SQUID Basics

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**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 $T_c = 9.2 \text{ K} = -264^\circ\text{C}$
- Typical operation at $4.2 \text{ K}$ (liquid helium)
- 1970s: SQUIDs = machined bulk Nb cylinders
- Today: Reliable Nb-AlO$_x$-Nb process on wafer scale
  $\rightarrow$ hundreds of SQUIDs in one run
- Virtually infinite lifetime, but caution:
  SQUID = ESD sensitive device!
  (ESD = electrostatic discharge)

Common high-$T_c$ material: $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ (YBCO)

- High-$T_c$ superconductivity discovered in 1986 by Bednorz & Müller
- Transition temperature $T_c \approx 92 \text{ K} = -181^\circ\text{C}$
- Typical operation at $77 \text{ K}$ (liquid nitrogen)
- Very challenging material $\rightarrow$ unsatisfactory junction technology
  $\rightarrow$ multi-layer process very difficult
  $\rightarrow$ no wafer-scale fabrication
### Low-$T_c$ SQUID vs. High-$T_c$ SQUID

<table>
<thead>
<tr>
<th></th>
<th>Low-$T_c$</th>
<th>High-$T_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SQUID noise</td>
<td>Very low (++)</td>
<td>Low (+)</td>
</tr>
<tr>
<td>Chip fabrication costs</td>
<td>Low (+)</td>
<td>Very high (--)</td>
</tr>
<tr>
<td>Reliability &amp; reproducibility</td>
<td>Very high (++)</td>
<td>Low (-)</td>
</tr>
<tr>
<td>Design flexibility</td>
<td>Very high (++)</td>
<td>Low (-)</td>
</tr>
<tr>
<td>Cooling efforts</td>
<td>Very high (--)</td>
<td>High (-)</td>
</tr>
</tbody>
</table>

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

1 JJ = rf SQUID

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

2 JJs = dc SQUID

- dc voltage $V_{dc}$ depends on flux $\Phi$
- Noise usually lower than of rf SQUID
- High-$T_c$: dc bias $\rightarrow$ 2...100 kHz ac bias
- Josephson effect: 10 $\mu$V dc $\rightarrow$ 4.8 GHz ac $\rightarrow$ might energize microwave resonances in parasitic L/C structures & cause excess noise by mixing in the nonlinear device
A SQUID is a superconducting ring interrupted by one or two regions of weak superconductivity, the Josephson junctions.

1 JJ = rf SQUID

Tank Circuit

\[ I_{\text{rf}} \]

\[ V_{\text{rf}} \]

2 JJ = dc SQUID

\[ I_{\text{dc}} \]

\[ V_{\text{dc}} \]

Period = flux quantum

\[ \Phi_0 = \frac{h}{2e} = 2.07 \times 10^{-15} \text{ Vs} \]

No absolute field sensor!
SQUID Sensitivity

Example

50 µT Earth field in 1 mm² SQUID loop: $2.4 \times 10^4 \Phi_0$

Noise level of state-of-the-art dc SQUID: $1 \times 10^{-6} \Phi_0/\sqrt{\text{Hz}}$

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

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

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

\[ \Phi = B \times A \rightarrow \text{magnetic field sensitivity increases with loop area } A, \]
\[ \rightarrow \text{make SQUID loop as large as possible!} \]

**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: \(0.9 \times \sqrt{200} \times 6 \text{ fT} = 76 \text{ fT}\)

Crest factor
(ratio peak-peak to rms)
Example: PTB High-Tc Magnetometer

\[ \text{\approx 1 cm}^2 \text{ single-layer YBCO magnetometers: } 20-30 \text{ fT/}\sqrt{\text{Hz}} @ 77 \text{ K} \]

\[ \text{\approx 1 cm}^2 \text{ multi-layer YBCO magnetometers: } \approx 10 \text{ fT/}\sqrt{\text{Hz}} @ 77 \text{ K} \]

Current record: 2.56 cm\(^2\) multi-layer \rightarrow 3.5 \text{ fT/}\sqrt{\text{Hz}} @ 77 \text{ K} \quad \text{M. I. Faley et al.,} \]

\[ J. \text{Physics: Conf. Series} \textbf{43}, 1199-1202 (2006) \]
### Some Signal Amplitudes

<table>
<thead>
<tr>
<th>Source</th>
<th>Amplitude (pT)</th>
</tr>
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<tbody>
<tr>
<td>Peripheral nerve signal (spine)</td>
<td>0.01</td>
</tr>
<tr>
<td>Low-(T_c) system noise (p-p in 200 Hz bandwidth)</td>
<td>0.2</td>
</tr>
<tr>
<td>Human brain</td>
<td>1</td>
</tr>
<tr>
<td>High-(T_c) system noise (p-p in 200 Hz bandwidth)</td>
<td>4</td>
</tr>
<tr>
<td>Human heart</td>
<td>50</td>
</tr>
<tr>
<td>Power line interference (“quiet” room)</td>
<td>(10^5)</td>
</tr>
<tr>
<td>Earth’s field (static)</td>
<td>(5 \times 10^7)</td>
</tr>
</tbody>
</table>

**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

\[ \frac{\delta \Phi}{\delta \Phi_p} = \frac{M_{in}}{L_{in} + L_p} \]

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

\[ 17 \text{ mm} \]

Courtesy of

D.Drung, Kryo 2014
Flux Transformer Coupling

\[ \Phi_p = \Phi_{p1} - \Phi_{p2} \]

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- Noise levels of 1 fT/\( \sqrt{\text{Hz}} \) 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 \( \rightarrow \) suppressed signal source near one coil \( \rightarrow \) amplitude only slightly reduced)

\[ \frac{\delta \Phi}{\delta \Phi_p} = \frac{M_{in}}{L_{in} + L_p} \]
Example: PTB Current Sensors

Input inductance $L_{in} \rightarrow 1 \text{ nH} \ldots 1.8 \text{ } \mu\text{H}$

Energy resolution $\varepsilon_c = S_i L_{in}/2 \rightarrow \approx 100 \text{ } h @ 4.2 \text{ K}$

Current noise $\sqrt{S_i} \rightarrow \approx 8 \text{ pA}/\sqrt{\text{Hz}} @ 3 \text{ nH}$

$\rightarrow \approx 0.2 \text{ pA}/\sqrt{\text{Hz}} @ 1.8 \text{ } \mu\text{H}$

$1/f$ corner frequency $\rightarrow \approx 4 \text{ Hz}$
Small-signal SQUID readout

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 $1 \, \text{nT}/\Phi_0 \rightarrow$ Human heart signal $\approx 0.05 \, \Phi_0$
Power line interference $\approx 300 \, \Phi_0$

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

FLL with Flux Modulation

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

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-\(\Phi\) characteristics

→ **Standard scheme useful for most applications**

**Direct Readout:**

(+) High system bandwidth can easily be obtained  
(+) Resonance-distorted V-\(\Phi\) 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)

- Preamp voltage noise reduced by increasing $V_{\phi}$ with a cooled L-R circuit
  - APF circuit acts as small-signal preamplifier
  - Noise temperature $\approx 2 \times$ operation temperature
- Reduced linear range $\Phi_{\text{lin}}$ → 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 $\Phi_{\text{lin}} = V_{pp} / V_{\Phi}$

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

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

  - **Flux modulation:** Matching transformer & demodulator (mixer)
    $\approx t_d \approx 100 \text{ ns} @ f_{\text{mod}} = 16 \text{ MHz}$

  - **Direct readout:** Preamp bandwidth & wires to the SQUID
    $\approx t_d \approx 15 \text{ ns} @ f_{3\text{dB}} = 20 \text{ MHz}$
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)

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

4.2 K systems: $\approx 1$ m distance between SQUID and FLL electronics $\rightarrow t_d \approx 10$ ns $\rightarrow \approx 20$ MHz is the maximum system bandwidth with room temperature FLL $\rightarrow$ reduce distance between SQUID and FLL $\rightarrow$ 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 $30 \times 20 \text{ mm}^2$ board
- Power dissipation $\approx 10 \text{ mW} @ 4.2 \text{ K}$ → keep low to minimize helium boil-off
- Extremely short loop delay $\approx 0.6 \text{ ns}$
- Very high FLL bandwidth $\approx 350 \text{ MHz}$
- Flux noise $0.35 \mu \Phi_0/\sqrt{\text{Hz}}$ (C3X16A)
- Fast step response and low distortion

![Graphs showing various waveforms and their characteristics.]

D.Drung, Kryo 2014
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**