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Current comparator for both AC and DC ratio measurements with 10^{-8}-level stability

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Dec 1st to 4th, 2025

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Why Current Ratio Matters in Industries ?

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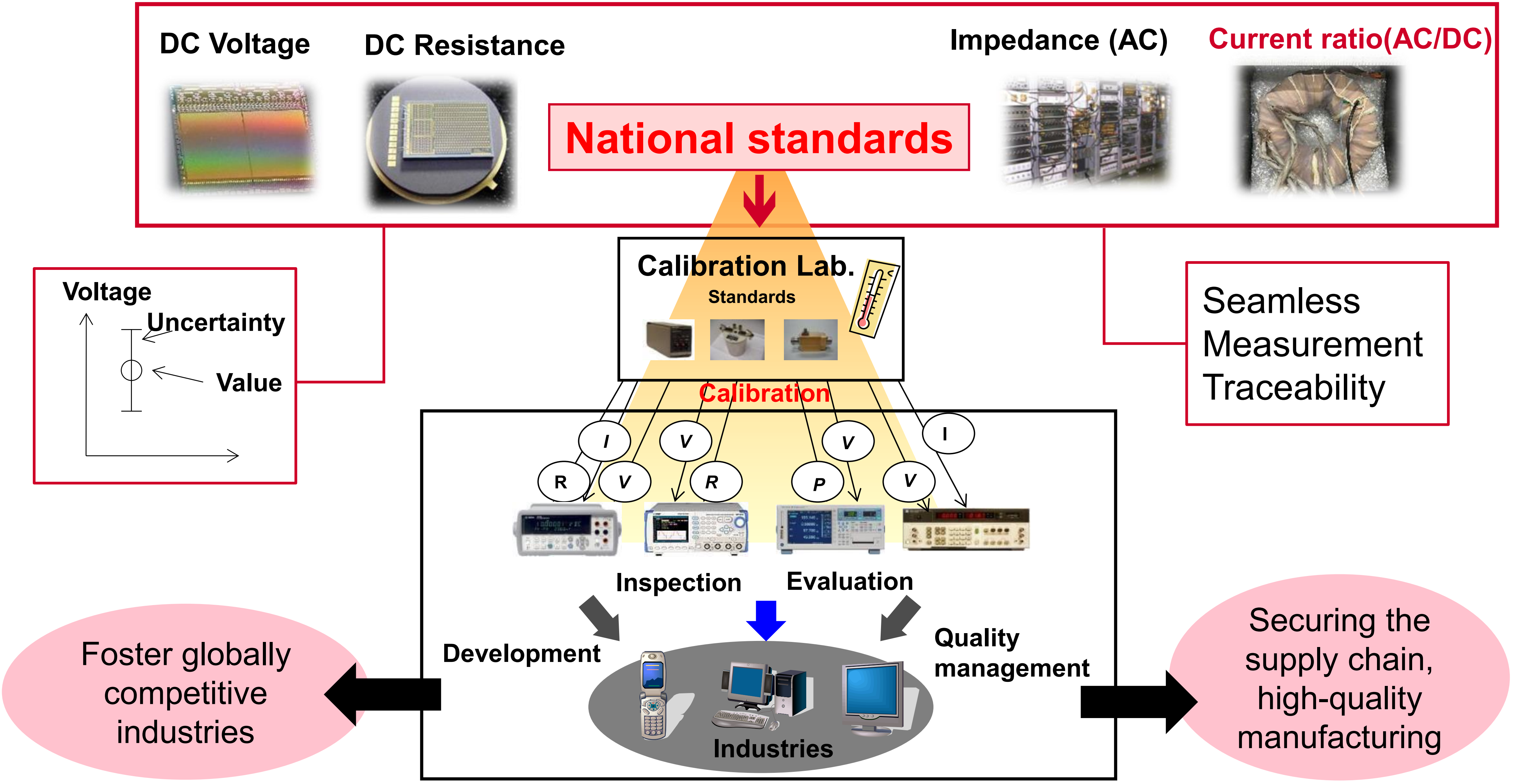
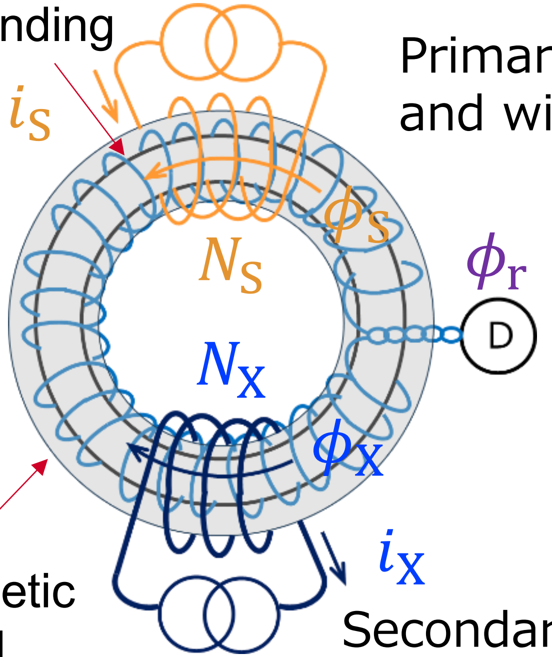
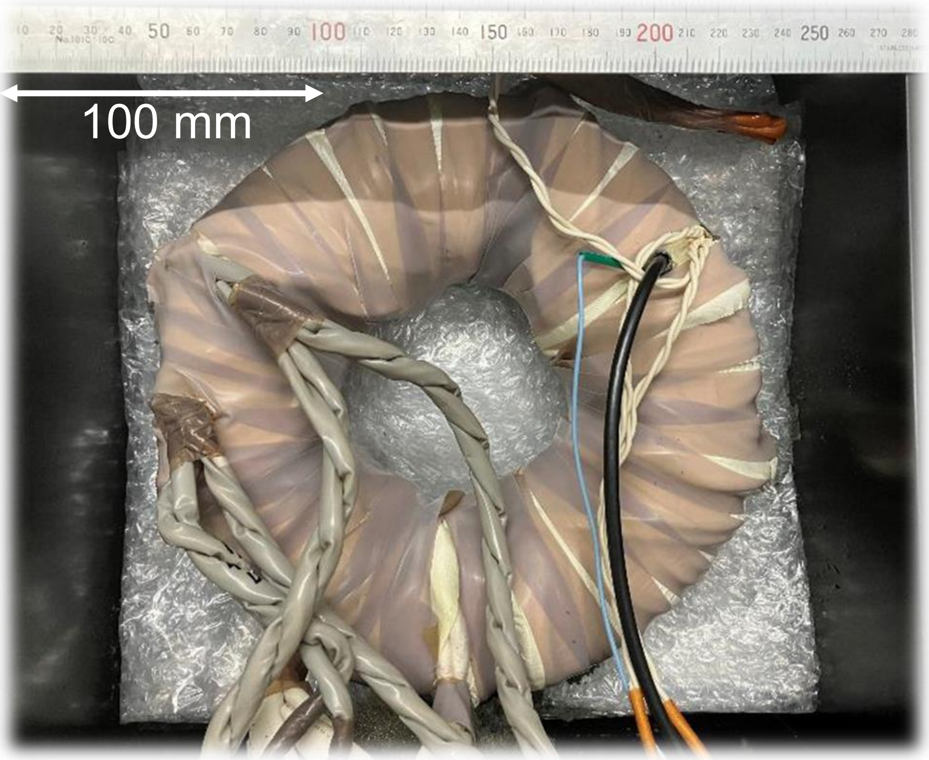


What is a Current Comparator?





Current ratio ($\phi_r \to 0$)

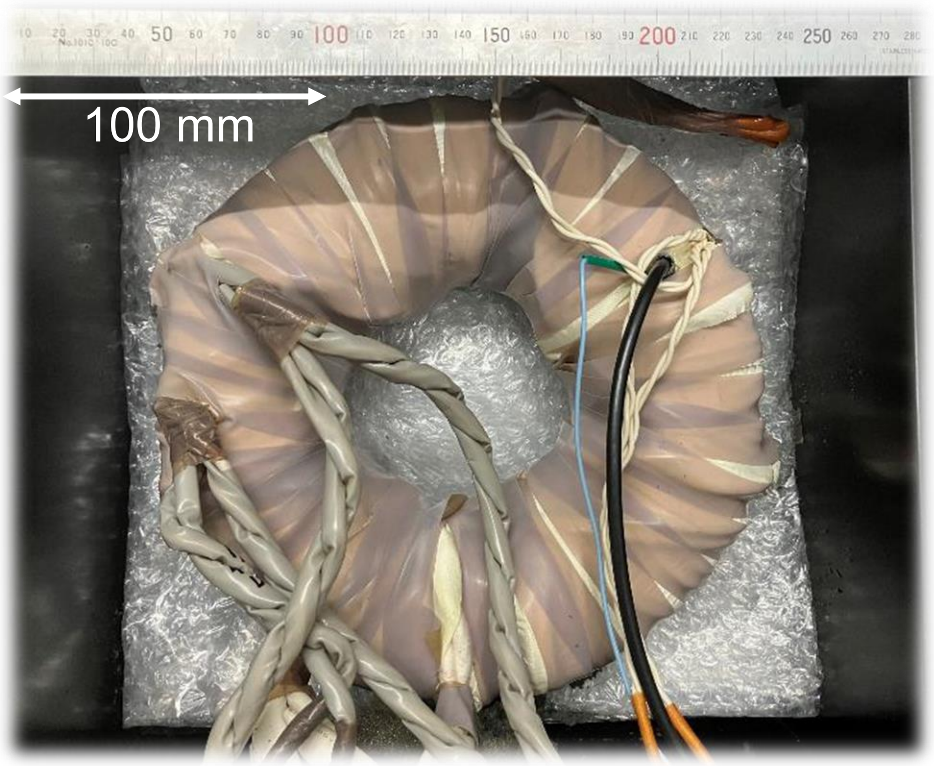
$$\frac{i_X}{i_S} = \frac{N_S}{N_X}$$

i_S, i_X : electric current

N_S, N_X, N_D : Number of winding

ϕ_S, ϕ_X, ϕ_r : Magnetic flux

Conventional AC current comparator



- Detection via flux balance
- Operates at room temperature
- Typically limited to ~10^{-6} level accuracy
- Complex winding (hundreds of turns)
- Heavy, no longer portable

Inside picture of ACC: courtesy from Tatsuji Yamada, AIST

W.J.M. Moore, P.N. Miljanic, The Current Comparator (1988)

Overall Configuration of Our Current Comparator

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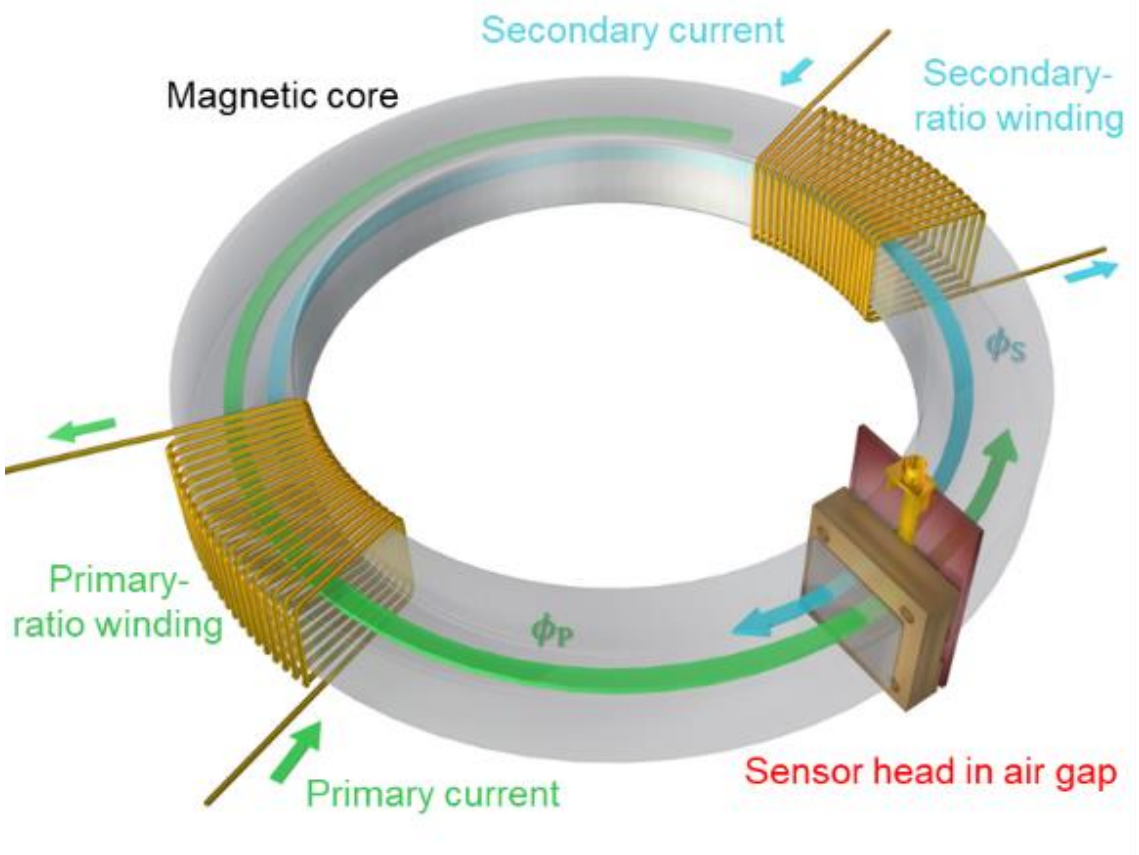

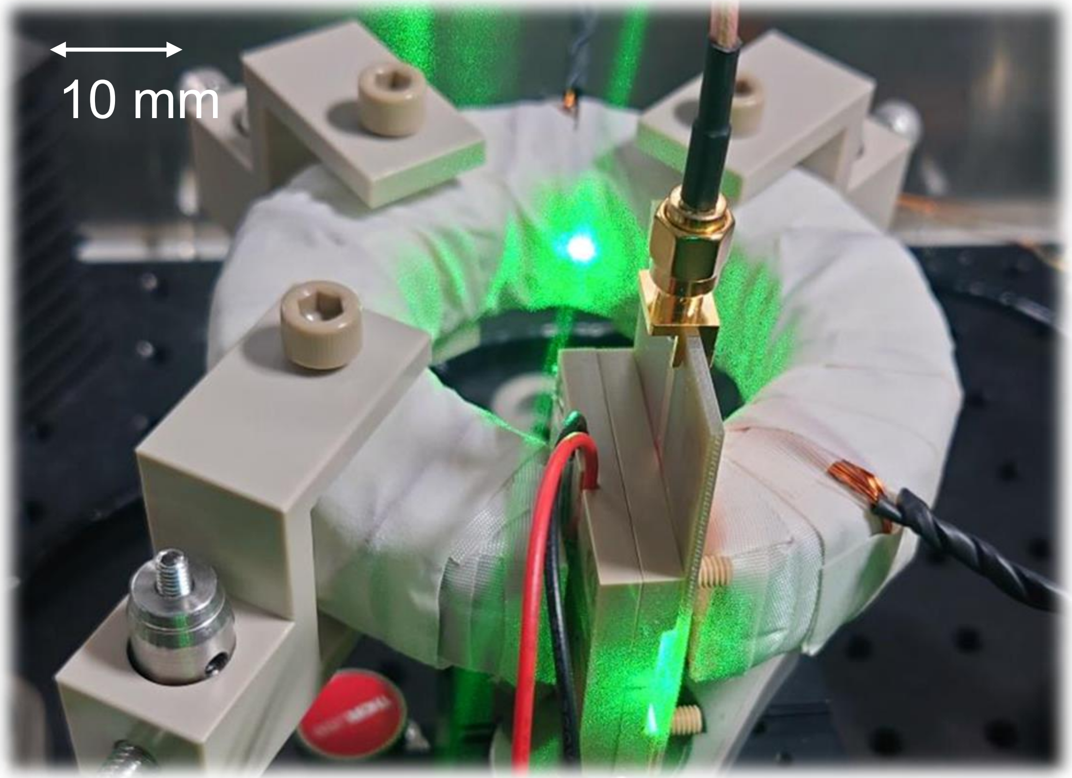

AC or DC current → Magnetic flux → NV-based null Detection

Structure of the NV-Diamond Sensor Head

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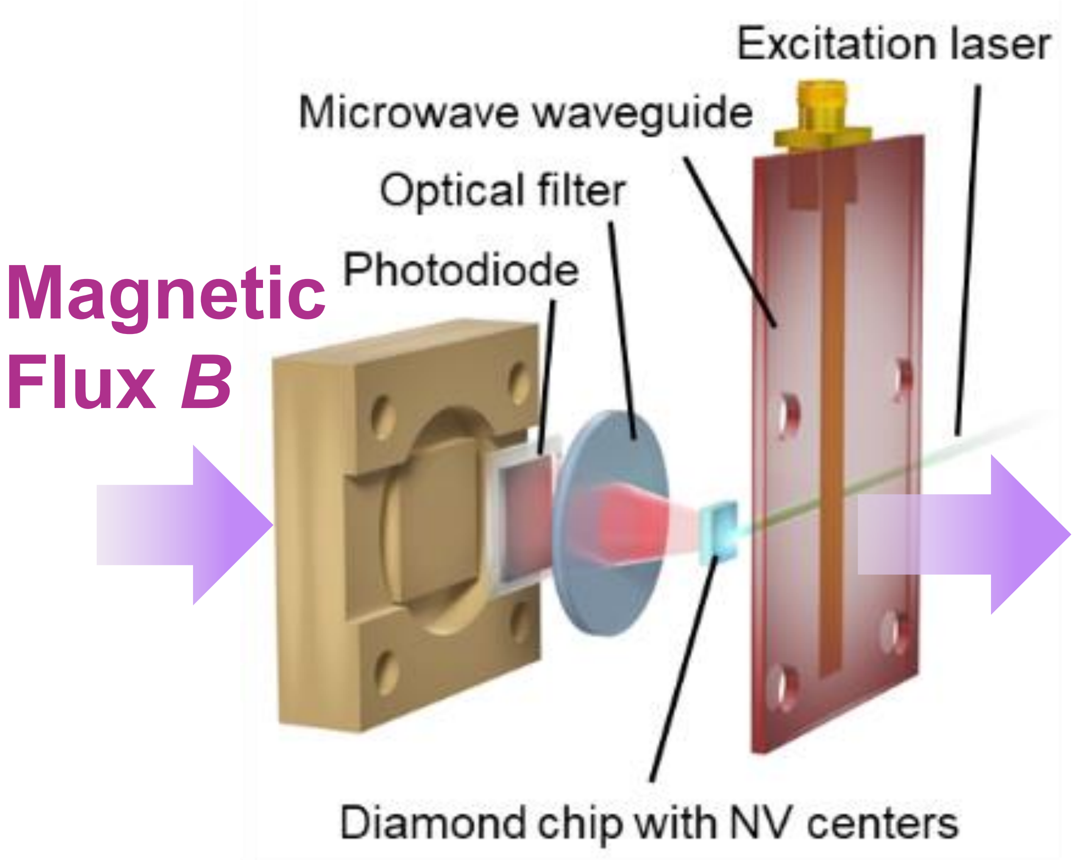

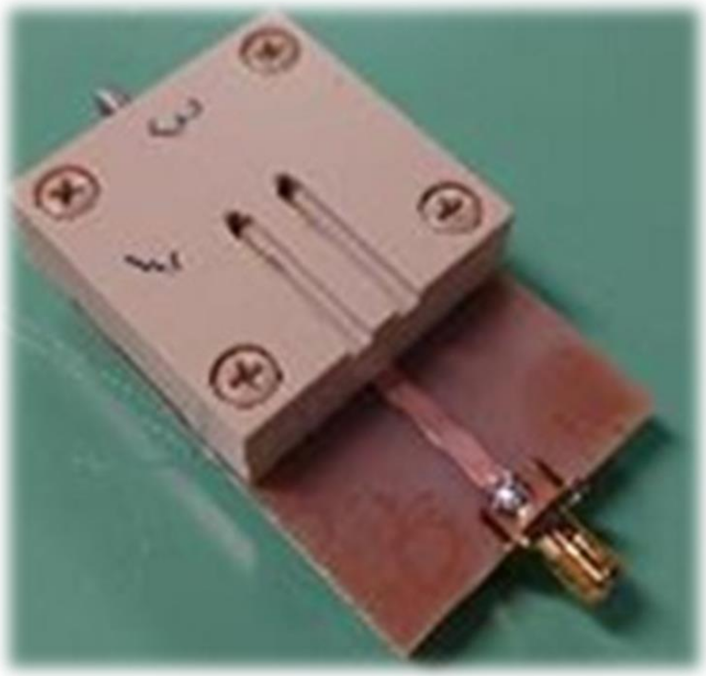

- **All components integrated within ~1 cm**
- **No external cryostat under ambient condition.**

Detecting the Magnetic Null Point with NV-Diamond Magnetometry

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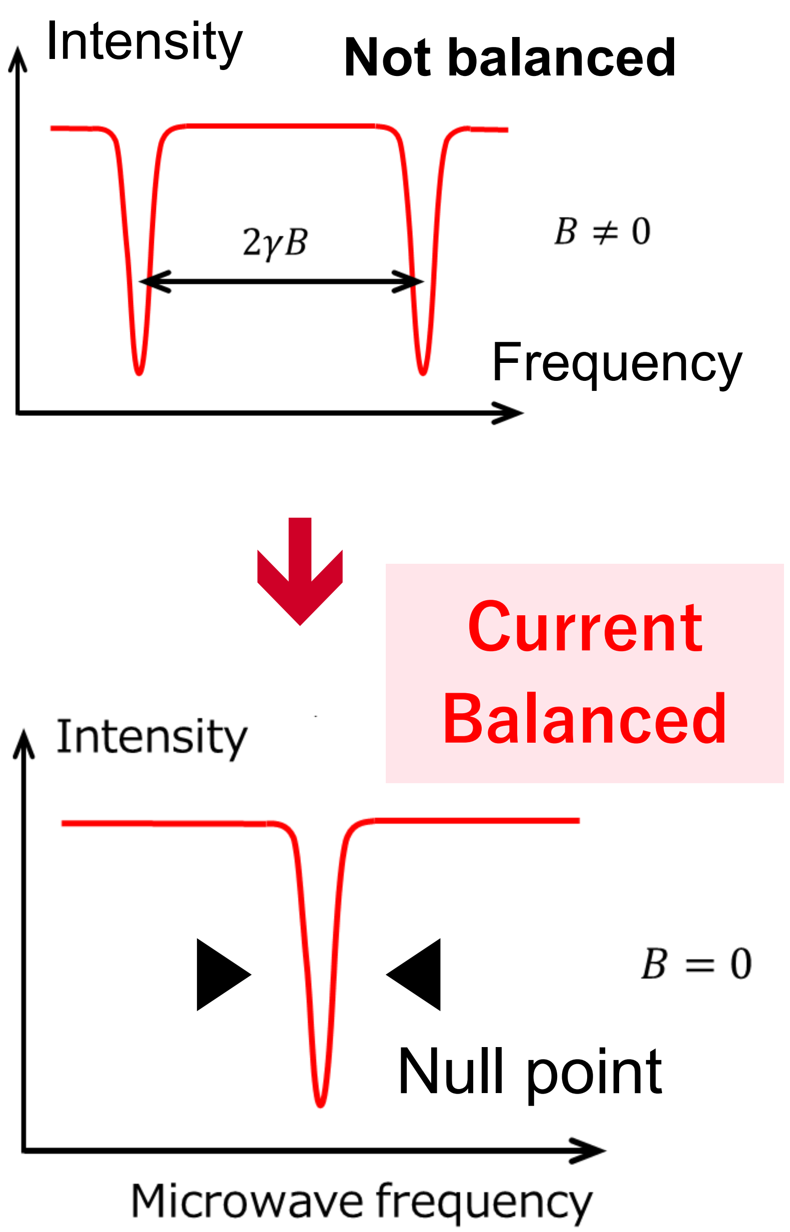

- NV centers detect local magnetic field via ODMR frequency shift
- Zeeman splitting disappears when residual magnetic flux $B = 0$
- This null condition corresponds to current balance in the comparator
- Allows direct detection of magnetic flux null without detection winding or SQUID

Why NV-Diamond ? – The optimal choice

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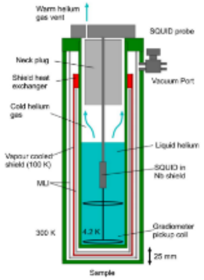
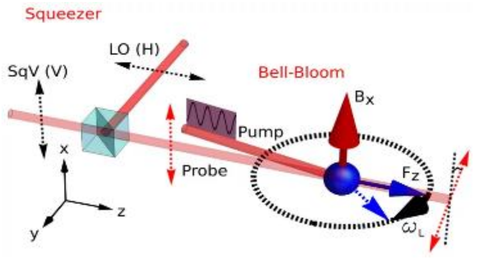
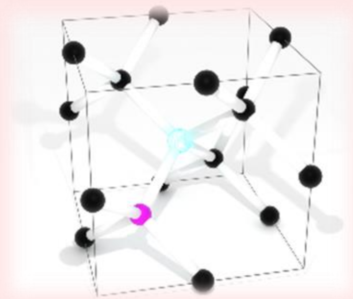
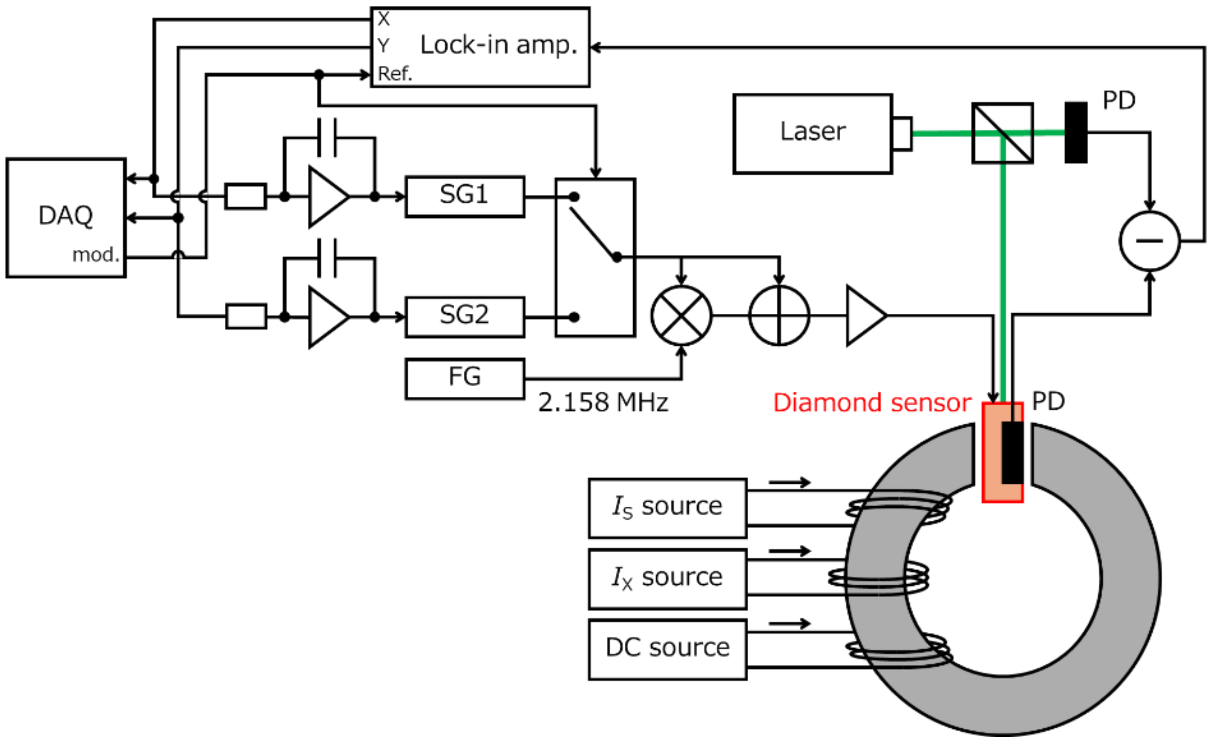
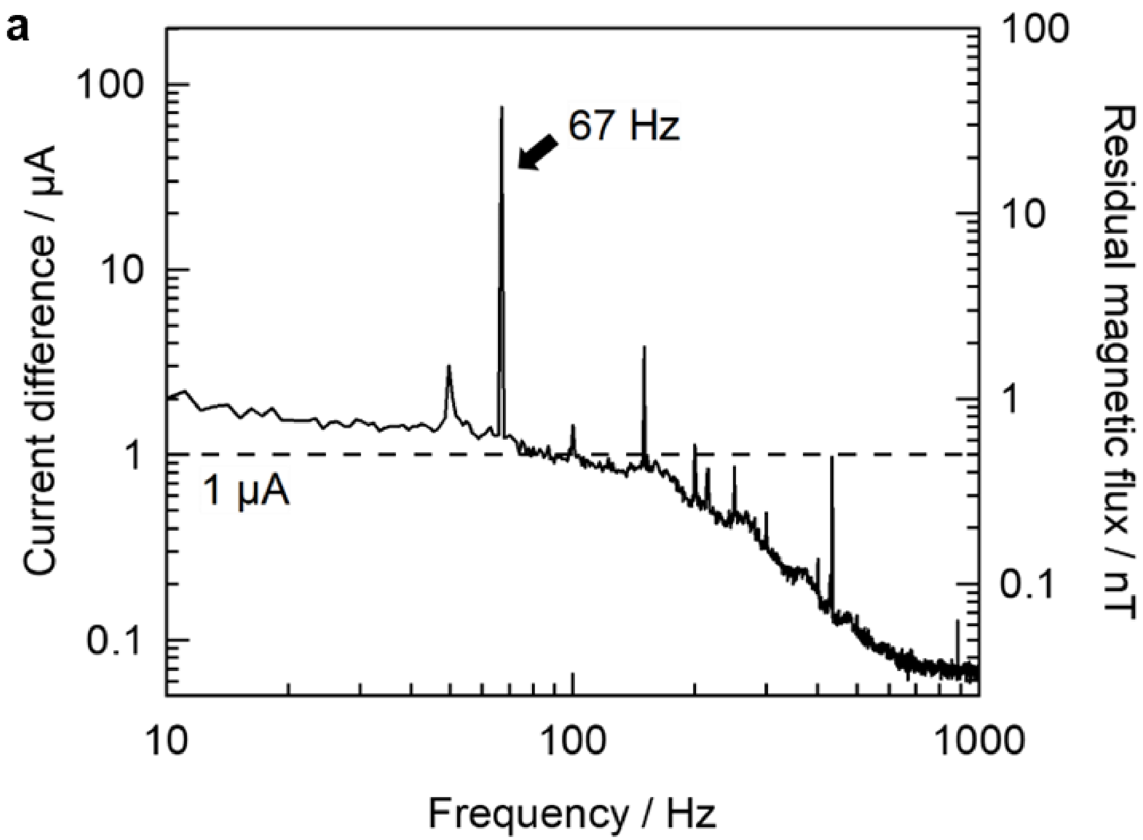
	SQUID (superconducting quantum interference device)	OPM (Optically pumped atomic magnetometer)	NV center (nitrogen-vacancy)
			
	Rainer Körber et al., Supercond. Sci. Thecnol. **29**, 113001 (2016)	C. Troullinou et al., Phys. Rev. Lett. **127**, 193601 (2021)	High linearity Vector sensing Wide operation temperature
■ Magnetic sensitivity	A few ten fT/Hz$^{0.5}$	A few fT/Hz$^{0.5}$	6 pT/Hz$^{0.5}$ *Appl. Phys. Lett.* 126, 194001 (2025)
■ Operation temperature	Cryogenic (4K)	Room temperature (some heated)	✓ Room temperature
■ Field Range	<μT	Low-field (SERF)	✓ DC to ~mT
■ Spatial resolution	millimeter to centimeter	Millimeter to centimeter	✓ Millimeter to Micrometer

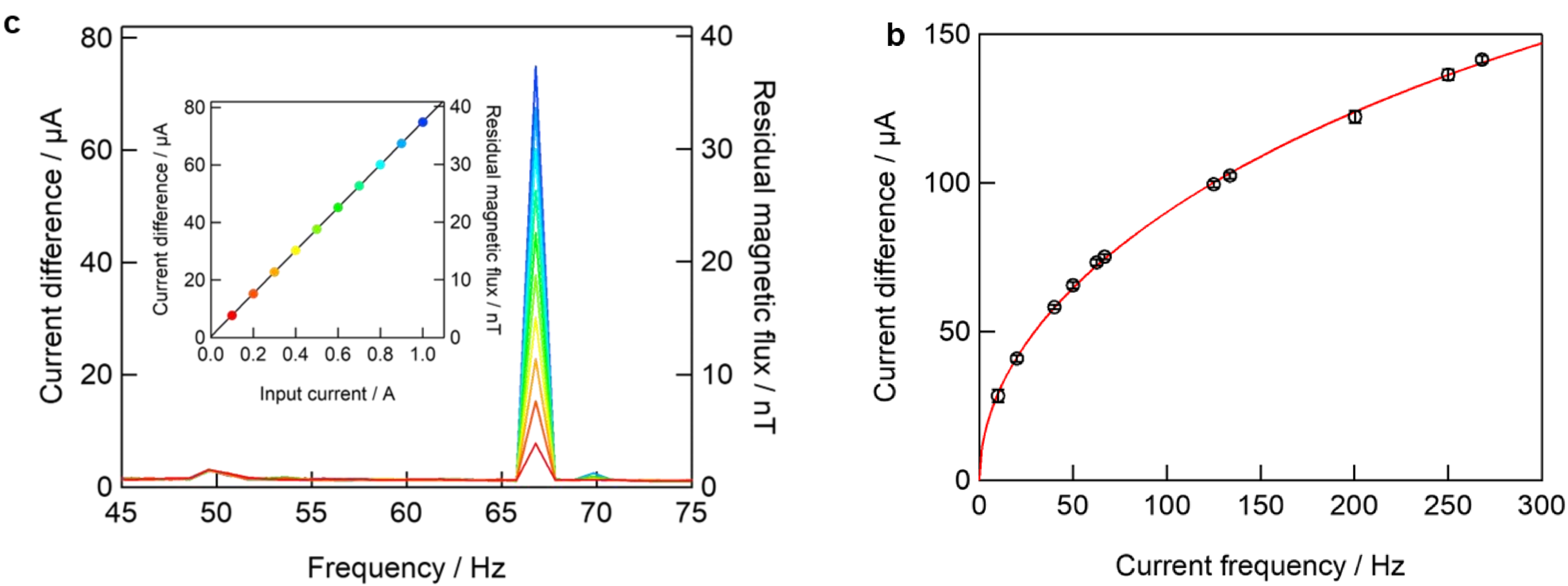
AC Ratio Error Measurement at 67 Hz





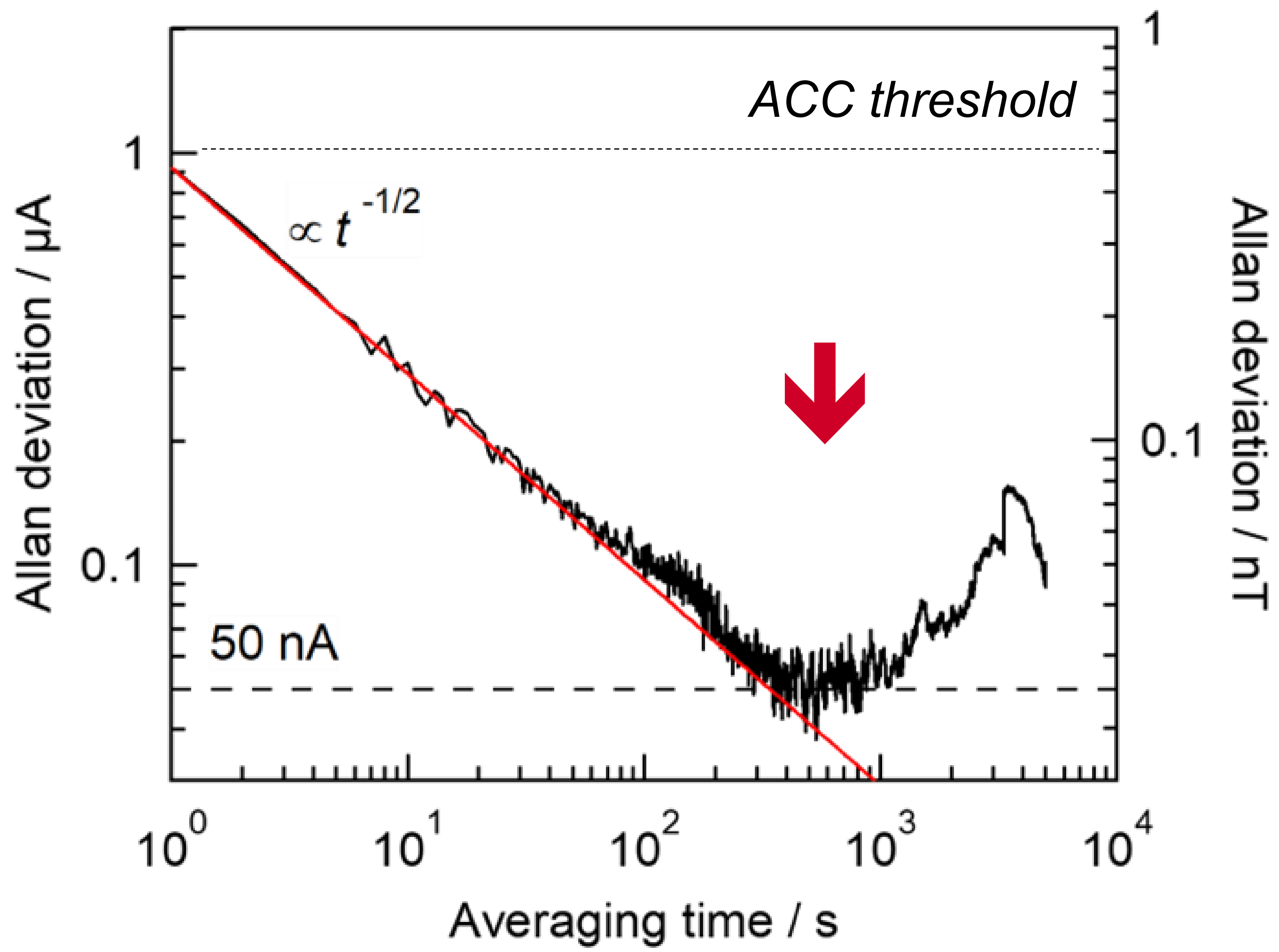
- Clear signal peak at 67 Hz extracted by DFT
- Residual magnetic flux converted to current difference
- Ratio error of 76 μA/A detected

Linearity and Frequency Response



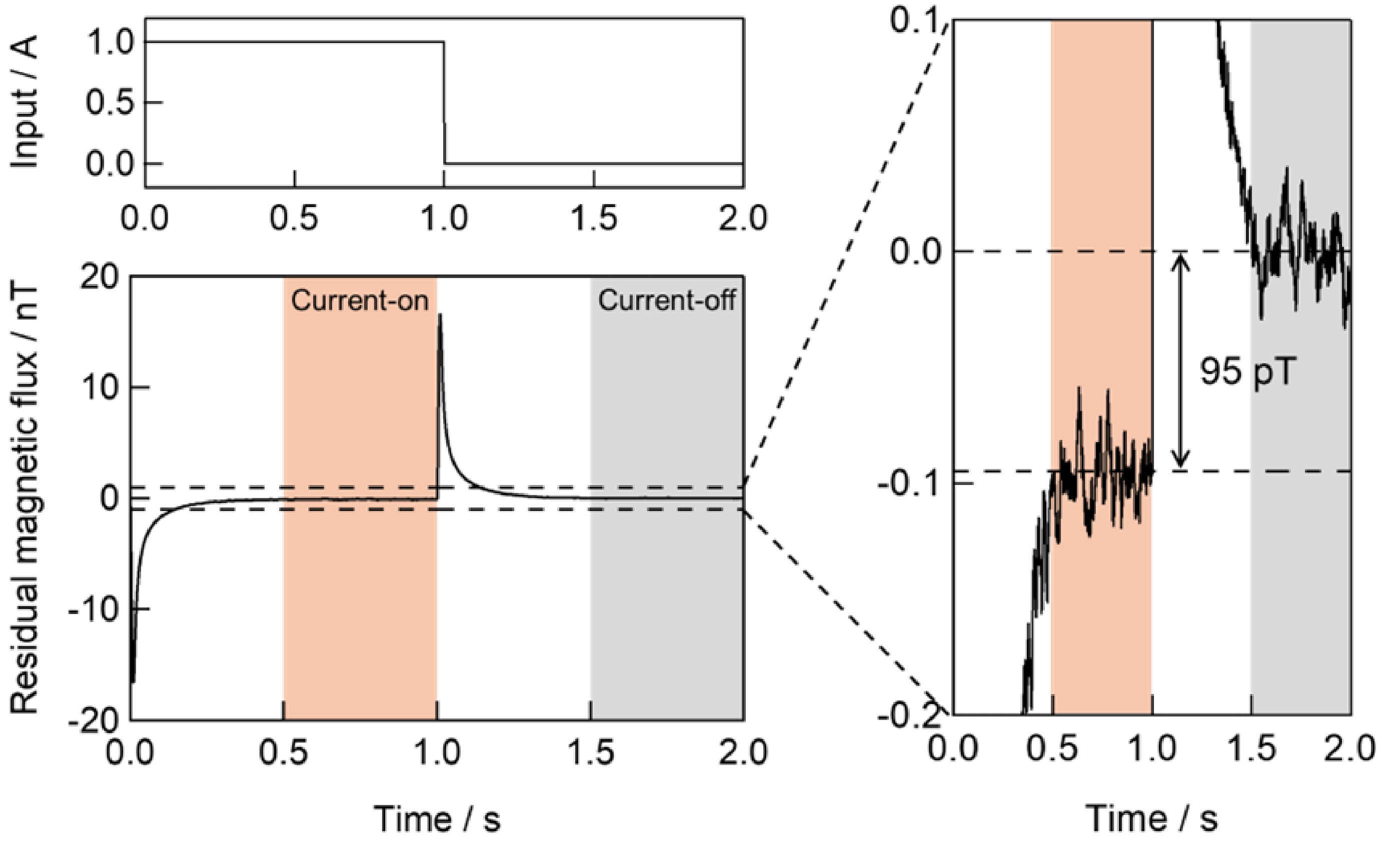
- Ratio error shows linear dependence on current amplitude
- System maintains performance up to 300 Hz

Statistical Stability of AC Measurements (Allan Deviation)



- $t^{-1/2}$ **dependence confirms white noise regime**
- **Minimum Allan deviation of 50 nA at 500 s**
- **Type-A uncertainty: 5×10^{-8} (1 A, 67 Hz)**

DC Current Ratio Measurement via Magnetic Null Detection



- DC current = 1 A applied to series windings
- Residual flux extracted from ODMR signal during current-on and off states
- Ratio error: 150 nA/A

Statistical Uncertainty in DC Ratio Measurement(Allan deviation)

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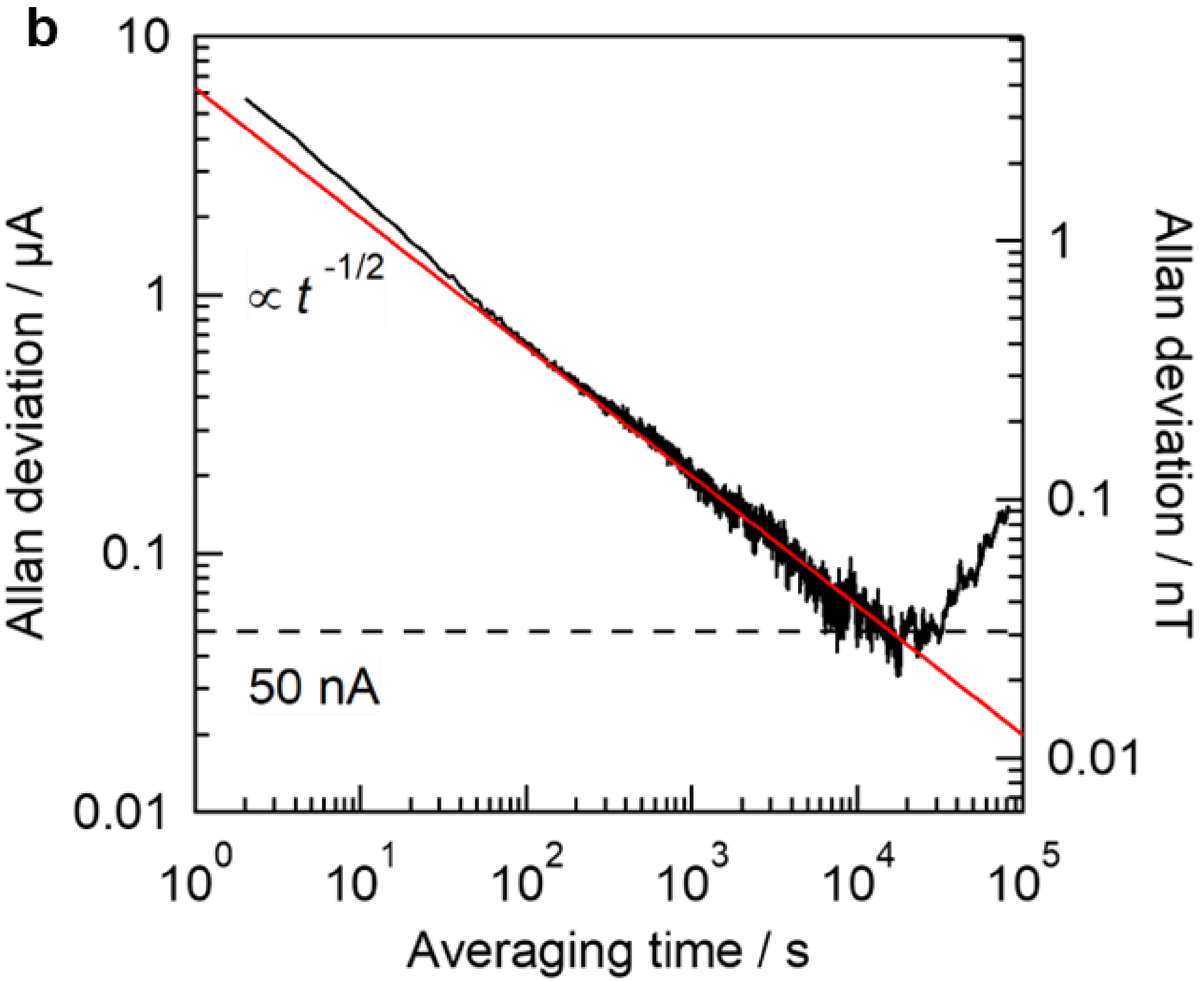

- **Allan deviation follows $t^{-1/2}$ trend**
  → random noise dominant
- **Minimum at 20000 s: 50 nA/A**
- **Potentially achievable CCC level under ambient conditions**

Outlook and Conclusion

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Key Takeaways

- **Unified AC/DC current comparator using NV-diamond**
- **10^{-8}-level ratio measurement at room temperature**
- **Cryogenics-free, compact, scalable implication**
- **Single platform for current calibration across AC and DC regime**

Future Applications

- **Supports NMI calibration chains and international standarization**
  - **AC/DC current standards**
  - **DC resistance standards**

- **Power electronics calibration**
- **Energy metering traceability**

Acknowledgements

We gratefully acknowledge the following individuals :

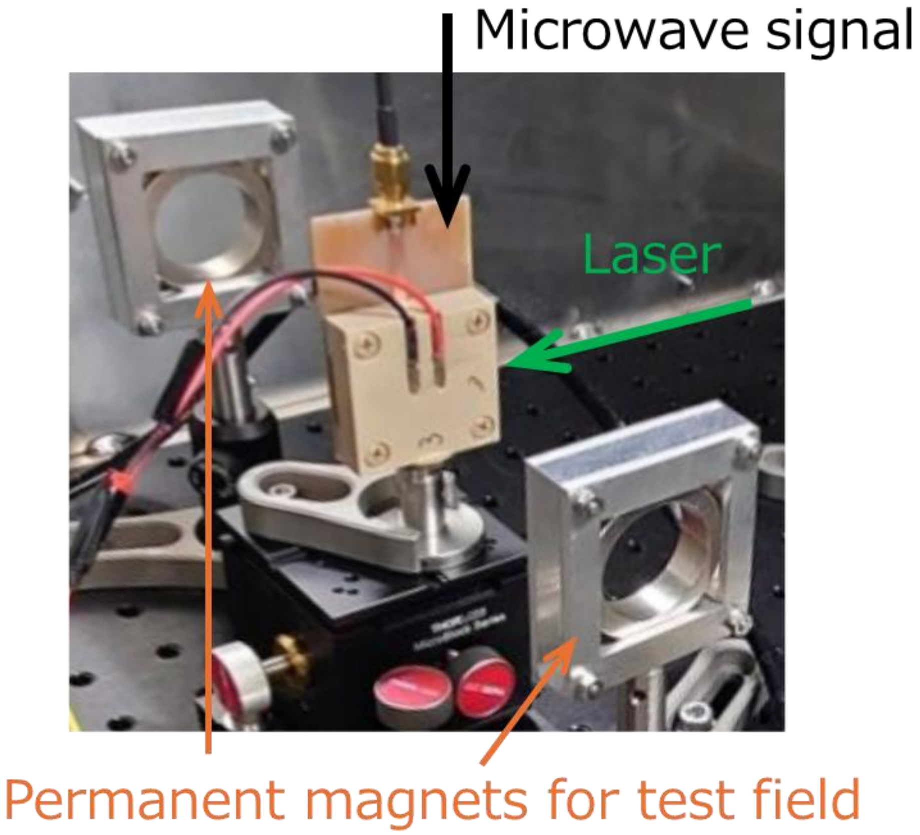
- Mutsuko Hatano, Nobu Kaneko, Takayuki Iwasaki, and Yuji Hatano, who jointly conceive the idea and offer comprehensive support throughout the project.
- Hidekazu Muramatsu for the development of the current comparator system and its precision evaluation with a help from Yuta Kainuma, Hiromitsu Kato, Norihiko Sakamoto, Tatsuji Yamada, and Chiharu Urano.
- Hiroshi Abe, Shinobu Onoda, and Takeshi Ohshima for creating NV centers in diamond
- Sho Okubo for discussing Allan deviation analysis of ac and dc signals.

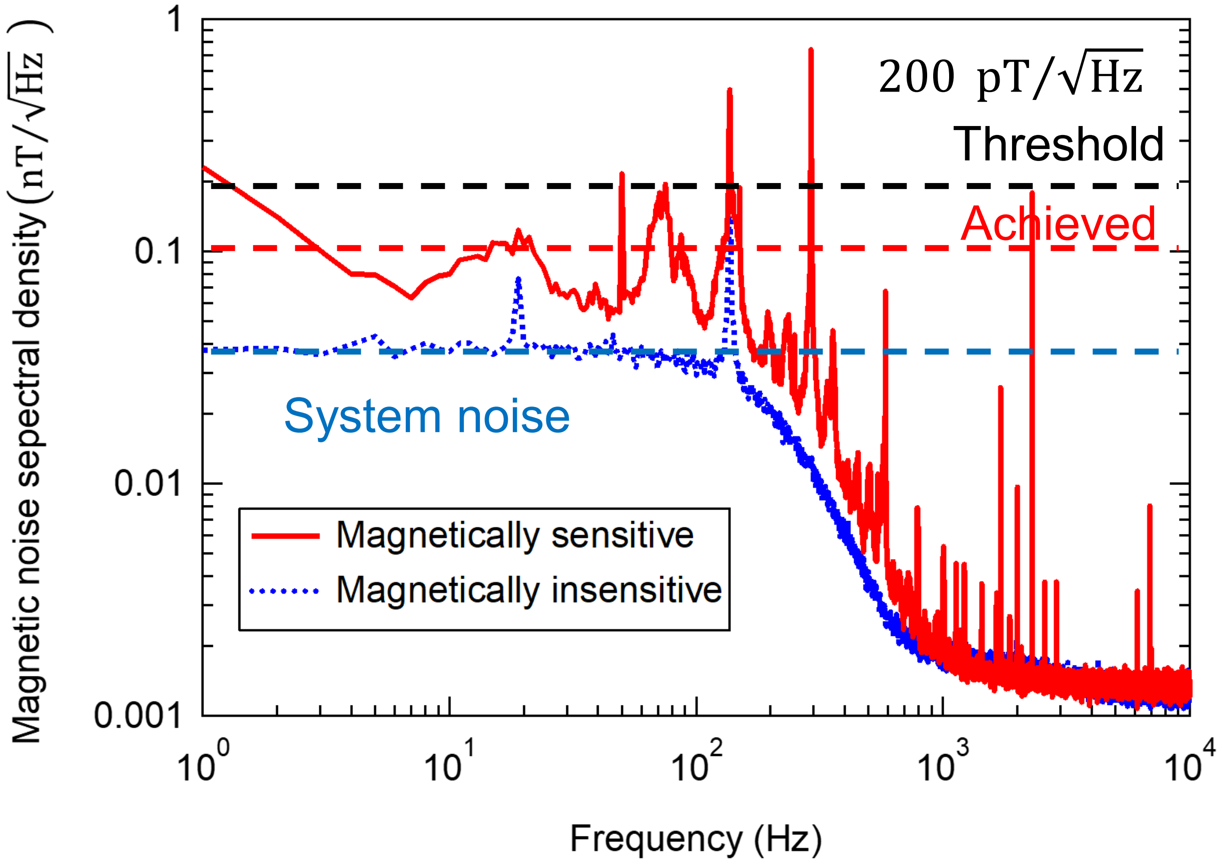
Funding Acknowledgment:

- MEXT Q-LEAP Grant Number JPMXS0118067395
- CSTI, SIP and BRIDGE programs
- JST ASPIRE, “Diamond spin qubits for quantum application (DIAMONDQTECH)”

Thank you for your attention

Appendix2: Sensor head performance

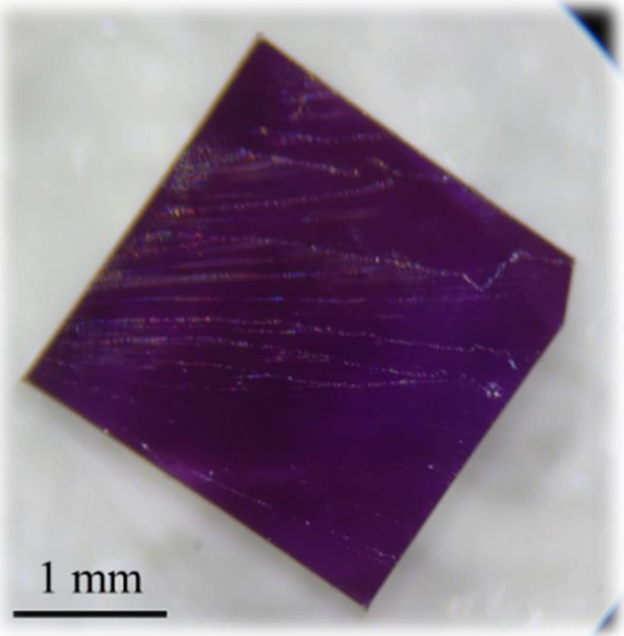




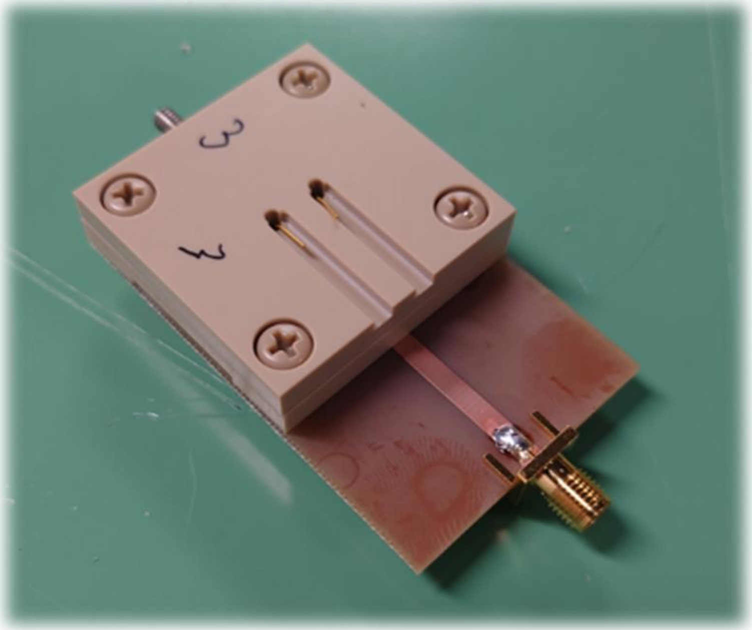
- **Magnetic sensor satisfied the required magnetic noise floor less than 200 pT.**

Appnendix3: Diamond chip, CP Waveguide, Outer view of the sensor

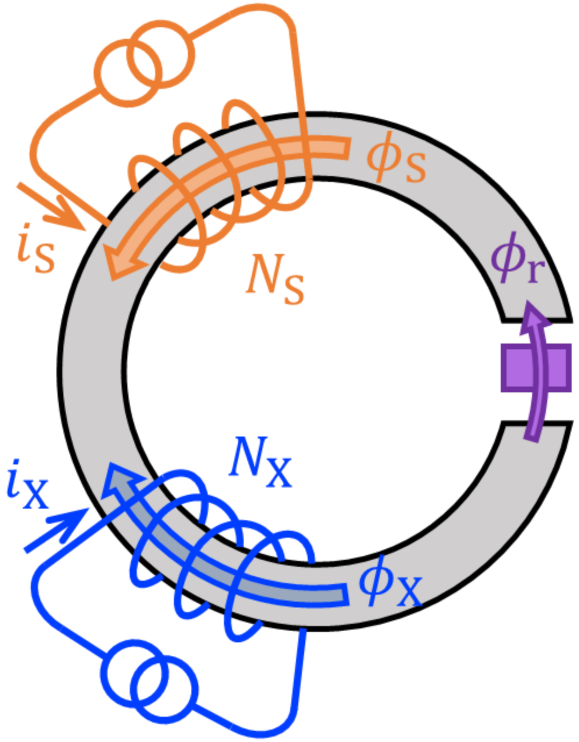
- **Type-Ib HPHT**

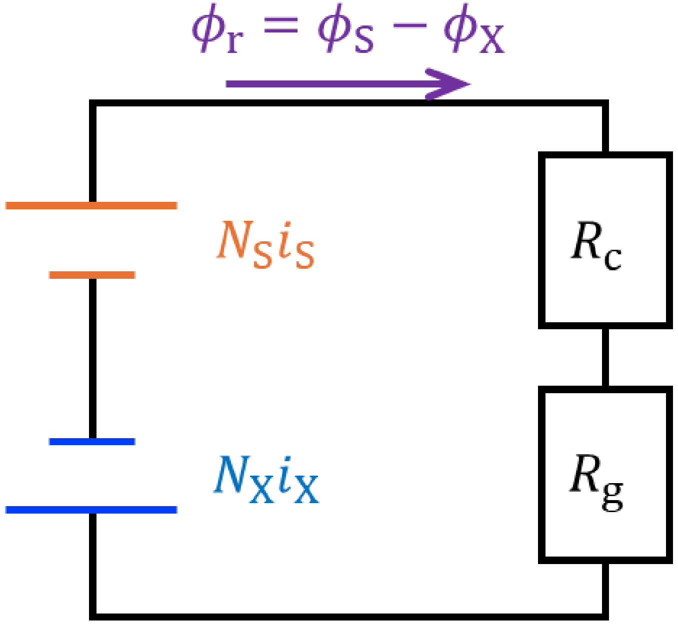


- **CP waveguide**



Appendix4: Magnetic Equivalent circuit analysis





The model of magnetic circuit

$R_c = \frac{L - l}{\mu_0 \mu_r S}$: Magnetic resistance of the core

$R_g = \frac{l}{\mu_r S}$: Magnetic resistance of the air gap

μ_0 : Permeability in vacuum

μ_r : Relative permeability of the core

S : Cross section of the core

L : Magnetic path length of the core

l : Size of the air gap

Estimated the magnetic flux detected by the diamond quantum magnetic sensor to achieve resolution of the current comparator with NV centers ($\equiv N_S i_S - N_X i_X$) of 10^{-6} A when $l = 2$ cm.

$$\frac{\phi_r}{S} = \frac{\mu_0 \mu_r}{L + (\mu_r - 1) l} (N_S i_S - N_X i_X) \sim \mathbf{188\ pT}$$