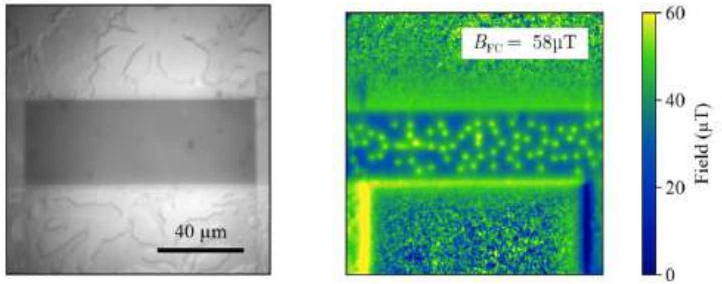
Workshop on Detection and Mitigation of Flux Trapping in Superconducting Digital Electronics
2024/12/13 (Fri) 14:20 – 14:45 (ID_028)
Talk 20min + Q&A 5min

Wide-field quantitative imaging of superconducting vortices using diamond quantum sensors

Related work: S. Nishimura, KS et al., Appl. Phys. Lett. **123**, 112603 (2023).



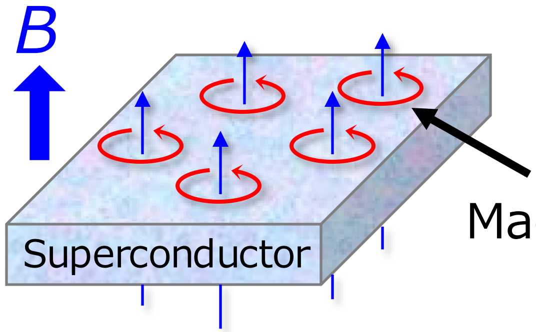
SCHOOL OF SCIENCE
THE UNIVERSITY OF TOKYO

Kento Sasaki

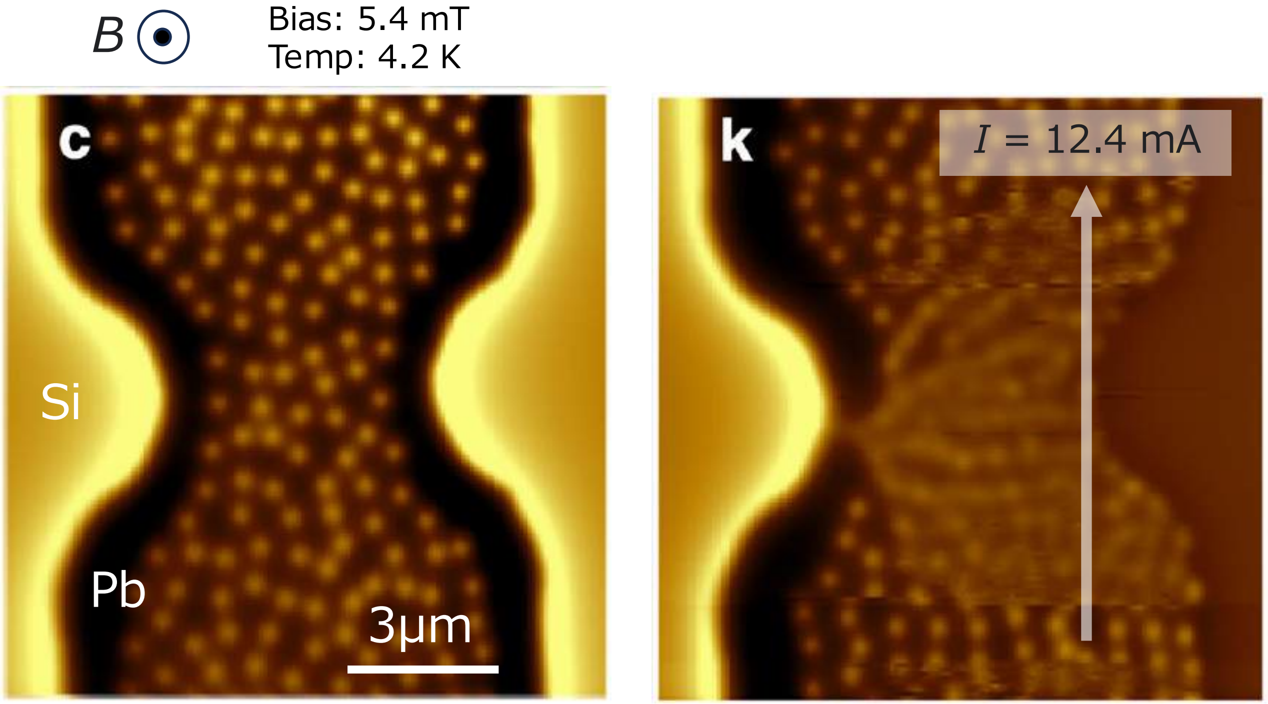
Department of Physics, The University of Tokyo

Contents

Visualization of superconducting vortices



Magnetic flux quantum
Φ_0 = 2.068 fWb



Vortices in Pb wire (Scanning SQUID)

Weizmann Institute / Zeldov group
L. Embon *et al.*, Nat. Comm. **8**, 85 (2017).

Superconducting vortices

- ✓ Fundamental
- ✓ Reproducible

Influences on IV characteristic

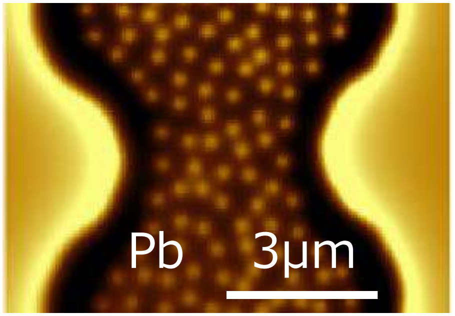
- ✓ Resistance M. Tinkham *"introduction to superconductivity"* (1973).
- ✓ Diode effect A. Gutfreund *et al.*, **14**, 1630 (2023).

Various imaging techniques

Other techniques are found in a review on conventional methods: S. J. Bending, Adv. Phys. **48,** 449 (1999).

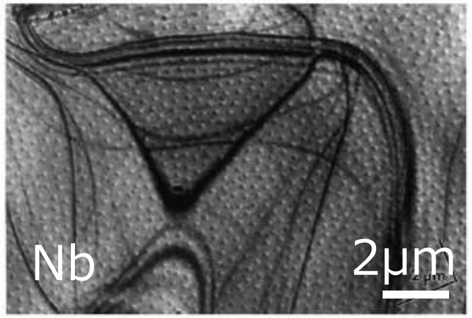
High resolution & Quantitative

Scanning SQUID



L. Embon *et al.*,
Nat. Comm. **8**, 85 (2017).

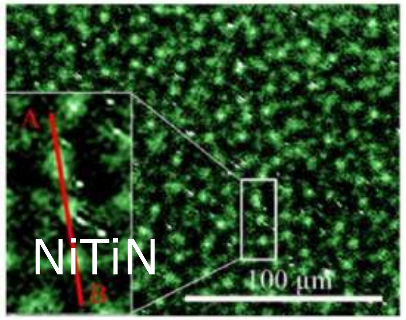
Electron microscope



K. Harada *et al.*,
Nature **360,** 51 (1992).

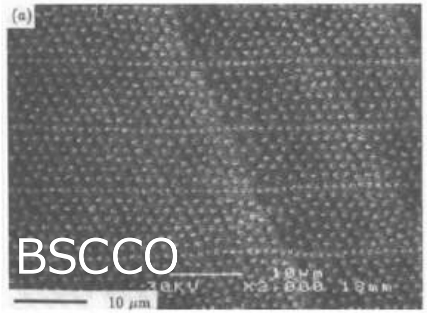
Wide-field

Magneto-optical imaging



Y. Tsuchiya *et al.*
Phys. C. Supercond. **470,** 1123 (2010).

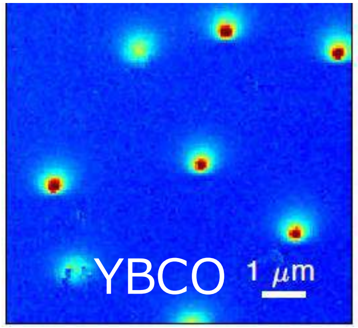
Bitter decoration



I. V. Grigorieva,
Supercond. Sci. Technol. **7,** 161 (1994).

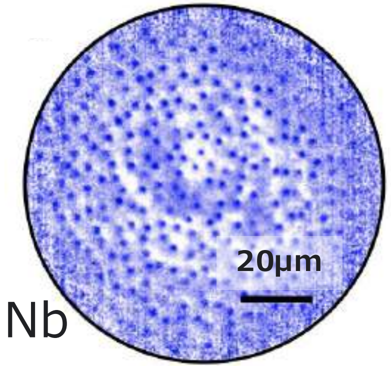
Diamond quantum sensors

Quantitative & High resolution or Wide-field/Versatile



Scanning type

V. Acosta *et al.*
J. Super. Nov. Magn. **32,** 85 (2018).



Wide-field type

S. E. Lillie *et al.*
Nano Lett. **20,** 1855 (2020).

This presentation

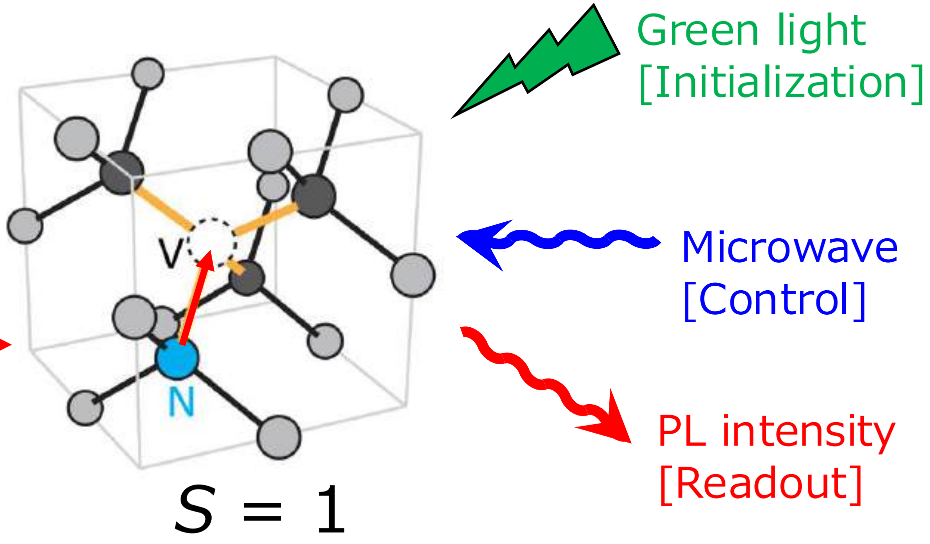
- Principles of diamond sensor
- Our wide-field technique
- Recent results on cuprate thin film

Contents

Color centers in diamond / NV center

More than a hundred···

J. E. Shigley and C. M. Breeding, Gems & Gemology **42**, 107 (2013).



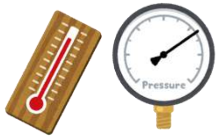
Nitrogen-vacancy (NV) center

- ✓ Electron spin S = 1
- ✓ Long spin lifetime even at RT (~1ms)
- ✓ Optical / Microwave control

Zeeman splitting

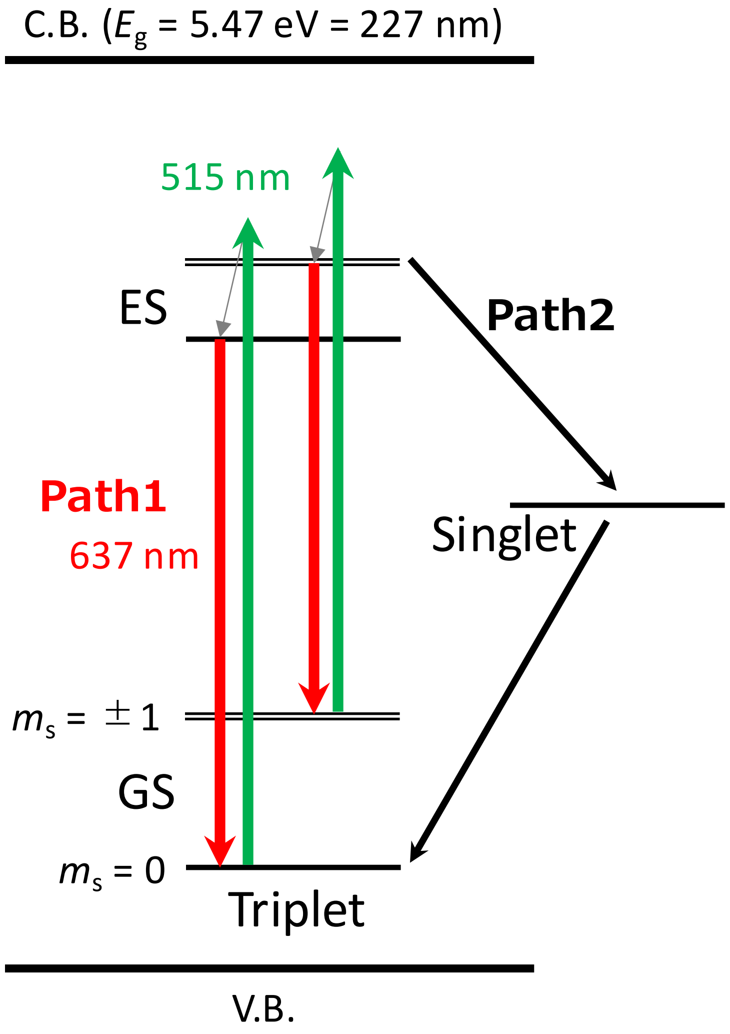
J. M. Taylor *et al.*, Nat. Phys. **4**, 810 (2008).

Lattice expansion



V. M. Acosta *et al.*, Phys. Rev. Lett. **104**, 070801 (2011).

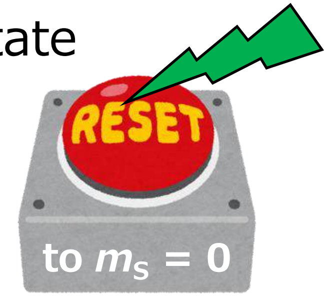
Optical transitions



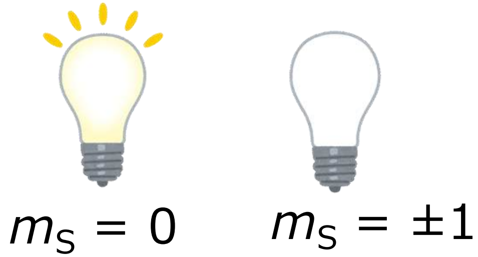
Path1: Photoluminescence, spin conservation

Path2: No luminescence, $m_S = \pm 1 \rightarrow m_S = 0$

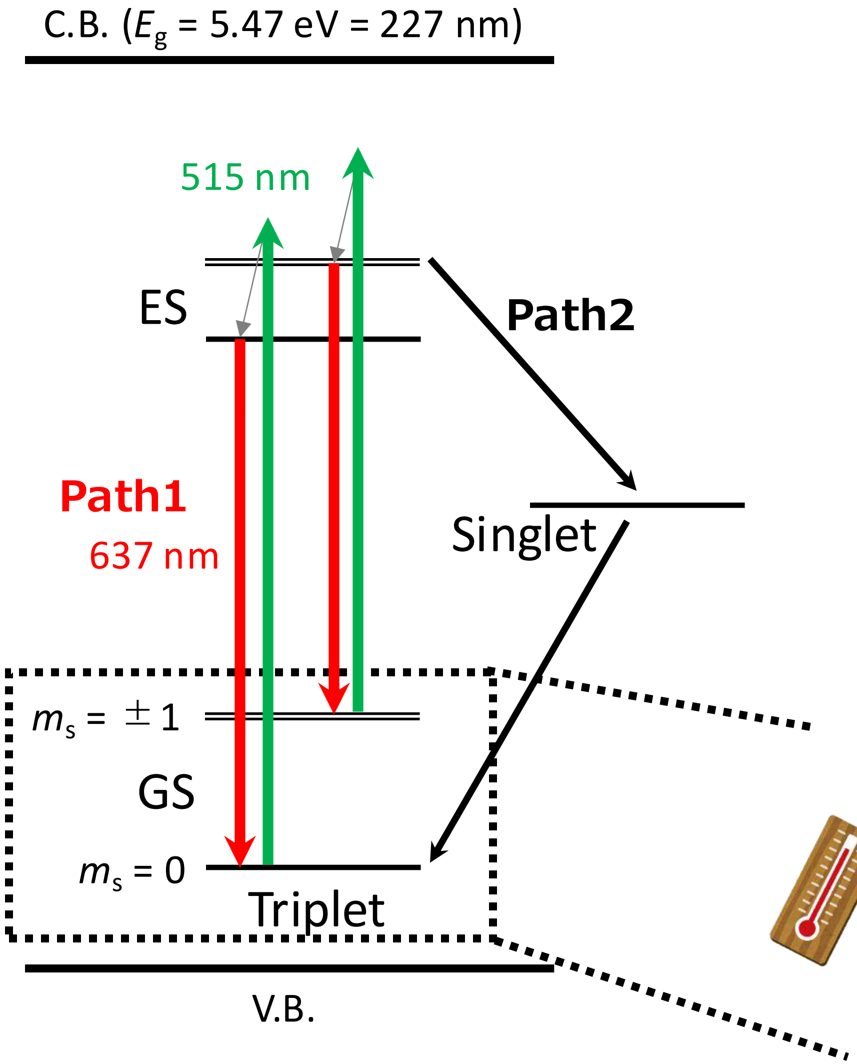
✓ Continuous excitation polarizes the NV center to $m_S = 0$ state
→ **Initialization**

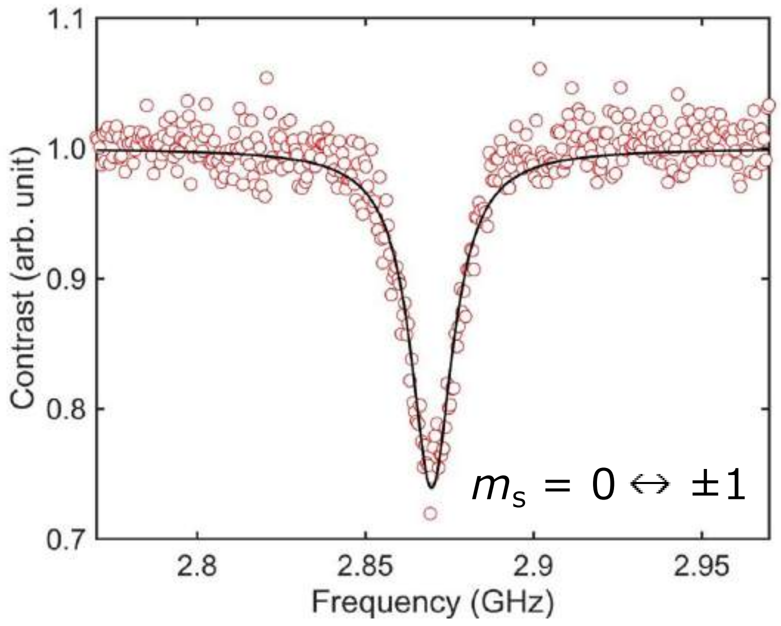


✓ $m_S = \pm 1$ state has less intensity due to the non-radiative transition
→ **Readout**

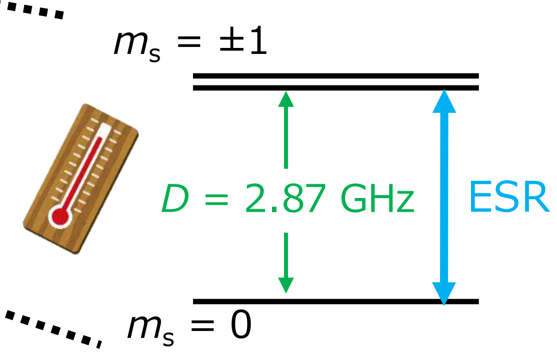


Optically detected magnetic resonance (ODMR)





ODMR spectrum

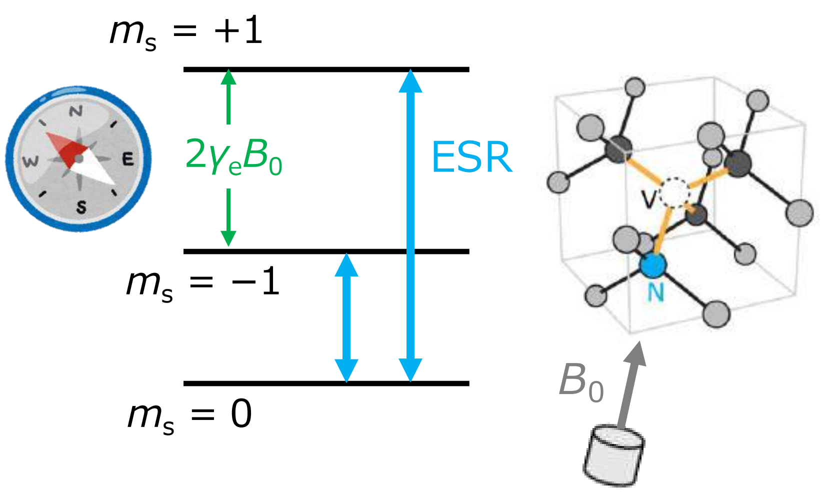


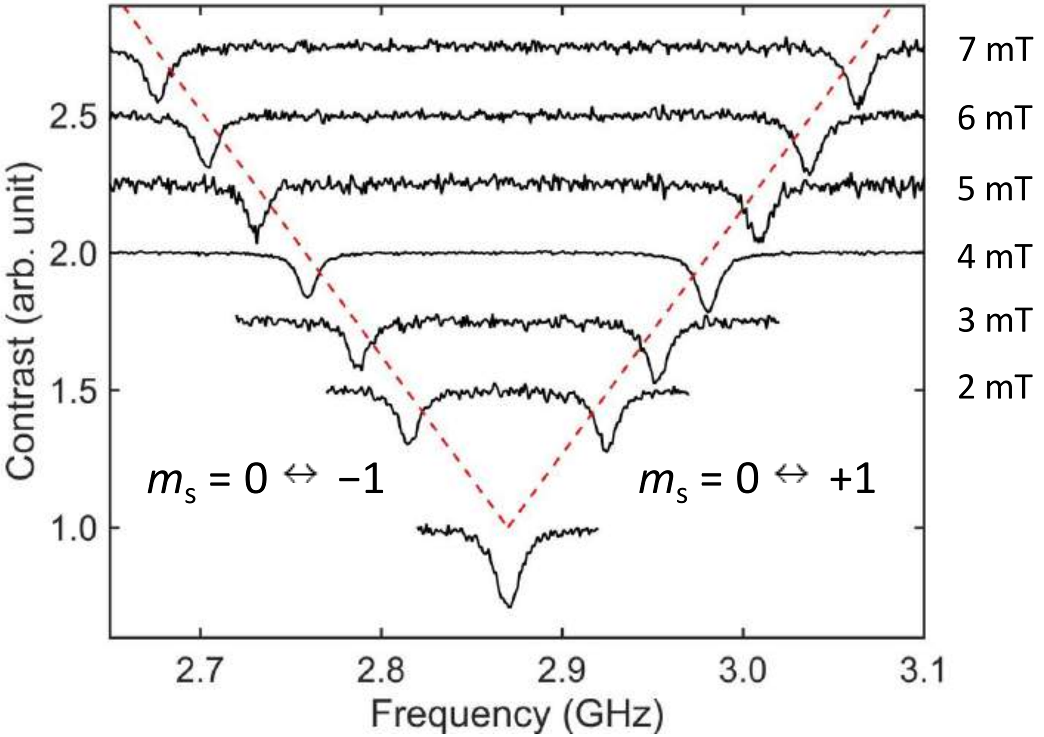
Zero-field splitting
(dipole interaction)

$$\hat{H} = D\hat{S}_z^2$$

dD/dT ~ -74 kHz/Kelvin

Magnetic field dependence





Zeeman splitting

$$\hat{H} = D\hat{S}_z^2 + \gamma_e B_0 \hat{S}_z$$

Magnetic field dependence

Quantitative!

Gyromagnetic ratio γ_e = 28.035 ± 0.002 GHz/T

Free electron + 0.03% ± 0.01%

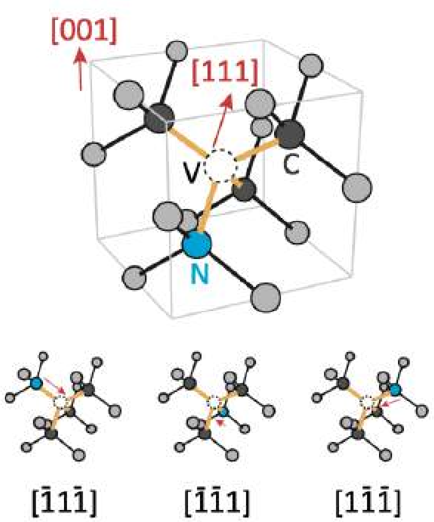
Felton *et al.*, Phys. Rev. B **79**, 075203 (2009)

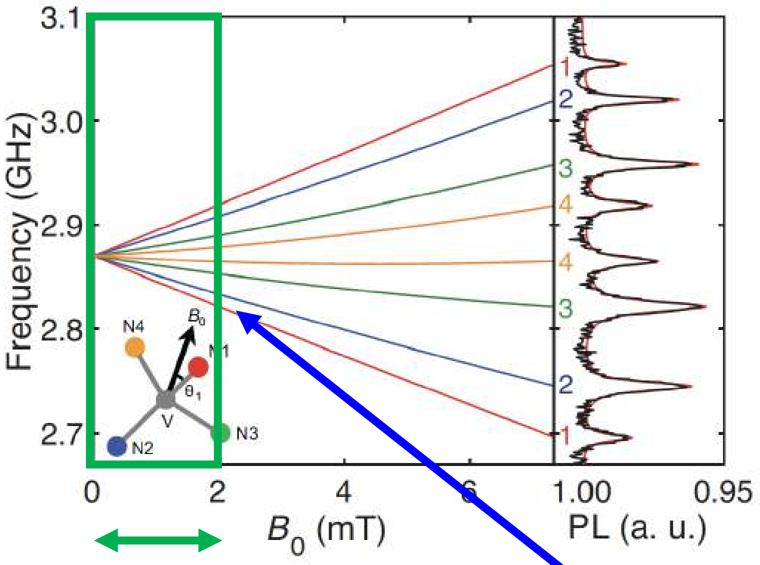
NV ensembles (Hatano group at Science Tokyo)

Spectral overlap is avoided with perfectly aligned NV ensemble

→ Magnetic field can be quantitatively estimated at low magnetic fields

Conventional NV ensemble





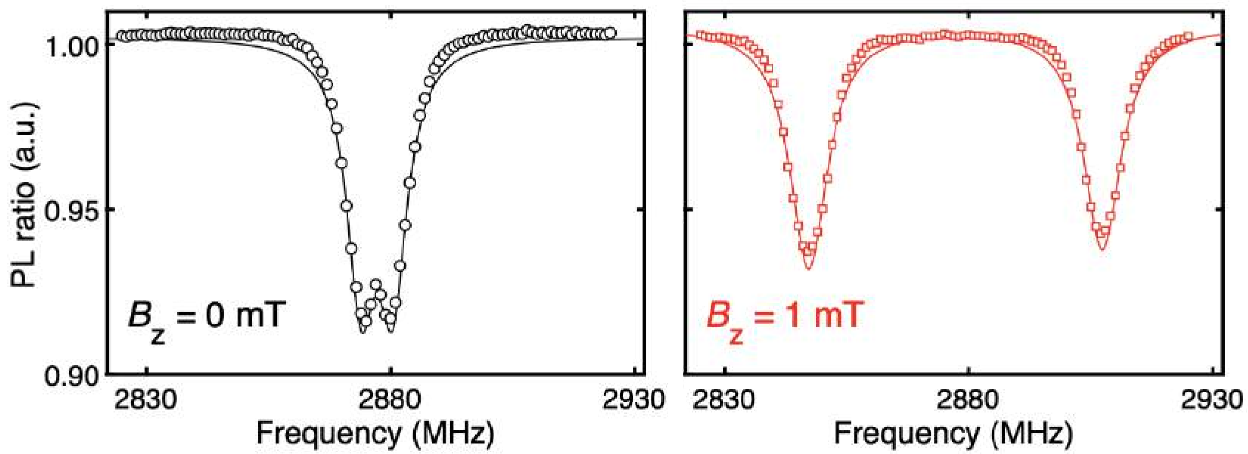
Vortex density < 1 μm²
(< 2 mT)

× Spectral overlap

Our case: Perfectly aligned NV ensemble

CVD growth on (111) substrate

Miyazaki APL 105, 261601 (2014); Tahara APL 107, 193110 (2015); Ishiwata APL 111, 043103 (2017); Ozawa APEX 10, 045501 (2017); Tsuji Diam. Relat. Mater. 123, 108840 (2022).



○ Avoiding spectral overlap

Contents

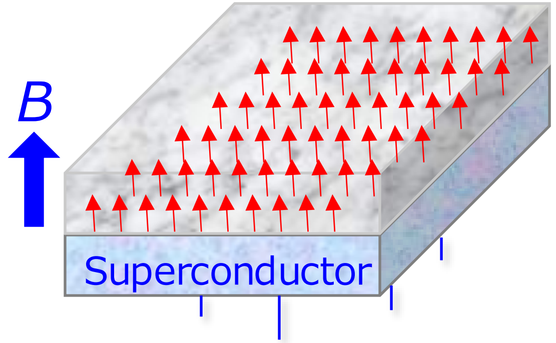
- Background
    - Vortex imaging techniques
- Diamond quantum sensing
    - Color centers in diamond
    - Principles
- **Our techniques and recent results**
    - **Experimental setup**
    - Quantitative visualization of vortices
- Summary & Outlook
- Acknowledgement

S. Nishimura, KS et al., Appl. Phys. Lett. **123**, 112603 (2023).

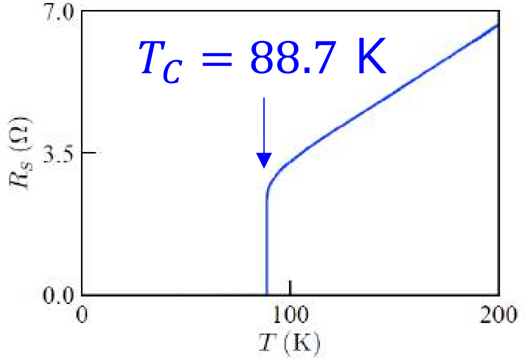
Experimental setup

S. Nishimura (D2)

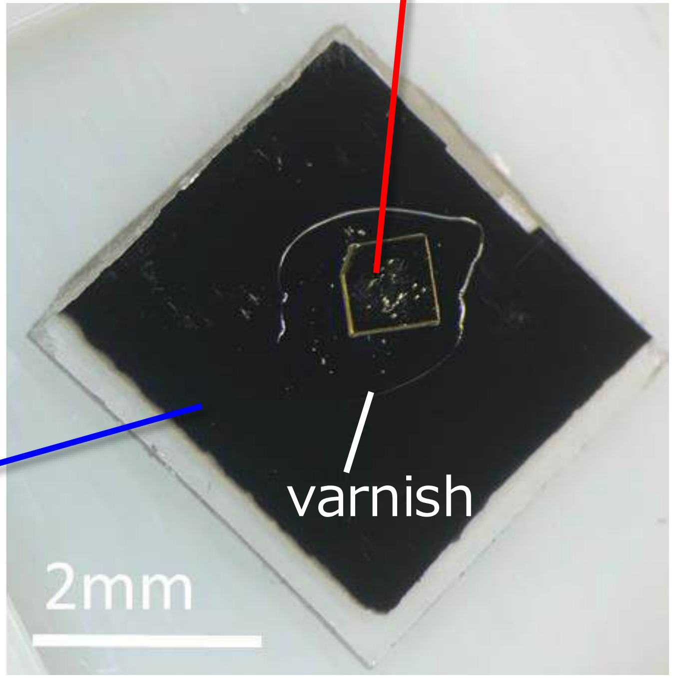
NV centers on diamond surface



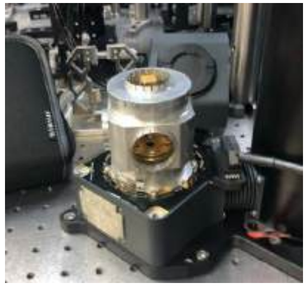
YBCO thin film (Ceraco)
thickness 250nm

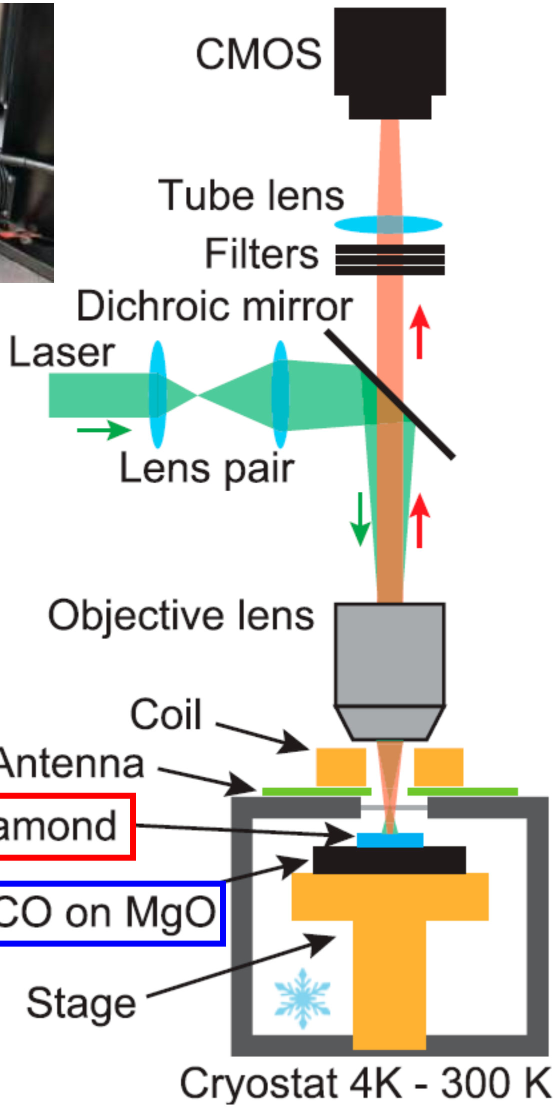


Perfectly aligned NV centers along [111] direction on (111) substrate



Optical cryostat

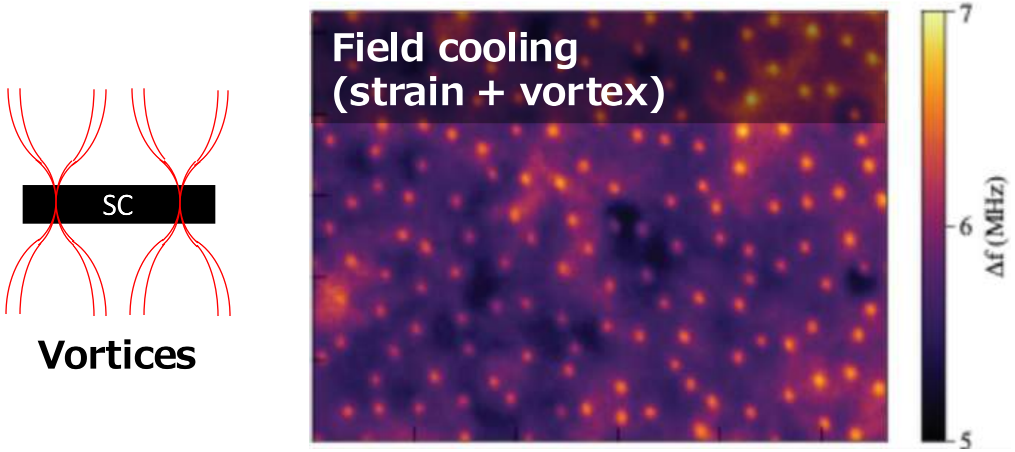


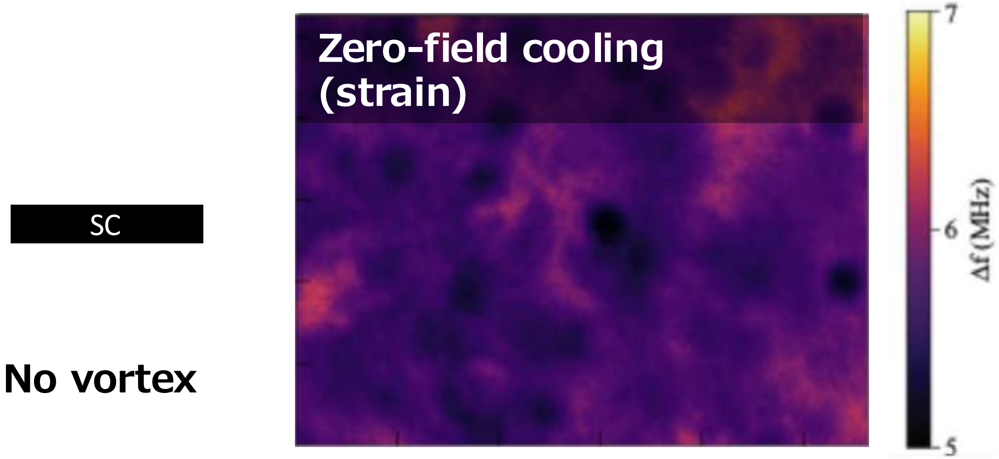


S. Nishimura, KS et al., Appl. Phys. Lett. **123**, 112603 (2023).

Quantitative analysis of stray field strength

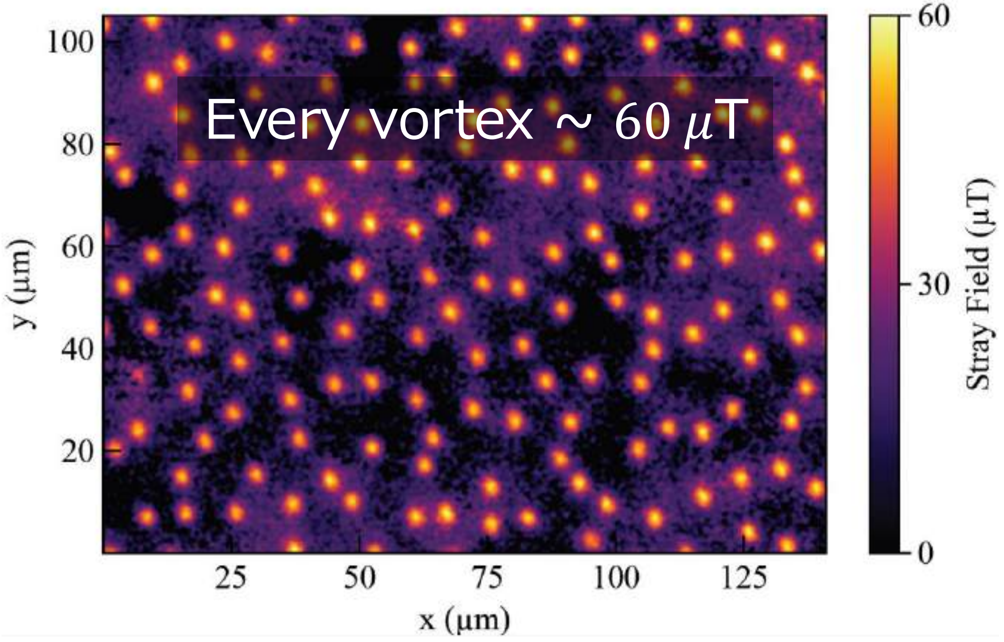
Obtain Δf map at ZFC and FC





Position-dependent strain subtracted

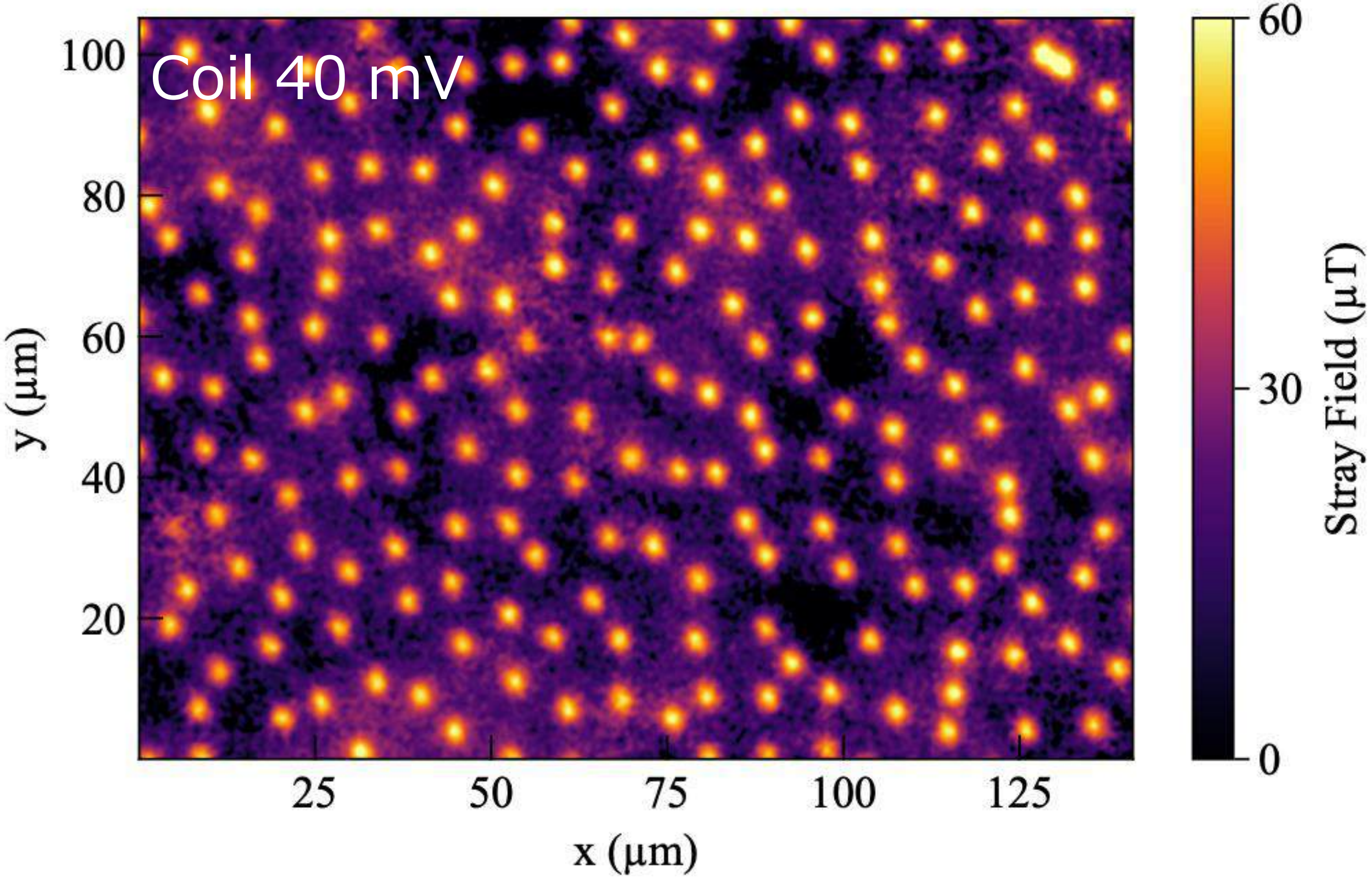
$$B_z = \sqrt{(\Delta f/2)^2 - E^2}/\gamma_e$$



S. Nishimura, KS et al., Appl. Phys. Lett. **123**, 112603 (2023).

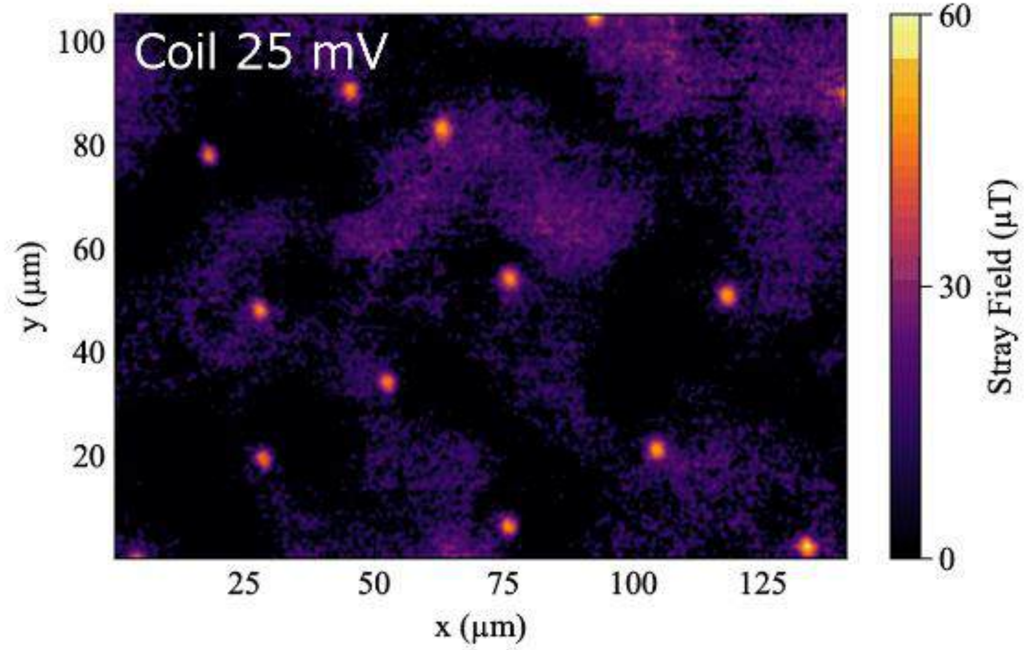
Visualization of vortices

Cool down in *B*-field from above T_C to below T_C.

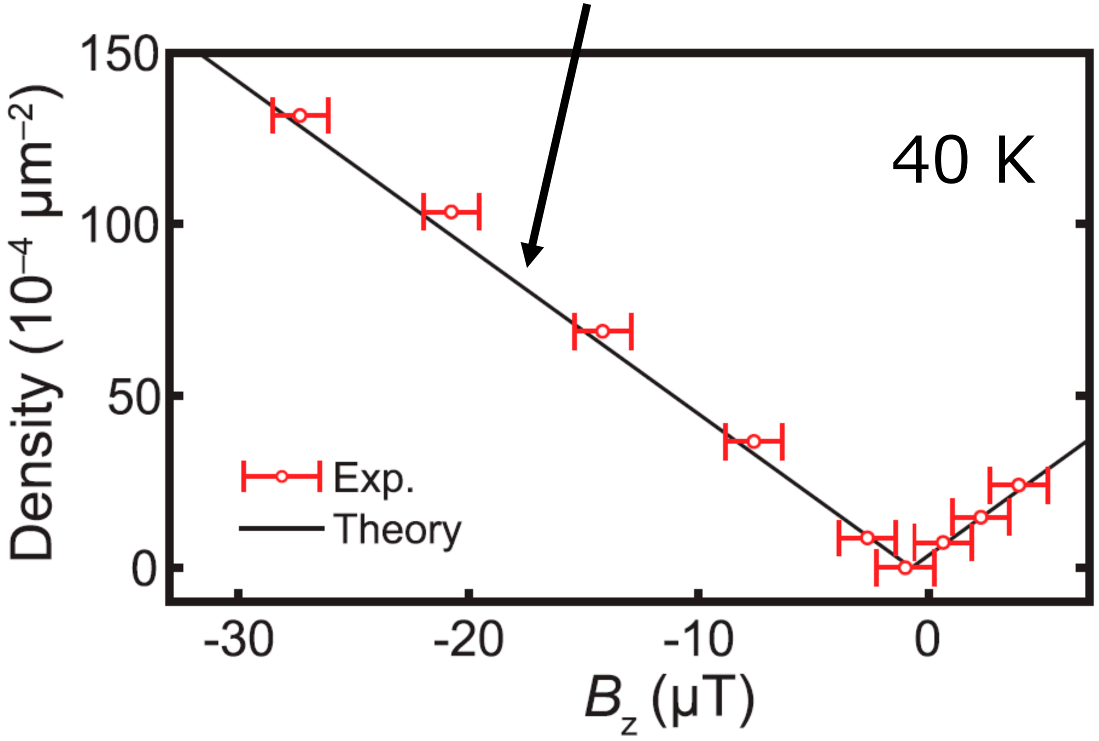


S. Nishimura, KS et al., Appl. Phys. Lett. **123**, 112603 (2023).

Vortex density ∝ Magnetic field

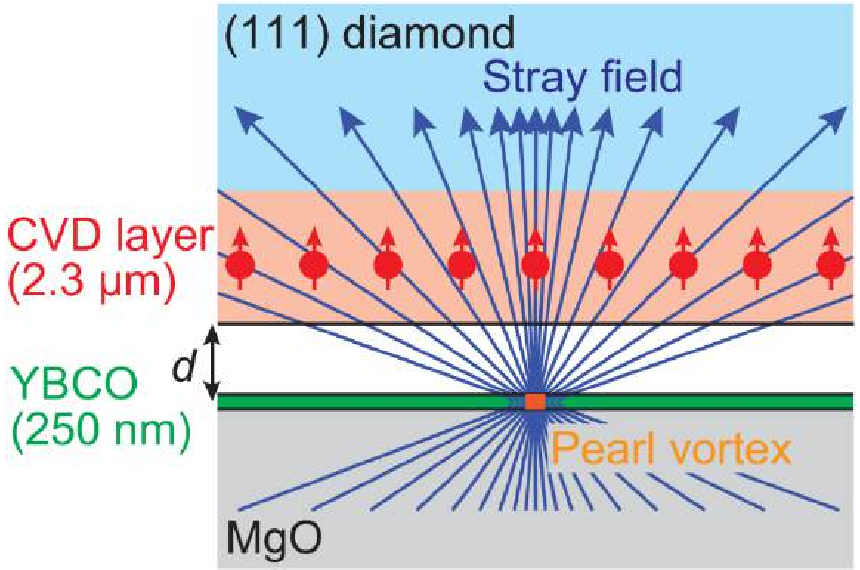


Magnetic flux quantum
Φ_0 = 2.068 fWb

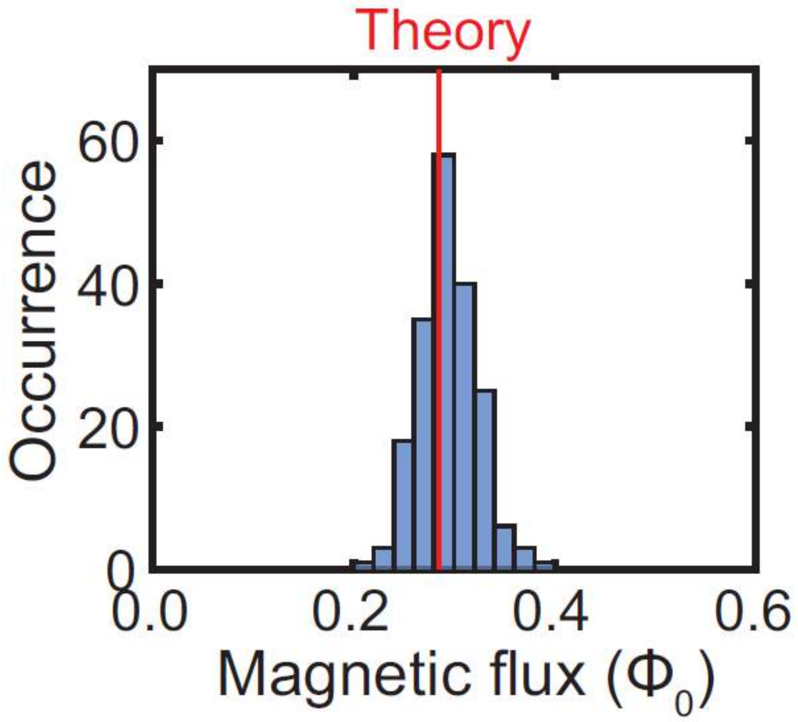


S. Nishimura, KS et al., Appl. Phys. Lett. **123**, 112603 (2023).

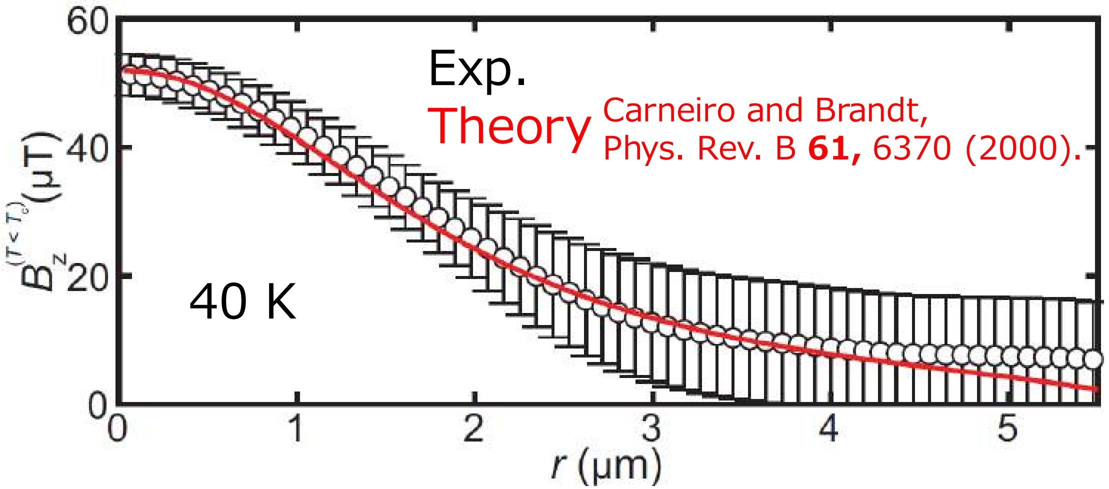
Estimation of quantitativity



Within ±10% accuracy



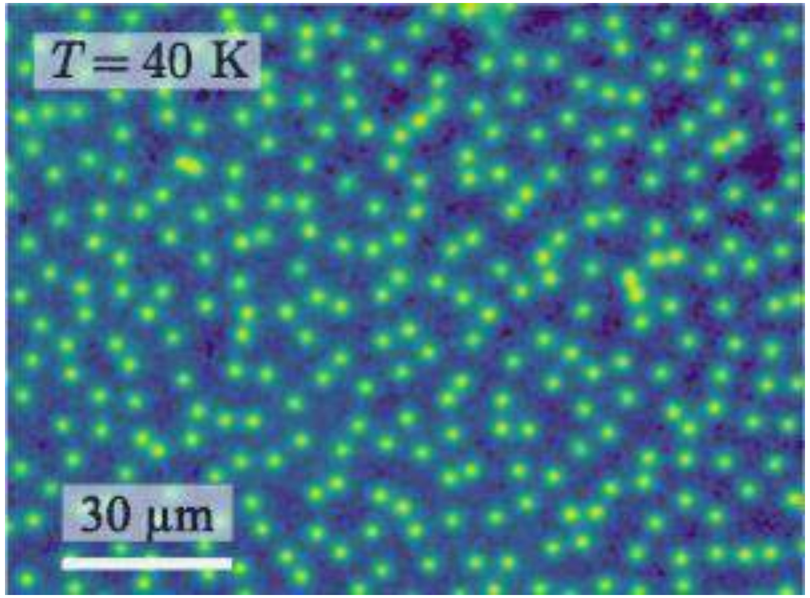
*190 vortices analyzed

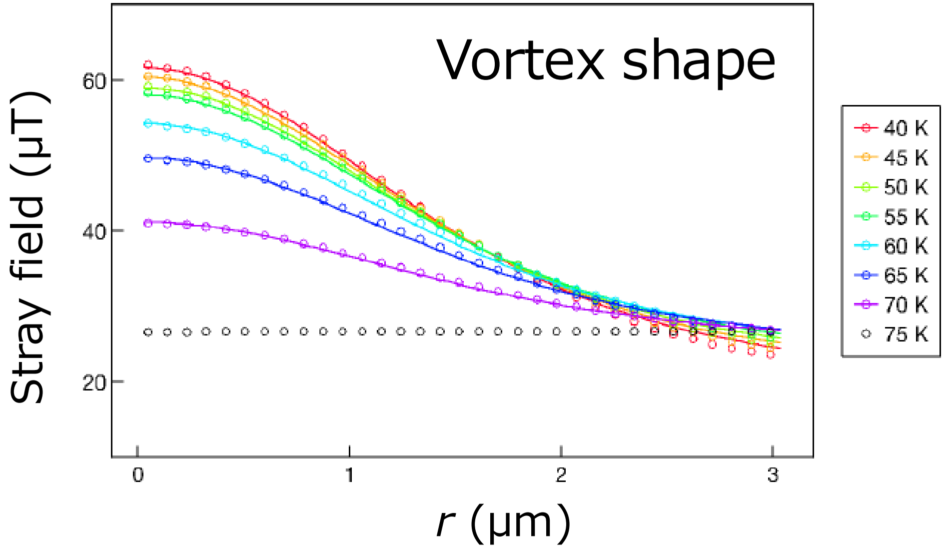


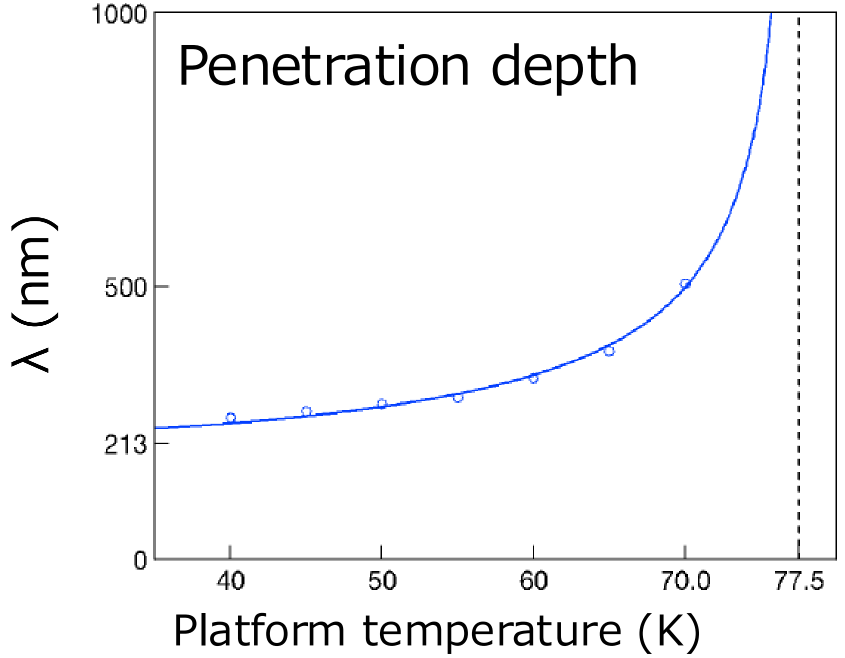
Technique to address
half-integer quantization

M. M. Salomaa, and G. E. Volovik, Rev. Mod. Phys. **59**, 533 (1987)
G. E. Volovik, J. Exp. Theor. Phys. Lett. **70**, 792 (1999)

Temperature dependence







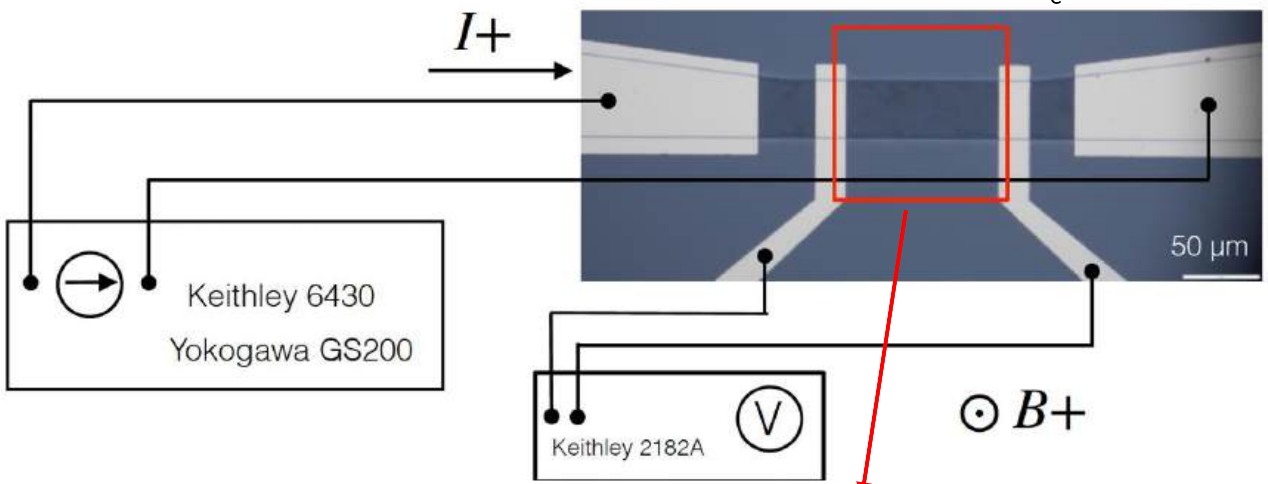
$$\lambda(T) = \left(\frac{m}{\mu_0 n_s e^2}\right)^{\frac{1}{2}} = \frac{\lambda(0)}{\sqrt{1-(T/T_c')^2}}$$

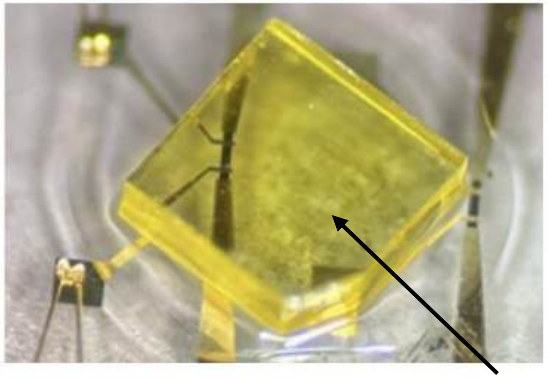
M. Prohammer and J. P. Carbott, Phys. Rev. B **43**, 5370 (1991).

S. Nishimura, KS et al., *in preparation*

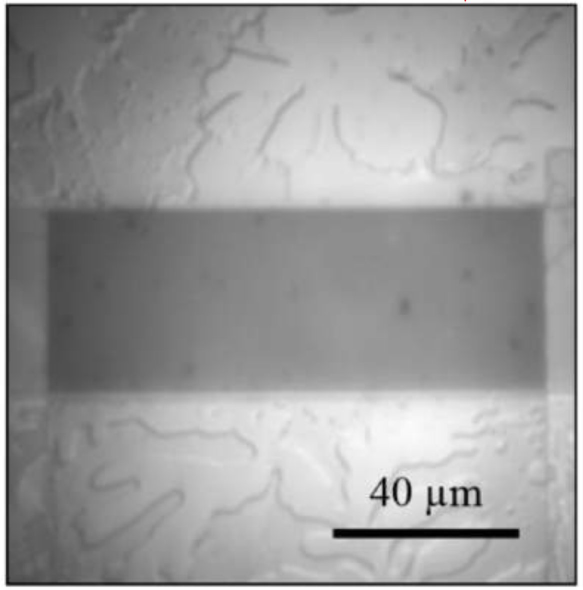
Imaging of YBCO wire

J_c > 1.5 MA/cm^2 @ 77K
→ I_c ~ 150 mA

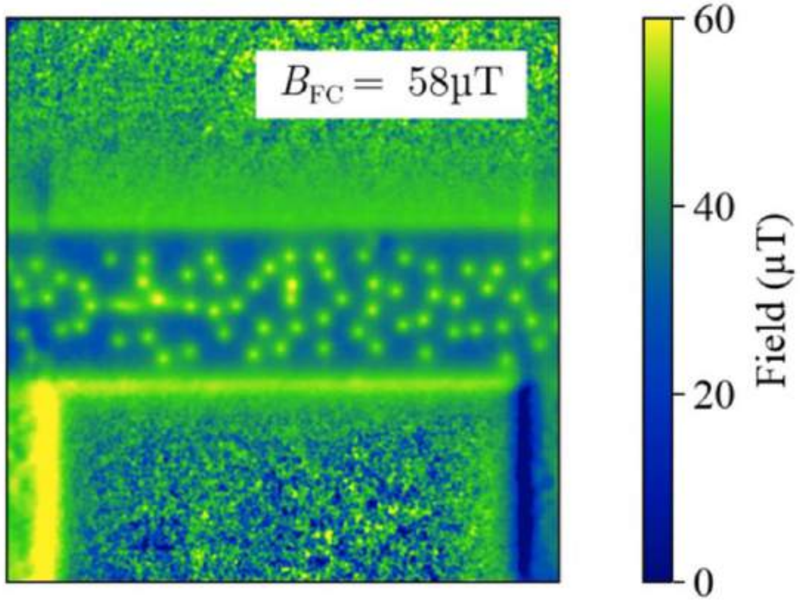




Diamond

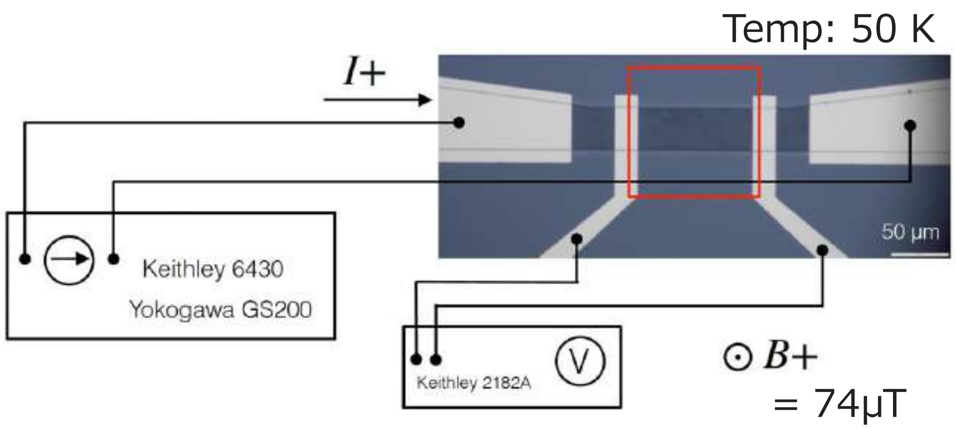


Optical image

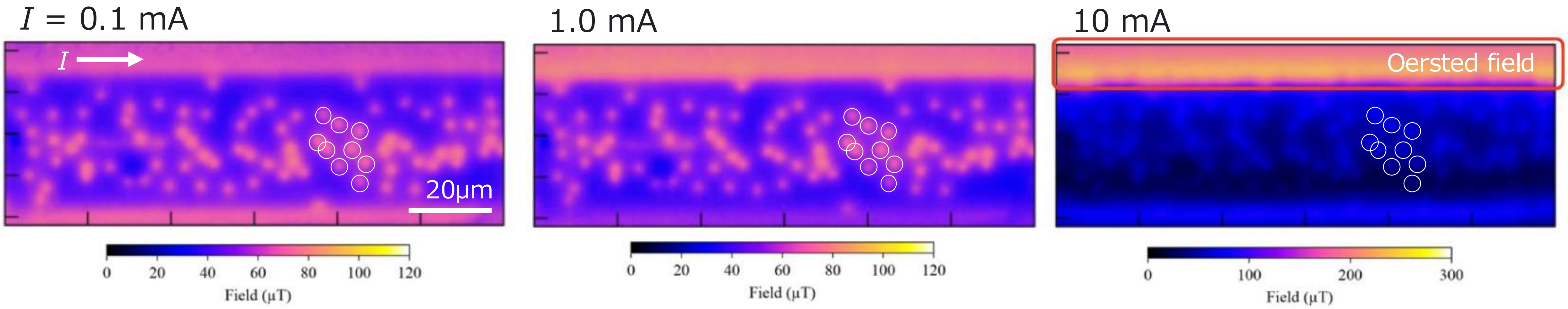


Magnetic image

Current bias after field cooling



We observed vortex pinning!



Summary & Outlook

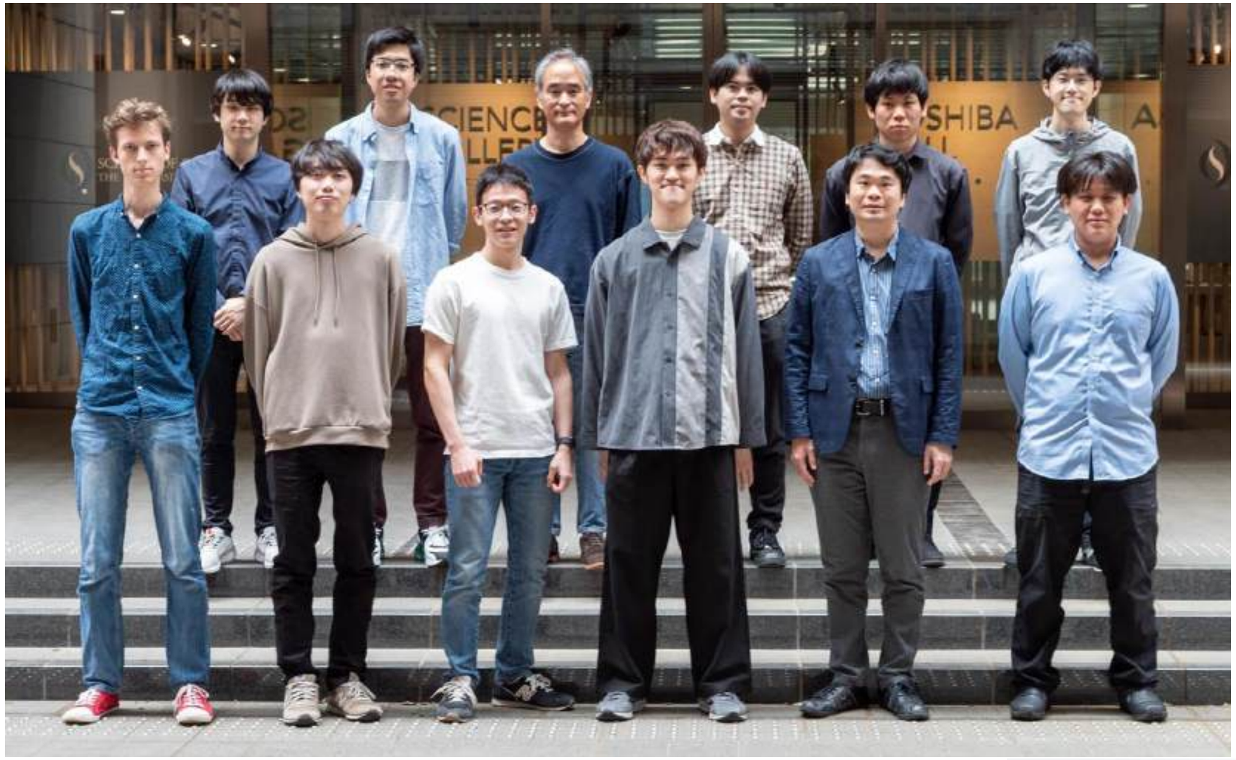
Summary

- Perfectlly aligned NV ensembles successfully visualizes the superconducting vortices
- Statistical analysis on 190 vortices supports 10% accuracy of our technique
- We could observe vortex pinning in YBCO wire at 50 K

Outlook

- Apply this technique on various matrials & device structures
  > Field cooling under current bias, Temperature dependence, etc.
  > Josephson junction
  > Pristine superconductors (ex. NbN single crystal)
  > Candidates of topological superconductors (ex. FeSe)
- Enhance precision, accuracy, FOV
  > Diamond sample (^{12}C enrichment, low strain/less NV centers, high quality substrate…)
  > Camera (Large and low noise CMOS sensor) & Coil (homogeneity, resolution, stability)

Acknowledgement



Group photo (2024)

Staff:
K. Kobayashi (PI)
<u>K. Sasaki</u>

D3: K. Ogawa
M. Tsukamoto

D2: Y. Nakamura
S. Nishimura

ODMR Meas.
Analysis

D1: H. Gu
K. Yamamoto

M2: T. Kobayashi
R. Suda

M1: R. Harada

Alumni: D. Sasaki

Collaborators
Sci. Tokyo : **T. Tsuji**, T. Iwasaki, M. Hatano

Diamond Growth

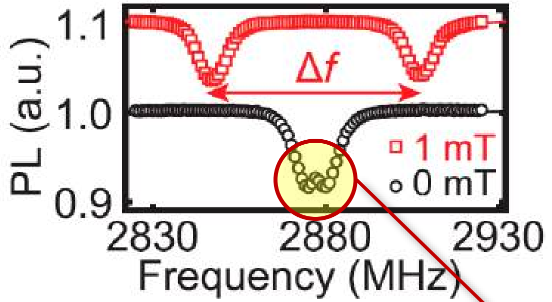
JSPS(KAKEN), MEXT(ARIM, WPI-MANA, Q-LEAP, FoPM), JST CREST, Kondo Memorial Foundation

Appendix

Optical power dependence

S. Itoh, KS et al., J. Phys. Soc. Jpn. **92**, 084701 (2023).
Y.-H. Yu et al., Phys. Rev. Appl. **21**, 044051 (2024).

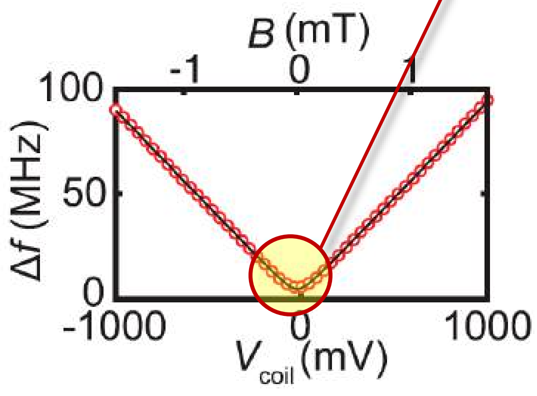
1. Obtain ODMR spectra



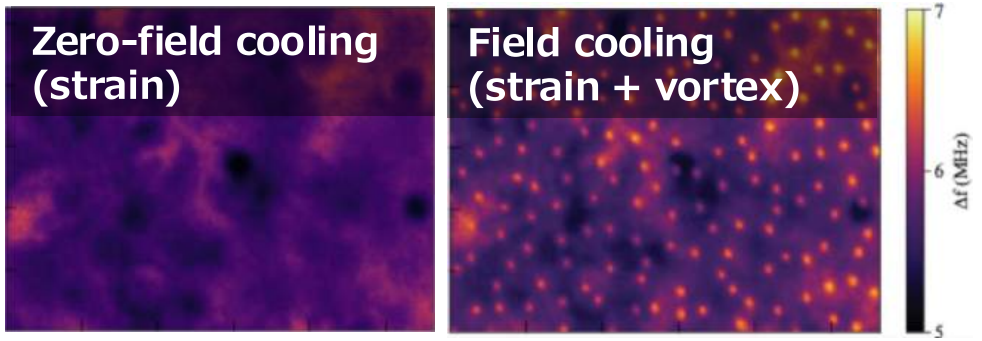
Strain

$$\mathcal{H} = DS_z^2 + \gamma B_z S_z + E\,(S_x^2 - S_y^2)$$

2. *B*-field calibration



3. Obtain Δf map at ZFC and FC



4. Position-dependent strain subtracted

$$B_z = \sqrt{(\Delta f/2)^2 - E^2}/\gamma$$

5. B field calculated at each pixel