GDR Mico

Imaging magnetic fields at the nanoscale: NV microscopy

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J.-P. Tétienne, L. Rondin, J.-F. Roch, V. Jacques

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L. Herrera Diez, K. Garcia,

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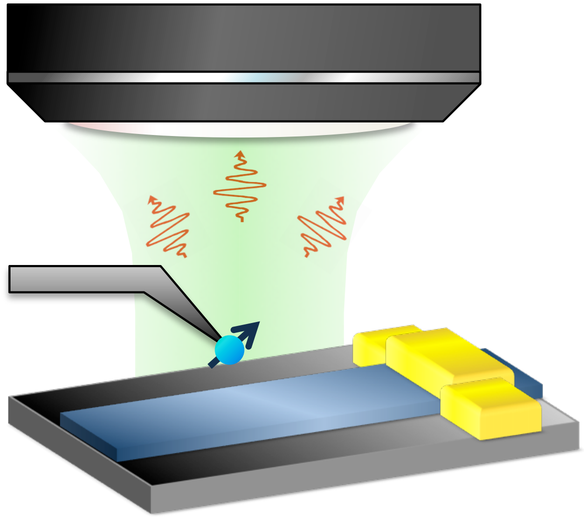
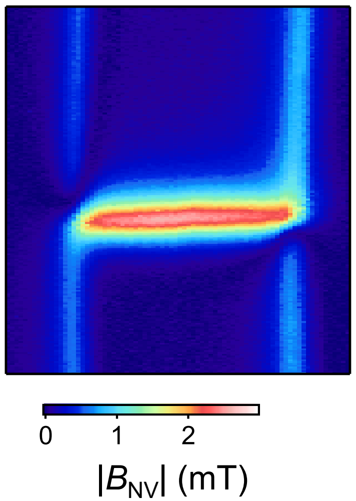
Plan



I. Presentation of NV microscopy



II. Recent experiments on domain walls in ultrathin ferromagnets

Plan

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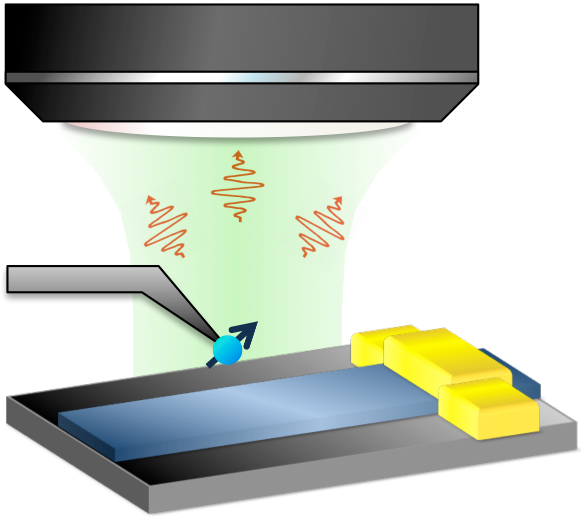
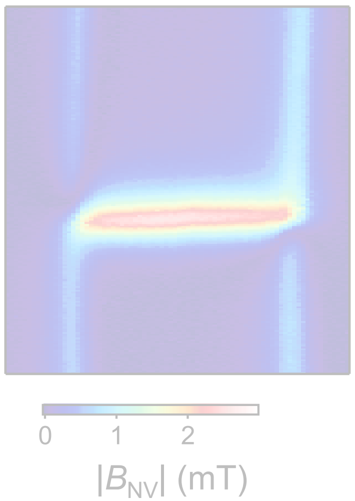




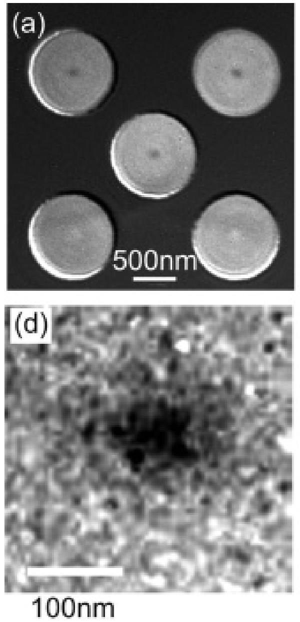
II. Recent experiments on domain walls in ultrathin ferromagnets

Nanoscale magnetic imaging

Nanoscale magnetic imaging

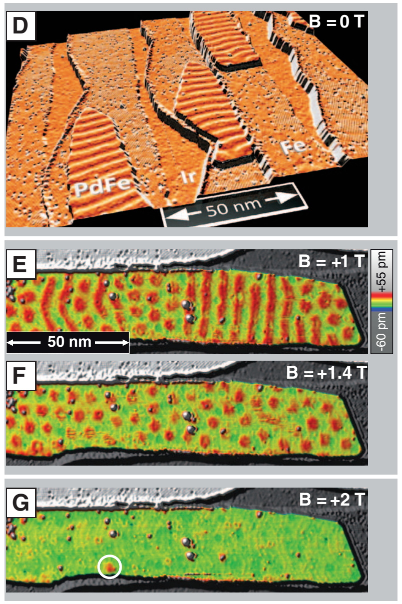
Magnetization measurement

X Rays



*Fischer P. et al. PRB **83**, 212402 (2011)*

SP-STM



*Romming N. et al. Science **341**, 636 (2013)*

Nanoscale magnetic imaging

Magnetization measurement

☹ strong experimental constraints
(vacuum, sample thickness, synchrotron…)

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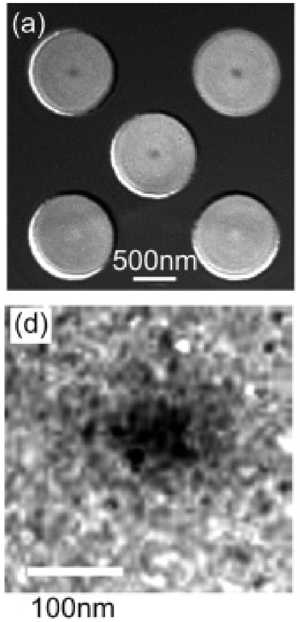

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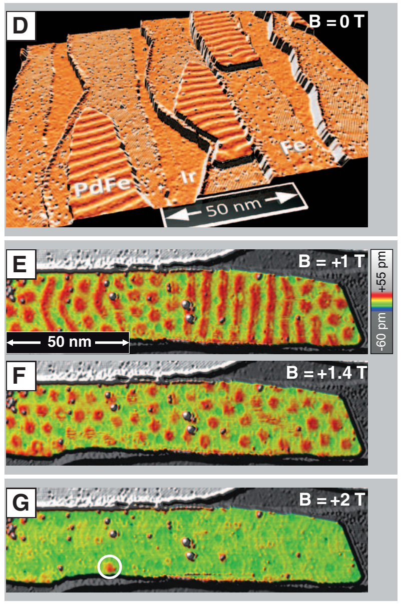

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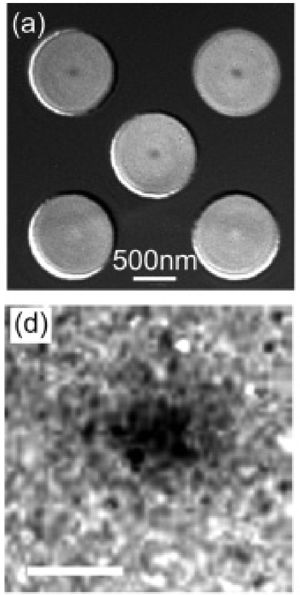

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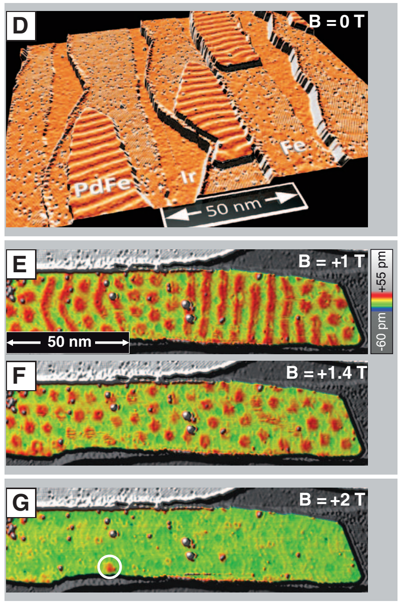

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Stray field measurement

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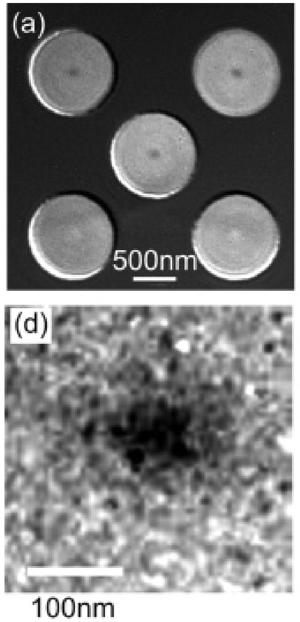

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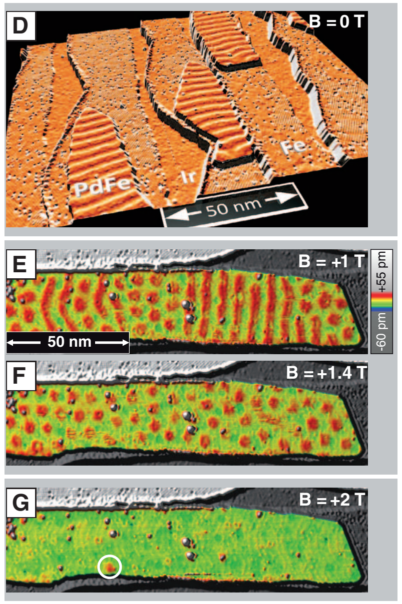

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Stray field measurement

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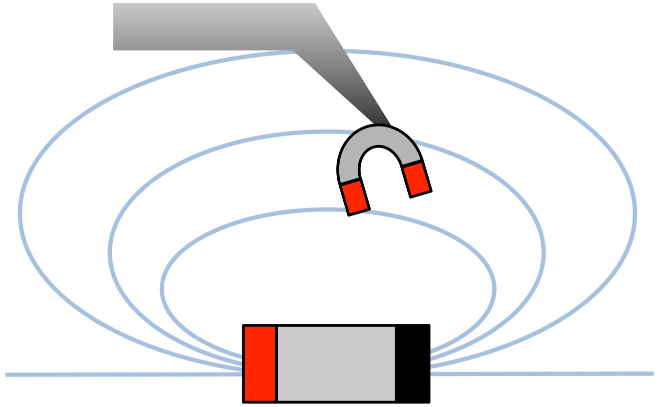

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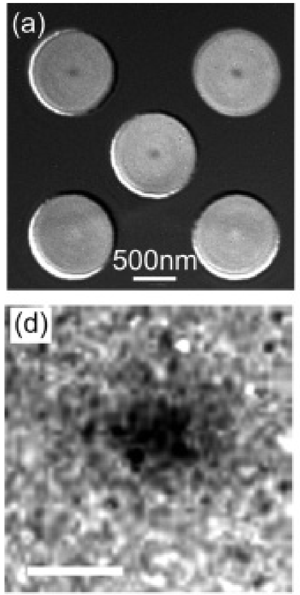

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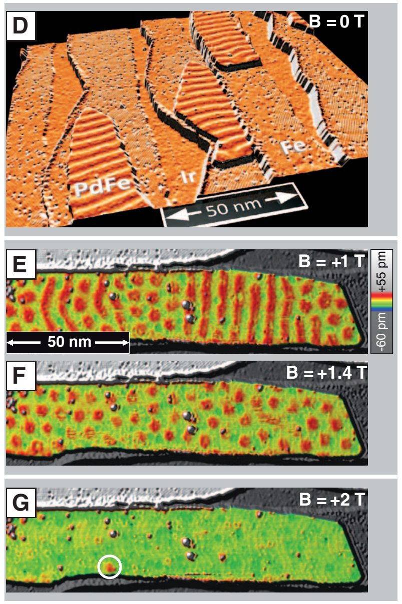

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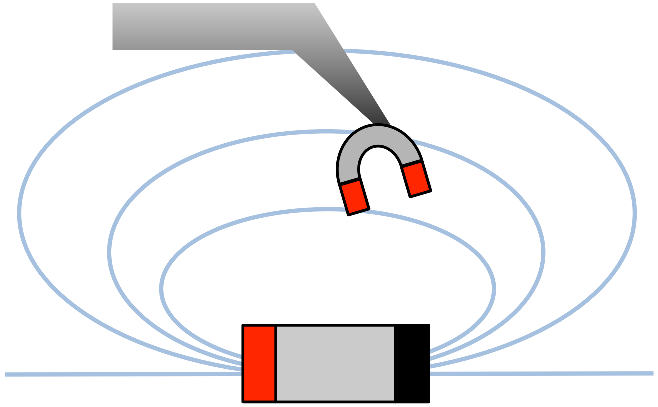

☺ versatile

☺ nanoscale resolution

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Magnetization measurement

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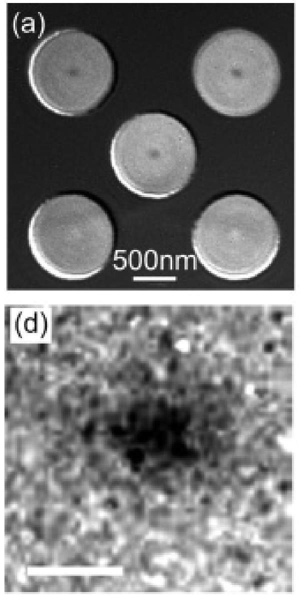

100nm

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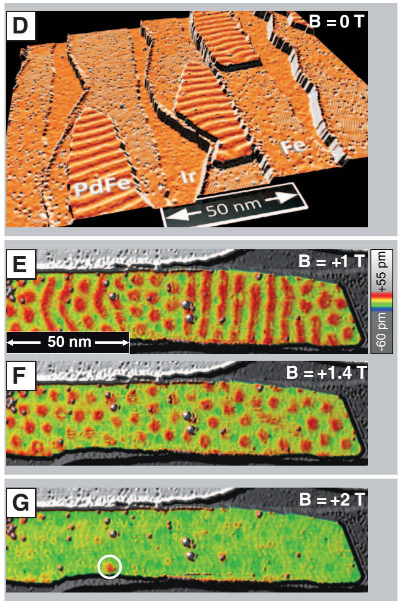

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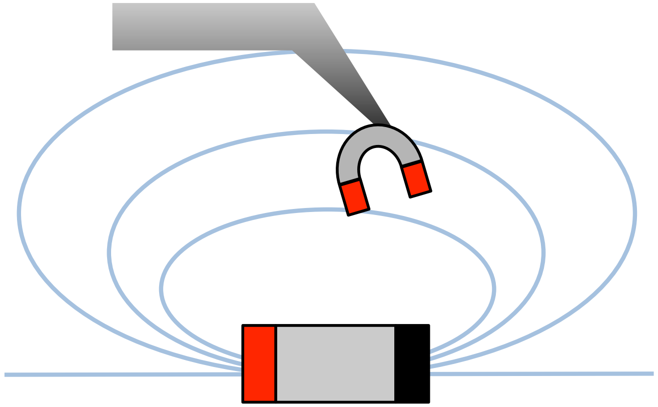
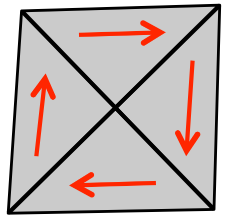


☺ versatile

☺ nanoscale resolution

2 um



J. M. Garcia et al. APL ***79****, 5 (2001)*

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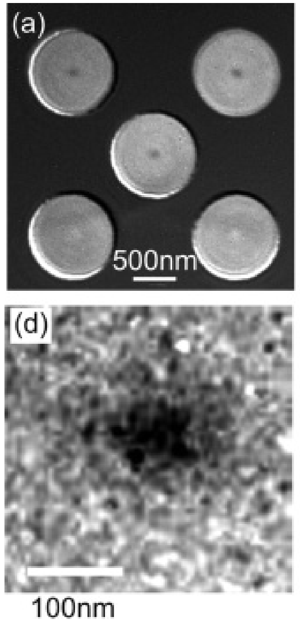

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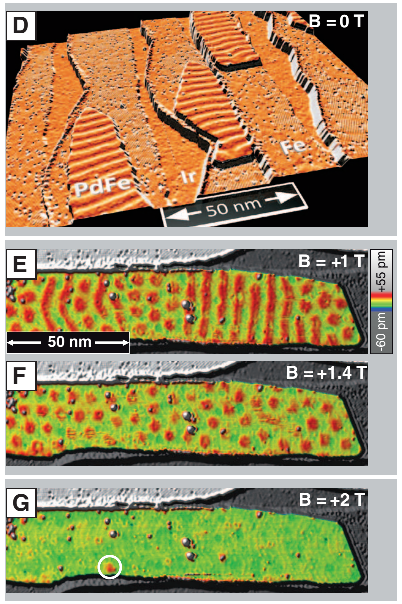

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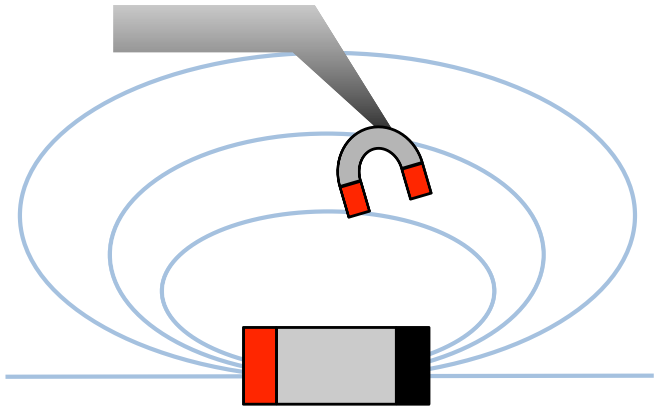
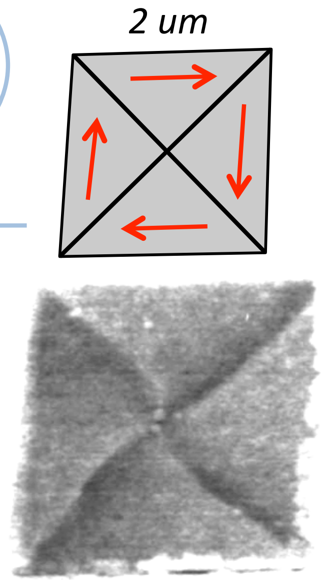


☺ versatile

☺ nanoscale resolution

☹ magnetic back action

☹ hardly quantitative



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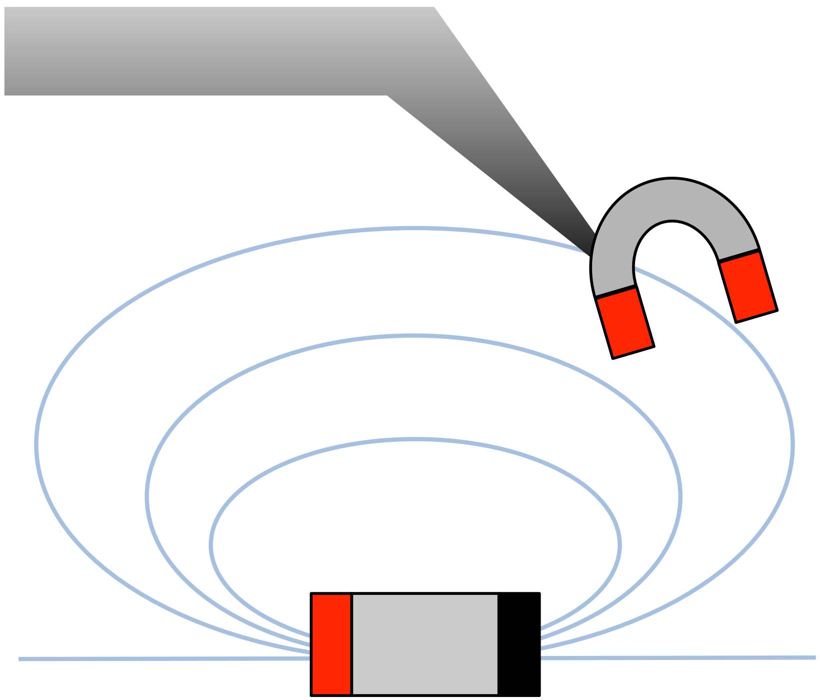
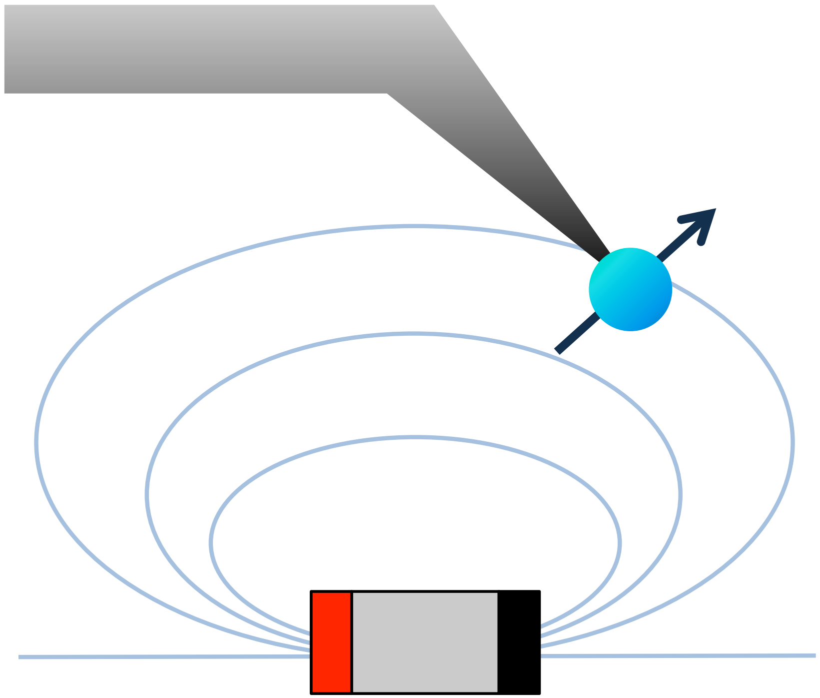


Single spin magnetometer

Attaching a single spin at the end of a tip



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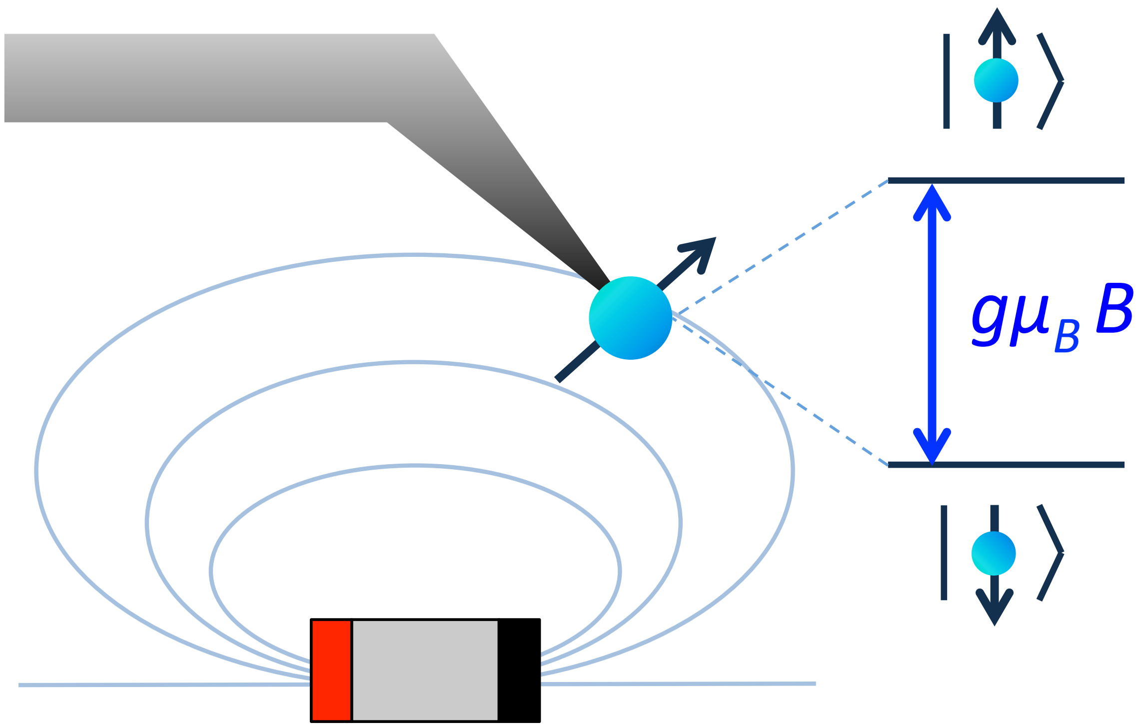
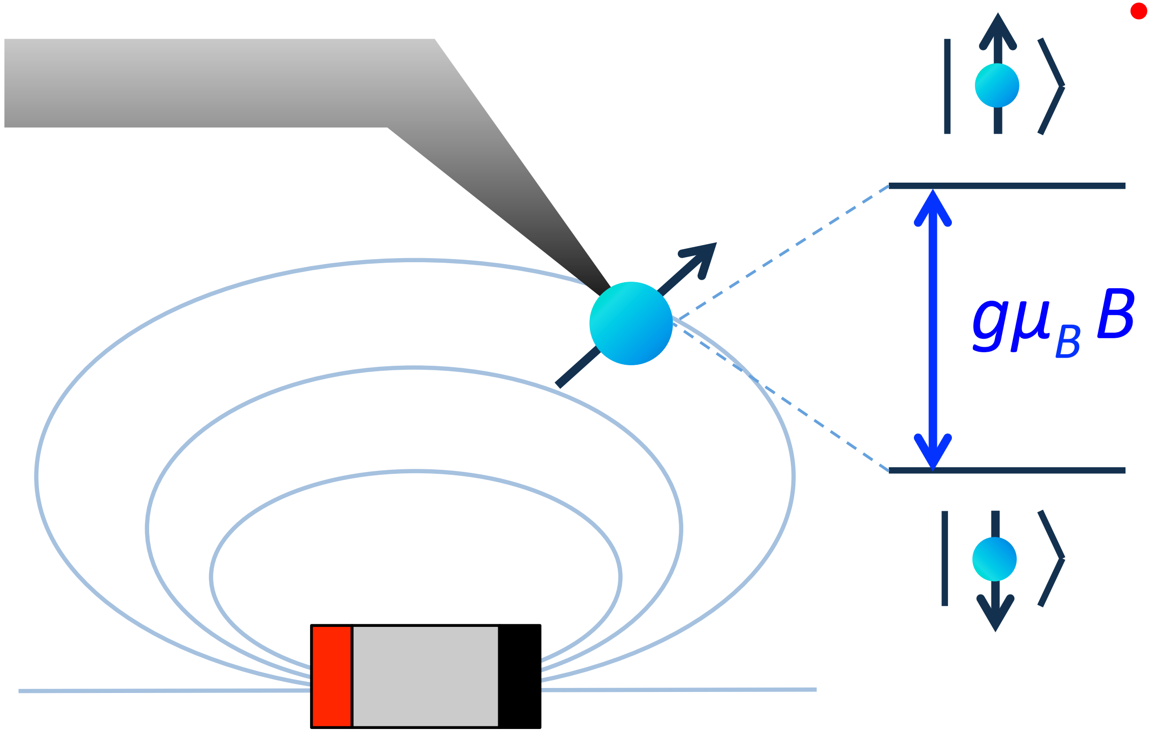


Single spin magnetometer

Attaching a single spin at the end of a tip

- non invasive
- quantitative
- atomic detection volume



B. Chernobrod et al., J. Appl. Phys. ***97****, 014903 (2005)*

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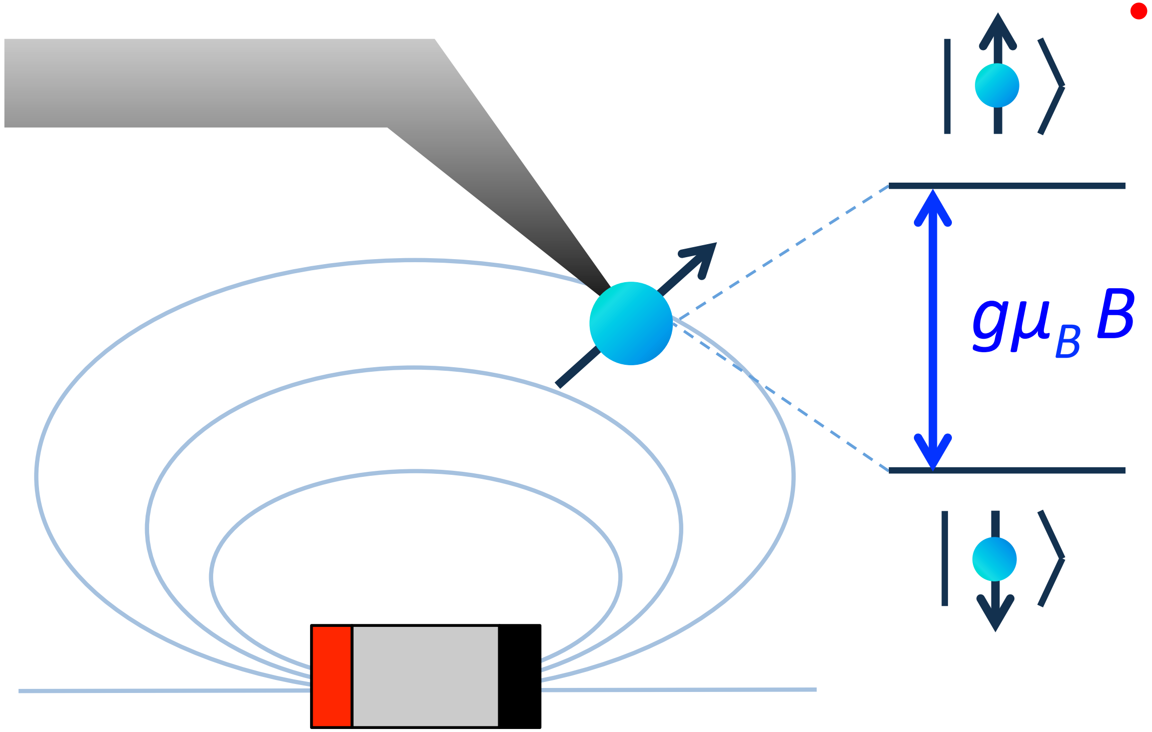

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NV defect in diamond

NV defect in diamond:
colour centre

diamant "Hortensia", musée du Louvre

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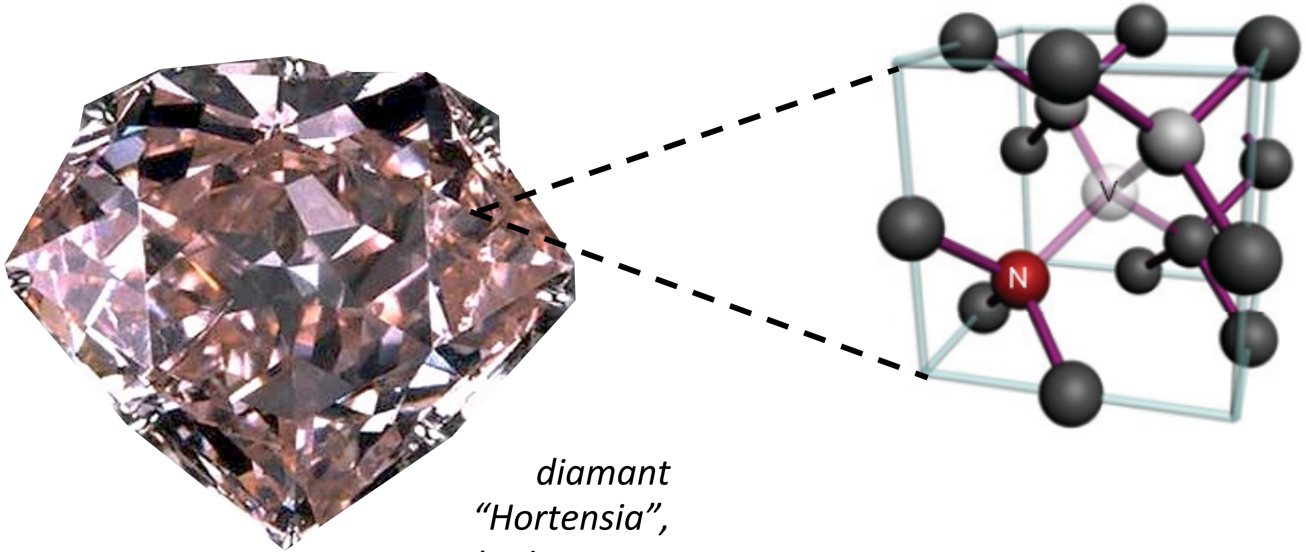
NV defect in diamond:
colour centre



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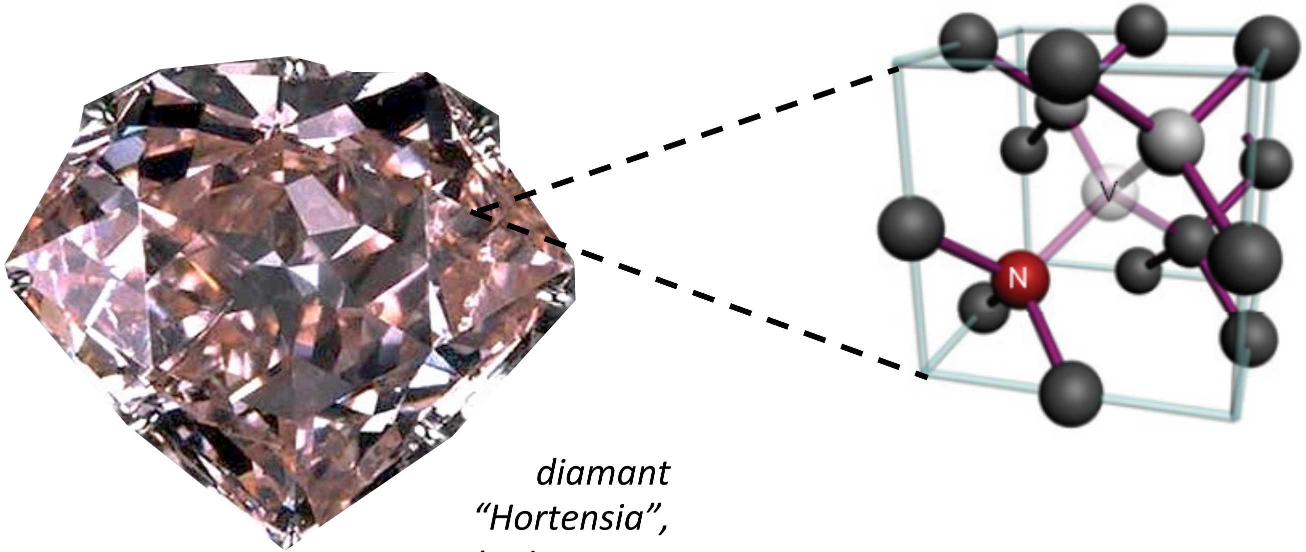

diamant
"Hortensia",
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Atom-like defect, trapped in the diamond matrix

NV defect in diamond

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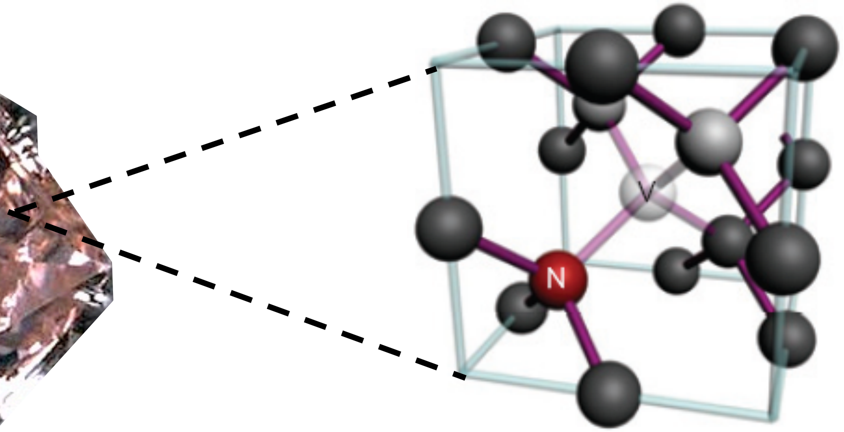

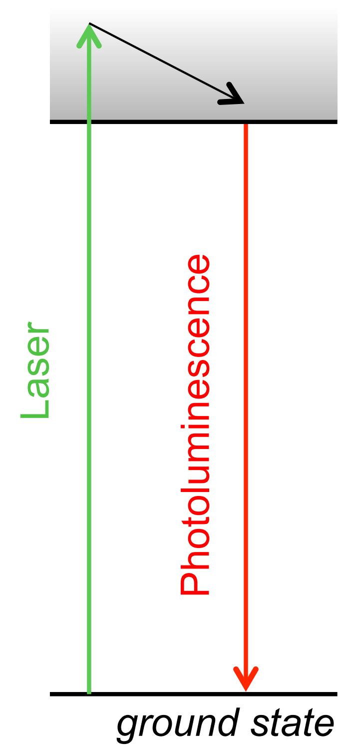

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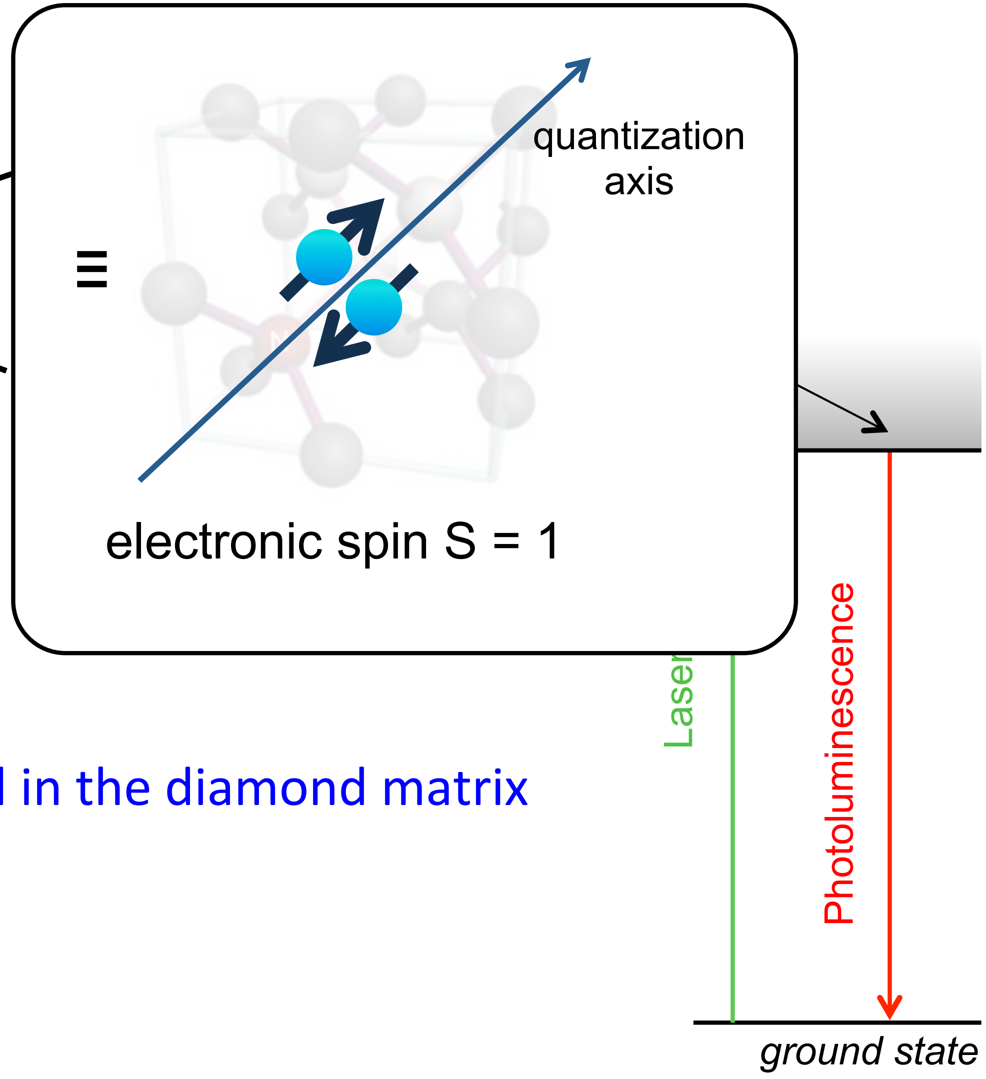

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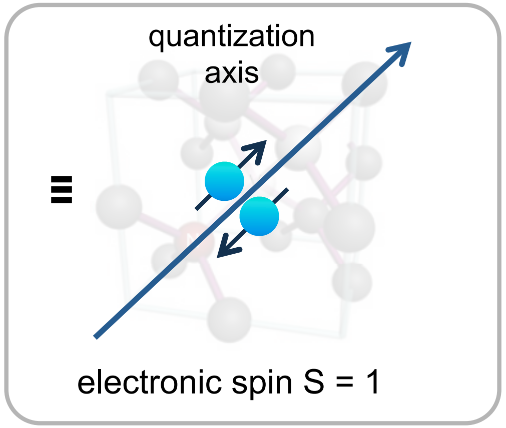

Spin properties and ODMR

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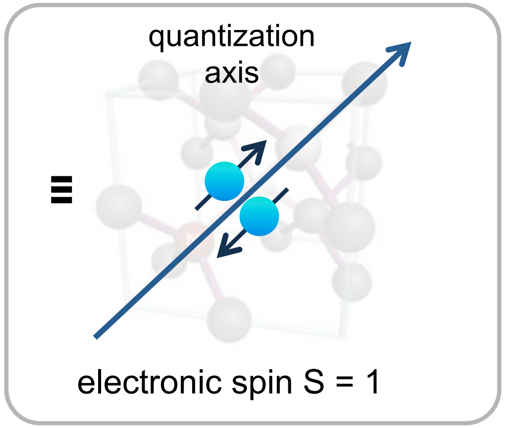
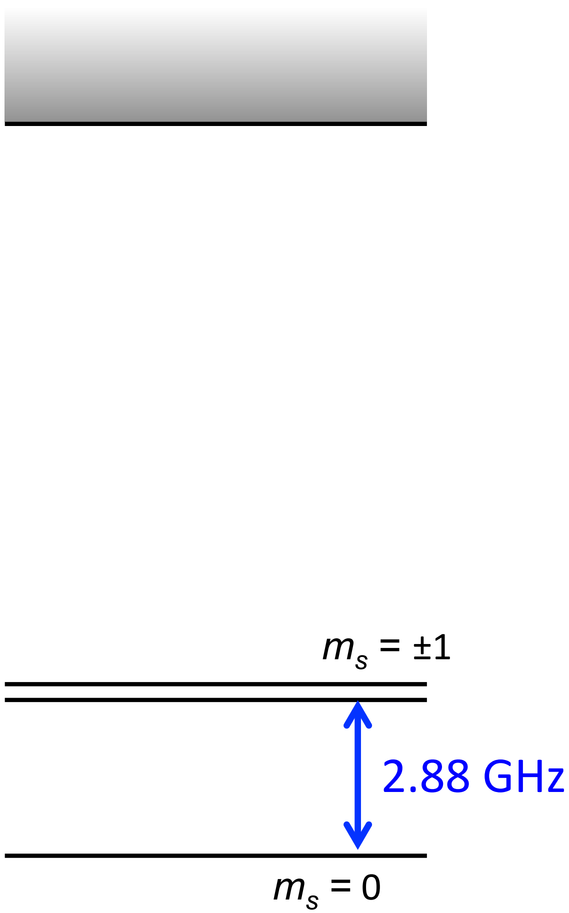
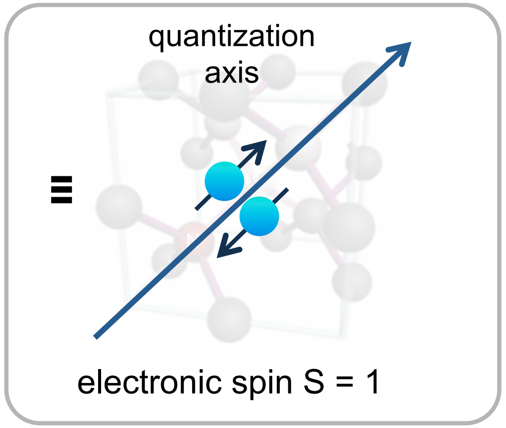


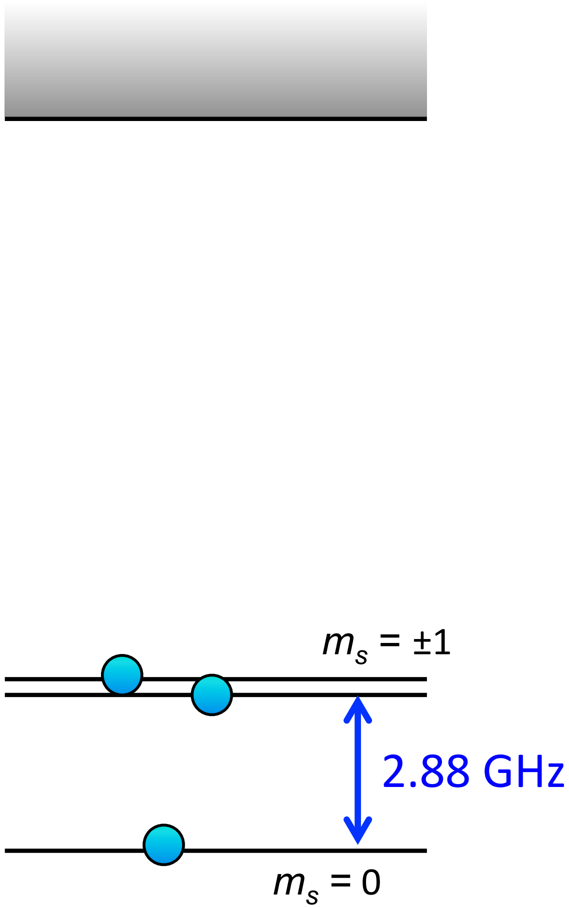


excited state

ground state

Spin properties and ODMR





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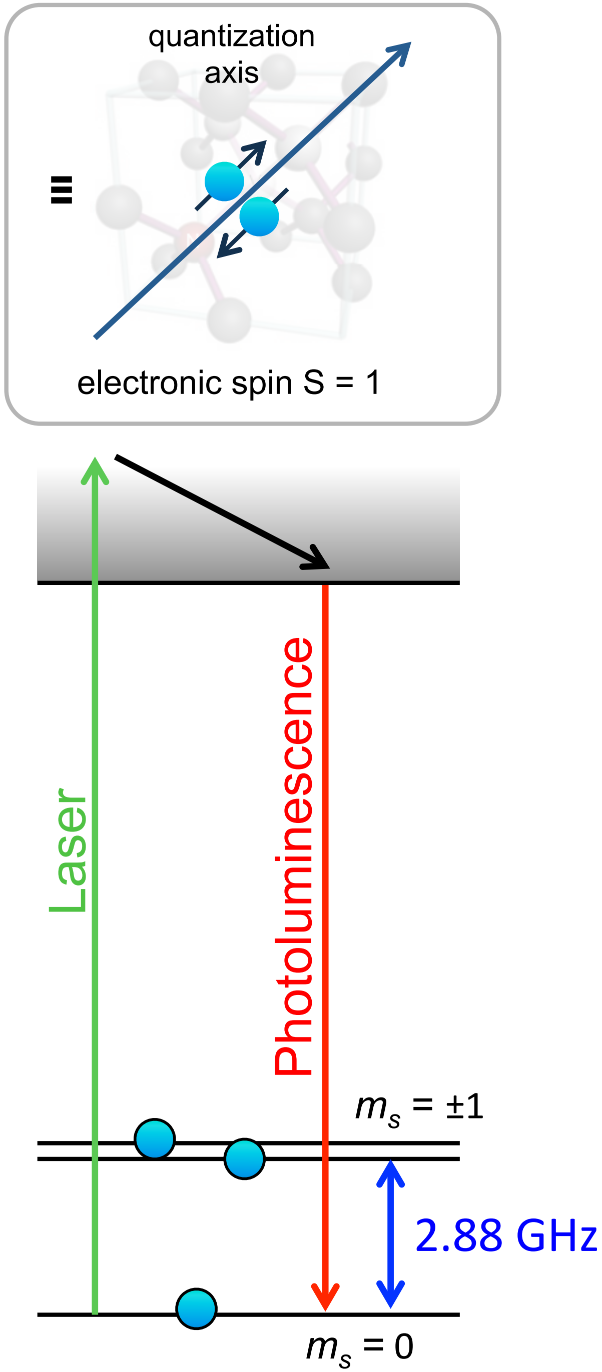

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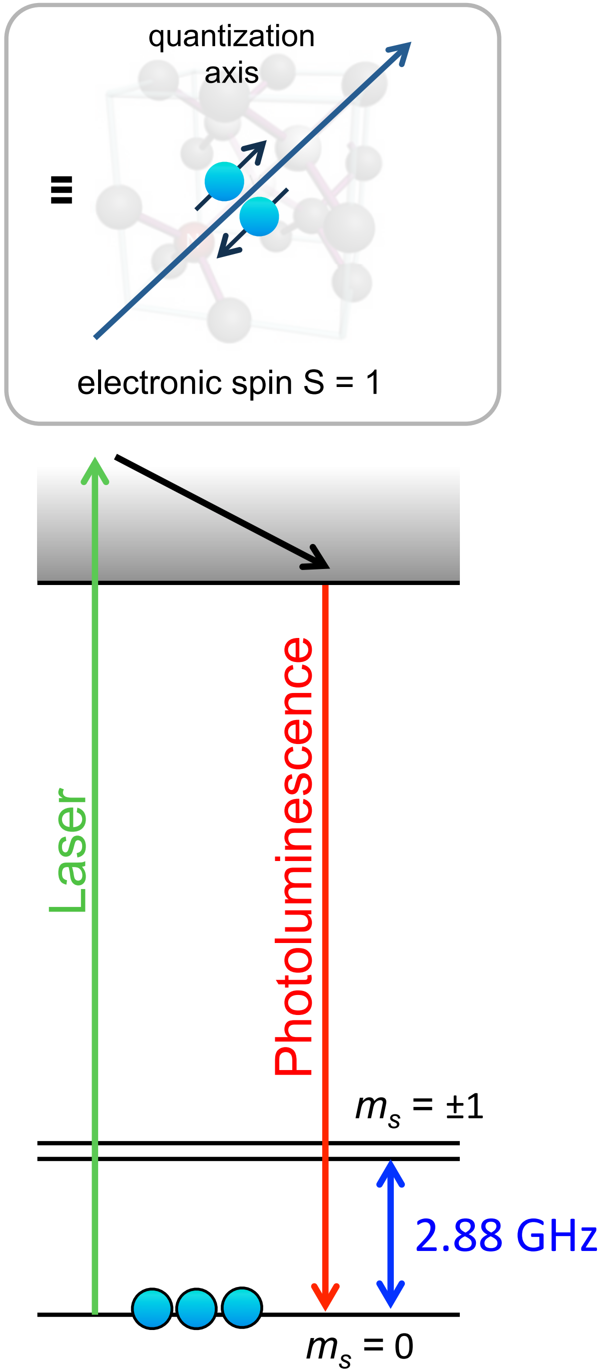

- optical pumping into | m_s = *0* >

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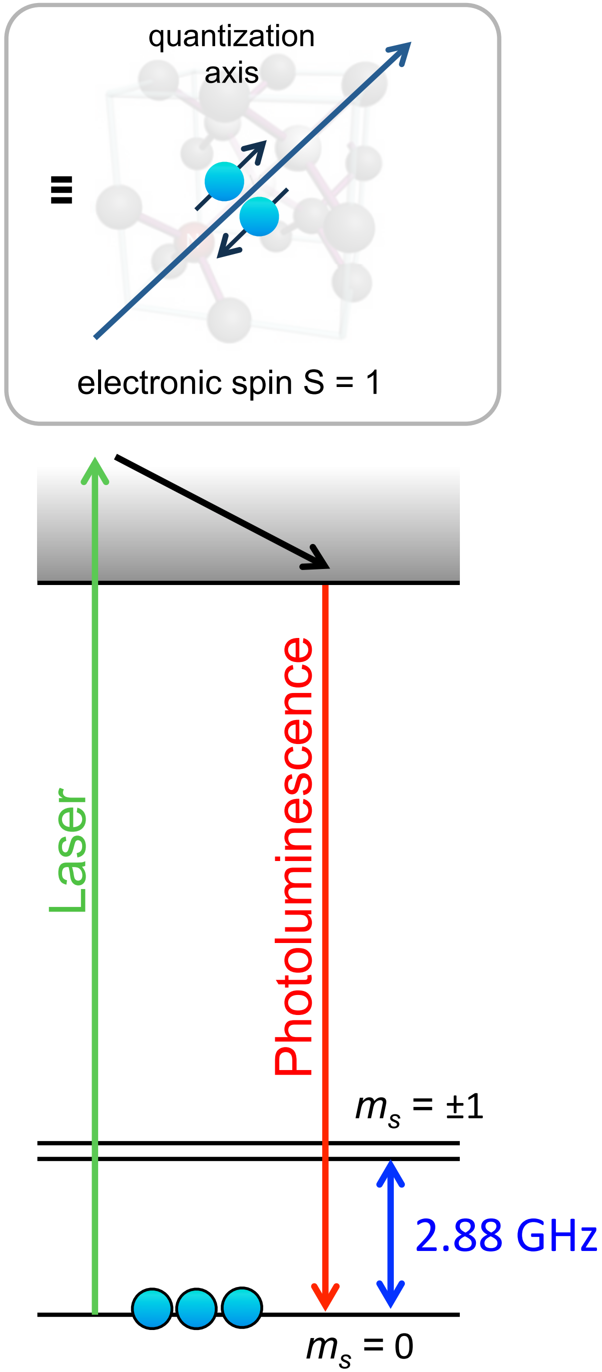

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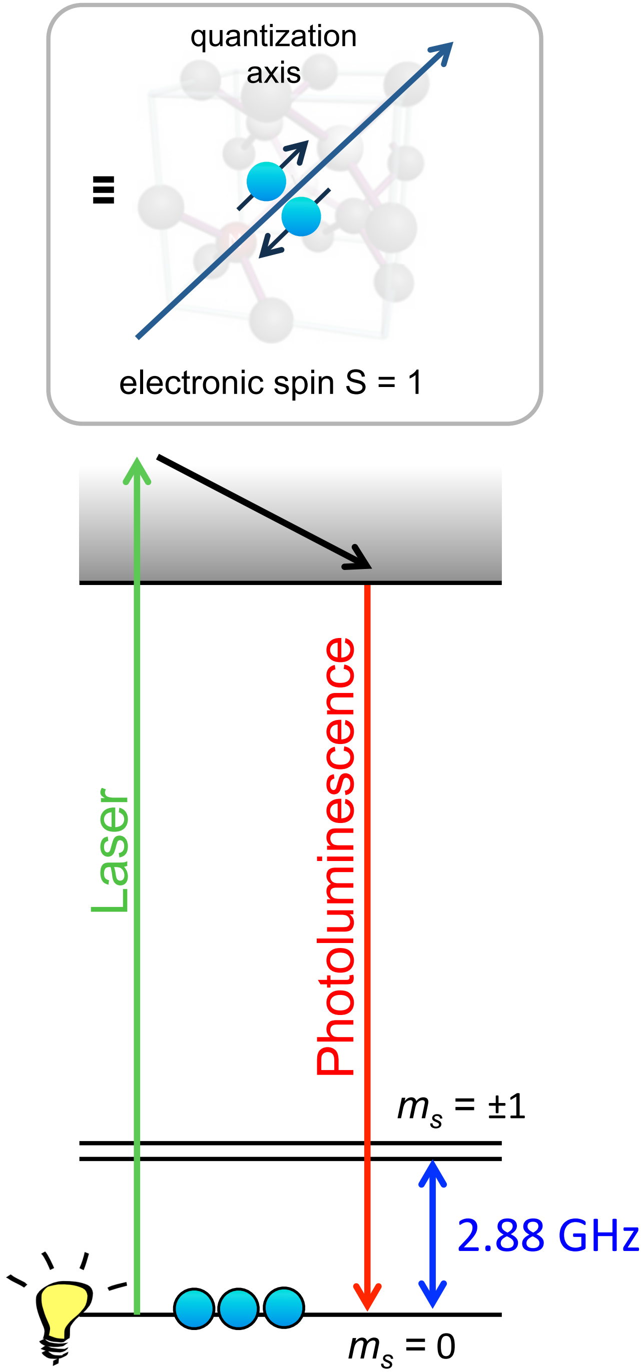

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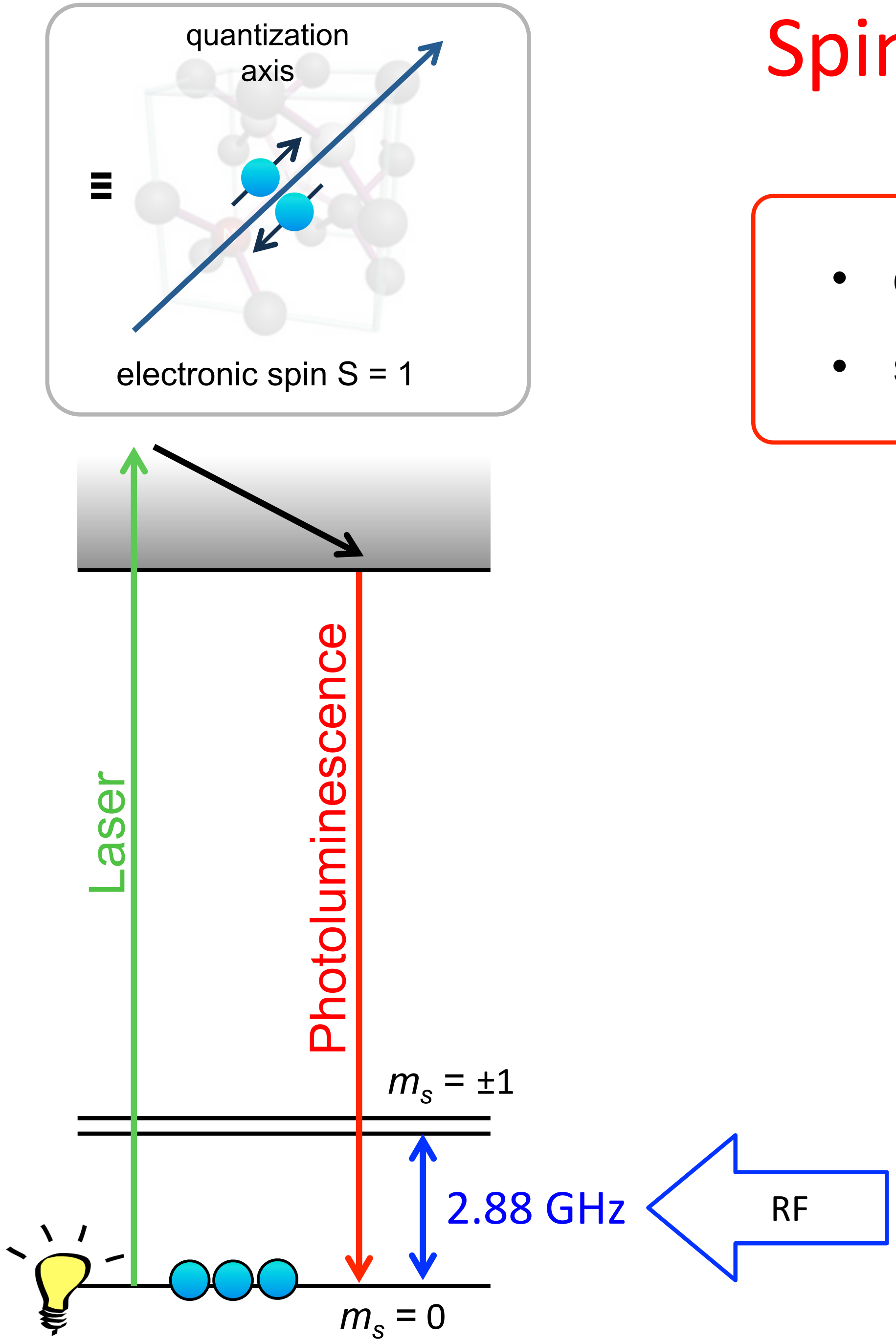

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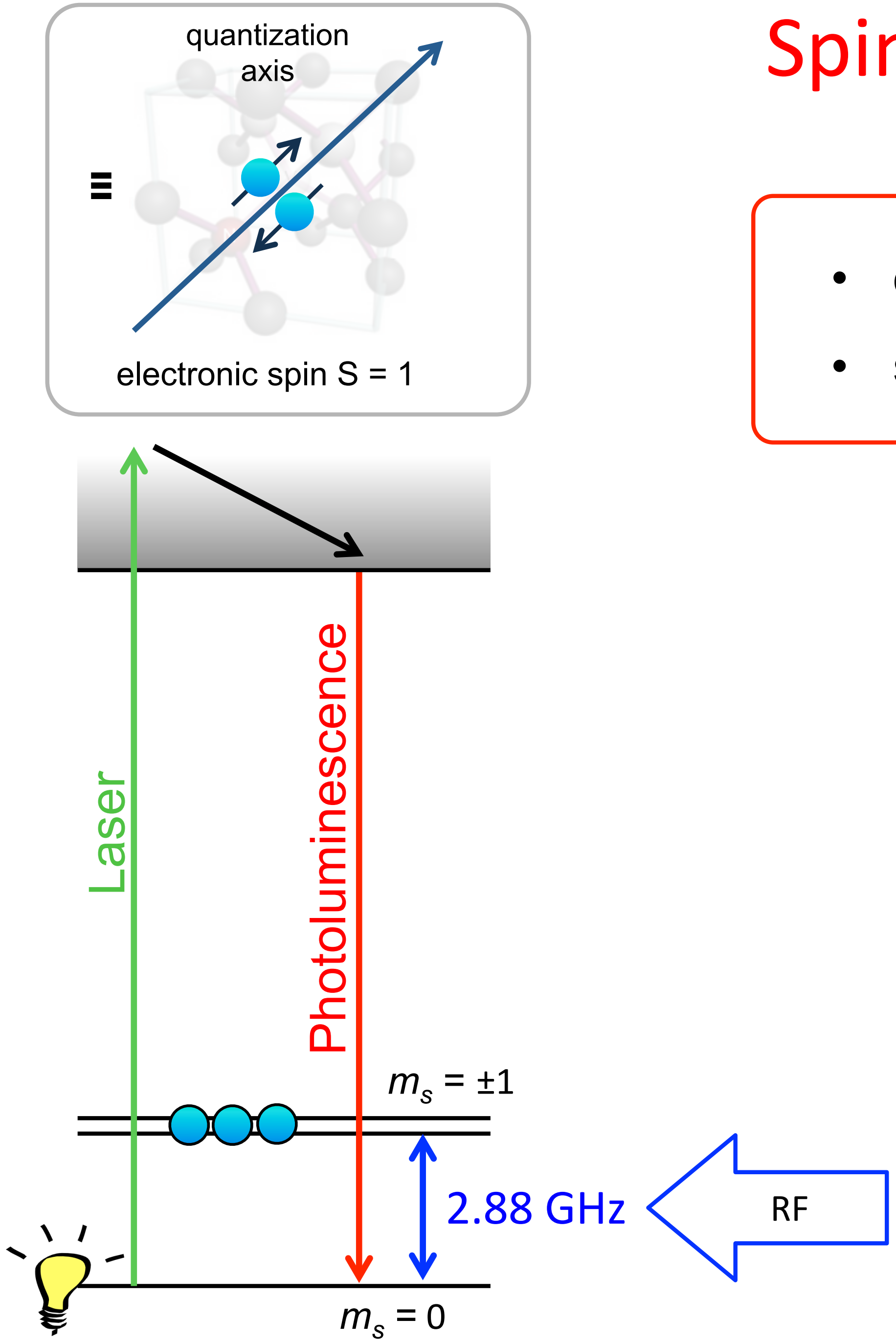

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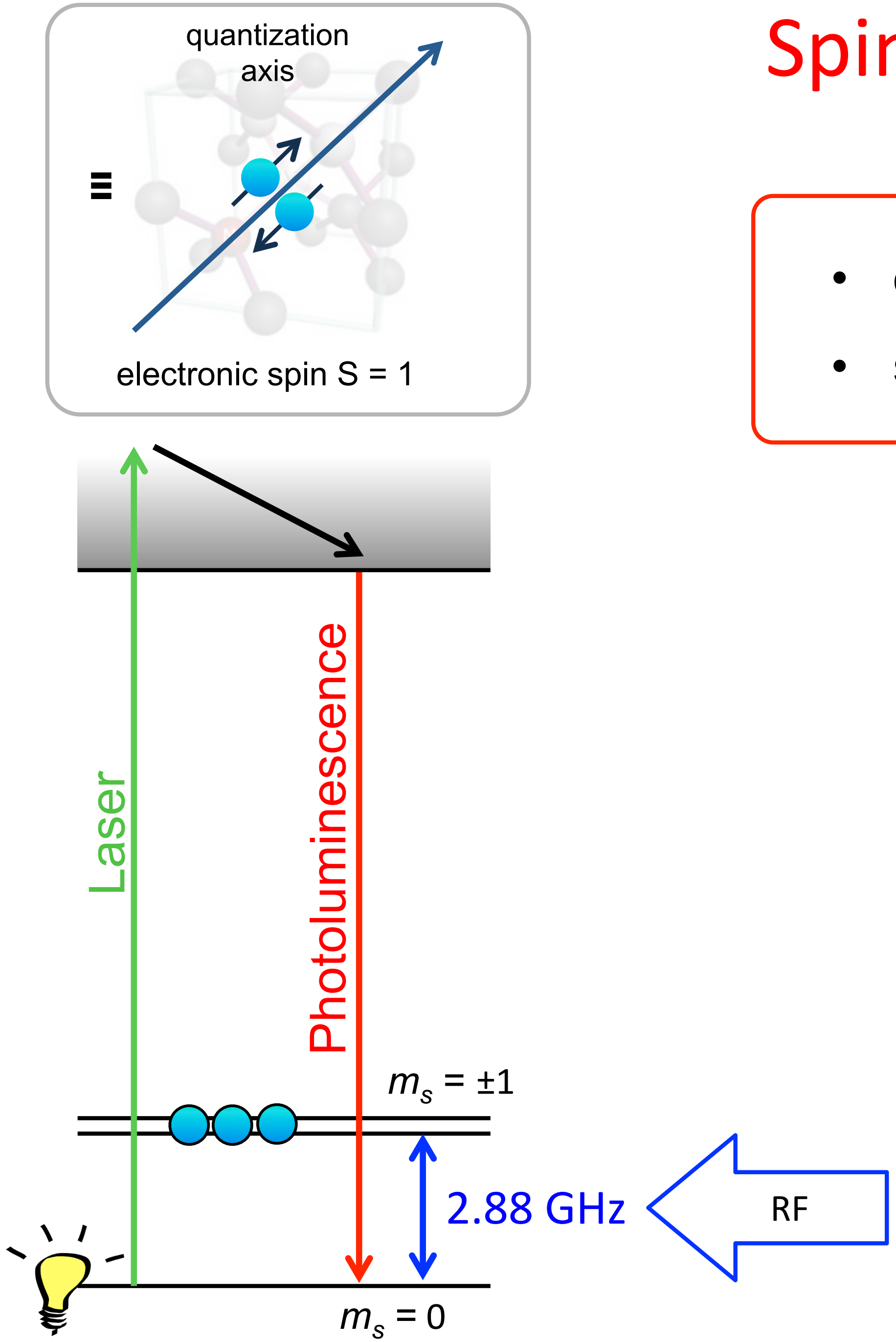

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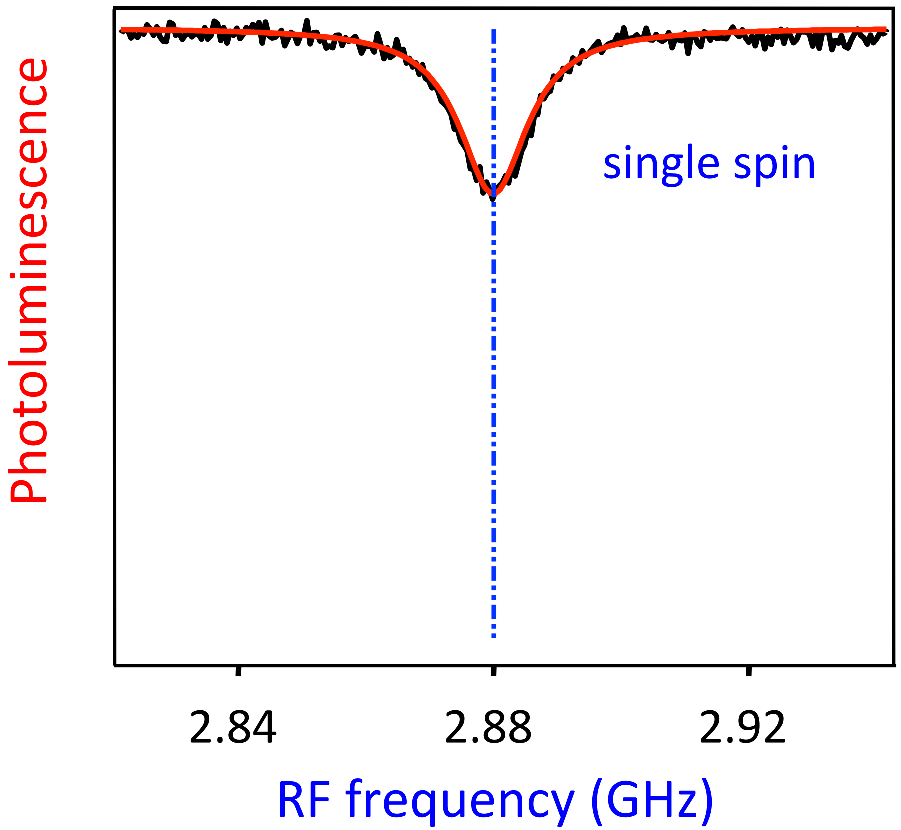

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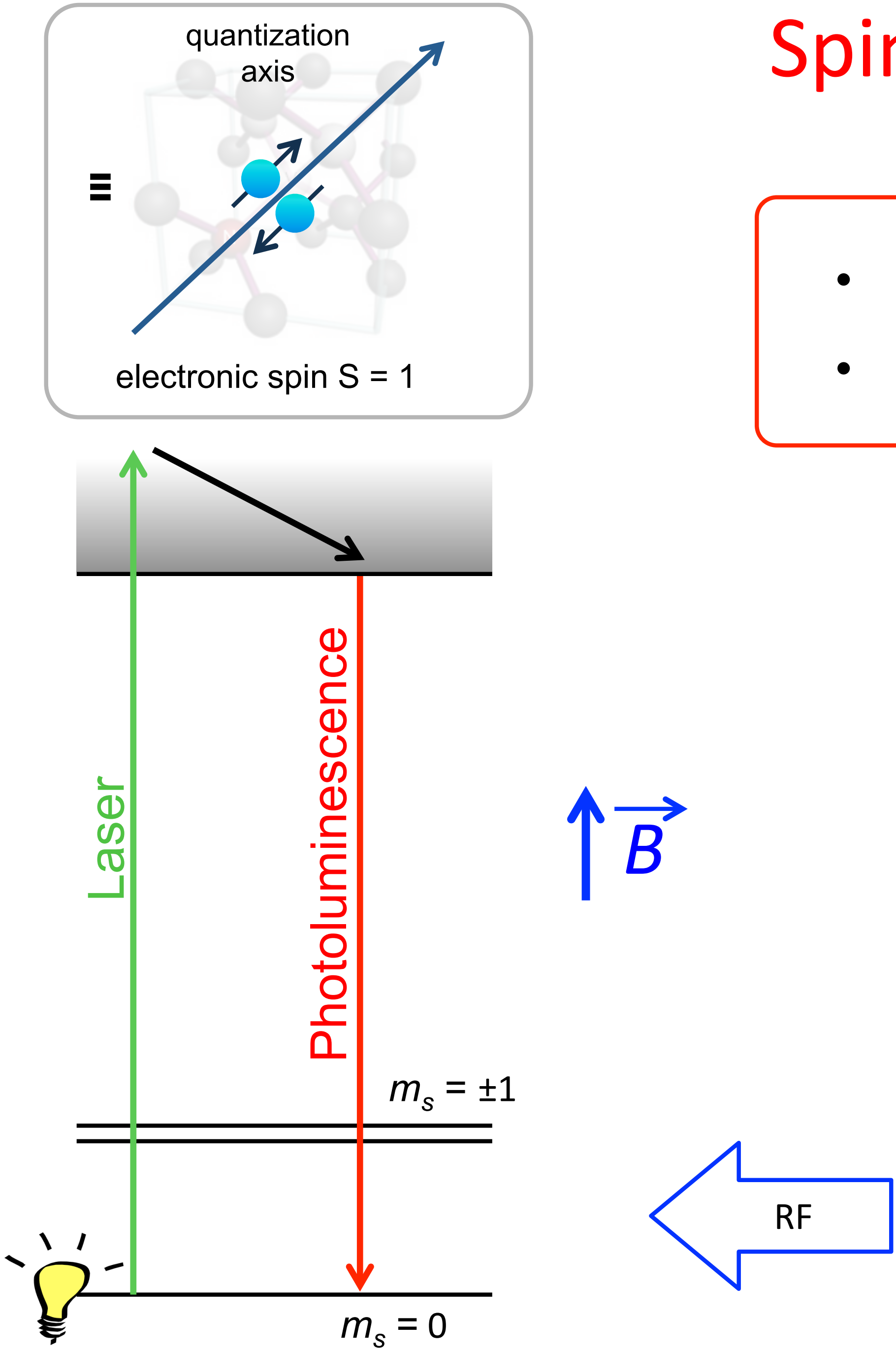

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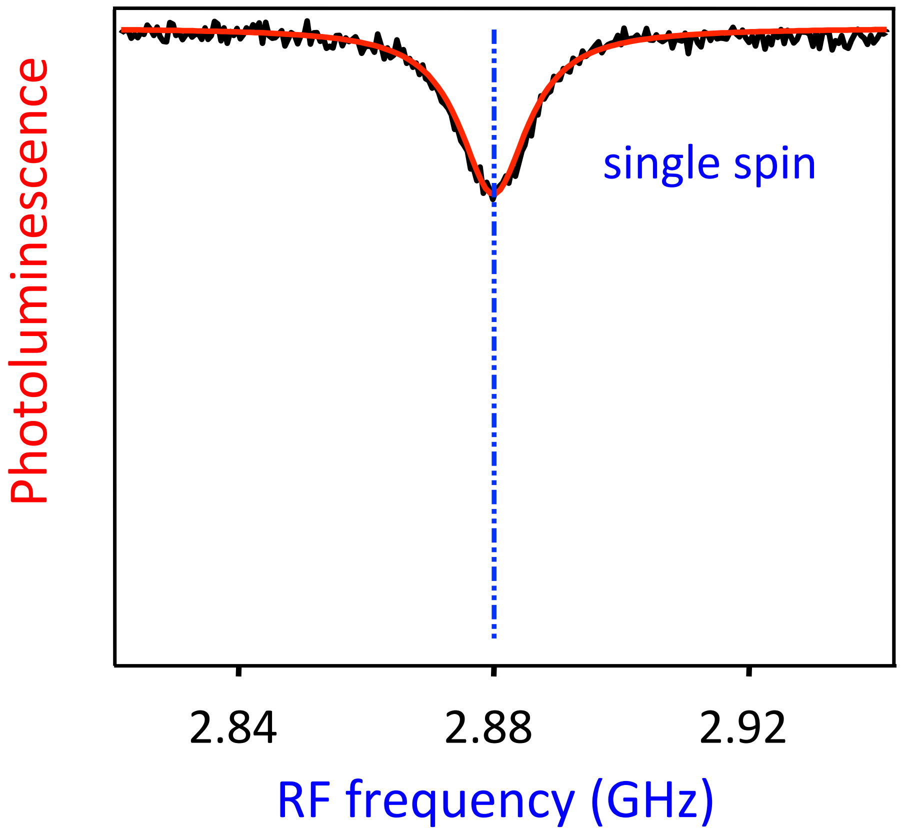

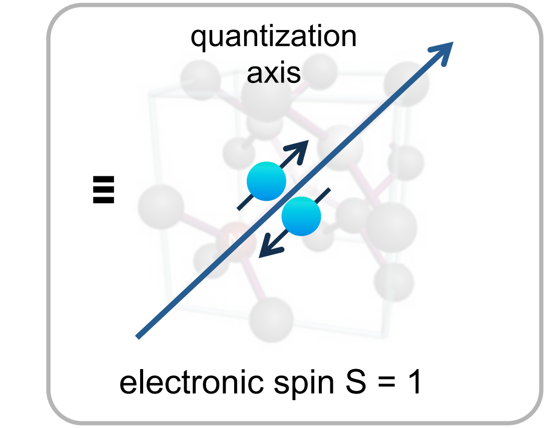

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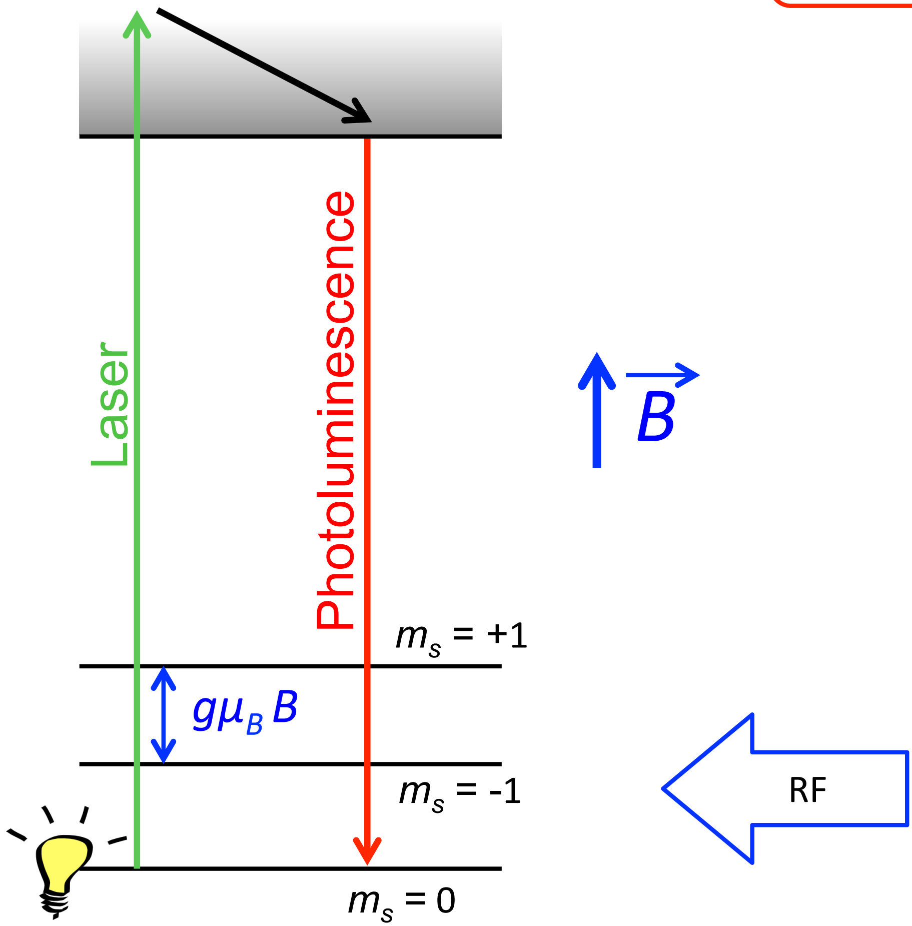

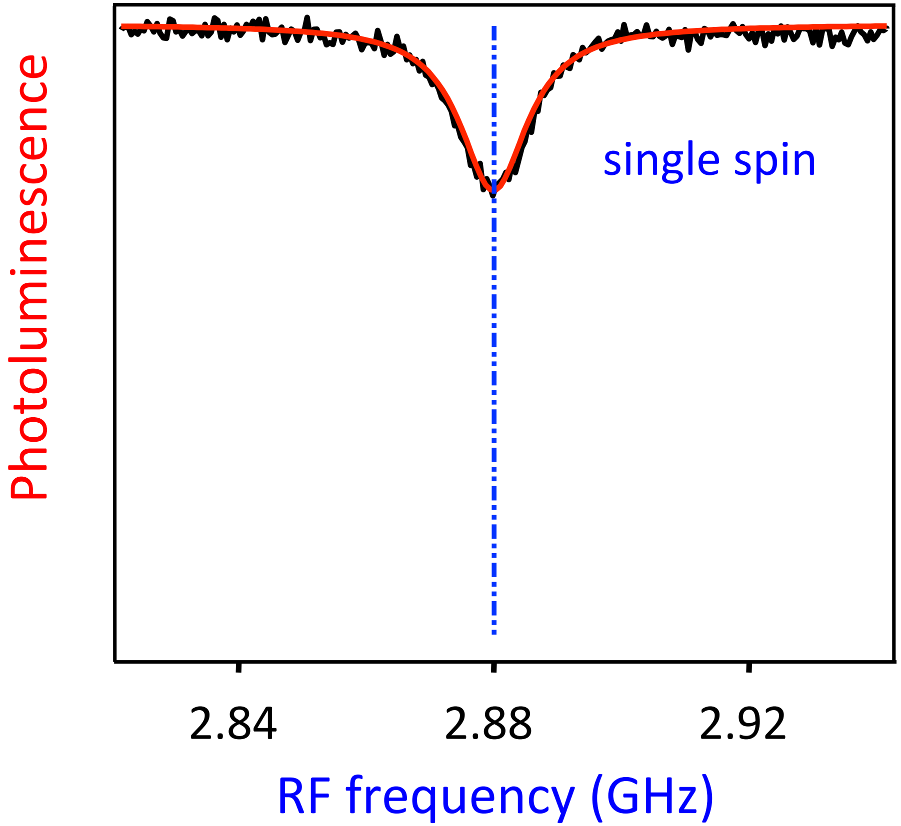

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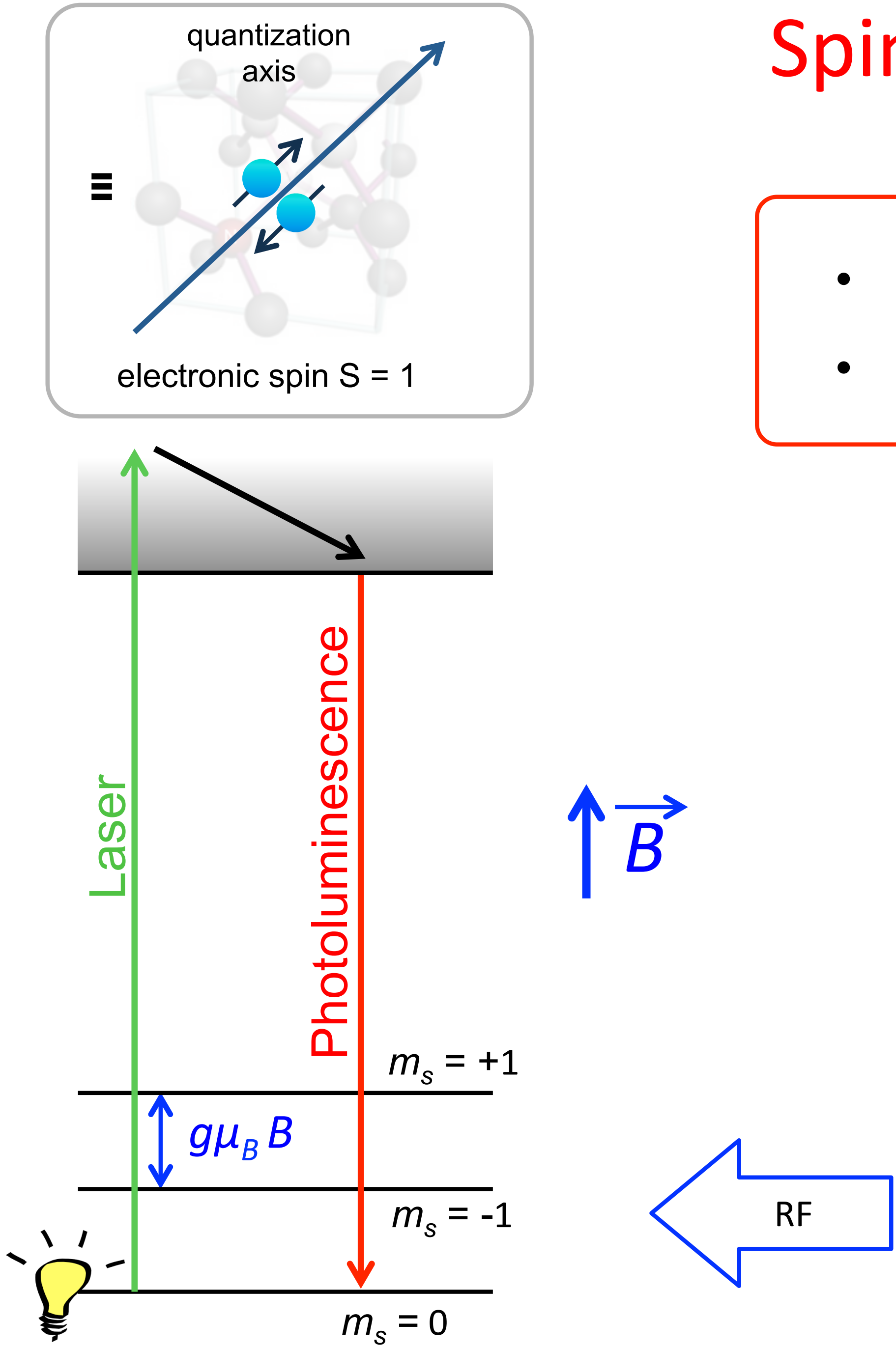

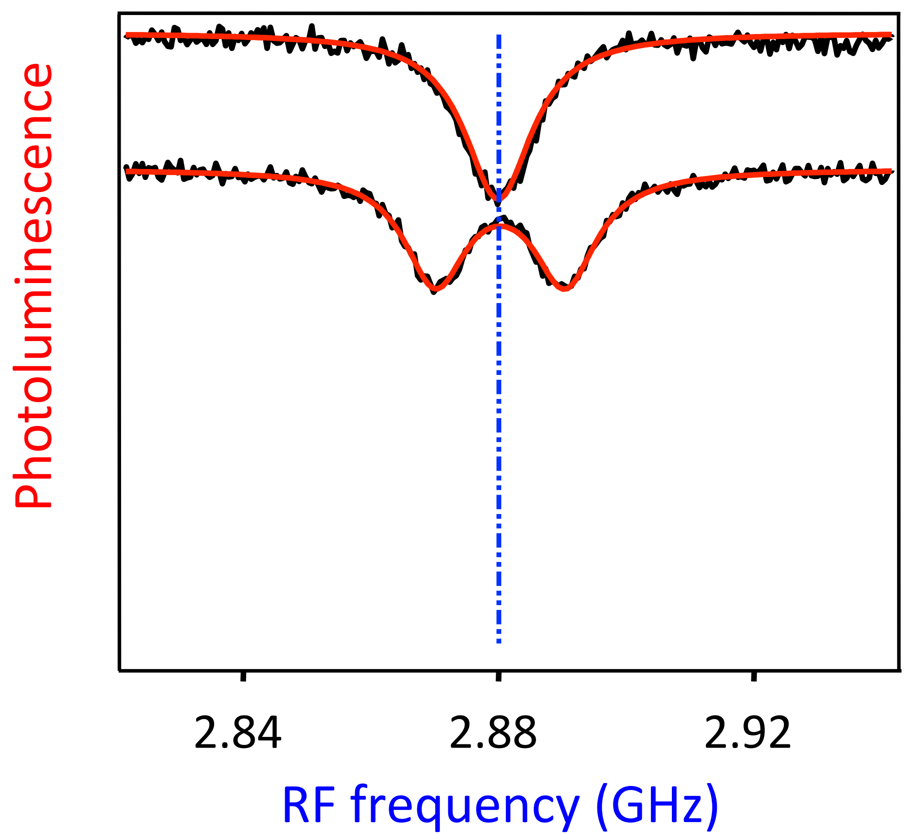

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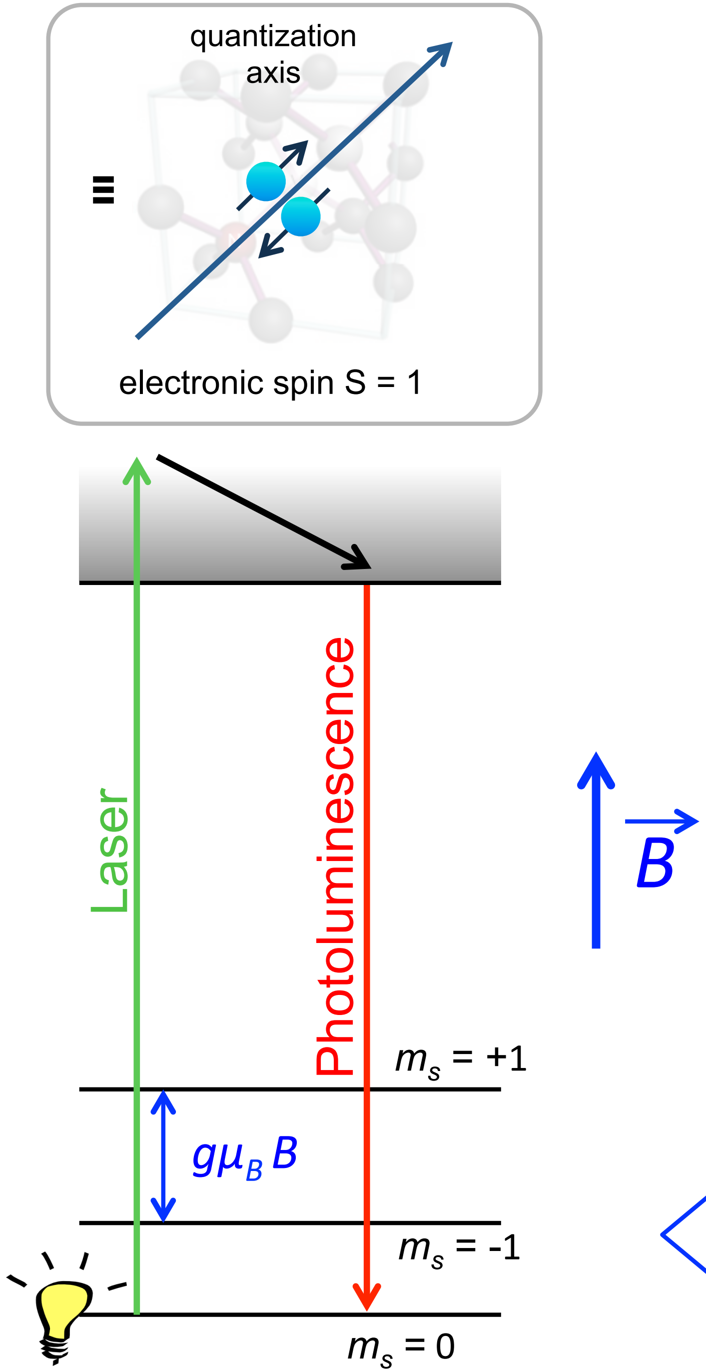

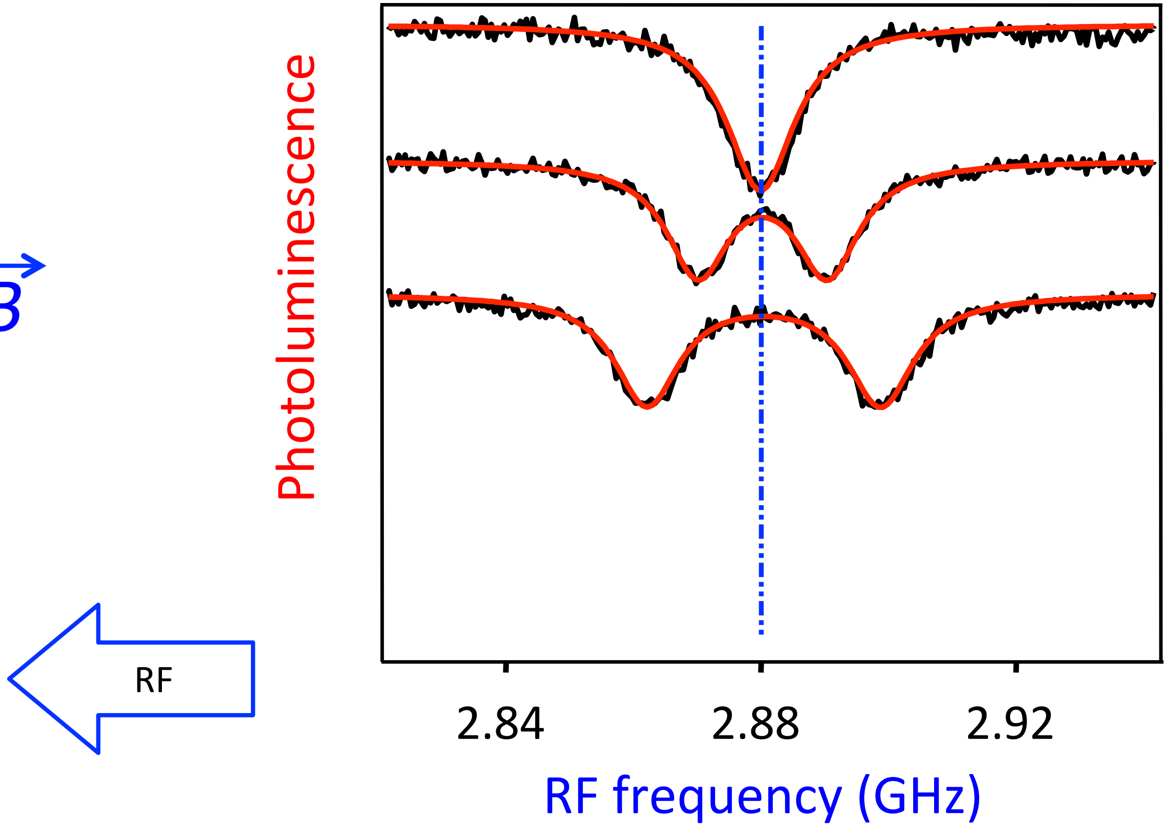

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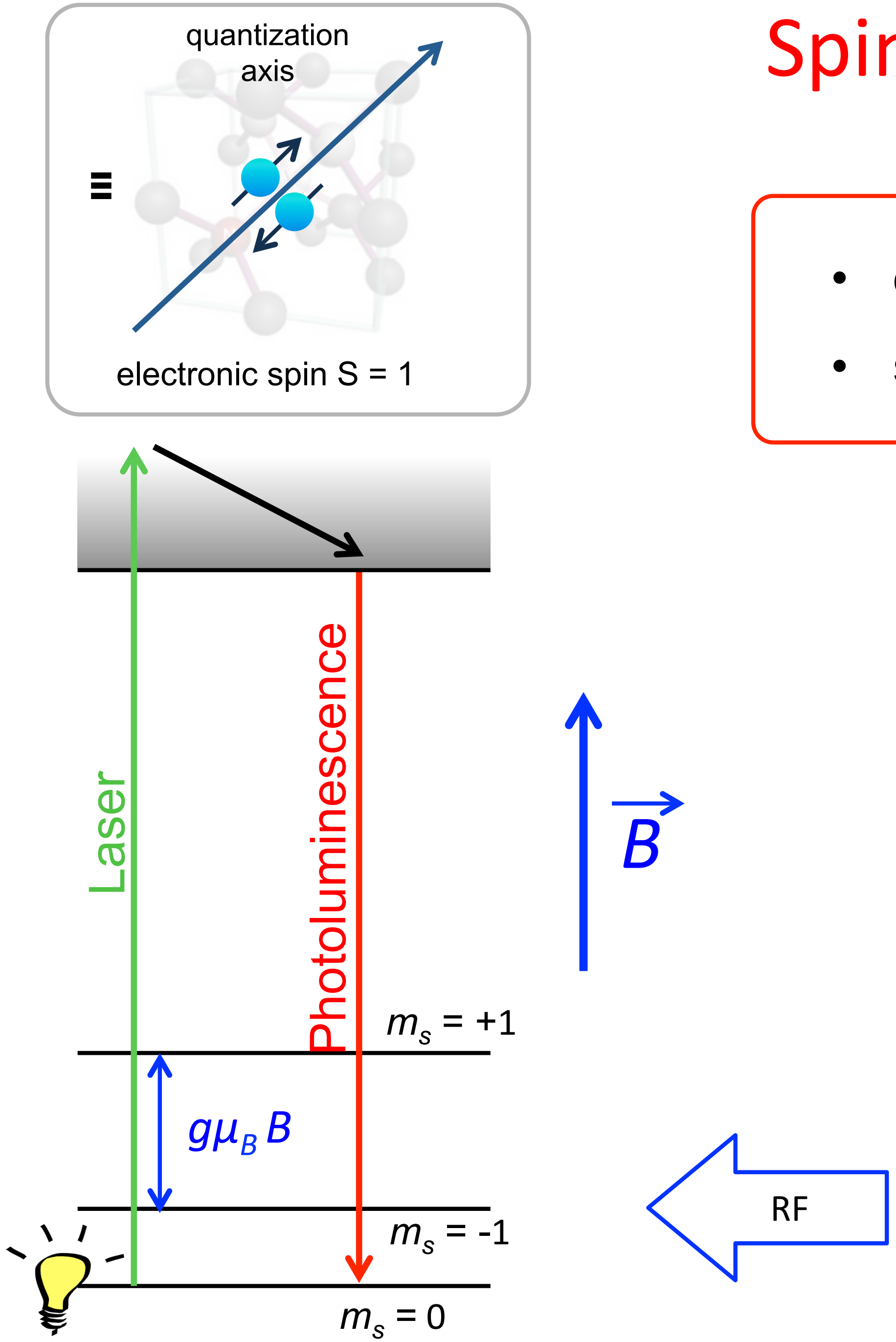

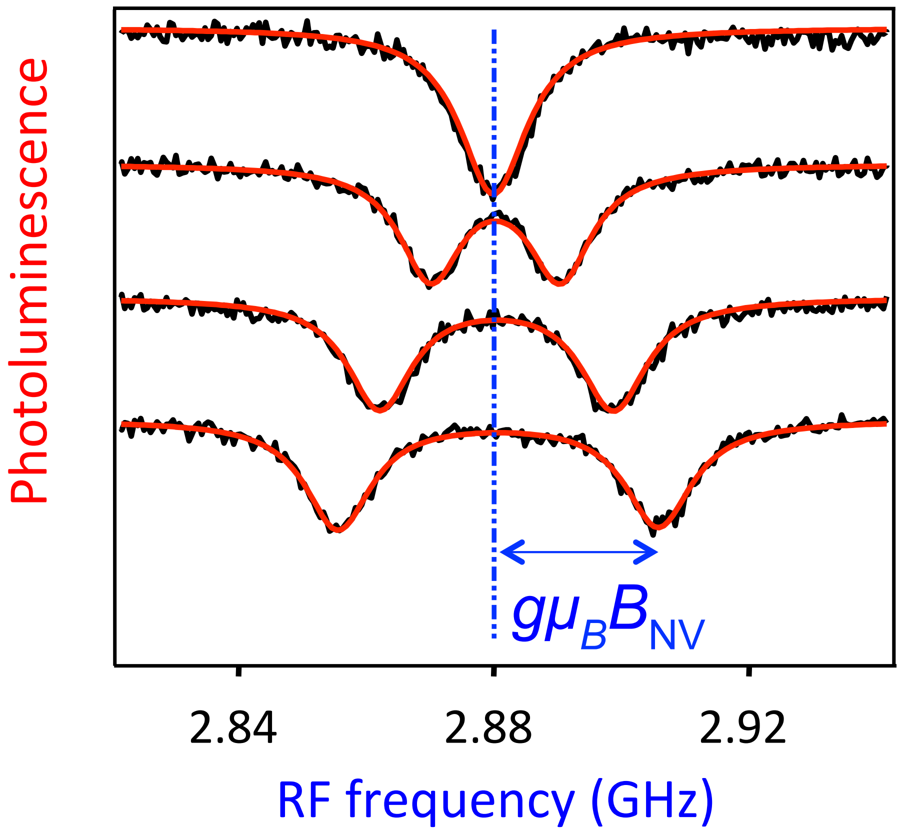

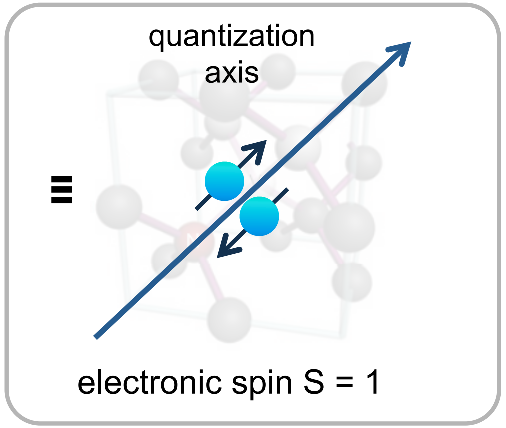

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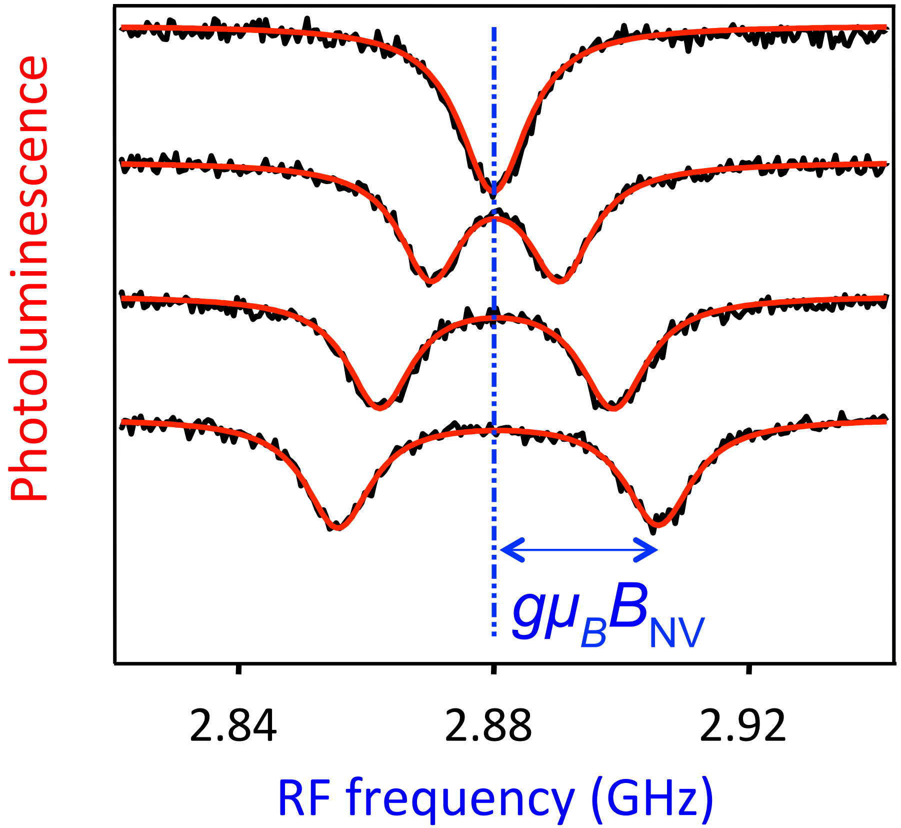
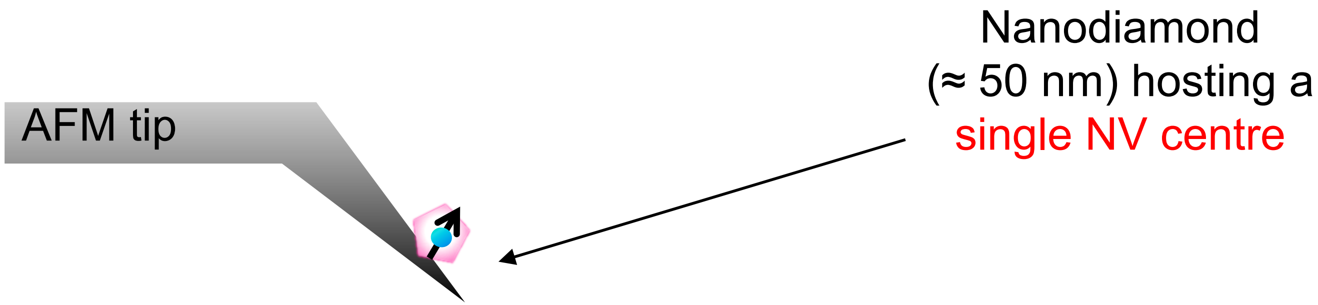


The NV centre is intrinsically an atomic size magnetometer

NV microscope: ND grafted at then end of the tip



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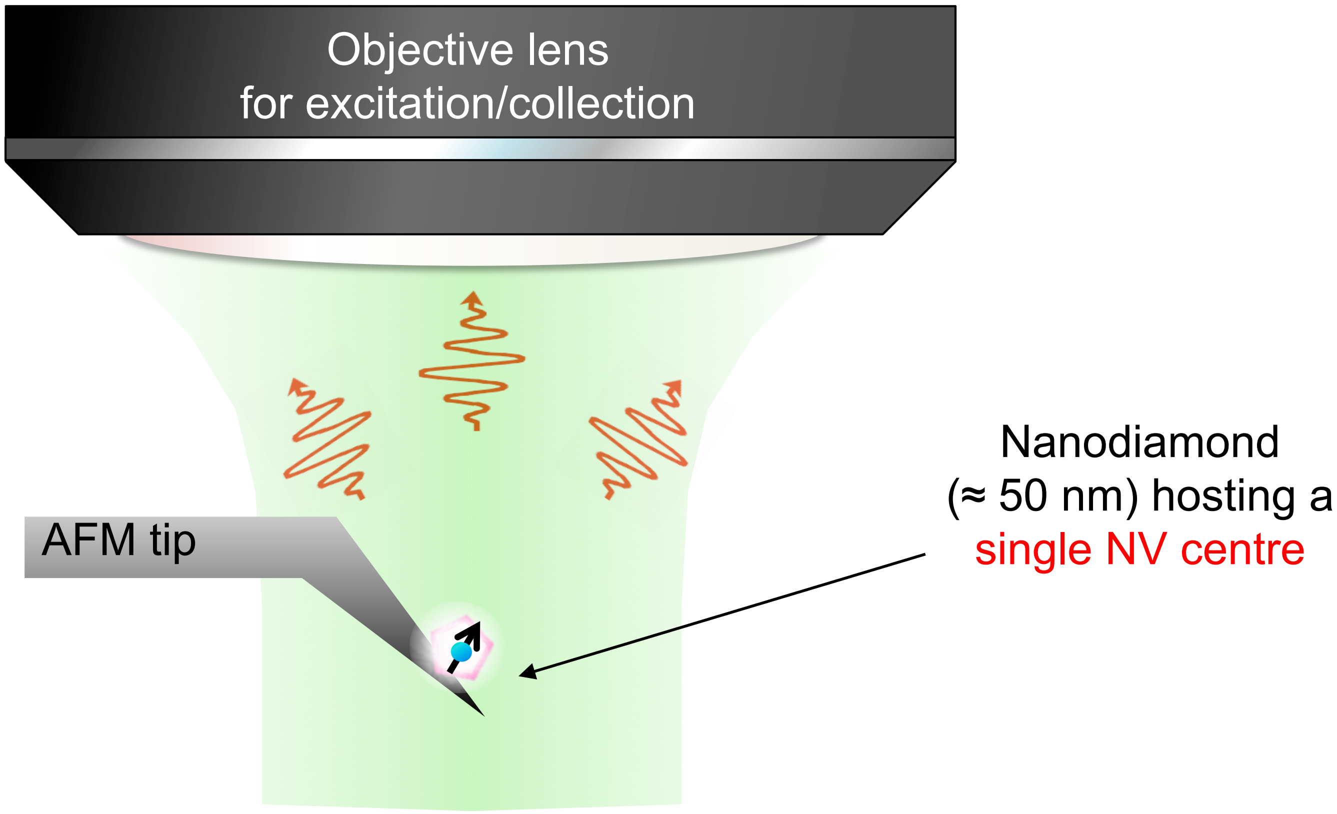
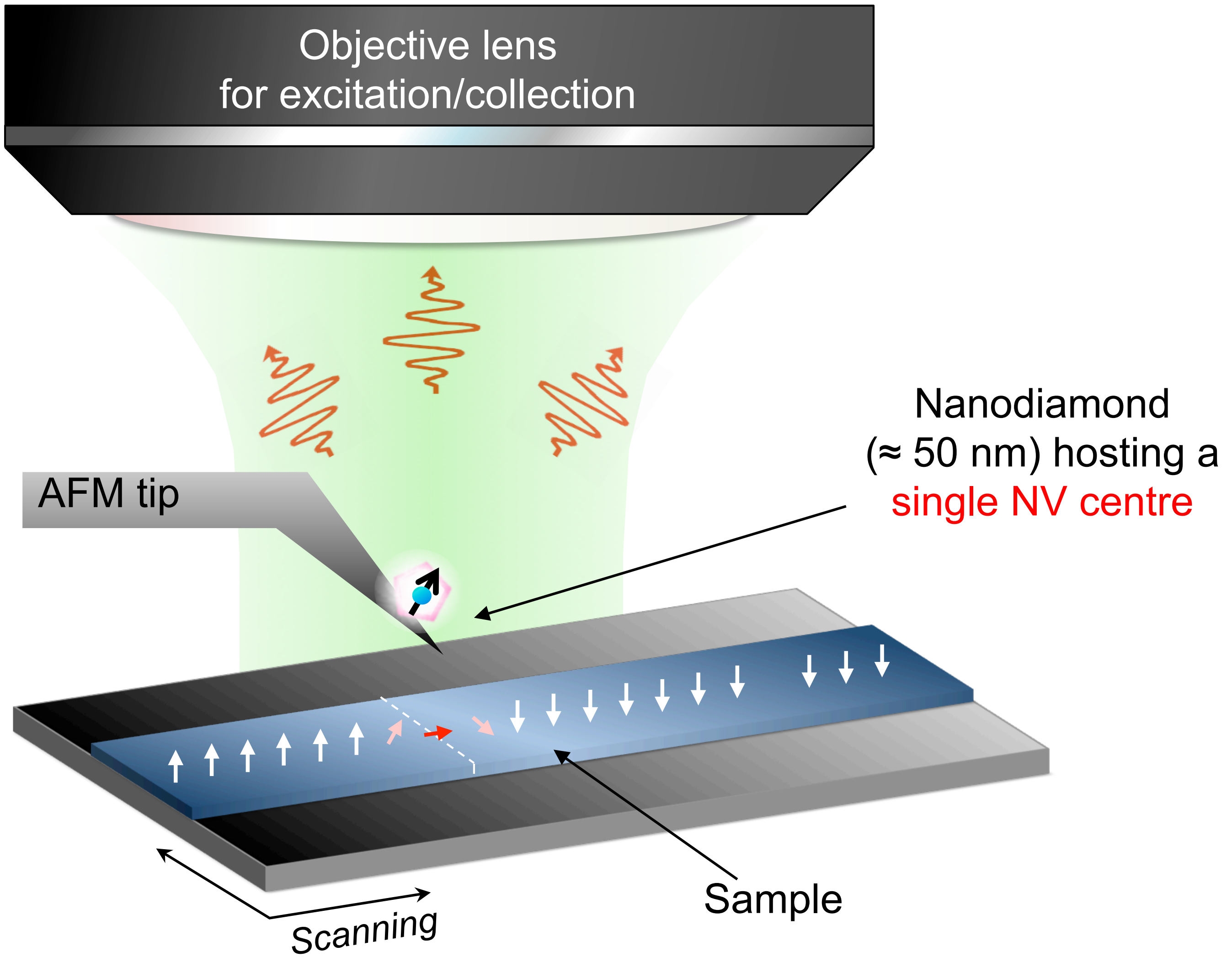
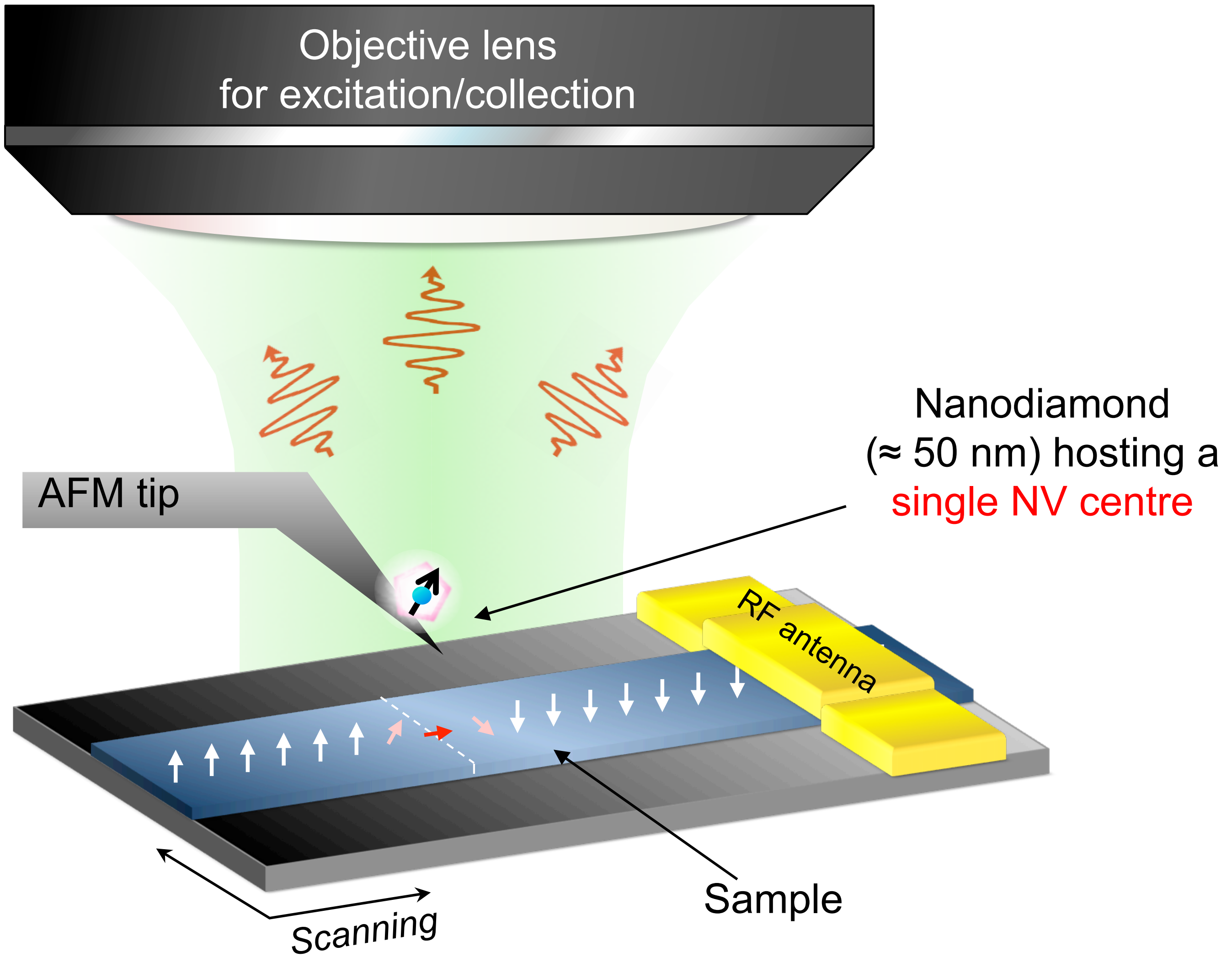


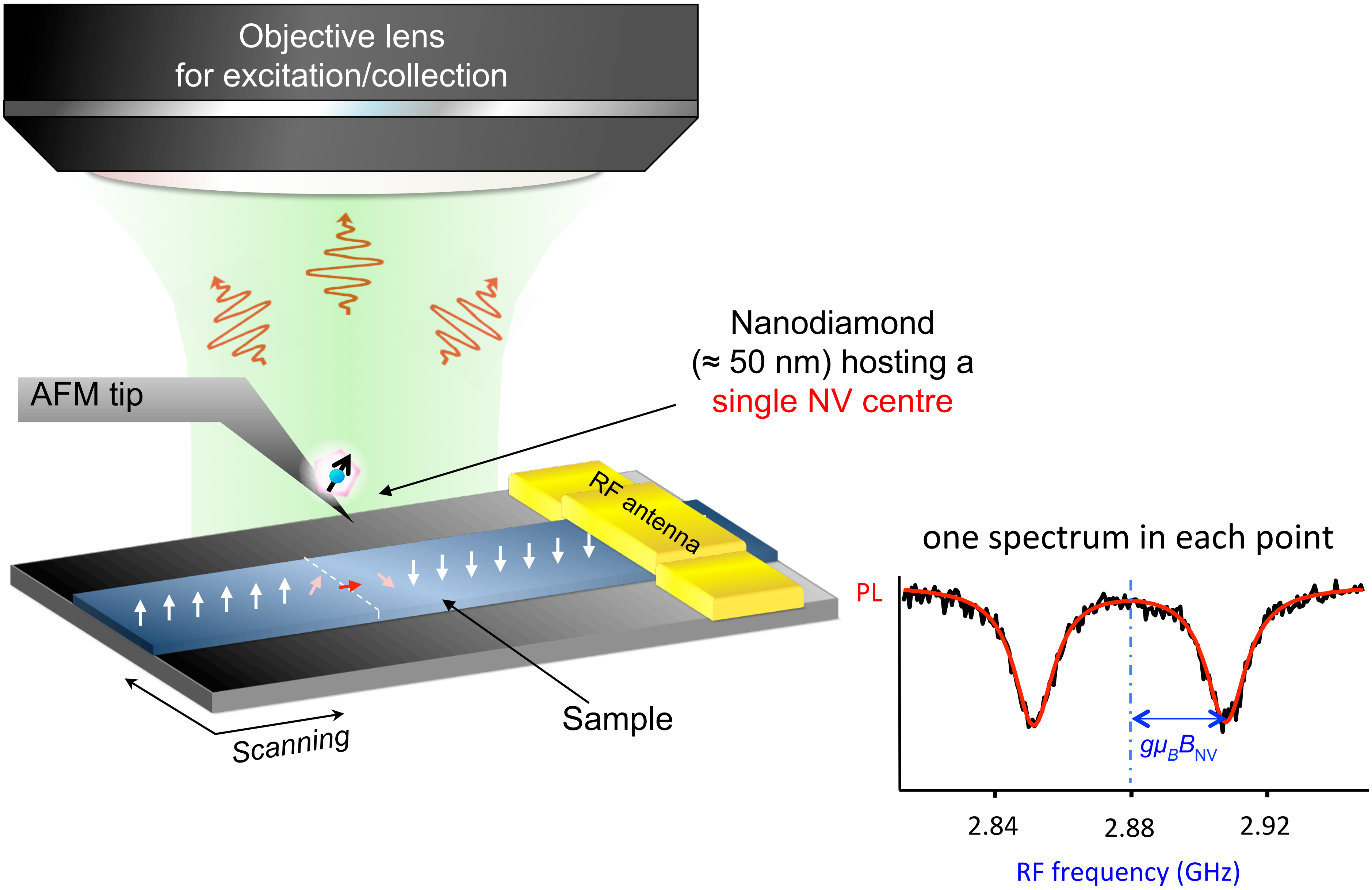
NV microscope: ND grafted at then end of the tip



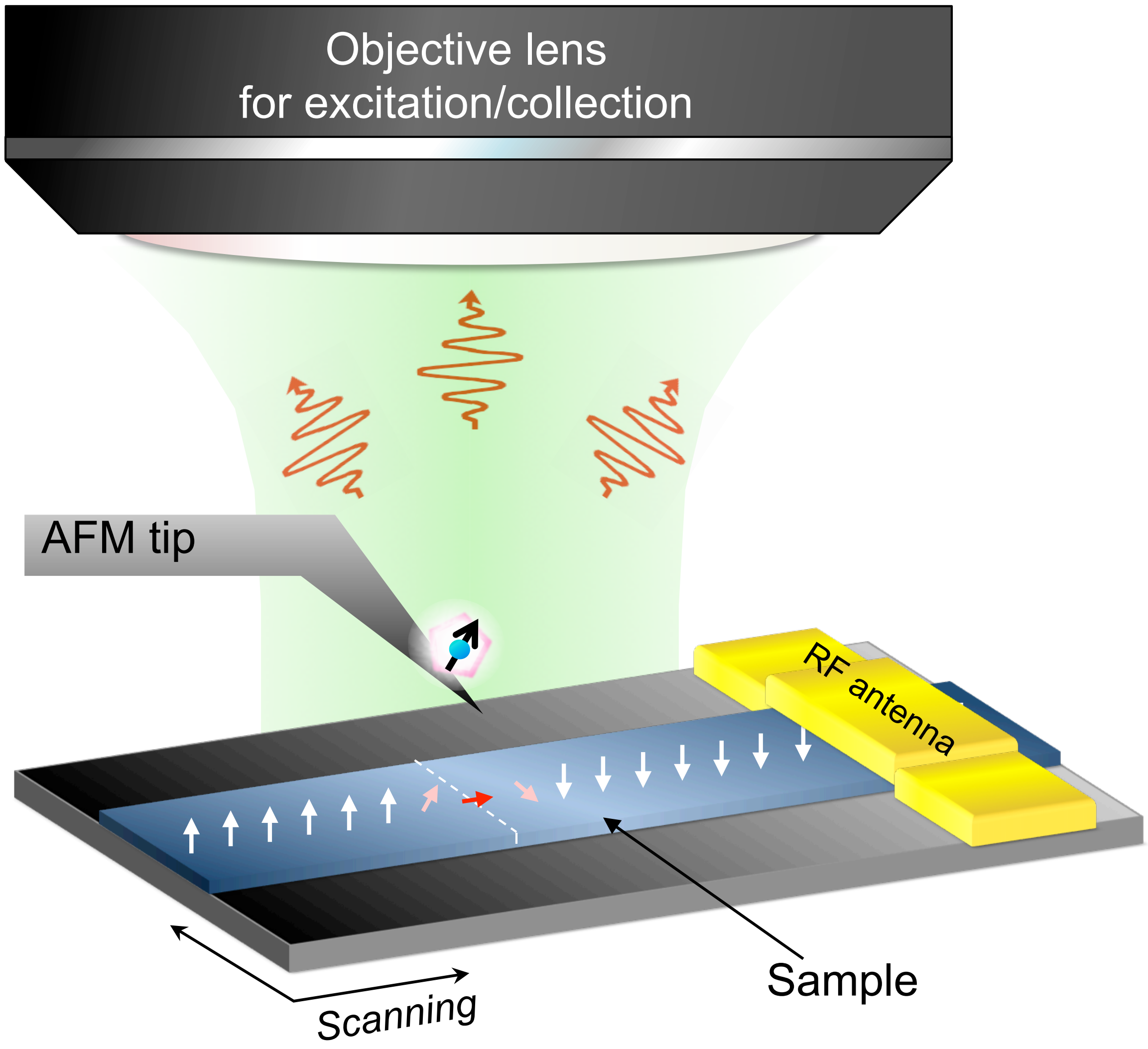
NV microscope: ND grafted at then end of the tip

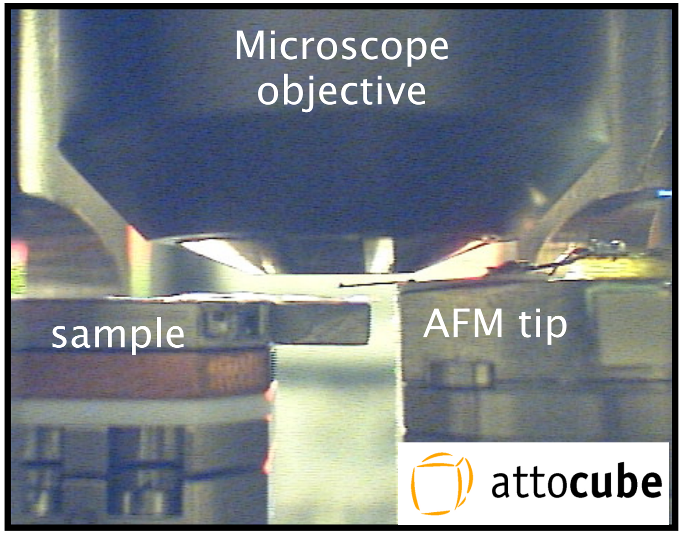


NV microscope: ND grafted at then end of the tip

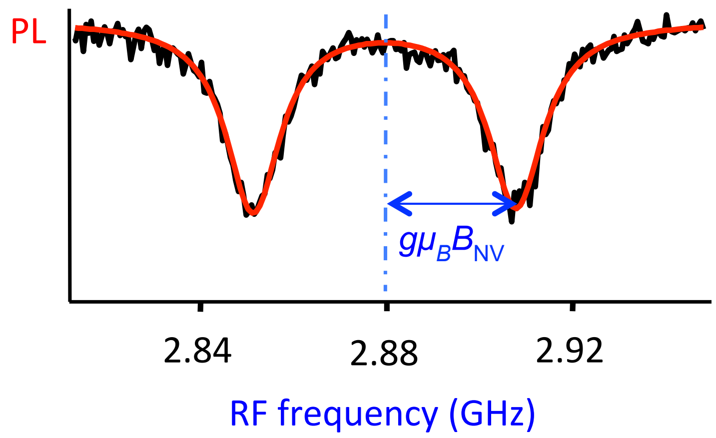


NV microscope: ND grafted at then end of the tip

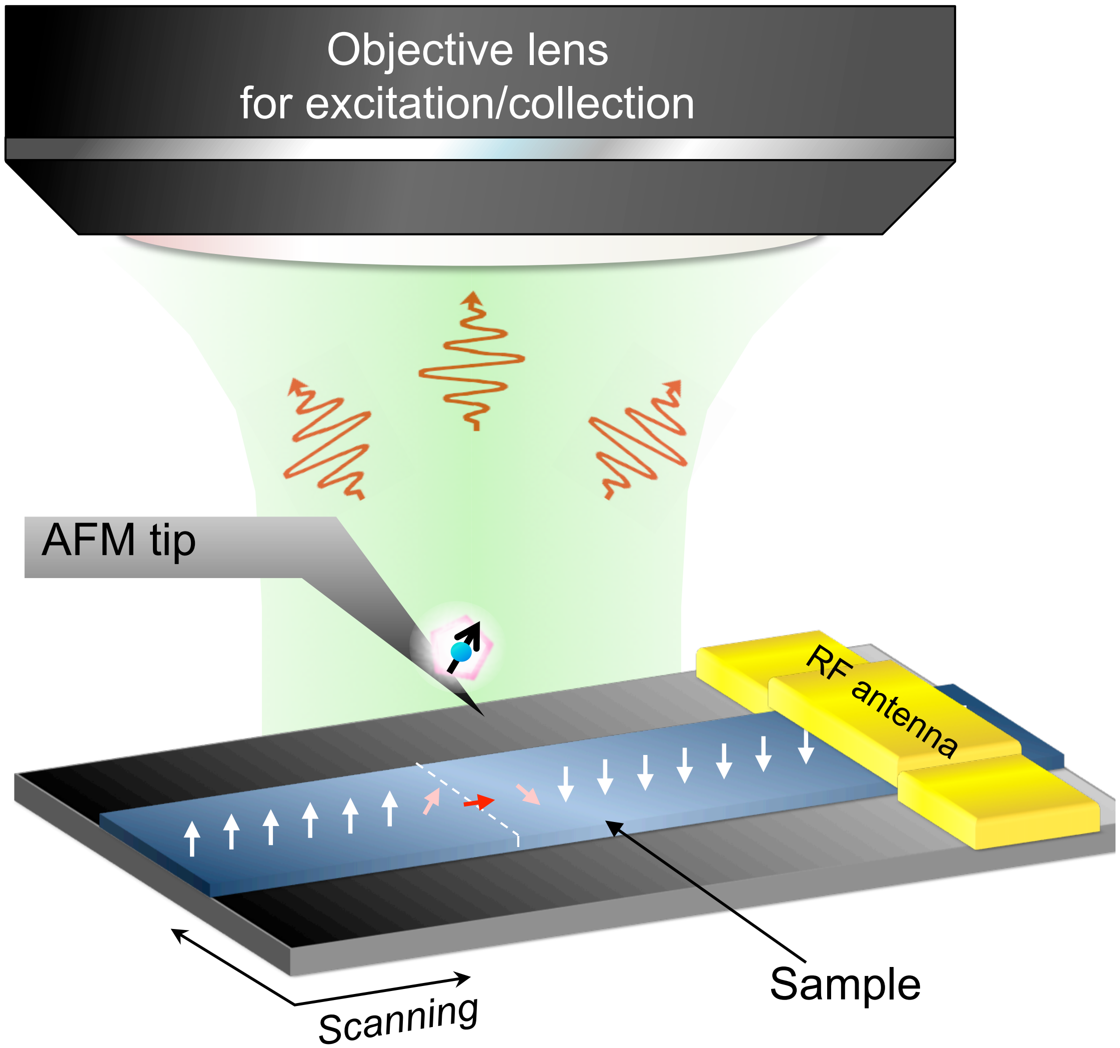


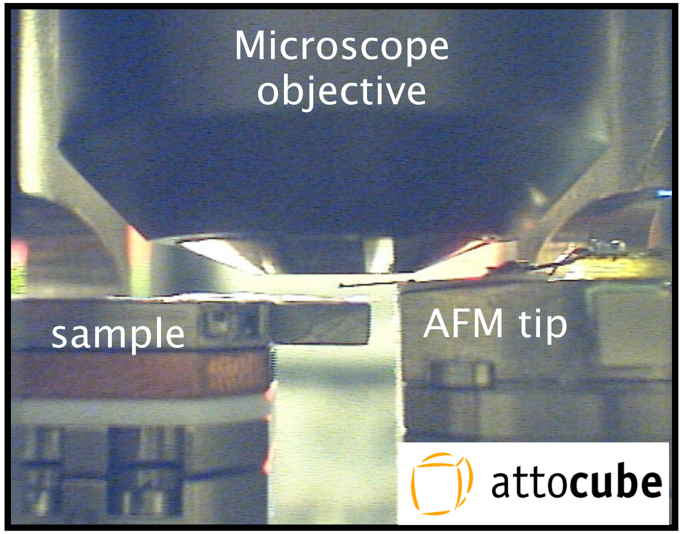


one spectrum in each point

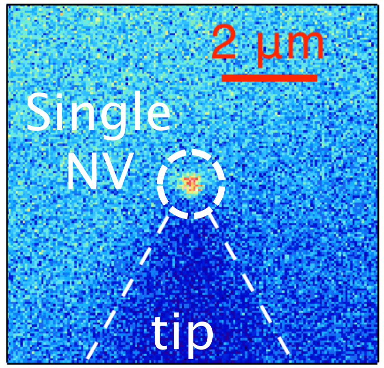


NV microscope: ND grafted at then end of the tip





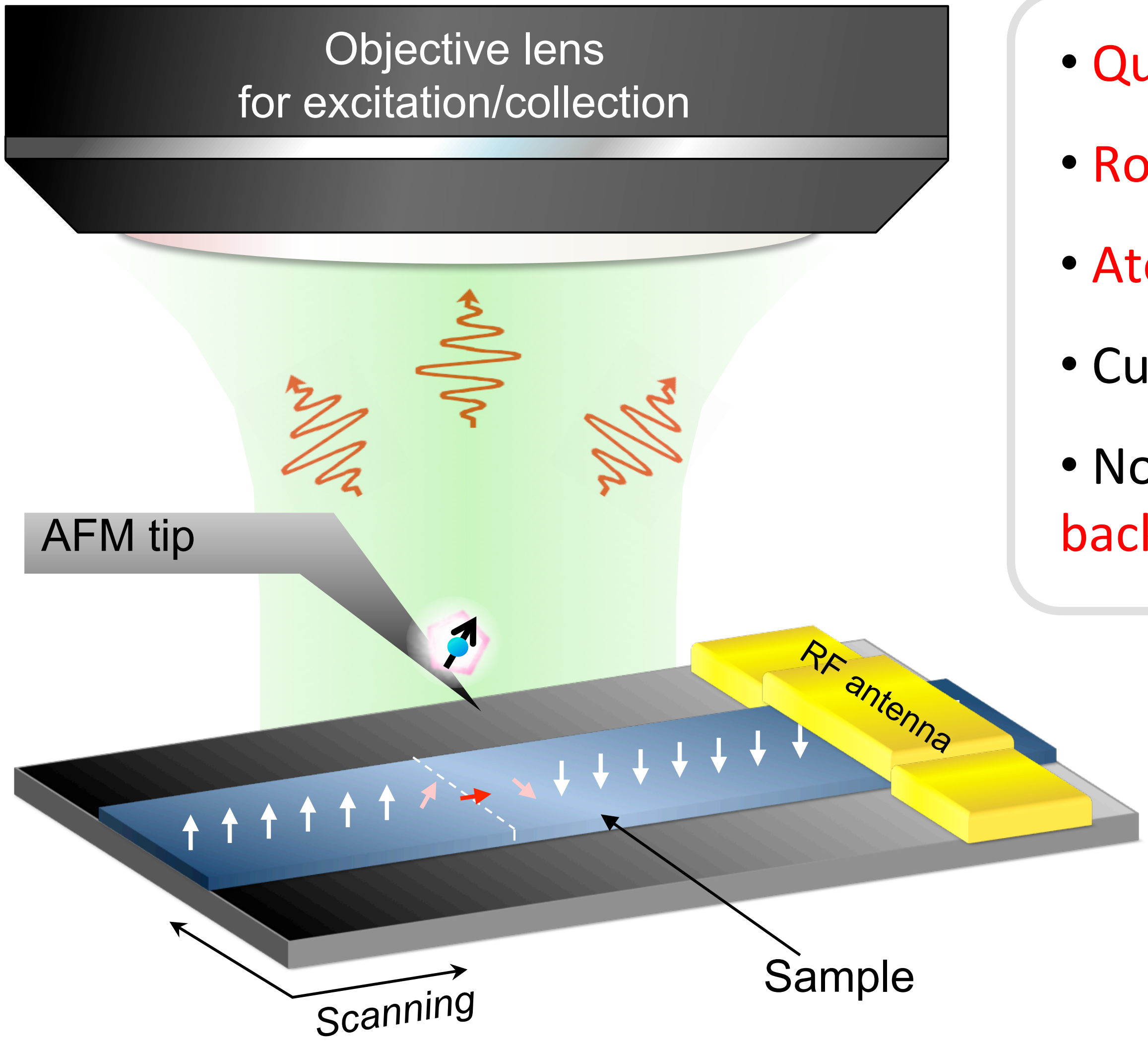
Single NV at the apex of
the AFM tip



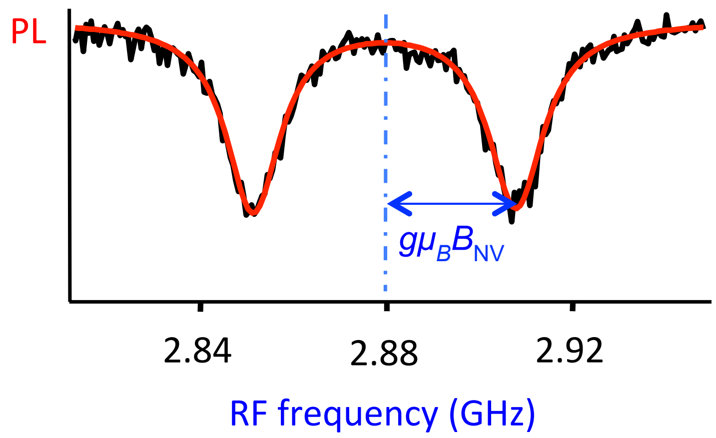
L. Rondin et al. *Appl. Phys. Lett.* **100**, 153118 (2012)

L. Rondin et al., *Nat. Comm.* **4**, 2279 (2013)

NV microscope: ND grafted at then end of the tip

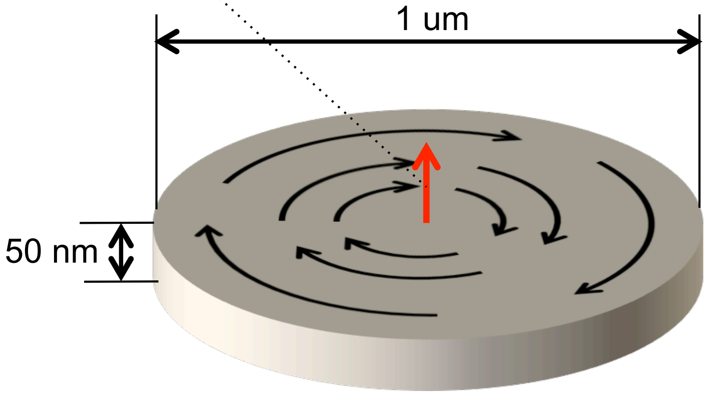


- Quantitative
- Room temperature operation
- Atomic sized detection volume
- Current sensitivity: 10 µT/√Hz
- Non-magnetic tip (ie. no magnetic back action)

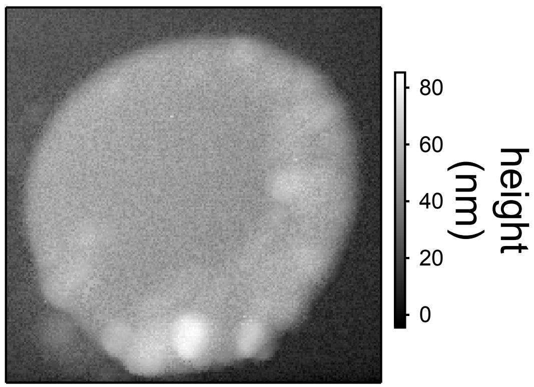


Imaging ferromagnetic vortices

vortex core: ~10nm

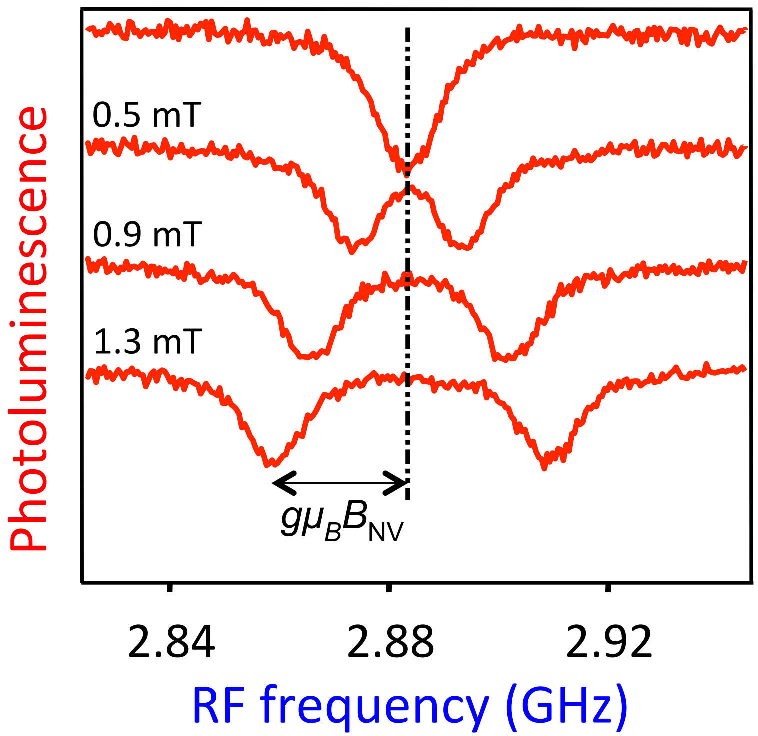


Permalloy disk – in plane magnetization

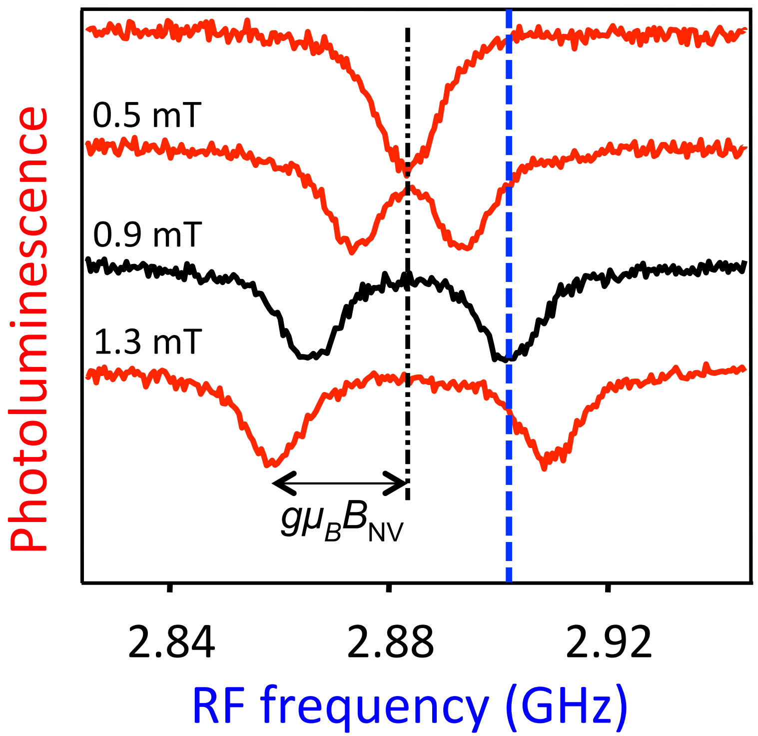


AFM topography

Imaging techniques



Imaging techniques

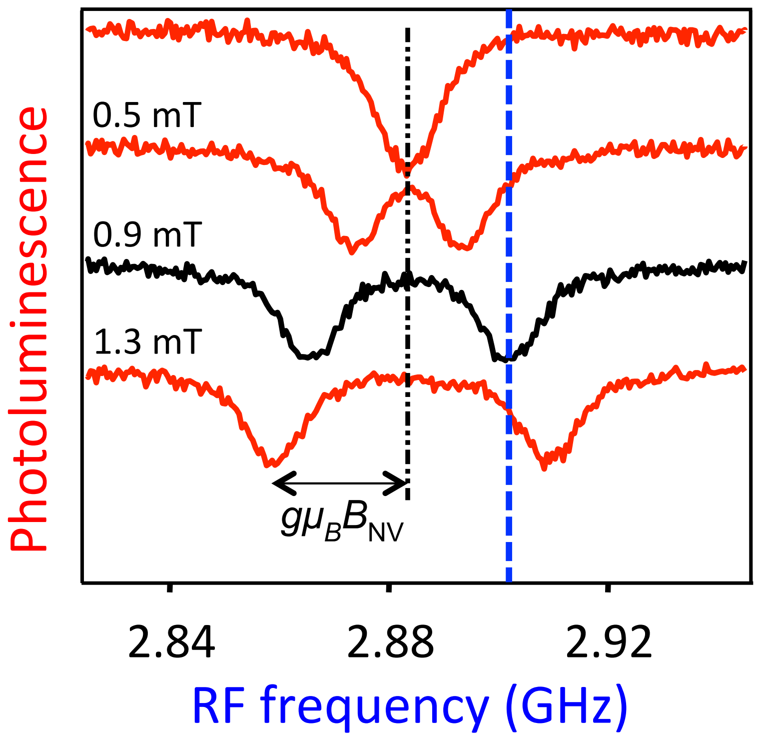


one RF frequency

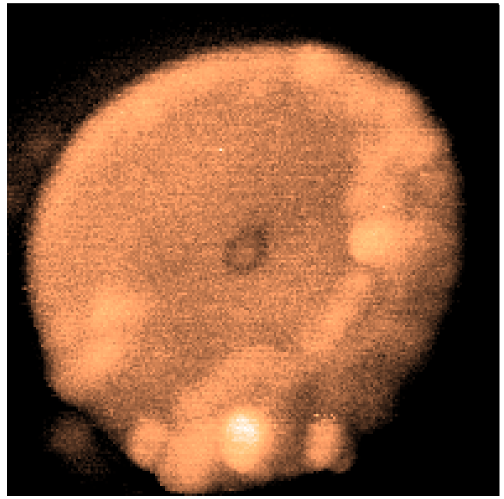
|||

one magnetic field value

Imaging techniques

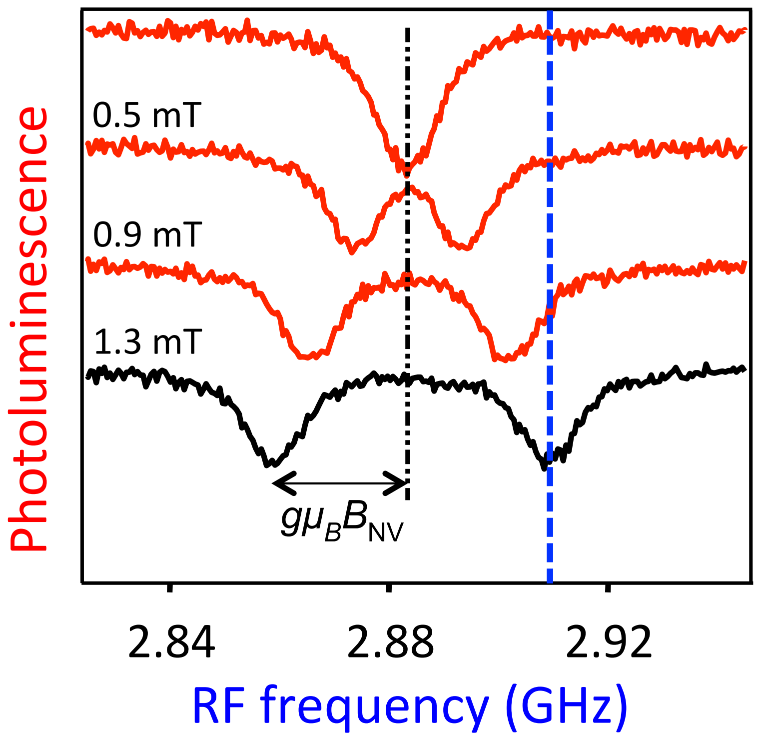


one RF frequency
|||
one magnetic field value



$|B_{NV}|$=0.9 mT

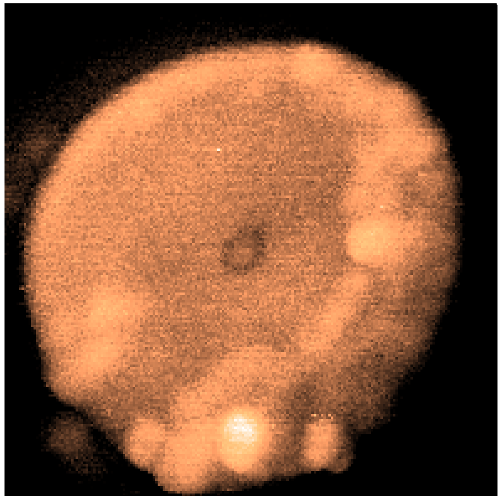
Imaging techniques



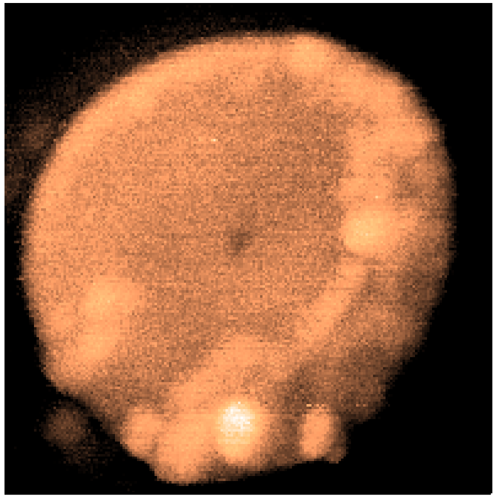
one RF frequency

|||

one magnetic field value

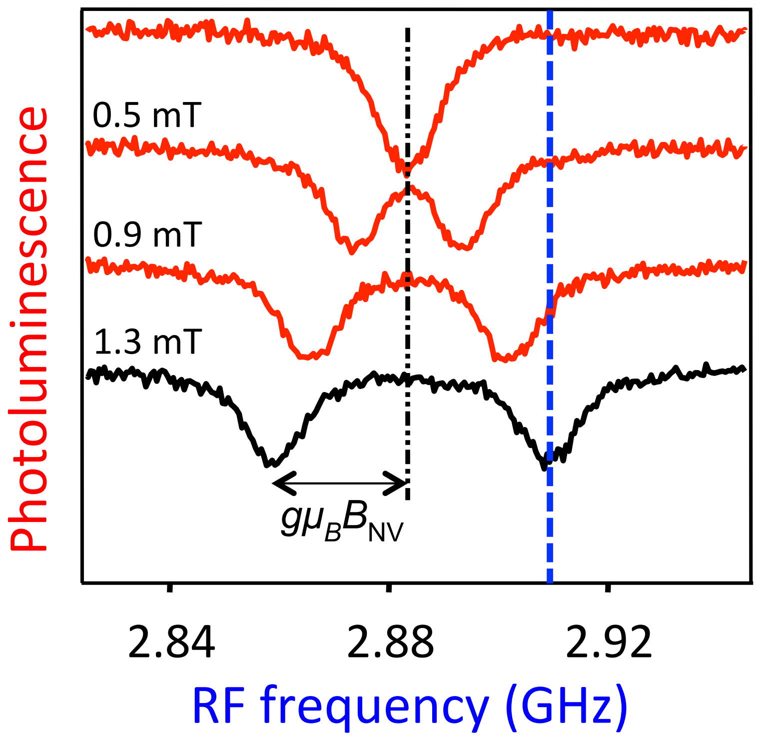


$|B_{NV}|$=0.9 mT



$|B_{NV}|$=1.3 mT

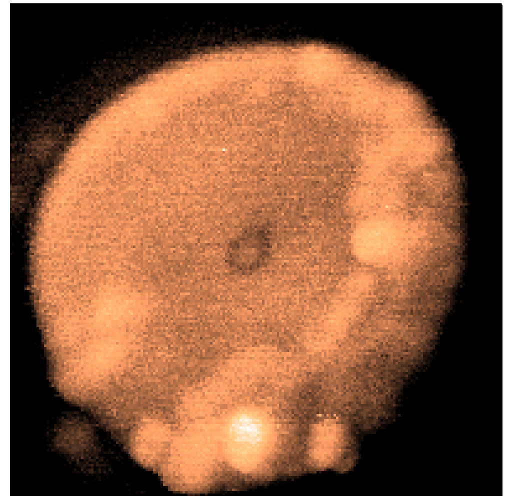
Imaging techniques



one RF frequency

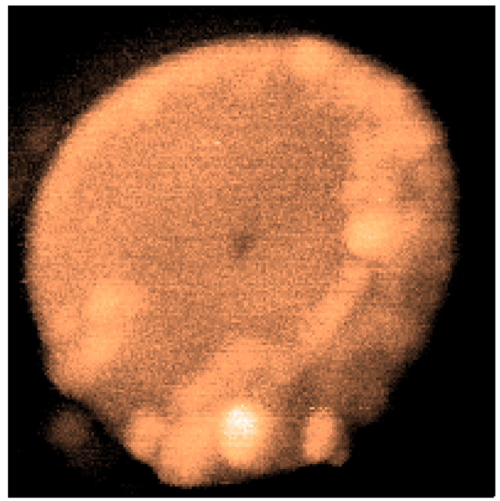
|||

one magnetic field value



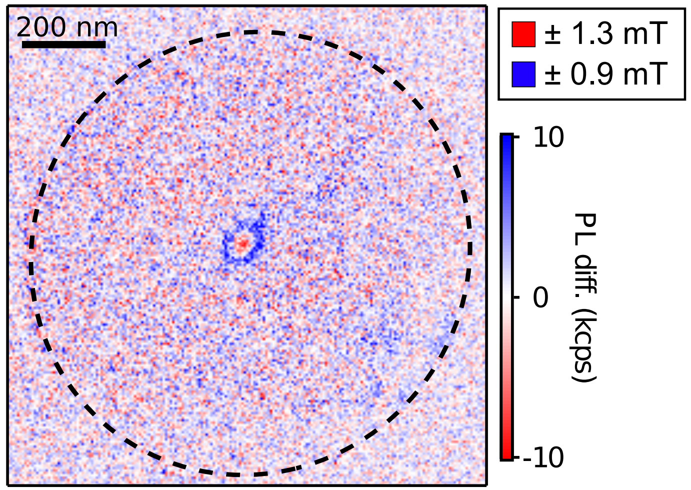
$|B_{NV}|$=0.9 mT

−

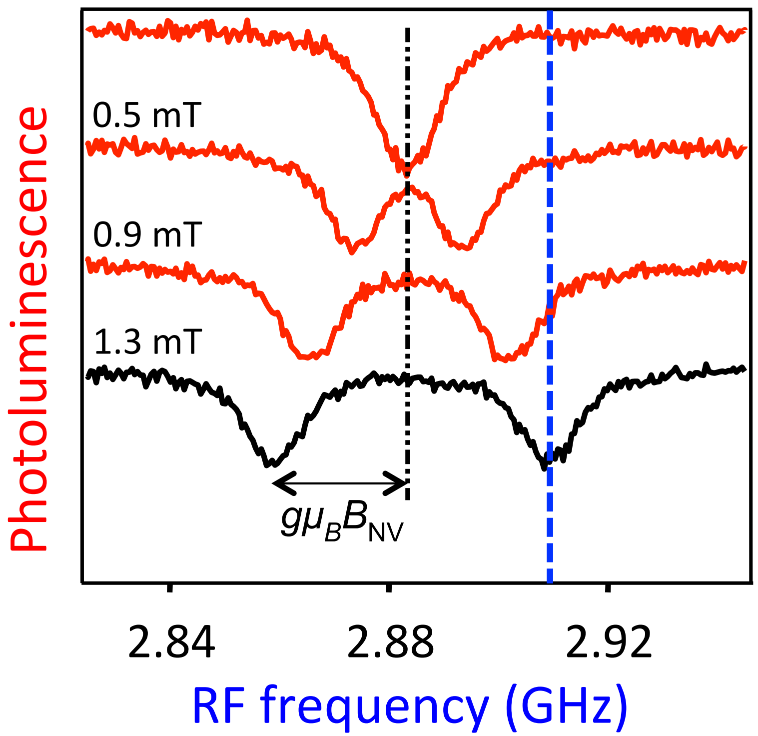


$|B_{NV}|$=1.3 mT

ISO-B imaging



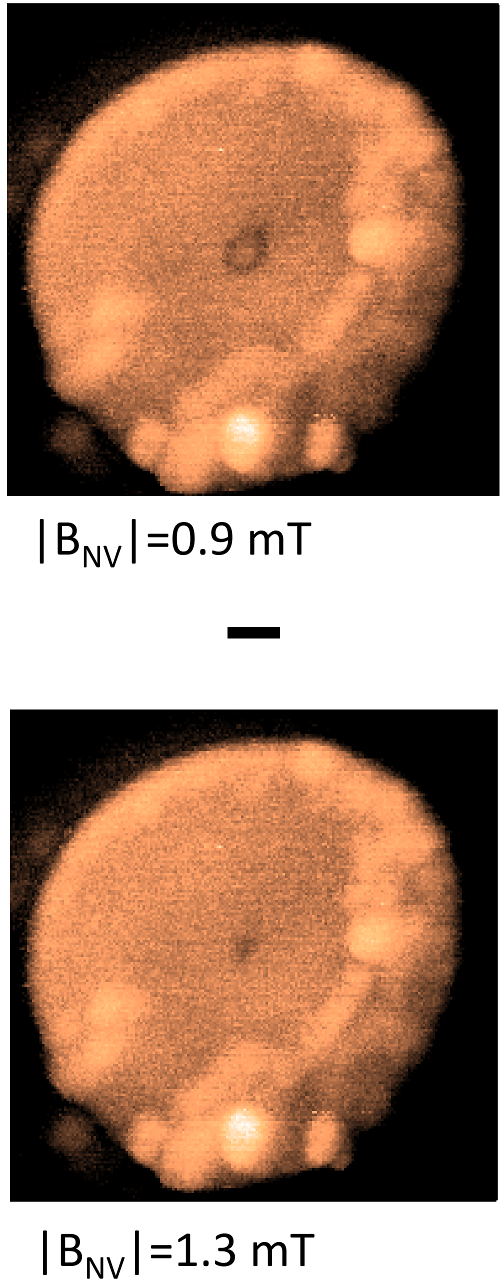
Imaging techniques



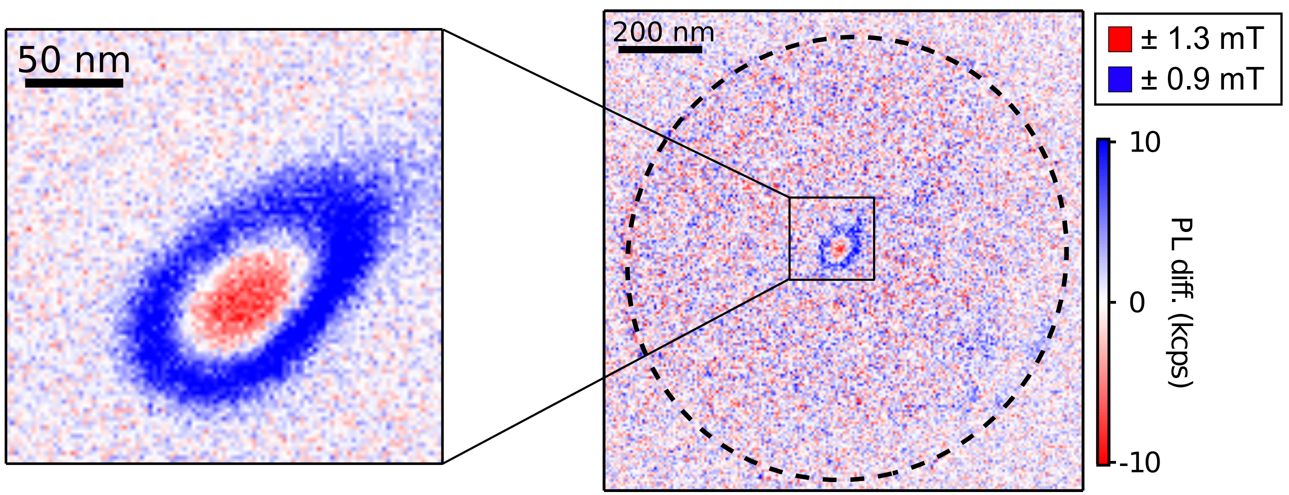
one RF frequency

|||

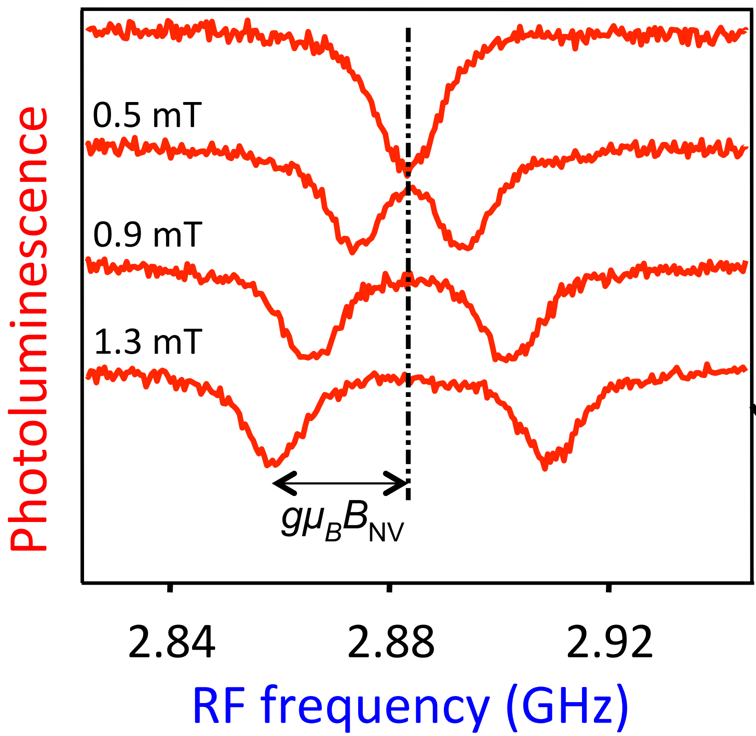
one magnetic field value



ISO-B imaging

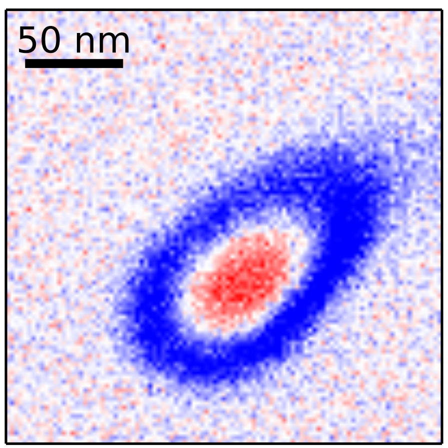


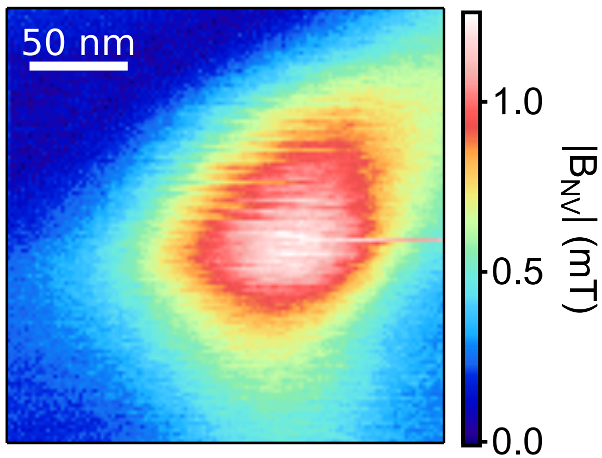
Imaging techniques



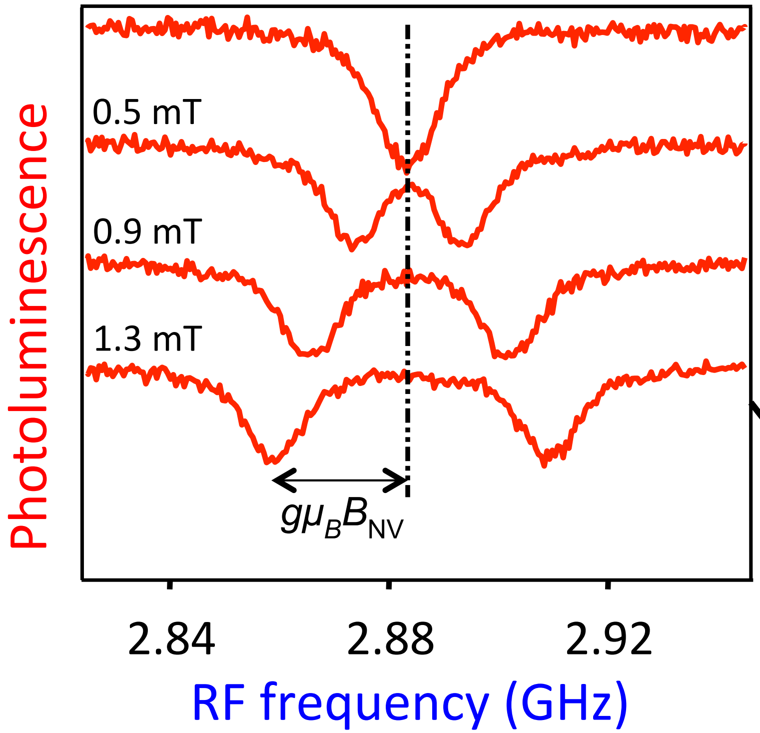
one spectrum per point

Full-B recording





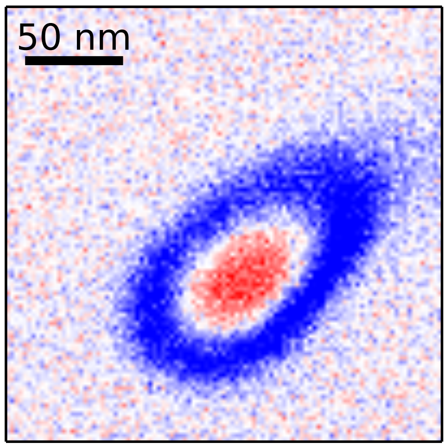
Imaging techniques

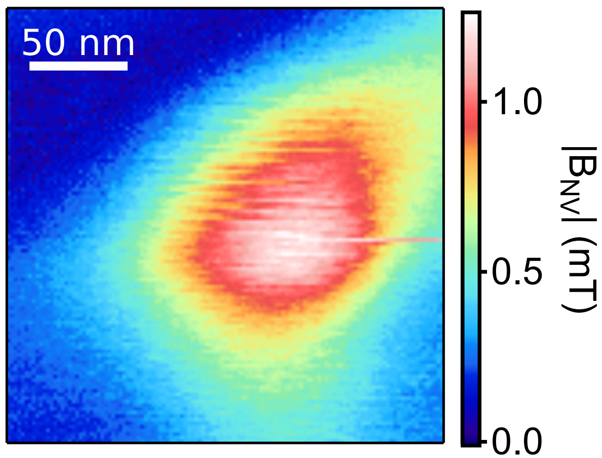


- iso-B: 40 ms per pixel
- full-B: 200 ms per pixel

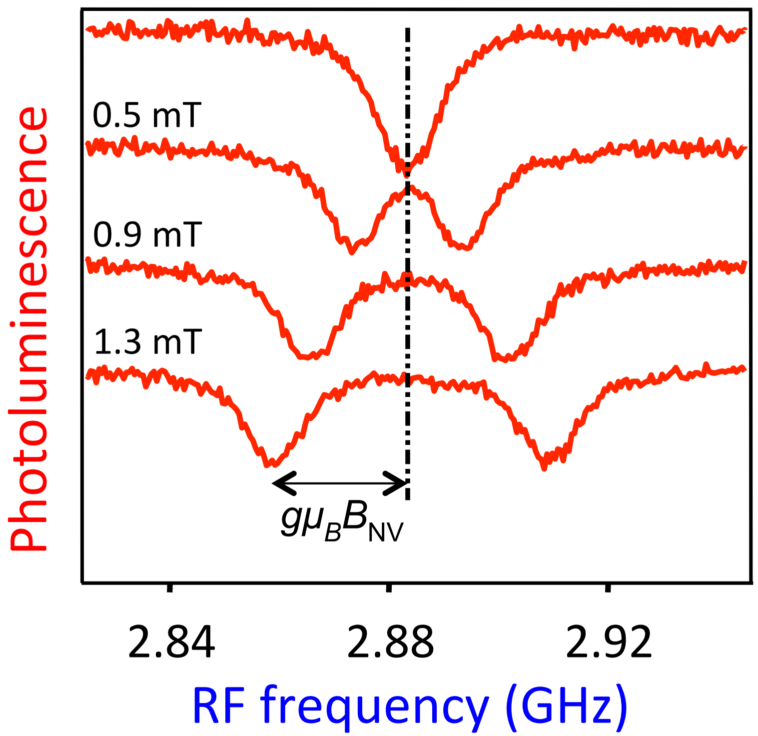
one spectrum per point

Full–B recording

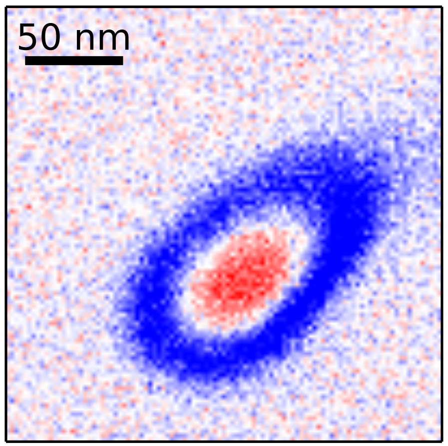




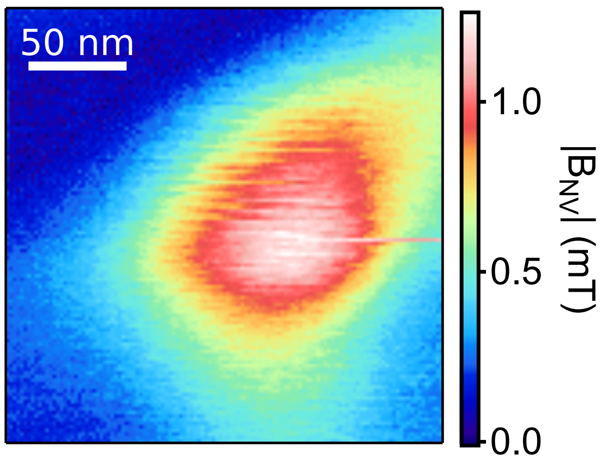
Imaging techniques



- iso-B: 40 ms per pixel
- full-B: 200 ms per pixel

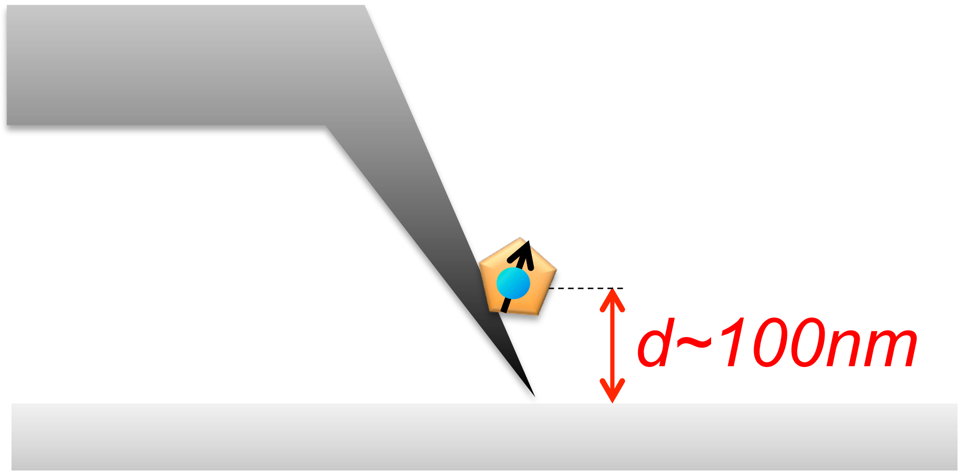


Full–B recording

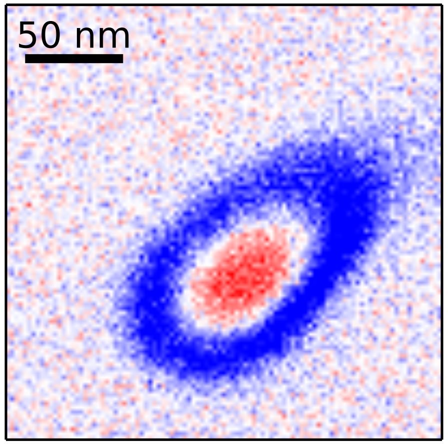


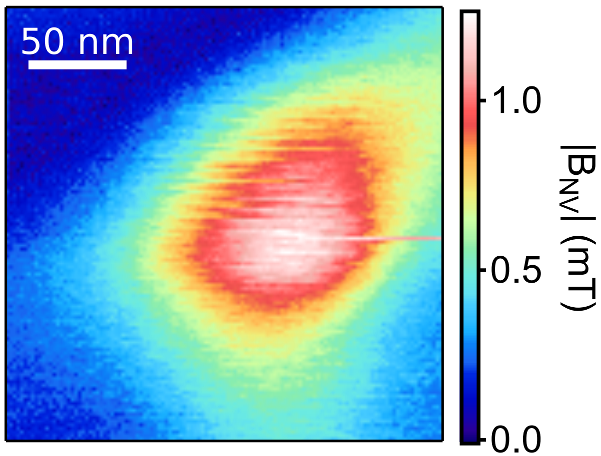
Resolving power: 50 nm

Imaging techniques

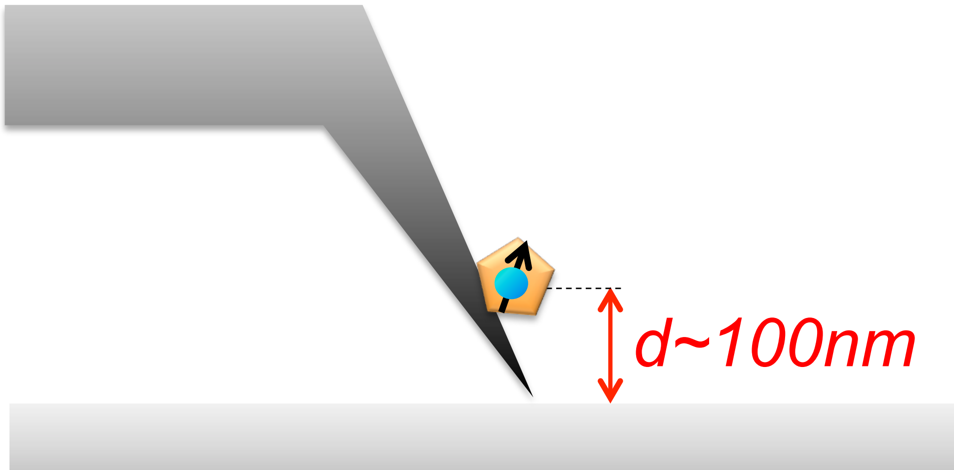


resolving power limited by probe to sample distance



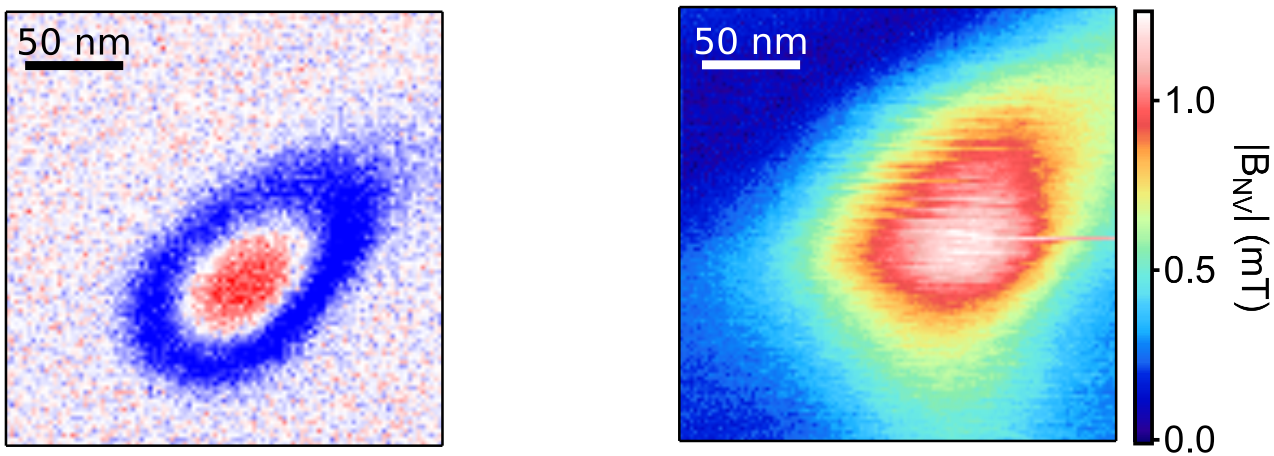


Imaging techniques

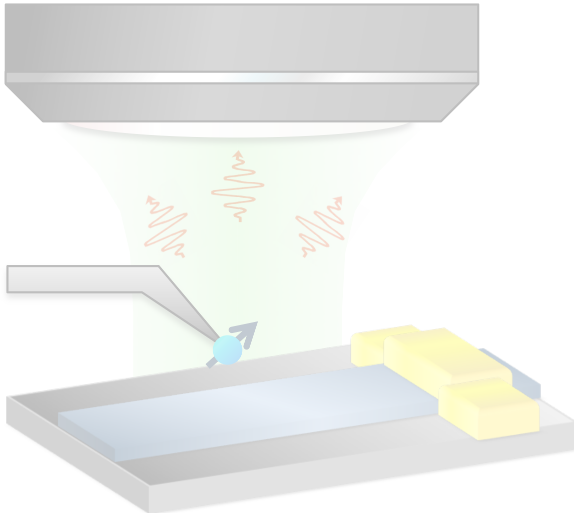


resolving power limited by probe to sample distance

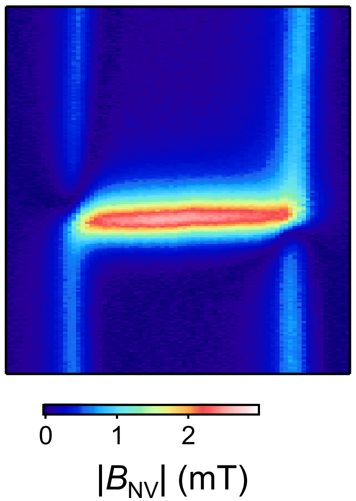
nm detail



Plan



I. Presentation of NV microscopy

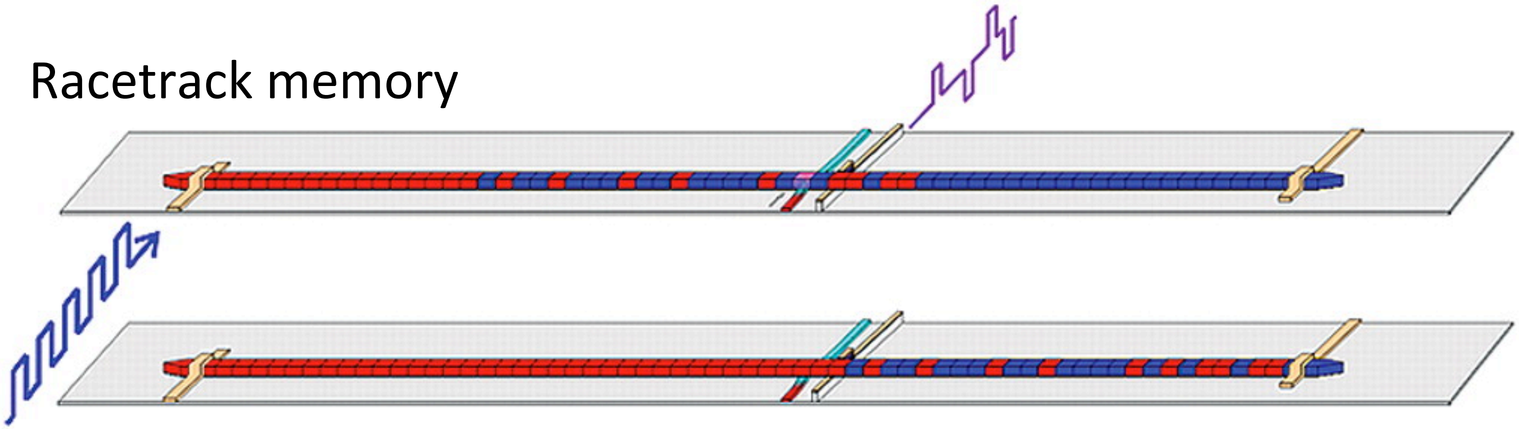


II. Recent experiments on domain walls in ultrathin ferromagnets

Motivations

Domain walls in ultrathin ferromagnets with perpendicular anisotropy are of fundamental interest for spintronic

Racetrack memory



*S. S. P. Parkin et al. Science **320**, 190 (2008)*

Motivations

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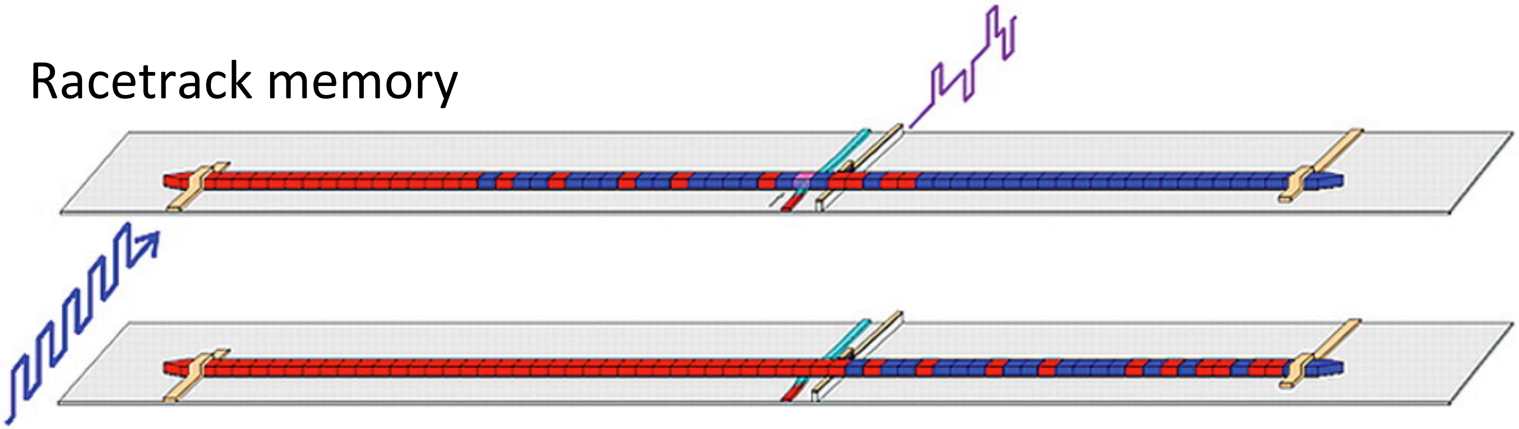
Racetrack memory



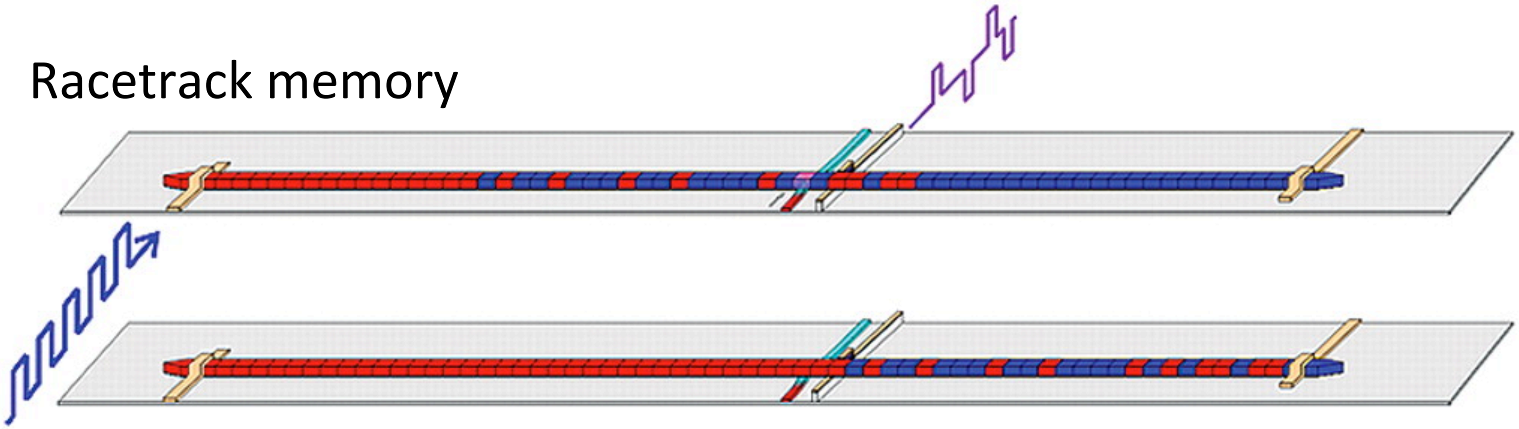
*S. S. P. Parkin et al. Science **320**, 190 (2008)*

- understanding the pinning
- determining the chirality of the walls (wall motion)

Motivations

Domain walls in ultrathin ferromagnets with perpendicular anisotropy are of fundamental interest for spintronic

Racetrack memory

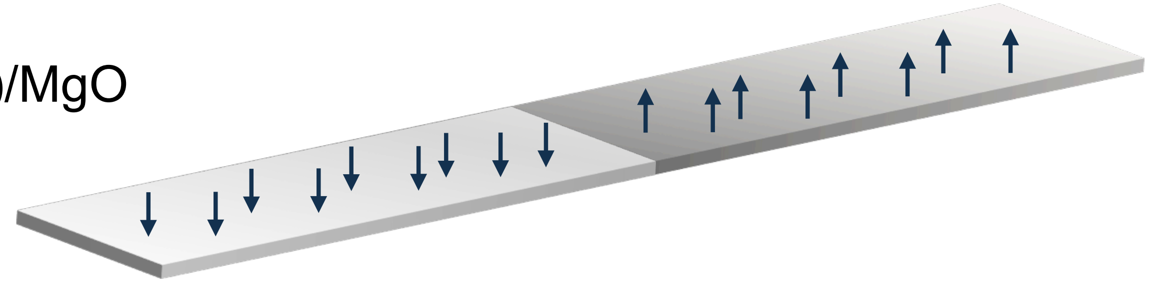


*S. S. P. Parkin et al. Science **320**, 190 (2008)*

- understanding the pinning
- determining the chirality of the walls (wall motion)

Sample at stake

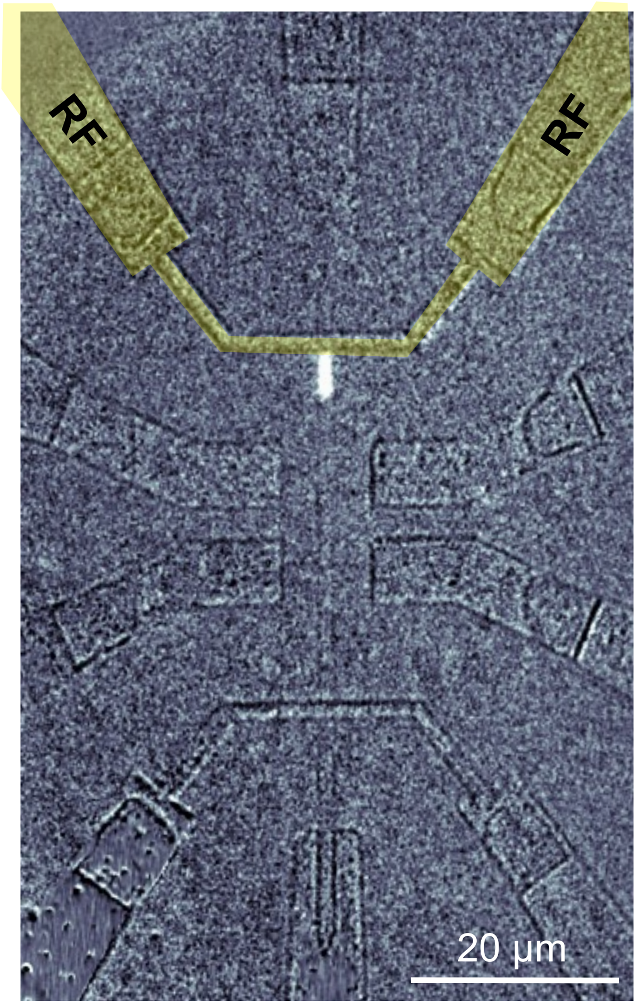
$Ta/Co_{40}Fe_{40}B_{20}$(1 nm)/MgO

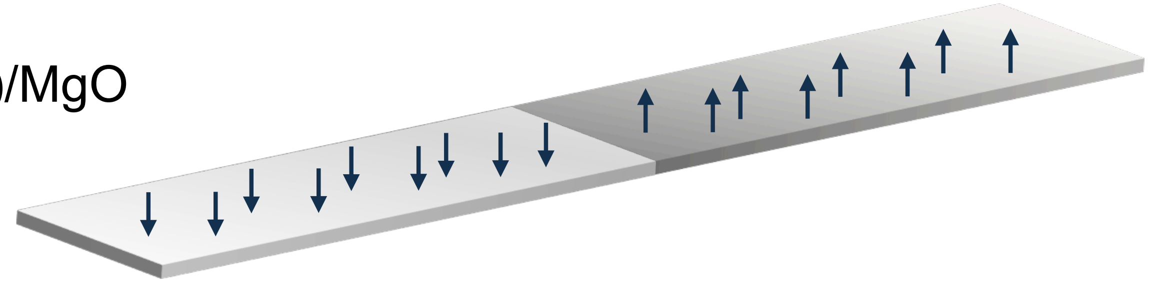


Sample at stake

$Ta/Co_{40}Fe_{40}B_{20}$(1 nm)/MgO

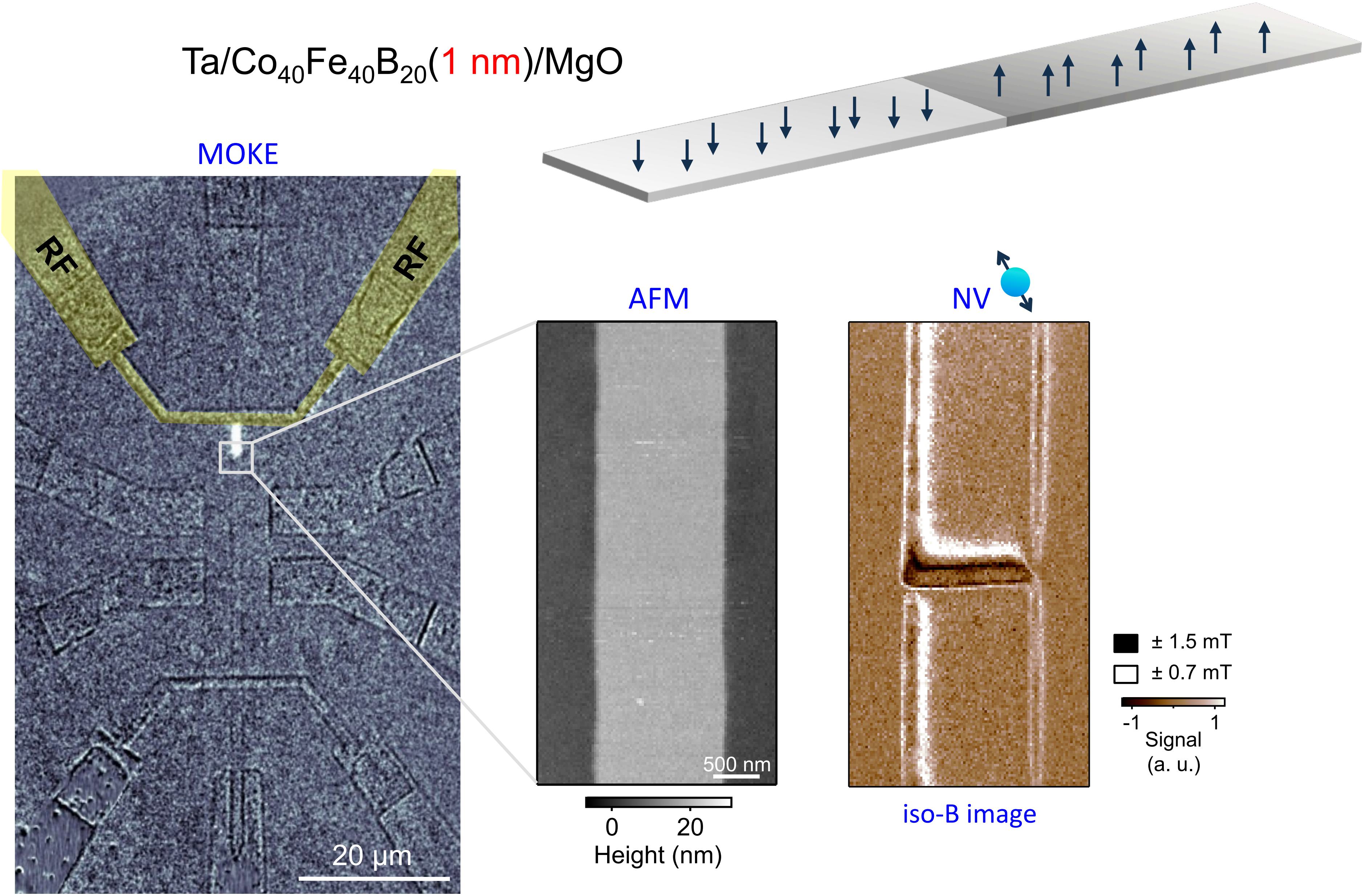
MOKE





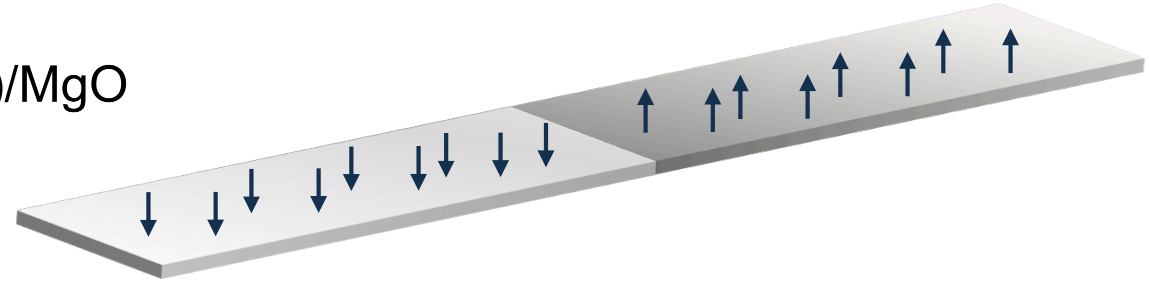
Sample at stake

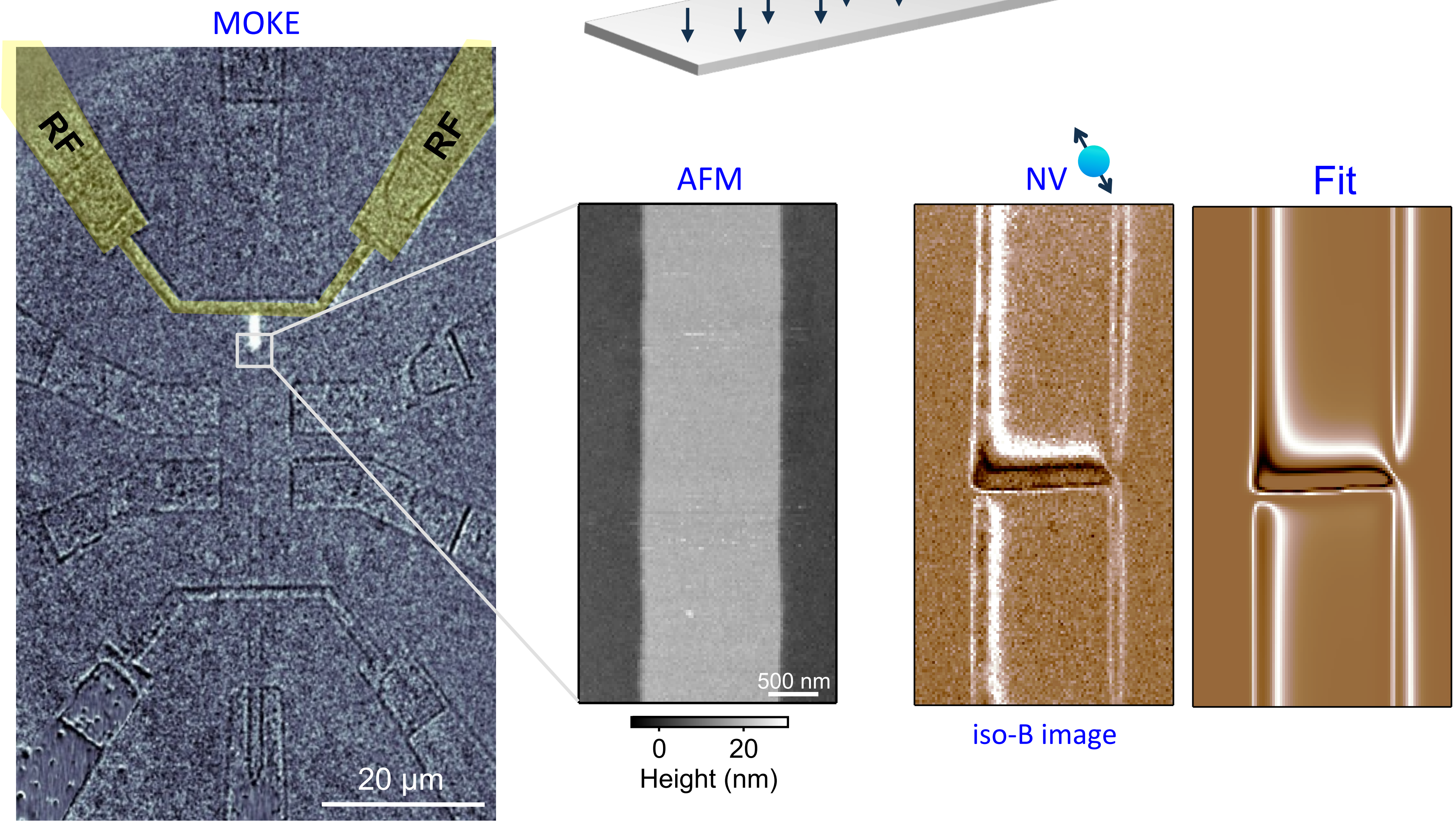
Ta/$Co_{40}Fe_{40}B_{20}$(1 nm)/MgO



Sample at stake

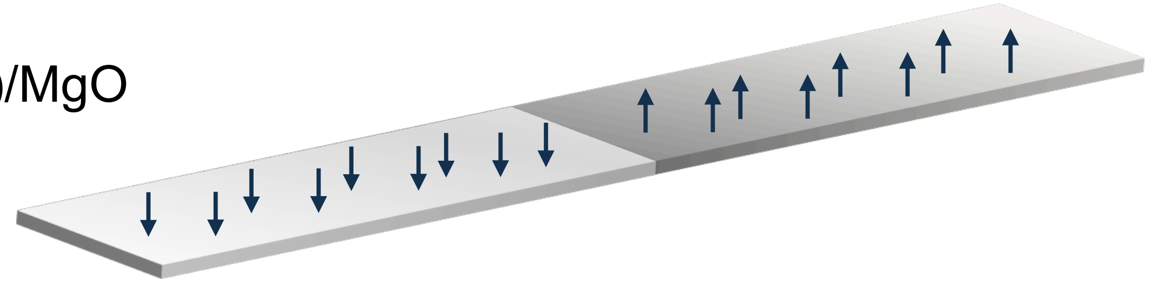
$Ta/Co_{40}Fe_{40}B_{20}$(1 nm)/MgO

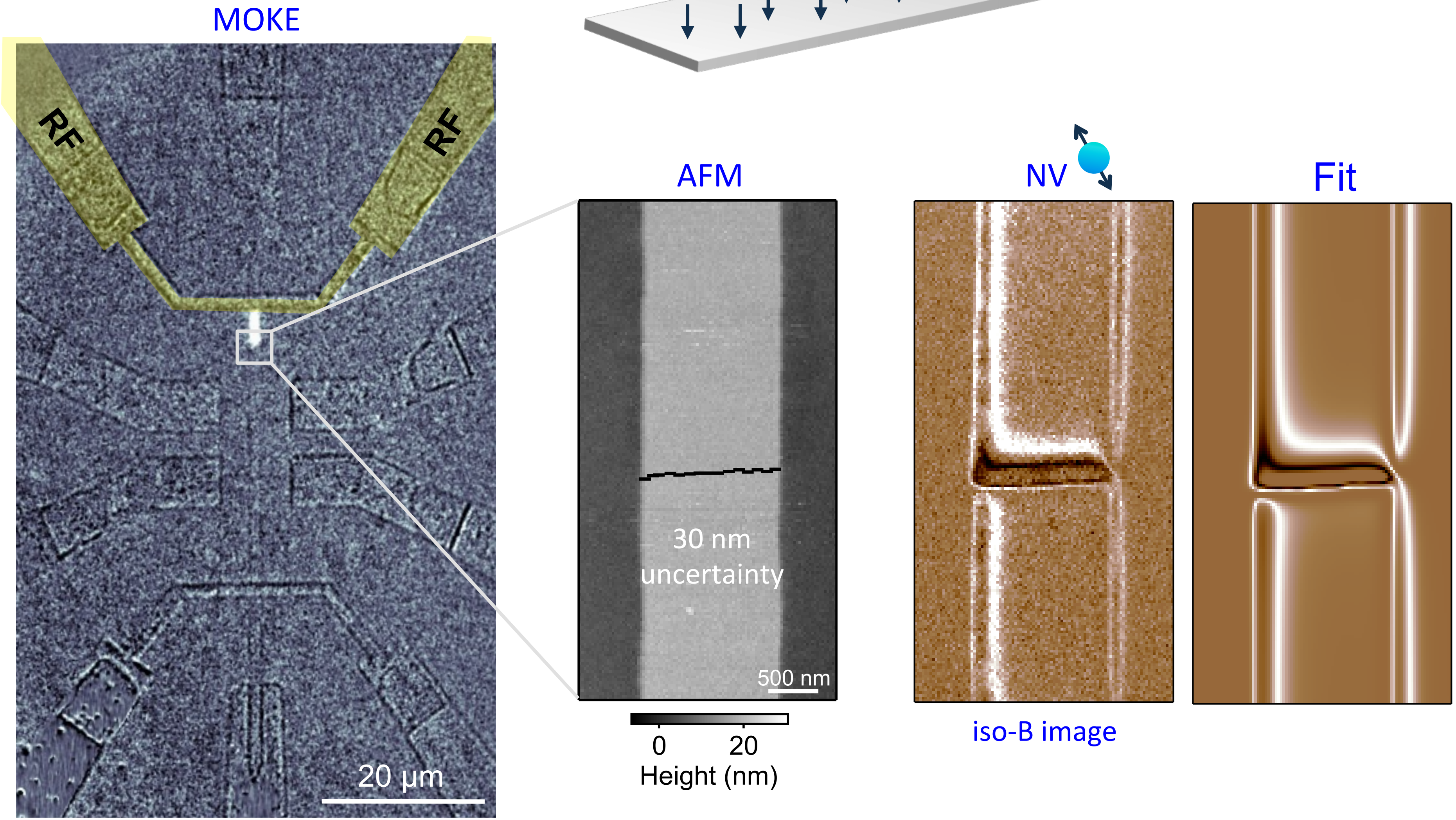




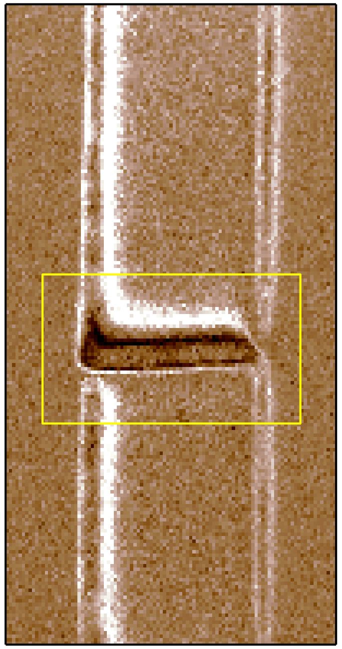
Sample at stake

Ta/$Co_{40}Fe_{40}B_{20}$(1 nm)/MgO

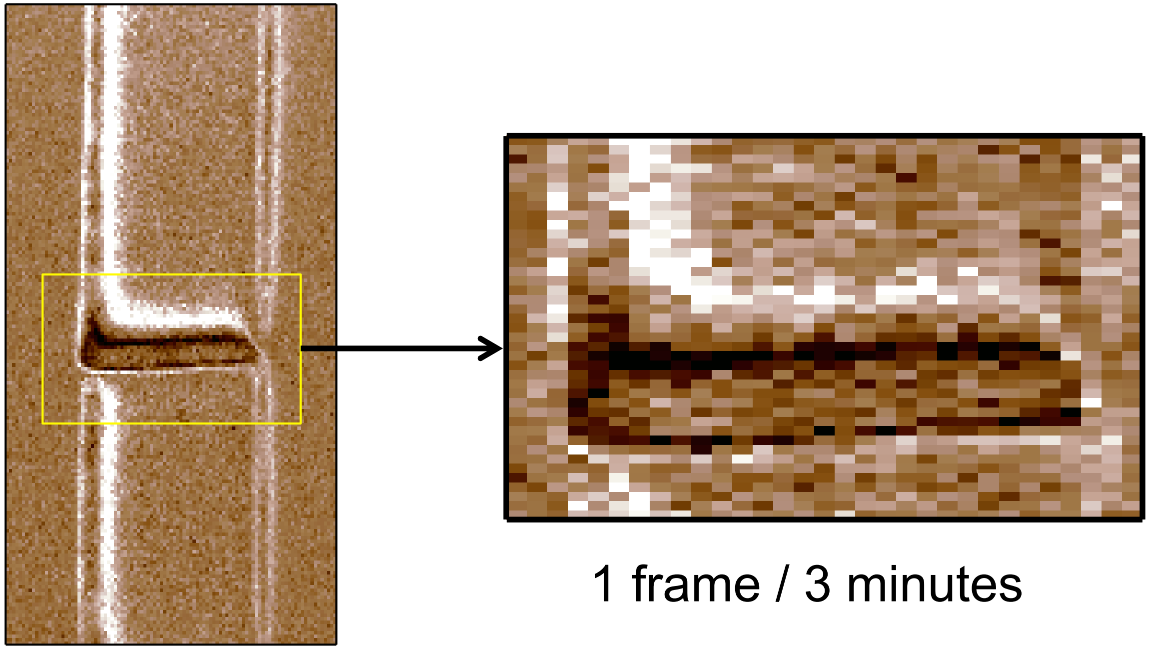




Observation of domain wall hopping

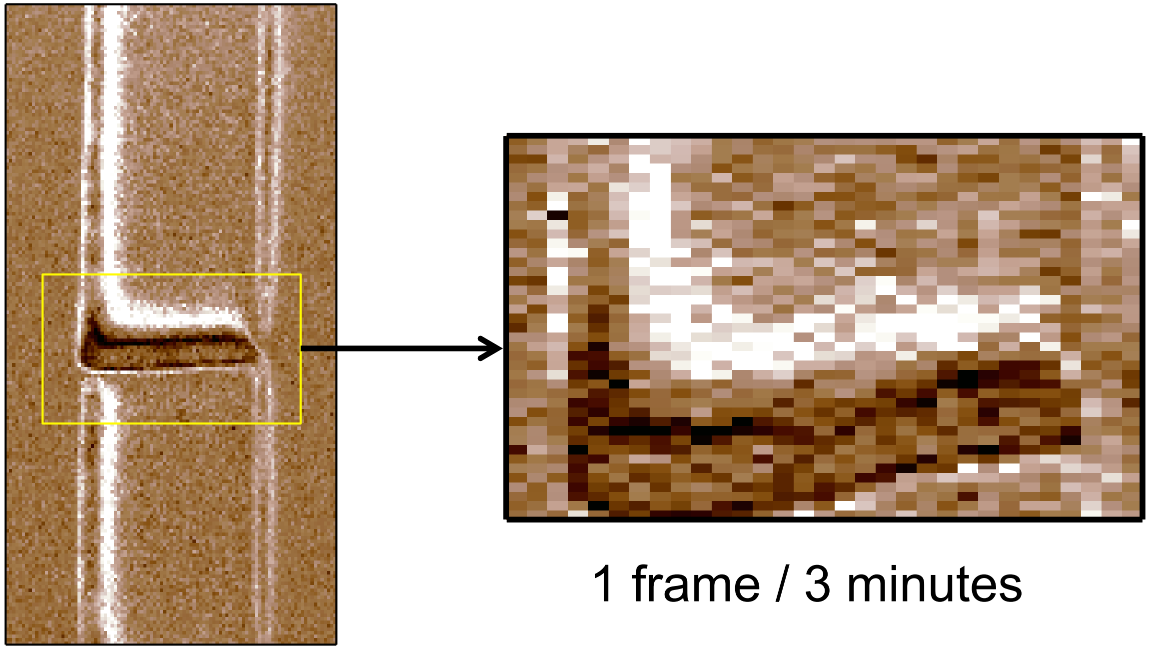


Observation of domain wall hopping



1 frame / 3 minutes

Observation of domain wall hopping



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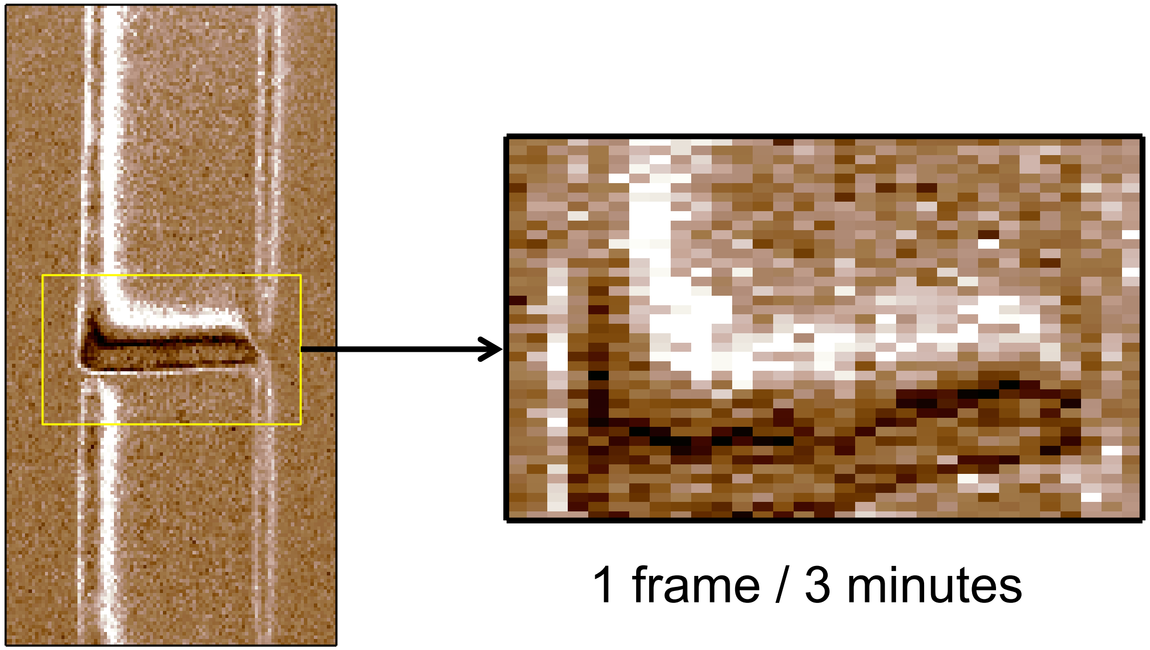
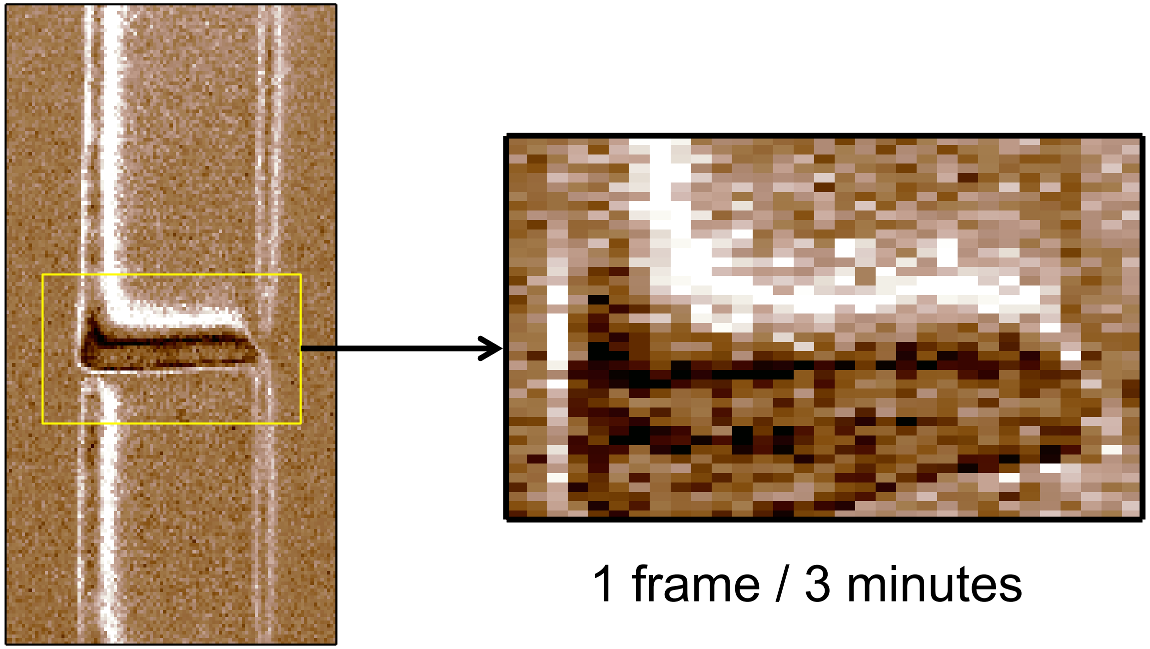
Observation of domain wall hopping



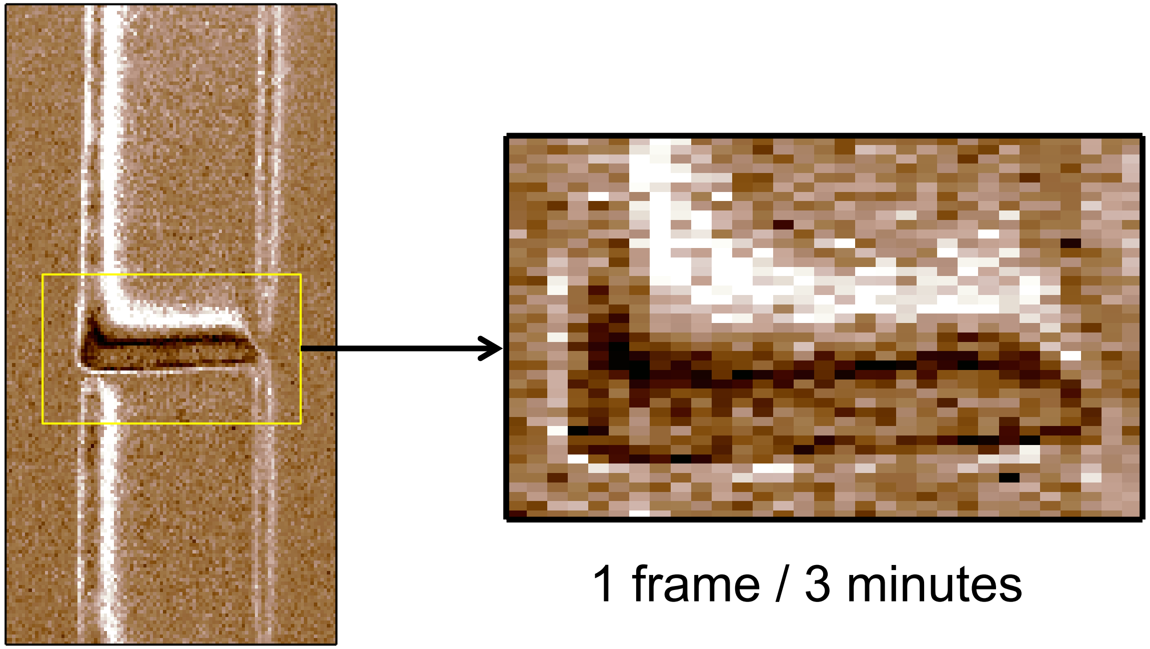
1 frame / 3 minutes

Observation of domain wall hopping



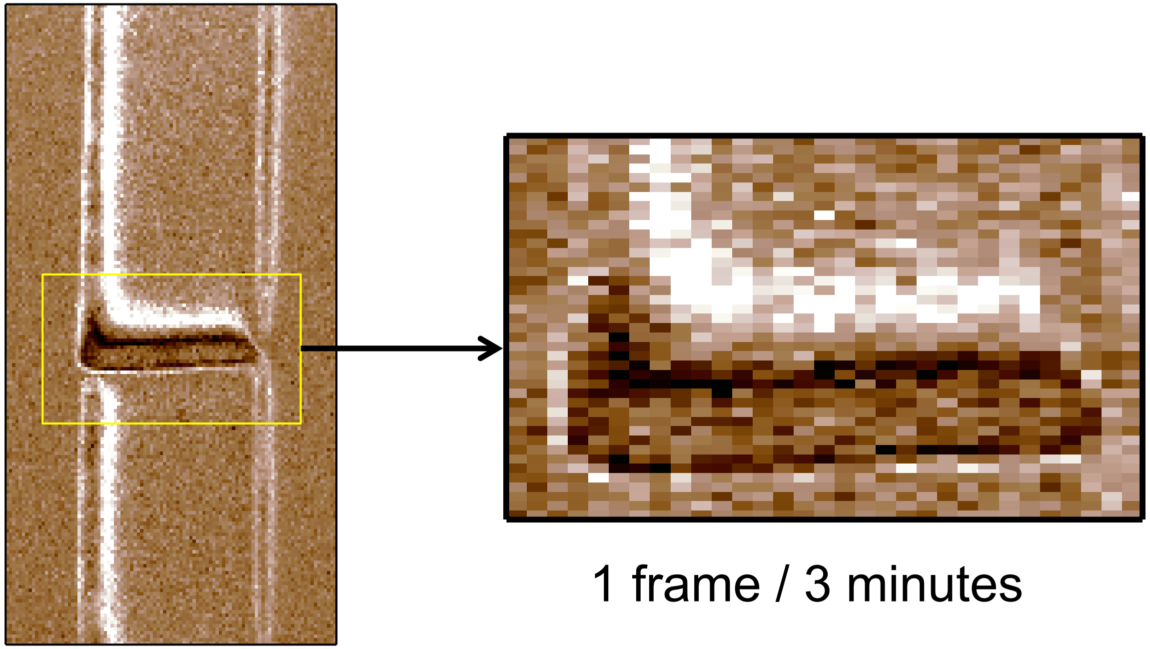
1 frame / 3 minutes

Observation of domain wall hopping



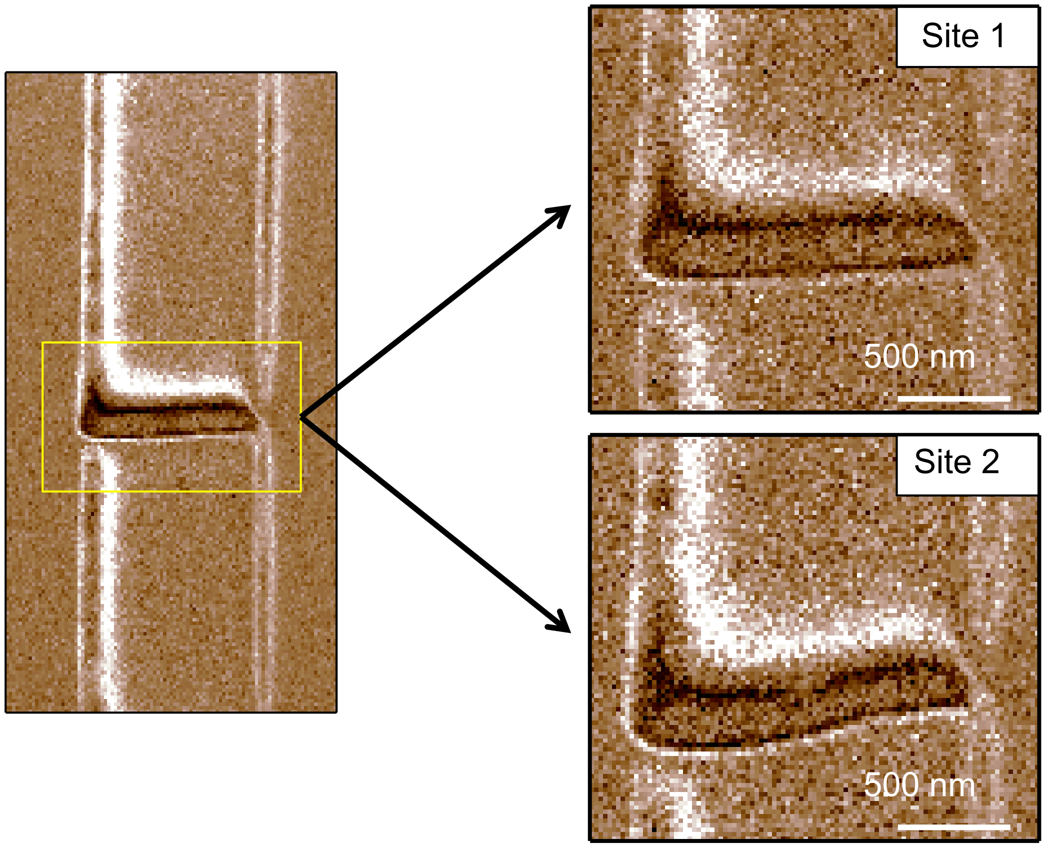
1 frame / 3 minutes

Observation of domain wall hopping

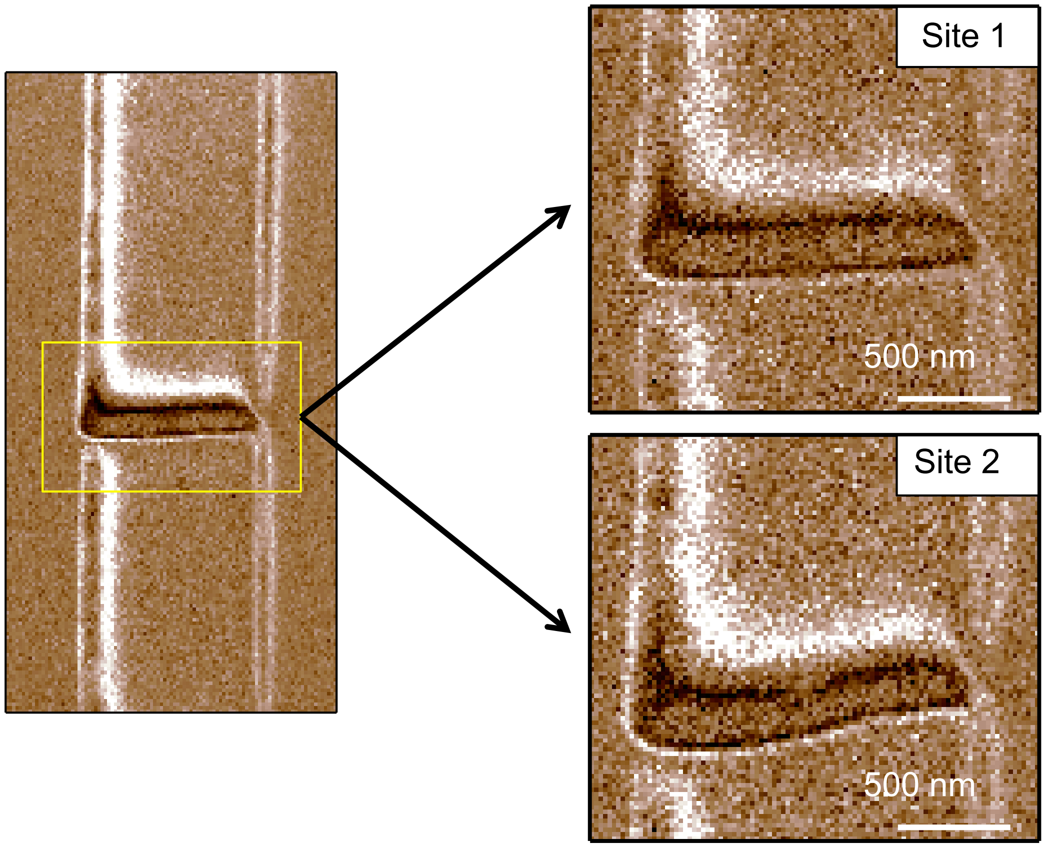


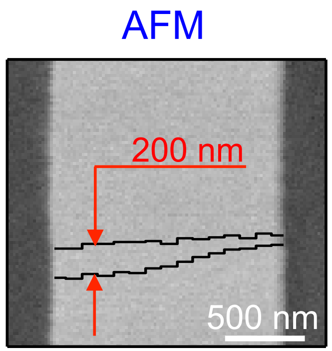
1 frame / 3 minutes

Observation of domain wall hopping

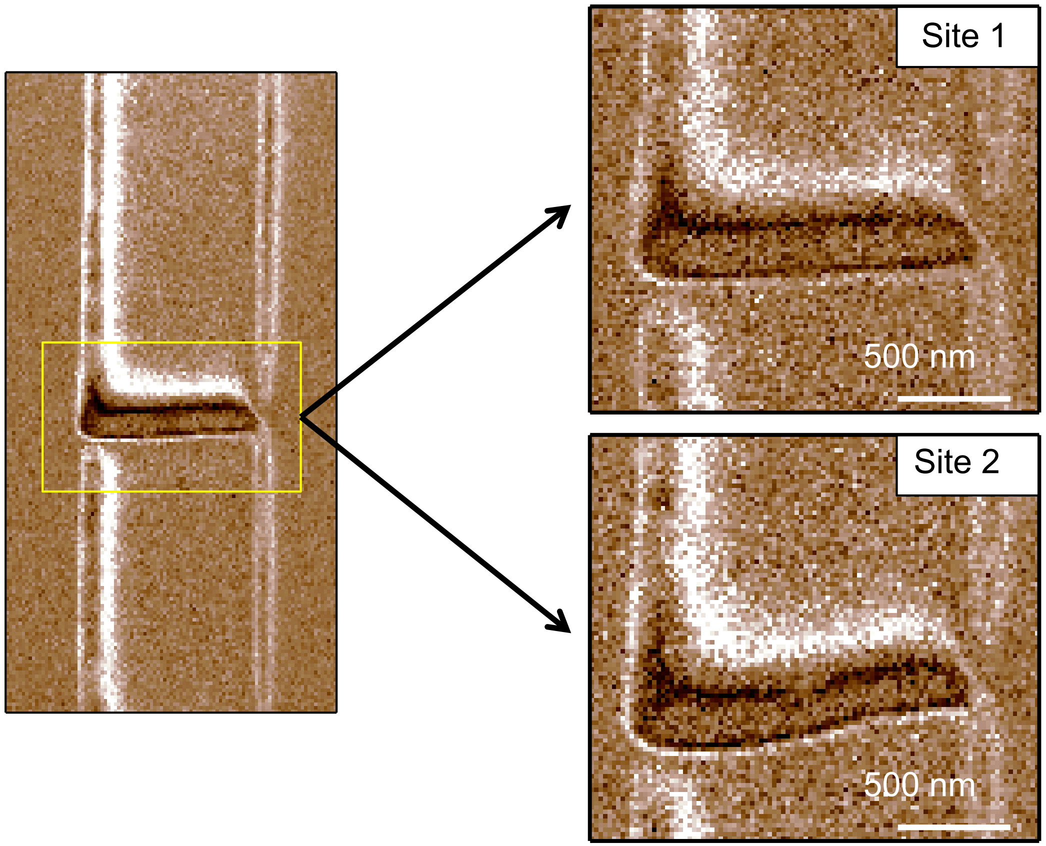


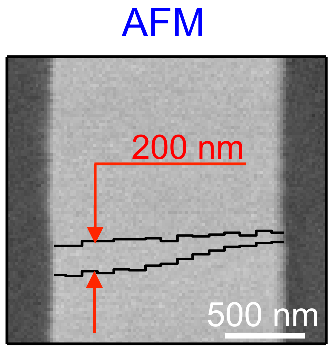
Observation of domain wall hopping





Observation of domain wall hopping

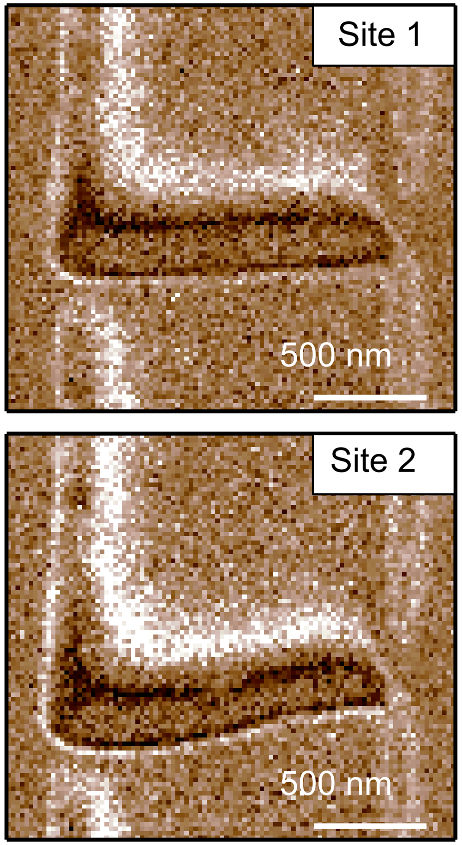




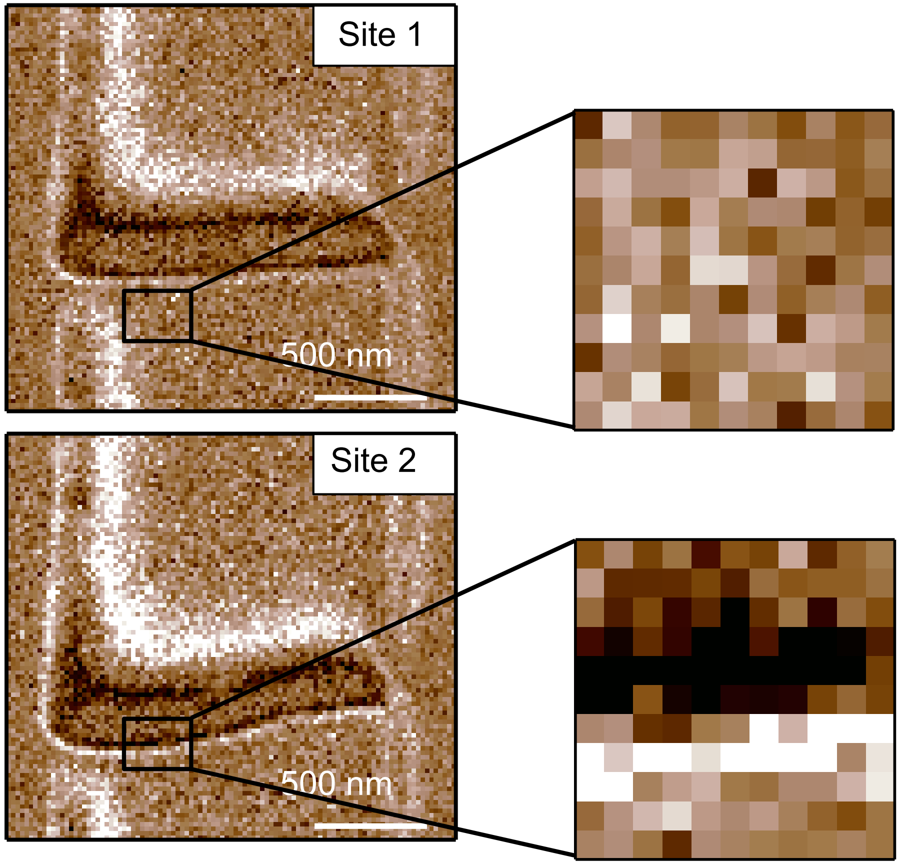
Thermally-activated domain wall hopping (or Barkhausen jumps) observed:

- in real time
- in real space
- at room temperature
- in zero magnetic field

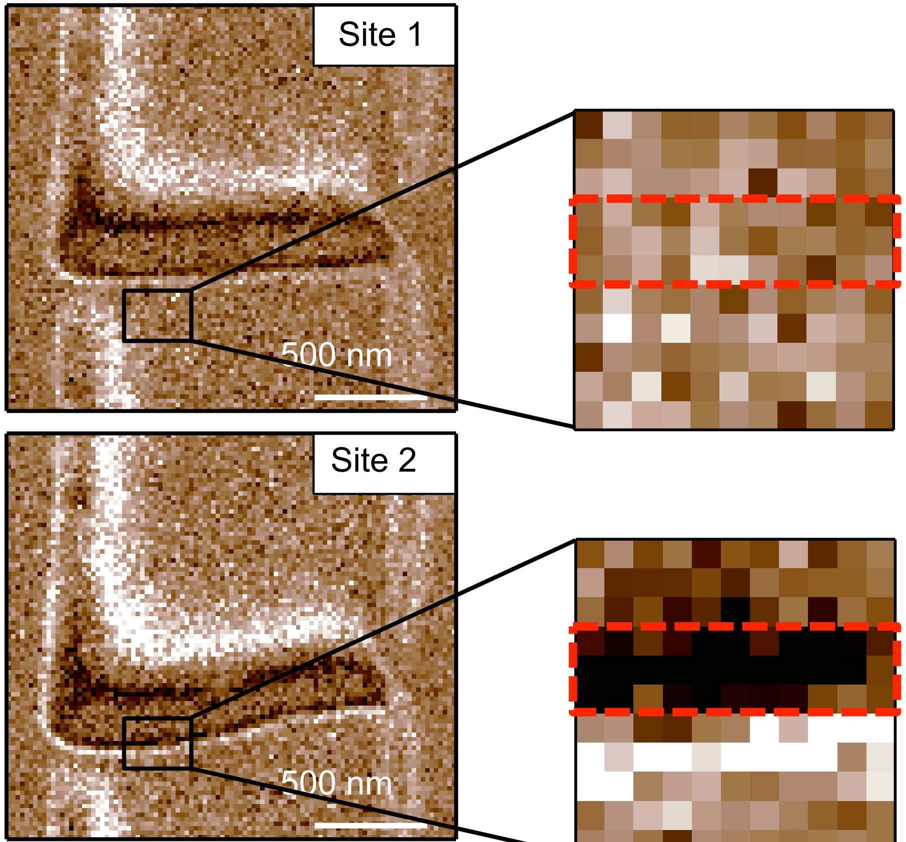
Observation of domain wall hopping

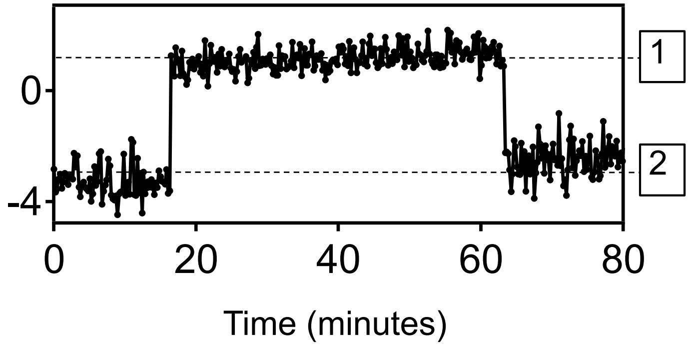


Observation of domain wall hopping

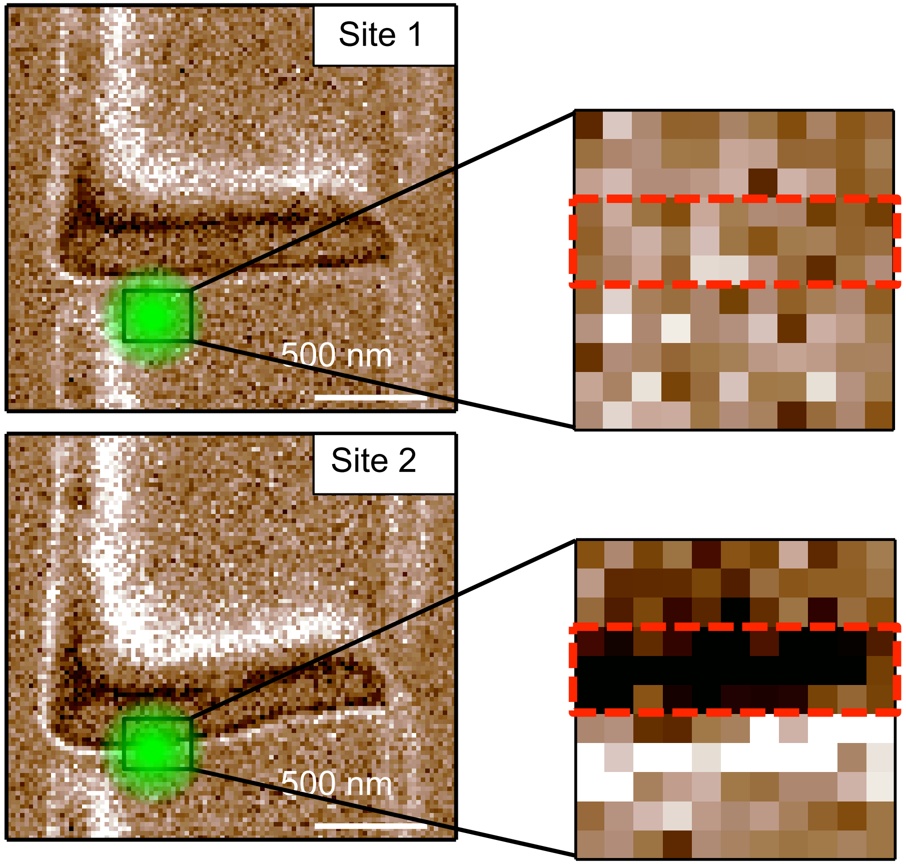


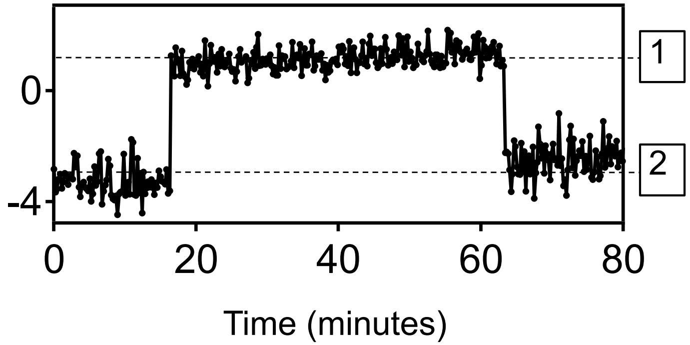
Observation of domain wall hopping



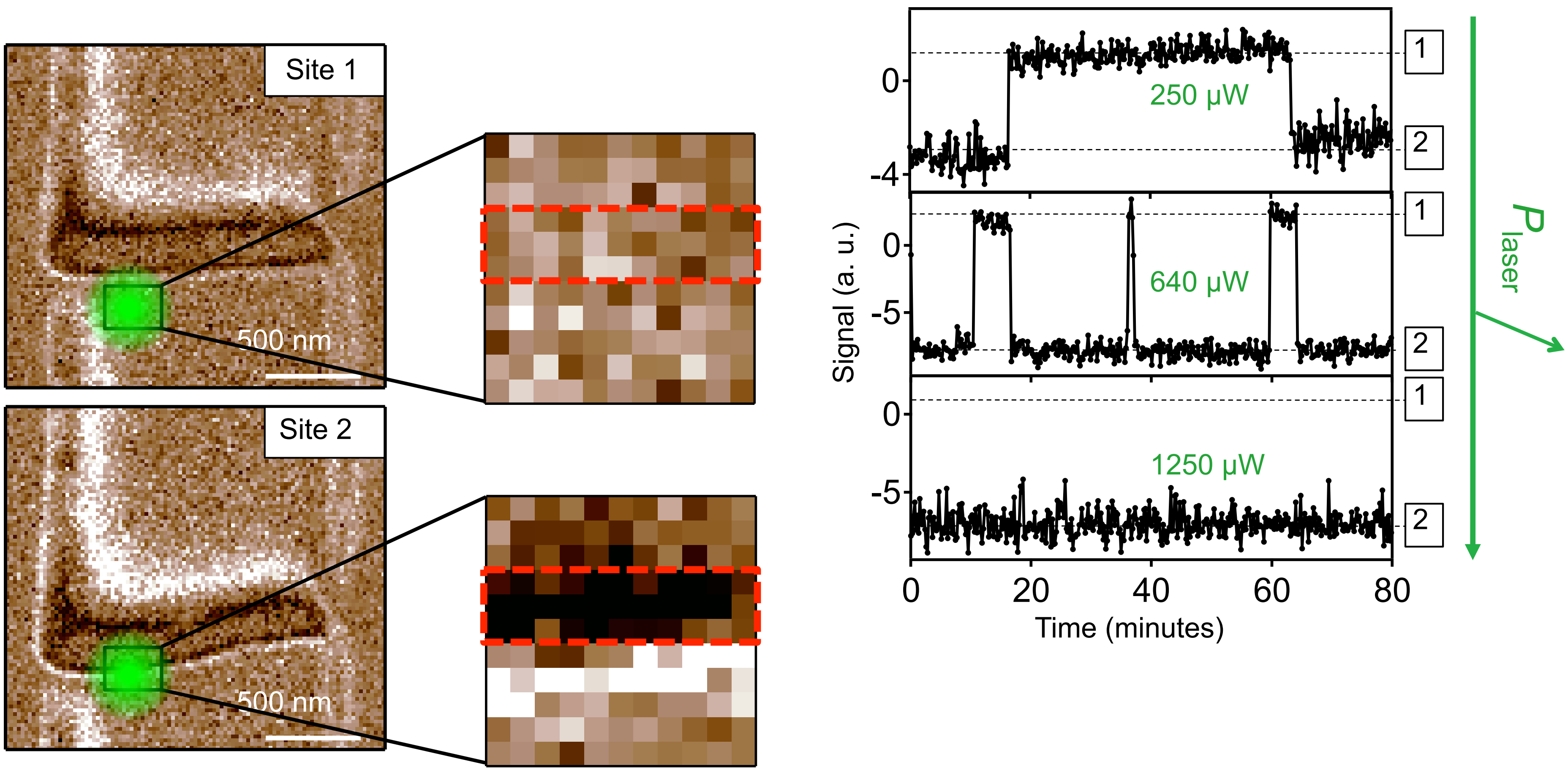


Observation of domain wall hopping

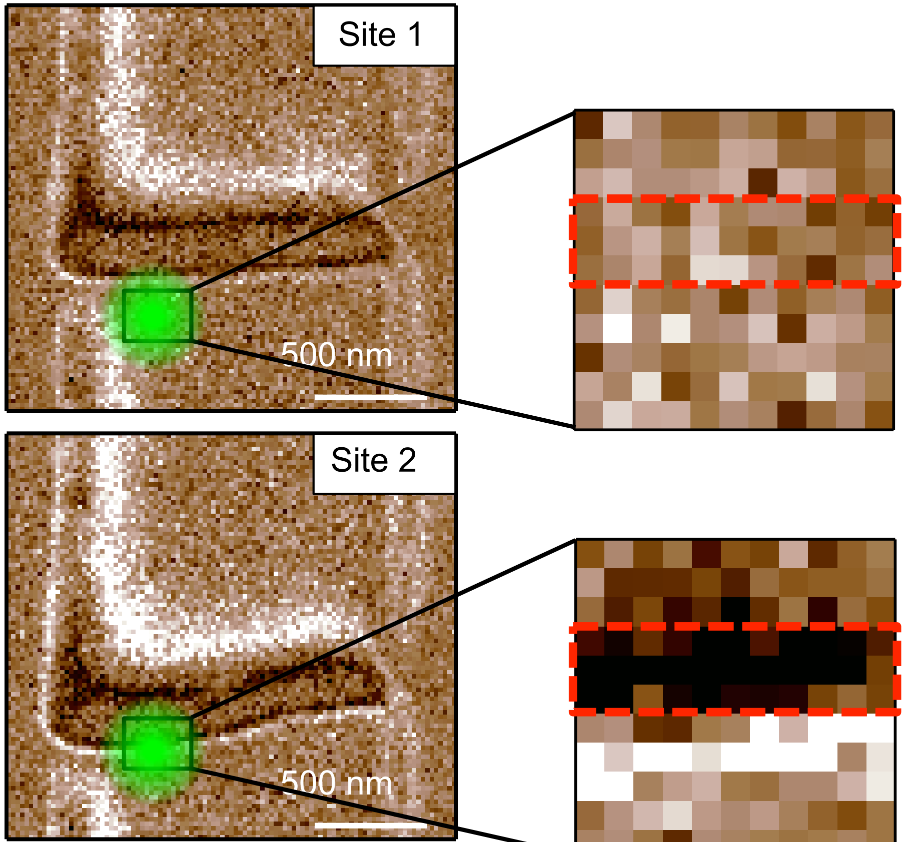


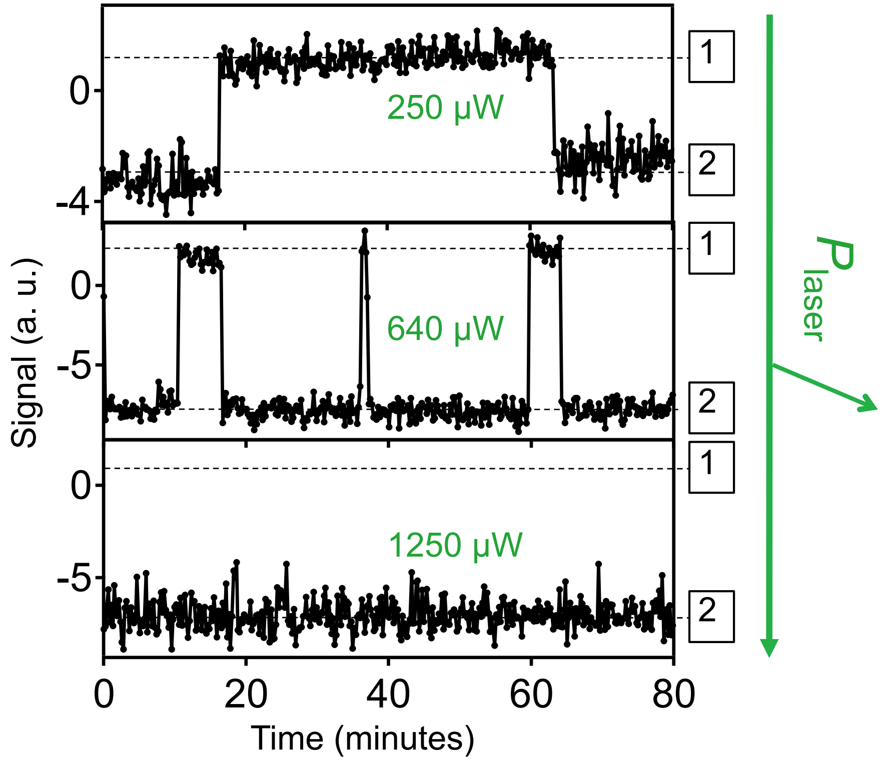


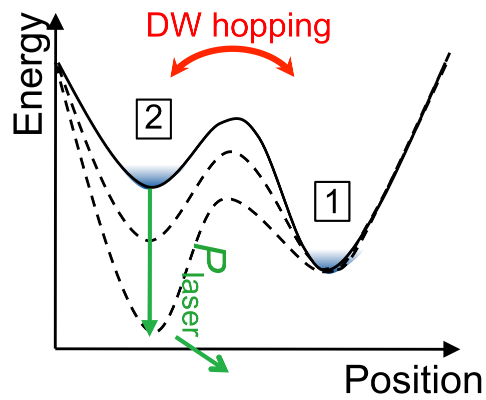
Observation of domain wall hopping



Observation of domain wall hopping

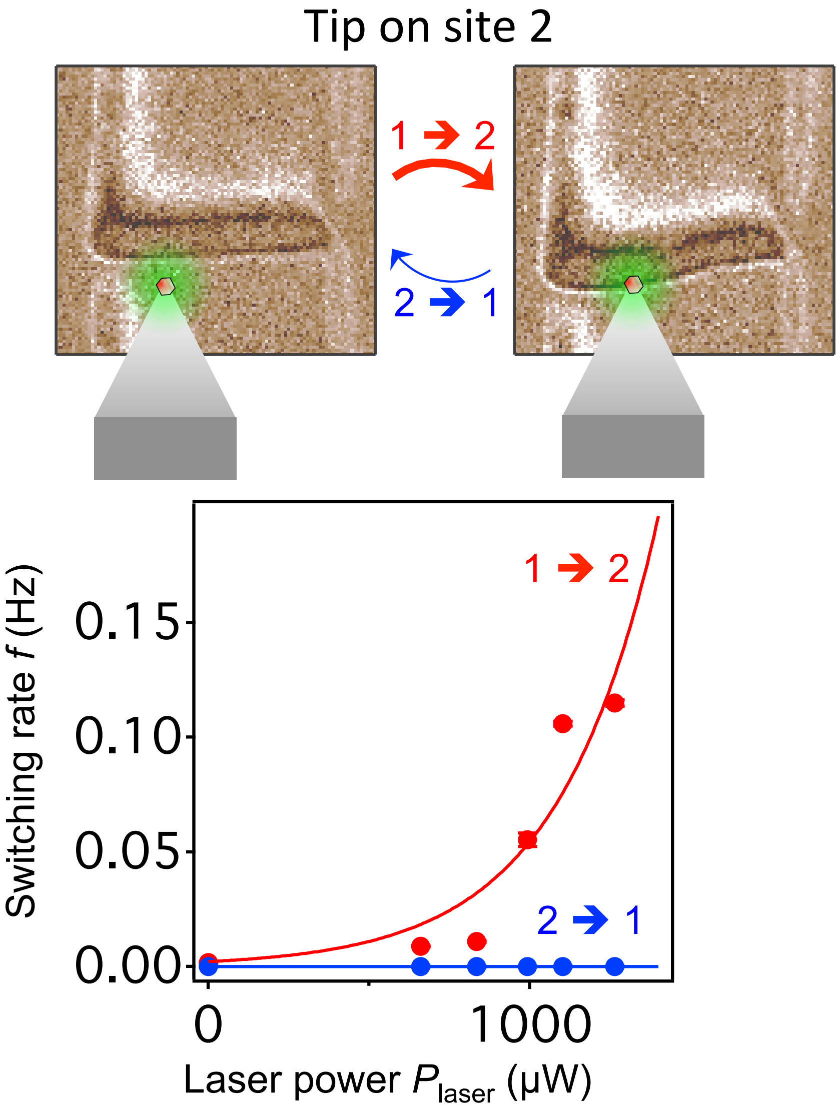




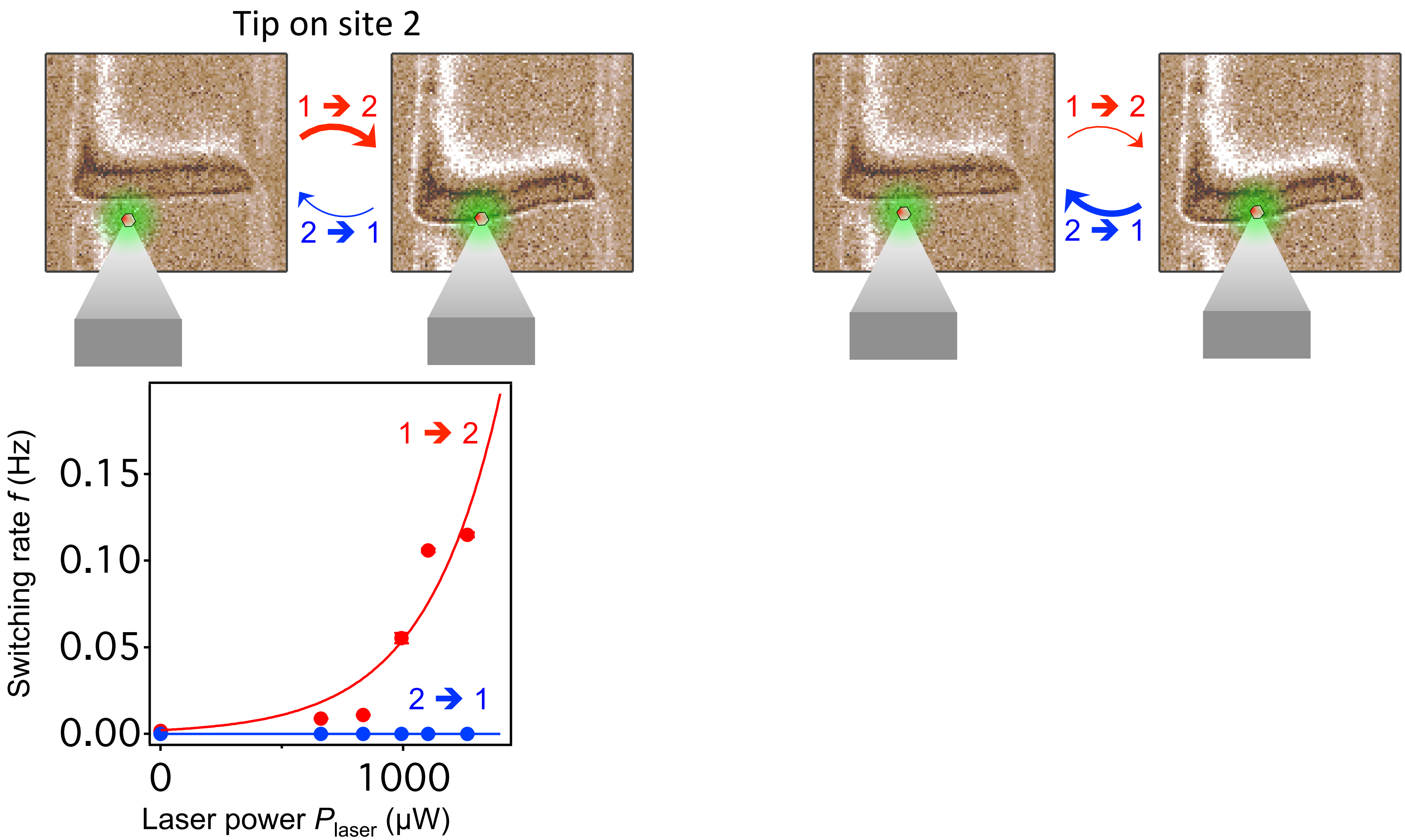


The laser tends to
pin the DW in site 2

Laser induced pinning

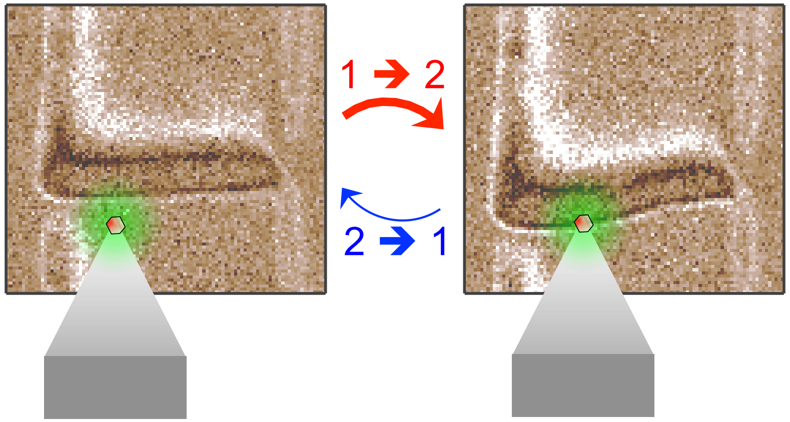


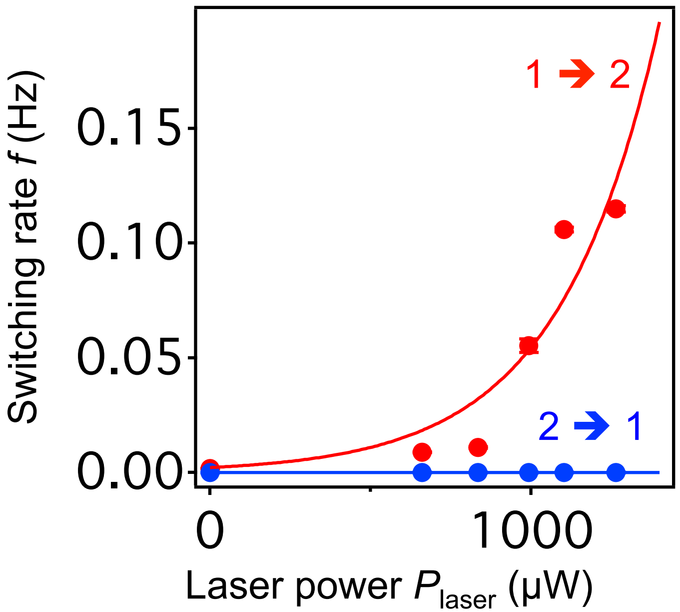
Laser induced pinning



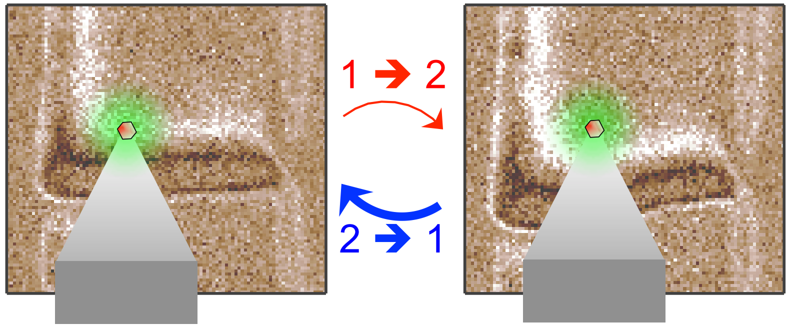
Laser induced pinning

Tip on site 2

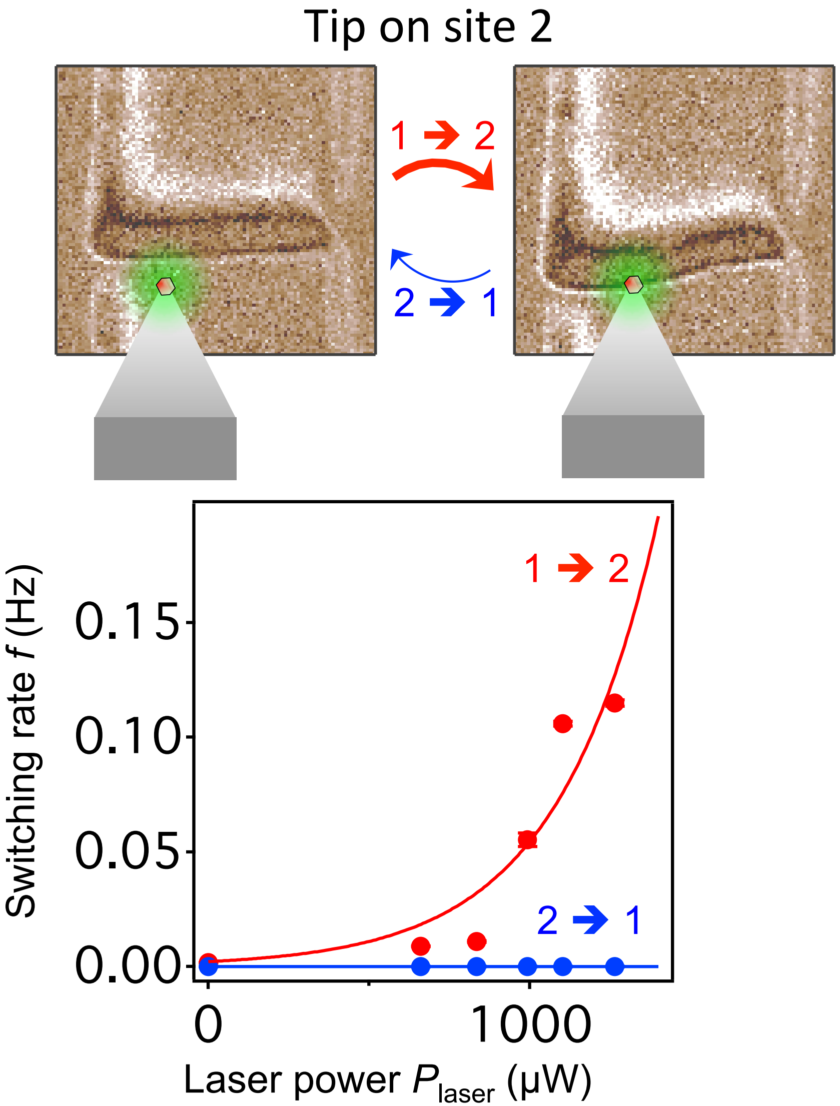


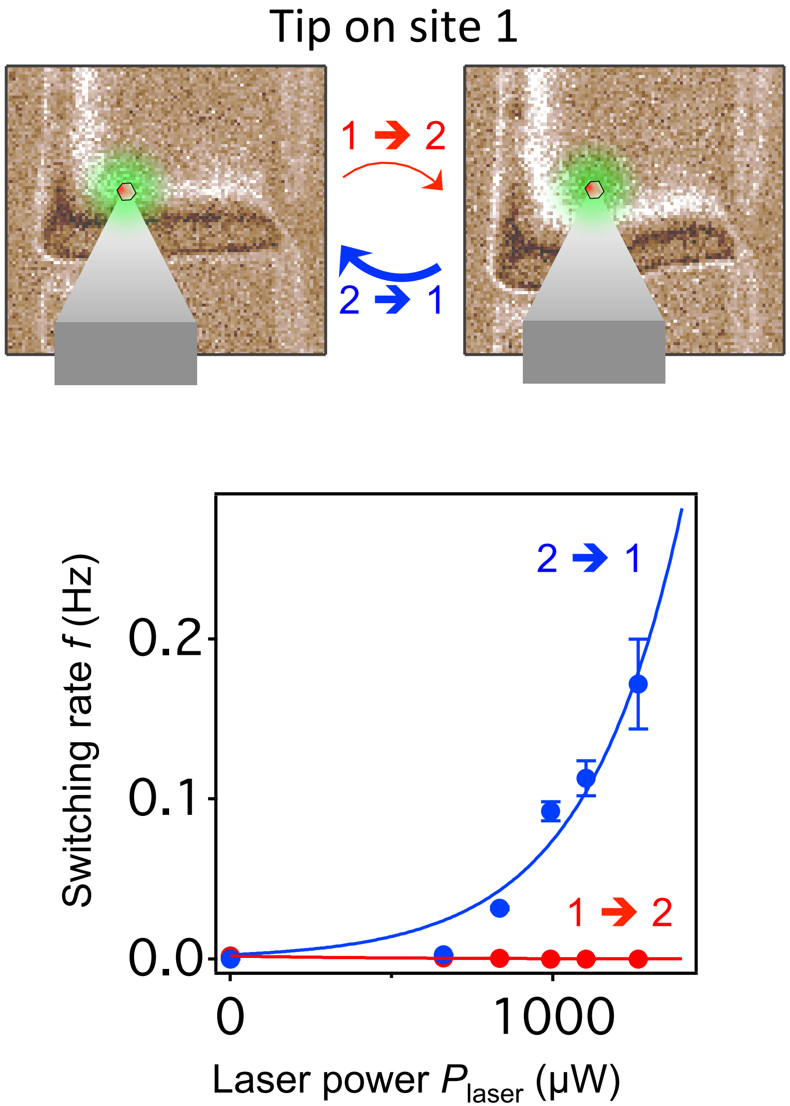


Tip on site 1



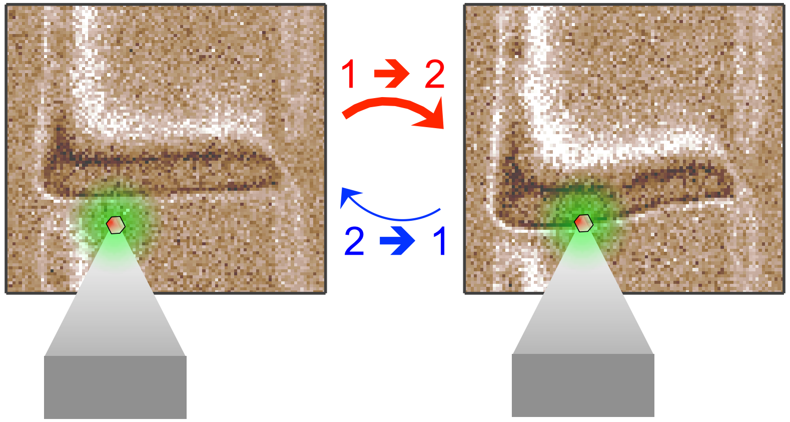
Laser induced pinning



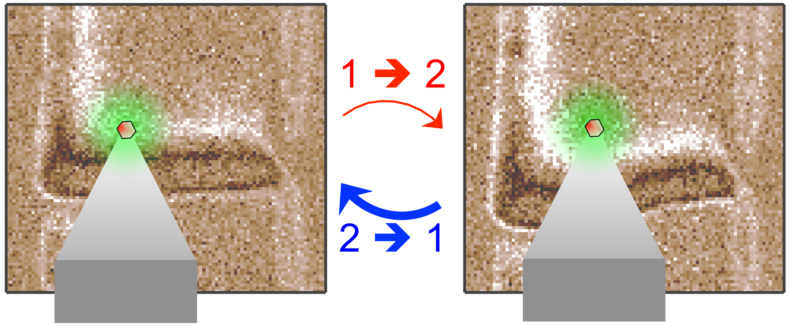


Laser induced pinning

Tip on site 2

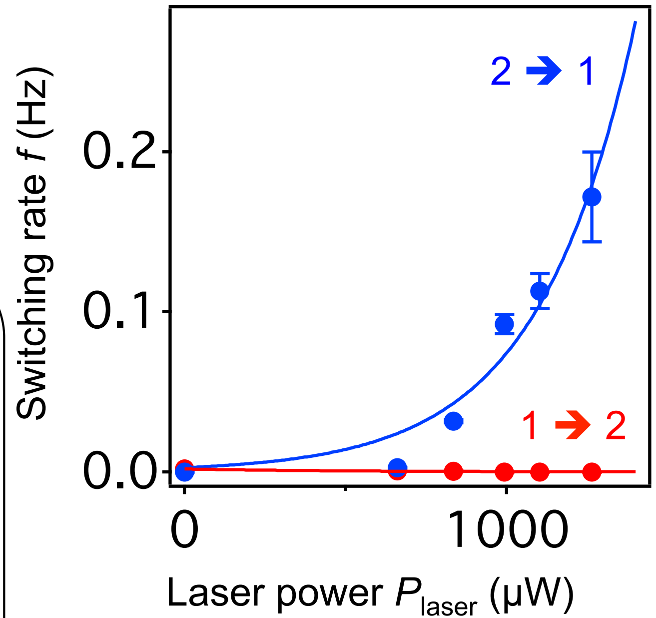


Tip on site 1

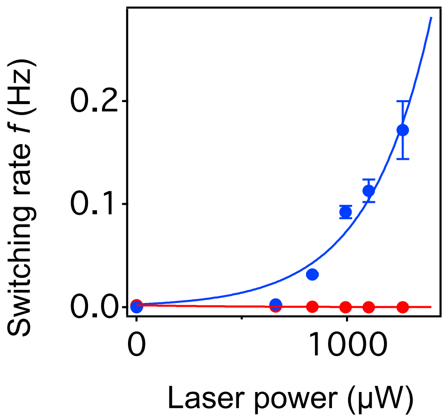


Laser-induced domain wall pinning

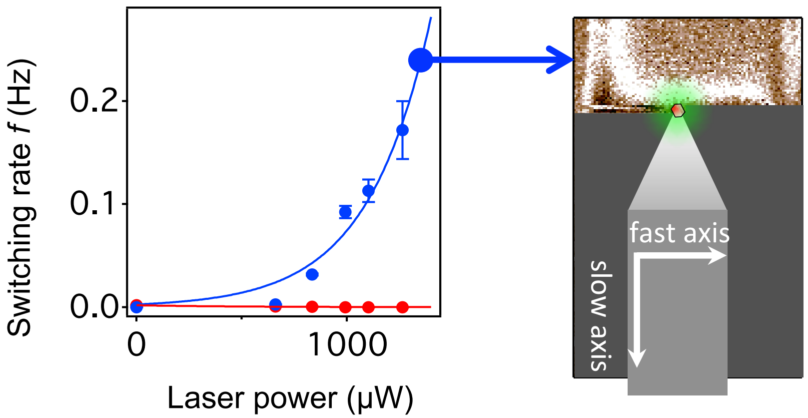
- modification of magnetic parameters of the layer caused by heating?
- magnonic effect?



Exploiting the effect

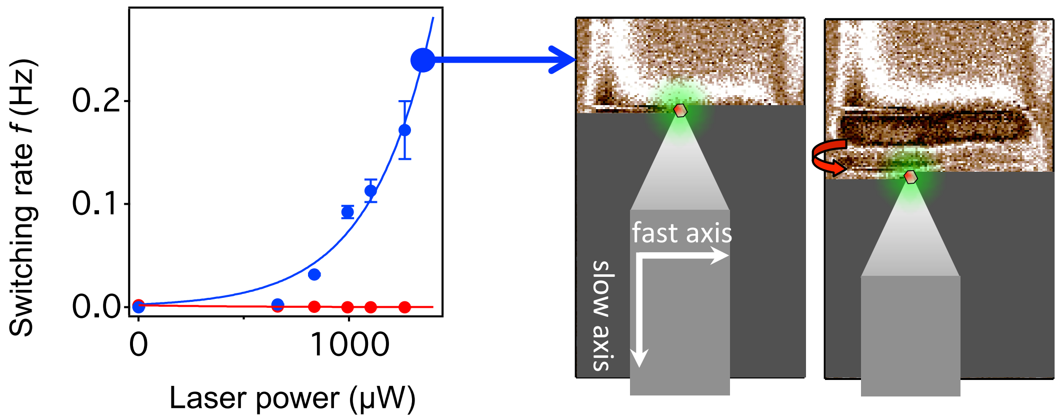


Exploiting the effect



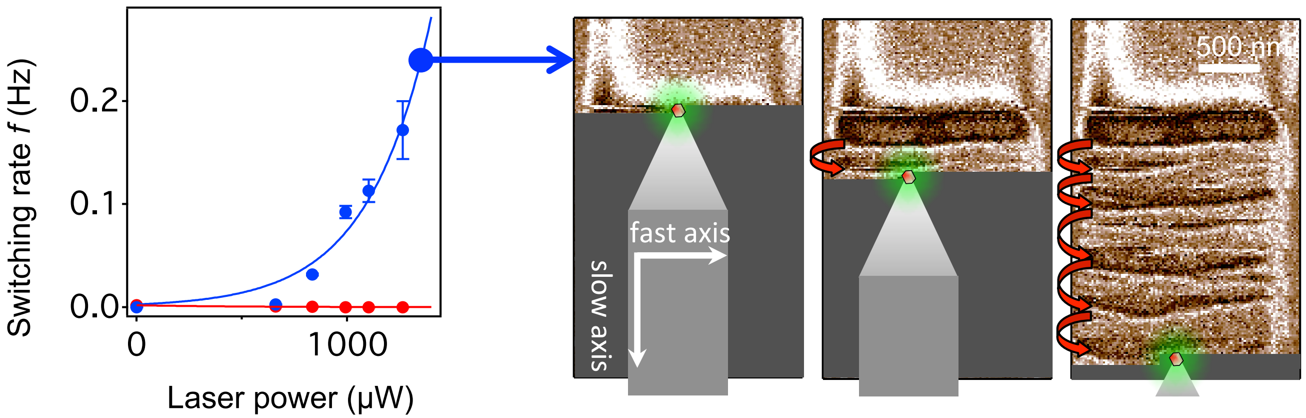
Exploiting the effect

(1) Dragging the DW



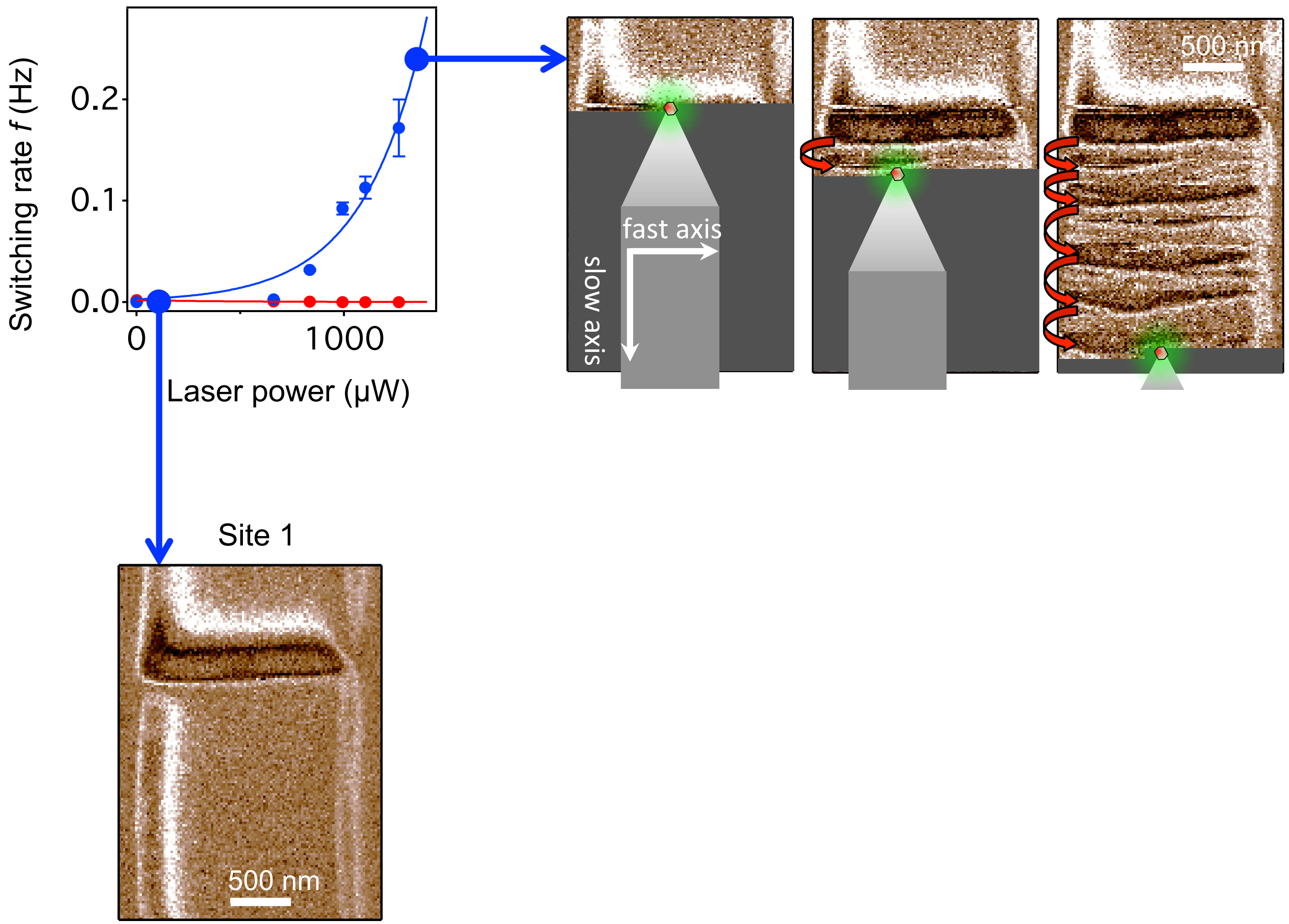
Exploiting the effect

(1) Dragging the DW

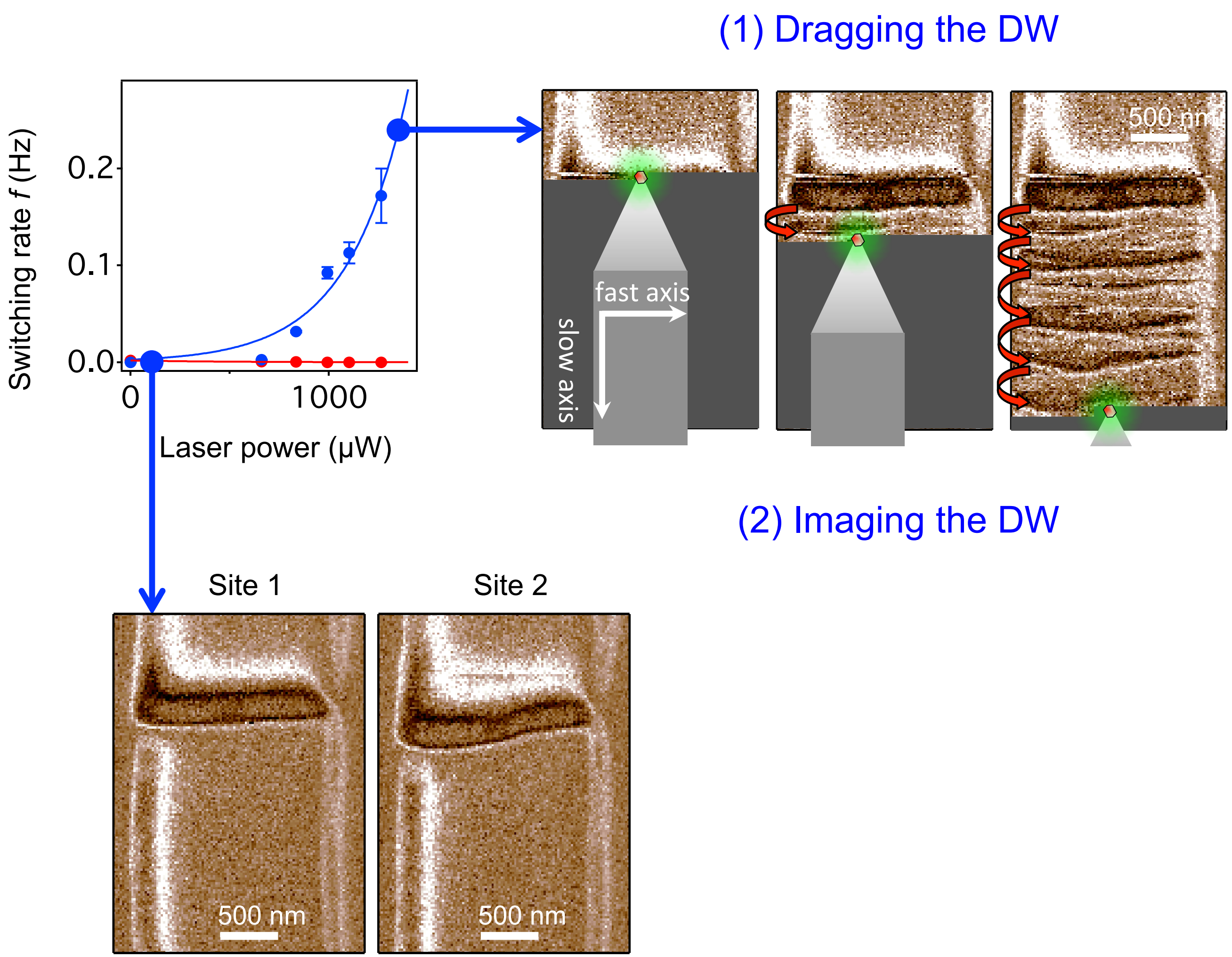


Exploiting the effect

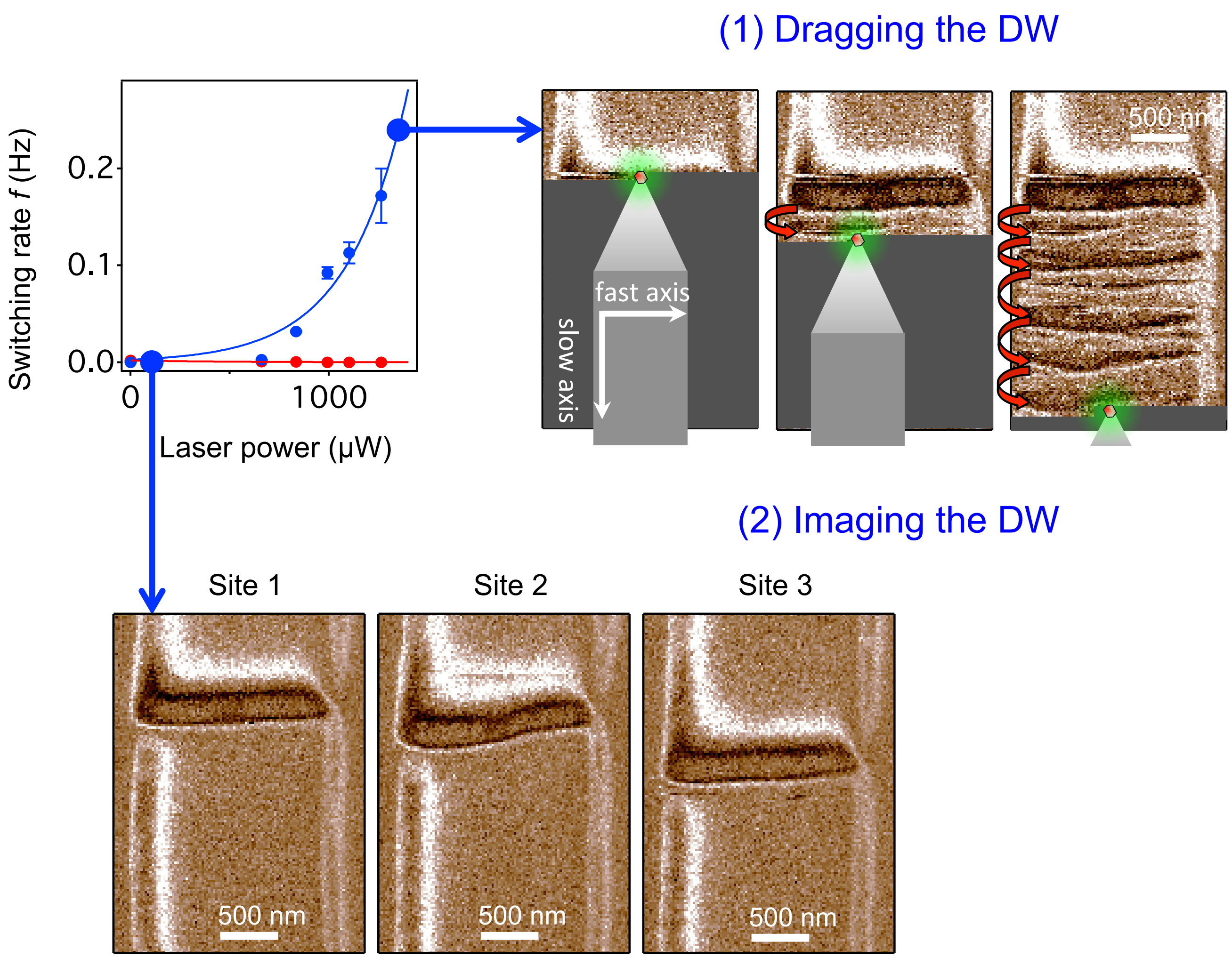
(1) Dragging the DW



Exploiting the effect

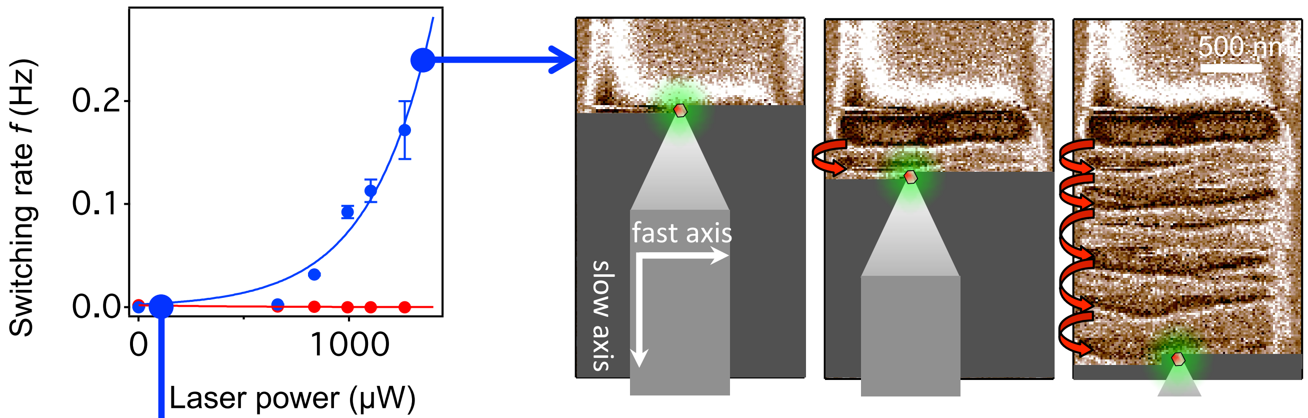


Exploiting the effect

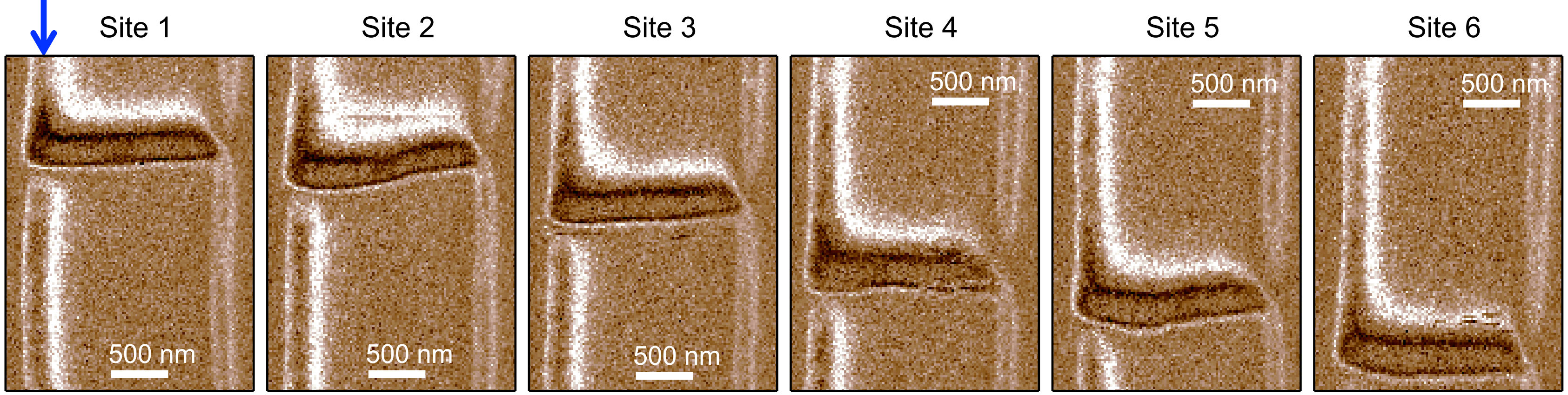


Exploiting the effect

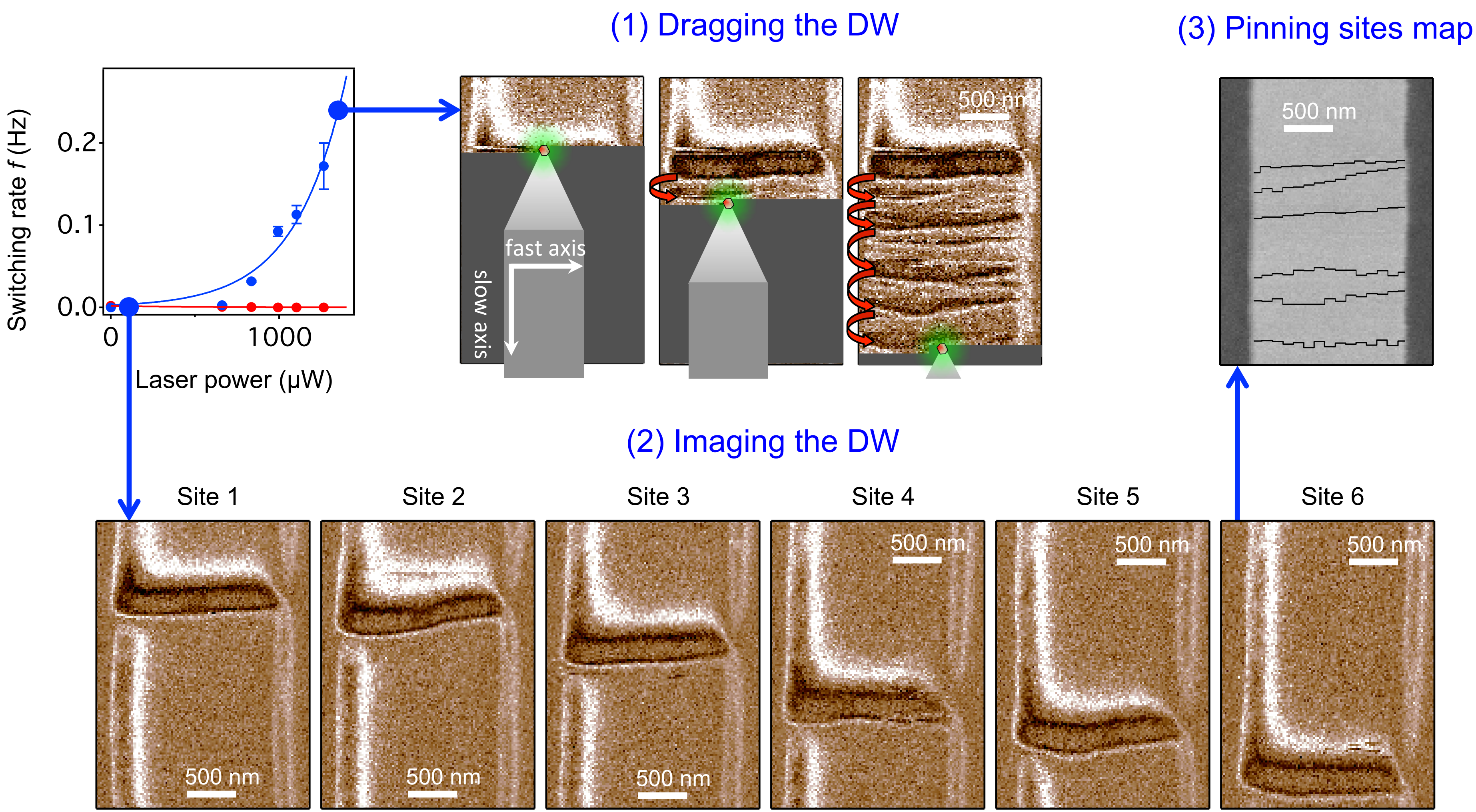
(1) Dragging the DW



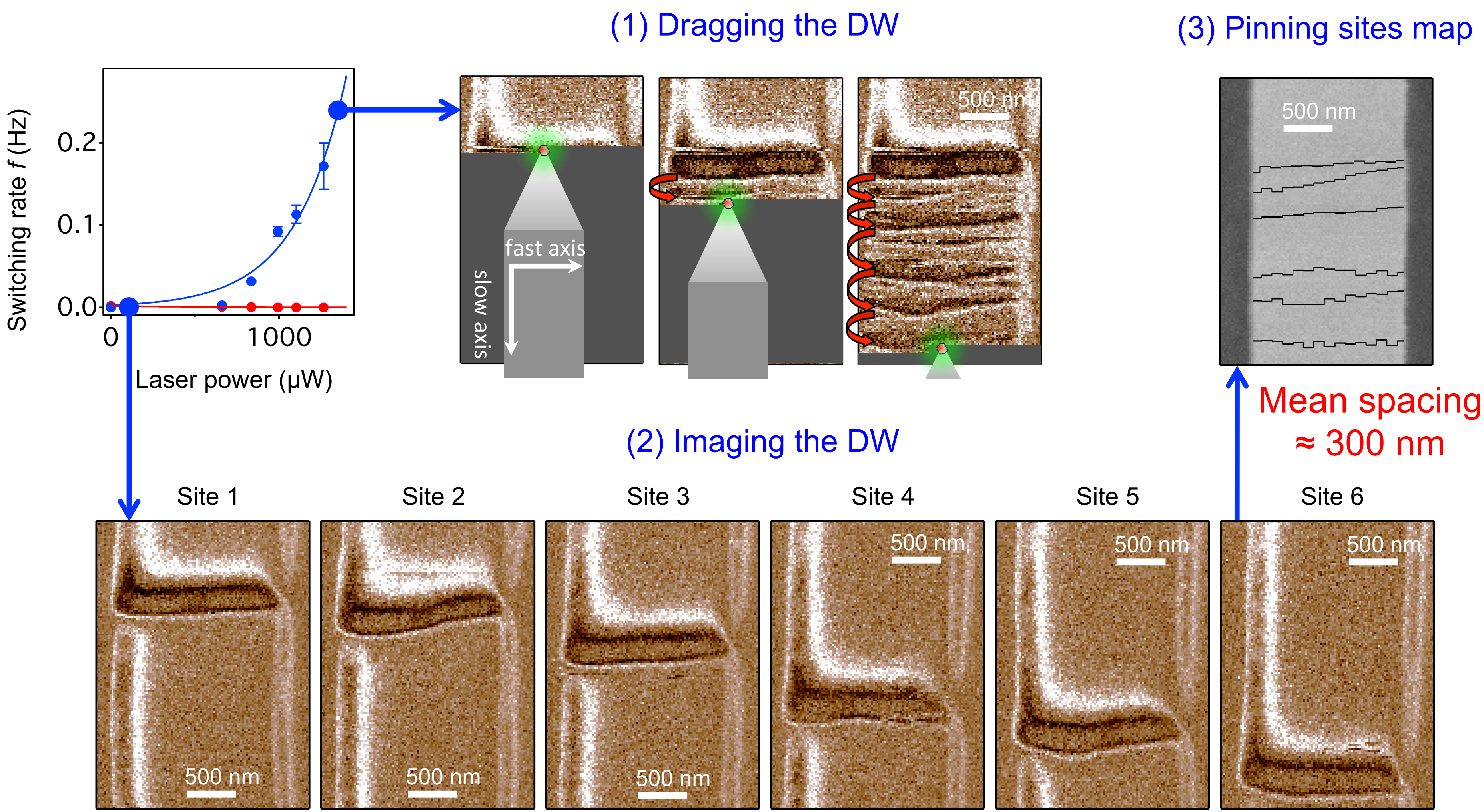
(2) Imaging the DW



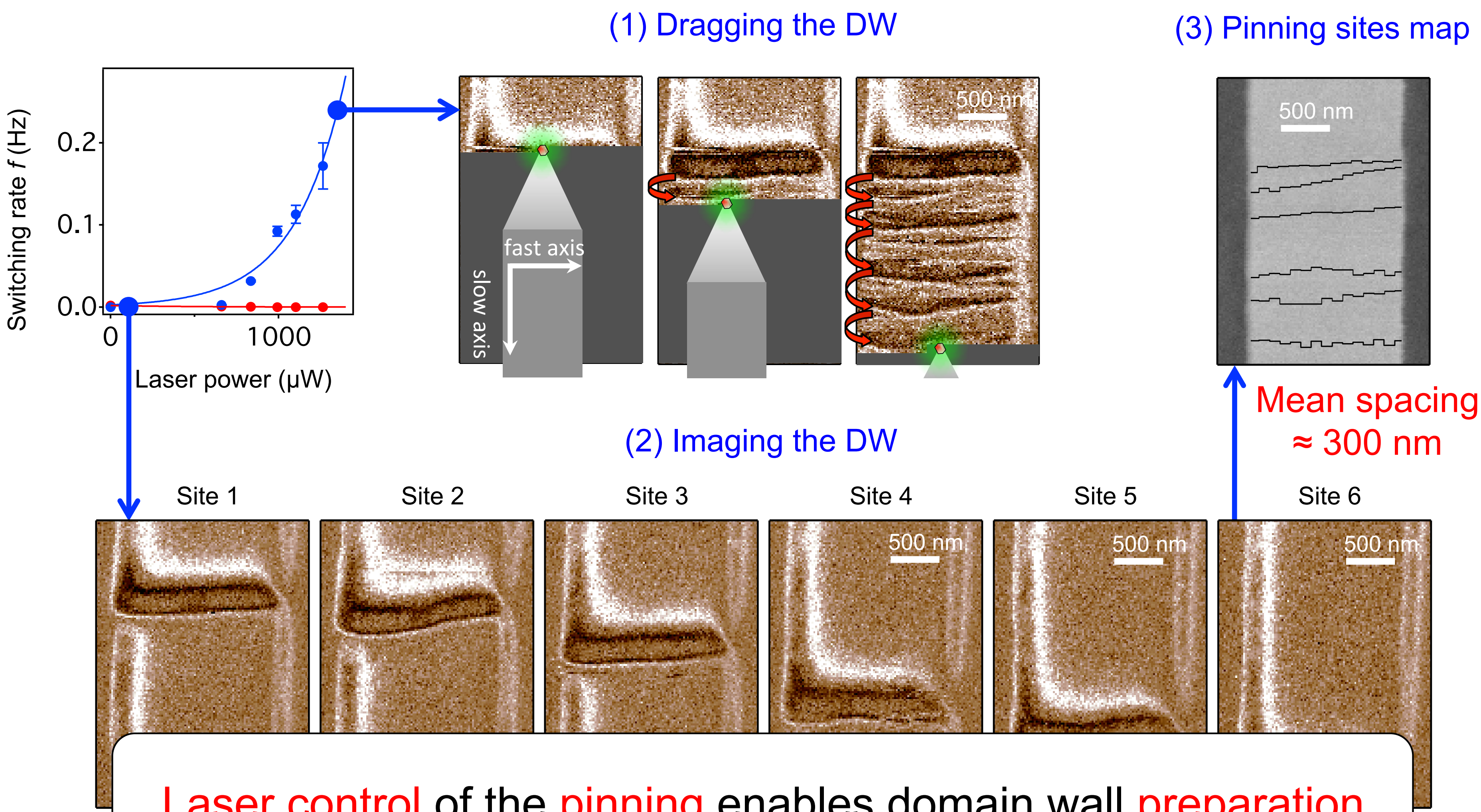
Exploiting the effect



Exploiting the effect



Exploiting the effect

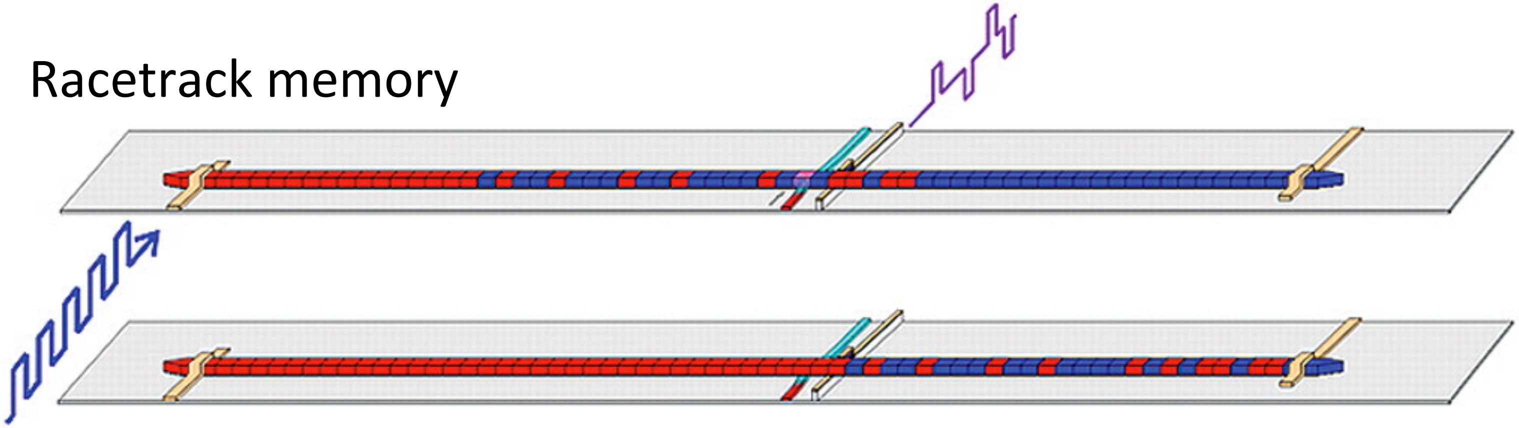


Laser control of the pinning enables domain wall preparation

Motivations

Domain walls in ultrathin ferromagnets with perpendicular anisotropy are of fundamental interest for spintronic

Racetrack memory



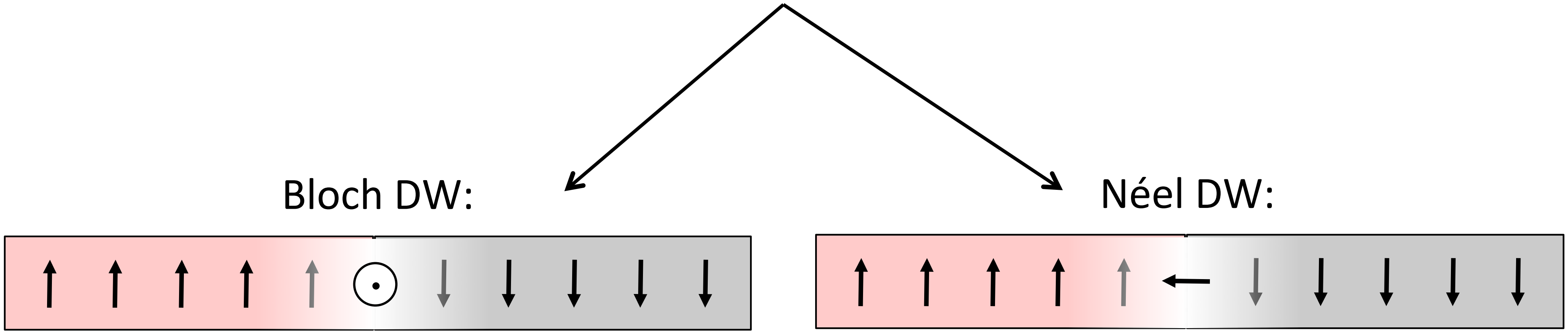
*S. S. P. Parkin et al. Science **320**, 190 (2008)*

- understanding the pinning
- determining the chirality of the walls (wall motion)

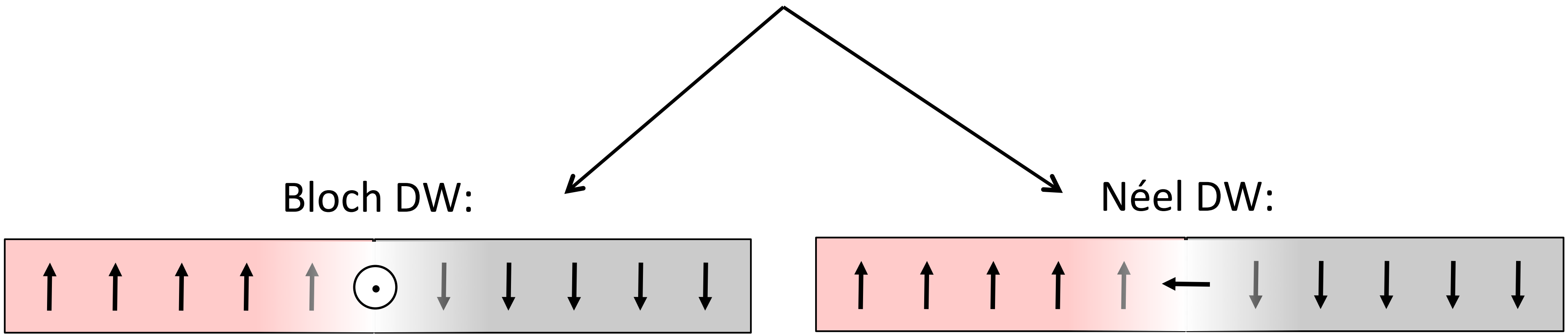
What is the nature of the wall ?

Bloch DW:

Néel DW:



What is the nature of the wall ?

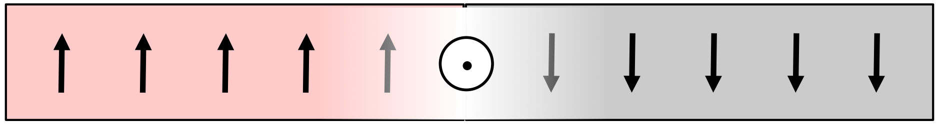


direct impact onto wall

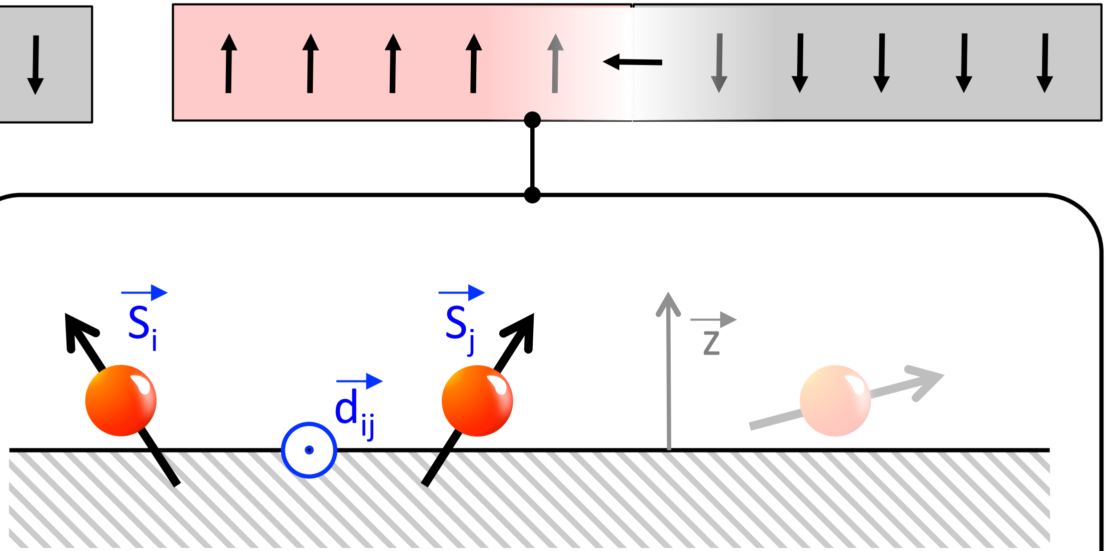
motion under current

What is the nature of the wall ?

Bloch DW:



Néel DW:



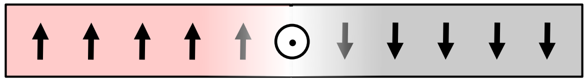
Dzyaloshinskii-Moriya interaction at the interface

$$E_{\mathrm{DM}} = \sum_{\langle i,j \rangle} \vec{d}_{ij} \cdot \left(\vec{S}_i \times \vec{S}_j \right)$$

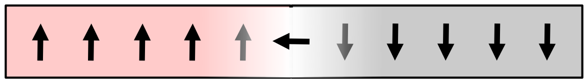
direct impact onto wall motion under current

Why using NV microscopy ?

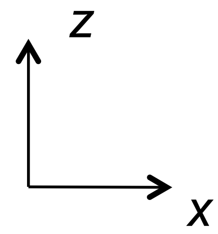
Bloch DW:



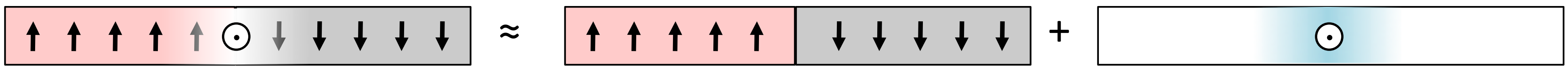
Néel DW:



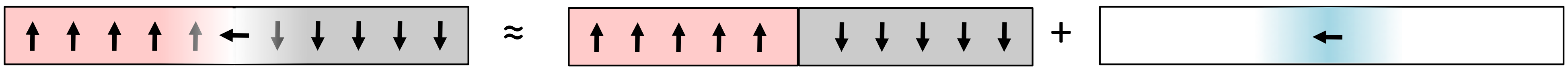
Why using NV microscopy ?



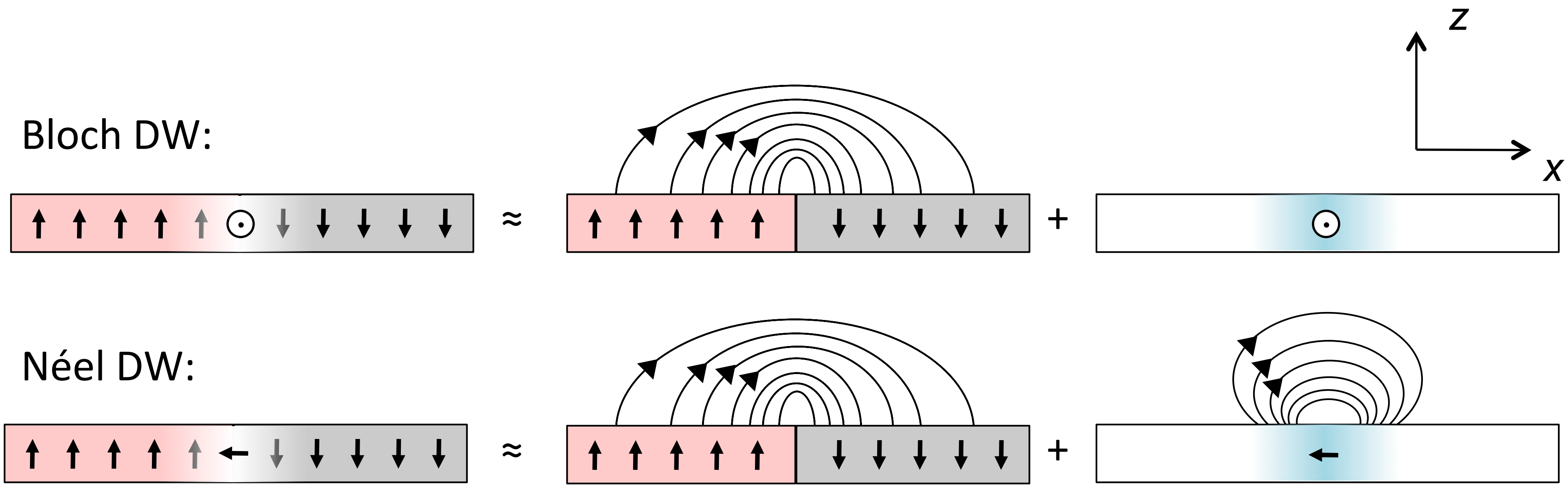
Bloch DW:



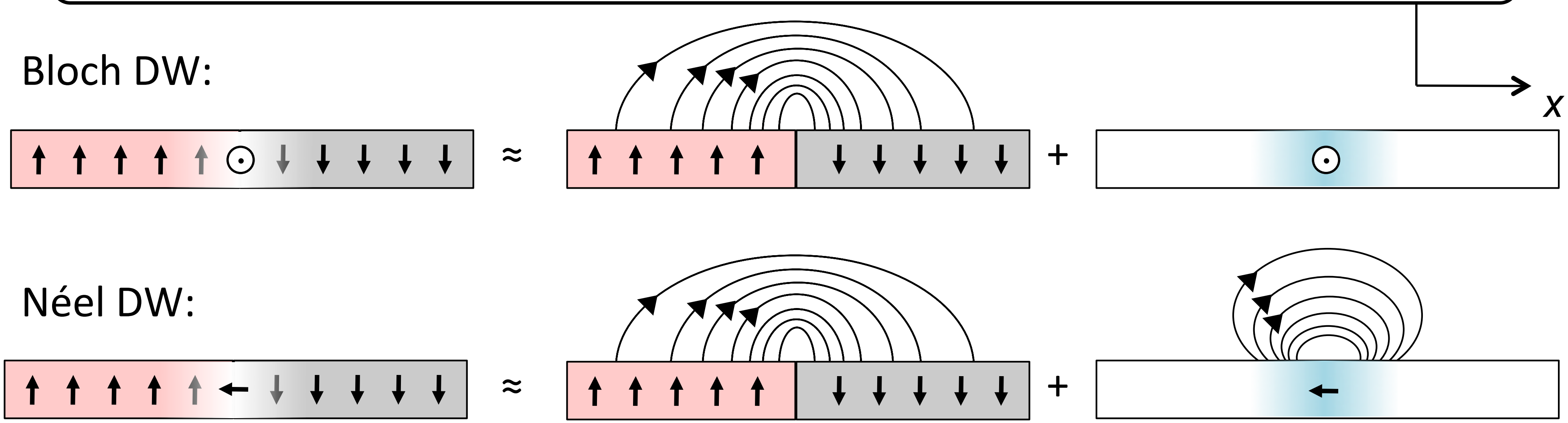
Néel DW:

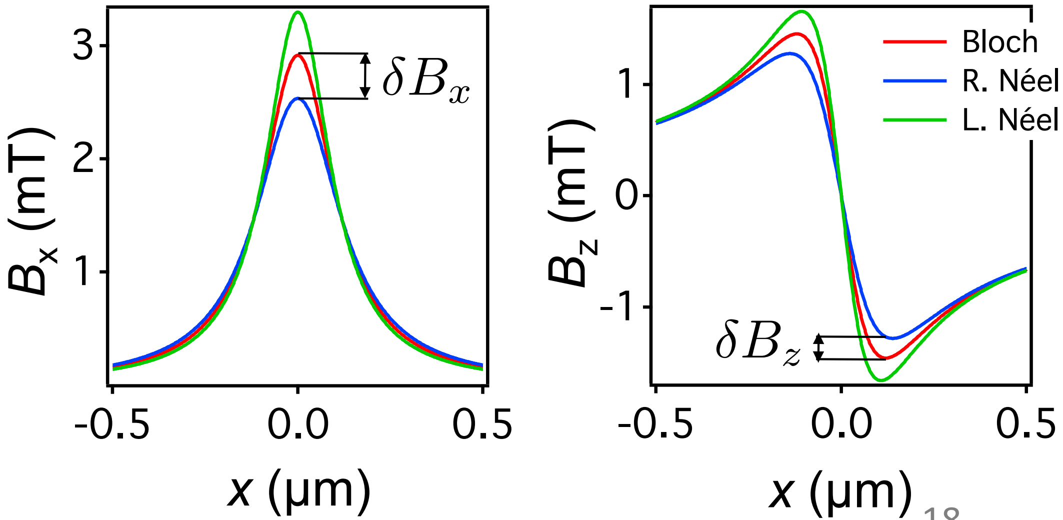


Why using NV microscopy ?



One can distinguish between a Néel DW and a Bloch DW looking at the stray field

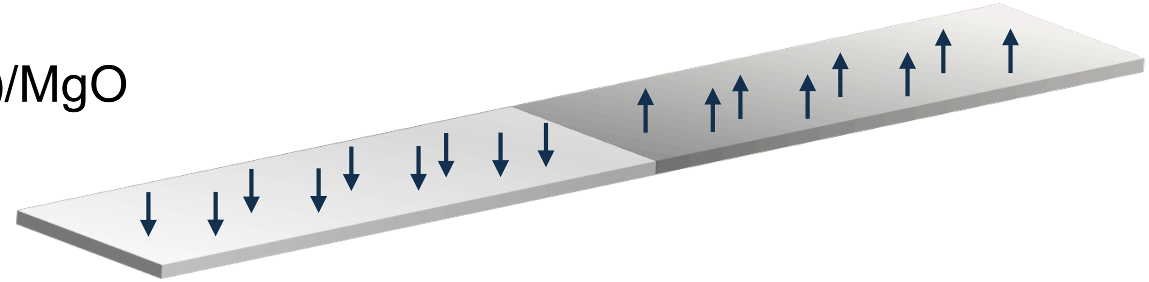




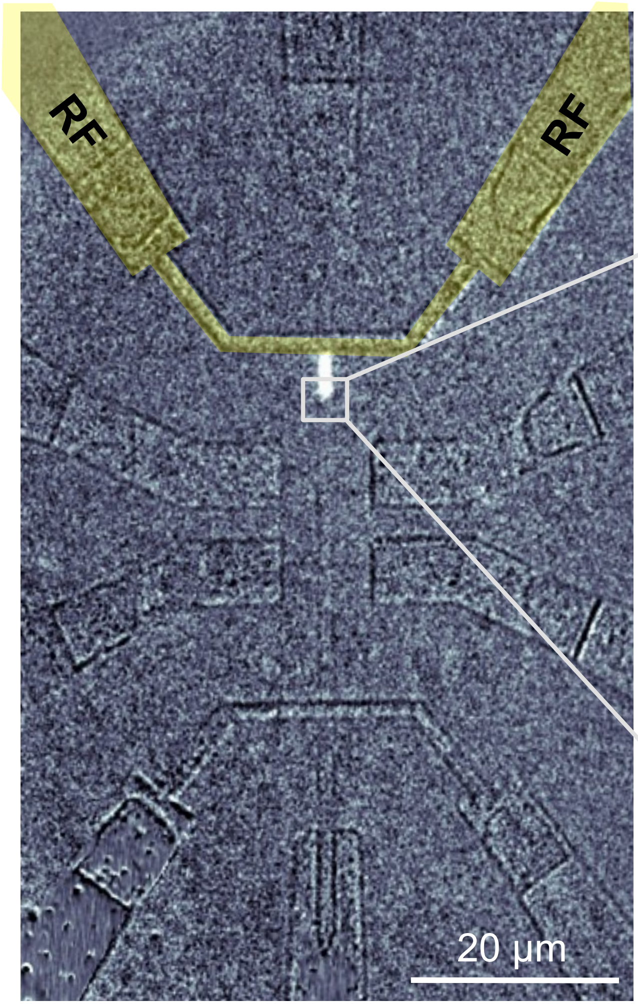
10% variation
@ 100 nm
on Ta/CoFeB(1 nm)/MgO

Same sample

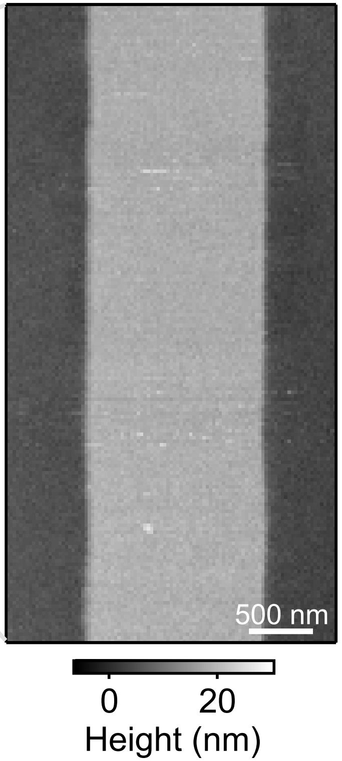
$Ta/Co_{40}Fe_{40}B_{20}$(1 nm)/MgO



MOKE

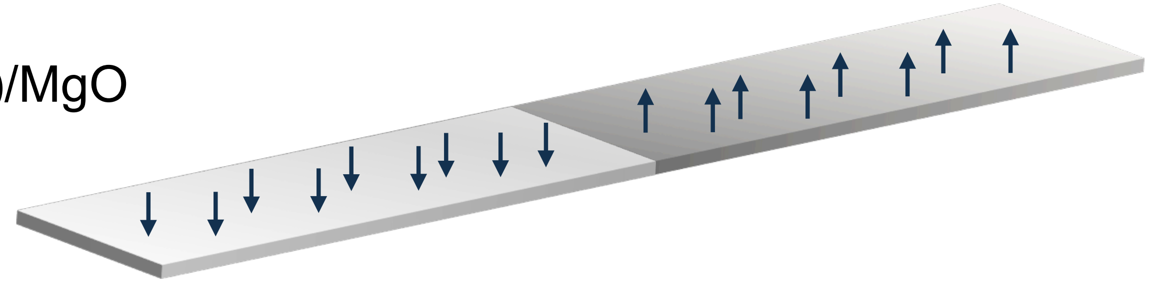


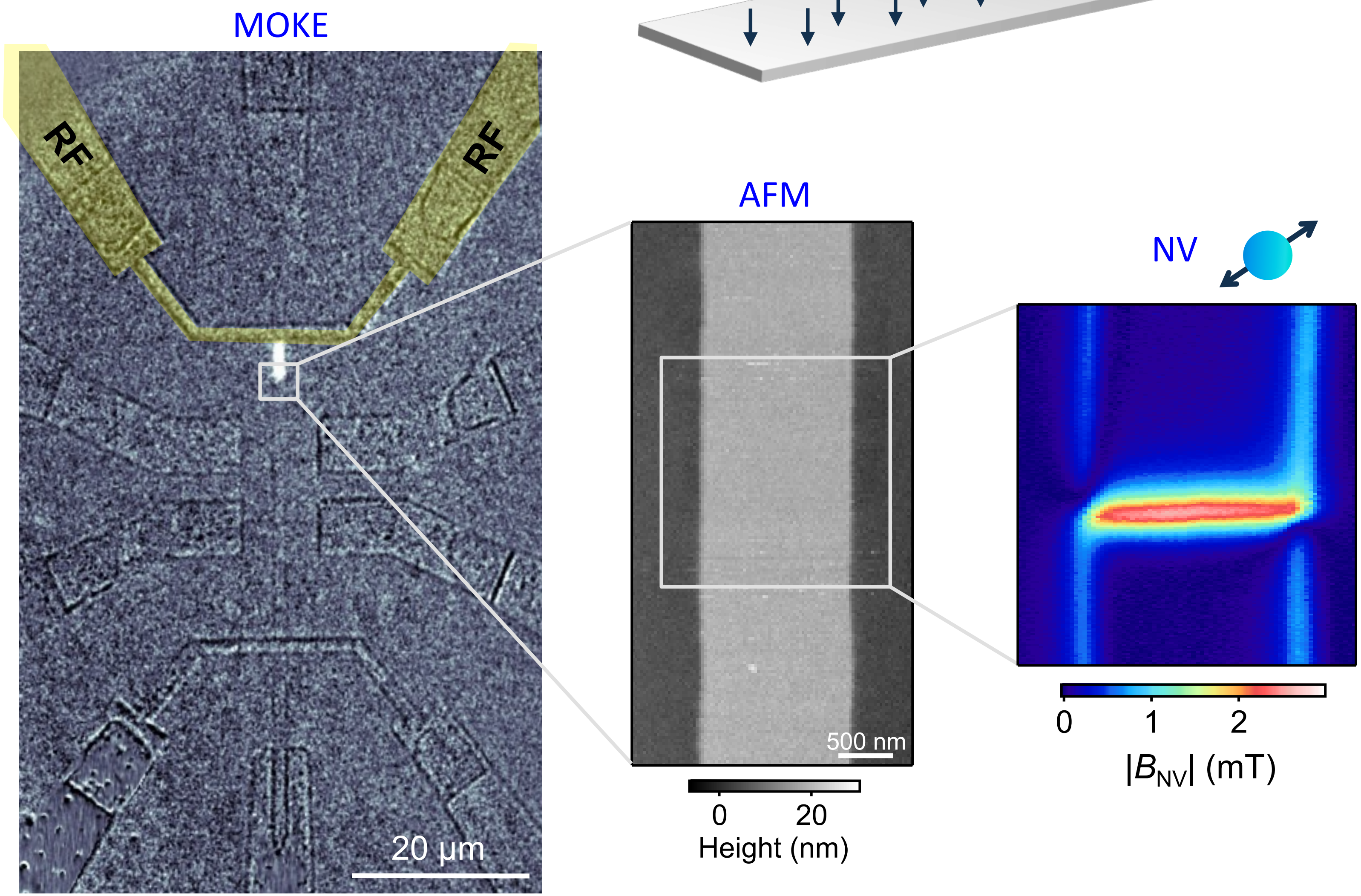
AFM



Same sample

$Ta/Co_{40}Fe_{40}B_{20}$(1 nm)/MgO





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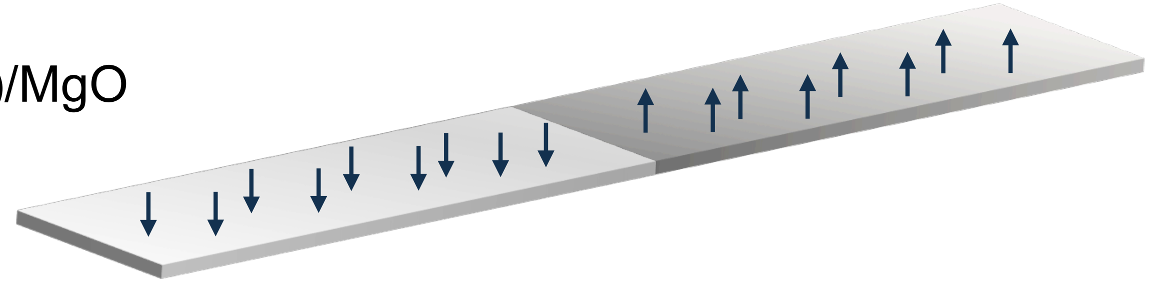

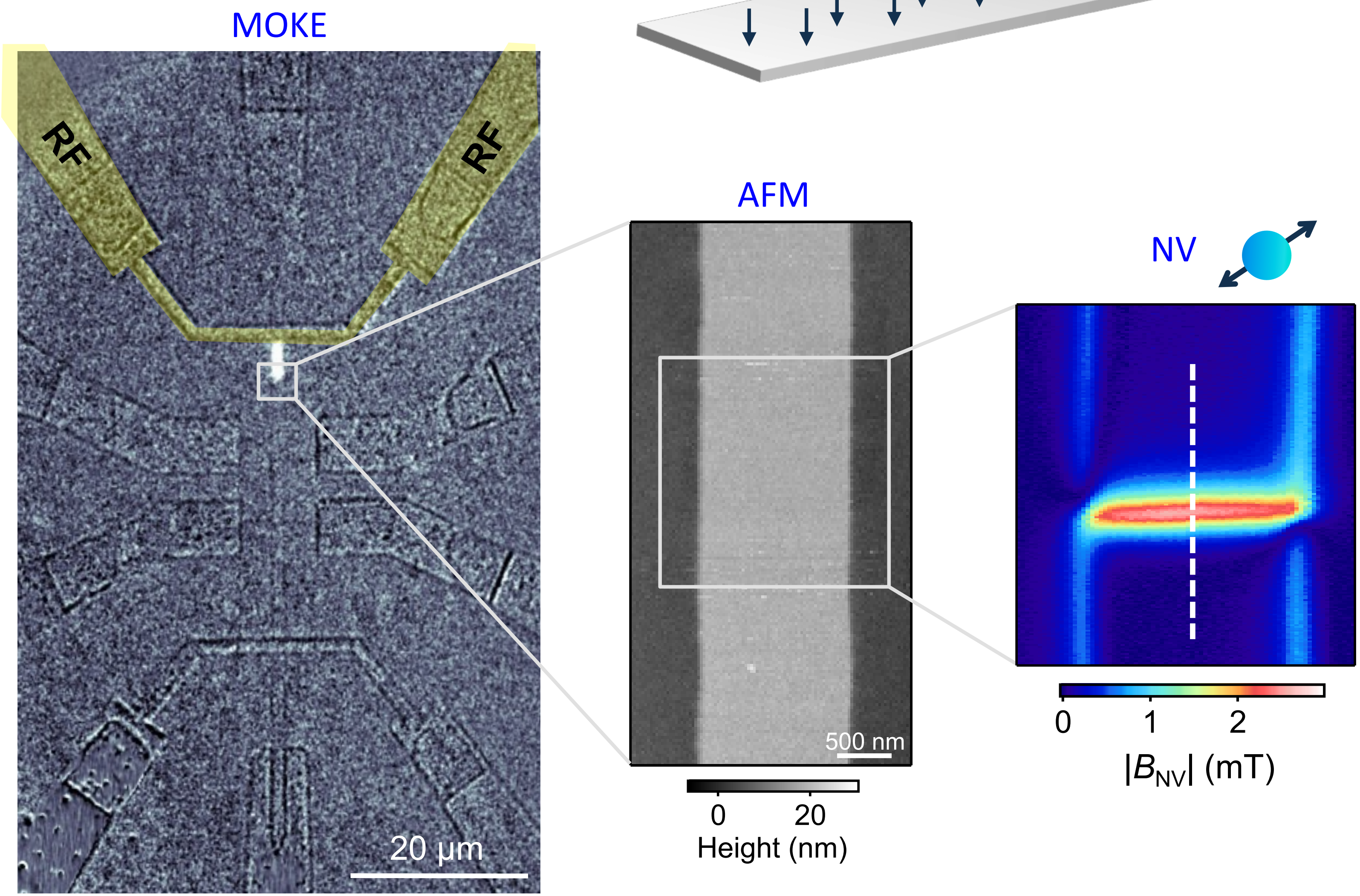

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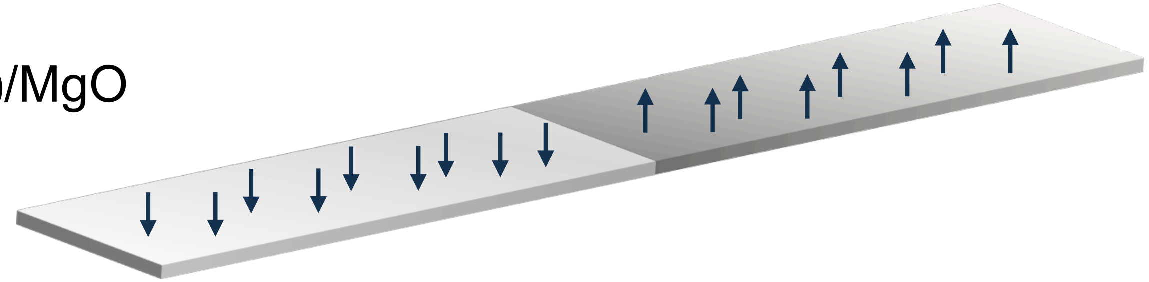
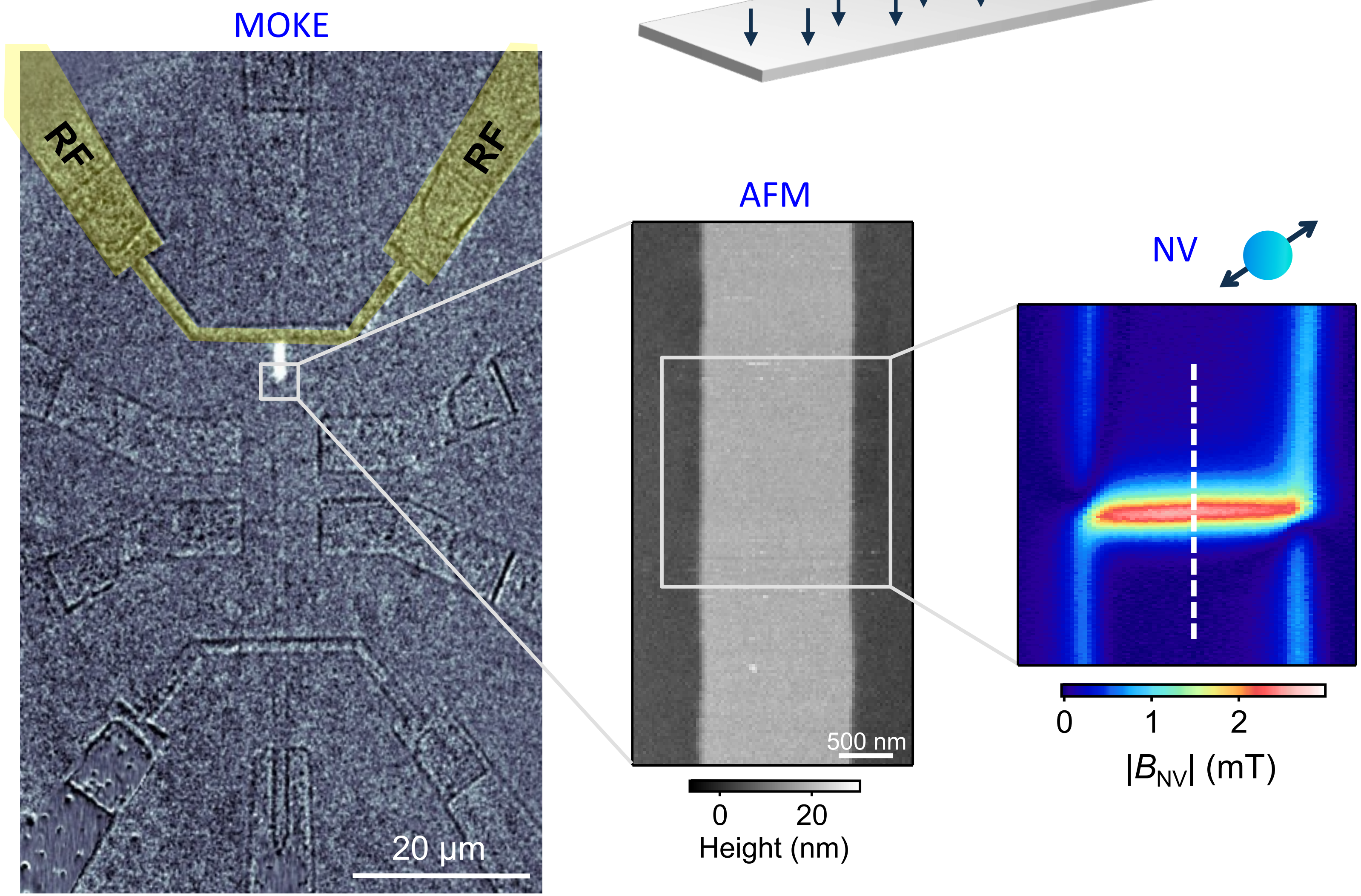
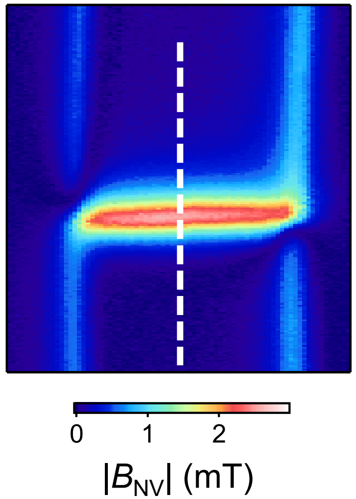




Comparison with simulations

Experiment



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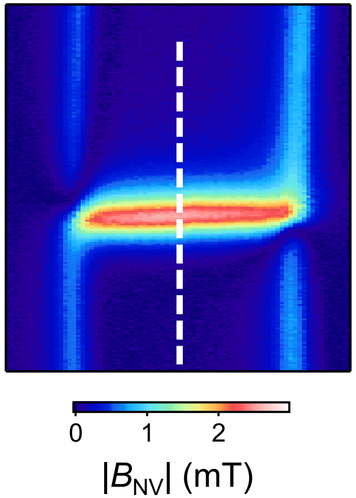
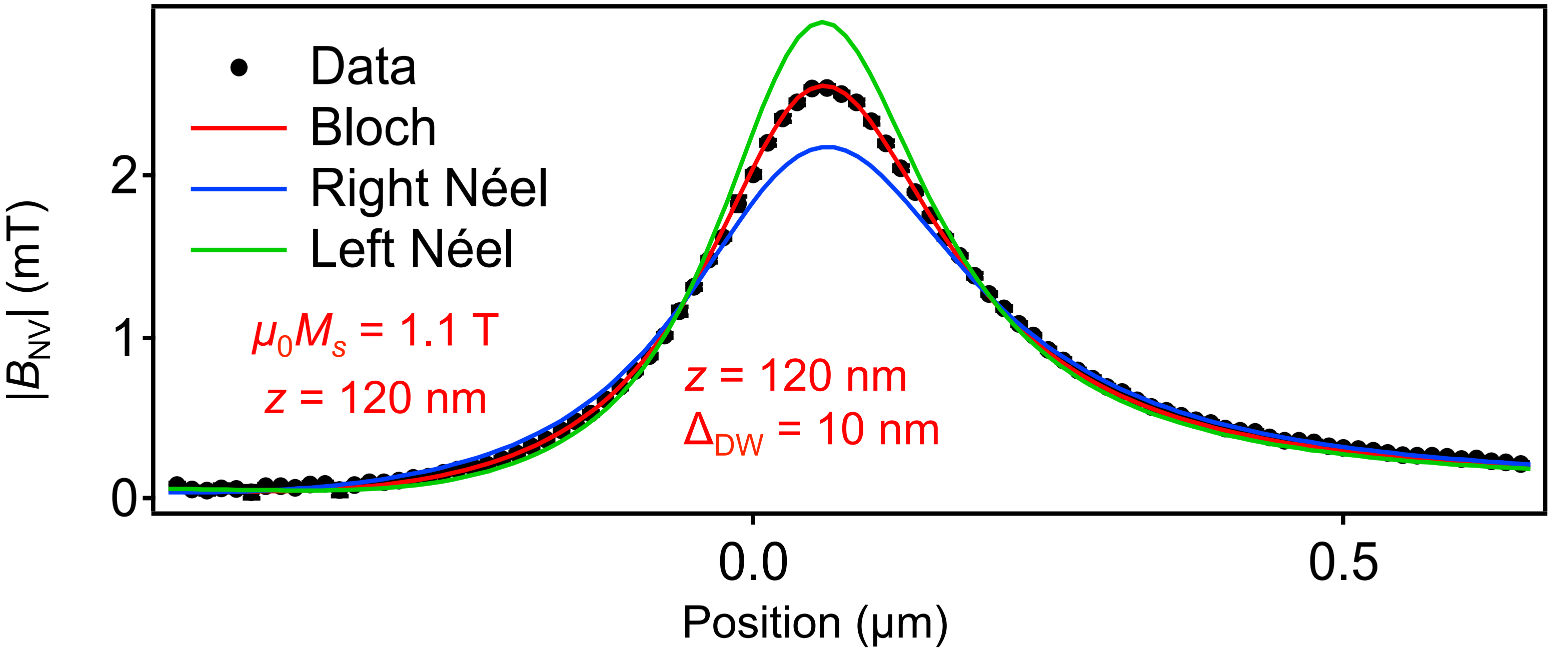
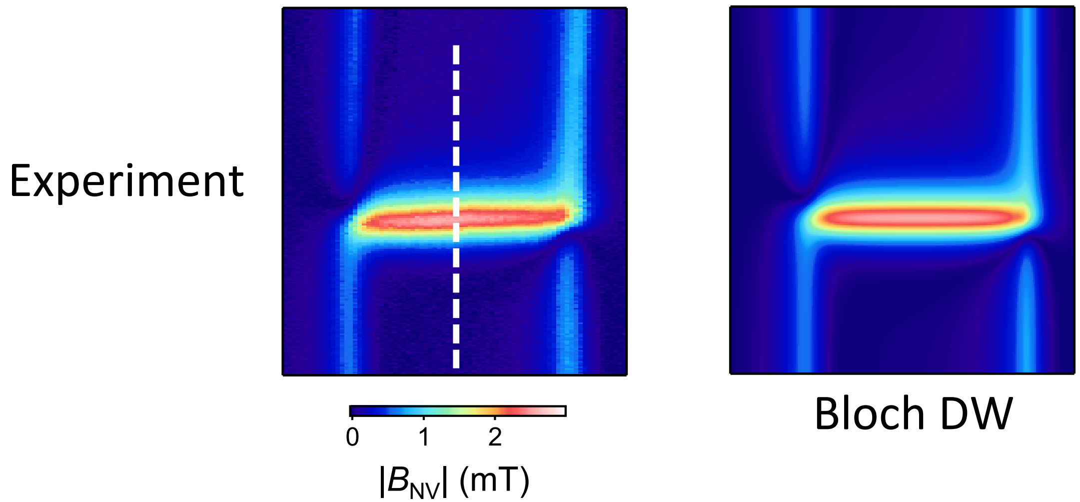
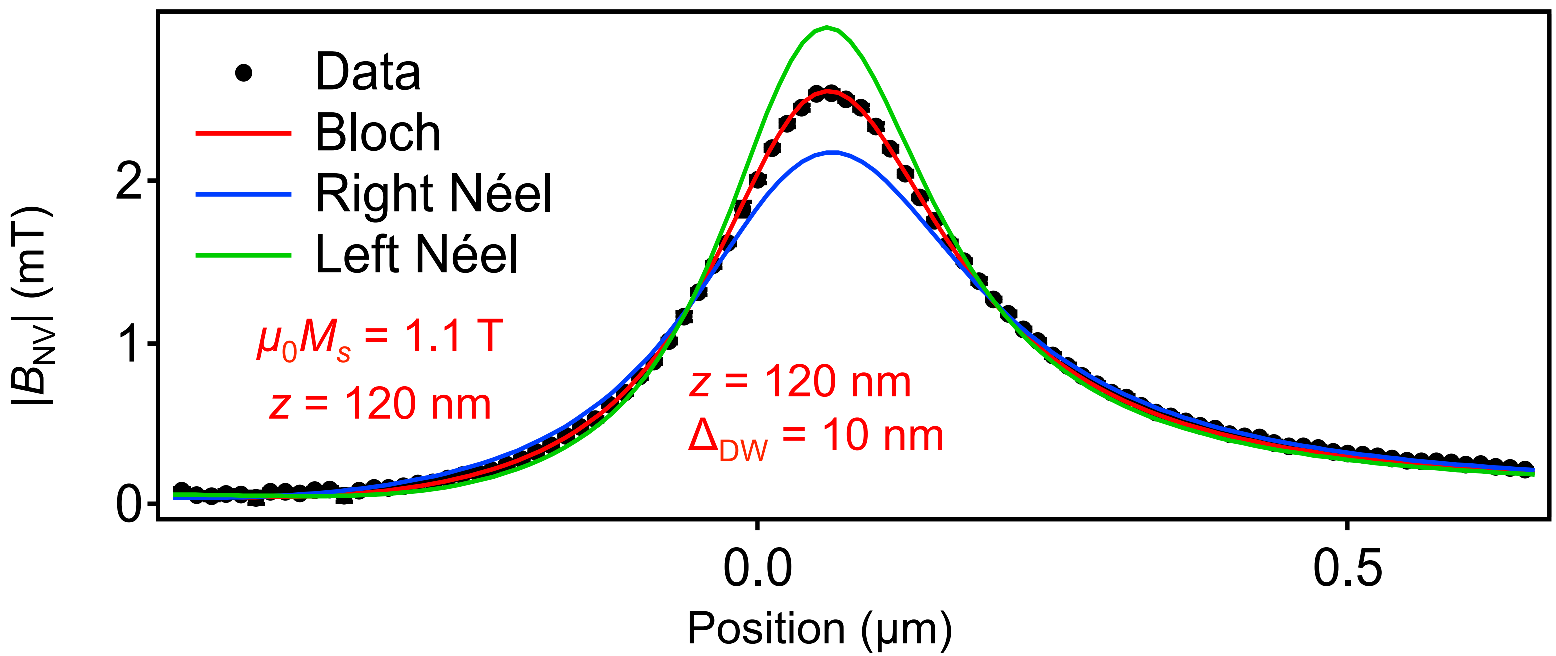




Comparison with simulations





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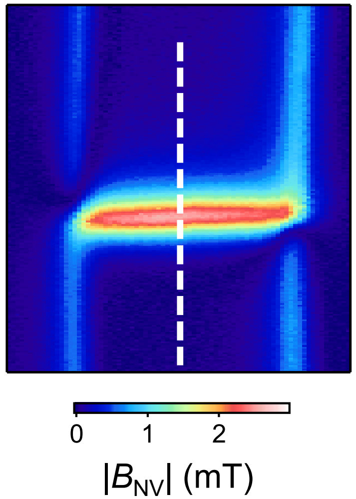
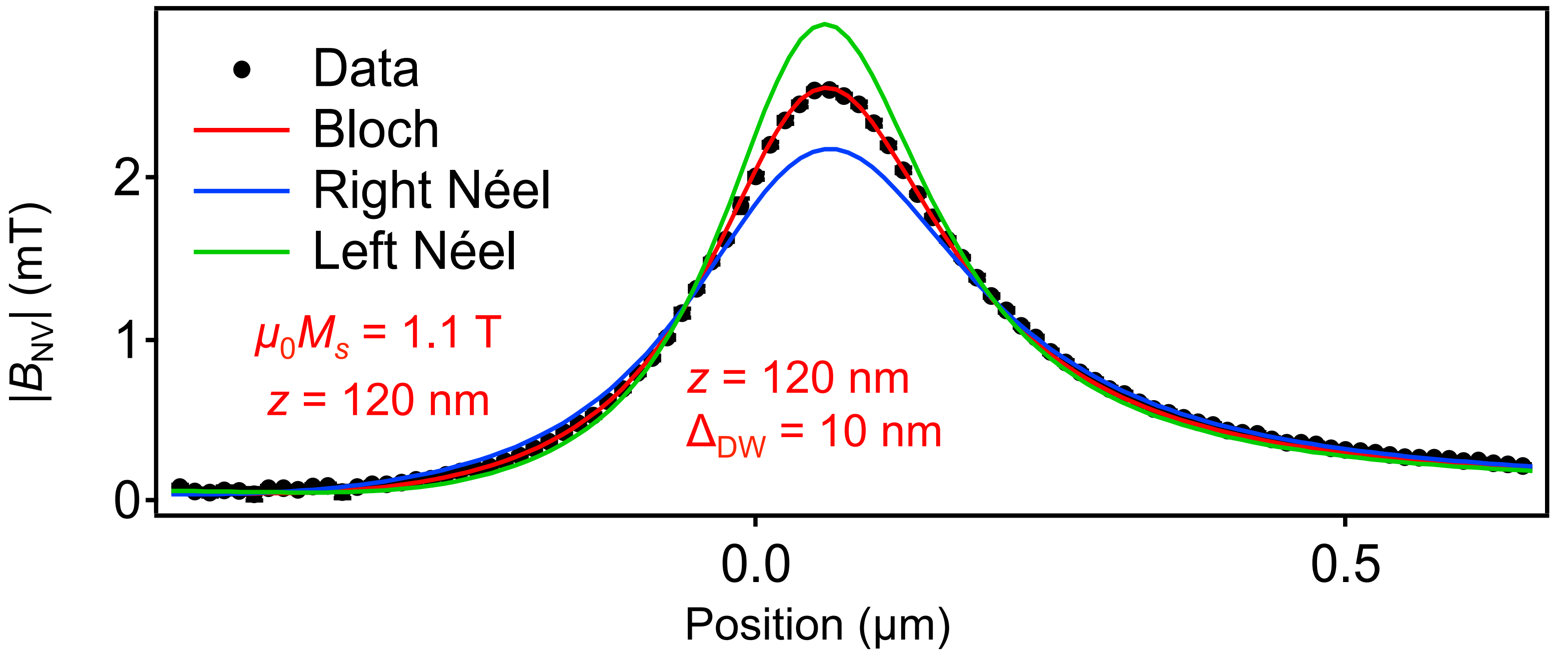


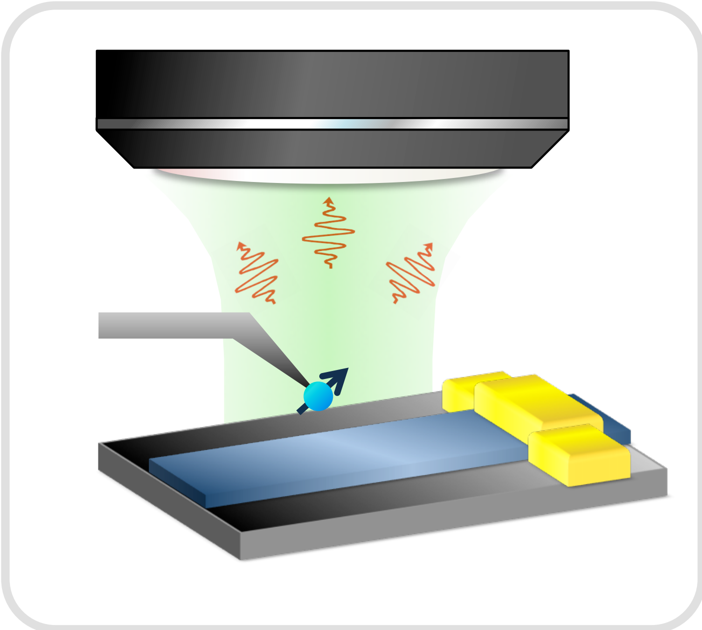


Conclusion

New magnetic field imaging technique :

- high resolution
- non invasive
- quantitative

Limited to B < 10mT



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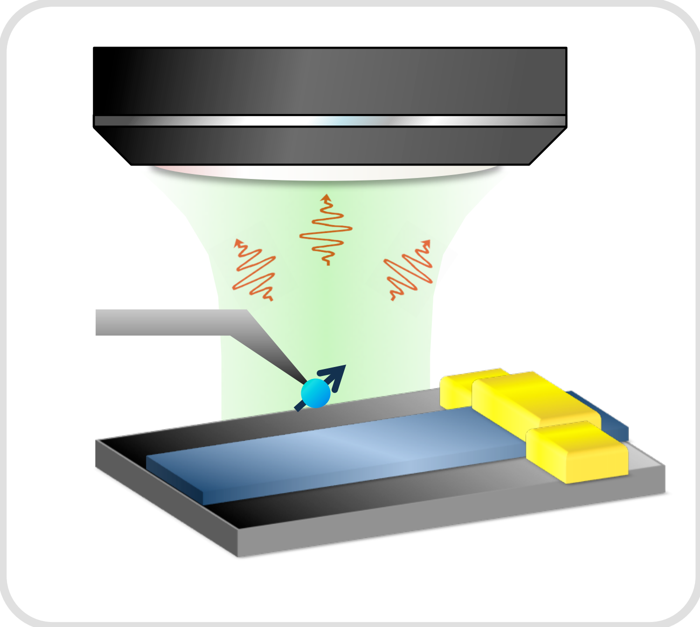

next:

going to low temperature (4K)

Conclusion

New magnetic field imaging technique :

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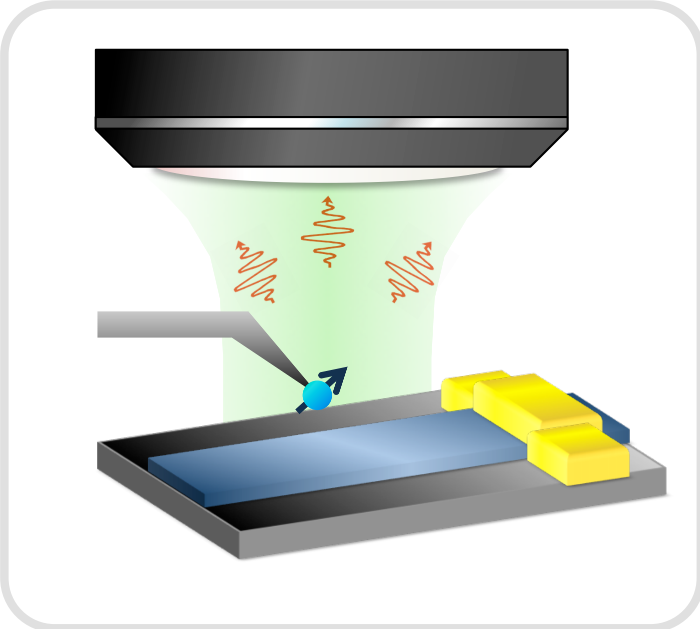
- quantitative

Limited to B < 10mT



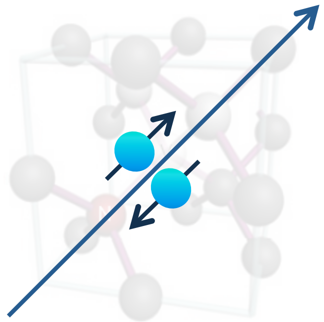
next:

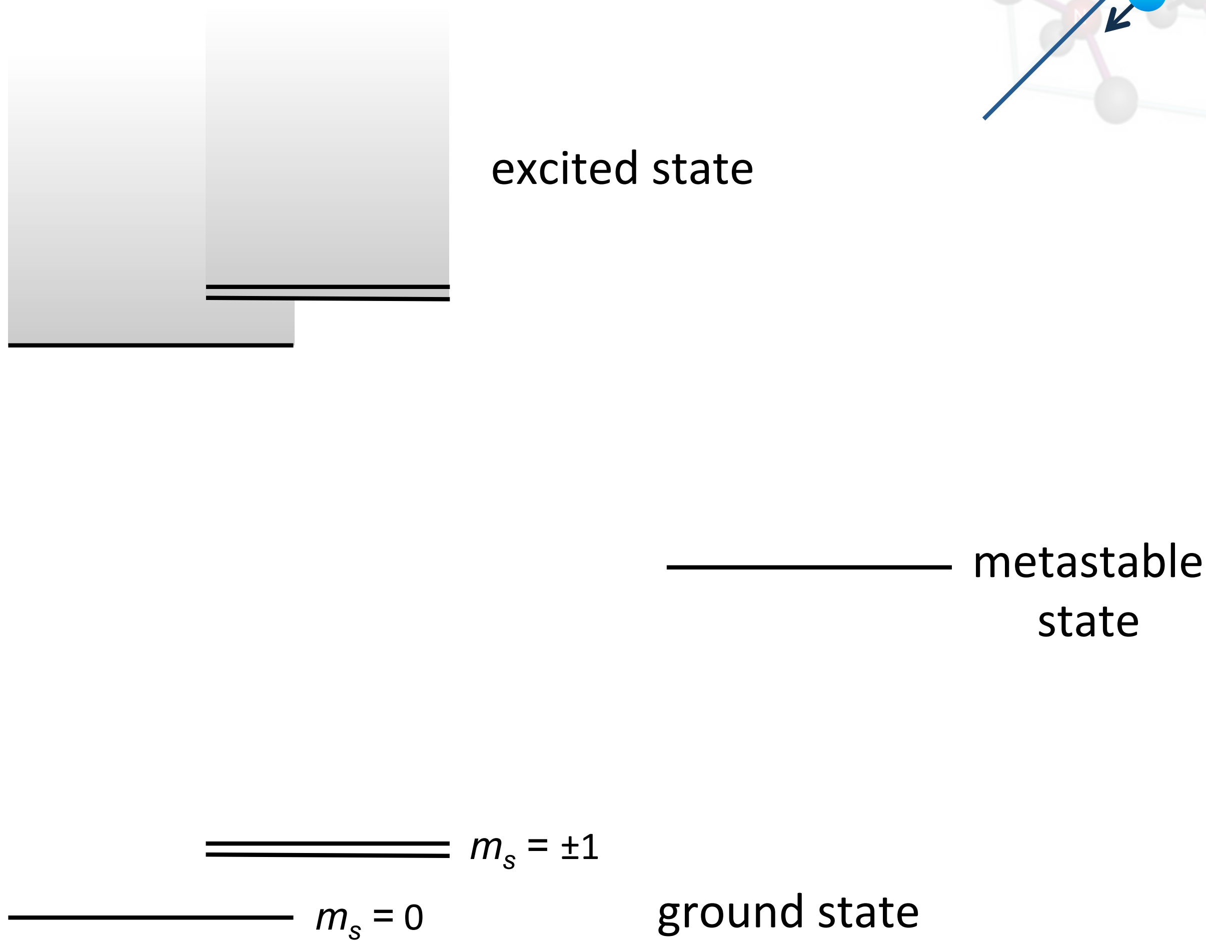
going to low temperature (4K)

Thank you

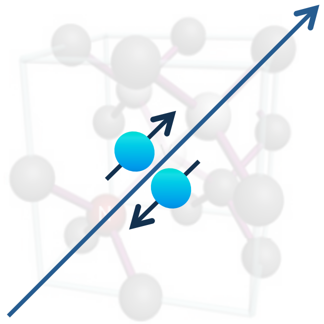
see the poster of J.-P. Tétienne for discussion

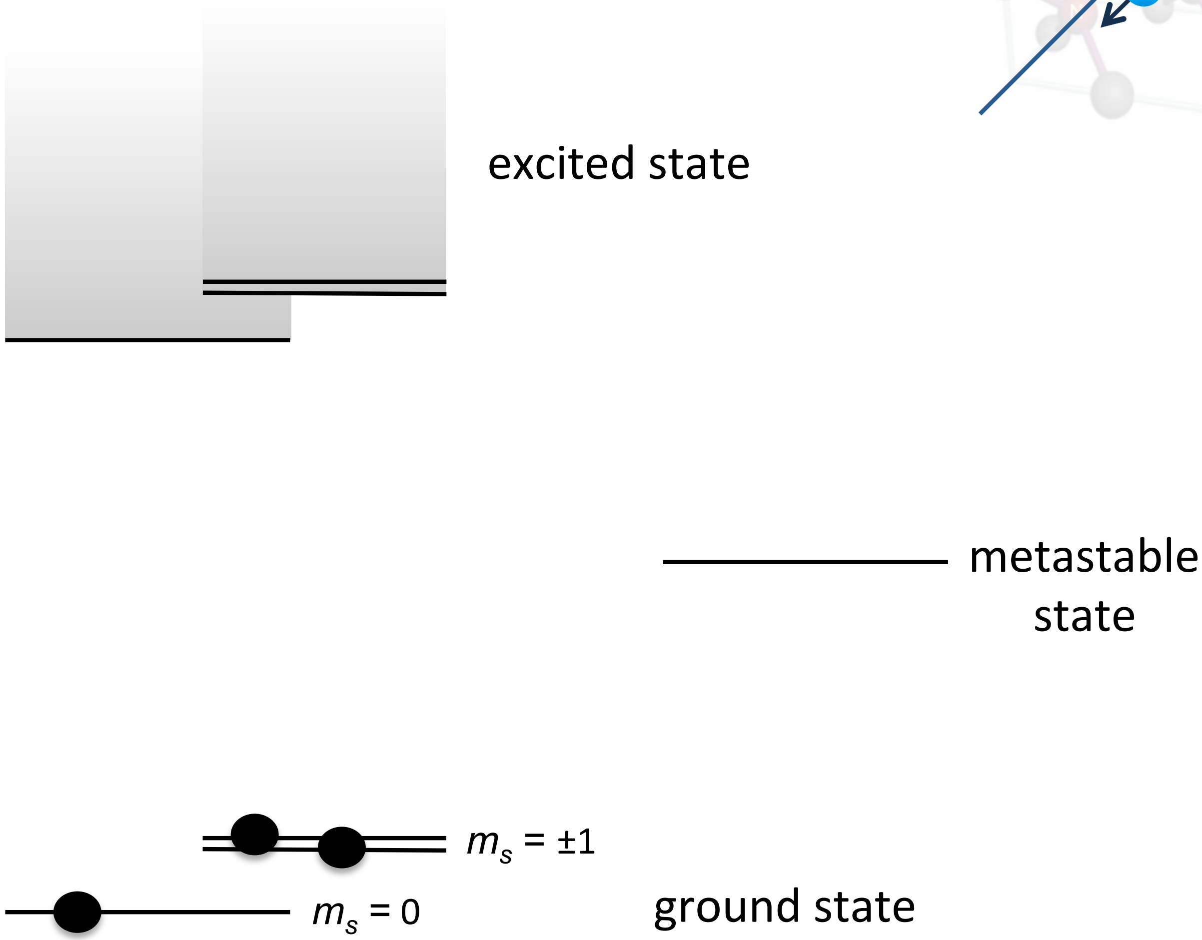
Simple level structure



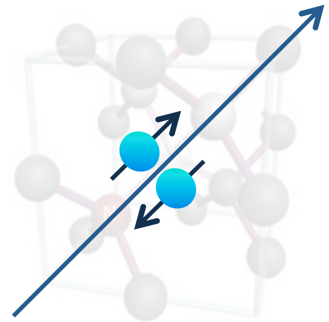


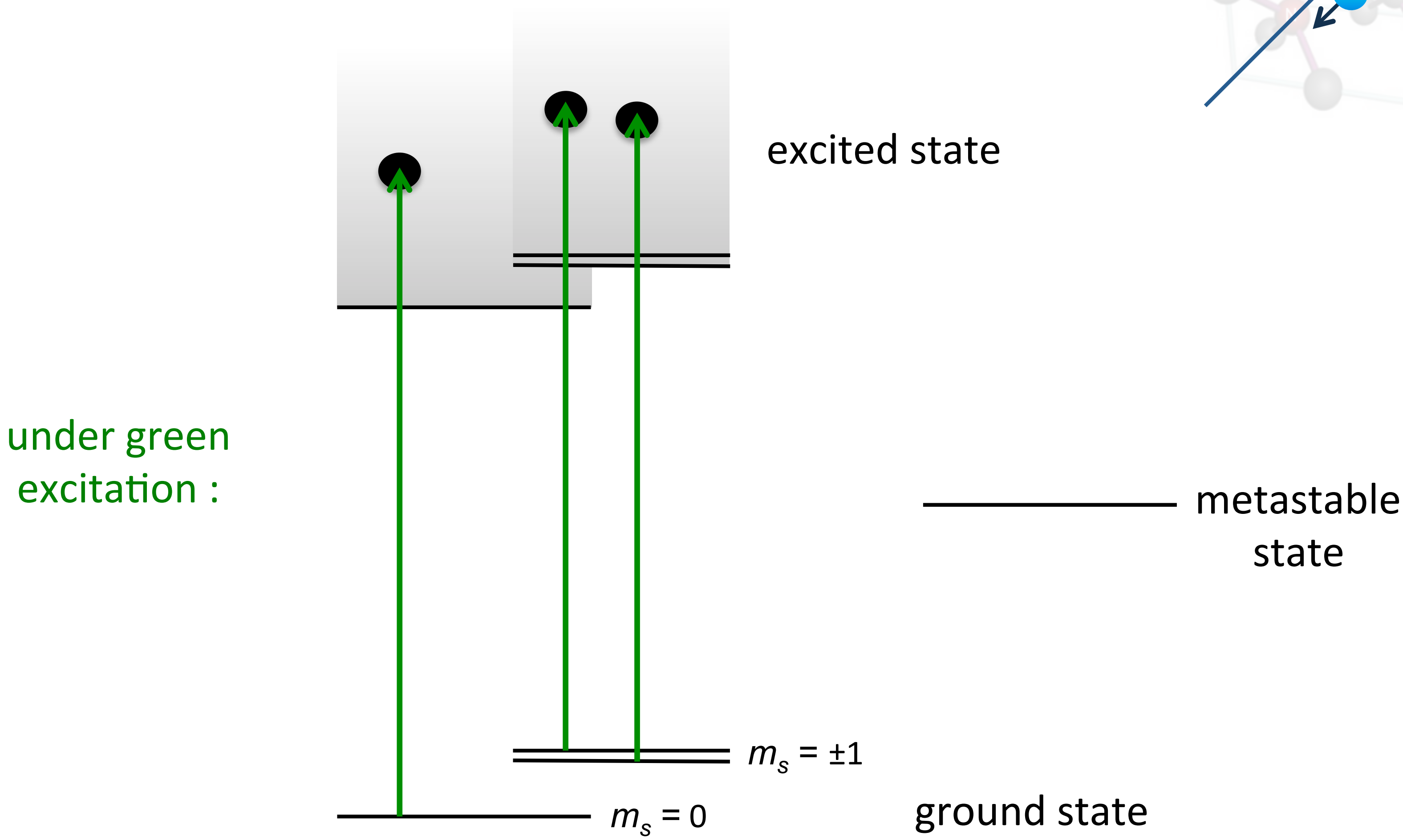
Simple level structure



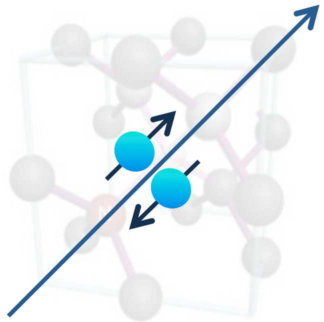


Simple level structure

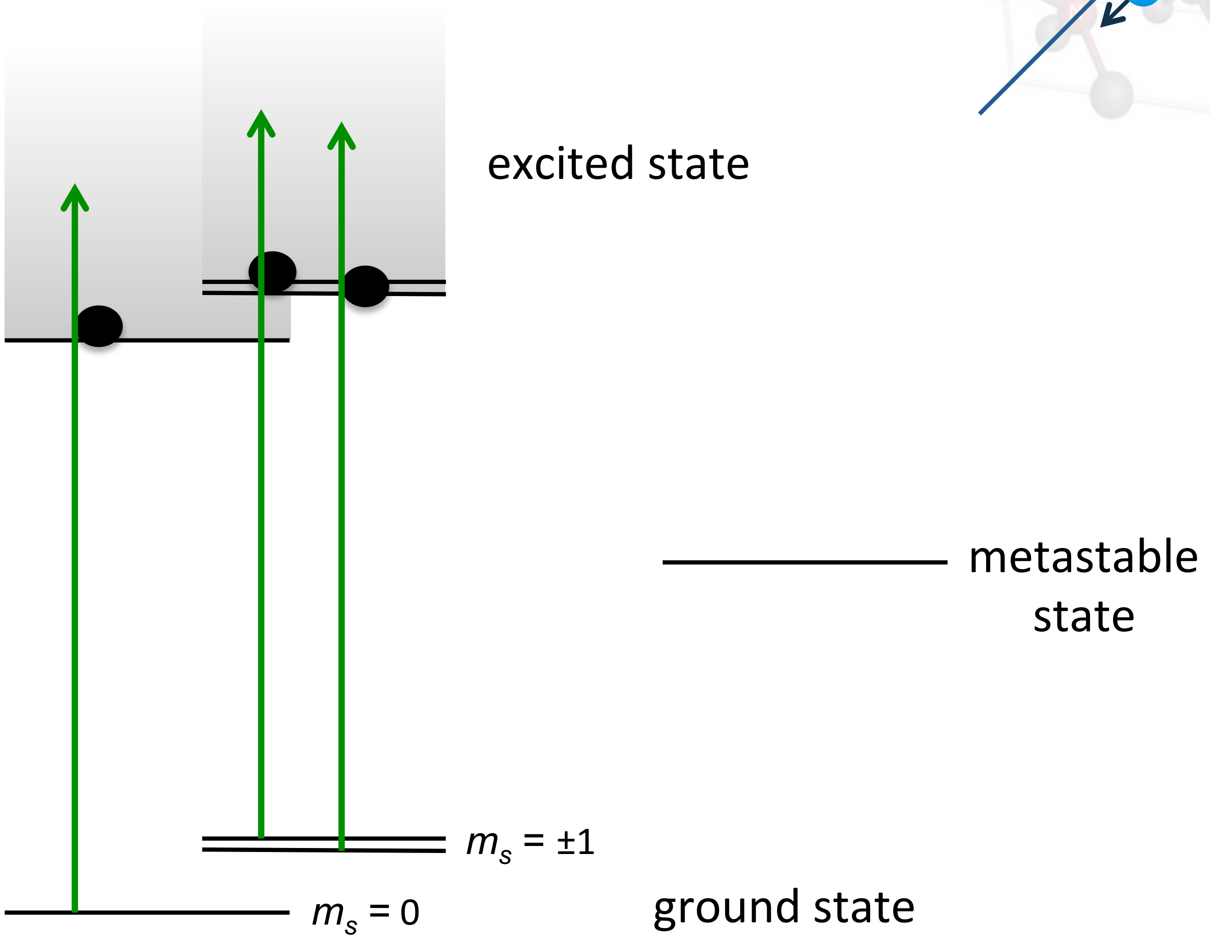




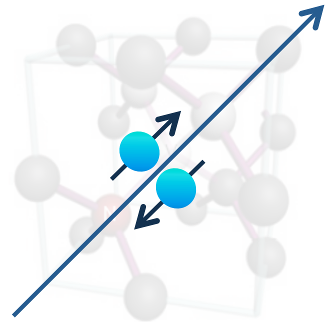
Simple level structure

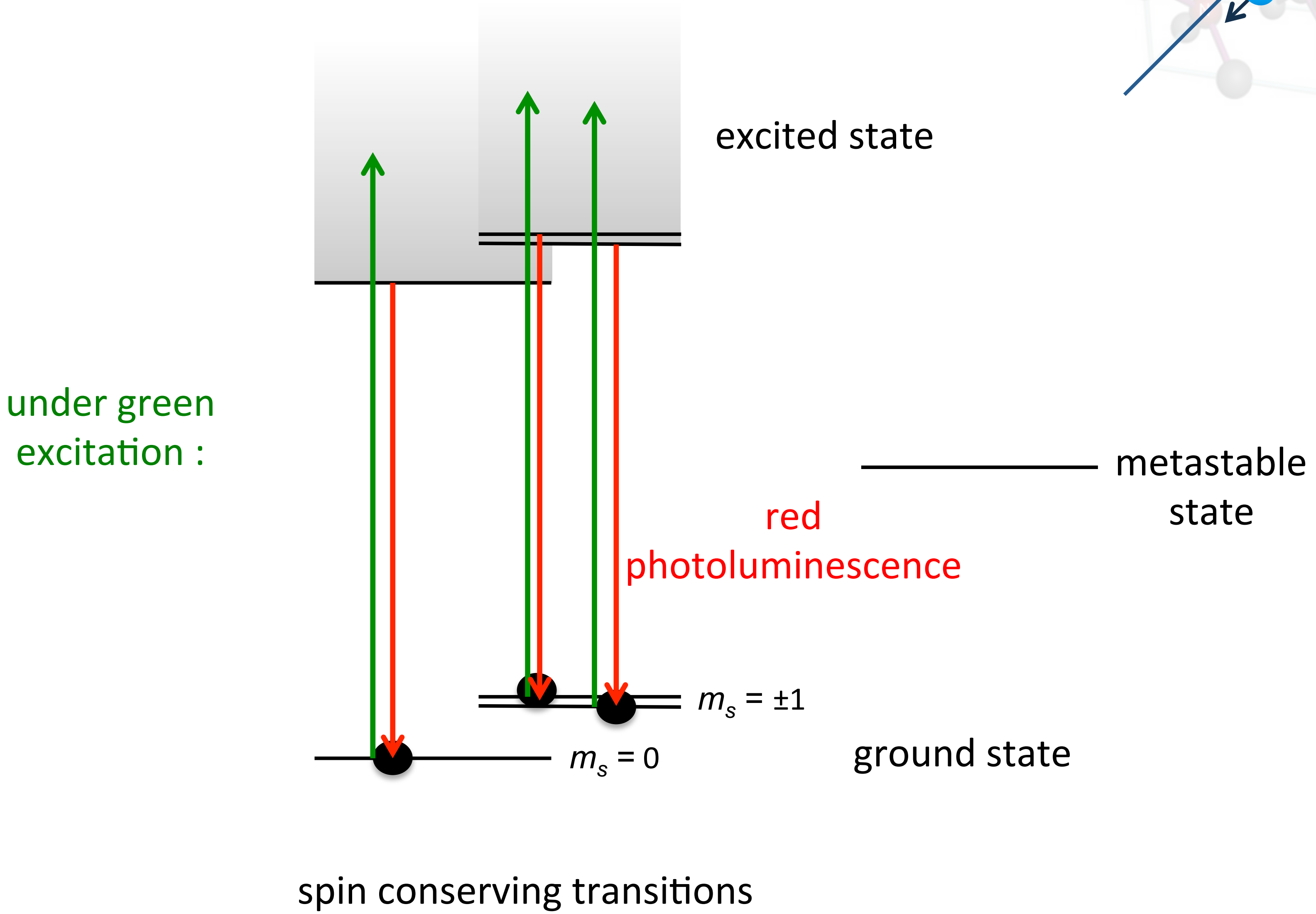


under green excitation :

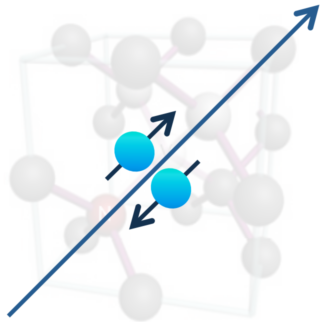


Simple level structure

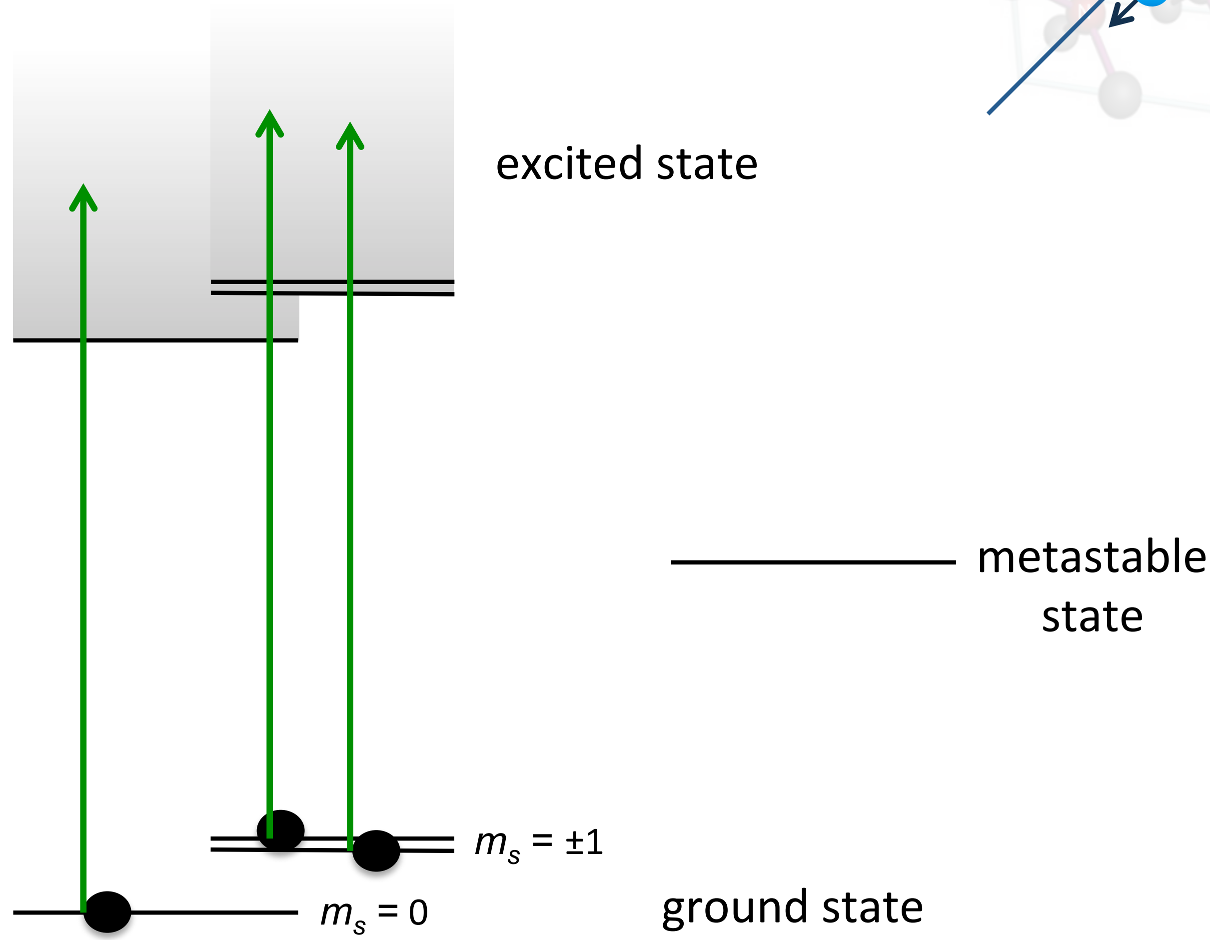




Simple level structure

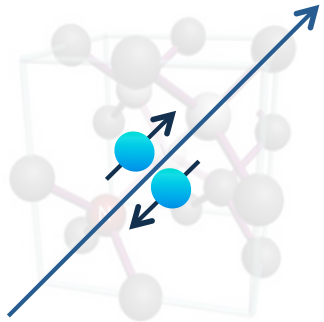


under green excitation :

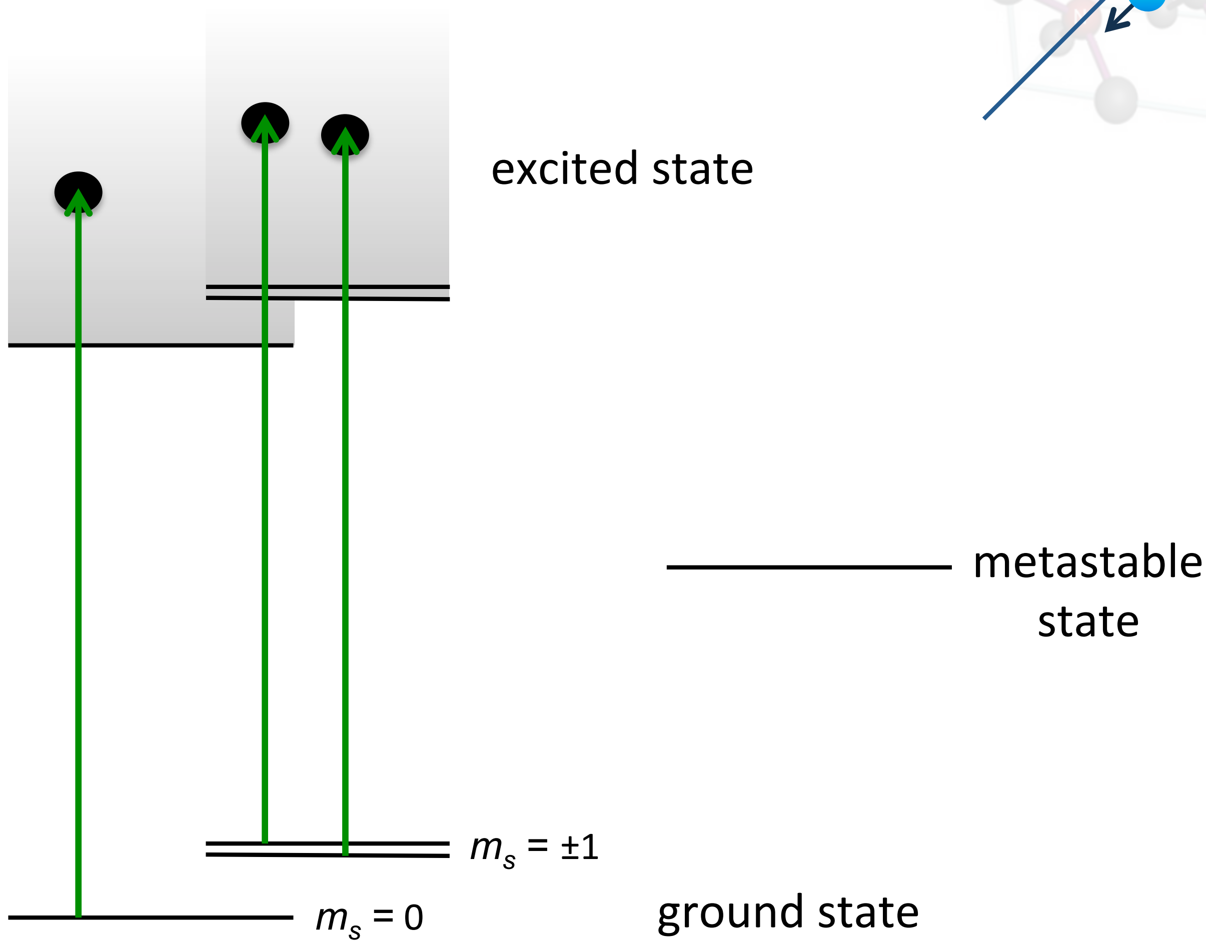


spin conserving transitions

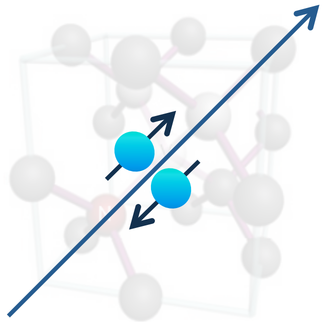
Simple level structure



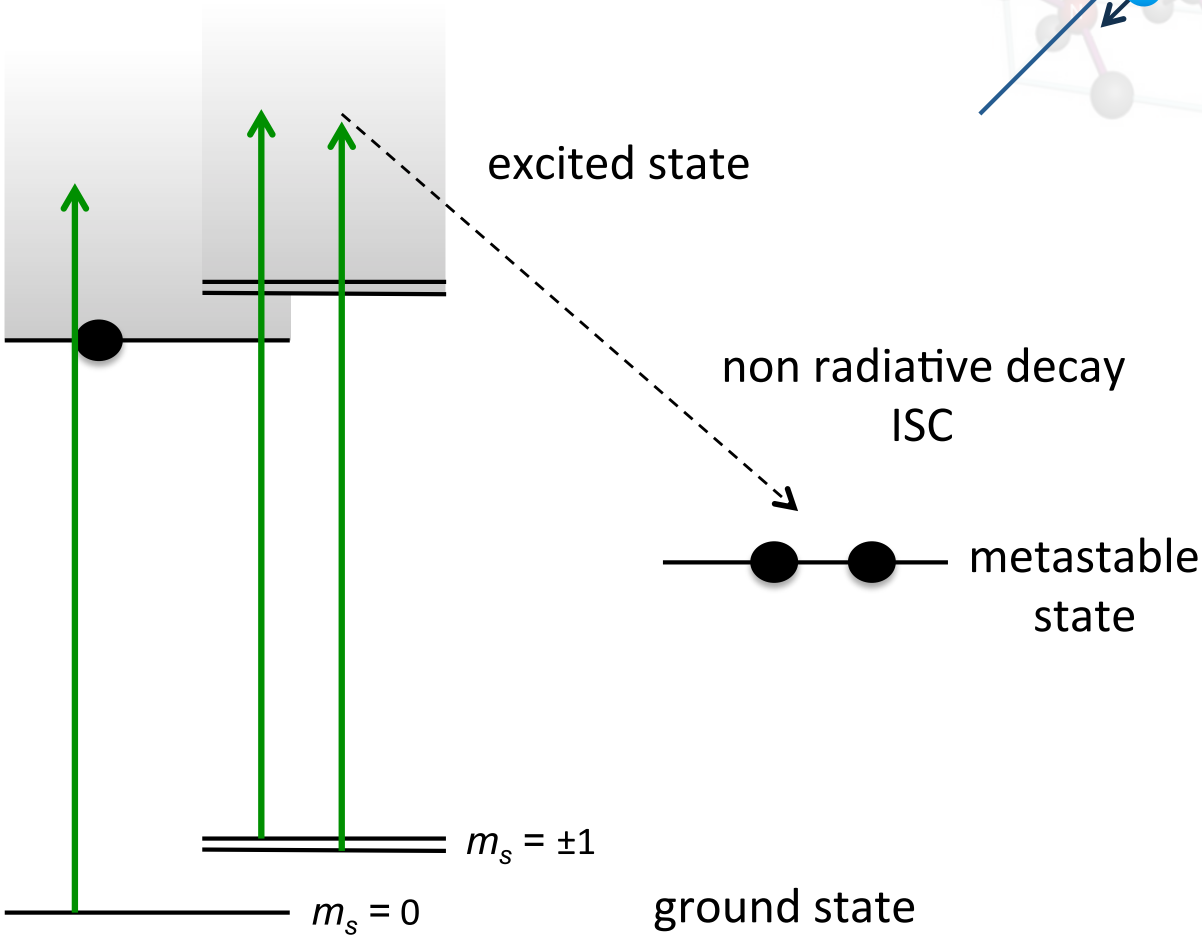
under green
excitation :



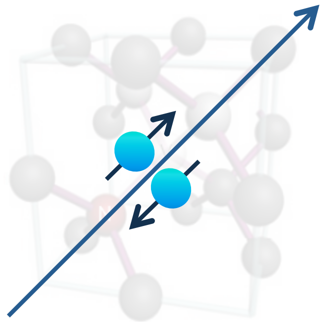
Simple level structure

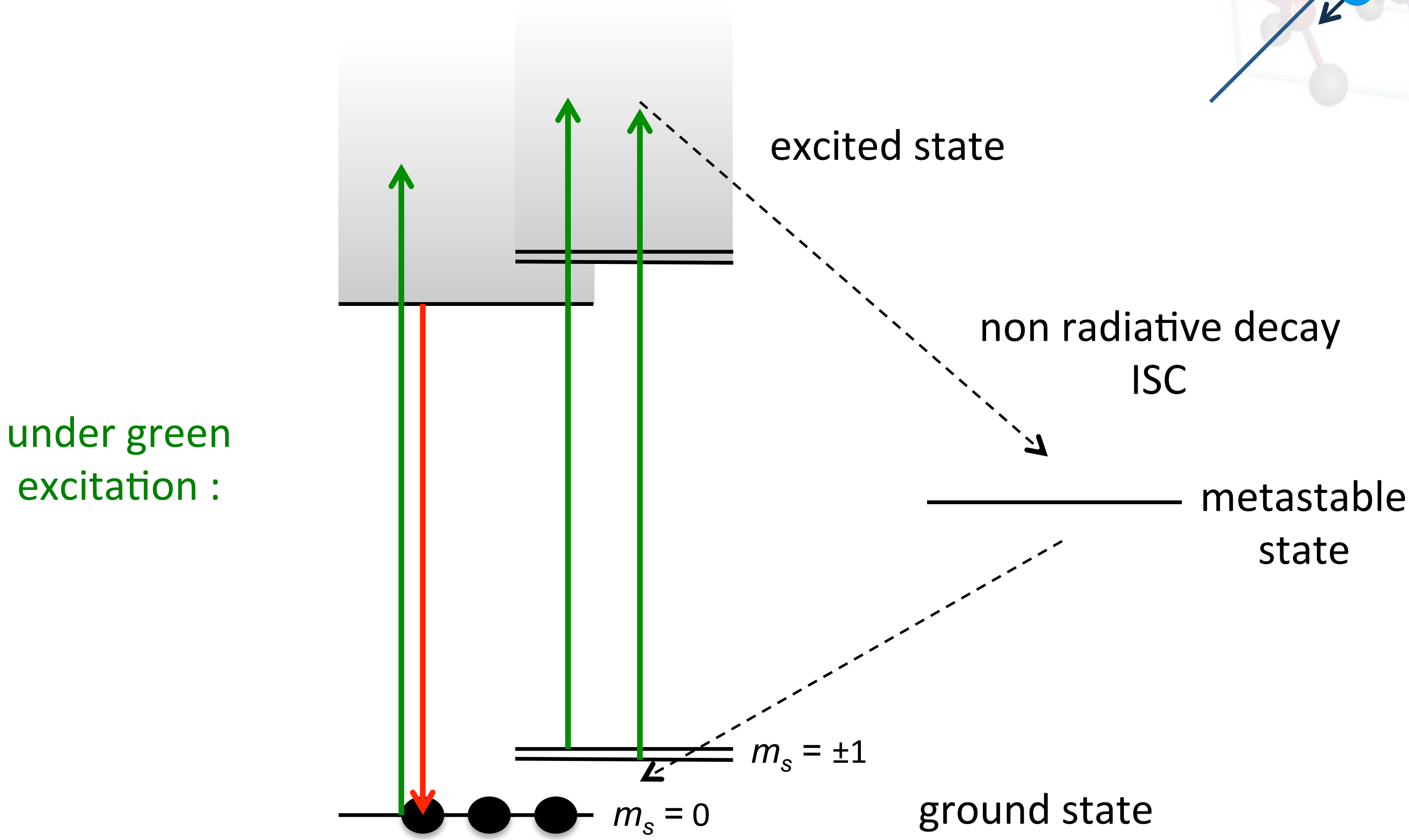


under green excitation :

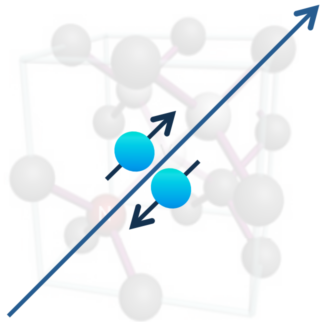


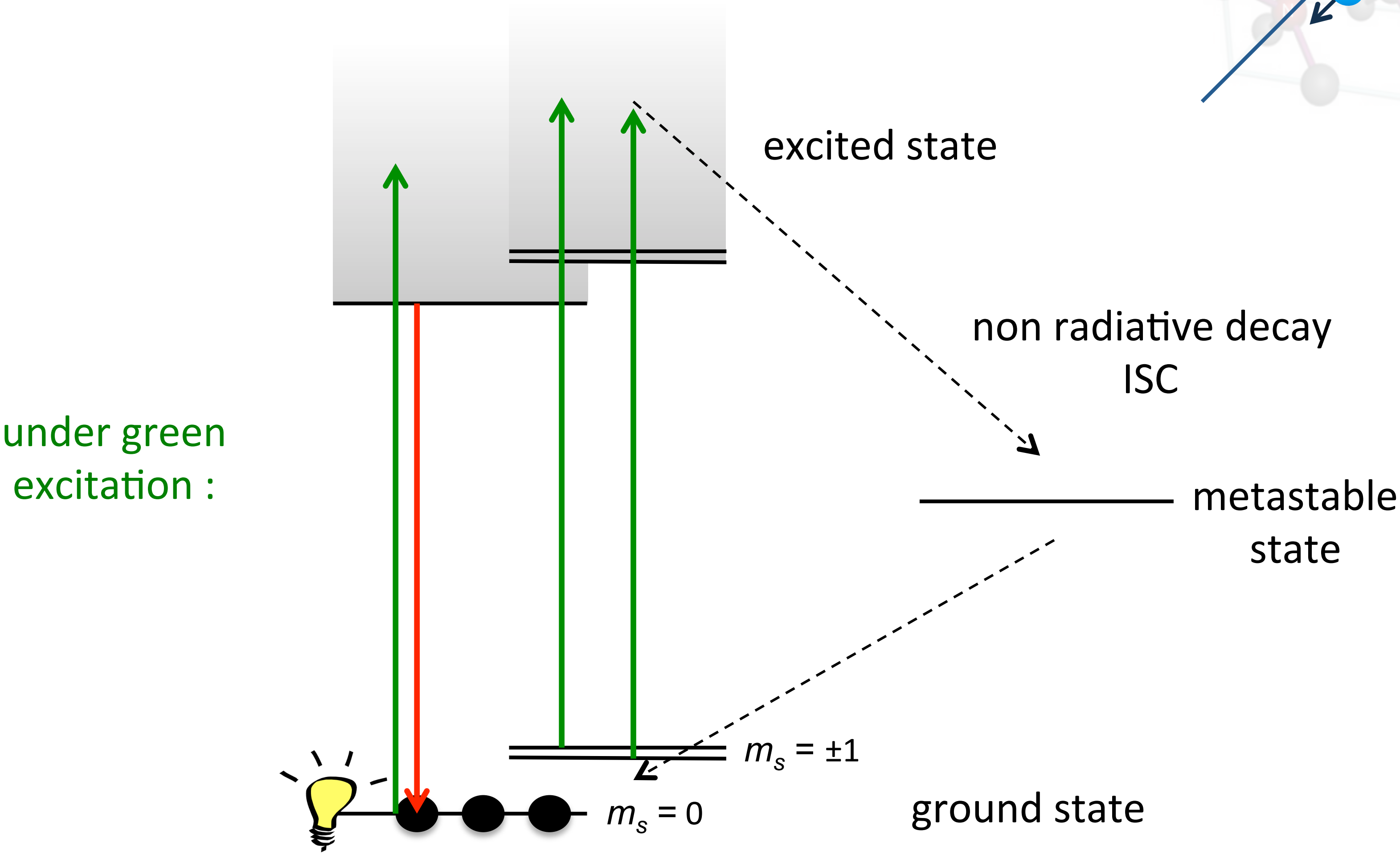
Simple level structure





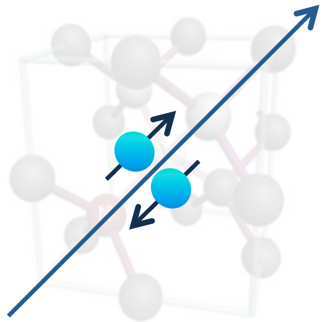
Simple level structure

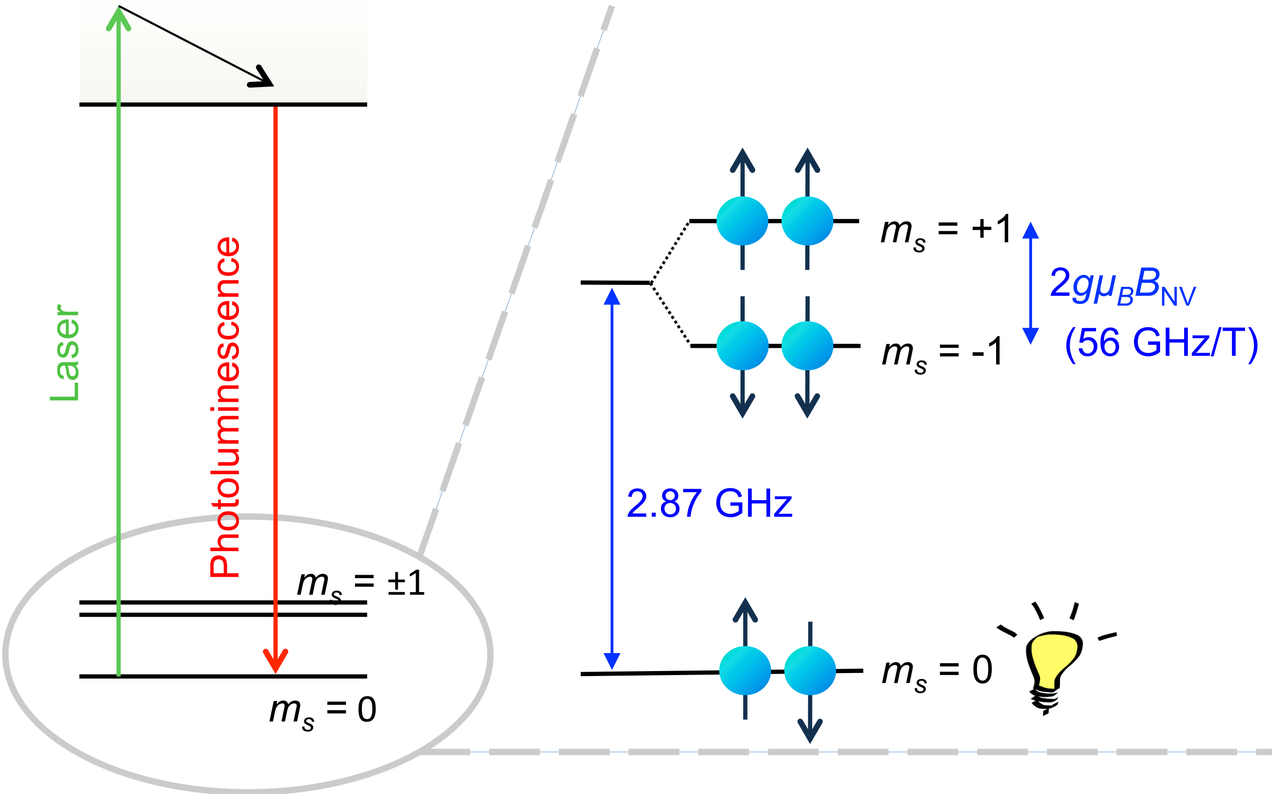




spin polarization into $m_s = 0$

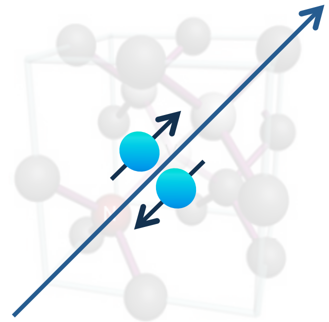
ODMR

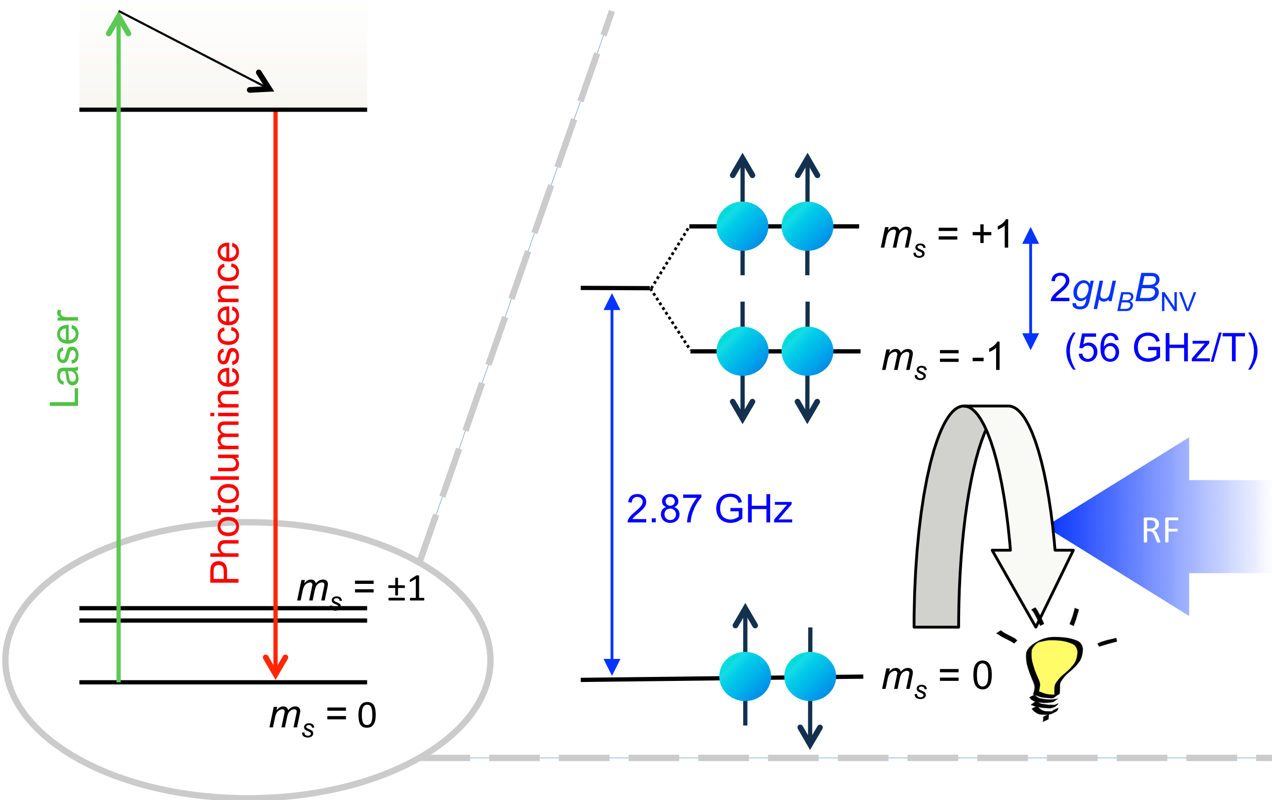




spin polarisation under
green excitation

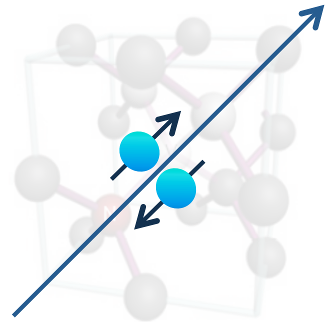
ODMR

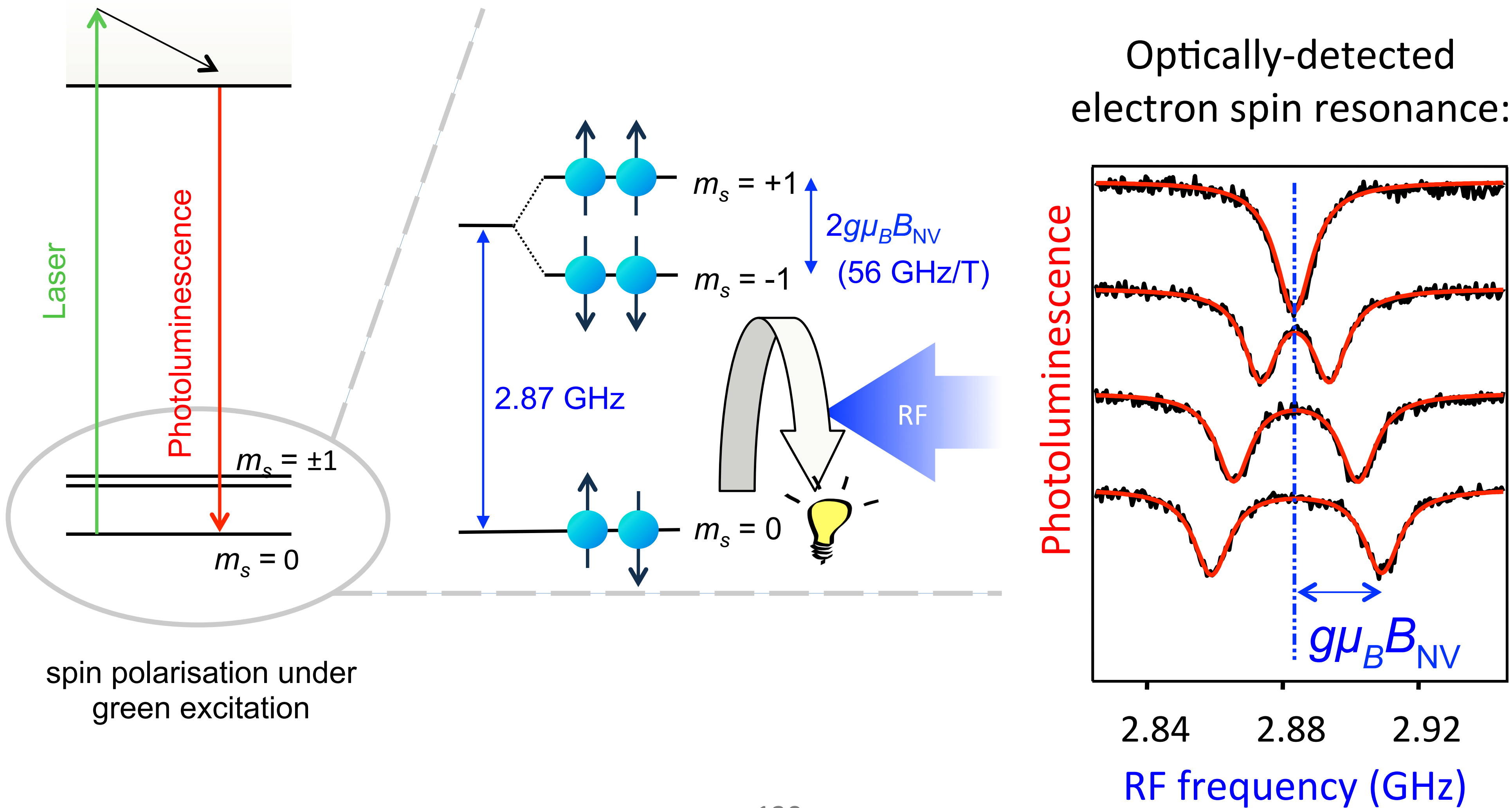




spin polarisation under green excitation

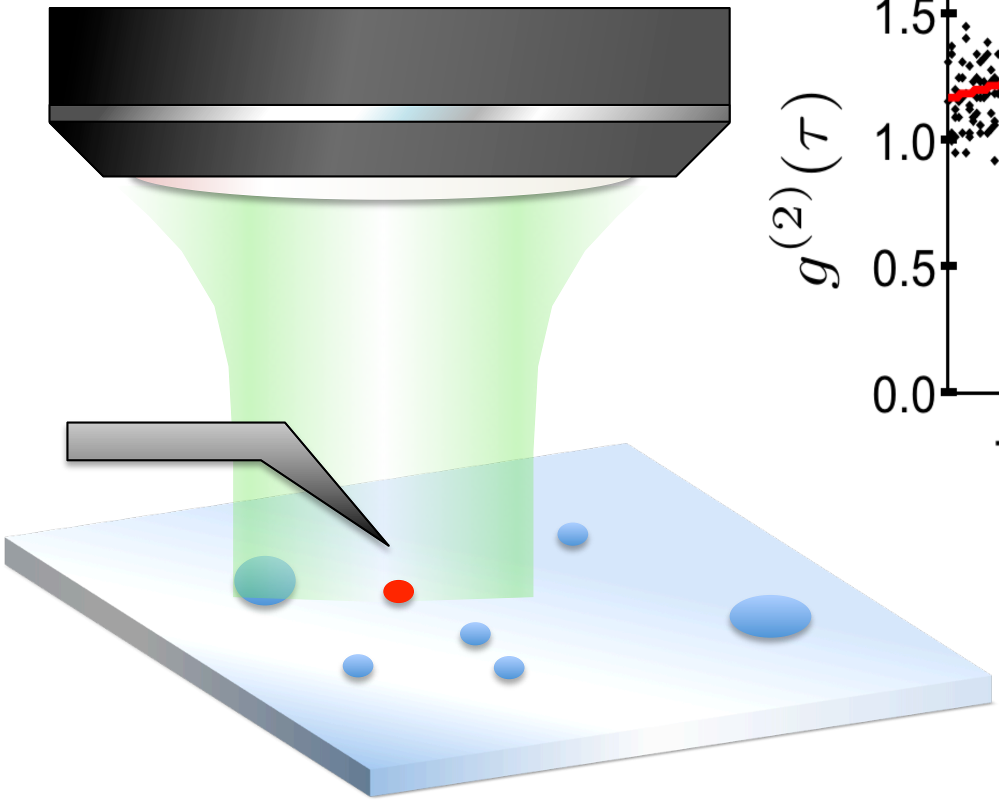
ODMR



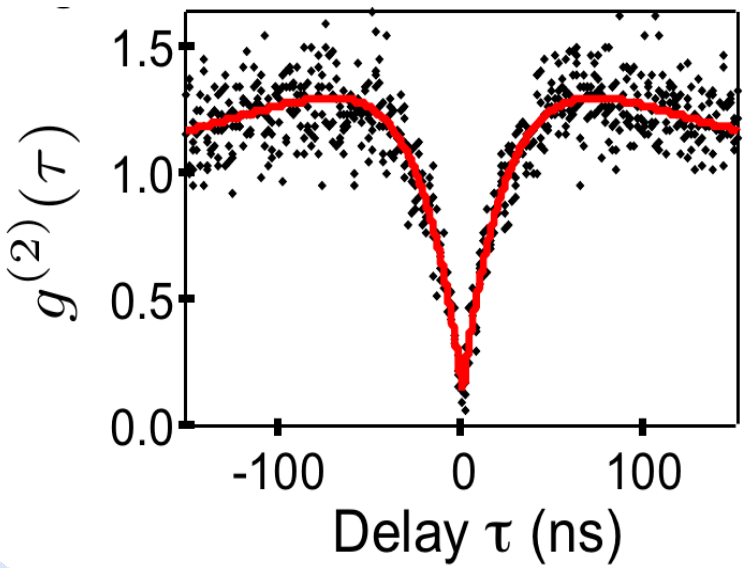


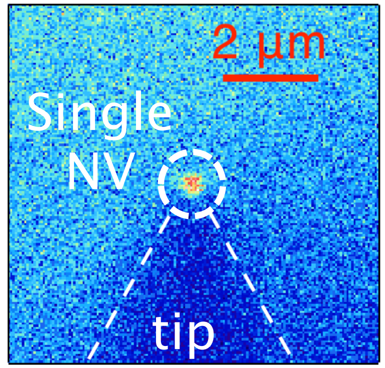
Laser
Photoluminescence
$m_s = \pm 1$
$m_s = 0$
spin polarisation under green excitation
$m_s = +1$
$m_s = -1$
$m_s = 0$
2.87 GHz
$2g\mu_B B_{NV}$
(56 GHz/T)
RF
Optically-detected electron spin resonance:
Photoluminescence
$g\mu_B B_{NV}$
2.84
2.88
2.92
RF frequency (GHz)

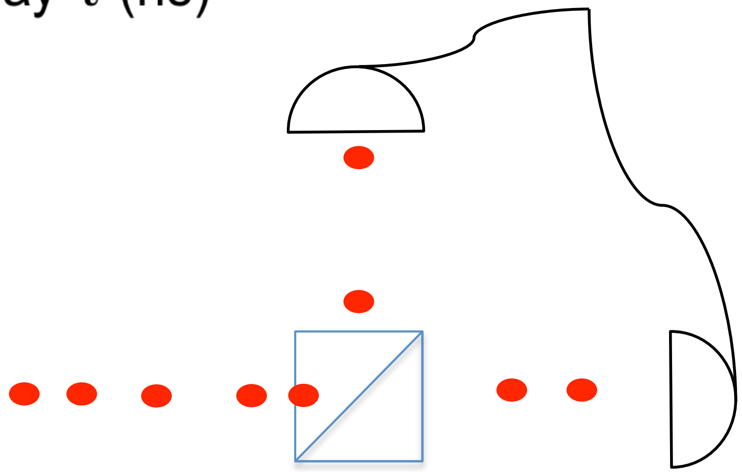
Attaching a nano-diamond



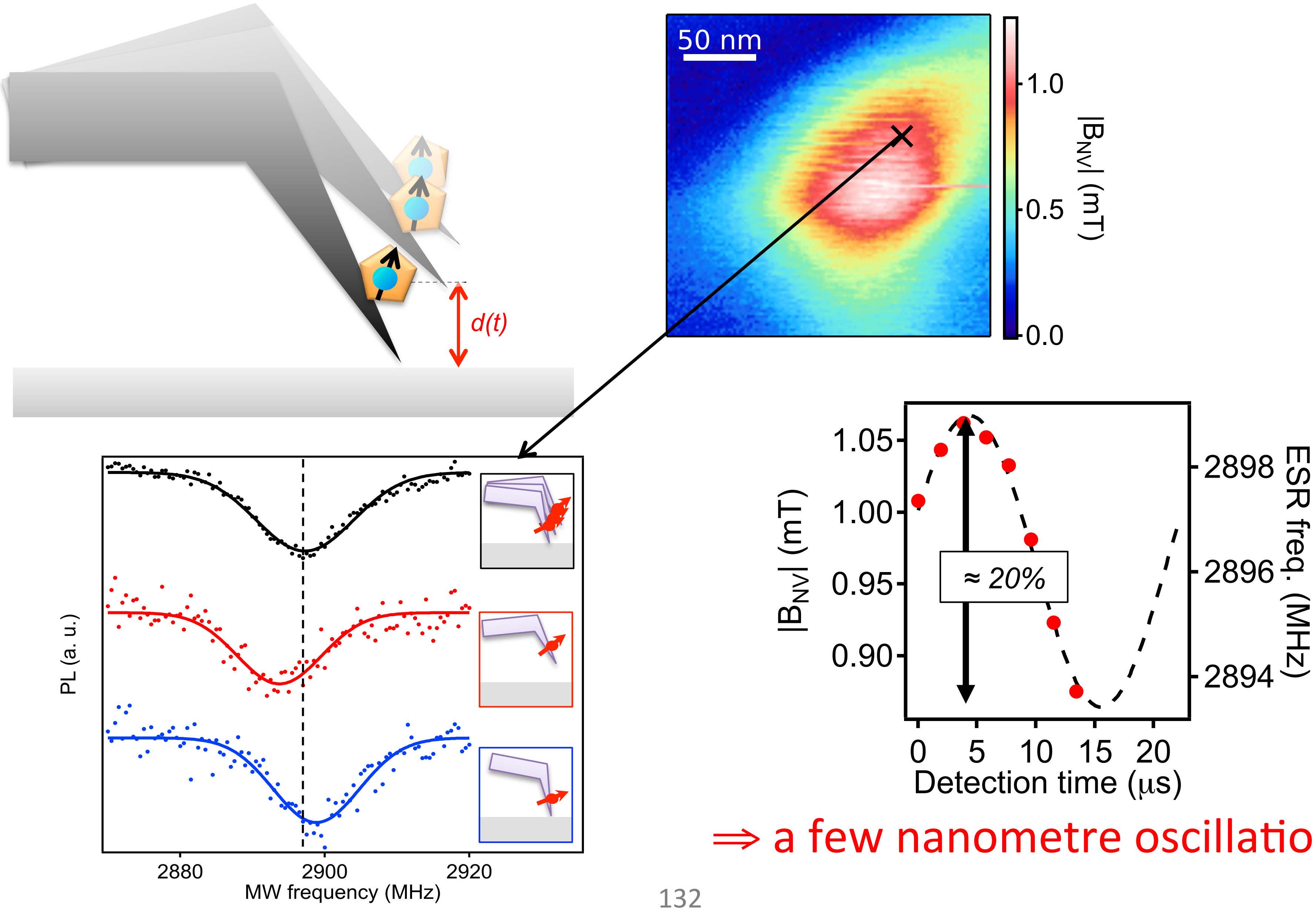
Single NV at the apex of the AFM tip







Effect of the tip tapping motion



⇒ a few nanometre oscillation

Fig. 3 – Laser-induced pinning of the domain wall

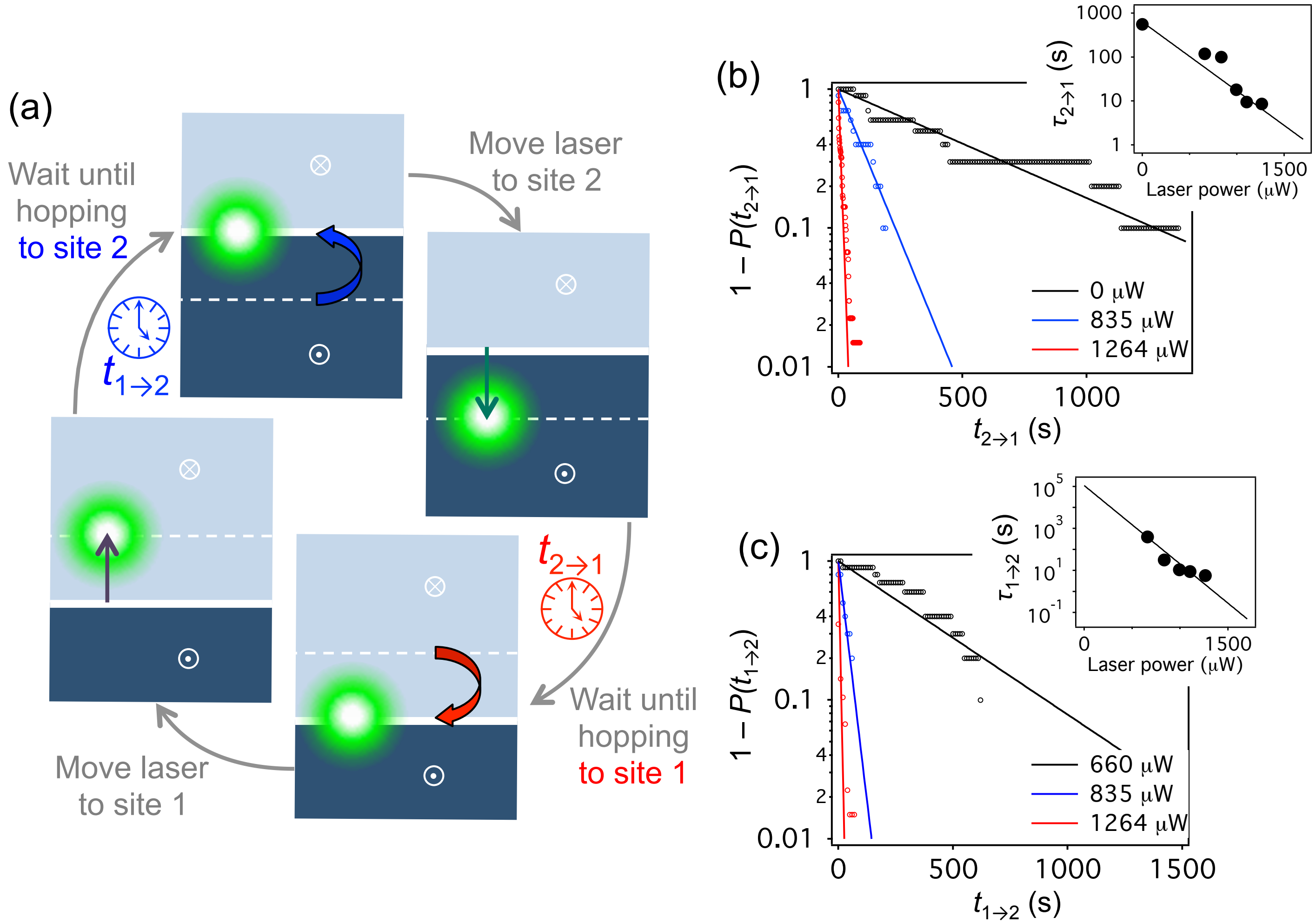


Fig. S9 – Laser pinning vs. power

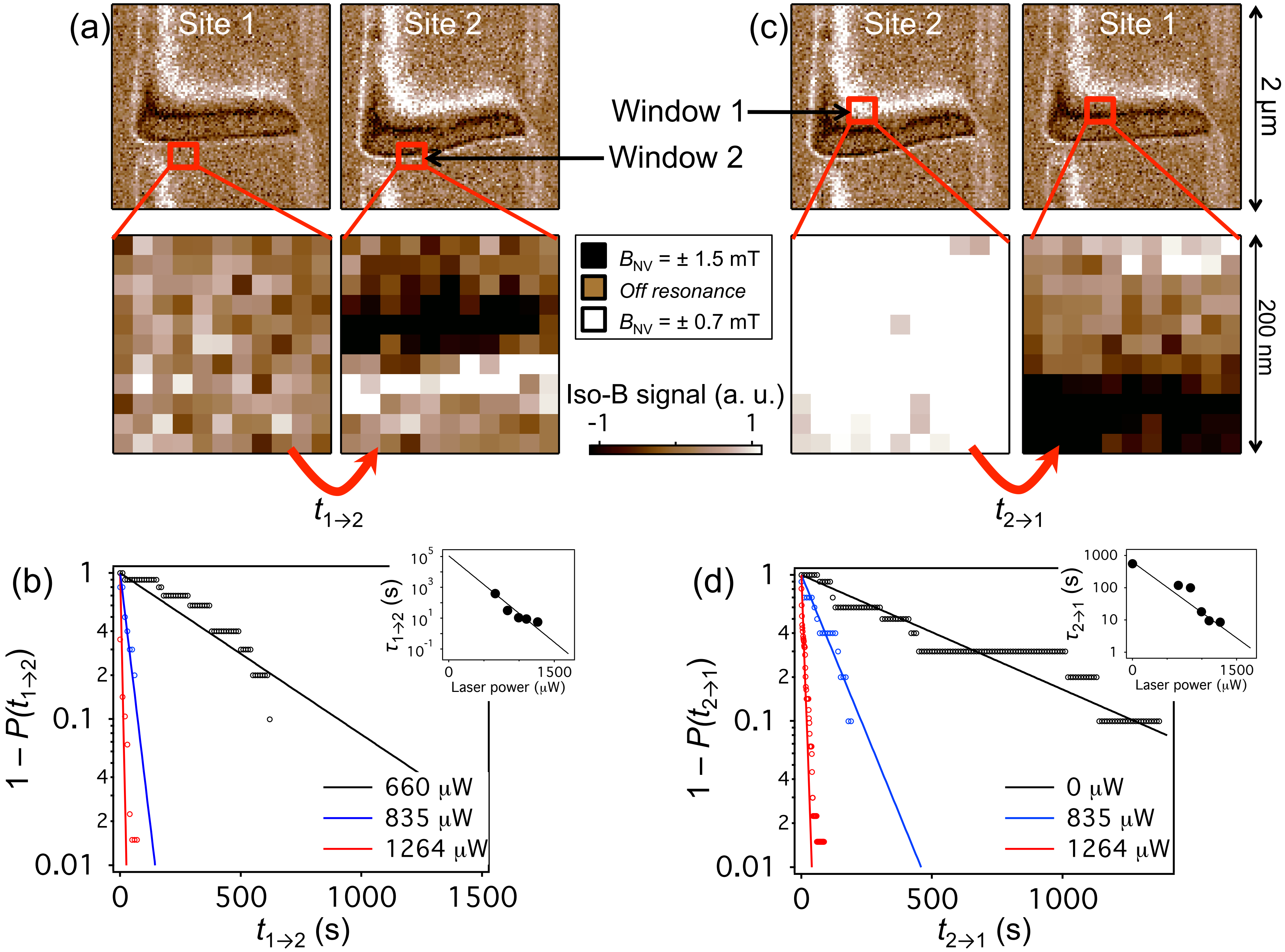


Fig. S10 – Temperature vs. Laser power

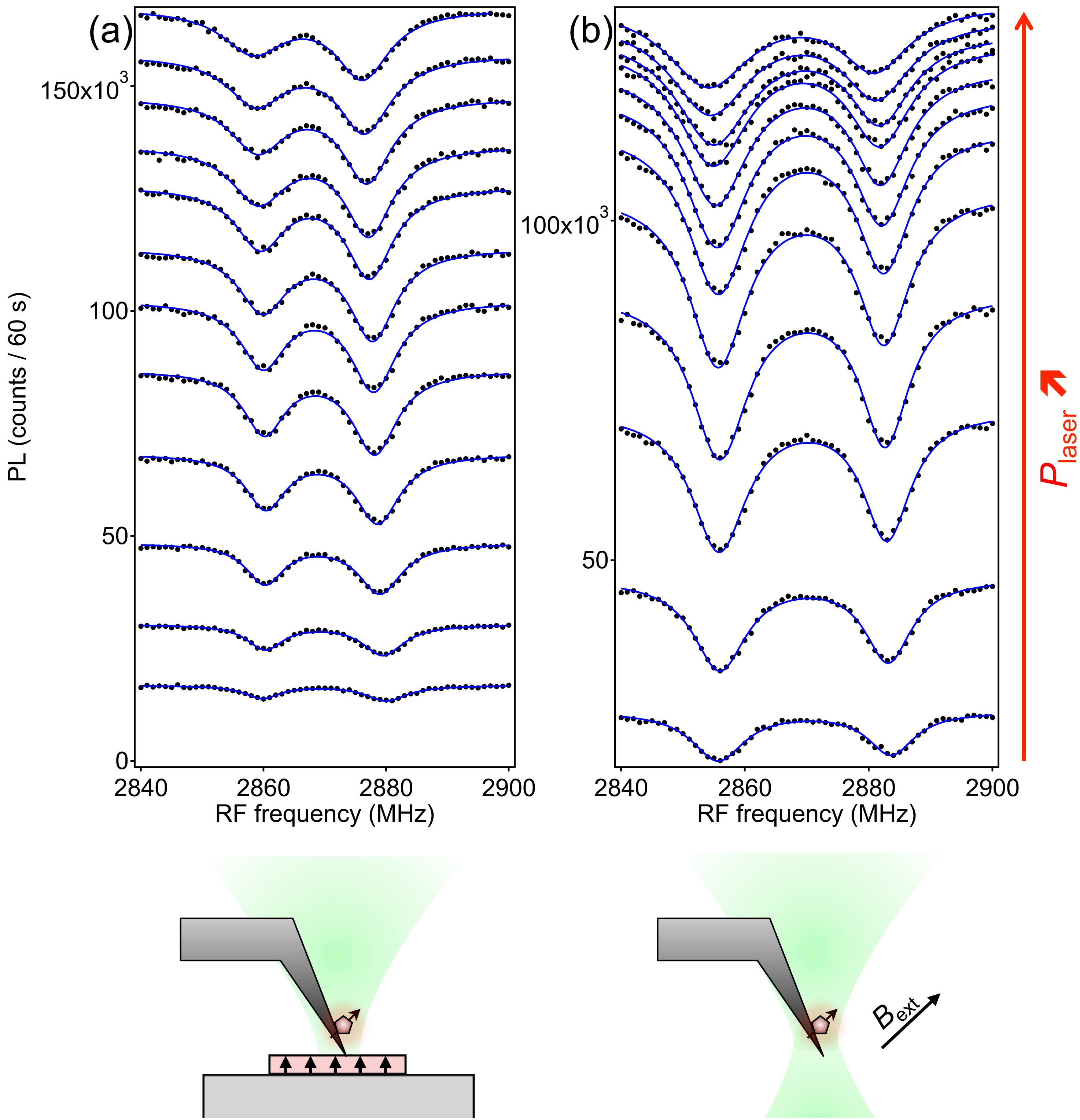


Fig. S10 –
Temperature vs.
Laser power

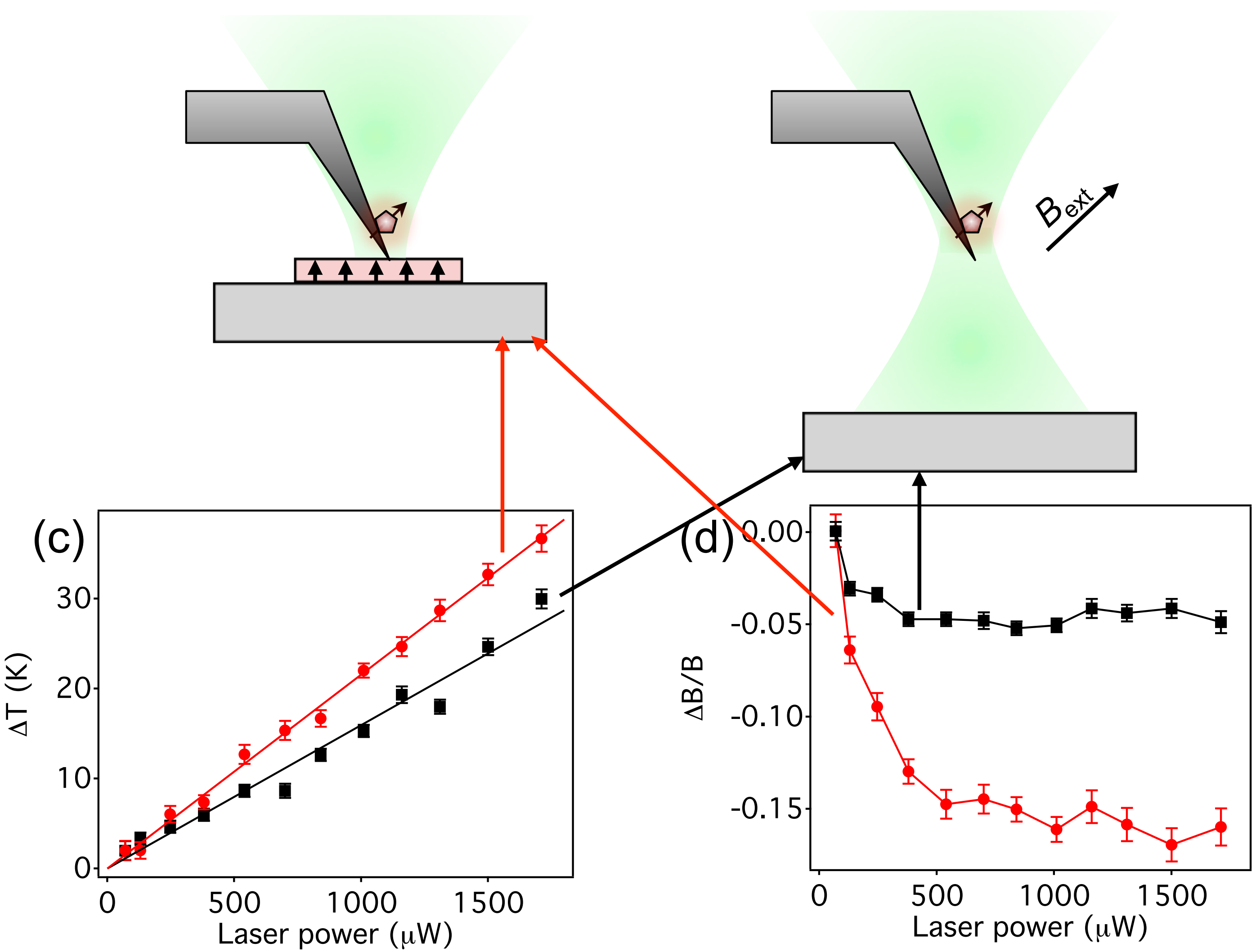
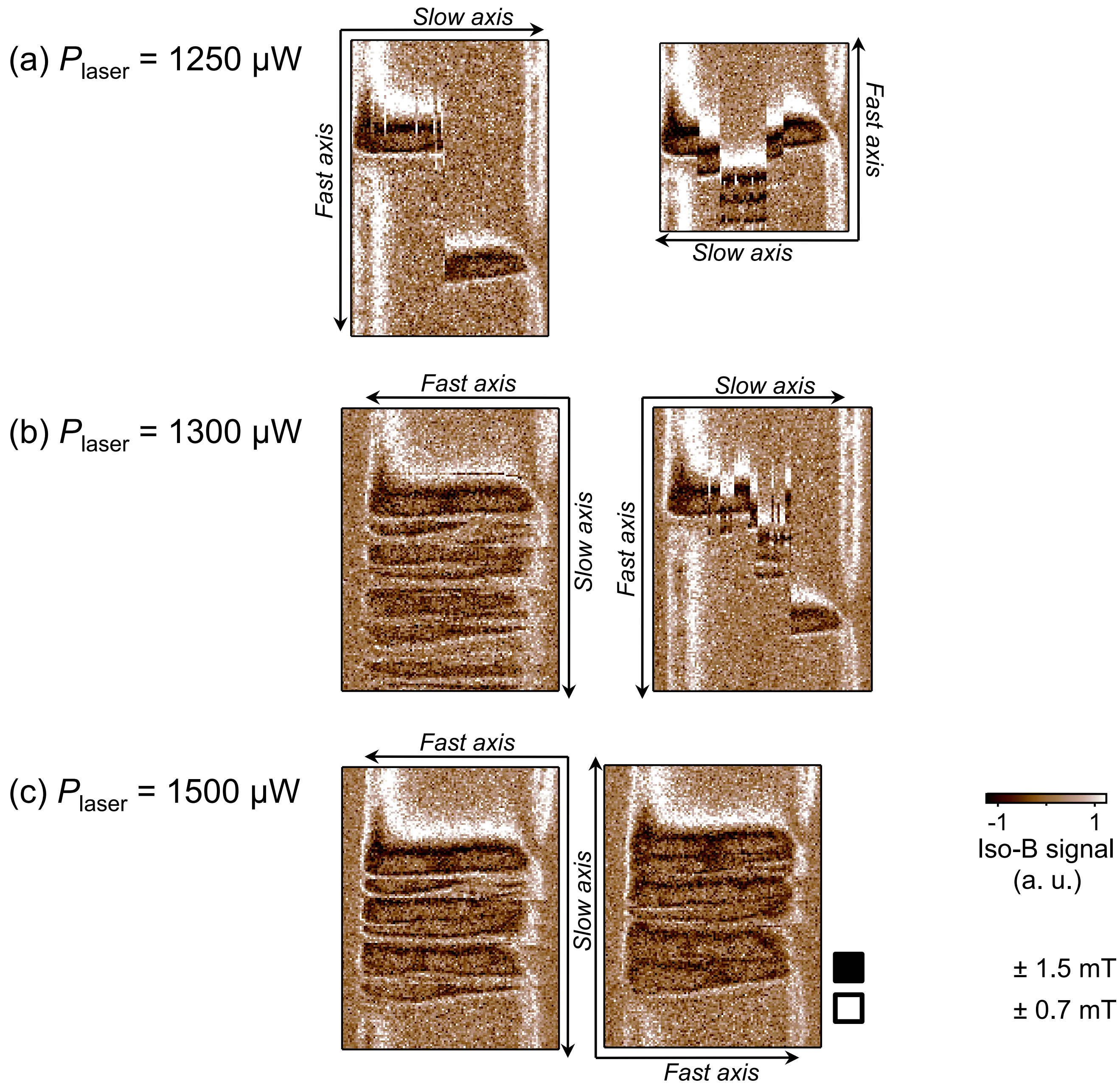
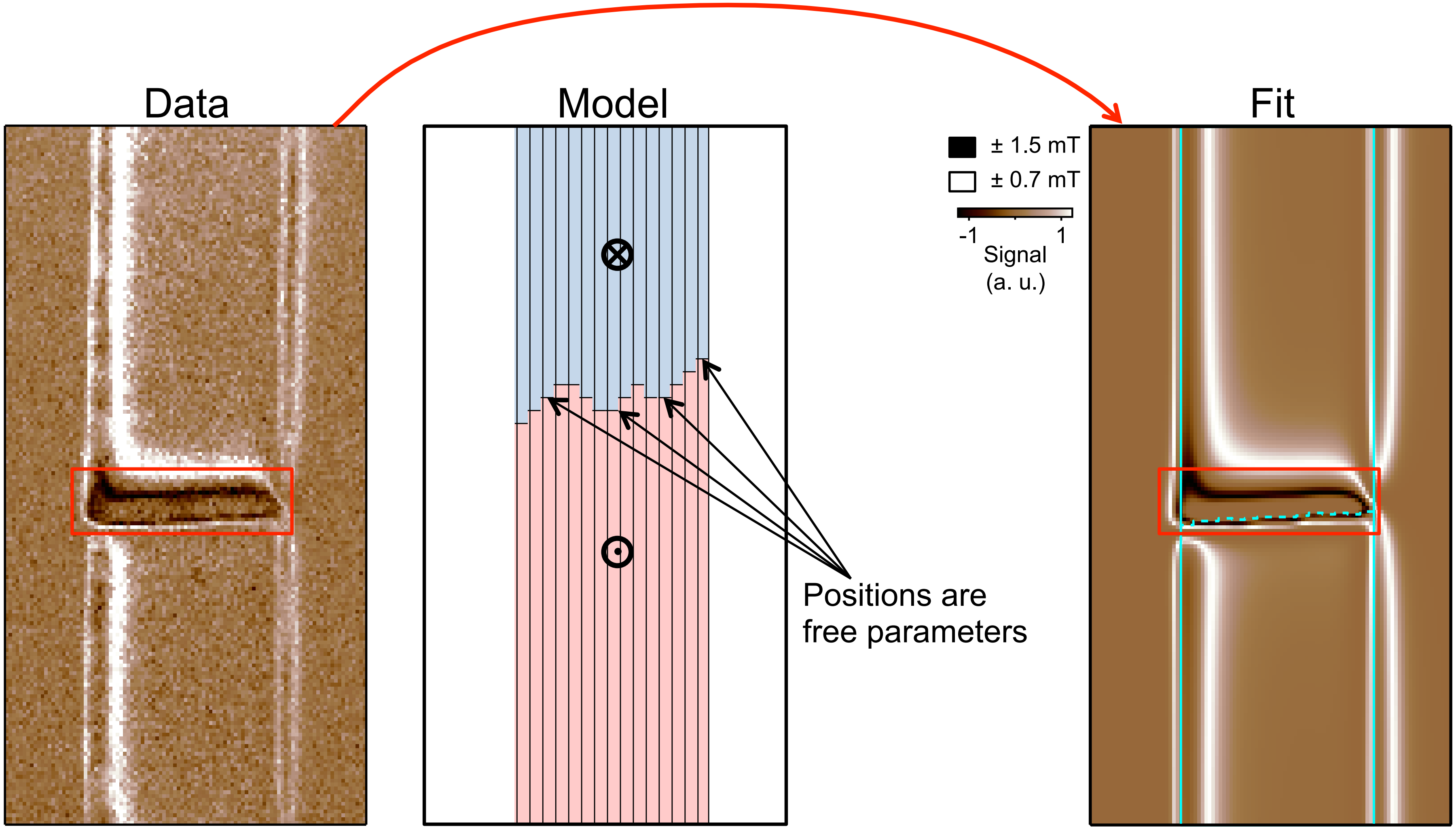


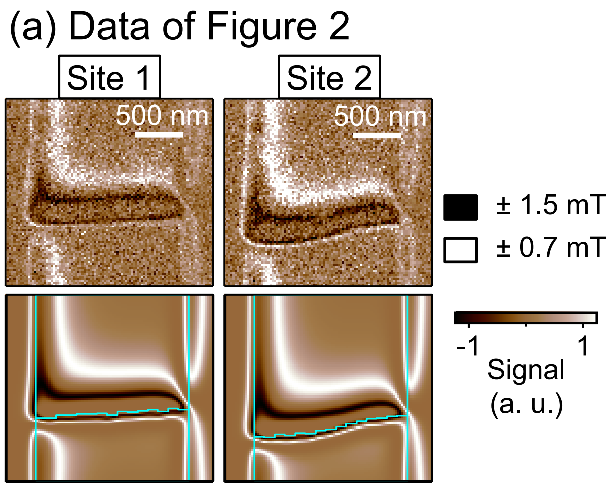
Fig. S11 – DW hopping vs. Laser power



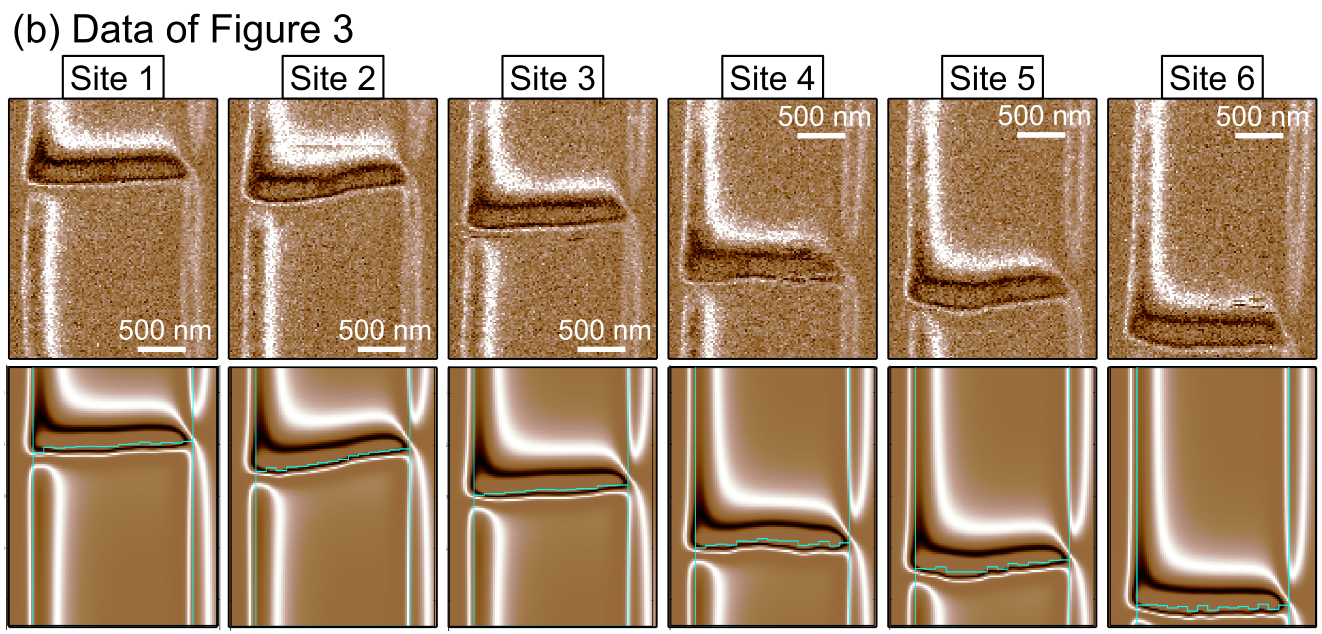
Fit procedure



Fit results

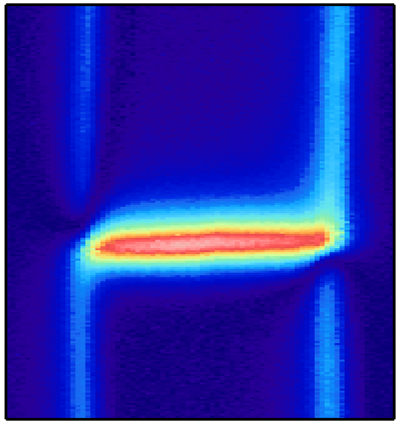


(a) Data of Figure 2
Site 1
Site 2
500 nm
500 nm
± 1.5 mT
± 0.7 mT
-1
1
Signal
(a. u.)

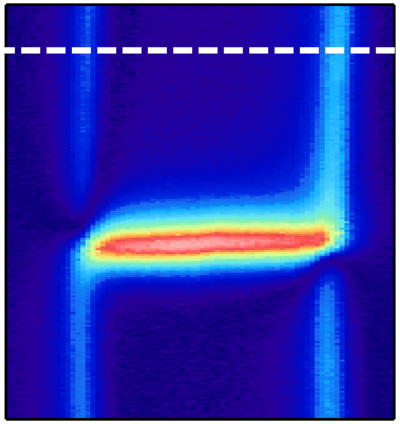


(b) Data of Figure 3
Site 1
Site 2
Site 3
Site 4
Site 5
Site 6
500 nm
500 nm
500 nm
500 nm
500 nm
500 nm

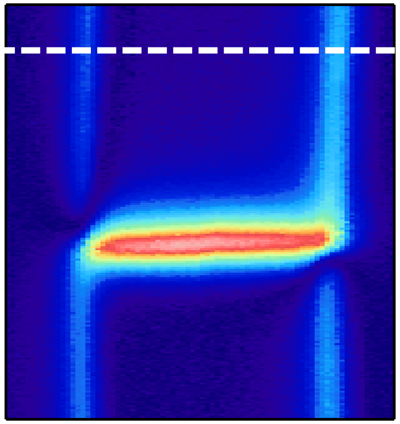
Measuring z and M_S

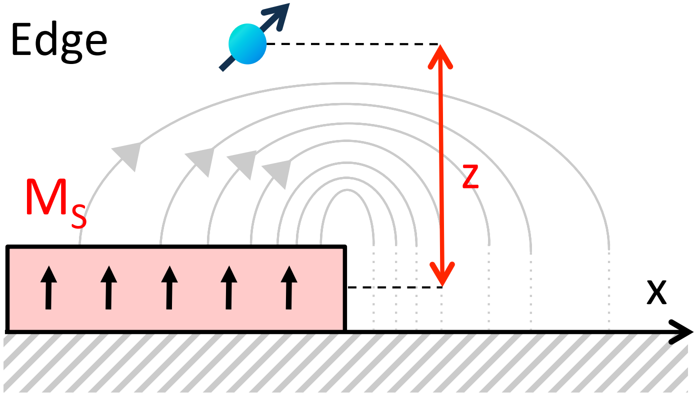


Measuring z and M_S

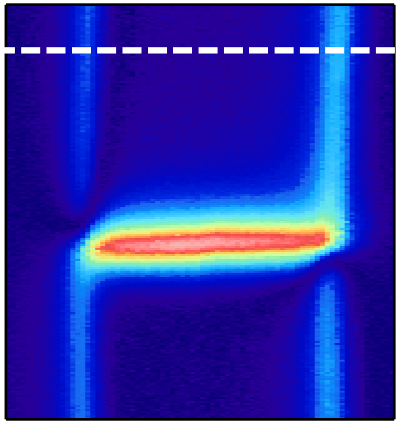


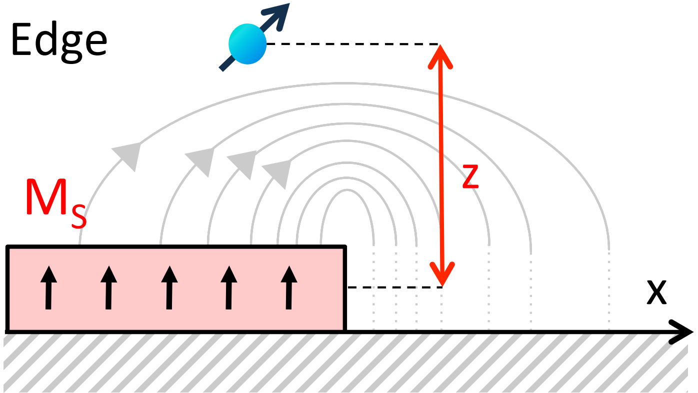
Measuring z and M_S





Measuring z and M_S

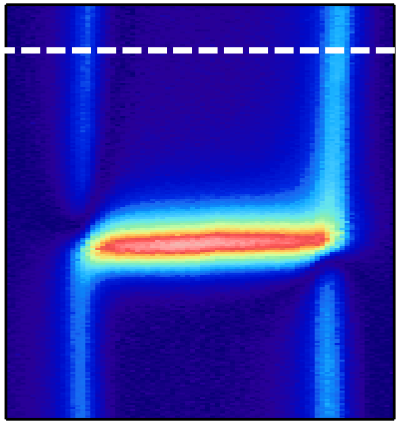


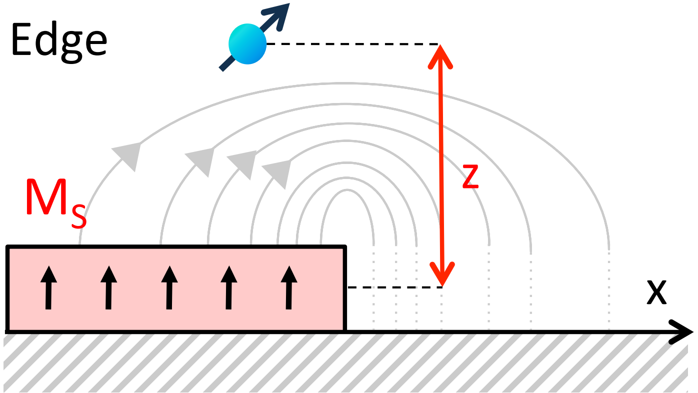


$$B_x = \frac{\mu_0}{2\pi} t \cdot M_S \left(\frac{z}{x^2 + z^2} \right)$$

$$B_z = -\frac{\mu_0}{2\pi} t \cdot M_S \left(\frac{x}{x^2 + z^2} \right)$$

Measuring z and M_S



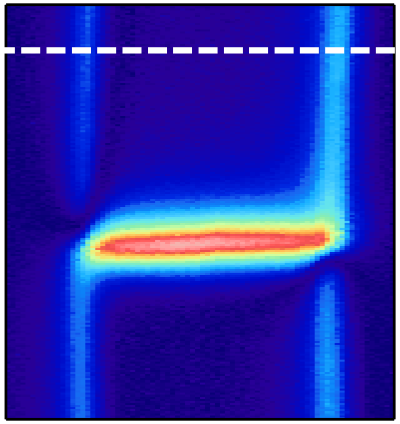


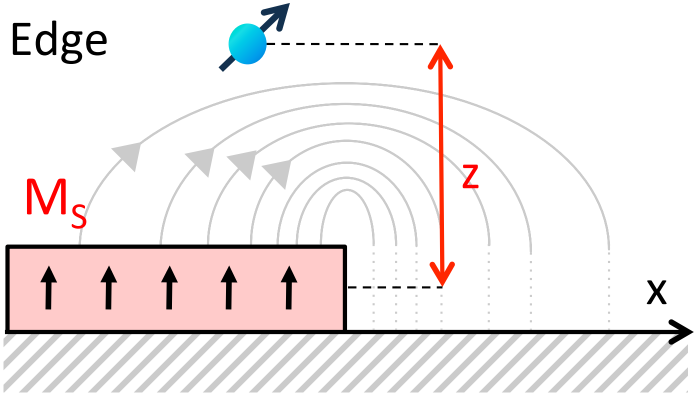
linear in M_S

$$B_x = \frac{\mu_0}{2\pi} t \cdot M_S \left(\frac{z}{x^2 + z^2} \right)$$

$$B_z = -\frac{\mu_0}{2\pi} t \cdot M_S \left(\frac{x}{x^2 + z^2} \right)$$

Measuring z and M_S





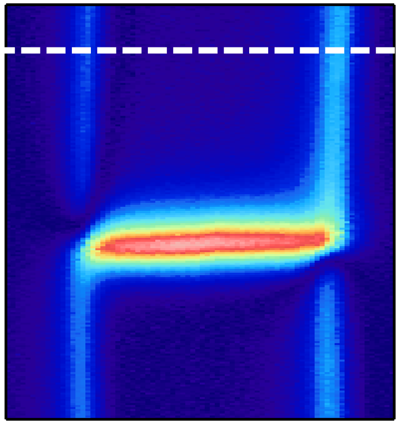
linear in M_S

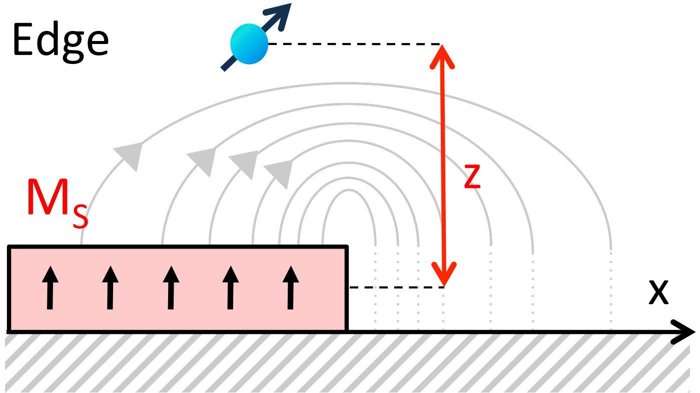
$$B_x = \frac{\mu_0}{2\pi} t \cdot M_S \left(\frac{z}{x^2 + z^2} \right)$$

$$B_z = -\frac{\mu_0}{2\pi} t \cdot M_S \left(\frac{x}{x^2 + z^2} \right)$$

Lorentzian in z

Measuring z and M_S



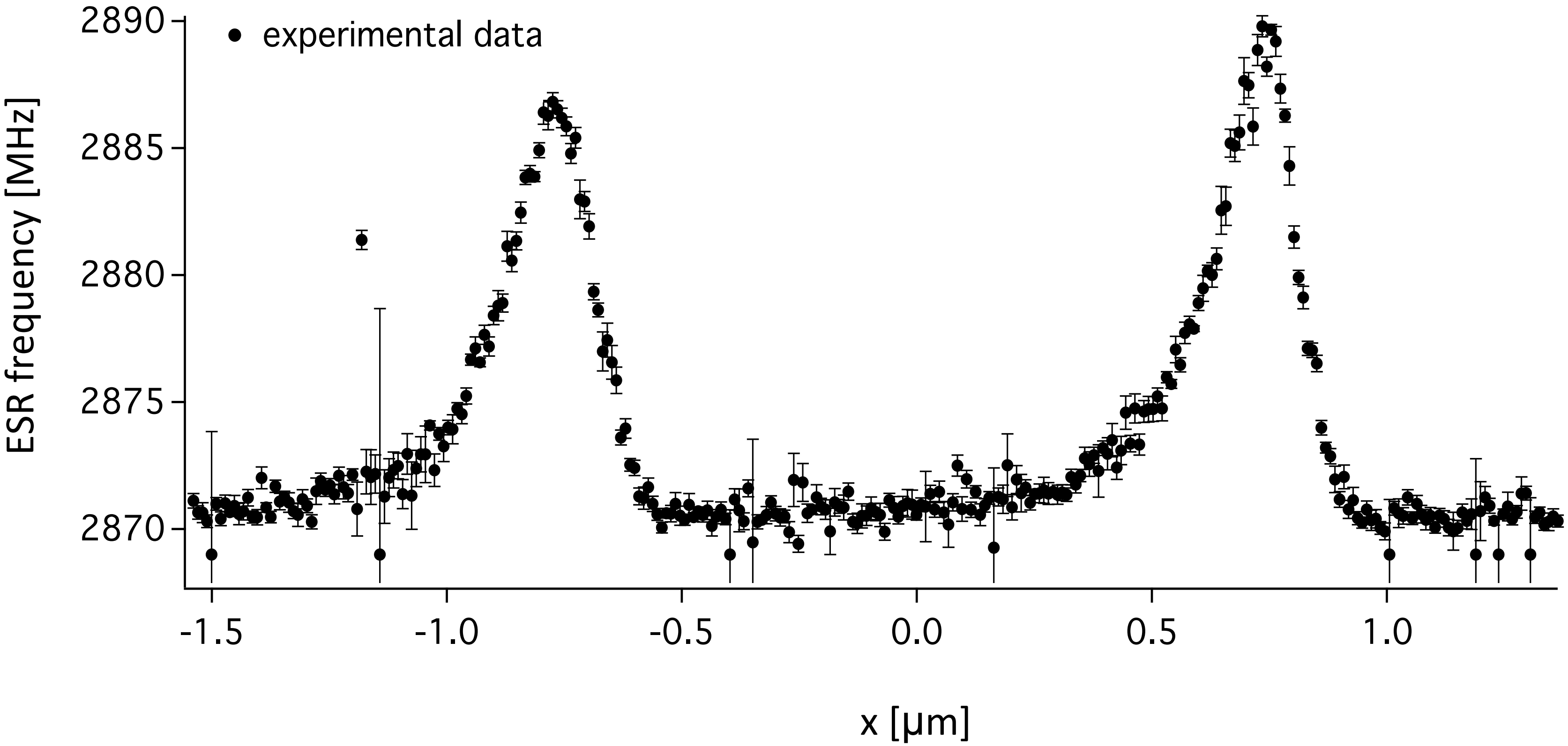


linear in M_S

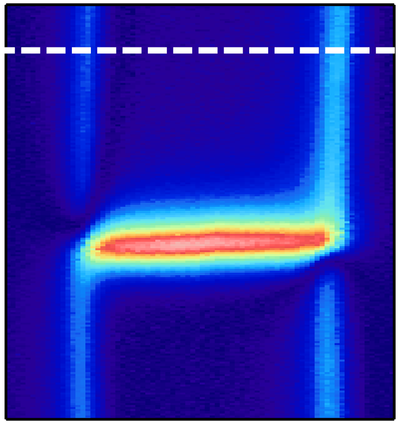
$$B_x = \frac{\mu_0}{2\pi} t \cdot M_S \left(\frac{z}{x^2 + z^2} \right)$$

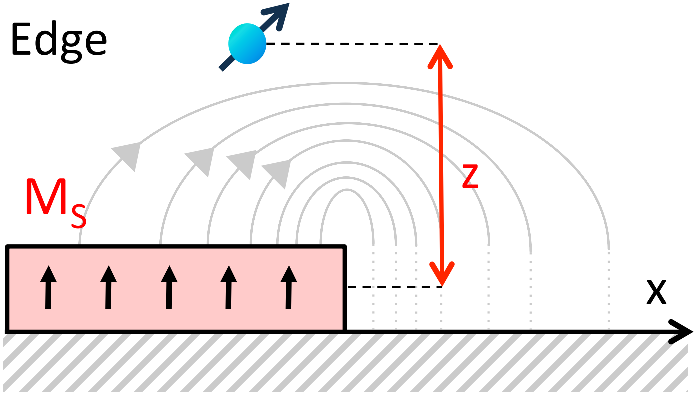
$$B_z = -\frac{\mu_0}{2\pi} t \cdot M_S \left(\frac{x}{x^2 + z^2} \right)$$

Lorentzian in z



Measuring z and M_S





linear in M_S

$$B_x = \frac{\mu_0}{2\pi} t \cdot M_S \left(\frac{z}{x^2 + z^2} \right)$$

$$B_z = -\frac{\mu_0}{2\pi} t \cdot M_S \left(\frac{x}{x^2 + z^2} \right)$$

Lorentzian in z