SQUIDs: From Cosmology to Magnetic Resonance Imaging in Microtesla Fields

- Milestones in superconductivity
- The SQUID
- Applications of SQUIDs: an overview
- Searching for cold dark matter with a SQUID
- Magnetic resonance imaging with a SQUID

The Finnish Academy
8 November 2004
### Centigrade/Kelvin/Fahrenheit Temperature Scales

<table>
<thead>
<tr>
<th>Temperature Event</th>
<th>°C</th>
<th>K</th>
<th>°F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room temperature</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ice point</td>
<td>0</td>
<td>273</td>
<td>32</td>
</tr>
<tr>
<td>Vostok, Antarctica -88 °C 8/24/60</td>
<td>-100</td>
<td>173</td>
<td></td>
</tr>
<tr>
<td>B.P. liquid nitrogen 77K</td>
<td>-200</td>
<td>73</td>
<td></td>
</tr>
<tr>
<td>B.P. liquid helium 4.2K</td>
<td>-273</td>
<td>0</td>
<td>-459</td>
</tr>
</tbody>
</table>
Milestones in Superconductivity

1911  Kamerlingh Onnes discovers zero resistance
The Discovery of Superconductivity

Resistance vanishes below the transition (or critical) temperature $T_c$
Magnetic Fields

The earth

- ~1 gauss
- $10^{-4}$ tesla

Bar magnet

- ~1000 gauss
- 0.1 tesla
Zero Resistance

Magnetic field

- Current persists forever
- Resistance at least one billion billion times less than copper
- Basis of superconducting magnets
A Few Other Superconductors

<table>
<thead>
<tr>
<th>Element</th>
<th>$T_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>1.2 K</td>
</tr>
<tr>
<td>Indium</td>
<td>3.4 K</td>
</tr>
<tr>
<td>Tin</td>
<td>3.7 K</td>
</tr>
<tr>
<td>Lead</td>
<td>7.2 K</td>
</tr>
<tr>
<td>Niobium</td>
<td>9.2 K</td>
</tr>
</tbody>
</table>

- “Type I” superconductors
- Driven normal by magnetic fields less than 2000 gauss
Milestones in Superconductivity

1911  Kamerlingh Onnes discovers zero resistance

1957  Bardeen, Cooper and Schrieffer develop “BCS” theory
Normal Metals vs. Superconductors

**Normal Metals**

- Electron has charge $-e$
- Scattering of electrons produces resistance.
- A current generates a voltage, and hence causes dissipation.

**Superconductors : BCS Theory**

- Electrons are paired together: these Cooper pairs have charges $-2e$
- Cooper pairs carry a supercurrent which encounters no resistance.
- A supercurrent generates no voltage, and hence causes no dissipation.
Milestones in Superconductivity

1911  Kamerlingh Onnes discovers zero resistance

1957  Bardeen, Cooper and Schrieffer develop “BCS” theory

1957  Alexei Abrikosov predicts Type II superconductors  Large-scale applications are made possible
Type II Superconductors

Alloys: ~2000 known

The secret of their success: Type II materials admit “vortices” of magnetic field, and the supercurrents flow around them.

High field magnets made possible.
Flux Quantization

\[ \Phi = n \Phi_0 \]

where

\[ \Phi_0 \equiv \frac{\hbar}{2e} \approx 2 \times 10^{-15} \text{ Wb} \]

is the flux quantum
Milestones in Superconductivity

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Large-scale applications are made possible

1960  Ivar Giaever invents tunnel junctions

1962  Brian Josephson invents “Josephson Tunneling”

Superconducting electronics is born
Josephson Tunneling

- Cooper pairs tunnel through barrier  
  
  Brian Josephson 1962

Josephson Tunneling

- Cooper pairs tunnel through barrier

Created the field of superconducting electronics

Diagram: Two superconductors separated by an insulating barrier. The barrier thickness is approximately 20 Å. The graph shows a plot of current vs. voltage, indicating a sharp increase in current at a certain voltage threshold, characteristic of Josephson tunneling.
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1986 Bednorz and Muller discover high-$T_c$ superconductivity

Large-scale applications are made possible

Superconducting electronics is born
Transition Temperature Over the Years

<table>
<thead>
<tr>
<th>Material</th>
<th>Year</th>
<th>Temperature (Kelvin)</th>
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<tbody>
<tr>
<td>Hg</td>
<td>1911</td>
<td>-100 °C</td>
</tr>
<tr>
<td>Pb</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nb</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NbN</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(La/Sr)CuO</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(La/Sr)CuO</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(La/Sr)CuO</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SrTiO3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MgB2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HgBa2Ca2Cu3O</td>
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<td></td>
</tr>
<tr>
<td>Bi2Sr2Ca2Cu3O10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>YBa2Cu3O7</td>
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<td></td>
</tr>
<tr>
<td>Nb3Ge</td>
<td></td>
<td></td>
</tr>
<tr>
<td>liquid He</td>
<td></td>
<td></td>
</tr>
<tr>
<td>liquid N2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
YBCO
Milestones in Superconductivity

1911  Kamerlingh Onnes discovers zero resistance  
       Nobel Prize 1913

1957  Bardeen, Cooper and Schrieffer develop “BCS” theory  
       Nobel Prize 1972

1957  Alexei Abrikosov predicts Type II superconductors  Large-scale applications are made possible  
       Nobel Prize 2003

1960  Ivar Giaever invents tunnel junctions  Superconducting electronics is born
       Nobel Prize 1973

1962  Brian Josephson invents “Josephson Tunneling”  
       Nobel Prize 1973

1986  Bednorz and Muller discover high-$T_c$ superconductivity  
       Nobel Prize 1987
The SQUID
The dc Superconducting Quantum Interference Device

- **dc SQUID**
  
  Two Josephson junctions on a superconducting ring

- **Current-voltage (I-V) characteristic modulated by magnetic flux $\Phi$:**
  
  Period one flux quantum $\Phi_o = h/2e = 2 \times 10^{-15}$ T m$^2$
Low-$T_c$ SQUID

Operating temperature = 4.2 K

**Multilayer device**: niobium - aluminum oxide - niobium

![Image of Nb-AlOx-Nb SQUID with input coil and Josephson junctions]
Superconducting Flux Transformer: Magnetometer and Gradiometer

\[ B_N \sim 1 \text{ fT Hz}^{-1/2} \]

Flux-locked SQUID

Flux-locked SQUID
Magnetic Fields

tesla

\[ 10^{-4} \]
Earth’s field

\[ 10^{-6} \]
Urban noise

\[ 10^{-8} \]
Car at 50 m

\[ 10^{-10} \]
Human heart

\[ 10^{-12} \]
Fetal heart

\[ 10^{-14} \]
Human brain response

\[ 10^{-16} \]
1 femtotesla

SQUID
Applications of SQUIDs: An Overview
Olli Lounasmaa

Olli was did much to bring SQUIDs to Finland, and greatly encouraged their application to Magnetoencephalography (MEG). MEG is the single biggest consumer of SQUIDs, and has important applications in both brain research and clinical diagnosis. Neuromag is a leading supplier of MEG systems around the world. Olli was also deeply involved with the use of SQUIDs to study nuclear ordering in copper and silver at ultralow temperatures.
Neuromag® 306-Channel SQUID System for Magnetoencephalography
Applications of Magnetoencephalography

Clinical (Reimbursable in the United States)
- Presurgical screening of brain tumors (evoked response)
- Location of epileptic foci (spontaneous signals)

Research
- Language mapping in the brain
- Identification of patients with schizophrenia
- Identification of patients with dyslexia
- Alzheimer's disease
- Parkinson's disease
- Neurological recovery following stroke or hemorrhage
CardioMag Imaging System for Magnetocardiography
Quantum Design "Evercool"

Cut-away Dewar View

- Coldhead controlled by remote compressor
- First stage cools the shield to 40 K
- Second stage cools the condenser to 4 K
- Condenser unit liquefies the helium gas
2G Superconducting Rock Magnetometer
SQUID Surveying for Minerals

System Geometry

Primary field

Secondary field

Conductor

135m

120m

115m

66m

Courtesy Cathey Foley (CSIRO)
MAGMA-C1 Scanning SQUID Microscope
Neocera, Inc.

A Non-Contact, Non-Destructive Next Generation Imaging tool for the Semiconductor Industry’s complex devices, advanced packages, and full assemblies
Atacama Pathfinder EXperiment
Gravity Probe-B
Tests of General Relativity

Courtesy Stanford University and NASA
UC Berkeley Flux Qubits

Qubit 1

Qubit 2

35 μm
Searching for Axions: The Microstrip SQUID Amplifier

University of Gießen
Michael Mück
Jost Gail
Christoph Heiden†

UCB, LBNL and LLNL
Marc-Olivier André
Darin Kinion
Jan Kycia

Support: DOE/BES
DOE/HEP
NSF
Cold Dark Matter

- Recent cosmic microwave background measurements indicate that
  ~25% of the mass of the universe is cold dark matter (CDM).

- A candidate particle is the axion, proposed in 1978 to explain the
  absence of a measurable neutron electric dipole moment.

- The axion is predicted to be a very light particle with no charge or spin.
Resonant Conversion of Axions into Photons

Pierre Sikivie (1983)

Primakoff Conversion

Expected Signal

\[ \frac{\Delta \nu}{\nu} \sim 10^{-6} \]
Axion Detector at Lawrence Livermore National Laboratory
Noise Temperature

\[ S_V^0 (f) = A^2 \cdot 4k_B[T + T_N(R)]R \]
LLNL Axion Detector

• Current system noise temperature: \( T_S = T + T_N \approx 3.2 \text{ K} \)
  
  Cavity temperature: \( T \approx 1.5 \text{ K} \)

  Amplifier noise temperature: \( T_N \approx 1.7 \text{ K} \)

• Time to scan the range of frequencies from \( f_1 \) to \( f_2 \):
  
  \[ \tau(f_1, f_2) \approx 4 \times 10^{16} (T_S/1 \text{ K})^2 (1/f_1 - 1/f_2) \text{ sec} \]

  For \( f_1 = 0.24 \text{ GHz, } f_2 = 2.4 \text{ GHz} \): \( \tau \approx 45 \text{ years} \)

• Note: There is only a factor of 2 to be gained in \( T_S \) by reducing \( T \) unless \( T_N \) is also reduced.
Microstrip SQUID Amplifier

Conventional SQUID Amplifier
- Source connected to both ends of coil

Microstrip SQUID Amplifier
- Source connected to one end of the coil and SQUID washer; the other end of the coil is left open
Gain vs. Coil Length

- Gain (dB) vs. Frequency (MHz)
- Coil Length (mm) vs. $v_{res}$ (MHz)

- 71 mm, 33 mm, 15 mm, 7 mm
Noise Temperature of Microstrip Amplifier

At 20 mK the noise temperature is 50mK, about 40 times lower than that of the current semiconductor amplifier
Microstrip SQUID Amplifier: Impact on Axion Detector

- Current LLNL axion detector: $T_S \approx 3.2 \text{ K}$
- For $T \approx T_N \approx 50 \text{ mK}$: $T_S \approx T + T_N \approx 100 \text{ mK}$
  
  $\tau \approx 45 \text{ years} \times (0.1/3.2)^2$
  
  $\approx 18 \text{ days}$
Summary

• Gain $\geq 20$ dB for frequencies $\leq 1$ GHz
• Cooled to 20 mK, $T_N$ is within a factor of 2 of the quantum limit
• Noise temperature 40 times lower than state-of-the-art cooled semiconductor amplifiers

Future directions

• Implement second-generation axion detector: expected to increase scan rate by three orders of magnitude
• Post-amplifier for radio-frequency single-electron transistor: should enable quantum-limited charge amplifier
Microtesla Nuclear Magnetic Resonance and Magnetic Resonance Imaging

- **Nuclear magnetic resonance**
  - Michael Hatridge
  - Nathan Kelso
  - SeungKyun Lee
  - Robert McDermott
  - Michael Mössle
  - Michael Mück
  - Whit Myers
  - Bennie ten Haken
  - Andreas Trabesinger
  - Erwin Hahn
  - Alex Pines

- **Magnetic resonance imaging**
Nuclear Magnetic Resonance

Energy

Protons

\[ E = +\mu_p B \]
\[ E = -\mu_p B \]

\[ \omega_0 = \gamma B_0 \]

\[ \nu_0 = 42.58 \text{ MHz/tesla} \]

Magnetic moment \((\mu_p B_0 \ll k_B T)\)

\[ M = N\mu_p \frac{N_{\uparrow} - N_{\downarrow}}{N_{\uparrow} - N_{\downarrow}} = \frac{N\mu_p^2 B_0}{k_B T} \]

Equilibrium

RF pulse

Precession
High Field MRI

3T MRI scanner (GE)  1.5T MRI scanner (GE)
“Most people”, Gordon said, “don’t realize that the ordinary hospital MRI works by changing the quantum state of atoms in your body ... But the ordinary MRI does this with a very powerful magnetic field - say 1.5 tesla, about twenty-five thousand times as strong as the earth’s magnetic field. We don’t need that. We use Superconducting QUantum Interference Devices, or SQUIDs, that are so sensitive they can measure resonance just from the earth’s magnetic field. We don’t have any magnets in there”.

Timeline
Michael Crichton, 1999
The “Cube”
MRI Coils

- $B_x$, $B_y$, $B_z$ compensation
- low noise cryostat
- gradiometer
- sample
- $dB_z/dx$
- $dB_z/dz$
- $B_0$ (precession field)
- polarization field
- $B_1$ (excitation field)
Red Pepper

\[ B_0 = 132 \mu T \]
\[ G = 100 \mu T/m \]
48 projections
1.5 min. acquisition
Corn

$B_0 = 132 \mu T$
$G = 100 \mu T/m$
48 projections
3 min. acquisition
Three dimensional images of pepper
T$_1$-weighted Contrast Imaging

- $T_1$ is the relaxation time of the proton spins
- $T_1$ depends strongly on the environment of the protons
- T$_1$-weighted contrast imaging is widely used in conventional MRI to distinguish different types of tissue
- $T_1$ (malignant tissue) > $T_1$ (normal tissue)
- T$_1$-contrast can be much higher in low fields
$B = 13.2 \text{ mT}$

$B = 300 \text{ mT}$

$T_1$ contrast images of agarose gel

$0.25\%$ agarose

$0.5\%$ agarose

$B_{\text{int}} = 10 \mu\text{T}$

$B_{\text{int}} = 132 \mu\text{T}$

$B_{\text{int}} = 13.2 \text{ mT}$

$B_{\text{int}} = 300 \text{ mT}$
$T_1$ contrast in 132 $\mu$T: water vs. gel

$A-B$ (arb. unit)

$t_d = 20$ ms  \quad t_d = 200$ ms  \quad t_d = 400$ ms

water  \quad gel

water  \quad 0.5\% agarose gel

40mm
Forearm (20 mm slice)

\[ B_p \sim 40 \text{ mT} \]
\[ B_0 = 132 \mu\text{T} \]

\[ B_0 = 4 \text{ T} \]

4T image:
Courtesy of Ben Inglis,
Henry H. Wheeler, Jr.
Brain Imaging Center,
UC Berkeley
Future directions for low-field MRI

- Reduce system noise
  - Increased signal-to-noise ratio
  - Reduced acquisition time

- Multichannel system
  - Increased signal-to-noise ratio
  - Improved spatial resolution
  - Increased coverage

- Combine low-field MRI with existing technology for magnetoencephalography (MEG)

- Low-cost “open” MRI system
  - Screening for tumors (with $T_1$-weighted contrast)
  - Imaging knee, foot, elbow, wrist ...
  - Monitoring $T_1$ in bone marrow