IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), April 2015.
Tutorial presentation given at KRYO 2014, Berlin, September 21-23, 2014.

SQUID Basics

Dietmar Drung

Physikalisch-Technische Bundesanstalt (PTB)
Berlin, Germany

Outline:
- Introduction
- Low-Tc versus high-Tc technology
- SQUID fundamentals and performance
- Readout electronics
- Conclusion

SQUID status as of 2007

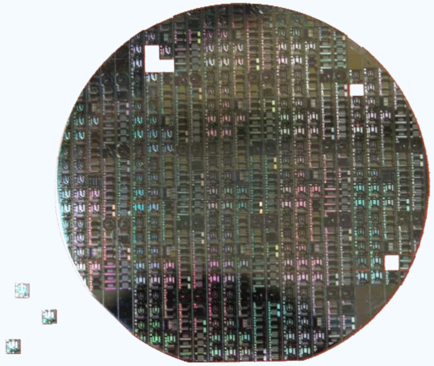
Introduction

The SQUID is an extremely sensitive detector of magnetic flux or of any physical quantity that can be converted into flux

- **Magnetic field or field gradient**
  Biomagnetism (MEG, MCG, magnetorelaxometry)
  Nuclear magnetic resonance (NMR, MRI)
  Non-destructive evaluation (NDE)
  Geophysical sounding
  SQUID microscopy
  Low-temperature noise thermometry (MFFT)
- **Susceptibility**
  Material sciences
- **Electric current**
  Readout of cryogenic radiation detectors (X-ray, VIS, Infrared, THz)
  Cryogenic current comparator (CCC) for realization of electrical units
  Low-temperature noise thermometry (CSNT)
- **Mechanical displacement**
  Gravitational wave detection

SQUID Materials and Fabrication

Common low-T_c material: Niobium



- Transition temperature **T_c = 9.2 K** = -264°C
- Typical operation at **4.2 K** (liquid helium)
- 1970s: SQUIDs = machined bulk Nb cylinders
- Today: Reliable Nb-AlO_x-Nb process on wafer scale
  → **hundreds of SQUIDs in one run**
- Virtually infinite lifetime, but caution:
  SQUID = ESD sensitive device!
  (ESD = electrostatic discharge)

Common high-T_c material: $YBa_2Cu_3O_{7-x}$ (YBCO)

- High-T_c superconductivity discovered in 1986 by Bednorz & Müller
- Transition temperature **T_c ≈ 92 K** = -181°C
- Typical operation at **77 K** (liquid nitrogen)
- Very challenging material → **unsatisfactory junction technology**
  → **multi-layer process very difficult**
  → **no wafer-scale fabrication**

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Low-T_c SQUID vs. High-T_c SQUID

	Low-T_c	High-T_c
SQUID noise	Very low (++)	Low (+)
Chip fabrication costs	Low (+)	Very high (--)
Reliability & reproducibility	Very high (++)	Low (-)
Design flexibility	Very high (++)	Low (-)
Cooling efforts	**Very high (--)**	**High (-)**

→ **Simplified cooling is main advantage of high-T_c SQUID**

But: Customers do not like cooling at all
(unless it is “invisible” → cryocoolers → magnetic interference!)

Cooling to cryogenic temperatures is main restriction for SQUID use, but is accepted if performance is really needed

Example: Helium-cooled magnets in MRI systems

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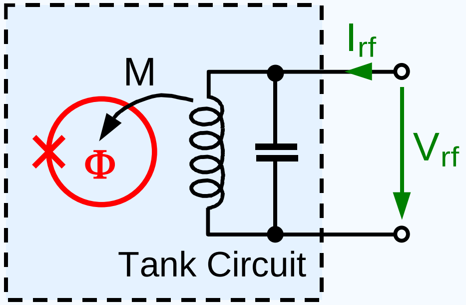
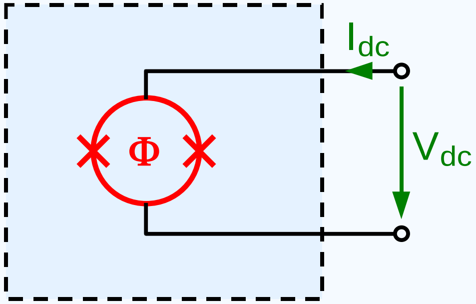
rf SQUID vs. dc SQUID

A SQUID is a superconducting ring interrupted by one or two regions of weak superconductivity, the Josephson junctions

1 JJ = rf SQUID



2 JJs = dc SQUID



- rf voltage V_{rf} depends on flux Φ
- Preamp noise **very crucial**
- High pump frequency → low noise
- 1970s: **30 MHz** bulk Nb rf SQUIDs
- Today: **≈1 GHz** high-T_c rf SQUIDs (Nb rf SQUIDs are “dying breed”)

- dc voltage V_{dc} depends on flux Φ
- Noise usually lower than of rf SQUID
- High-T_c: dc bias → 2...100 kHz ac bias
- Josephson effect: **10 μV dc → 4.8 GHz ac** → might energize microwave resonances in parasitic L/C structures & cause excess noise by mixing in the nonlinear device

rf SQUID vs. dc SQUID

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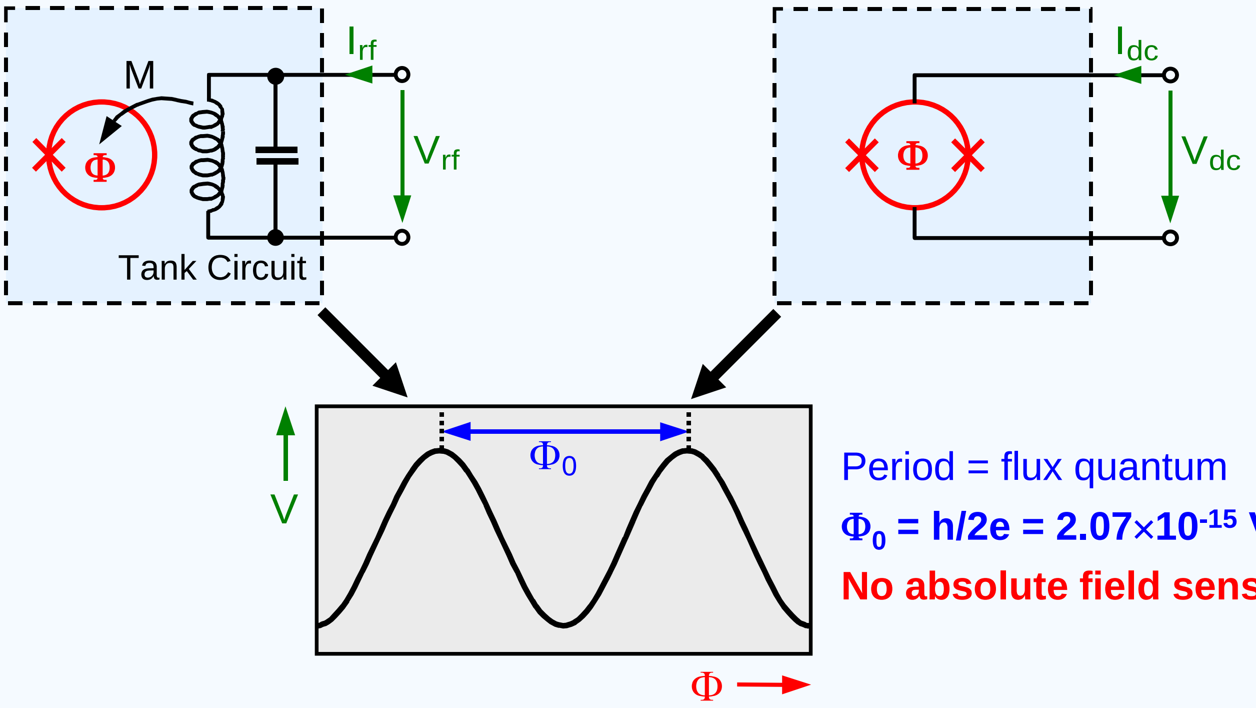
1 JJ = rf SQUID

2 JJs = dc SQUID

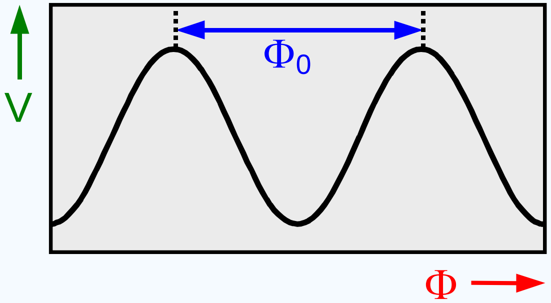


Period = flux quantum

$\Phi_0 = h/2e = 2.07 \times 10^{-15}$ Vs

No absolute field sensor!

SQUID Sensitivity



SQUID ≡ extremely sensitive, nonlinear flux-to-voltage converter

Example

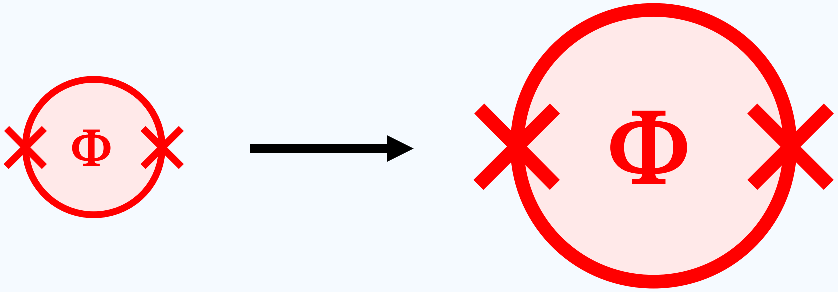
50 µT Earth field in **1 mm²** SQUID loop: **$2.4\times10^{4}\ \Phi_0$**

Noise level of state-of-the-art dc SQUID: **$1\times10^{-6}\ \Phi_0/\sqrt{\text{Hz}}$**

→ rms noise in 1 Hz bandwidth: **$10^{-6}\ \Phi_0 = 4\times10^{-11}$ of Earth field!**

The SQUID has to be shielded very well from external fields!
rf interference might completely suppress V-Φ characteristic!
Use perfect “Faraday cage” around all sensitive structures!

Sensitivity Enhancement



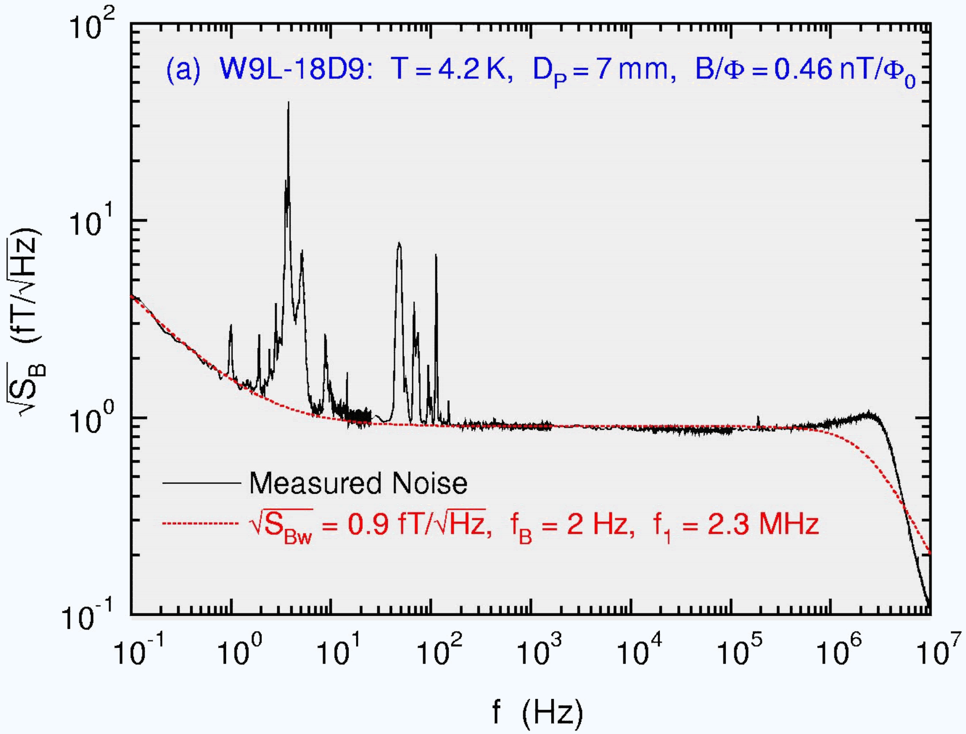
$\Phi = B \times A$ → magnetic field sensitivity increases with **loop area A**,
→ make SQUID loop as large as possible!

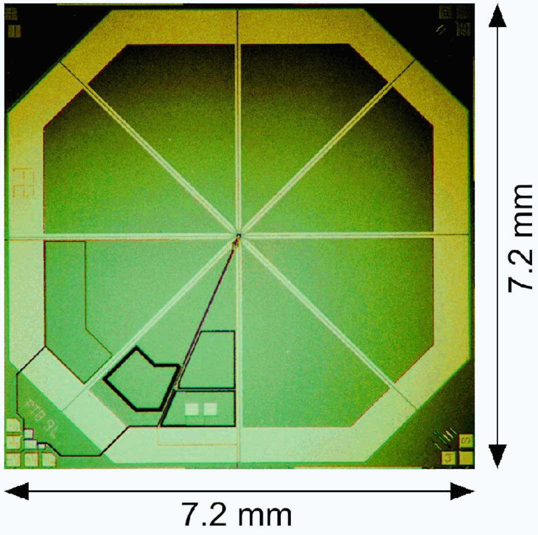
Problem: **loop inductance L** also increases with loop size,
small L required for good flux noise!

Solutions: (1) **Multiloop SQUID** → many loops in parallel to reduce L
→ high sensitivity but limited design flexibility

(2) Large pickup coil coupled to SQUID via **flux transformer**
→ standard scheme with high design flexibility

Example: PTB Low-T_c Multiloop Magnetometer





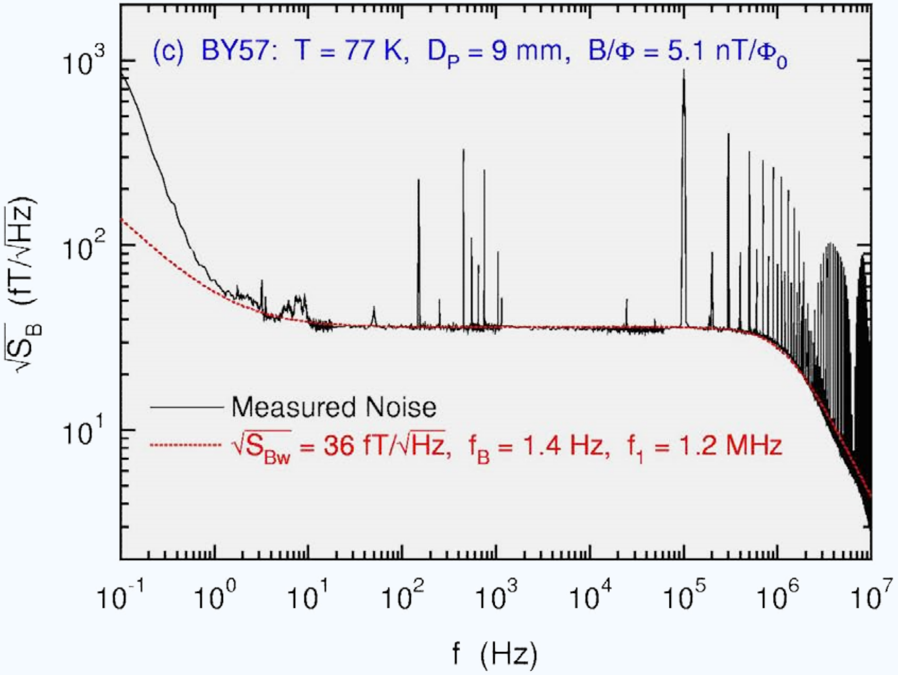
Peak-to-peak noise in 200 Hz bandwidth: $0.9 \times \sqrt{200} \times 6$ fT = 76 fT

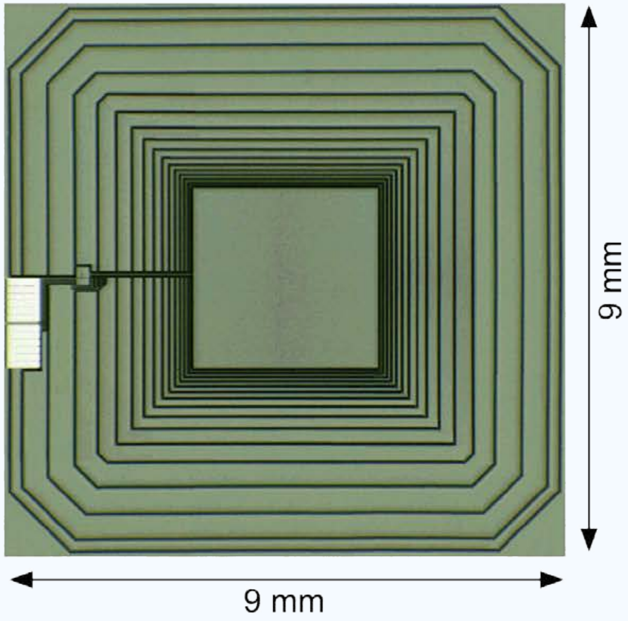
↑

Crest factor

(ratio peak-peak to rms)

Example: PTB High-T_c Magnetometer





≈1 cm^2 single-layer YBCO magnetometers: 20-30 fT/√Hz @ 77 K

≈1 cm^2 multi-layer YBCO magnetometers: ≈10 fT/√Hz @ 77 K

Current record: 2.56 cm^2 multi-layer → **3.5 fT/√Hz @ 77 K** M. I. Faley et al., *J. Physics: Conf. Series* **43**, 1199-1202 (2006)

Some Signal Amplitudes

Peripheral nerve signal (spine)	**0.01 pT**
Low-T_c **system** noise (p-p in 200 Hz bandwidth)	**0.2 pT**
Human brain	**1 pT**
High-T_c **system** noise (p-p in 200 Hz bandwidth)	**4 pT**
Human heart	**50 pT**
Power line interference ("quiet" room)	**10^5 pT**
Earth's field (static)	**5×10^7 pT**

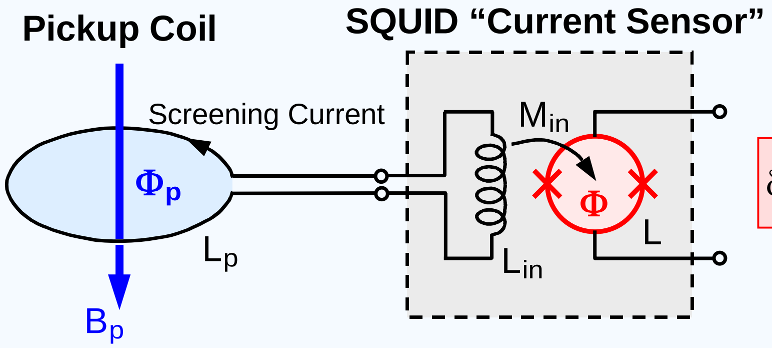
Environmental noise must be suppressed by factor $>10^4$

Shielded room: Expensive and massive (but simplifies system design)

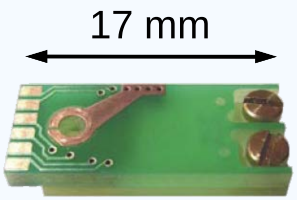
Gradiometer: Low-T_c SQUID → Wire-wound gradiometer coils

High-T_c SQUID → Electronic / software gradiometer

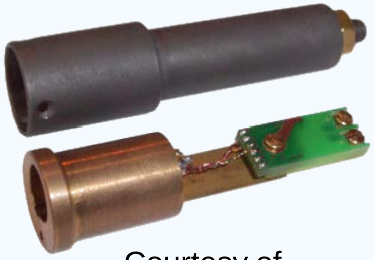
Flux Transformer Coupling



$$\delta\Phi / \delta\Phi_p = \frac{M_{in}}{L_{in} + L_p}$$

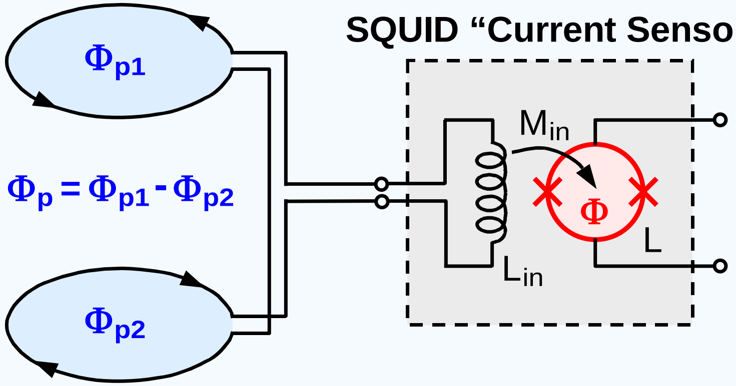


- Flux transfer into SQUID maximized for $L_{in} = L_p$
- Typical values: $L \approx 100$ pH, $L_{in} \approx L_p \approx 1\ \mu$H, $M_{in} \approx 10$ nH
- Noise levels of **1 fT/√Hz** readily achievable
- SQUID inside superconducting Nb shield
  ("current sensor" with screw terminals for wire connection)
- Pickup coil can be adapted to specific application



Courtesy of MAGNICON GbR

Flux Transformer Coupling



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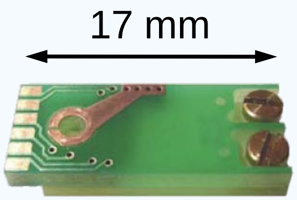

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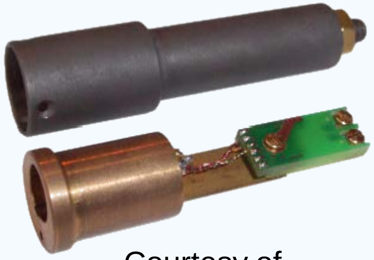
- Noise levels of **1 fT/√Hz** readily achievable
- SQUID inside superconducting Nb shield
  (“current sensor” with screw terminals for wire connection)
- Pickup coil can be adapted to specific application
- Gradiometric coil configurations for noise suppression
  (noise from remote sources equal in both coils → suppressed
  signal source near one coil → amplitude only slightly reduced)



Courtesy of MAGNICON GbR

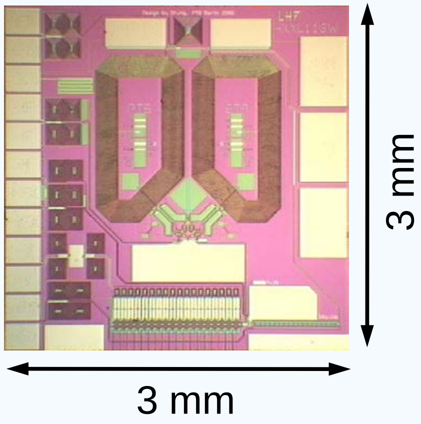
Example: PTB Current Sensors

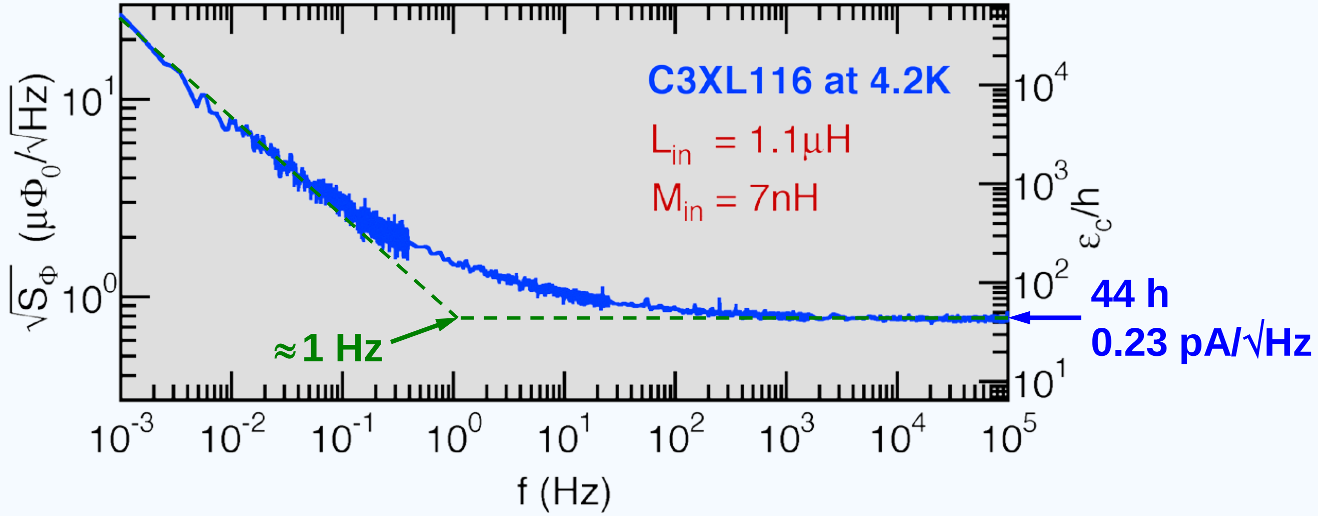
Input inductance L_{in} → 1 nH ... 1.8 µH

Energy resolution $\varepsilon_c = S_I L_{in}/2$ → ≈100 *h* @ 4.2 K

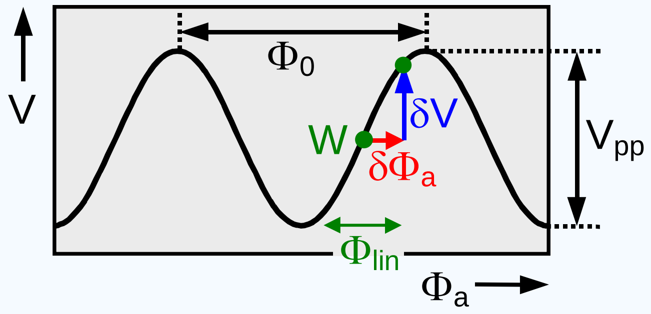
Current noise $\sqrt{S_I}$ → ≈8 pA/√Hz @ 3 nH
→ ≈0.2 pA/√Hz @ 1.8 µH

1/f corner frequency → ≈4 Hz





Small-signal SQUID readout



Small change in applied flux $\delta\Phi_a$
results in
small change in SQUID voltage δV

Main problems:

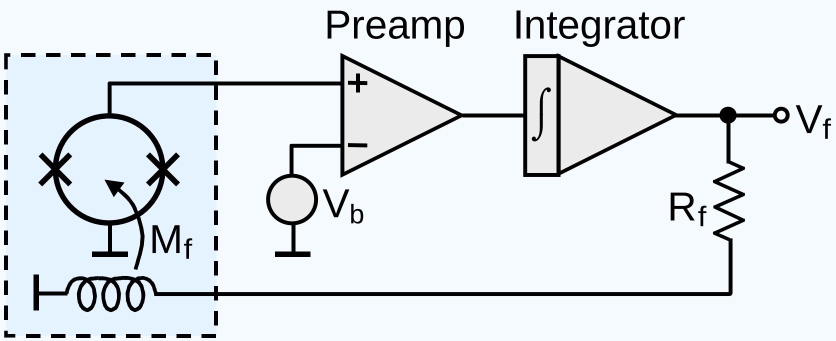
- Very small voltage across the SQUID: **$V_{pp} \approx 10...50\ \mu V$**
- Transfer coefficient **$V_\Phi = dV/d\Phi$** depends on SQUID working point
- Very small linear flux range: **$\Phi_{lin} << \Phi_0$**

Example: Magnetometer with 1 nT/Φ_0 → Human heart signal ≈ 0.05 Φ_0
Power line interference ≈ 300 Φ_0

Main tasks of a SQUID electronics:

- **Amplifies the weak SQUID voltage without adding noise**
- **Linearizes transfer function to provide sufficient dynamic range**

Basic Flux-locked Loop (FLL)



Feedback flux counterbalances applied flux

→ Output voltage V_f depends linearly on applied flux

→ Large dynamic range possible (limit: A/D converter in data acquisition unit)

→ Transfer function does no longer depend SQUID working point

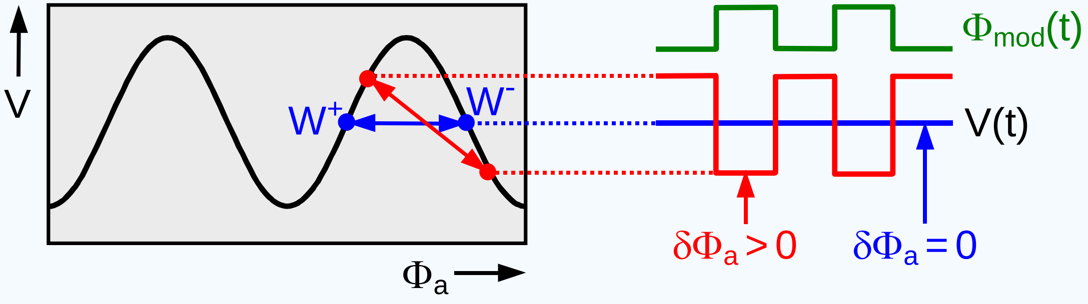
Problems with direct readout:

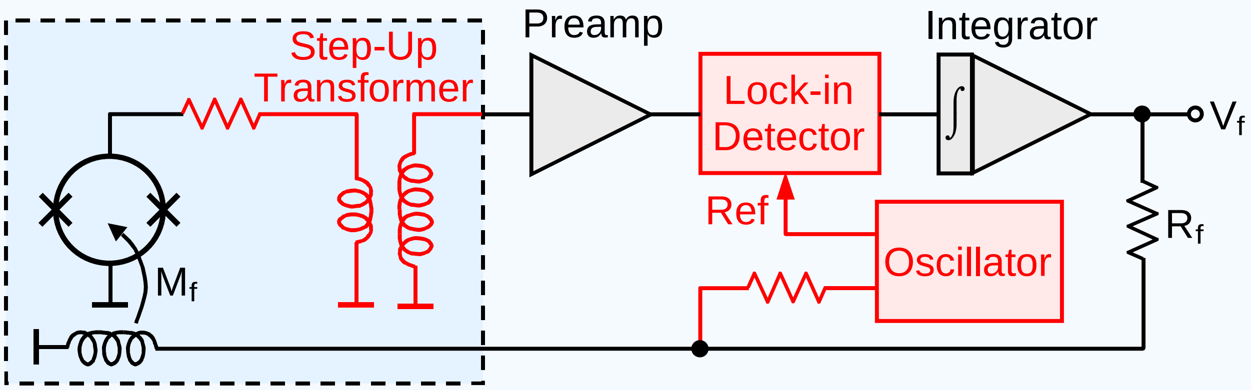
- Low SQUID impedance → Bipolar preamp → high noise temperature
- 1/f noise of preamplifier contributes to system noise

→ Reason for the introduction of flux modulation

R. L. Forgacs and A. Warnick, *Rev. Sci. Instrum.* **38**, 214-220 (1967)
J. Clarke, W. M. Goubau, and M. B. Ketchen, *J. Low Temp. Phys.* **25**, 99-144 (1976)

FLL with Flux Modulation





- Modulation frequency f_{mod} typically **100...500 kHz** → Optimum JFET performance
- Wideband systems with f_{mod} up to **33 MHz** were demonstrated

A. Matlashov et al., *IEEE Trans. Appl. Supercond.* **11**, 876-879 (2001)

Flux Modulation vs. Direct Readout

Flux Modulation Readout:

(+) FET with low noise temperature can be used
(+) Preamplifier low-frequency noise is suppressed
(+) In-phase JJ critical current fluctuations are suppressed
(-) Modulation frequency limits bandwidth
(-) Needs smooth, well-behaved V-Φ characteristics

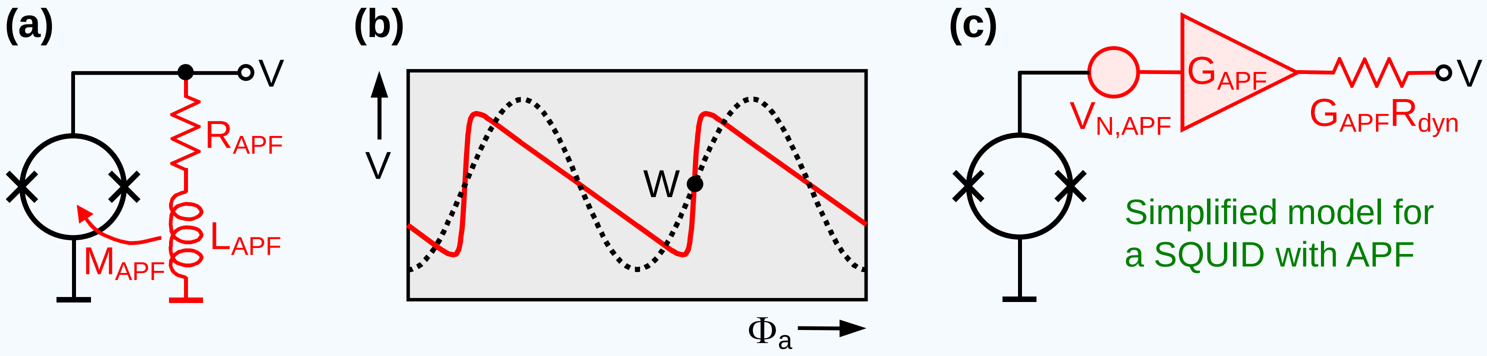
→ **Standard scheme useful for most applications**

Direct Readout:

(+) High system bandwidth can easily be obtained
(+) Resonance-distorted V-Φ characteristics manageable
(+) Electronics more compact than with flux modulation
(-) Preamplifier with low 1/f noise required
(-) More difficult to keep preamplifier noise low enough

→ **Particularly attractive for wideband systems**

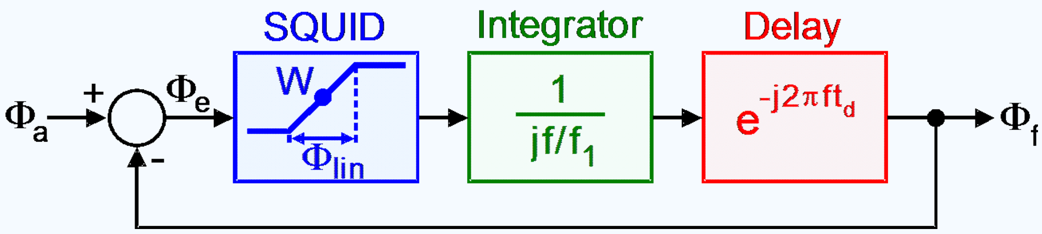
Additional Positive Feedback (APF)



Simplified model for a SQUID with APF

- Preamp voltage noise reduced by increasing V_Φ with a cooled L-R circuit
  → **APF circuit acts as small-signal preamplifier**
  → **Noise temperature ≈ 2 × operation temperature**
- Reduced linear range Φ_{lin} → Do not make APF gain unnecessarily high
- Current noise might be suppressed by bias current feedback (BCF)
- Simple feedback electronics → **Well suited for multichannel systems**

Simplified Model for FLL Dynamics



SQUID: Infinitely fast but nonlinear flux-to-voltage converter
Basic parameter: linear flux range $\Phi_{lin} = V_{pp} / V_\Phi$

Integrator: Ideal one-pole integrator with gain proportional to 1/f
(f_1 = unity-gain frequency of open feedback loop)

Delay: Represents delay on transmission lines plus phase shifts caused by electronic components and SQUID

Flux modulation: Matching transformer & demodulator (mixer)
® **$t_d \approx$ 100 ns** @ $f_{mod} = 16$ MHz
R. H. Koch et al., *Rev. Sci. Instrum.* **67**, 2968-2976 (1996)

Direct readout: Preamp bandwidth & wires to the SQUID
® **$t_d \approx$ 15 ns** @ $f_{3dB} = 20$ MHz
D. Drung et al., *Supercond. Sci. Technol.* **19**, S235-S241 (2006)

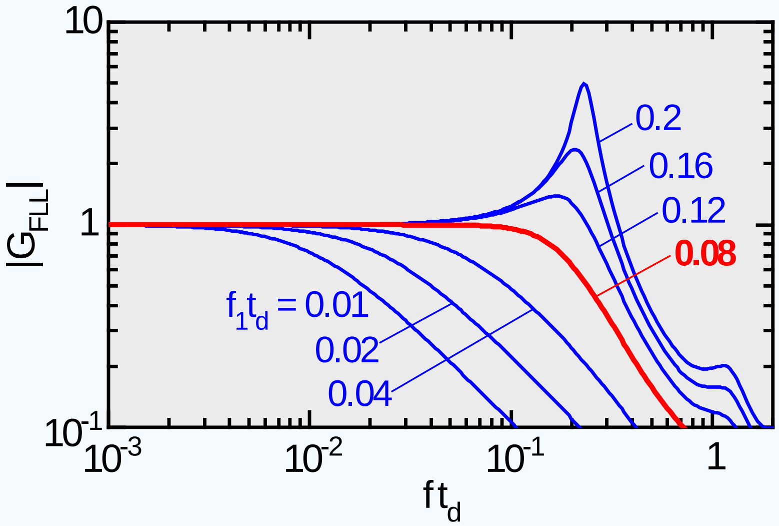
Delay-time Limit

Loop delay limits unity-gain frequency f_1:

Small $f_1 \rightarrow$ FLL with first-order low-pass response $f_{3dB} \approx f_1$

Large $f_1 \rightarrow$ peak in frequency response (stability impaired)

$\mathbf{f_1 = 0.08 / t_d} \rightarrow$ optimally flat frequency response with $\mathbf{f_{3dB} = 2.25\, f_1}$

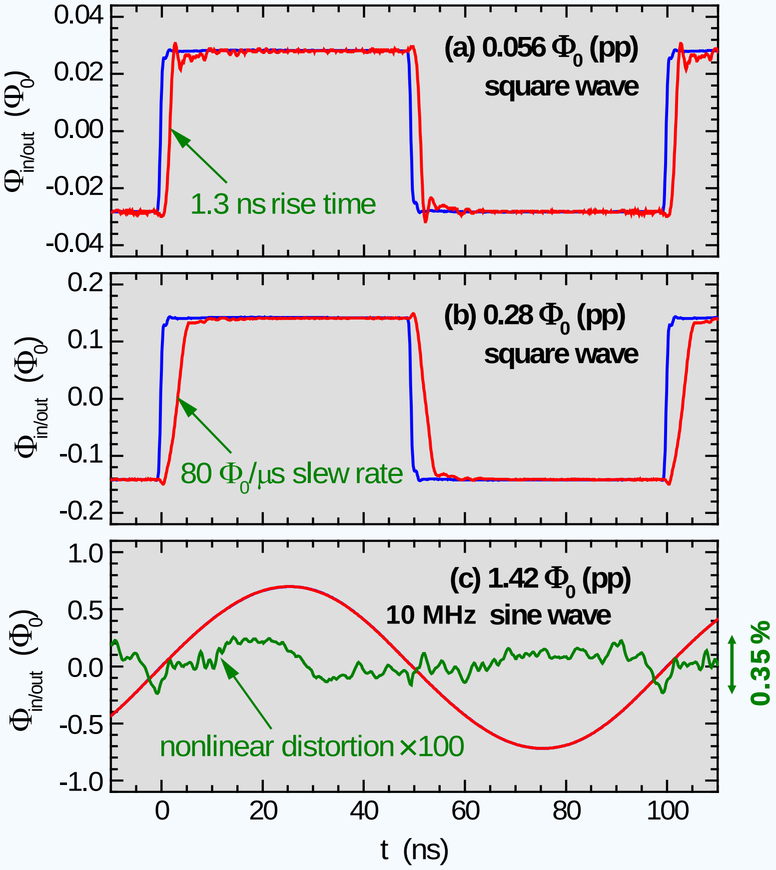


4.2 K systems: ≈1 m distance between SQUID and FLL electronics → $t_d \approx 10$ ns

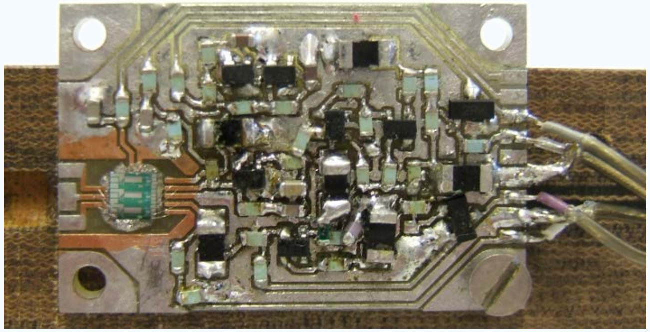
→ ≈ **20 MHz is the maximum system bandwidth with room temperature FLL**

→ reduce distance between SQUID and FLL → max. bandwidth with “cold” FLL

Example: PTB "Cold" FLL Demonstrator



- Complete FLL operated at 4.2 K
- Design with discrete SiGe transistors
- SQUID + FLL on **30 × 20 mm²** board
- Power dissipation ≈ **10 mW @ 4.2 K**
  → keep low to minimize helium boil-off
- Extremely short loop delay ≈ **0.6 ns**
- Very high FLL bandwidth ≈ **350 MHz**
- Flux noise **0.35 µΦ_0/√Hz** (C3X16A)
- Fast step response and low distortion



Conclusion

- Modern low-T_c SQUIDs are **extremely sensitive, versatile & robust**
- Main restriction: **operation at cryogenic temperatures**
- For specific applications, complete systems are available
  → biomagnetism, material sciences, etc.
- General purpose laboratory systems are also available
  → **user can design pickup coil for his specific application**
- User-friendliness greatly improved in the past decades
  → **systems fully computer controlled**