Detection of Superconductivity Using NV Centers in Nanodiamonds

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Outline

- Motivation
- Various cross-relaxation, level anti-crossing features in Diamond NV centers
- Near zero-field cross relaxation feature in single crystal diamonds and nanodiamonds
- Applications

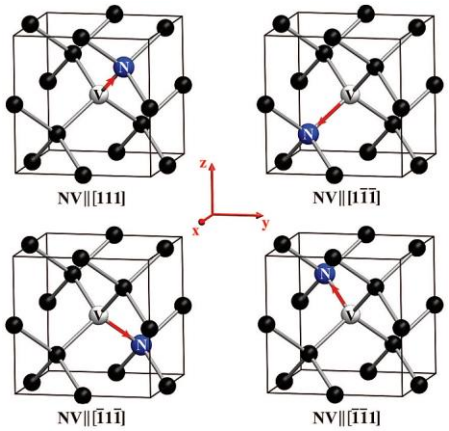
Diamond NV centers- Applications

Sensitive to:

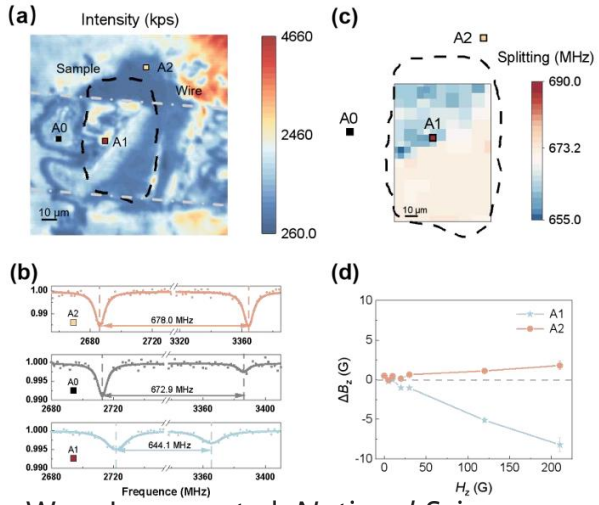
- Magnetic field
- Temperature
- Pressure
- ……

Key Properties for Sensing:

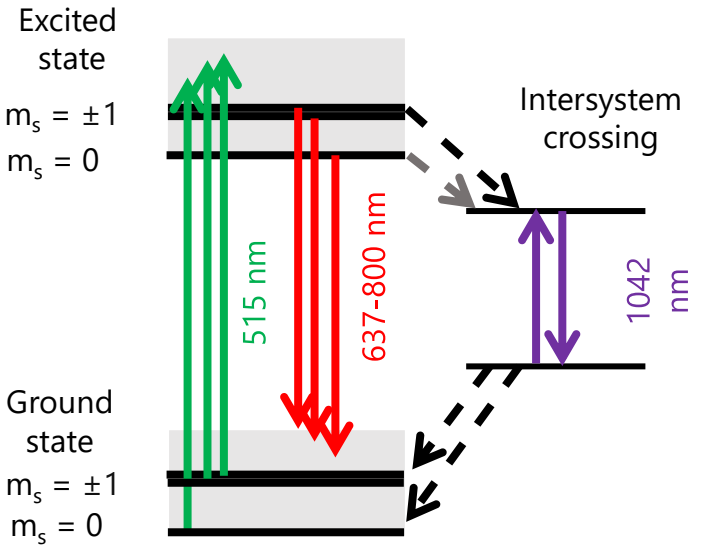
- Room temperature operation
- Optical initialization & readout
- Nanoscale spatial resolution
- High magnetic field sensitivity
- Biocompatible & chemically stable

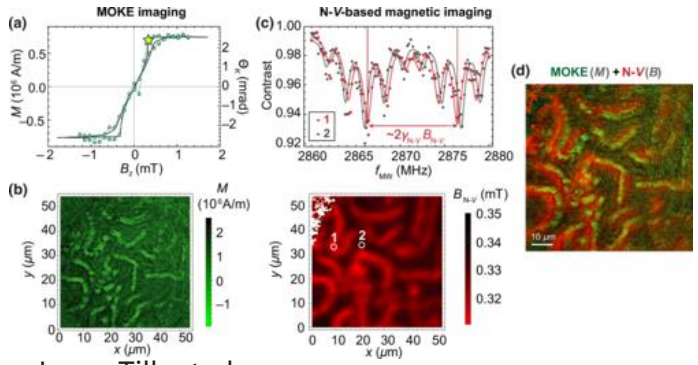


L.M Pham et. al, PhysRevB.86.121202



Wen, Junyan, et al, *National Science Review* (2025): nwaf268.





Lenz, Till, et al., *Physical Review Applied* 15.2 (2021): 024040.

Limitations of Microwave-Based Methods

Technical Complexity:

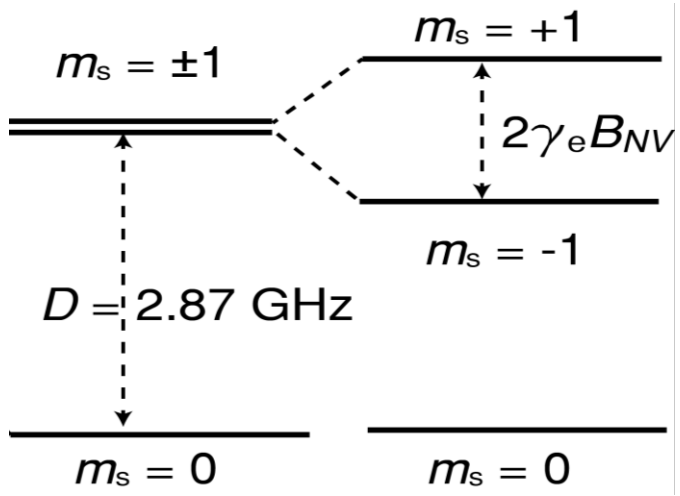
- MW generation, amplification, and delivery required
- RF design for homogeneous MW fields
- Power broadening & heating effects

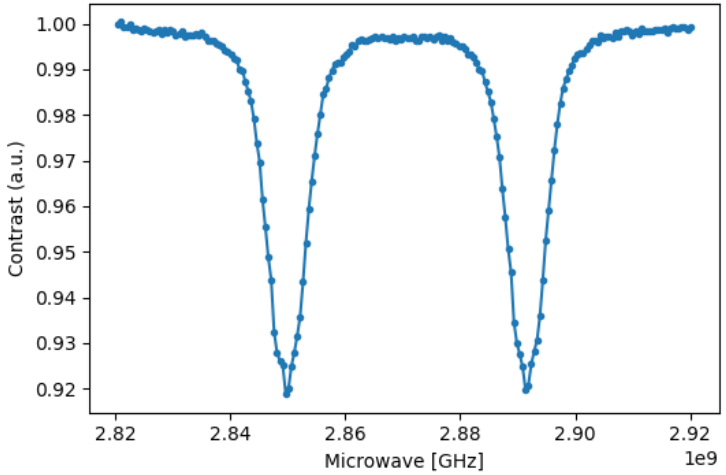
Interference & Heating:

- MW heating of conductive samples (e.g., thin films)

Biological Applications:

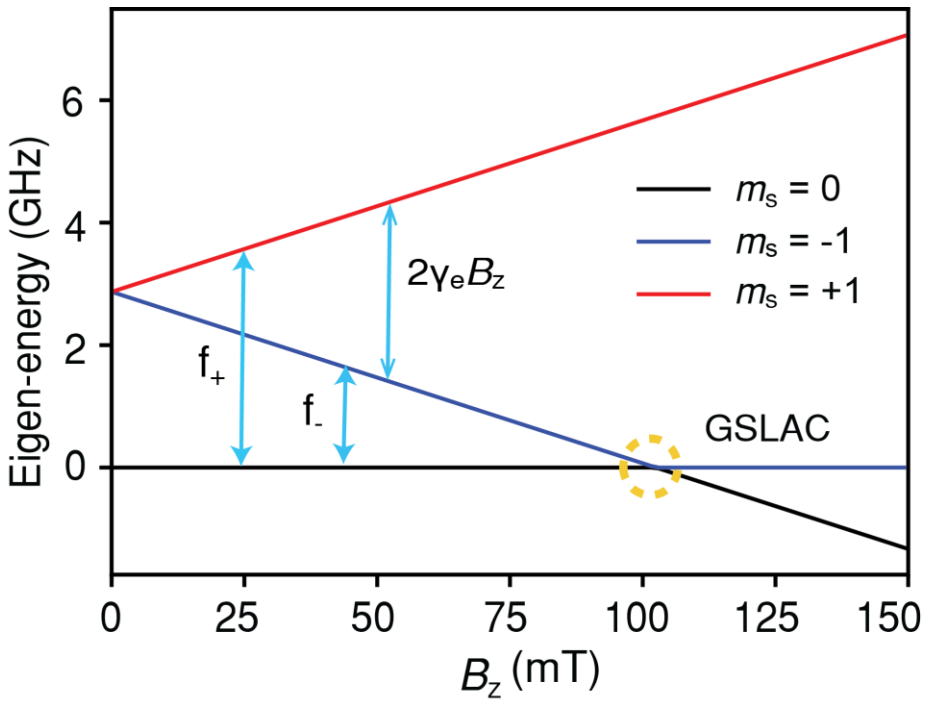
- Potential MW damage to cells/tissues
- Limited penetration in aqueous environments

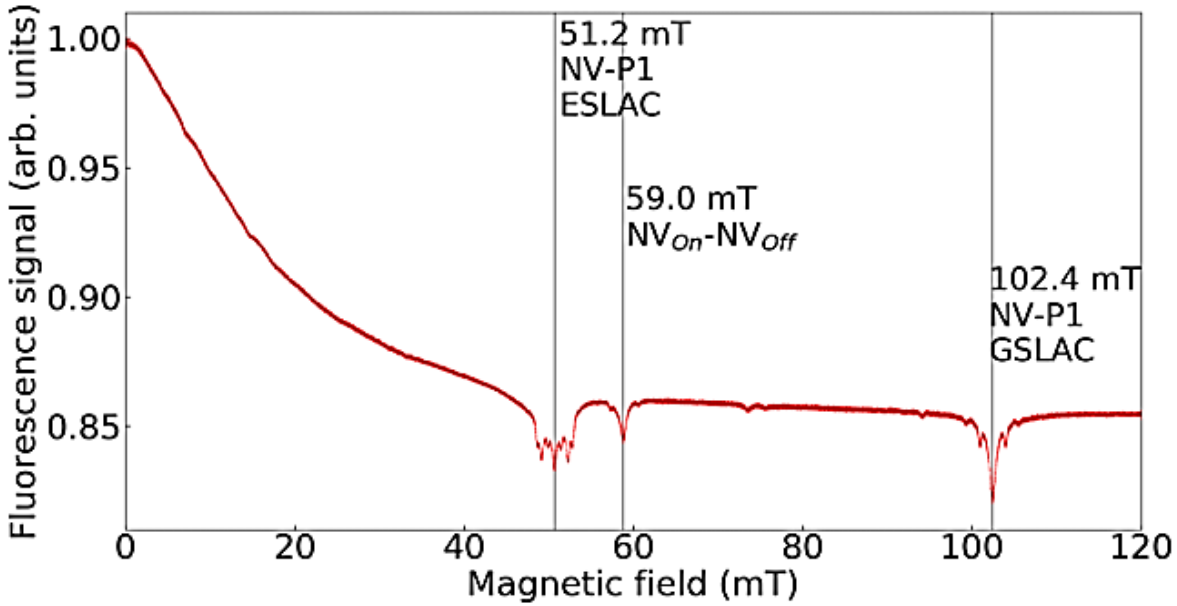




Fluorescence as a function of magnetic field

- Ground state level anti-crossing (GSLAC)
- The PL signal as a function of the applied axial magnetic field
- Gradual decay- non-aligned NV centers due to spin-mixing of Zeeman sublevels
- Reduction of optical pumping





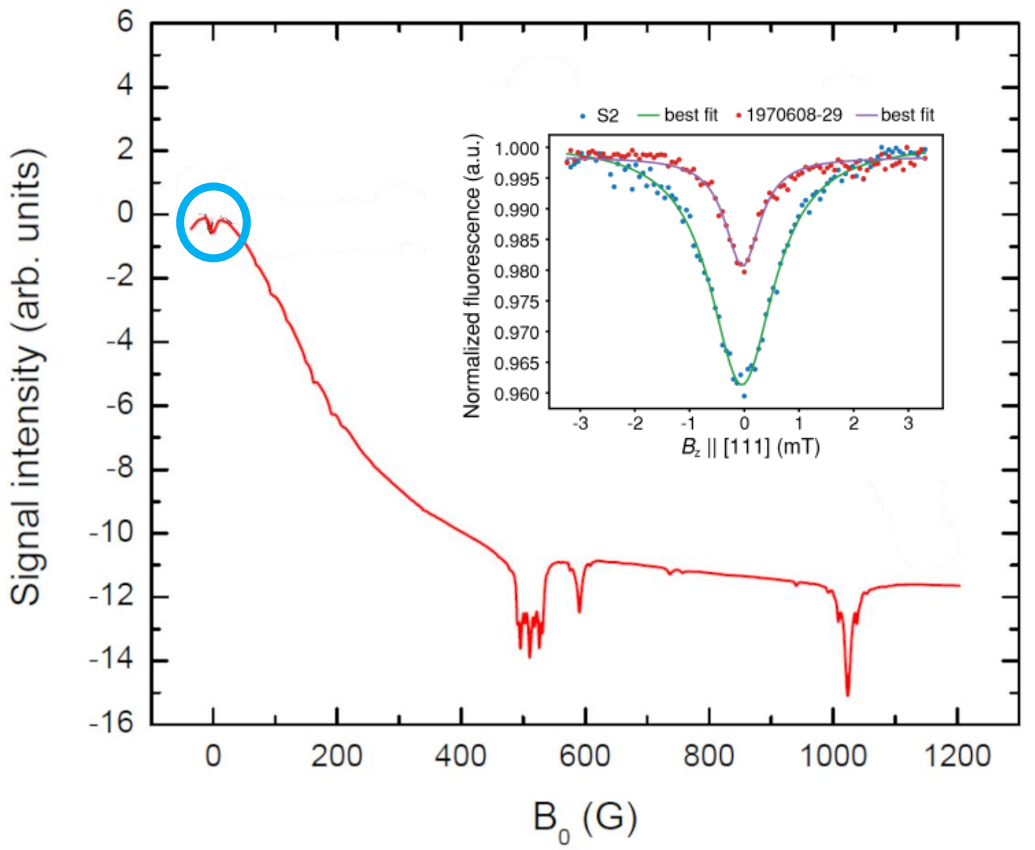
Lazda, Reinis, et al., *Physical Review B* 103.13 (2021): 134104.

The microwave-free solution

Cross-Relaxation at Near-Zero Magnetic Field

Physical Mechanism:

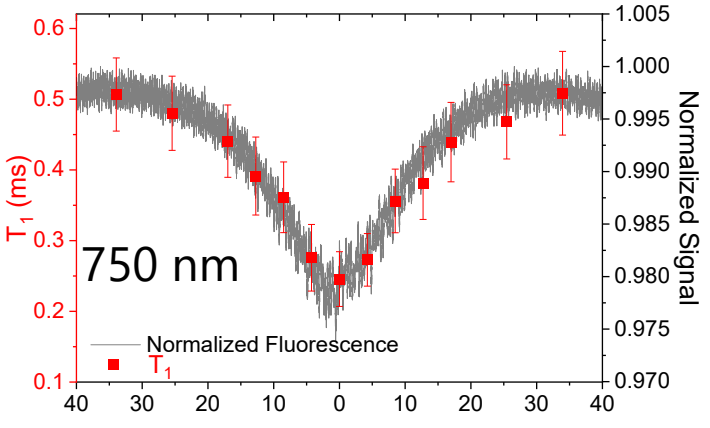
- Dipolar coupling between differently-oriented NV sub-ensembles
- exchange polarization when level energies align
- Enhanced spin relaxation (T_1) at resonance
- **Measurable dip in fluorescence without microwaves**!
- NV density dependent linewidth and contrast

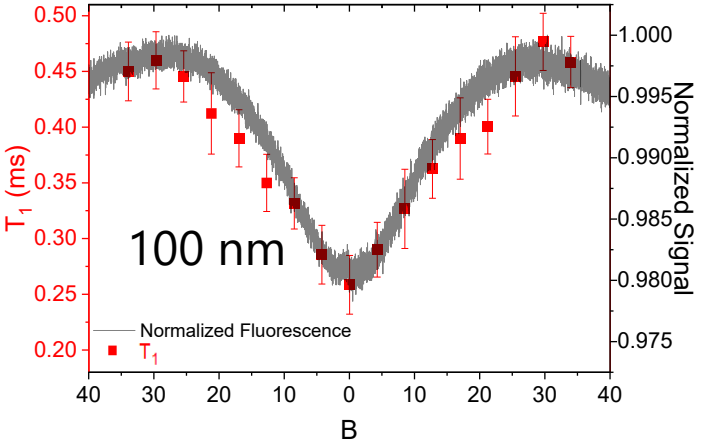


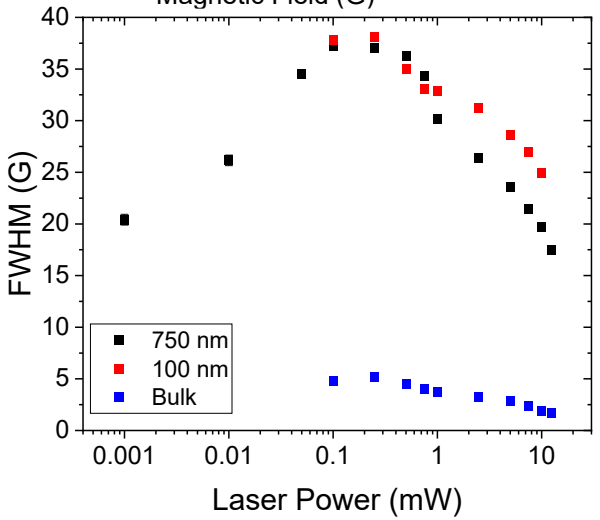
Anishchik SV, Ivanov KL., J Magn Reson. 2019;305:67-76, https://arxiv.org/pdf/2301.09666

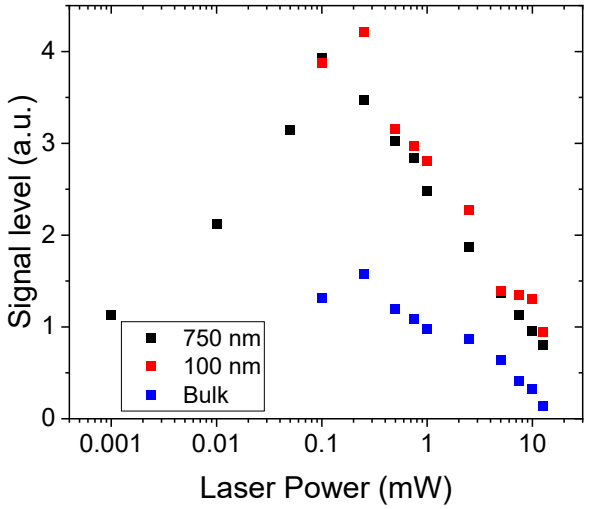
Zero-field feature in nanodiamonds

- Enhancement of the relaxation occurring at the zero-field feature
- Nanodiamonds size dependence
- Laser power dependence
- ensemble → microwave-free magnetometry









Dhungel, Omkar, et al, *Optics Express* 32.12 (2024): 21936-21945.

Nanodiamonds for Magnetometry

Why Nanodiamonds?

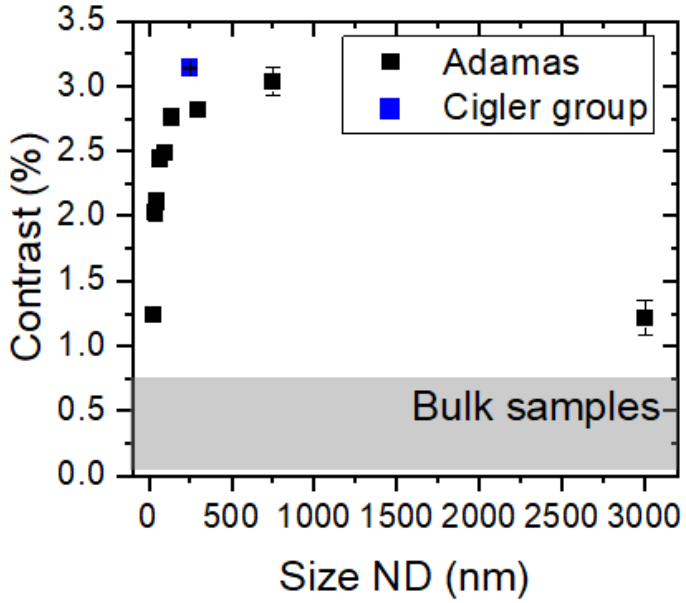
- Submicron dimensions (30-1000 nm)
- Minimal standoff distance to sample
- Flexible deposition on textured surfaces
- "Salt-and-pepper" technique

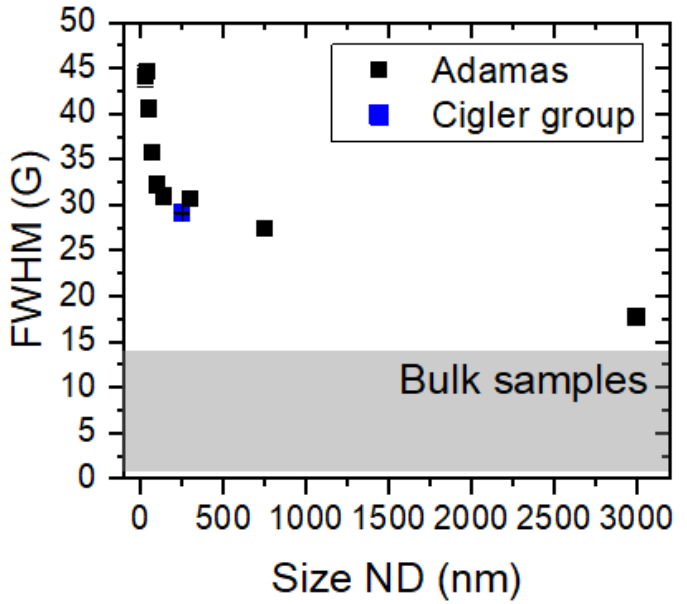
Size Effects (30-3000 nm range):

- Smaller NDs: broader features, higher strain
- **Optimal size: ~200 nm for balance**
- Non-monotonic contrast vs. Size

Applications:

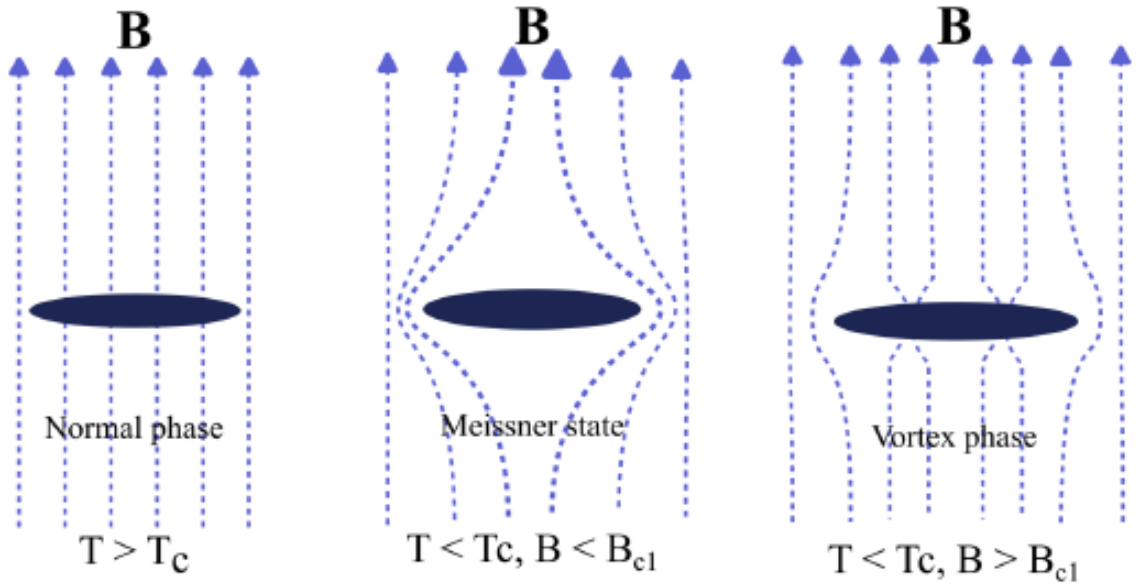
- Wide-field imaging
- Arbitrary-shaped surfaces
- Biological systems (biocompatible)





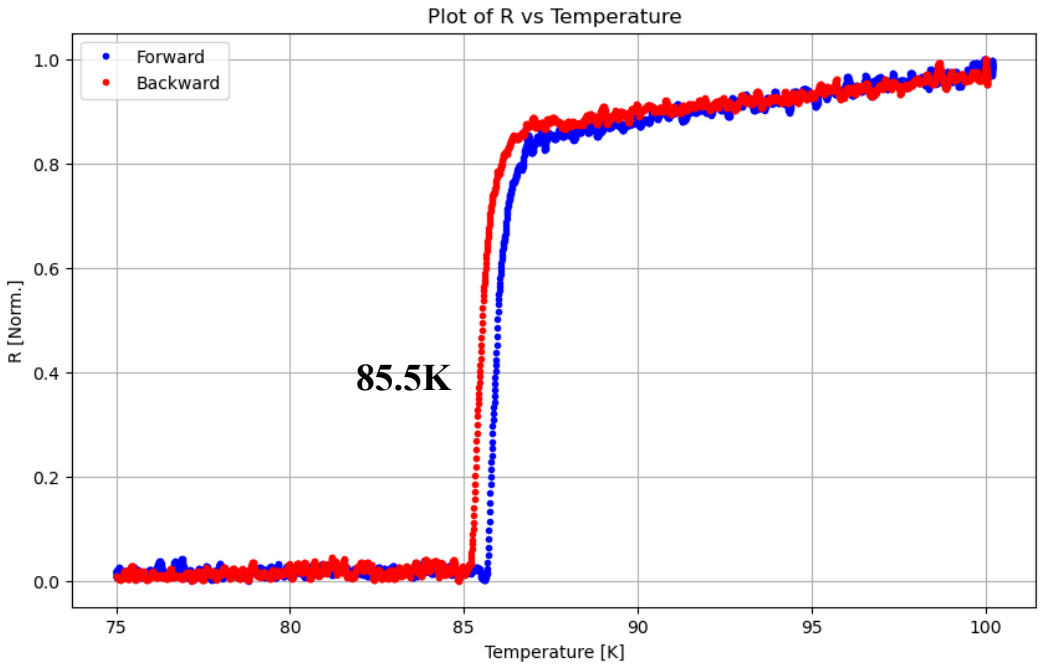
Type II superconductors

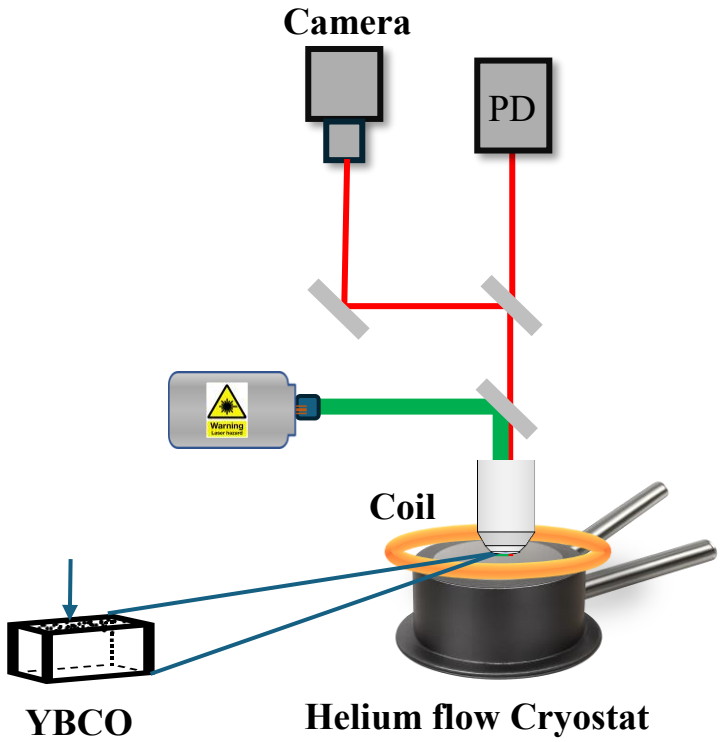
- Meissner state
- Vortex state
- Nanodiamonds deposited on YBCO



Superconductivity application

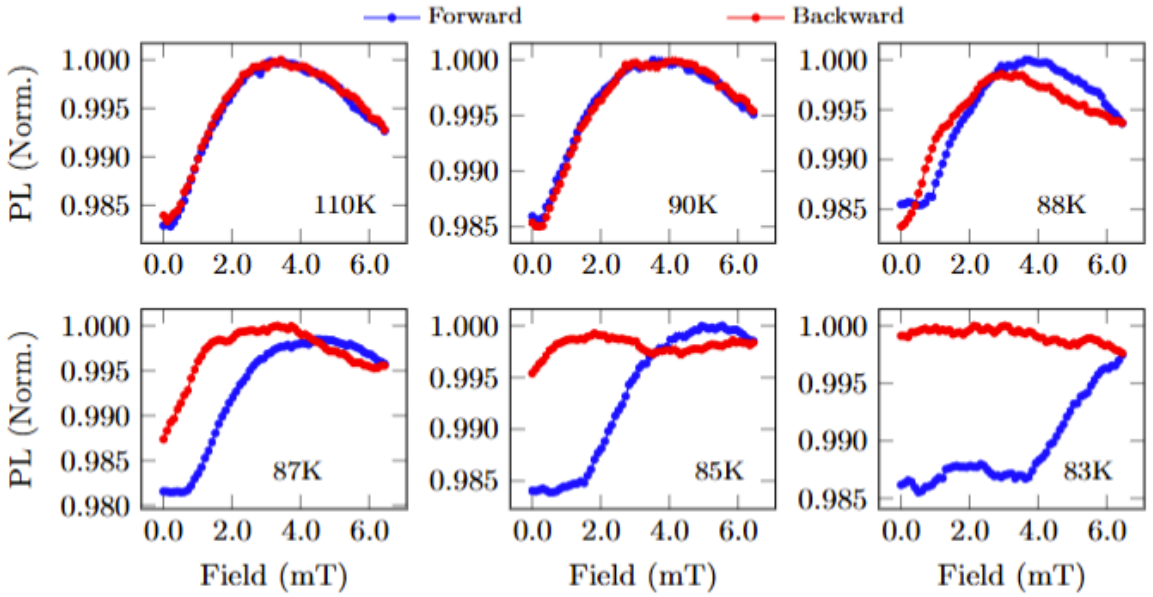
Method: Lock-in detection of fluorescence modulation





- NDs deposited on Superconductor (YBCO)
- 3 Hz, 10G amplitude modulated signal feed into lock-in- Extracted R from Lock-in
- Shining the green light on NDs and small modulated magnetic field can be used to extract superconducting property (Miessner effect).

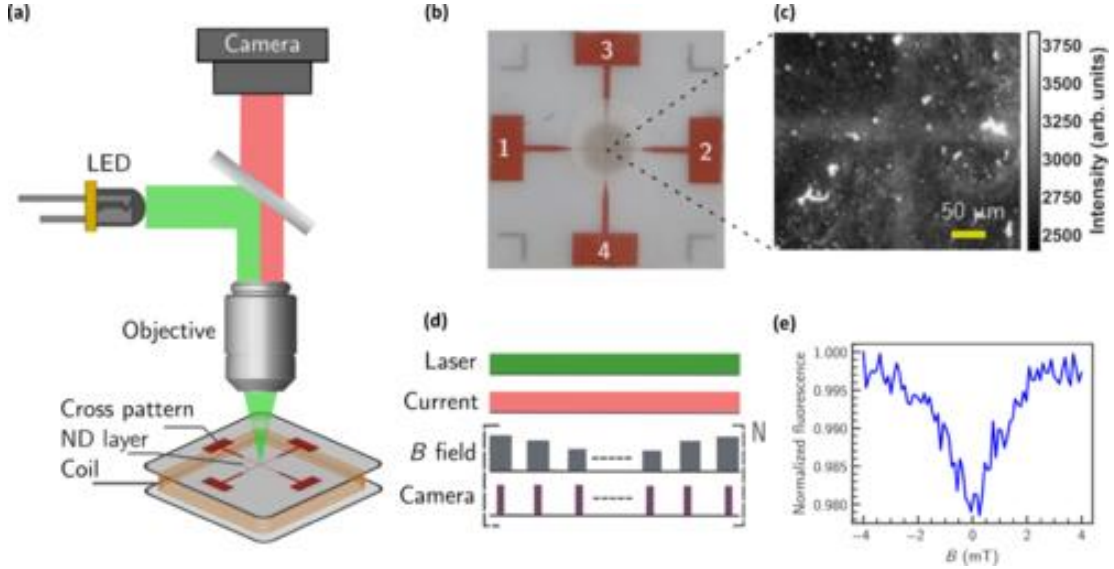
Lower critical field

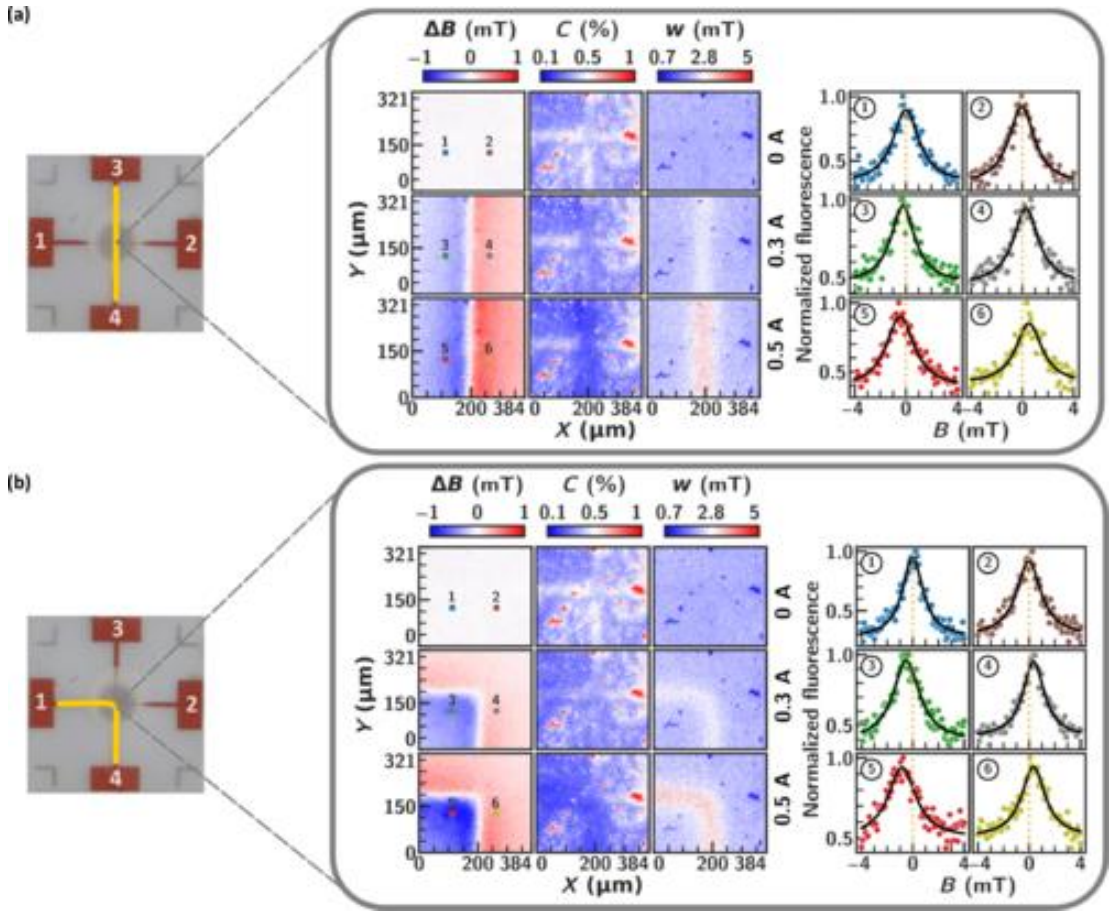


- Magnetic field scan- forward and backward
- Fluorescence level rise when there is a transition from Meissner to intermediate state
- Extract the critical field for each temperature.
- can provide information about London penetration depth and the coherence length.
- Understanding vortex dynamics, pinning, and flux creep—phenomena.

Wide-field magnetic field imaging

- Magnetic field imaging using ZFR in NDs
- Per pixel sensitivity: 5 μT/√Hz

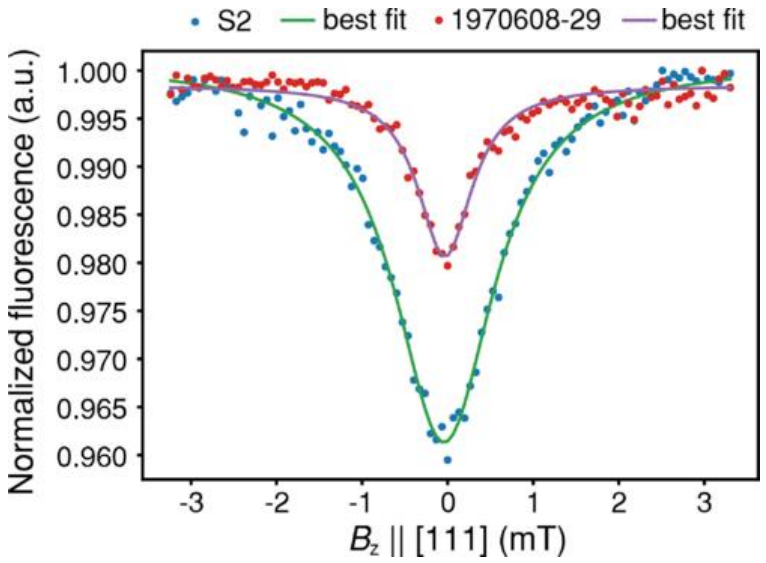


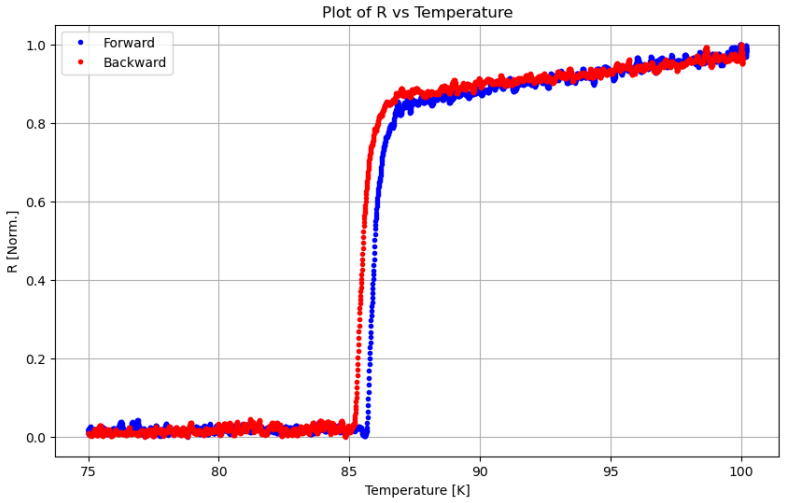


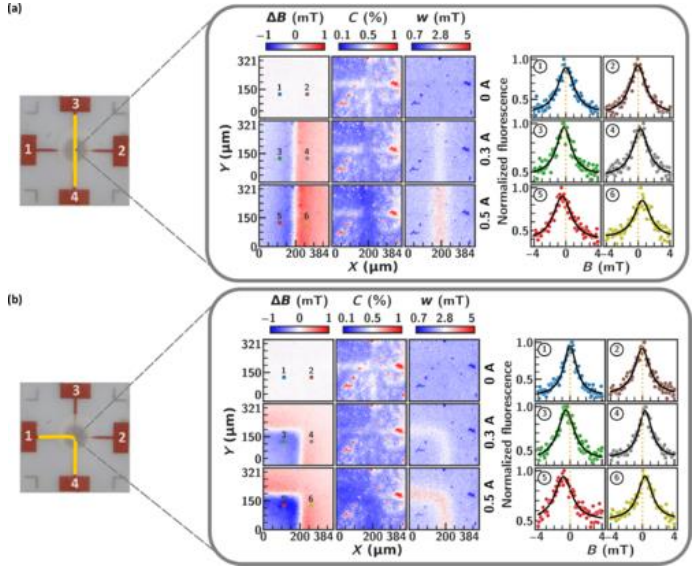
Sengottuvel, Saravanan and Dhungel, Omkar, et al. *Physical Review Applied* 23.3 (2025): 034001.

Conclusion

- Cross-relaxation feature characterization and magnetometry applications
- Extension in the field of biology and condensed matter system
- No microwaves, orientation free and low magnetic field
- Sensitivity optimization, diamond engineering







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MUQUABIS Multiscale Quantum BioImaging and Spectroscopy