Superconducting quantum interference devices and their applications

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SQUIDs and Their Applications

• Superconducting Quantum Interference Devices
• Theory and Applications
• Magnetometer for neutron EDM experiment
• Geomagnetic monitoring
• Tracking groundwater flow
• Magnetotellurics – mapping the subsurface with natural geomagnetic probe
• Technical challenges
• Future, hybrid magnetometers, options for cooling
SQUID Magnetometers

- Superconducting Quantum Interference Devices
- fT/Hz\(^{-1/2}\) magnetometers
- Track changes in magnetic flux (not absolute magnetometers) - Easily disrupted by interference

[SQUID]\(^2\) - SQUID with Shielding QUalified for Ionosphere Detection - permanently installed at LSBB
SQUIDs - Principle

Josephson Junctions

Critical current

\[ I_c = I_0 \sin(\varphi_2 - \varphi_1) \]

DC SQUID

Critical current

\[ I = I_0 \cos\left(\frac{e\Phi}{\hbar}\right) \]

Voltage across loop varies periodically with the flux through loop

Superconducting Loop

Flux quantization

\[ \Phi = n\left(\frac{\hbar}{2e}\right) \]
SQUID – control circuit

- Applications: Magnetoencephalography; Material studies (Magnetization, Susceptibility); Geophysics; Nuclear magnetic resonance; Superconducting thermometer readout

Connect pick-up loop or input circuit

Linearize response with feedback circuit
Neutron Electric Dipole Moment

• The neutron EDM is a probe for New Physics which could explain the matter-antimatter asymmetry of the Universe

• Measure Larmor spin precession frequency of stored UCN in electric and magnetic field

\[ h \nu_0 = 2\mu \cdot B + 2d \cdot E \]

• Next generation of cryogenic experiments require magnetometer to track 0.1pT field in superfluid helium
cryoEDM 12-channel SQUID system

- Track magnetic field in neutron cell to 0.1pT resolution
- Pick-up loops separated from SQUIDs by ~1.5m – TWPs screened by superconducting capillaries
- SQUIDs and pick-up loops operate in 0.5K superfluid
- SQUID sensors by Supracon AG, Germany
- Preamplifiers: Star Cryoelectronics, USA
- Control, digitization and software developed by Oxford University
cryoEDM  SQUID system
SQUID magnetometry measurements at LSBB

- Collaboration with geophysicists – SQUIDs for geomagnetism
- Tested latest cryoEDM SQUID electronics with software reset control in low noise laboratory
- Simultaneous measurements with two SQUID systems
### Measurements at LSBB

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Hydrogeology with SQUIDs

• Use two SQUID magnetometers to subtract ionospheric background

• Detect local variations in the magnetic field – groundwater flow (electrokinetic effect)
Result:
Magnetic Signal at Water Flow Point

SQUID signal at flow point
Red periods – disrupted by interference
Reference SQUID signal in Capsule
INTERMAGNET data

Increase to 1.4l/min over 3 hours following heavy rainfall
Water flow rate ~0.2l/min
Magnetic signal during water flow anomaly

- All magnetic anomalies can be attributed to telluric currents or mechanical disturbance.
- Result fits null hypothesis (no electrokinetic signal) – limit $B_{EK} < 0.2 \text{nT}$.
Magnetotellurics: Exploration Geophysics with natural magnetic source

**Probe:** Geomagnetic fluctuations generated in ionosphere

**Telluric currents** induced in ground – proportional to electrical conductivity

Simultaneous measurement of magnetic signals and electric fields at multiple locations ... compare to model predictions ... infer subsurface conductivity ... measure groundwater level

Novel Magnetic Sensors Workshop, Rutherford Appleton Laboratory, 12 March 2015
Magnetotellurics: Applications

- Monitor groundwater
  - Saline Intrusion
- Monitoring deep aquifers
  - CO₂ storage?
  - Contamination from shale gas fracking?
- Exploration geophysics
  - Groundwater in arid environments?
  - Geothermal energy?
  - Mineral deposits?
  - Hydrocarbons?
- Mapping flooded underground cavities?
Towards a Worldwide Network of SQUIDs for Near-Space and Earth Studies

- Continuous geomagnetic monitoring essential to study space weather, ionosphere interactions, seismo-magnetic effects
- SQUIDs offer improved sensitivity, broader bandwidth and higher dynamic range than existing systems (fluxgates)
- Network required to distinguish global signals, search for directional or polarization information from earthquake precursors

Practical Issues: Cooling SQUIDs

- Liquid Helium
  - Expensive, difficult to transport to remote areas, requires regular refilling
  - Required for low noise measurements
- Liquid Nitrogen
  - Much cheaper easier to handle
  - High Tc SQUIDs $\sim \times 10$ worse resolution, potential issues with 1/f noise
- Cryocoolers
  - High capital cost, low long term running cost
  - Significant power consumption
  - Generate vibrational and magnetic noise
  - Potential for improvement
Hybrid Magnetometry

- SQUIDs and fluxgates
  - Allow a SQUID magnetometer to recover from interference induced glitches?
- SQUIDs and induction coils
  - SQUIDs for quasi dc / low frequencies
  - Induction coils for audio frequencies
- SQUIDs and atomic magnetometer
  - Calibrate absolute field through Larmor frequency of precessing nuclei
  - Helium-3 suited for cryogenic environment
Future

- Geophysics / Industry
  - Can the better magnetic field resolution of SQUIDs improve the power of exploration geophysics with magnetotellurics?
- Geomagnetic monitoring
  - Build up worldwide network of SQUID geomagnetic observatories
  - Demonstrate reliability of instruments
  - Investigate correlations – search for space weather / seismomagnetic effects
- Hybrid SQUID – $^3$He magnetometer