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Quantum sensing with superconducting flux qubits

Hiraku Toida

NTT Basic Research Laboratories, Superconducting Quantum Circuits Research Group

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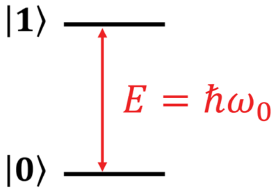
Quantum Sensing

1. Use of two-level nature

Energy levels are sensitive to external fields

- Sensitivity ∝ (# of qubits)$^{1/2}$

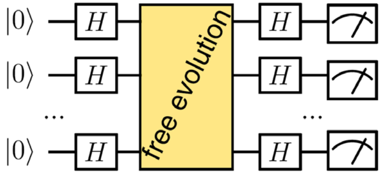


2. Use of quantum coherence

Phase accumulation during free evolution of superposition states

- Filter functions can be applied. (Frequency selectivity, DC or AC)
- Sensitivity ∝ (# of qubits)$^{1/2}$

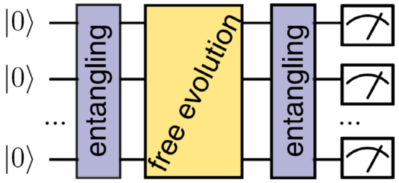
$$\frac{1}{\sqrt{2}}\left(|g\rangle + e^{-i\delta\omega t}|e\rangle\right)$$



3. Use of quantum entanglement

Phase accumulation during free evolution of entangled states

- Sensitivity ∝ (# of qubits)^{1} (Heisenberg limit)



C. L. Degan et al., Reviews of Modern Physics **89**, 035002 (2017)

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Superconducting flux qubit

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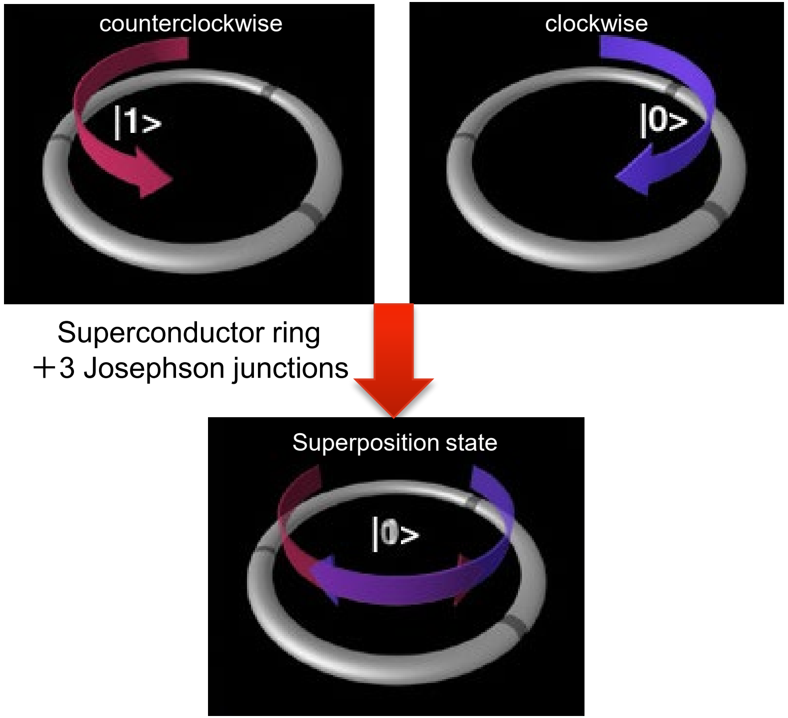
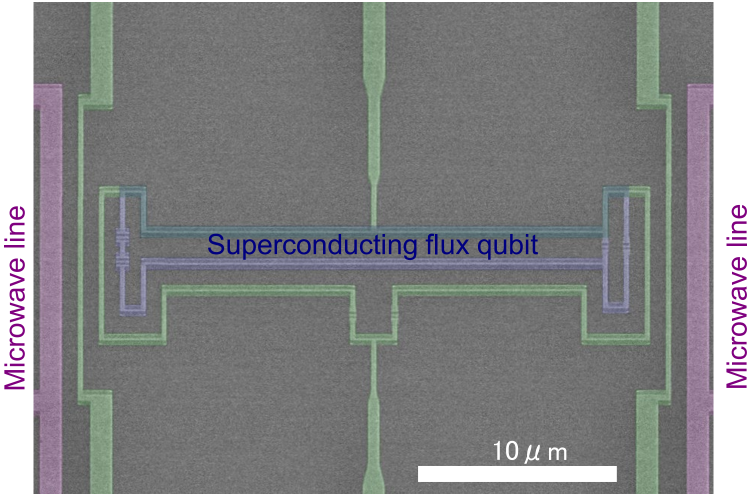
Circulating current in superconducting flux qubit



Mooij *et al.*, *Science* **285,** 1036 (1999)

SEM picture of superconducting flux qubit



Interaction between the circulating current and magnetic field is large.

→ Sensitive magnetic field detection is possible.

Superconducting flux qubit

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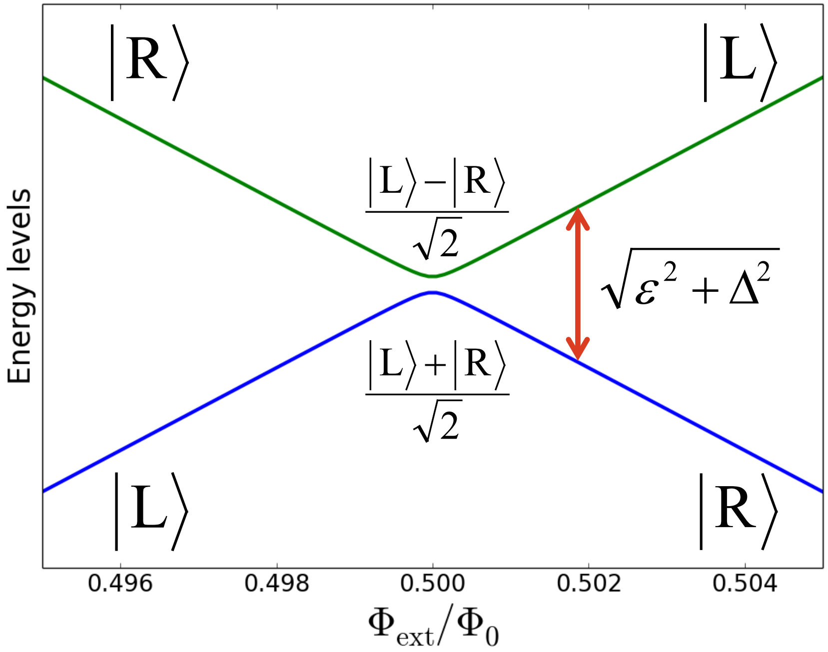

$$\hat{H} = \frac{1}{2}\left(\varepsilon\hat{\sigma}_z + \Delta\hat{\sigma}_x\right) = \frac{\sqrt{\varepsilon^2 + \Delta^2}}{2}\hat{\sigma}'_z$$

Magnetic field dependence

$$\begin{cases} \varepsilon = 2I_p\left(\Phi_{ext} - \Phi_0/2\right) \\ I_p \text{ : Persistent current (const.)} \\ \Delta \text{ : Tunnel energy (const.)} \\ \hat{\sigma}_z, \hat{\sigma}_x \text{ : Pauli matrix} \end{cases}$$

- The energy eigenstate is liner combination of |L⟩ and |R⟩.
- Transition frequency has dependence on the magnetic flux → Sensitive to magnetic field.
- Large persistent current I_p is desired. (I_p ~ 300 nA in design)

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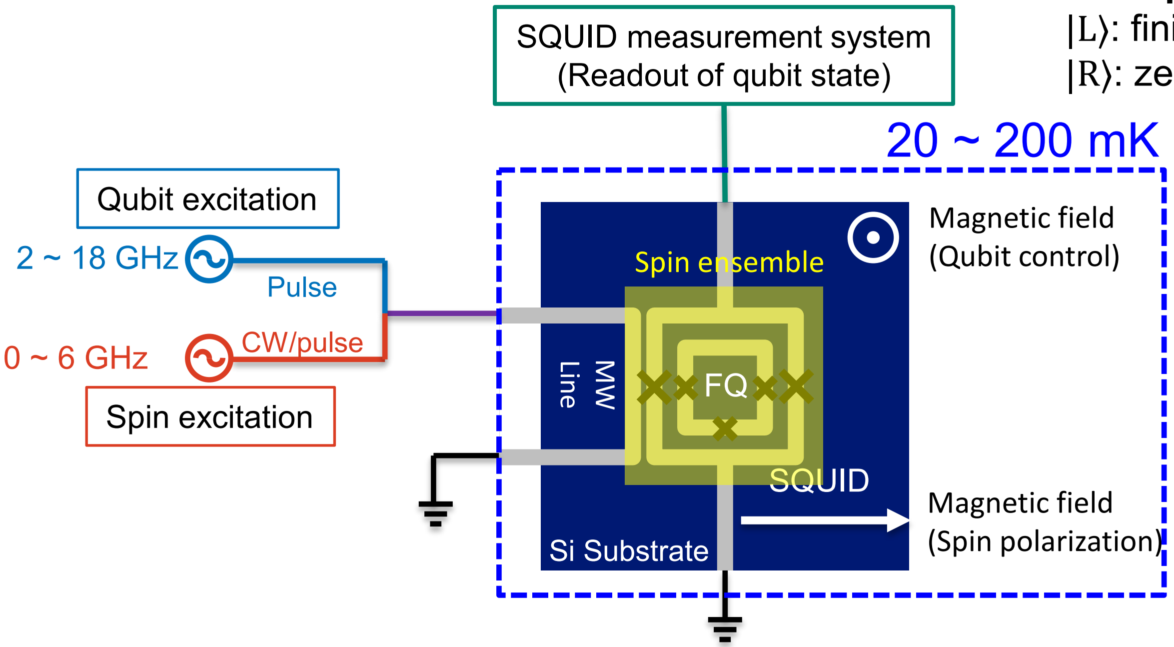
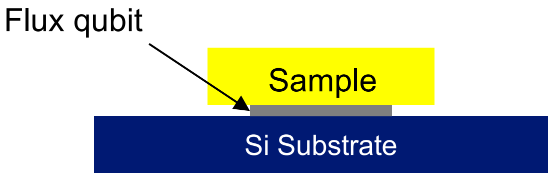
Spin detection using a flux qubit

Example:
|L⟩: finite voltage output
|R⟩: zero voltage output

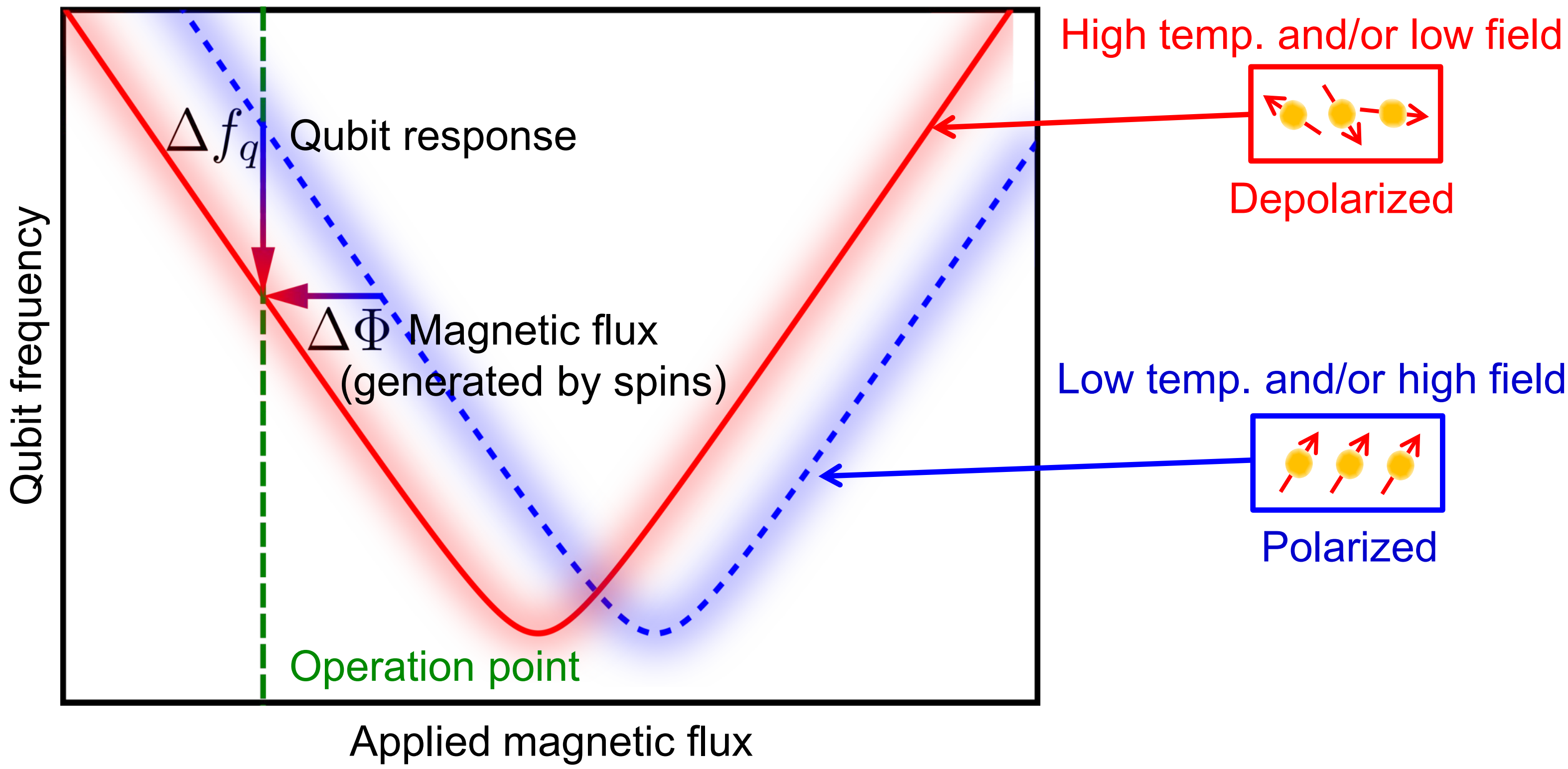




Cross section

In-plane field and temperature dependence → Magnetometry
In-plane field and frequency dependence → Electron spin resonance

Spin detection using a flux qubit



Spin polarization is converted to qubit frequency

Toida *et al.*, 2019 Commun. Phys.

Electron spin detection using SC magnetometers

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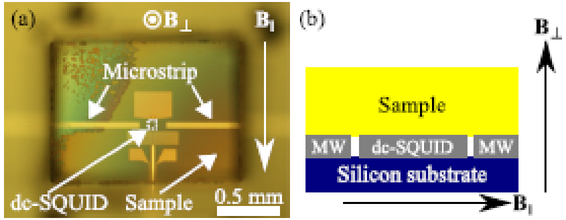
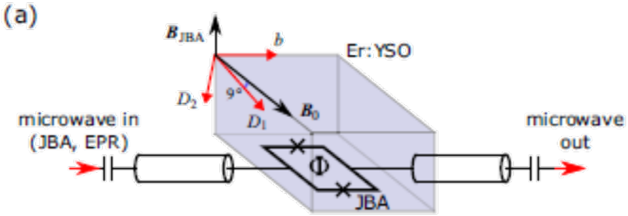
SQUID



10^6 spins/√Hz

Toida *et al*, 2016 APL

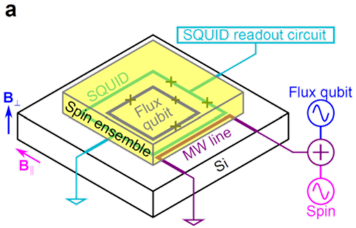
Josephson bifurcation amplifier (JBA)



Fast readout → 15,000 spins/√Hz

Budoyo *et al*, 2018 PRMaterials

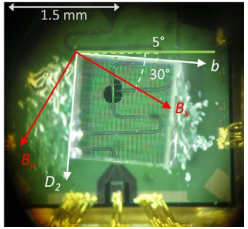
Flux qubit (SQUID readout)



Sensitive magnetometer → 400 spins/√Hz

Toida *et al.*, 2019 Commun. Phys.

Flux qubit (JBA readout)

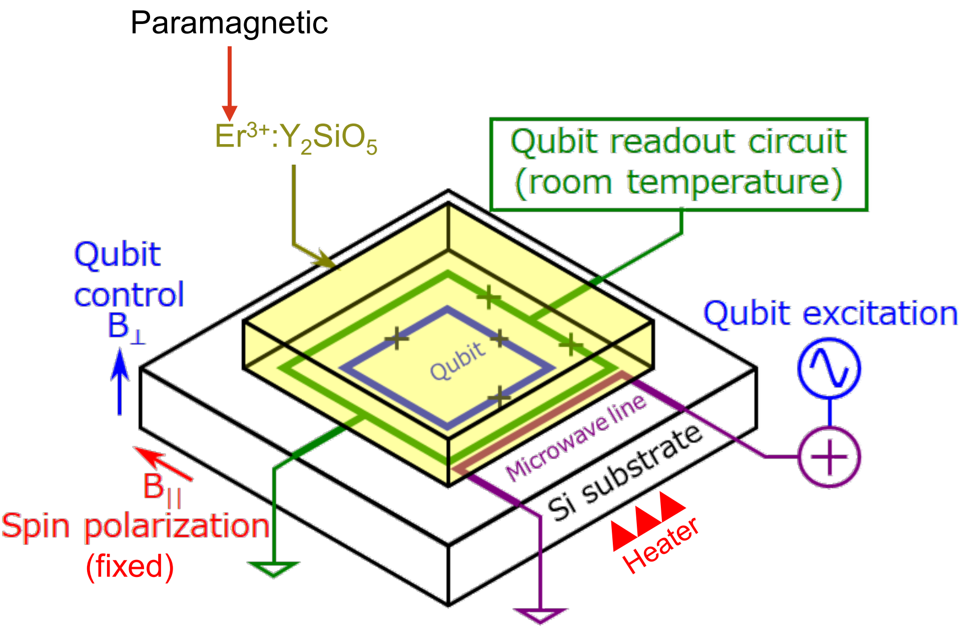


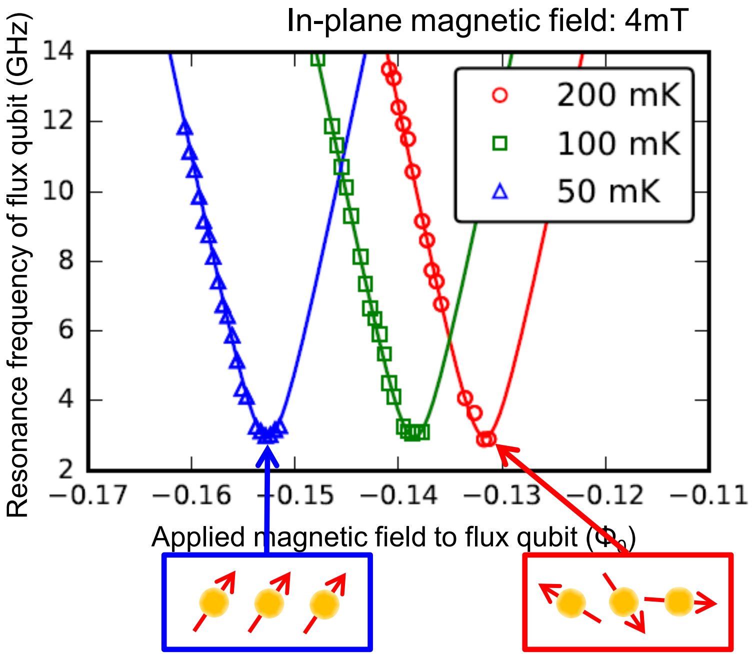
20 spins/√Hz

Budoyo *et al.*, 2020 APL

Sensitive spin detection is realized using SC spin detectors. (Now 12 spins/√Hz)

Spin detection of $Er^{3+}:Y_2SiO_5$

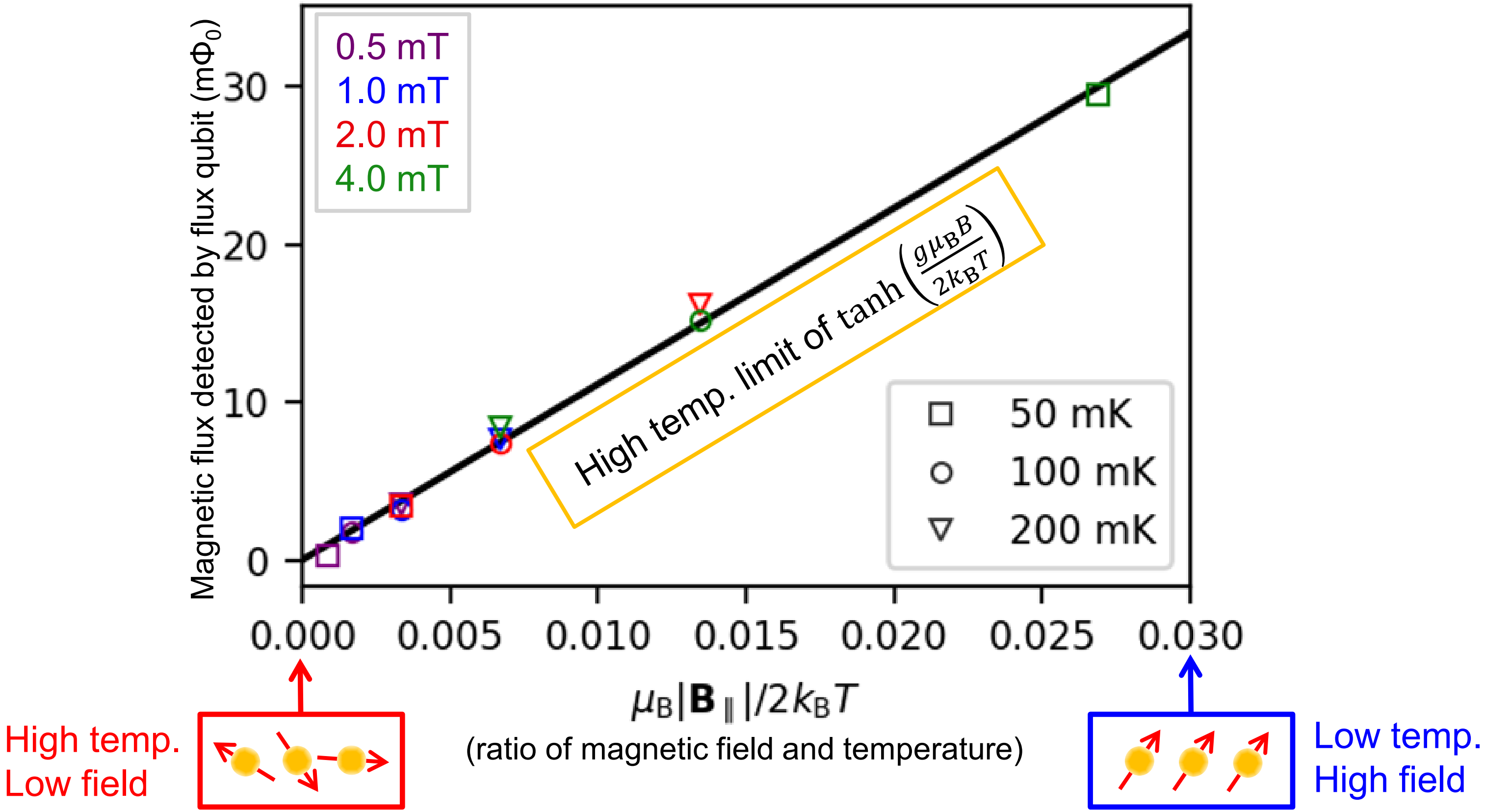




Magnetization from electron spins is detected by a flux qubit

H. Toida *et al*., Commun. Phys., **2**, 33 (2019)

Spin detection of $Er^{3+}:Y_2SiO_5$

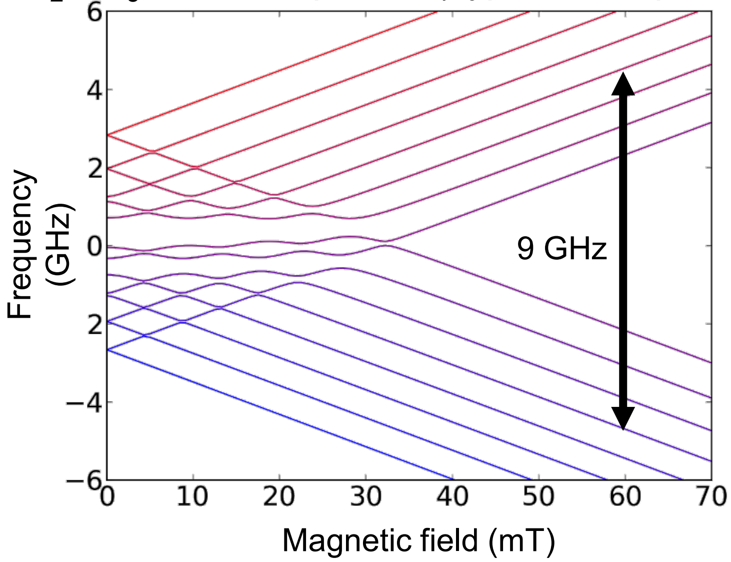


Curie's raw in the high temperature limit is confirmed.

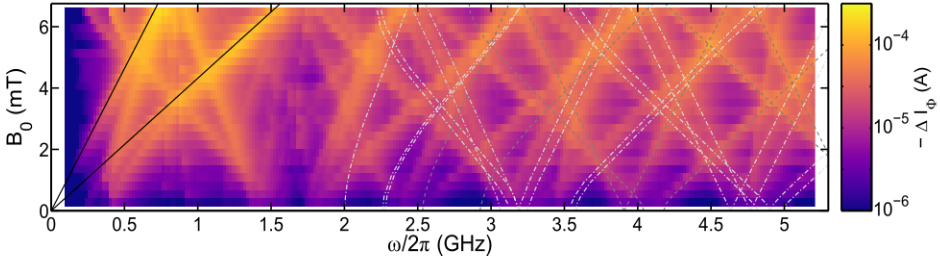
H. Toida *et al*., Commun. Phys., **2**, 33 (2019)

Application to material parameter estimation

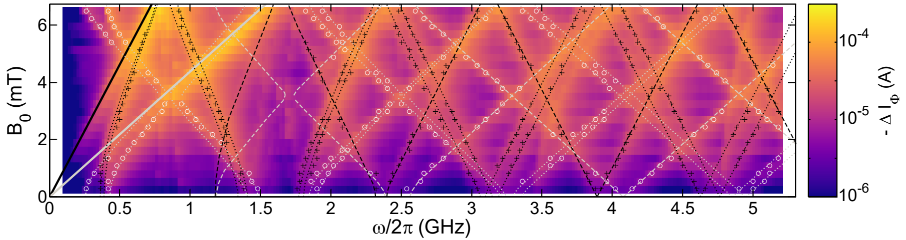
$Er^{3+}:Y_2SiO_5$, nuclear spin 7/2 (hyperfine + quadrupole)



Parameters from X band ESR spectrum



Parameters from our ESR spectrum



Standard ESR spectrometer
→ 0 – 0.3 T, X band ~9 GHz

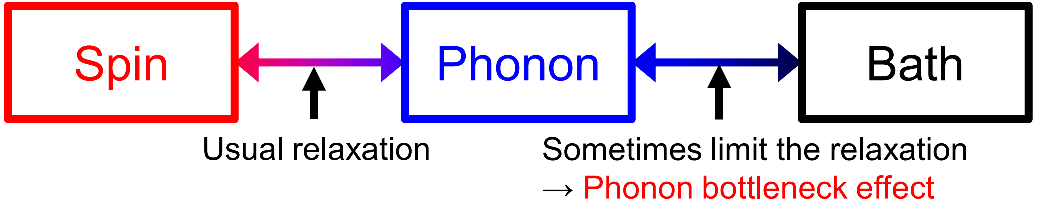
Effect of hyperfine and quadruple interaction is small in the high field region
→ parameter estimation is not trivial

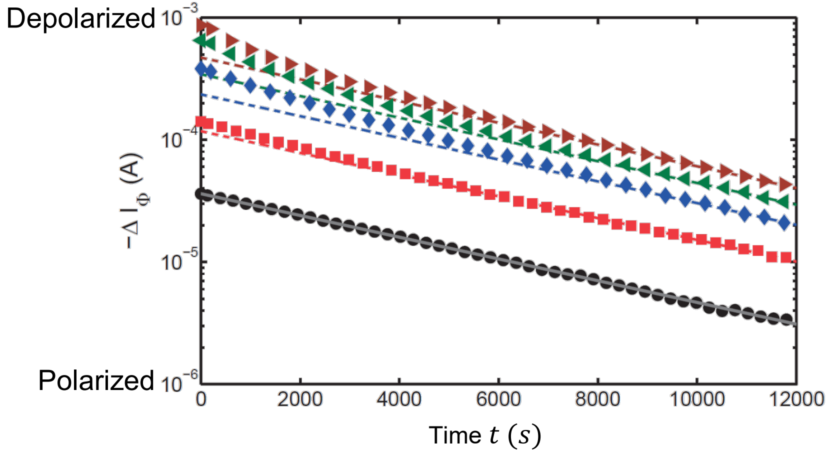
ESR spectrometer using magnetometer
→ 0 - 6.5 mT, 0 - 5.2 GHz

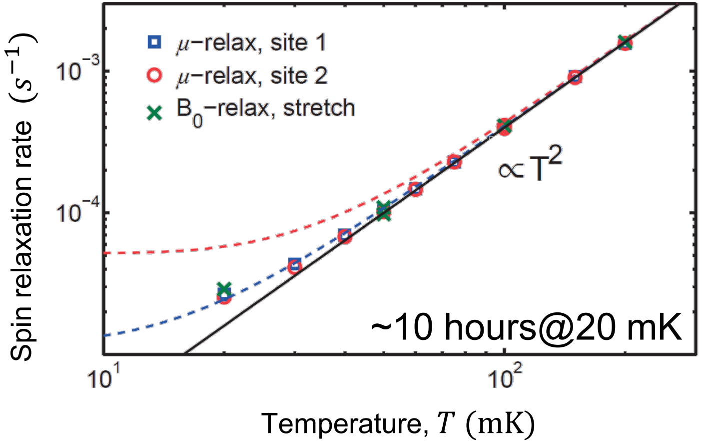
Effect of hyperfine and quadruple interaction is large in the small field region
→ suitable for parameter estimation

Guillot-Noël *et al.*, *Phys. Rev. B* **74**, 214409 (2006), Budoyo *et al.*, *Appl. Phys. Express* **11**, 043002 (2018)

Measurement of spin relaxation time







→ non-exponential decay curve

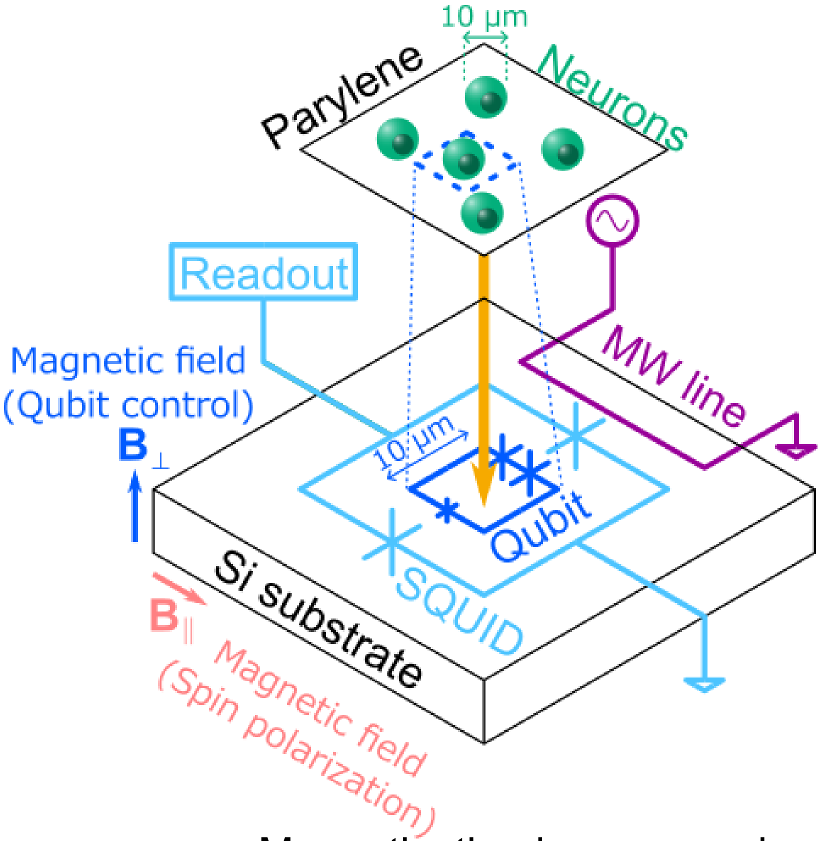
→ spin relaxation rate $\propto T^2$

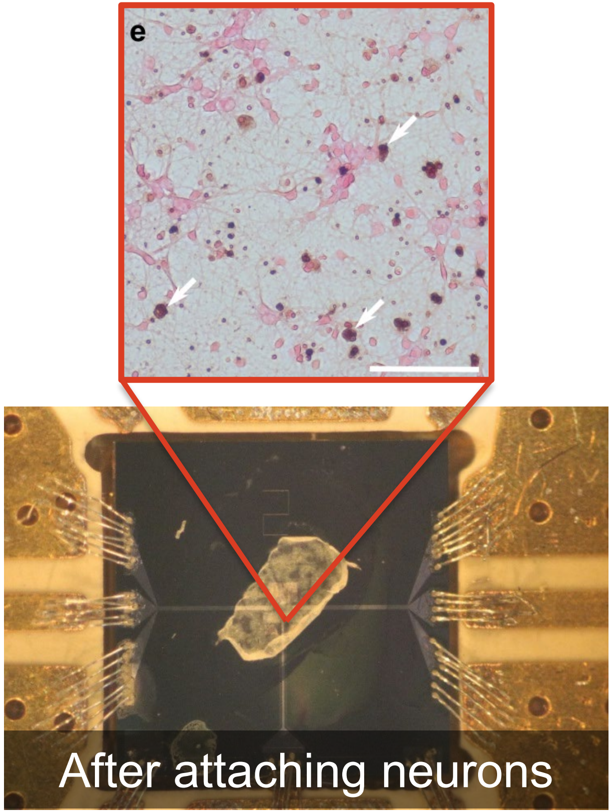
Phonon bottleneck effect is suggested.

(Our ESR is suitable to observe the effect because no energy is transferred to measurement system)

Budoyo *et al.*, *Appl. Phys. Express* **11**, 043002 (2018)

Magnetometry of neurons





Magnetization is measured as a function of temperature.

H. Toida *et al.*, Comminucation Physics **6**, 19 (2023)

Magnetometry of neurons

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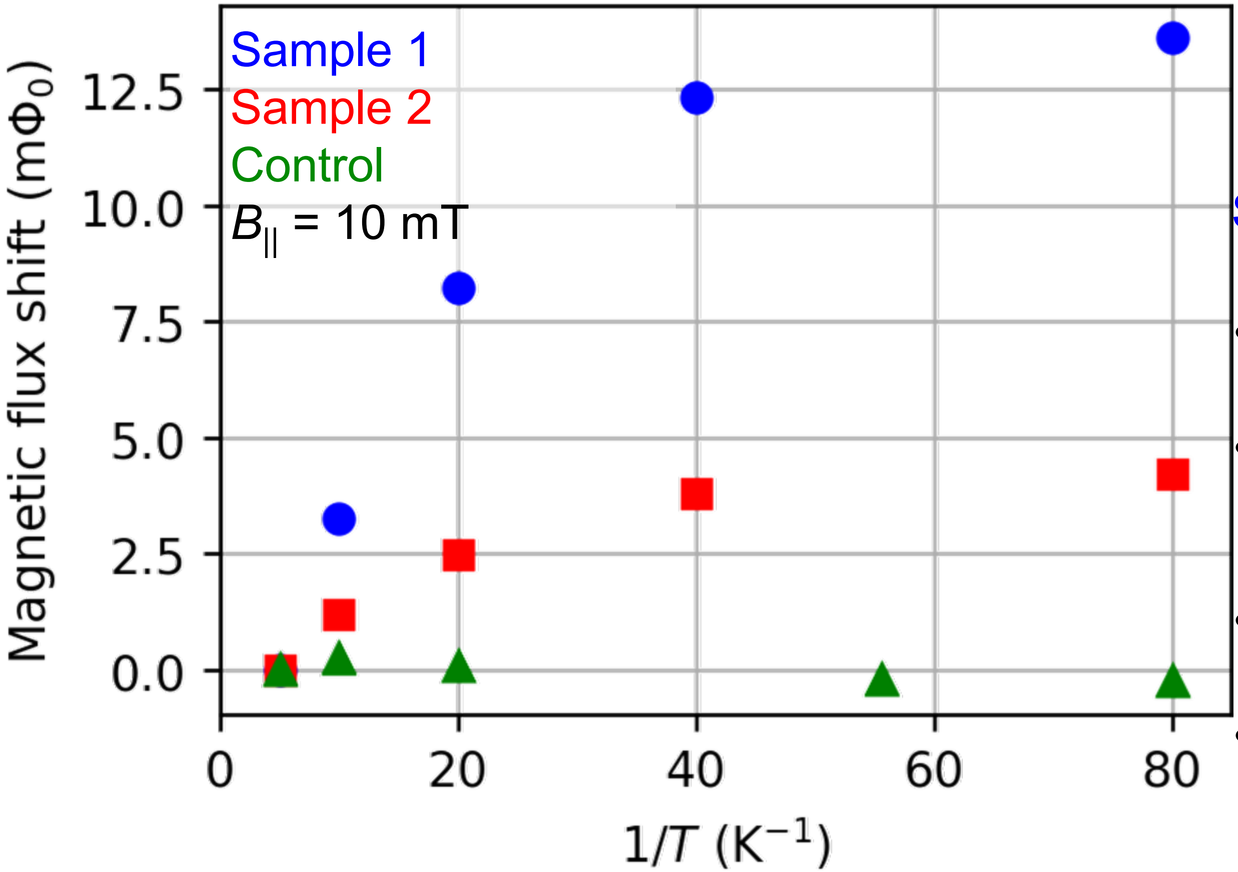

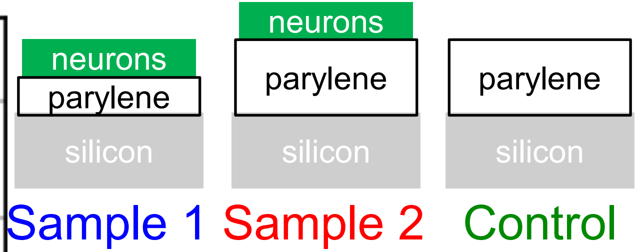

- Control experiment shows smaller magnetization.
- Sample with thinner insulator shows larger signal.
- Spins in neurons are observed.
- Spins are identified as Fe^{3+} ions. (Details are not discussed here.)

H. Toida *et al.*, Comminucation Physics **6**, 19 (2023)

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Thermometry using Ramsey oscillations

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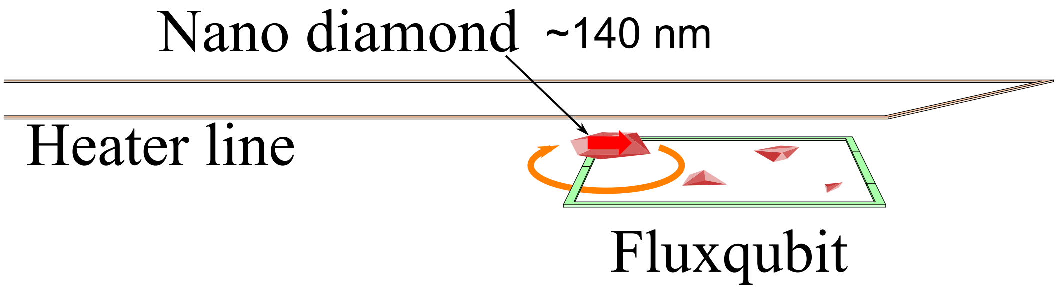
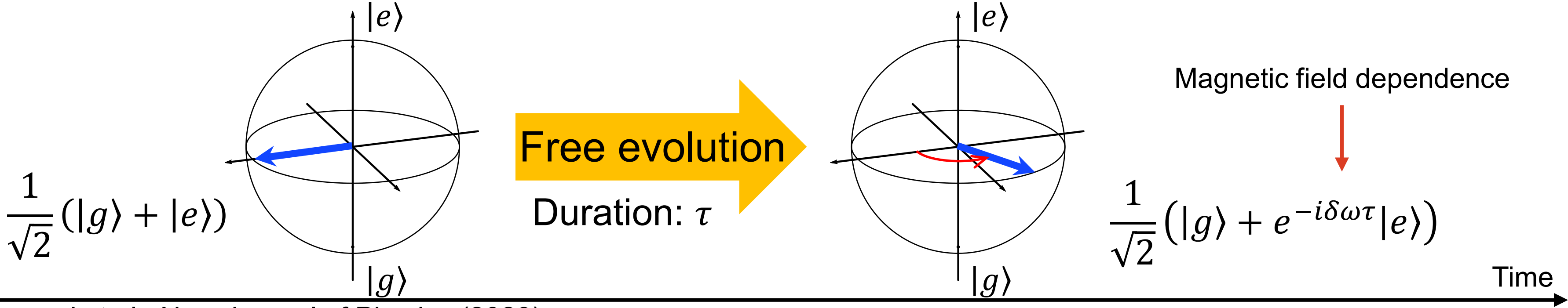


1. The temperature of nano diamond is controlled by heater power.
2. The magnetization of nano diamond changes as a function of the temperature.
3. The magnetic field (magnetization) changes Ramsey frequency of the qubit.



K. Kakuyanagi et al., New Journal of Physics (2023)

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Thermometry using Ramsey oscillations

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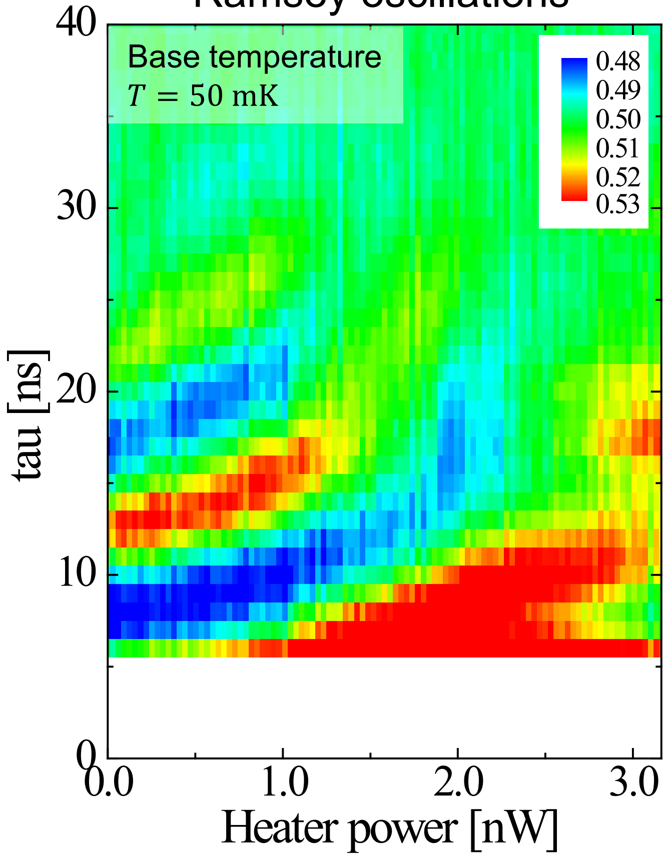
Ramsey oscillations



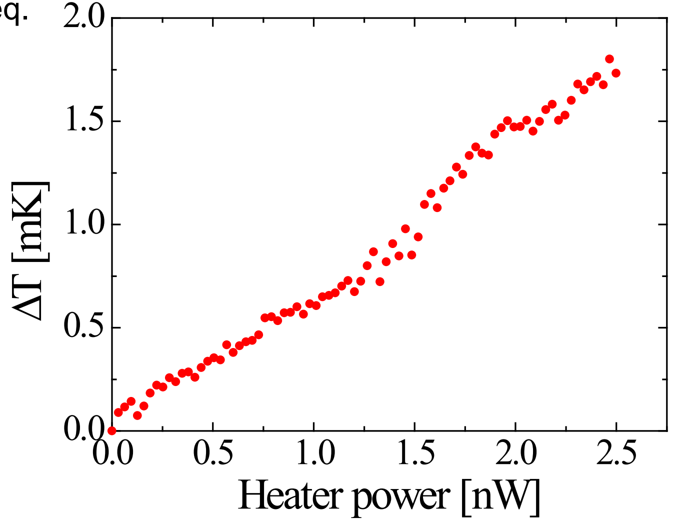
Microwave freq.

Ramsey frequency:

$$\delta\omega = \sqrt{\Delta^2 + \varepsilon(B)^2} - \omega_0$$

Calibration constants

Temperature difference



Sensitivity: 1.3 $\mu\mathrm{K}/\sqrt{\mathrm{Hz}}$ @ 9.1 mK

K. Kakuyanagi et al., New Journal of Physics 2023

Estimation of the sensitivity of FQ ESR

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Noise in qubit measurement
(e.g., Variation in switching probability)

(Slope of qubit spectrum)$^{-1}$

$$\sigma P_{\mathrm{SW}} \times \frac{\partial f_{\mathrm{q}}}{\partial P_{\mathrm{SW}}} \times \frac{\partial \Phi}{\partial f_{\mathrm{q}}} \times \frac{\partial N}{\partial \Phi}$$

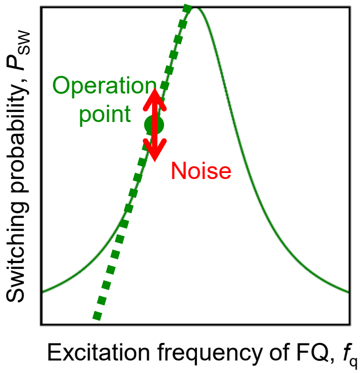
Linewidth of FQ

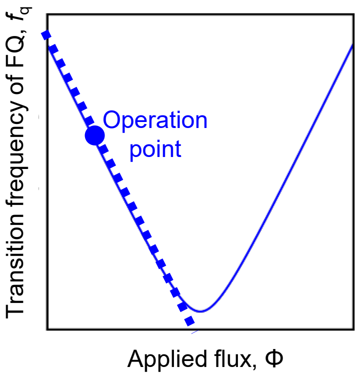
(magnetic flux generated by single spin)$^{-1}$

Narrow linewidth / small slope

tradeoff

Wide linewidth / large slope





Our best sensitivity ~ 12 spins/√Hz

H. Toida *et al*., Commun. Phys., **2**, 33 (2019), H. Toida *et al*., arXiv:2406.14948

$1/f$ noise of qubit readout devices (SQUID)

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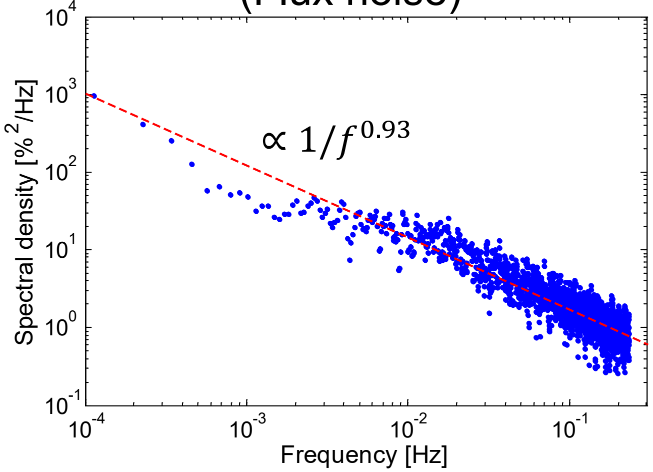
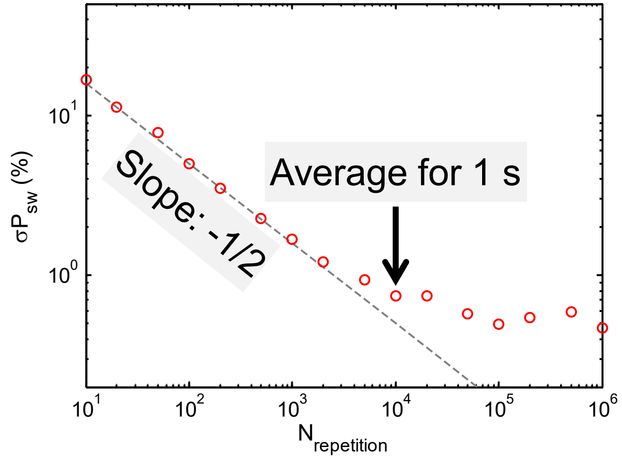
Power spectrum density

(Flux noise)



Readout noise vs. averaging



- Averaging is less effective for long integration time due to $1/f$ flux noise
- $1/f$ flux noise also limits the coherence time (linewidth) of the flux qubit

→ limitation factor of the sensitivity

Budoyo *et al.*, 2020 APL

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Our Team

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Quantum Sensing (Theory)

Dr. Munro (→ OIST)

Dr. Matsuzaki (→ Chuo Univ.)

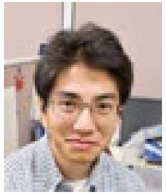
Biomaterial

Dr. Teshima

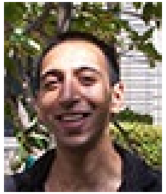
Dr. Sakai

Superconducting Circuits

Dr. Saito



Dr. Kakuyanagi



Dr. Mahboob

Dr. Toida

Dr. Budoyo

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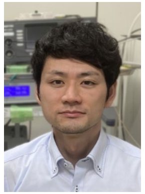
ESR Spectroscopy

Prof. Ono



Prof. Hori

Shizuoka University

Summary

Sensitive spin detection using flux qubits is realized

- Sensitivity: 12 spins/√Hz, Spatial resolution: ~ μm
- Magnetometry, electron spin resonance, thermometry
- Application: solid state material, biomaterial, etc.

Future works

- Single spin detection
- Spin imaging
  - Qubit array
  - Scanning qubit
  - Microwave interference
- Entanglement sensor using multiple flux qubits