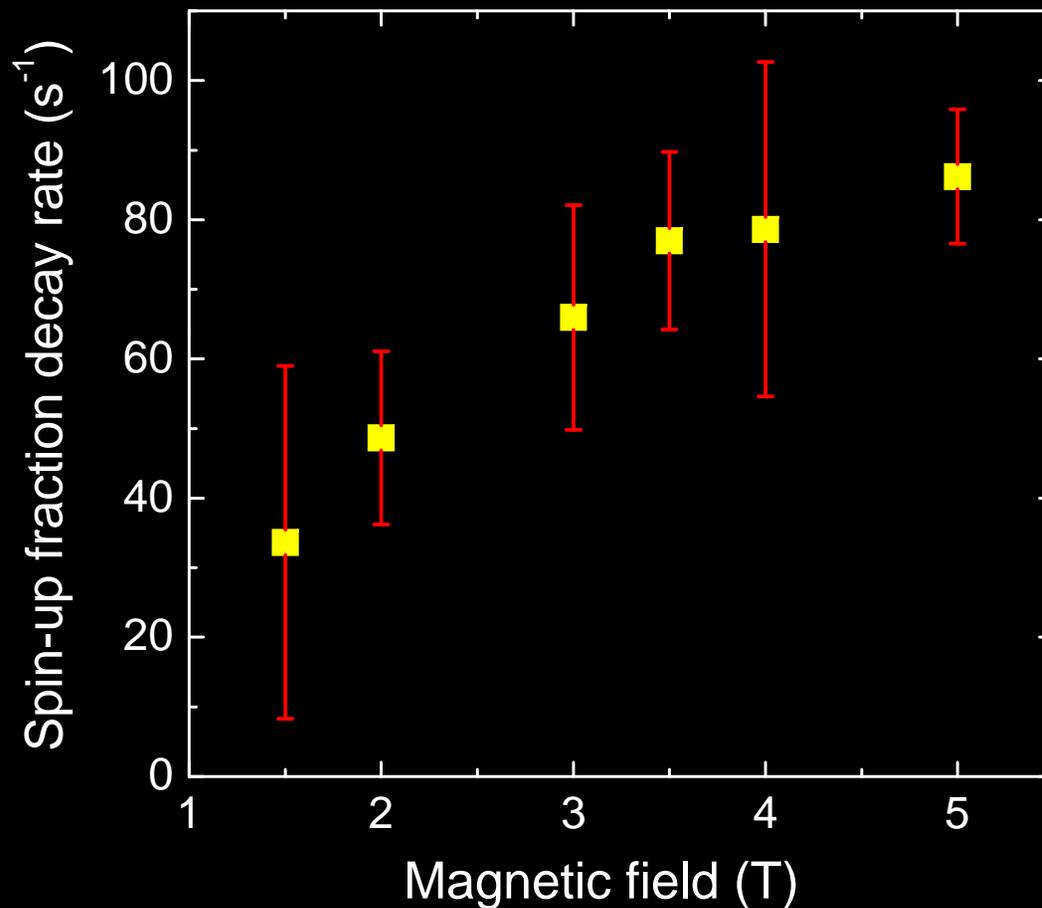
Spin lifetime up to ~ 50 ms

Single-shot vs. average



Blip-counting and current-averaging are equivalent

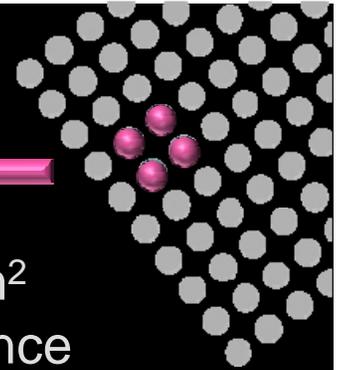
Field dependence of spin lifetime



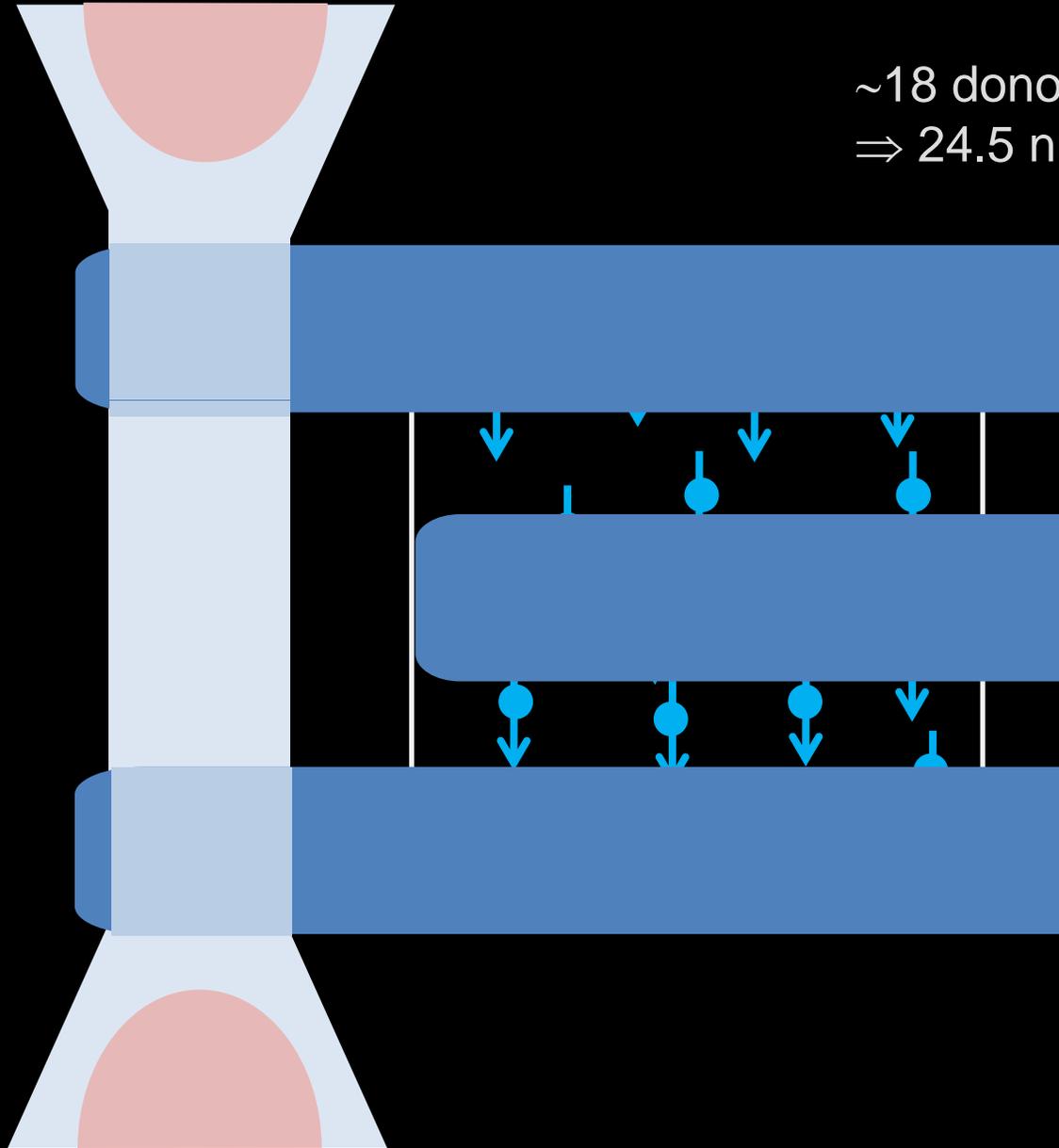
Incompatible with energy relaxation (expected $\propto B^5$)

See e.g. Tahan, arXiv:0710.4263

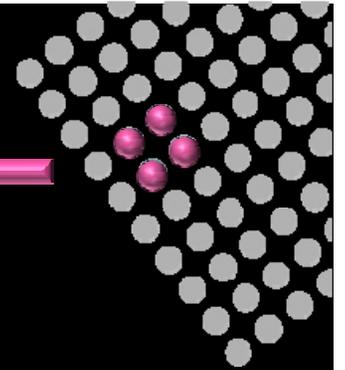
Spin diffusion



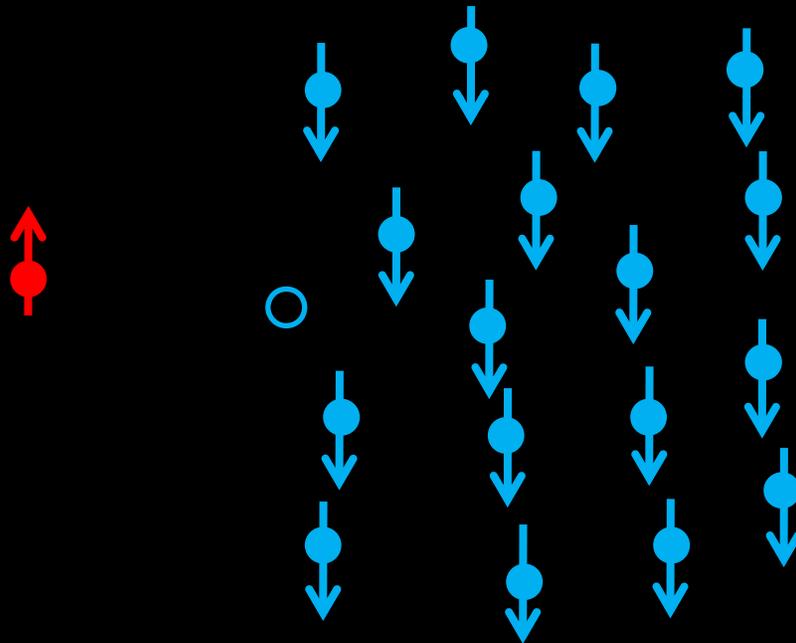
~18 donors in $90 \times 90 \text{ nm}^2$
 $\Rightarrow 24.5 \text{ nm}$ typical distance



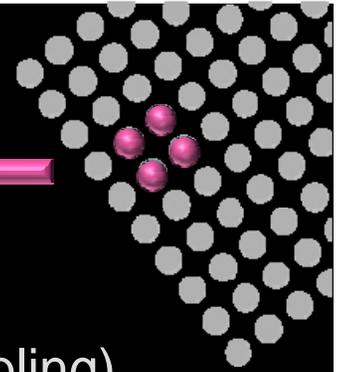
Spin diffusion



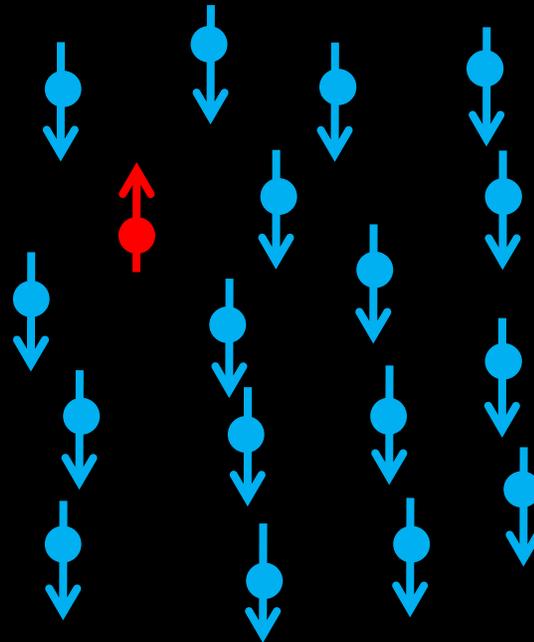
load spin-up



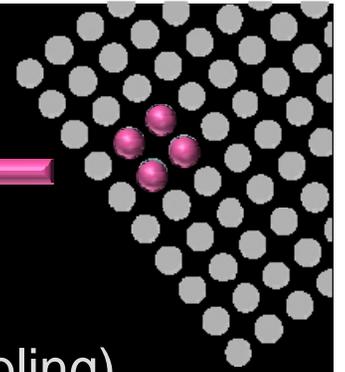
Spin diffusion



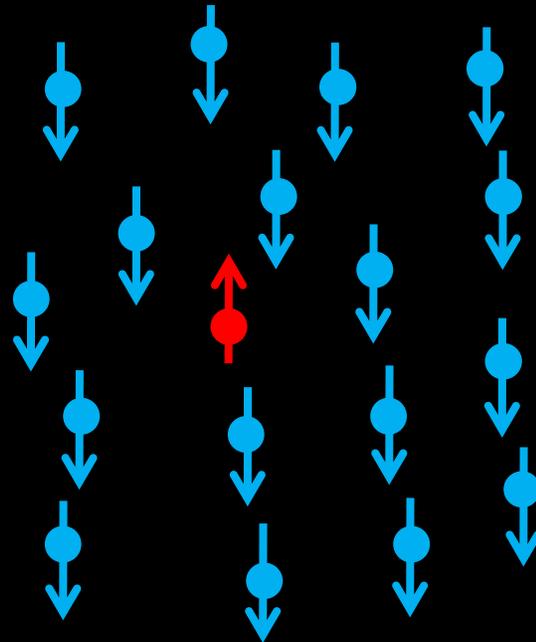
energy-conserving electron spin flip-flops
("B" term: $S_i^+S_j^- + S_i^-S_j^+$ in the dipole-dipole coupling)



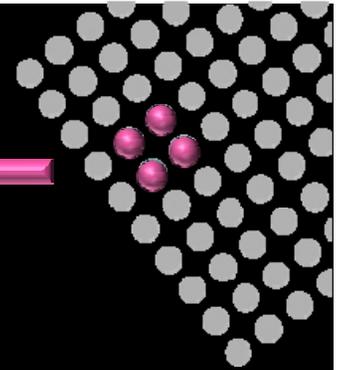
Spin diffusion



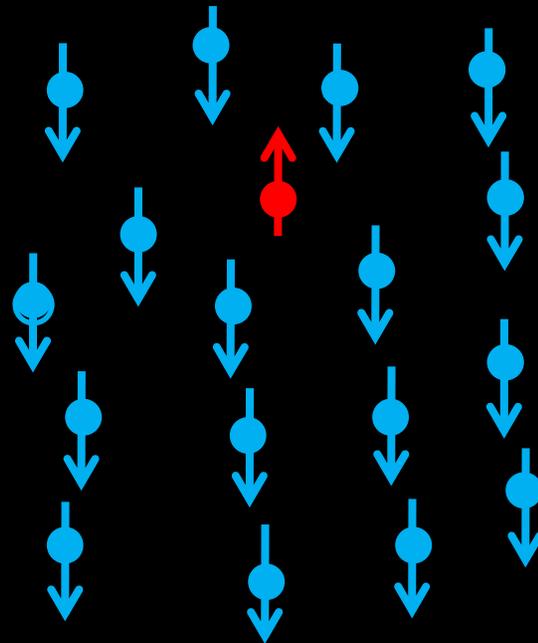
energy-conserving electron spin flip-flops
("B" term: $S_i^+S_j^- + S_i^-S_j^+$ in the dipole-dipole coupling)



Spin diffusion

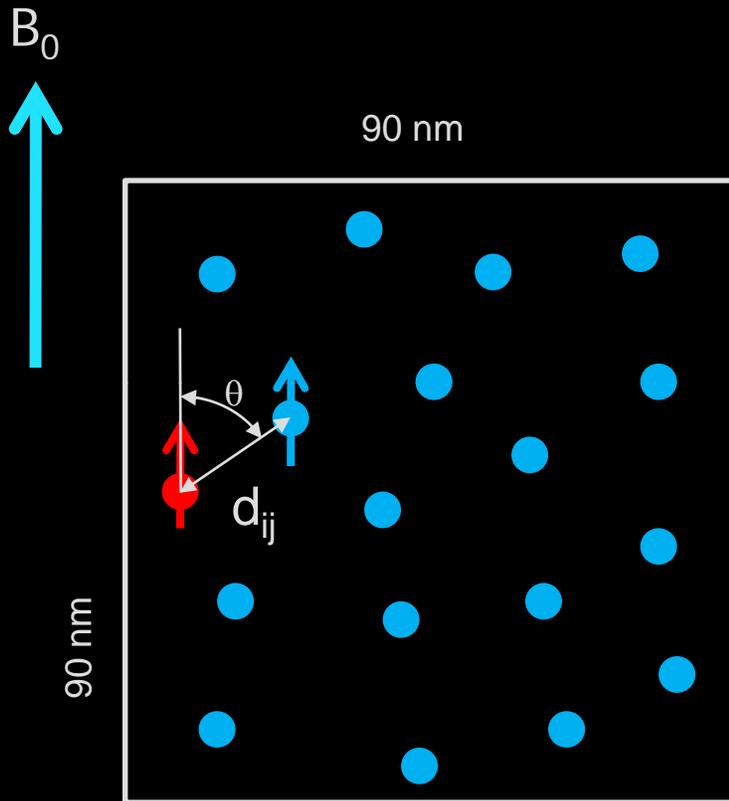


read spin-down



The excitation is still present in the system (**no energy relaxation**)
but has diffused away from the measured donor

Spin diffusion calculation



~18 donors in $90 \times 90 \text{ nm}^2$
 \Rightarrow 24.5 nm typical distance

Flip-flop rate:

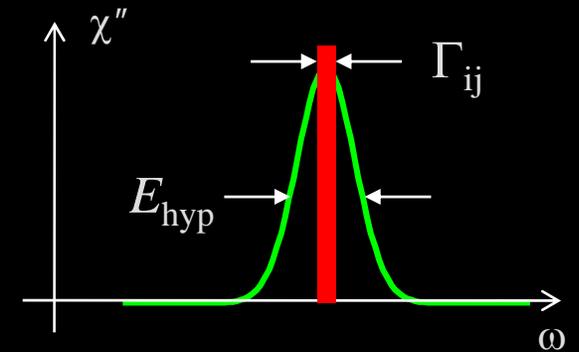
$$\Gamma_{ff} \approx \sqrt{\sum_i \sum_j \Gamma_{ij}^2 \Phi_{ij}^{(hyp)}}$$

$$\Gamma_{ij}^2 = \left(\frac{\mu_0}{4\pi\hbar} \right)^2 \frac{1}{12} S(S+1) g^4 \mu_B^4 \frac{(1-3\cos^2\theta)^2}{d_{ij}^6}$$

$$\Phi_{ij}^{(hyp)} \approx \frac{\hbar\Gamma_{ij}}{2\sqrt{\pi}E_{hyp}}$$

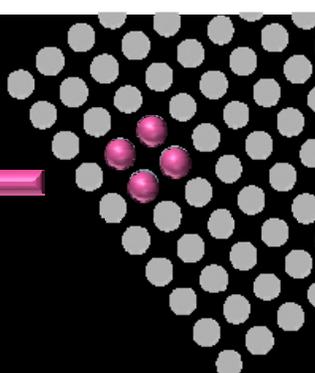
$$E_{hyp} = 2g\mu_B \langle B_{hyp} \rangle$$

$$\langle B_{hyp} \rangle = 2.5 \text{ G}$$



Calculated $\Gamma_{ff} \approx 100 \text{ s}^{-1}$ in agreement with the experiment

Summary & Outlook



MOSFET donor-based spin qubit architecture

Large charge transfer signals
Tunnel rates consistent with donor position

Single-shot spin readout

Measured spin lifetime related to dipolar flip-flops

Measure counted 1-donor devices $\rightarrow T_1$

ESR on qubit – Rabi oscillations – single-spin coherence

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