MAGNETOMETRY • SUPERCONDUCTIVITY

How a SQUID works

Superconducting **QU**antum **I**nterference **D**evice

The most sensitive magnetometer ever built, resolving fields below 10^{-15} tesla, a hundred-billionth of Earth's field.

Frank Rathmann

Brookhaven National Laboratory

From a prediction to five Nobel Prizes

Most physicists know the Josephson effect, fewer know the device's history, or how many prizes this corner of physics has collected.

1962	1964	1970	1971	1985
Josephson predicts the effect	First SQUID, Ford Labs	Zimmerman's practical SQUID	First MEG, at MIT	Macroscopic quantum tunnelling

THE SUPERCONDUCTIVITY NOBEL LINEAGE

1972	1973	1987	2003	2025
BCS theory	**Josephson effect**	**High-T_c superconductivity**	**Superconductor & superfluid theory**	**Macroscopic quantum tunnelling**
Bardeen, Cooper, Schrieffer	Brian Josephson	Bednorz, Müller	Ginzburg, **Abrikosov**, Leggett	Clarke, Devoret, Martinis

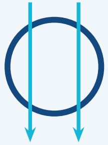
Highlighted: the 1973 and 2025 prizes are the most directly SQUID-related; John Clarke (2025) is himself a SQUID pioneer.

Two quantum effects make it possible

A SQUID rests on two macroscopic quantum phenomena working together.

1 Flux quantization

In a closed superconducting loop the trapped magnetic flux cannot take just any value. The Cooper-pair wavefunction must close on itself, so the flux is locked to whole multiples of one tiny quantum.



superconducting loop

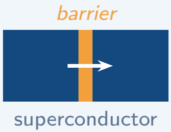
$$\Phi = n\,\Phi_0$$

$$\Phi_0 = h/2e$$

$$\approx 2.07 \times 10^{-15}\ \mathrm{Wb}$$

2 Josephson tunnelling

Separate two superconductors by an ultrathin barrier → a **Josephson junction**. Cooper pairs tunnel across it, carrying a supercurrent with zero voltage. The phase difference δ of the wavefunction sets that current.



DC effect

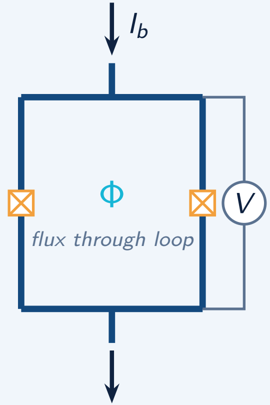
$$I = I_c \sin\delta$$

AC effect

$$\frac{d\delta}{dt} = \frac{2eV}{\hbar}$$

The DC SQUID: a loop that counts flux quanta

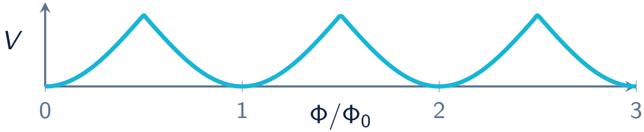
Two junctions on one loop turn magnetic flux into a measurable voltage.



Bias the loop with a steady current. The two tunnelling paths interfere like a two-slit experiment, so the loop's critical current is modulated by the enclosed flux:

$$I_{\max} = 2\, I_c \left|\cos(\pi\, \Phi/\Phi_0)\right|$$

Voltage oscillates with flux, one full period per quantum Φ_0 → the steep slope makes the SQUID a flux-to-voltage transducer.



What a flux-to-voltage converter is good for

A SQUID senses anything you can turn into magnetic flux: current, voltage, position or magnetization.

Biomagnetism

Brain (MEG) and heart (MCG) imaging of femtotesla biosignals.

Materials science

Magnetic susceptometry and scanning SQUID microscopy of quantum materials.

Metrology

The Josephson voltage standard and quantum electrical units.

Geophysics & NDE

Mineral and geomagnetic surveys; non-destructive flaw detection.

Astronomy

Ultra-low-noise amplifiers and multiplexed cryogenic-detector readout.

Quantum computing

Josephson/SQUID circuits as qubits and their readout.

Medical tools: reading the body's magnetic fields

Biomagnetism is the SQUID's largest application: non-invasive, millisecond-resolution functional imaging.

MEG (brain)

$\sim$300 sensors cooled to 4.2 K.

Presurgical mapping of focal epilepsy.

Eloquent-cortex mapping in brain tumours.

First whole-head system: 1992.

MCG (heart)

Adult and fetal arrhythmia detection.

Tsukuba study: 10 085 patients (2008–2016).

Clinically approved and reimbursed in Japan.

In-vitro & beyond

Magnetic-nanoparticle readout for cancer detection.

Also lung, intestine, fetus and spine studies.

Scale: an evoked brain field is about **40 fT**, roughly a **billionth** of Earth's $\sim$50 μT field.

At the frontier (2024–2026)

Where SQUIDs are heading, and where they now serve as the quantum-limited readout for other sensors.

Dark-matter searches

Near-quantum-limited SQUID amplifiers power axion haloscopes such as ADMX. In 2025 a qubit photon-counter beat them by $20\times$ above 5 GHz; CERN's DarkQuantum uses SQUID amplifiers at low frequency.

Cryogen-free rivals

Optically pumped magnetometers (OPMs) now enable wearable, on-scalp MEG and MCG with no liquid helium, yet SQUIDs remain the sensitivity benchmark they are measured against.

NanoSQUID microscopy

SQUID-on-tip and SQUID-on-lever probes image currents, magnetism and dissipation in quantum materials at sub-100 nm resolution (2025–2026).

How good does it get? Record sensitivities

The SQUID remains the most sensitive magnetic sensor known; here is the state of the art.

1–3 fT$/\sqrt{\mathrm{Hz}}$

typical biomagnetic systems (roadmap: 0.1 fT)

5×10^{-18} **T**

lowest field resolved, with days of averaging

$\approx \hbar$

energy resolution near the quantum limit

0.29 $\mu_B/\sqrt{\mathrm{Hz}}$

single-electron-spin sensitivity (39 nm tip)

$< 1\ \mu$**K**$/\sqrt{\mathrm{Hz}}$

thermal sensitivity for nanoscale imaging

$$K_J = 2e/h$$

$$V = f/K_J$$

realizes the SI volt

Further reading

Foundational papers, key textbooks, and the most recent milestones.

- **B. D. Josephson**, *Phys. Lett.* **1**, 251 (1962): the original prediction of the effect.
- **Jaklevic, Lambe, Silver & Mercereau**, *Phys. Rev. Lett.* **12**, 159 (1964), first quantum interference: the SQUID.
- **J. Clarke & A. I. Braginski**, *The SQUID Handbook*, Vols. 1–2 (Wiley-VCH, 2004 & 2006): the standard reference.
- **M. Tinkham**, *Introduction to Superconductivity*, 2nd ed. (Dover, 2004): the classic graduate textbook.
- **R. Körber et al.**, *SQUIDs in biomagnetism: a roadmap*, *Supercond. Sci. Technol.* **29**, 113001 (2016).
- **Vasyukov et al.**, single-electron-spin scanning SQUID, *Nat. Nanotechnol.* **8**, 639 (2013).
- **Nobel Prize in Physics 2025**: Scientific Background (Clarke, Devoret & Martinis), nobelprize.org.