Quantum Sensing Workshop

February 29, 2024

CANADA FIRST
RESEARCH EXCELLENCE FUND

TQT Transformative Quantum Technologies

Agenda

1. Introduction to NV lecture
2. Hands on NV's (zero field)
3. Break (snacks & coffee)
4. Discussion
5. Introduction
to sensing with NV lecture
6. Hands on NV's (with field)
7. Discussion/Applications

Michael Grabowecky

Quantum Technology Lab Co-ordinator

TQT

Carola Purser

Senior Scientist

QVIL

About TQT

February 29, 2024

Our Vision

To develop and deliver impactful quantum devices to further Canada’s leadership position in the next quantum revolution.

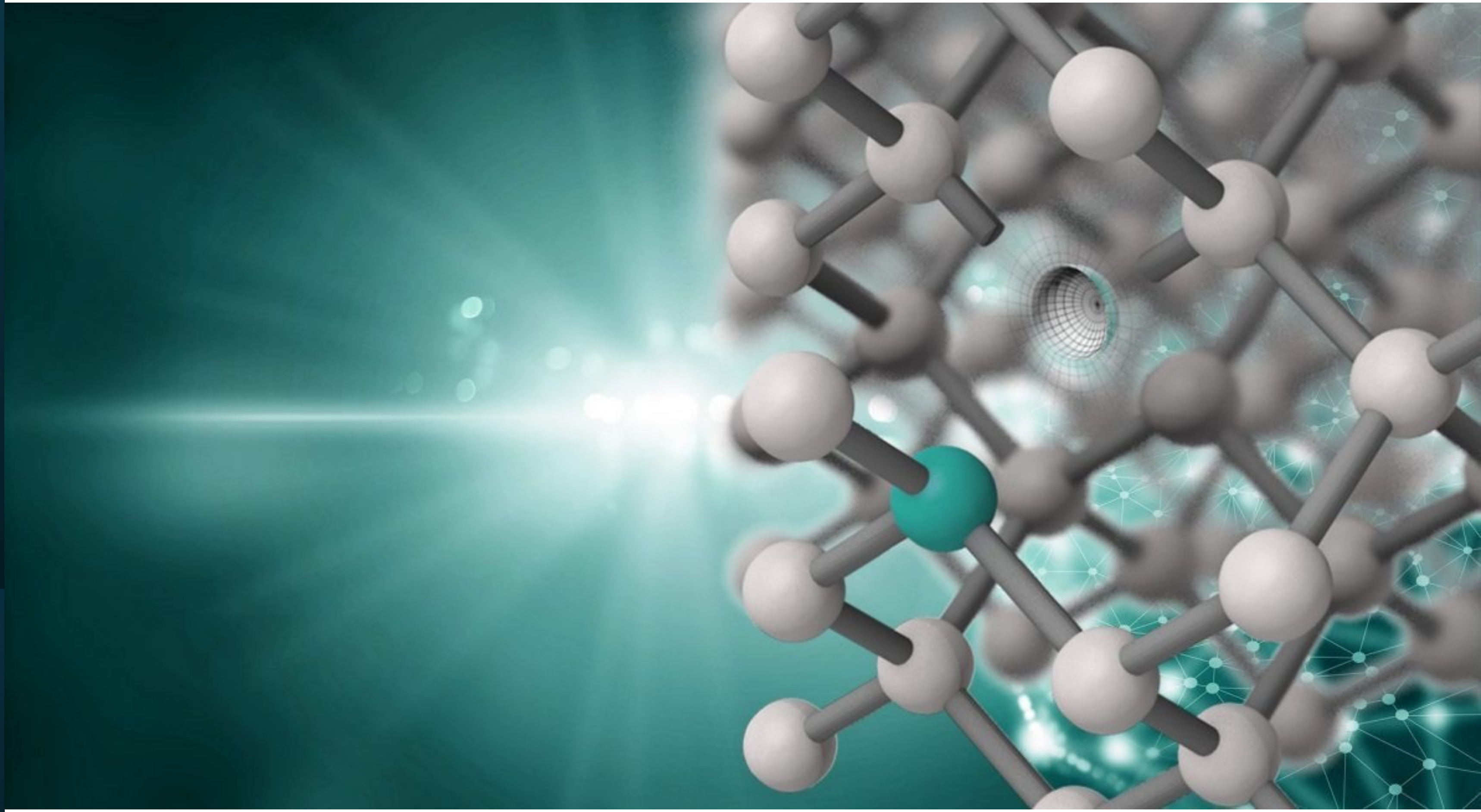
Our Program

Collaborative Research Initiative

- Recruitment of the “best and the brightest”
- Grand Challenge research & seed fund
- Connect to early adopters, industry & others
- Shared research infrastructure
- Technology development and commercialization

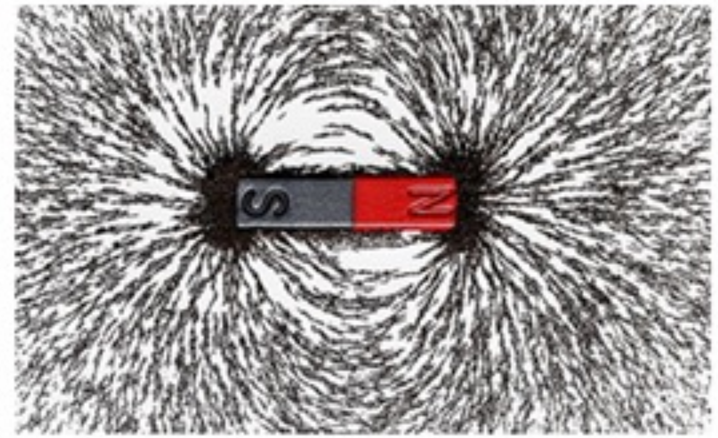
Impact of spin-based quantum sensors & intro to nitrogen vacancy centers

Michael Grabowecky,
mgrabowe@uwaterloo.ca



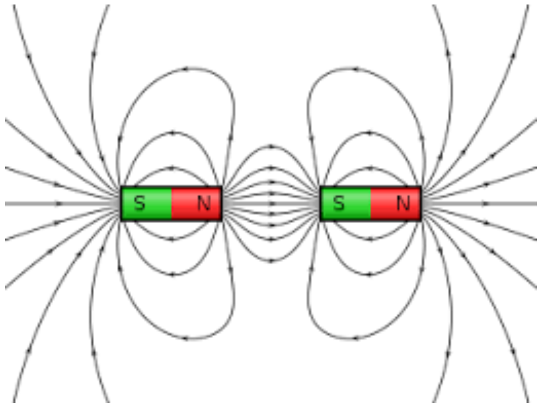
UNIVERSITY OF WATERLOO | Department of Physics and Astronomy
IQC Institute for Quantum Computing
TQT Transformative Quantum Technologies

Classical Magnetic Field Sensing



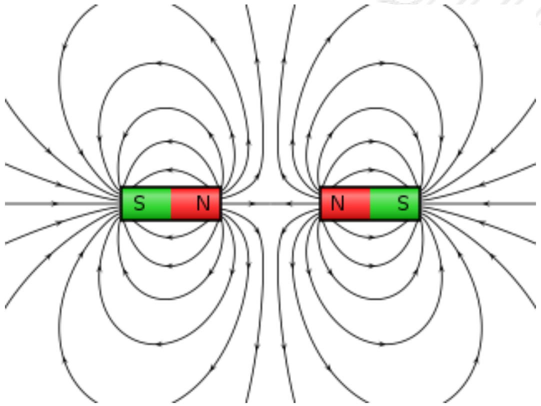
Consider naïve approaches classically

- Two magnets have high/low energy orientations.



Low Energy

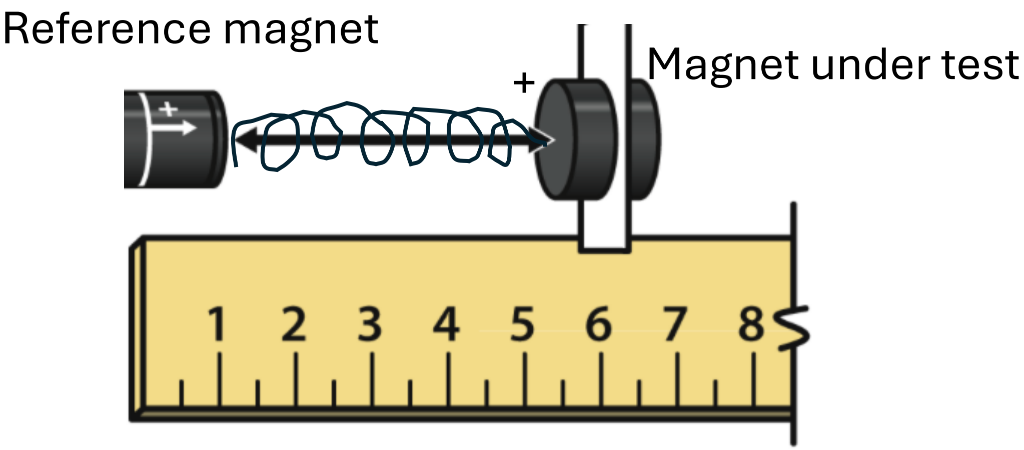
0



High Energy

1

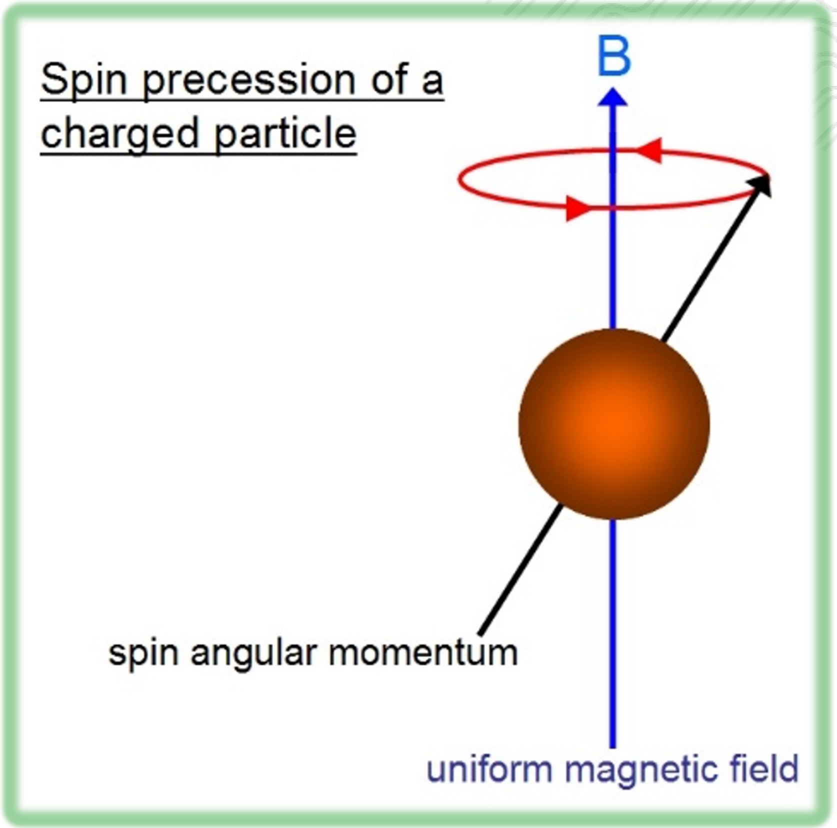
Easy to tell between these two



Quantum mechanical magnets: Spins

- Consider a single electron. Behaves like a tiny bar magnet (2 orientations, Zeeman interaction)
- External fields produce a torque on the electron yielding “Larmor” **precession**

$$f_L = \gamma|B|$$



Resonance: consider a swing set. Need to push at just the right times (frequency) to swing higher.

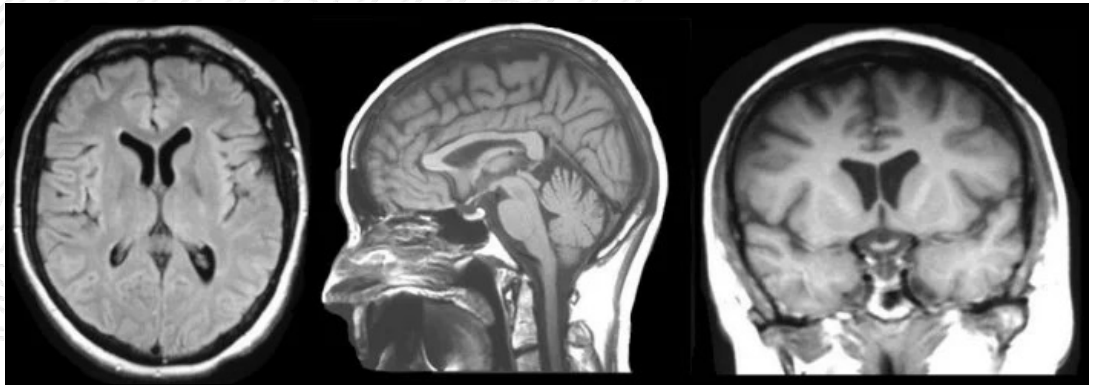
Same principle for spins, need to apply magnetic field fluctuations at just the right frequency (Larmor frequency) to change the spin quantum state

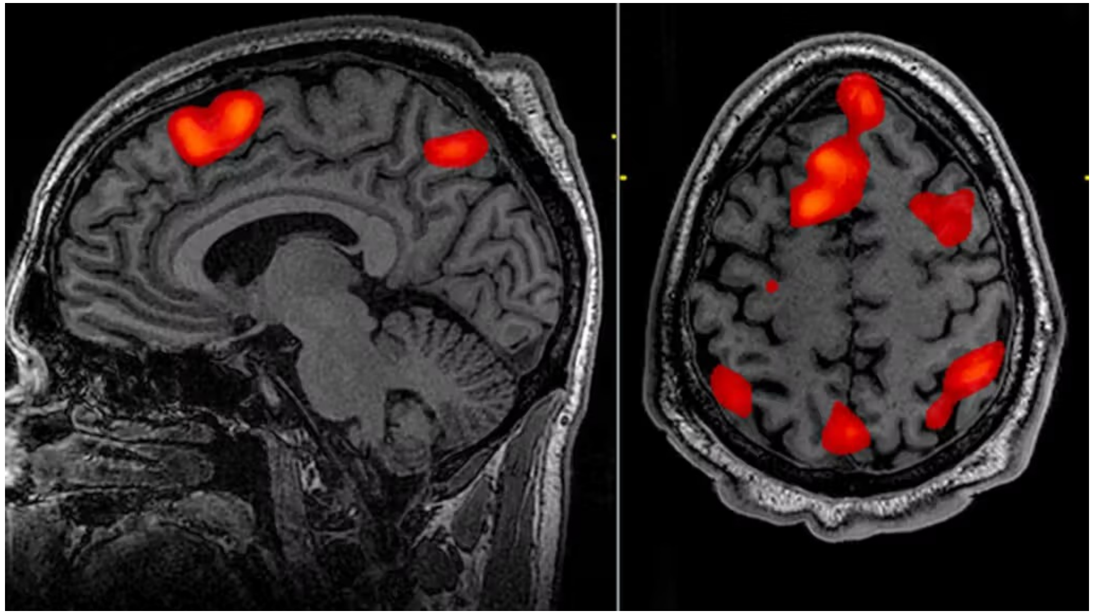
Where spin-based sensors are used today

MRI & fMRI

-Produce high contrast images of the body

-Monitor blood flow and electrical activity in the brain

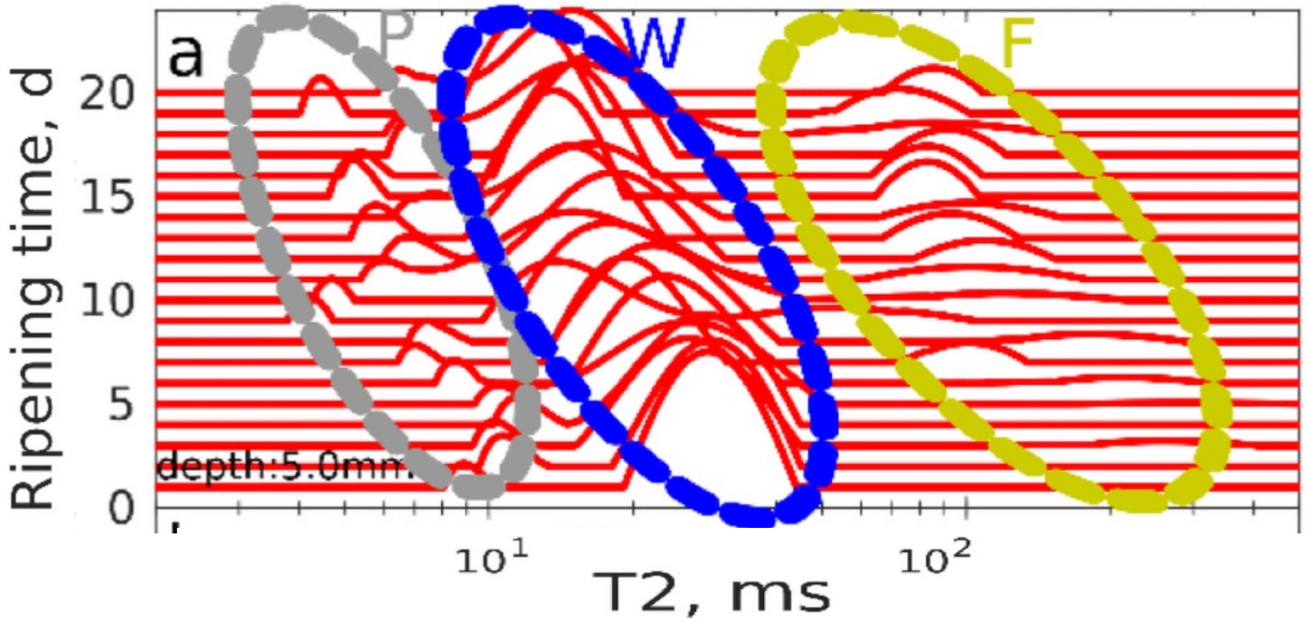




Where spin-based sensors are used today

Food quality assurance:

- Cheese ripening (flavor)
- Chocolate texture (slimy vs. chalky)



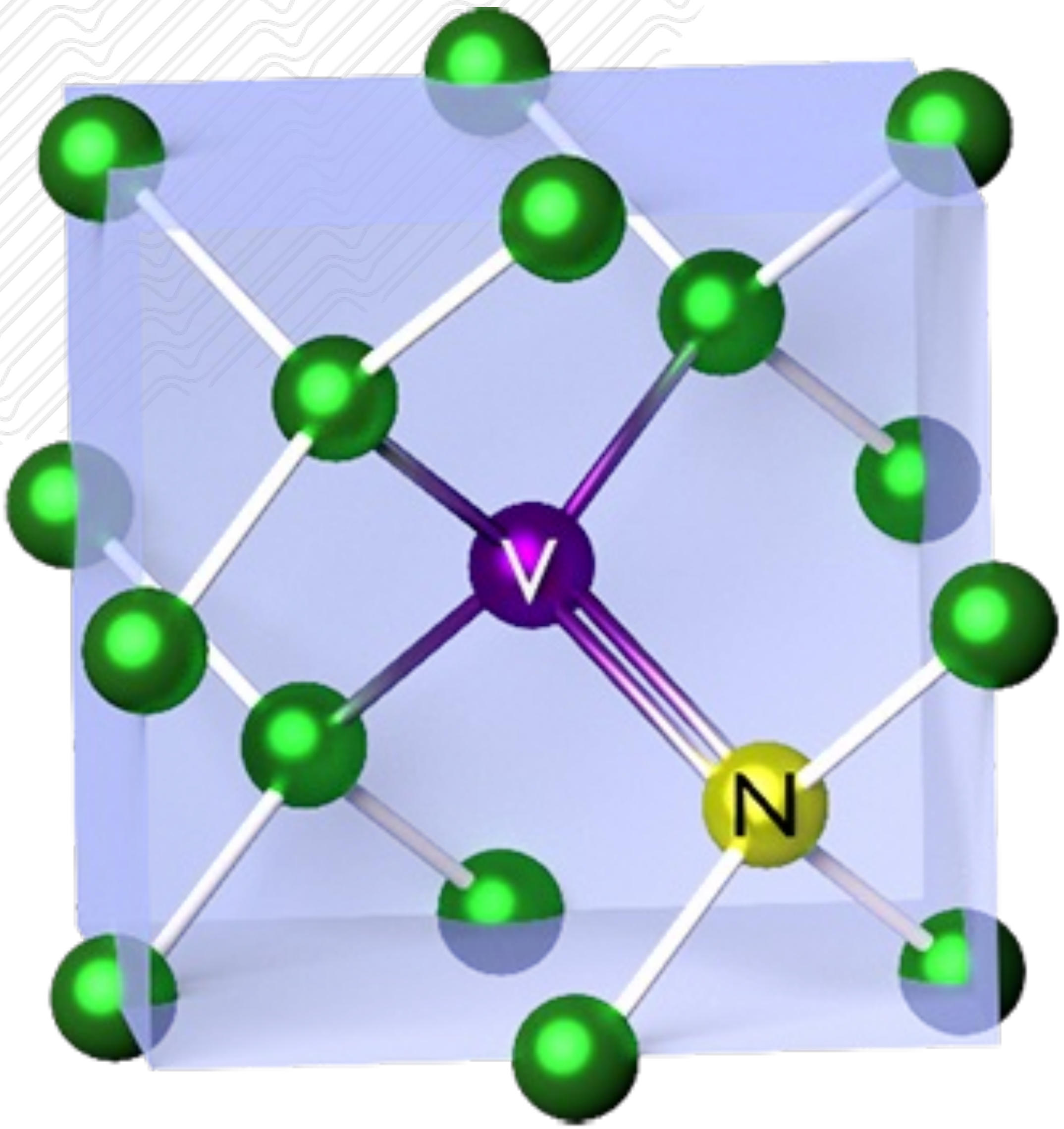
Where spin-based sensors are used today

Oil Industry:

- Refining (wax content to monitor viscosity)
- Oil exploration (porosity and permeability of core samples)

What is an NV Center in diamond?

- Diamond consists of carbon crystal lattice (green in figure)
- Nitrogen atom (N) appears as a defect in this lattice causing a vacant adjacent lattice site (V)
- Electrons are trapped in the vacancy



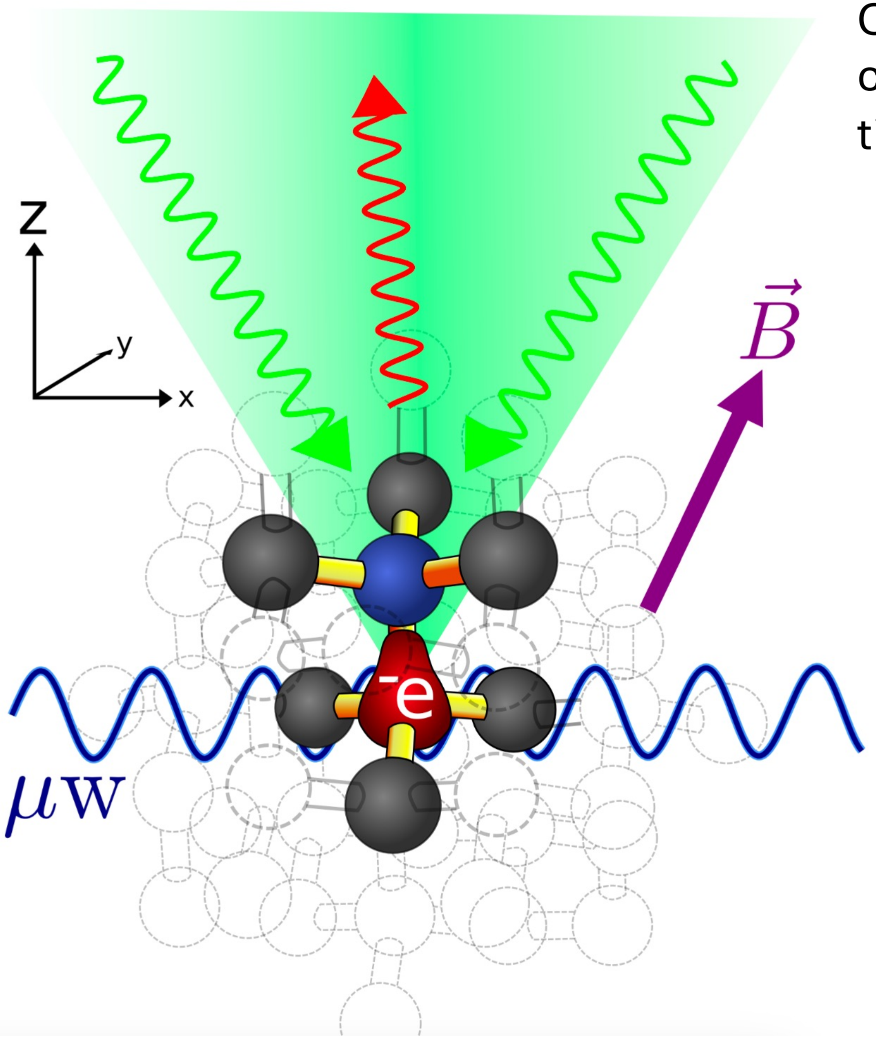
Optical properties of NV centers

Simplest quantum experiment needs only 3 things:

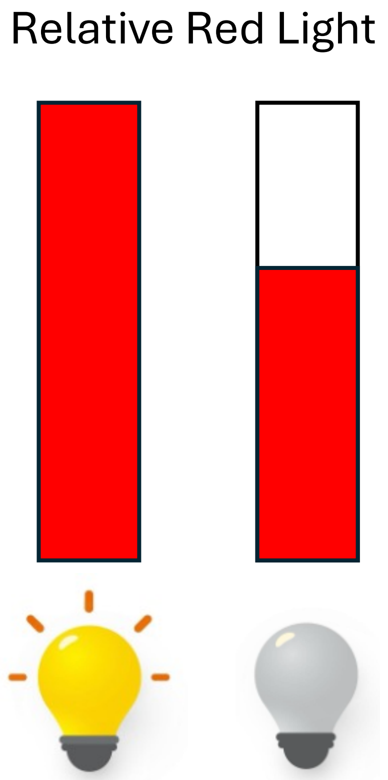
- Diamond
- Laser (reset the sensor, turn on measurement)
- Photodiode

Resonant microwave radiation causes oscillations of the NV electrons

$f_{\mu W} = 2.87$GHz (similar frequency to your microwave at home)



Oscillations are observed via a change in red light observed over time



Why use NV quantum sensors?

- Can be built compactly
- Relatively simple to operate
- Robust: Diamonds are strong!
- Room temperature operation

Useful when:

- Have a small change in field and want to detect that change
- There is something happening at the surface of a material

First hands-on session (roadmap)

1. Overview of the apparatus
2. Use a laser to initialize the sensor
3. Use microwave radiation to start oscillations of the NV electrons (Resonance)
4. Explore how long the quantum behavior lasts

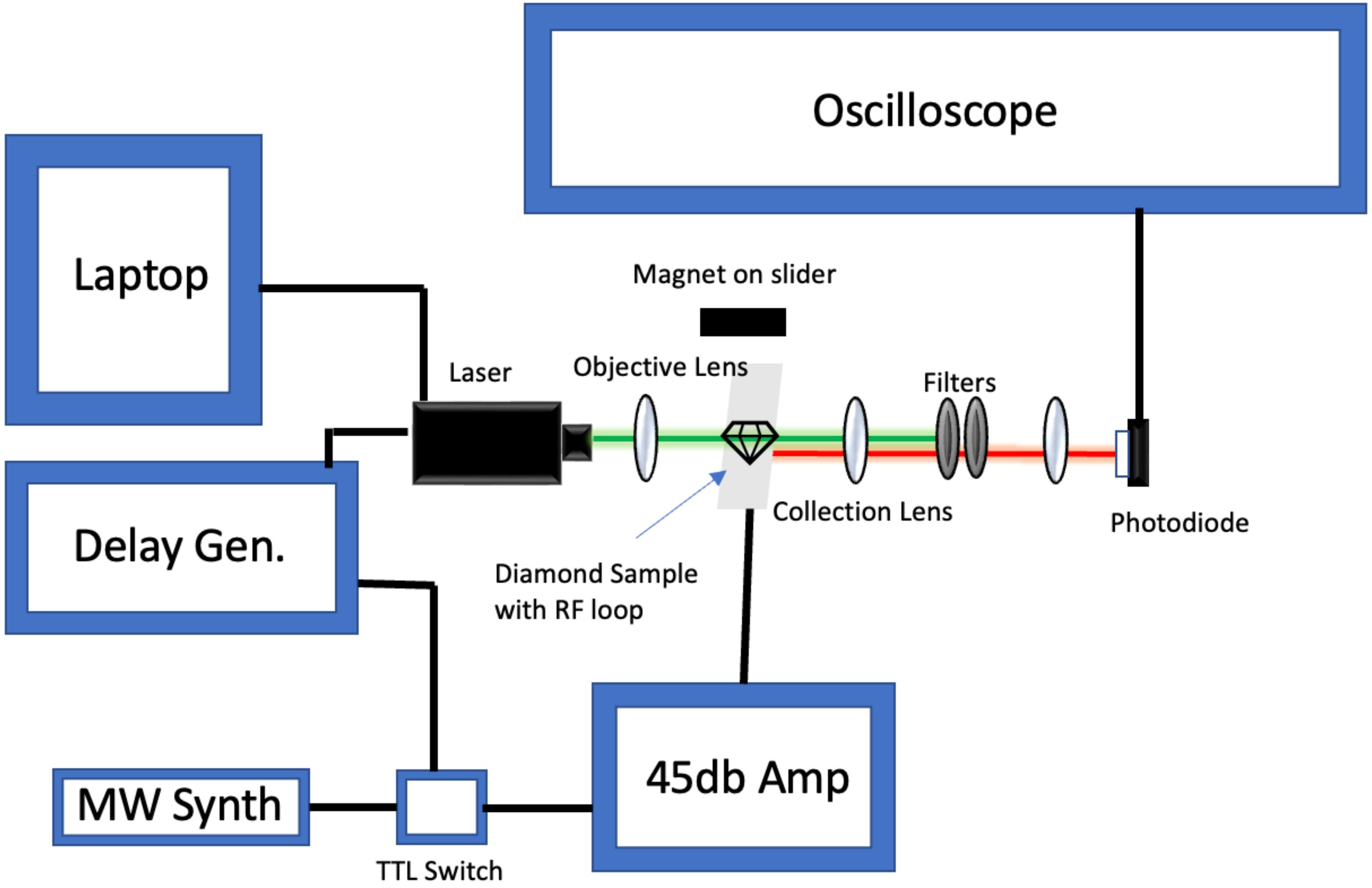
References

- https://www.journalofdairyscience.org/action/showPdf?pii=S0022-0302%2823%2900033-4
- https://nmr.oxinst.com/application-detail/putting-nmr-at-the-core-of-petrochemical-analysis
- https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2999310/
- https://link.springer.com/article/10.1007/BF02635583
- https://www.sciencedirect.com/science/article/pii/S0141391000000768?ref=cra_js_challenge&fr=RR-1
- https://www.sciencedirect.com/science/article/pii/S0924224420307238?ref=cra_js_challenge&fr=RR-1

Experimental Setup

Simplest experiment needs only 3 things:

- Laser
- Diamond
- Photodiode



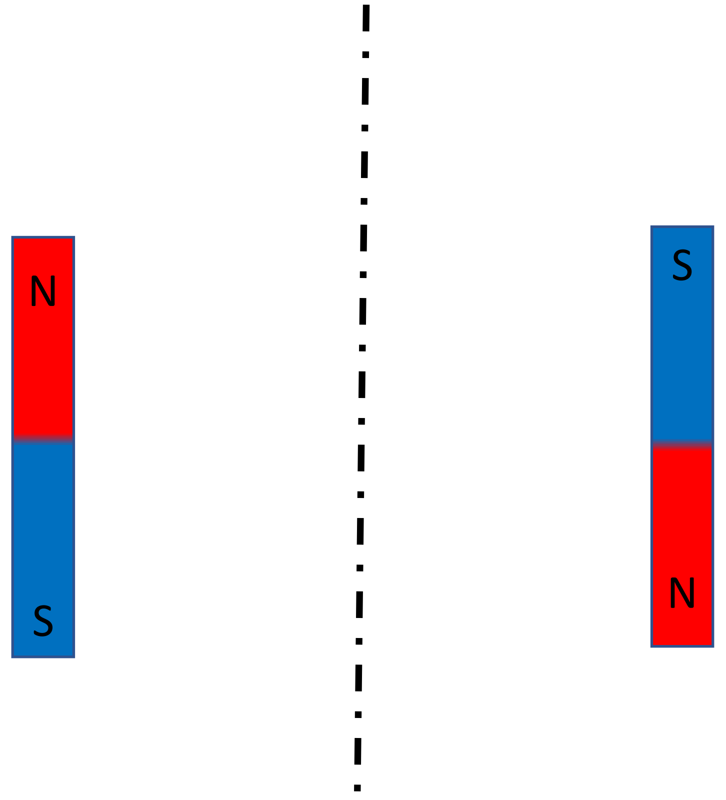
Sensing modalities and technologies with NV centers

DR. CAROLA PURSER

QUANTUM VALLEY IDEAS LAB

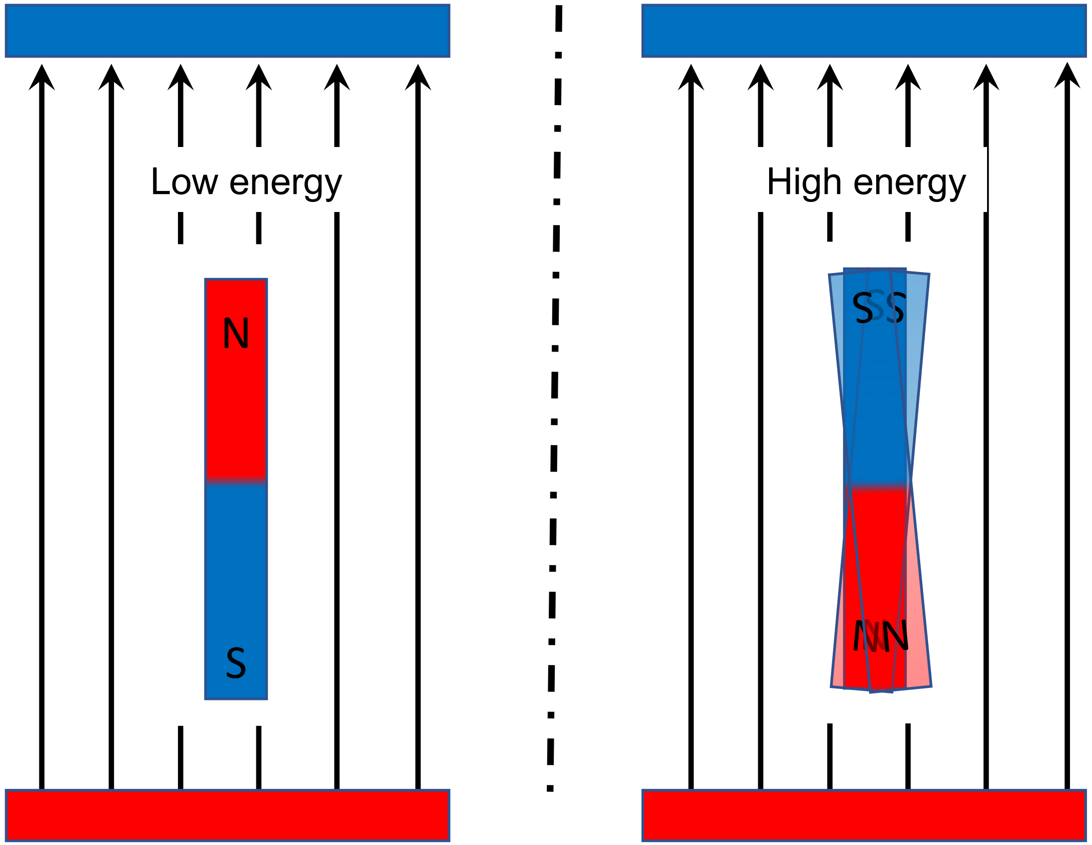
Measuring a magnetic field

With no magnetic field, the orientations of these bar magnets have no energy difference.

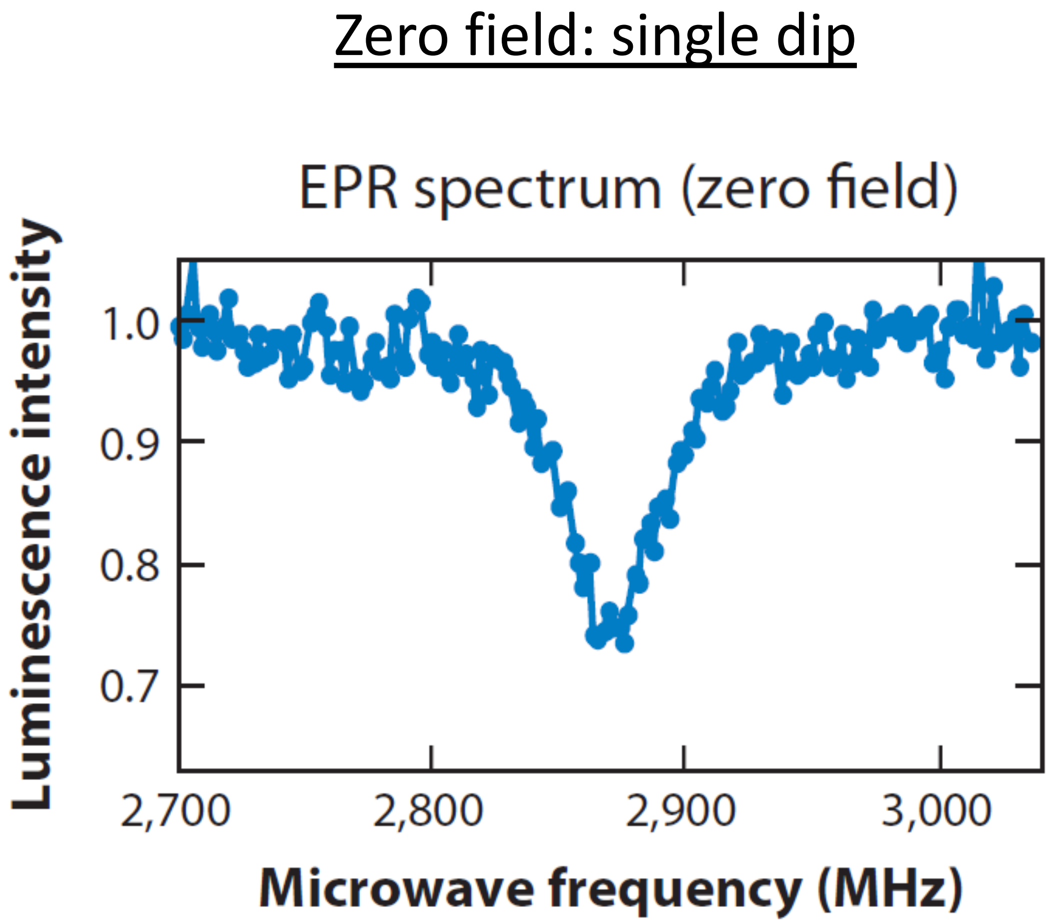


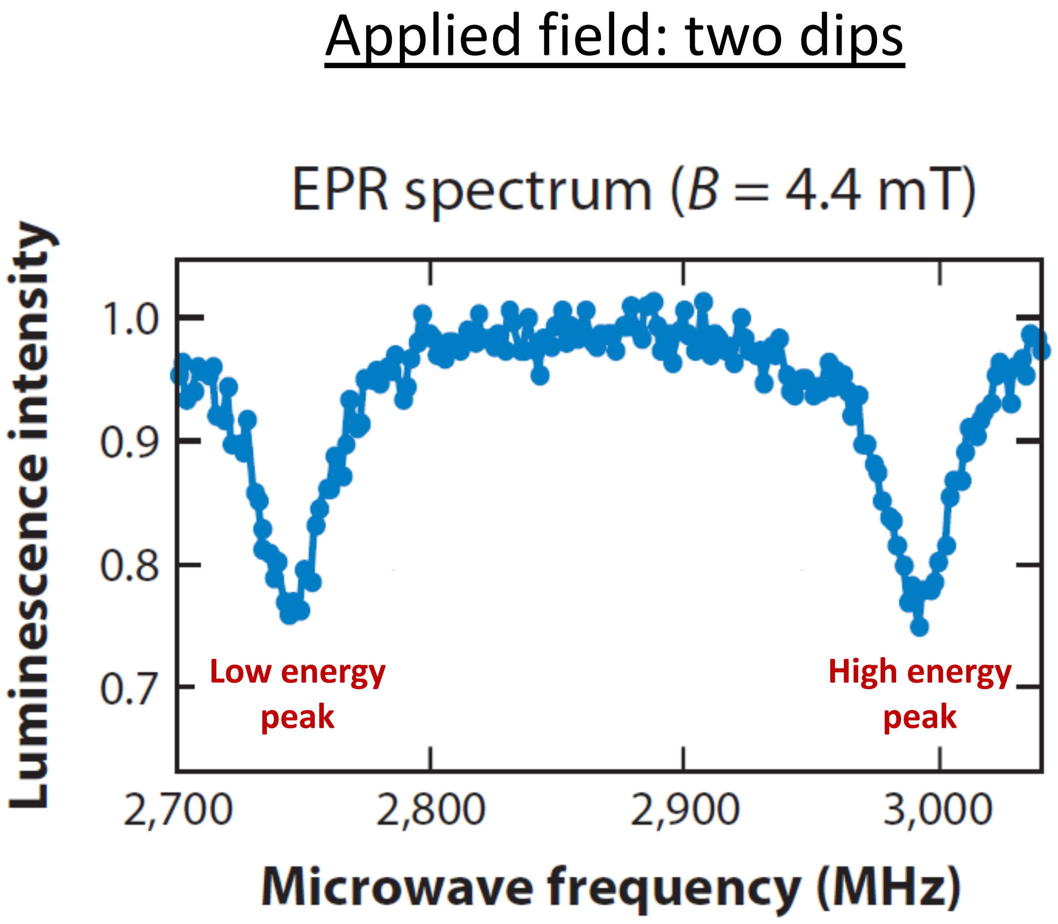
Measuring a magnetic field

In the presence of a field, one orientation has lower energy than the other.



Measuring a magnetic field with NV spins

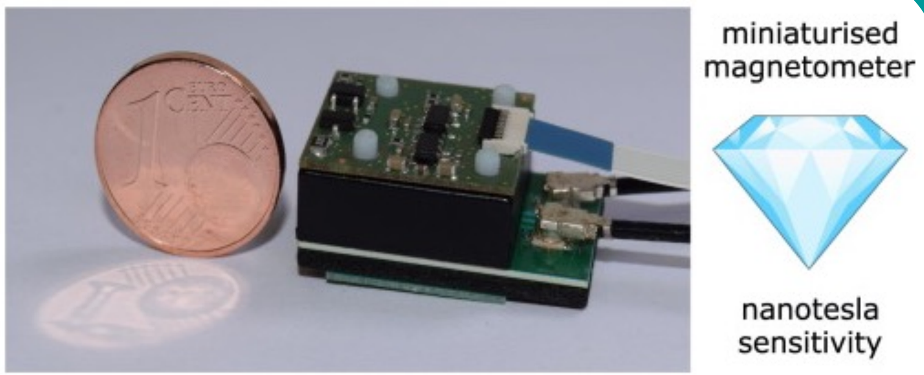




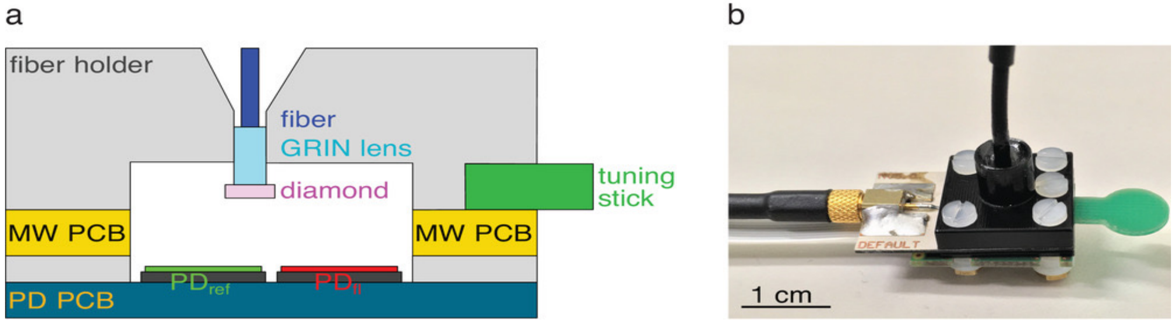
Commercial NV: packaged sensors

Commercial interests can take a lab from benchtop to packaged sensor

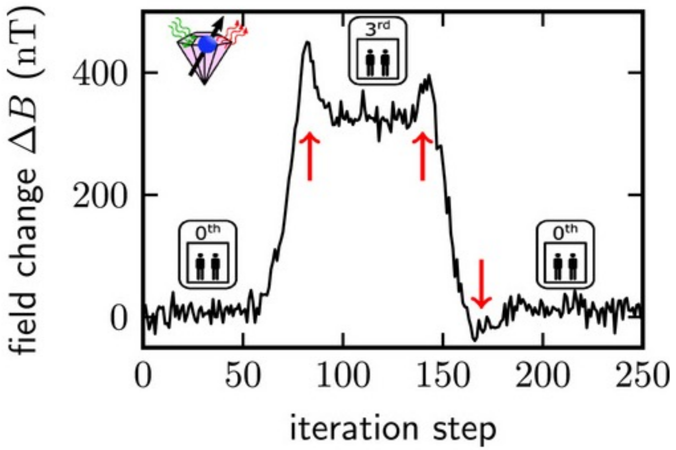
How else might a packaged magnetometer be useful?



https://doi.org/10.1016/j.diamond.2019.01.008

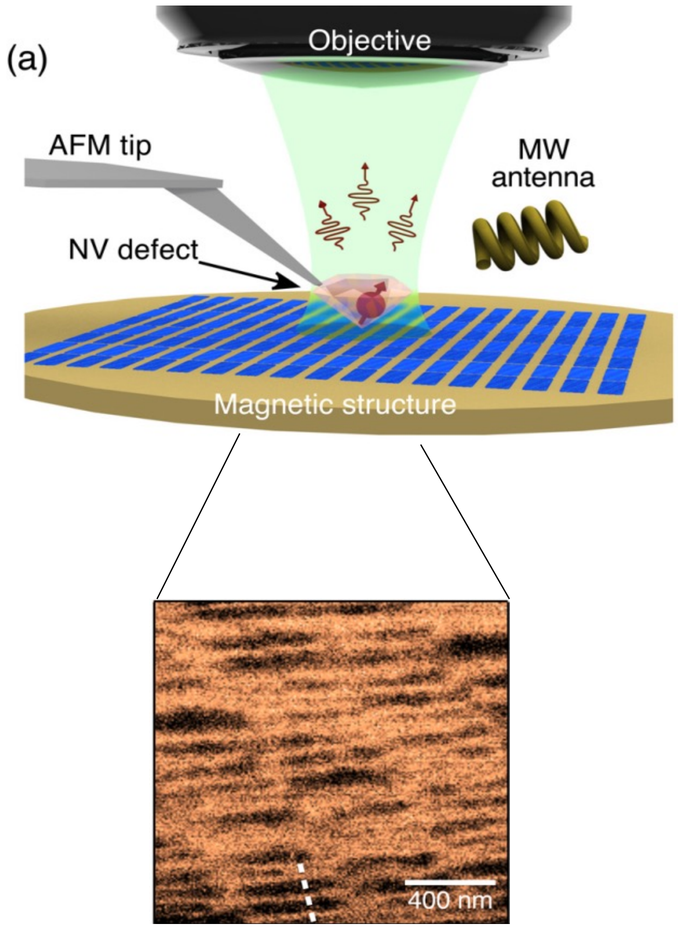


Sensing motion of an elevator with magnetometer placed on 3rd floor

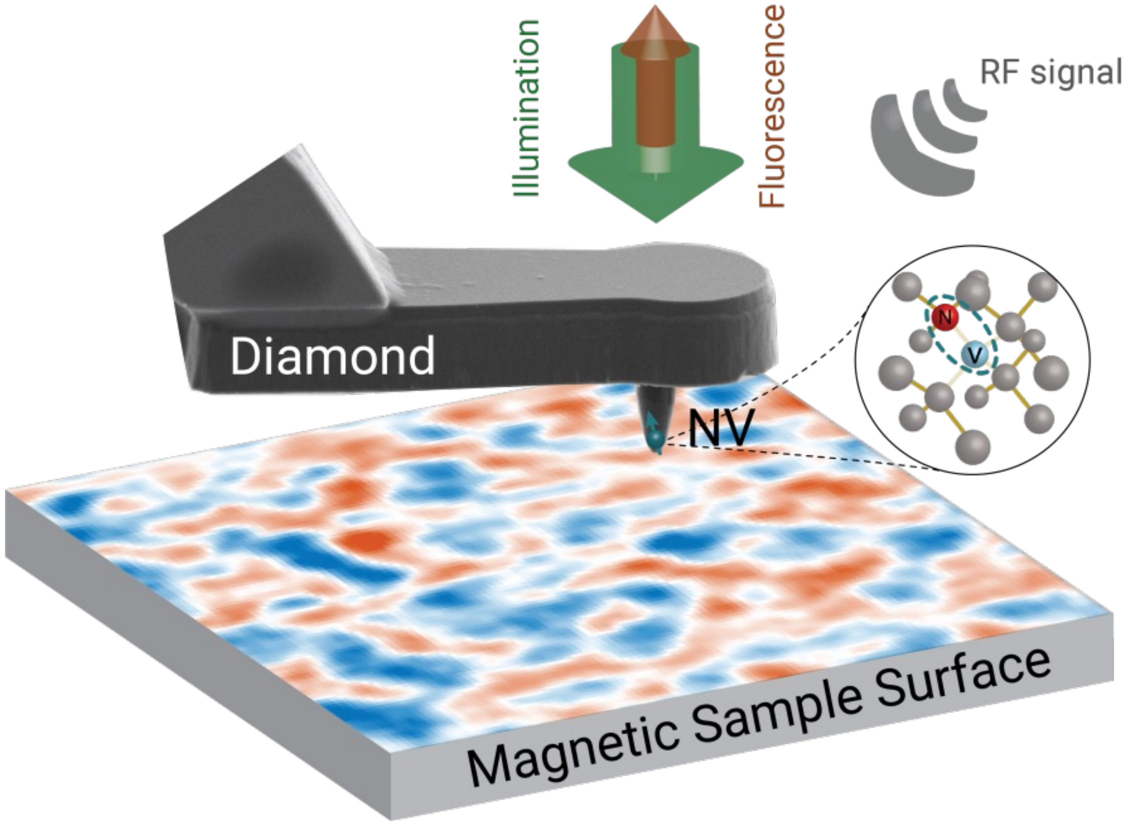


Felix M. Stürner, Andreas Brenneis et al., "Integrated and Portable Magnetometer Based on Nitrogen-Vacancy Ensembles in Diamond," Advanced Quantum Technologies, 2021

Example sensing with scanning NV



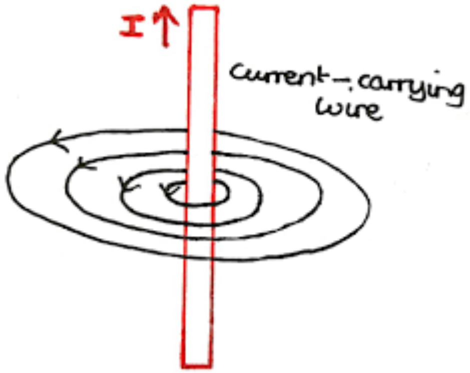
L. Rondin ,et al., “Nanoscale magnetic field mapping with a single spin scanning probe magnetometer,” Appl. Phys. Lett. (2012)

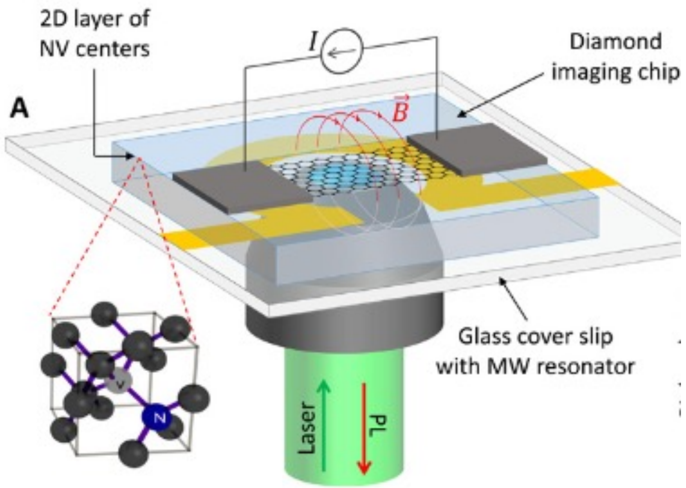


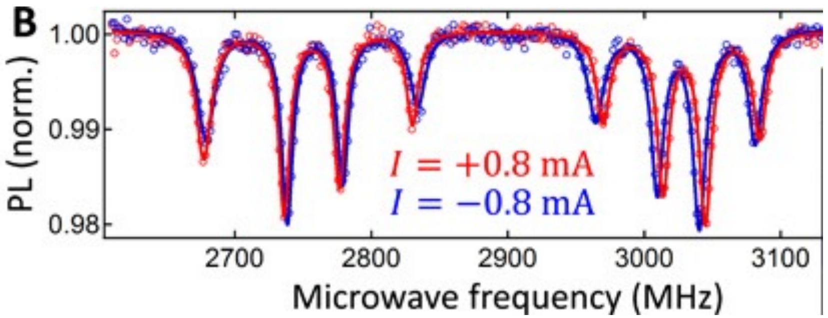
https://qzabre.com/en/technology

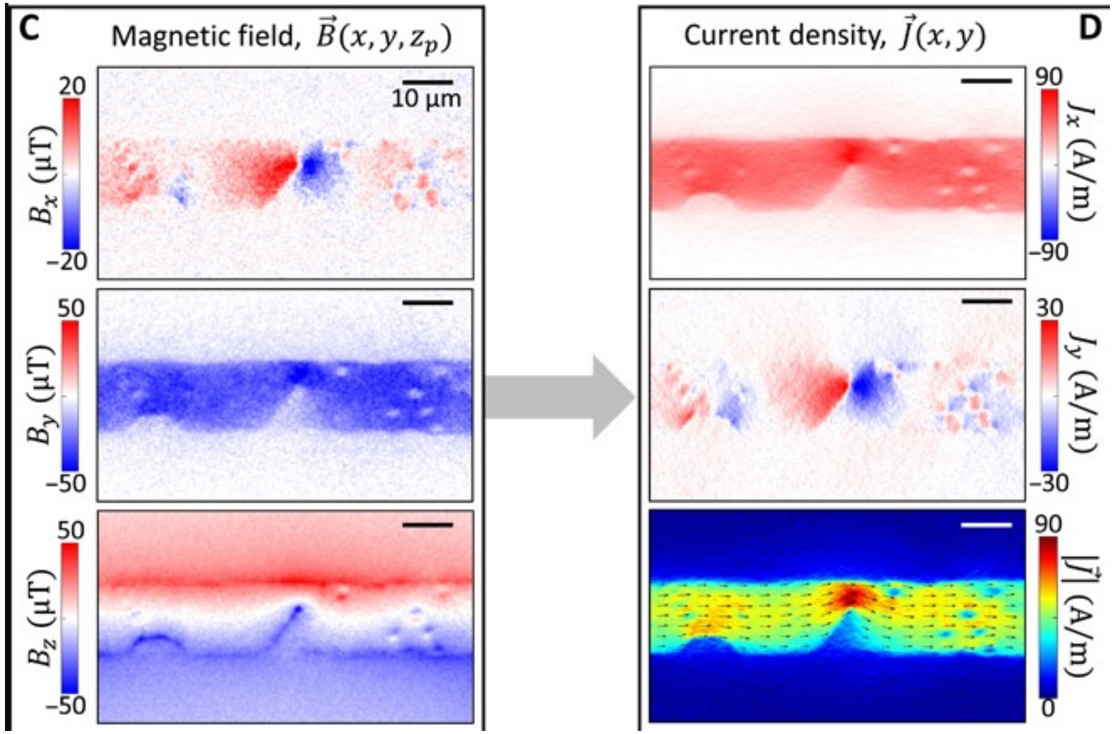
Imaging currents with an NV sensor

Recall: electric currents generate magnetic fields.
Since we can detect magnetic fields using NV centers, we can also measure proximate electric currents





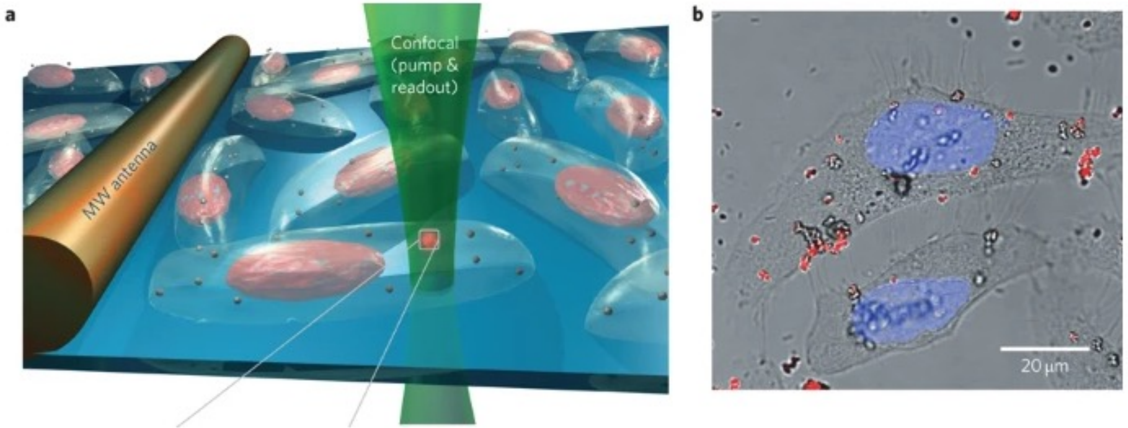




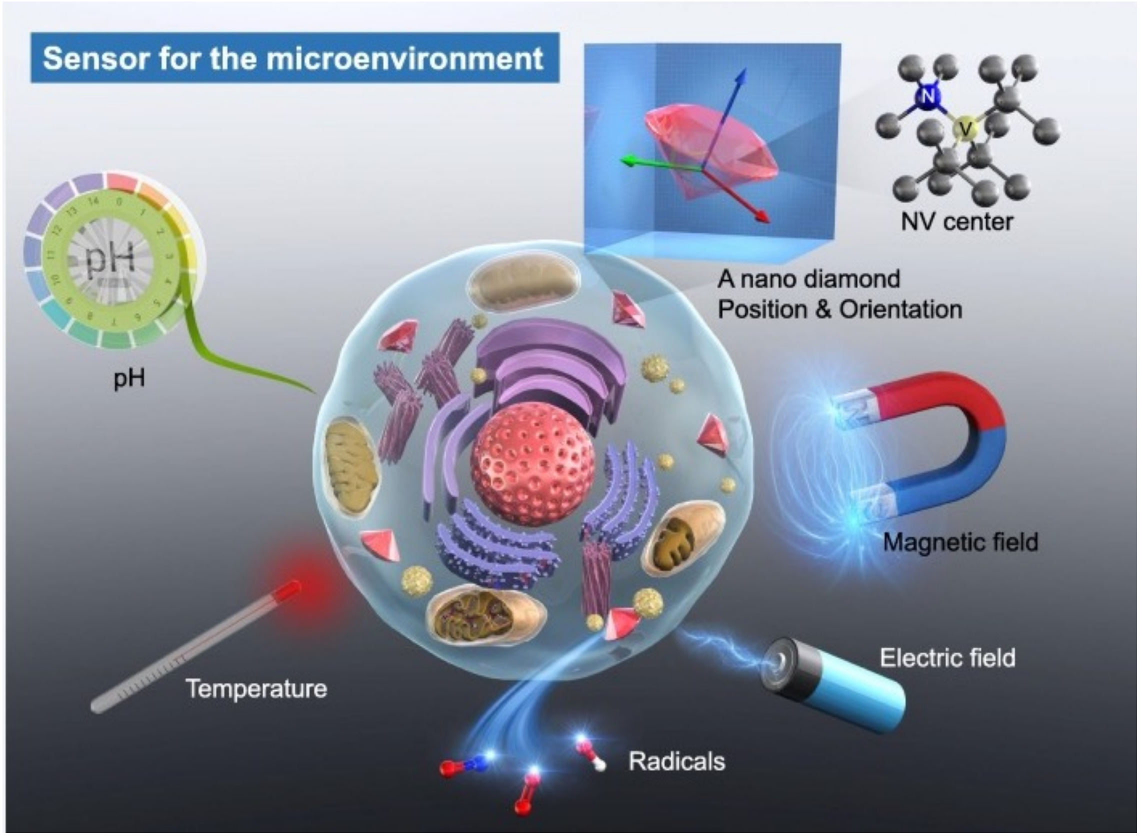
Jean-Philippe Tetienne, et al., "Quantum imaging of current flow in graphene," Science Advances, 2017.

Biosensing applications

- Intrinsic bio-compatibility of diamond means that NV-based quantum sensors can be placed in cells
- Diamonds can take the form of nanocrystals >10 nm
- Surface functionalization can be used to place diamonds in desired regions or bind molecules of interest to the diamond surface



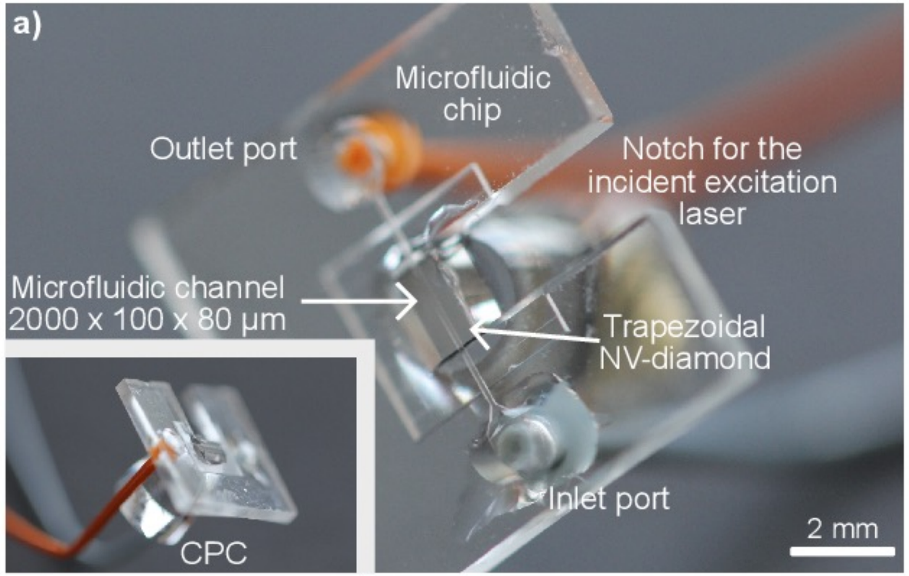
McGuinness, L., Yan, Y., Stacey, A. *et al.* Quantum measurement and orientation tracking of fluorescent nanodiamonds inside living cells. *Nature Nanotech* **6**, 358–363 (2011).



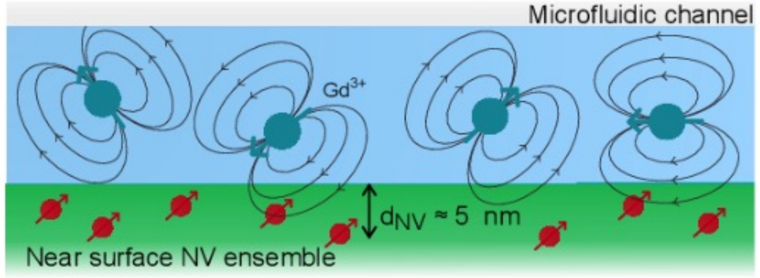
Takuya F. Segawa, Ryuji Igarashi, "Nanoscale quantum sensing with Nitrogen-Vacancy centers in nanodiamonds – A magnetic resonance perspective," Progress in Nuclear Magnetic Resonance Spectroscopy, 2023.

Diamond-based lab on a chip

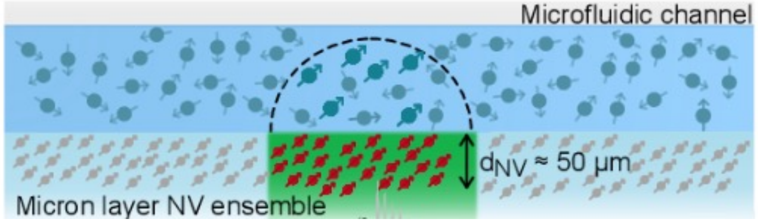
Designing microfluidic channels in the diamond or at the diamond surface enables chemical analysis using the sensitivity of NV centers to magnetic fields



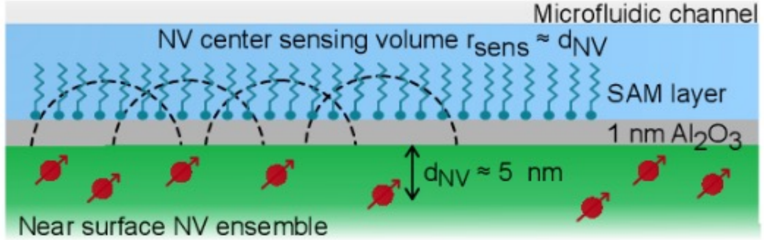
Flow of ions



Flow and concentration of spins (magnetic moments)



Screening for bio-molecules



R. D. Allert, F. Bruckmaier, N. R. Neuling, et al. “Microfluidic quantum sensing platform for lab-on-a-chip Applications” Lab on a Chip, 2022.