IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), No. 41, July 2017.
This keynote presentation Tu-KEY-02 was given at ISEC 2017.

SQUID Fundamentals and Applications

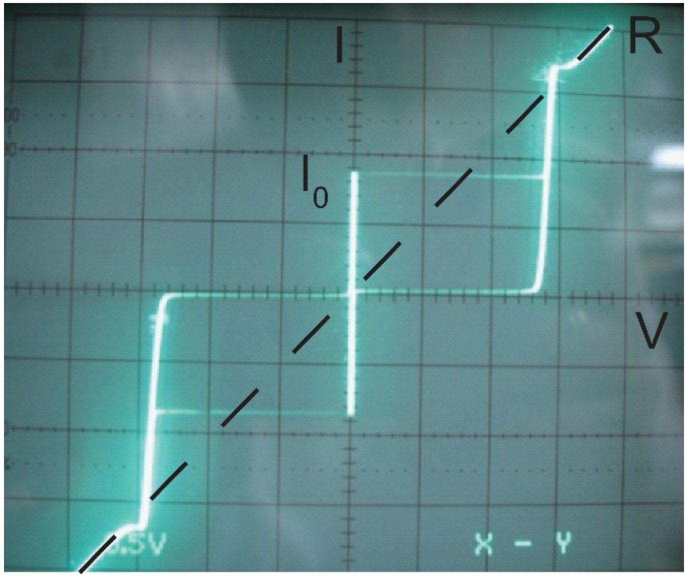
Robin Cantor
STAR Cryoelectronics

- **What are Josephson Junctions and DC SQUIDs?**
- **SQUID Readout Electronics**
- **SQUID Applications**
  - **Biomagnetism**
  - **Geophysics**
  - **Non-Destructive Testing**
  - **Basic Research**

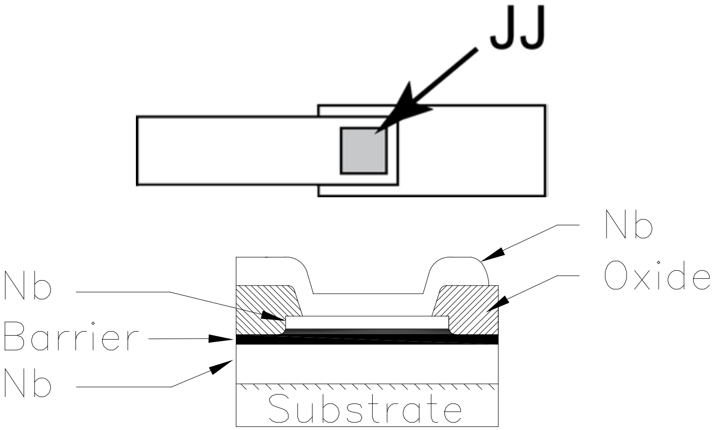
What Is A Josephson Junction?

Two superconductors coupled by a weak link

- Thin insulating barrier (superconductor–insulator–superconductor or SIS junction)
- Thin layer of non-superconducting metal (superconductor-normal metal-superconductor or SNS junctions)
- A physical constriction at which superconductivity is weakened
- Predicted in 1962 by Brian Josephson, confirmed experimentally by Anderson and Rowell in 1963



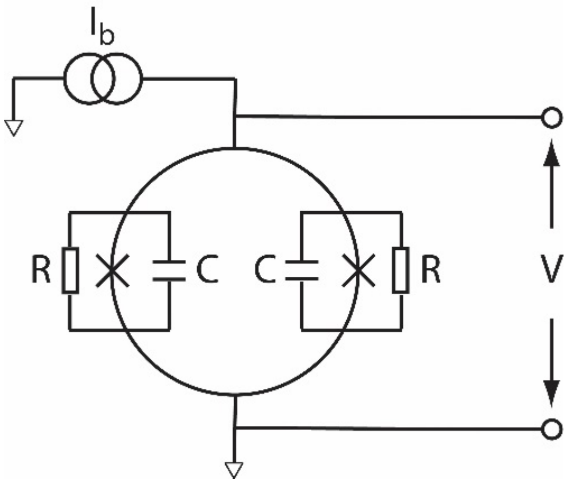
Low temperature superconductor (LTS) window-type junction, patterned using Selective Nb Etch Process (SNEP)



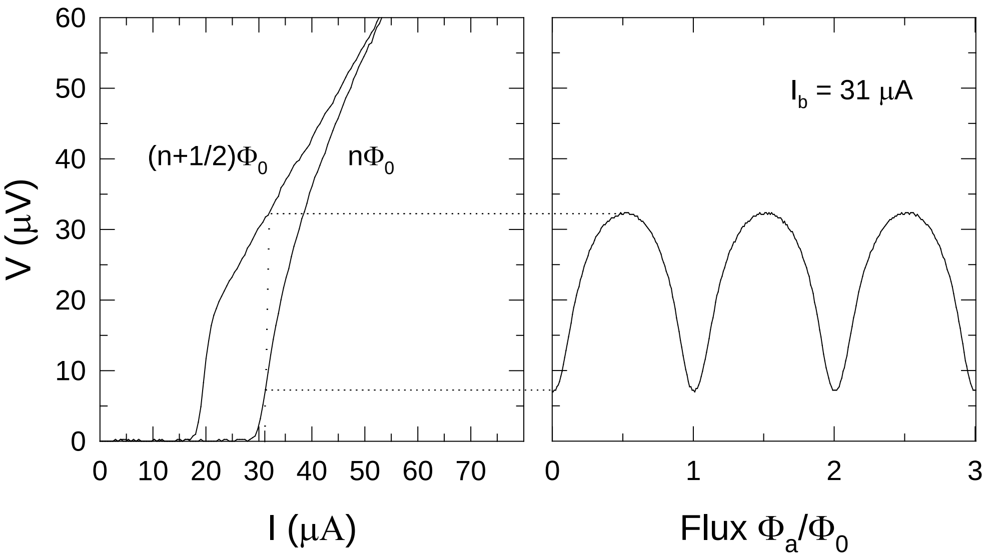
What Is A DC SQUID?

- Two Josephson junctions connected in parallel with superconducting wire
- Usually operated using DC current bias

Resistively Shunted Junction (RSJ) model



Voltage-current (V-I) and voltage-flux (V-Φ) characteristics



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Basic DC SQUID Design

Optimal Design Parameters

Stewart-McCumber parameter: $\beta_c = \frac{2\pi}{\Phi_0} I_0 R^2 C < 1$

Modulation parameter: $\beta_L = \frac{2LI_0}{\Phi_0} \approx 1$

Energy resolution: $\varepsilon = \frac{S_\Phi}{2L} \approx 16 k_B T \sqrt{LC} \propto \frac{C_s}{J_c}$

For lowest noise performance (LTS window-type junctions),

- Low SQUID inductance — $L \sim 10$ to 100 pH
- Low capacitance junctions — $C << 1$ pF
- High critical current density — $J_c \sim 1{,}000$ to 100 A/cm^2

For A_J ~10 µm^2, J_c = 1 µA/µm^2 = 100 A/cm^2

For A_J ~1 µm^2, J_c = 10 µA/µm^2 = 1,000 A/cm^2

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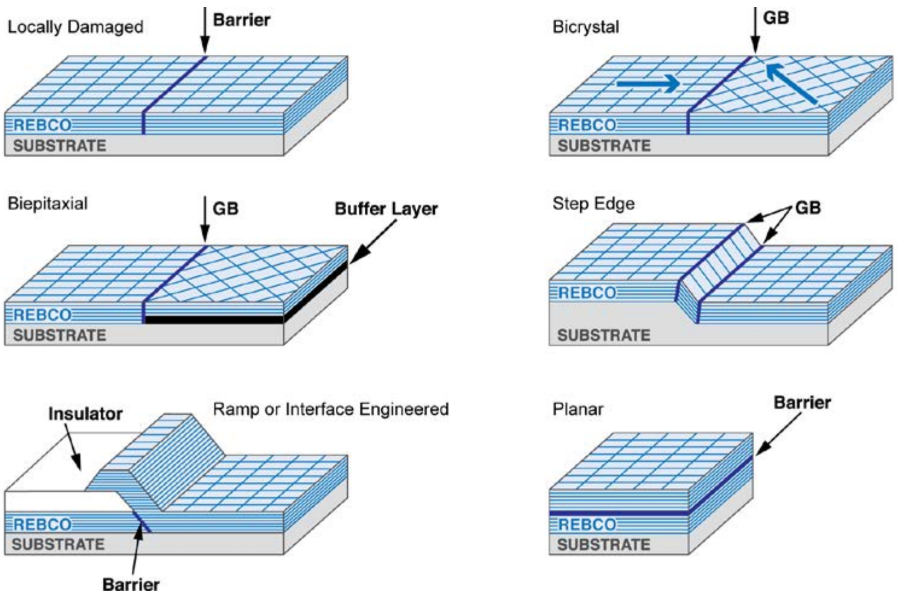
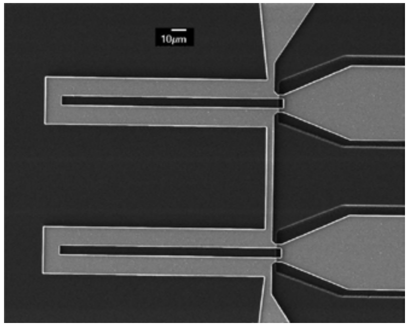
Junction Fabrication, HTS





– Step-edge dual SQUID
– ~30 fT/Hz½ for 8x8 mm² magnetometer

M. I. Faley et al., IEEE Trans. Appl. Supercond. **26**, 2016, 1600404.

Locally Damaged Weak Links (e.g., UCSD, ESPCI)

- Focused beam or irradiation
- Low R_n, I_cR_n at 77 K; weak V-Φ
- Single-layer; attractive for dense circuits

Bicrystal

- STO with 24, 30 or 36 degree angles
- Yields ~100%, reasonable uniformity
- Single-layer; constrained by GB

Step Edge (e.g., CSIRO, Juelich)

- High I_cR_n (200-300 µV), Φ_n ~4 µΦ_0 (75 K)
- Good uniformity; single-layer

Ramp Edge (e.g., STI, SUSTERA)

- Deposited or interface engineered barrier; enables multilayer designs
- 10 fT/Hz½ for 15x15 mm² magnetometer with 20-turn input coil; high 1/f noise below 1 kHz

S. Adachi et al., IEICE Trans. Electron. **E95-C**, 2012 337.

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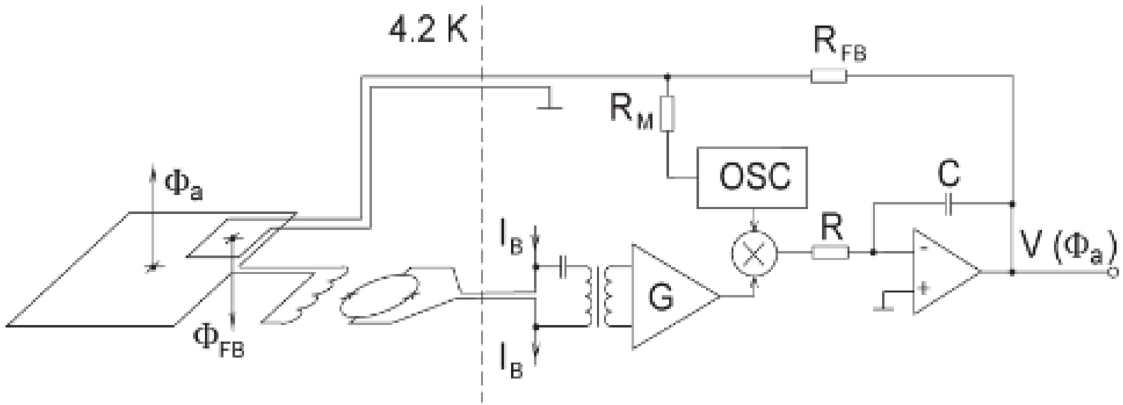
Readout Electronics

AC Flux Modulation

$$S_{\Phi,\mathrm{tot}} = S_{\Phi} + S_{V,\mathrm{amp}} \Big/ \left| \frac{\partial V}{\partial \Phi_a} \right|^2$$

- Square-wave modulation, f_{mod} ~0.1 to 2 MHz
- Transformer used to step up SQUID output signal, impedance match to FET
- Robust against thermal drifts and 1/f noise not due to critical current fluctuations
- Four-wire connection to SQUID using warm transformer only
- Bandwidth limited to ~f_{mod}/2



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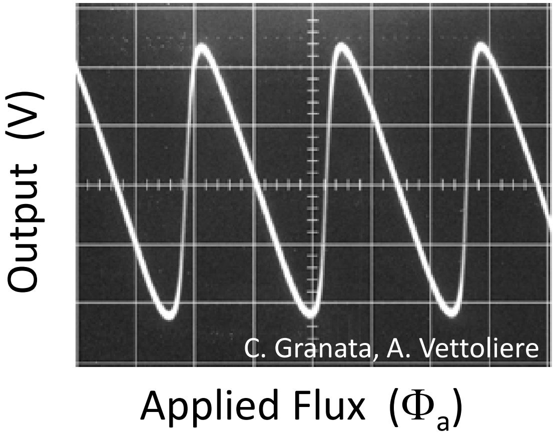
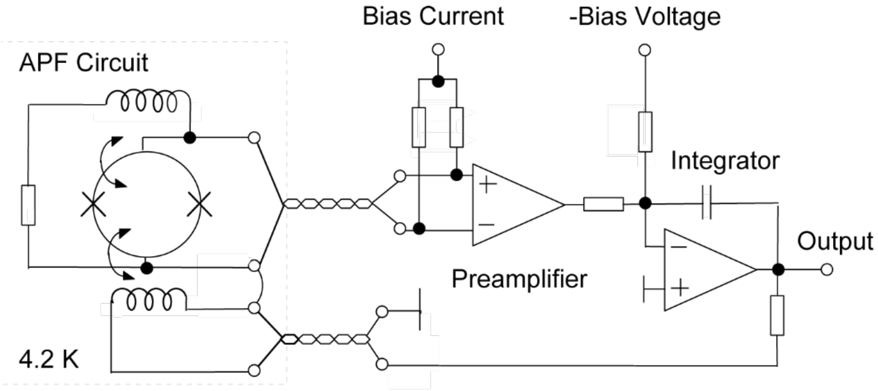
Readout Electronics

Direct-Coupled

- SQUID output directly-coupled to room-temperature preamplifier
- Additional Positive Feedback (APF) steepens ∂V/ ∂Φ to reduce preamplifier noise contribution
- Four-wire connection to SQUID
- Wideband operation, up to 20 MHz





D. Drung and M. Mück, SQUID Electronics, in The SQUID Handbook, Fundamentals and Technology of SQUIDs and SQUID Systems, Volume I (eds J. Clarke and A. I. Braginski), 2004.

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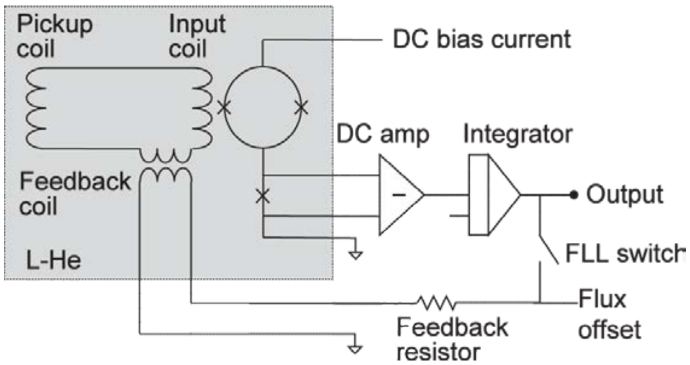
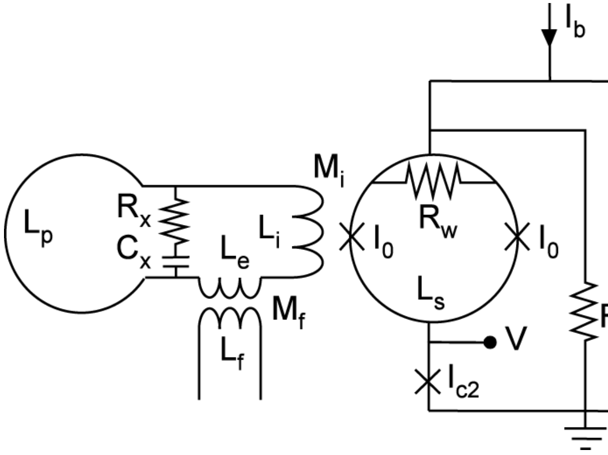
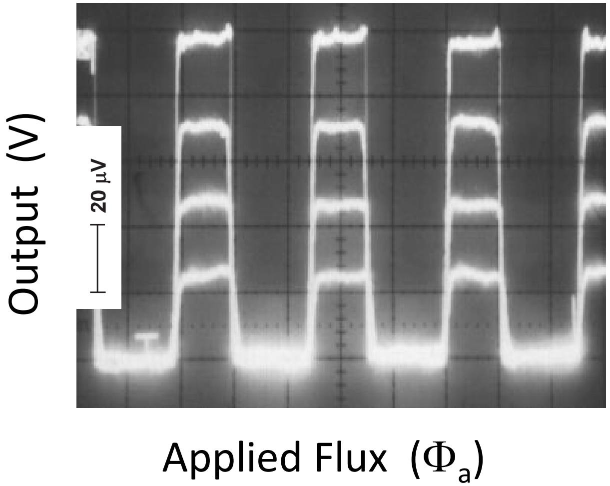
Readout Electronics

Relaxation Oscillation SQUIDs

- Hysteretic "signal" SQUID with $I_{c1,min} < I_{c1}(\Phi_a) < I_{c1,max}$
- Hysteretic "reference" SQUID or JJ with $I_{c1,min} < I_{c2} < I_{c1,max}$
- $R_{sh}L_{sh}$ sets relaxation oscillation frequency, read out time-averaged DC voltage across reference JJ:
  - zero if $I_{c1}(\Phi_a) < I_{c2}$, non-zero if $I_{c1}(\Phi_a) > I_{c2}$
  - for $I_{c1}(\Phi_a)$)= I_{c2}, very large $\partial V/ \partial\Phi$
- Five-wire connection to SQUID







Y-H. Lee et al., IEICE Trans. Electron. E88-C, (2005), 168.

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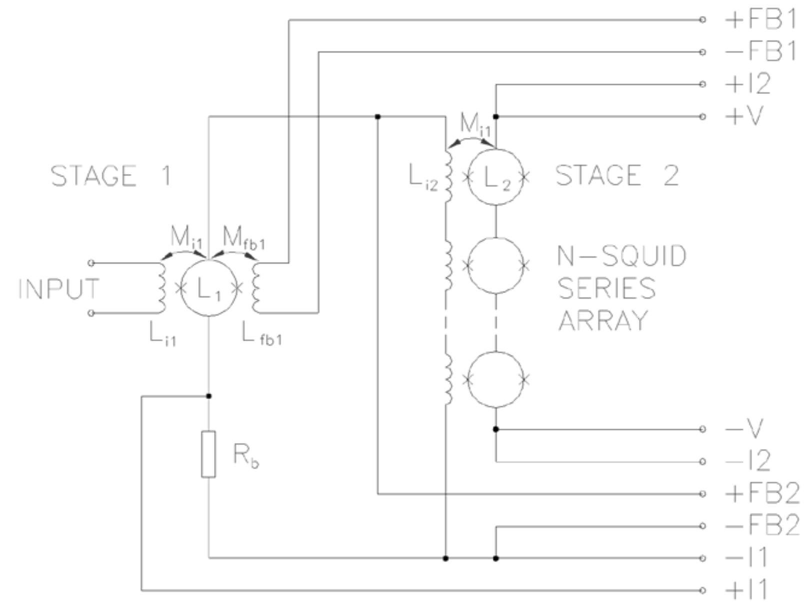
Readout Electronics

Two-Stage SQUID Readouts

- Low-noise, single-SQUID input stage, series SQUID array (SSA) output stage (or DROS)
- Voltage-biased input SQUID coherently modulates output SQUID array
- $|\partial V/\partial \Phi|_{array} \propto N$, $V_{n,array} \propto N^{1/2} \Rightarrow S^{1/2}_{\Phi,array} \propto 1/N^{1/2}$
- Output gain $G \propto dV_{out}/dI_{in}$ >400 V/A allows direct coupling to room-temperature preamplifier
- Wideband operation ~120 MHz
- Eight-wire connection to input SQUID, SSA
- Parasitic resonances can be problematic
- High array input inductance
- High power dissipation
- S. Boyd (UNM/STARCryo) - new class of arrays offering low input inductance, and low power dissipation



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Applications

- **Biomagnetism**
  - Magnetocardiography (MCG)
  - Magnetoencephalography (MEG)
  - Ultra-Low-Field MRI, combined ULF-MRI/MEG
  - Super-Paramagnetic Relaxometry for Cancer Diagnostics
  - Immunoassay for Diagnosis of Alzheimer's Disease
  - (Immunoassay for Influenza – Sobhan Sepehri et al., Chalmers Univ.)
  - (Magnetospinography for spinal cord functional imaging - Y. Adachi et al., KIT, Japan)
- Geophysics
- Non-Destructive Testing

Magnetocardiography

- Acute myocardial infarction (AMI) - a leading cause of morbidity and mortality worldwide.
- Treat within 70 minutes, or mortality and morbidity rise dramatically.
- MCG can provide definitive test results within minutes after admission with high negative and positive predictive values
- Sudden cardiac death (SCD) - sudden, unexpected death caused by loss of heart function (sudden cardiac arrest); largest cause of natural death in the U.S., causing about 325,000 adult deaths in the U.S. each year. SCD is responsible for half of all heart disease deaths.
- Typical MCG signals: 1 to 100 pT, 0.1 to 100 Hz
- Fewer than 20 to 25 MCG systems installed worldwide
- Challenges
  - Ambient noise sources
  - Liquid cryogens
  - Competition from conventional technologies (e.g., SPECT, $3M system cost, $1B market in US)

Magnetocardiography

Hitachi High Technologies Corp., Japan

MC6400

- 64 axial gradiometers, <20 fT/Hz$^{1/2}$ (all channels)
- Liquid helium cooling
- Japanese insurance reimbursement since 2003
- In use at two hospitals in Japan
  - Tsukuba University Hospital since 2007.
  - National Cerebral and Cardiovascular Center, Osaka
- 100 patients per month average
- Total patients >10,000 between 2008 and 2016

Magnetocardiography

Biomagnetik Park GmbH, Germany

CS-MAG II

- 64-channel LTS axial gradiometers with DROS
- Liquid helium cooling
- Installations in Hamburg, Coburg, and Berlin, Germany; Hong Kong, China
- Approvals by CE, FDA, KFDA

Magnetocardiography

Mesuron LLC, USA

Avalon-H90

- Liquid helium cooled
- Millisecond, high spatial resolution imaging of the heart within 90 seconds
- Targeting rapid diagnosis in emergency rooms
- Proprietary techniques to eliminate background noise

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Magnetocardiography

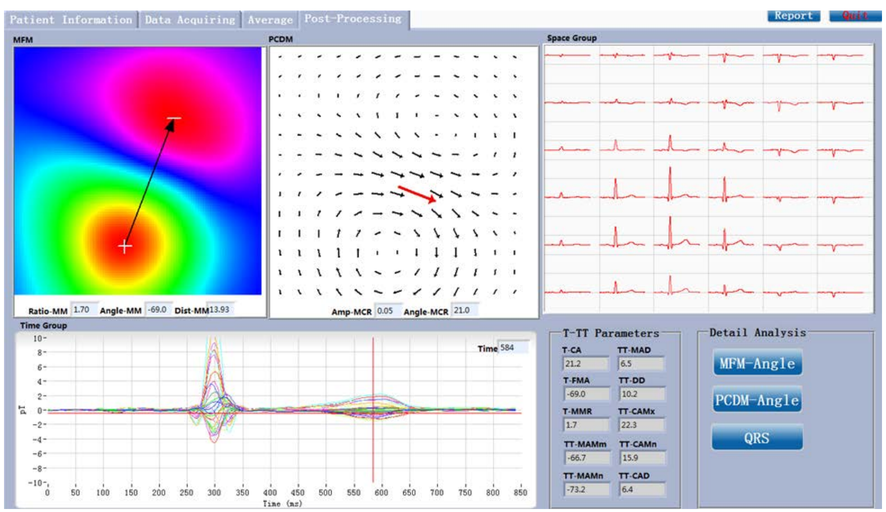
Cryoton Co. Ltd., Russia

MAG-SCAN

- 9 or 32 2nd order axial gradiometers
- 20-mm diameter, 55 mm baseline, 0.1% balance
- Unshielded operation
- 1 fT/Hz intrinsic, 20-40 fT/Hz installed
- Liquid helium cooled
- Software development by SOFTMAG Group, Kiev
- Approved for clinical Federal Service on Surveillance in Healthcare and Social Development of the Russian Federation

Magnetocardiography

Shanghai Medi Instruments, Ltd., China



- 1st and 2nd order gradiometers, with reference magnetometers
- 4 channels, 9 measurement positions
- Liquid helium cooled
- Installed at two hospitals in China
- Over 1,000 patient exams for clinical trials
- >95% accuracy in terms of sensitivity, specificity, PPV and NPV

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Magnetocardiography

Indira Gandhi Centre for Atomic Research
India

- 37 channels, 1st order axial gradiometers
- Liquid helium cooled
- Located in two-layer MSR
  (70 db at 1 Hz, 100 dB at 10 Hz)
- ~11 $fT/Hz^{½}$ average noise (all channels)
- Clinical studies of >150 patients

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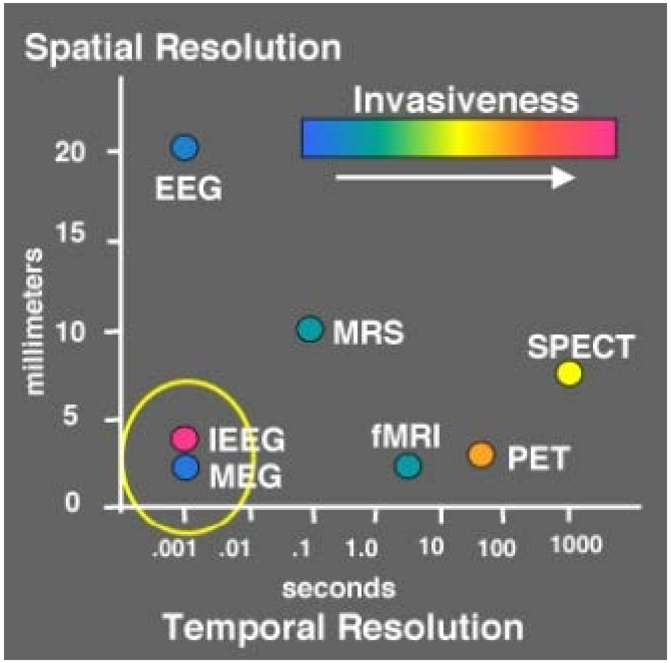
Magnetoencephalography

- Functional neuroimaging technique to map brain activity with high spatial and high temporal resolution
- Direct measure of brain function; fMRI, PET and SPECT are indirect and based on brain metabolism
- Typical MEG signals: 0.5 fT to 10 pT, up to 1 kHz
- Clinical applications
  - Epilepsy
  - Functional imaging (presurgical mapping)
  - Neurological and psychiatric diseases may be associated with abnormal brain oscillations
- Around 200 systems installed



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Magnetoencephalography

Elekta, Finland

Neuromag TRIUX

- Array of 102 sensor locations
- Each location consists of two orthogonal planar gradiometers and one magnetometer, total of 306 channels
- No helium consumption
- 100 systems installed since 1989

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Magnetoencephalography

CTF MEG International Services LP
Canada

CTF MEG 275

- 151 or 275 axial gradiometers distributed over whole cortex (cMEG) or abdominal region (fMEG)
- Additional reference channels used for noise cancellation
- Synthetic higher-order gradiometers for rejecting magnetic noise outside the brain region
- Liquid helium cooled

Magnetoencephalography

Yokogawa Electric Corp., Japan

MEGvision

- 160, 1st order axial gradiometers
- Liquid helium cooling with autofill
- Low boil-off dewar design
- Operated in two-layer MSR
- Acquired by Ricoh, Japan, March 2016
- Projecting sales of $437M by 2025

Magnetoencephalography

Compumedics Limited, Australia

Orion LifeSpan™ MEG

- LTS axial gradiometers with DROS
- No helium consumption
- Two MEG-in-one system design with dual adult/pediatric helmet options (192 ch. adult, 144 ch. pediatric)
- CURRY neuroimaging platform

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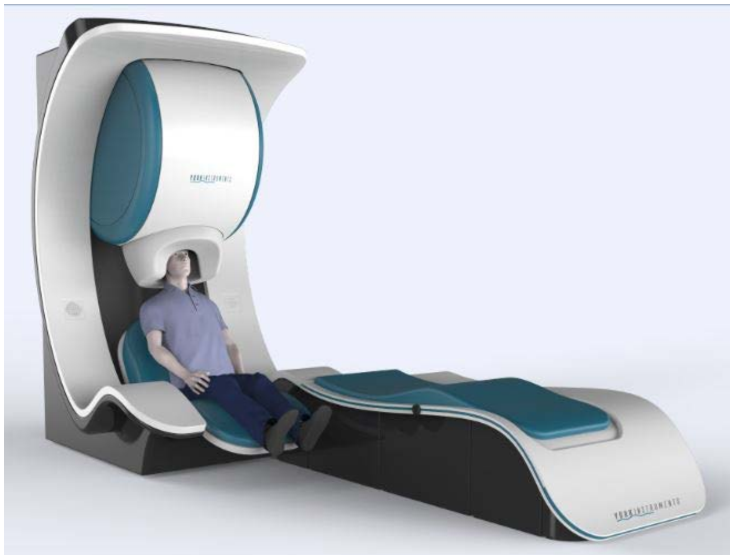
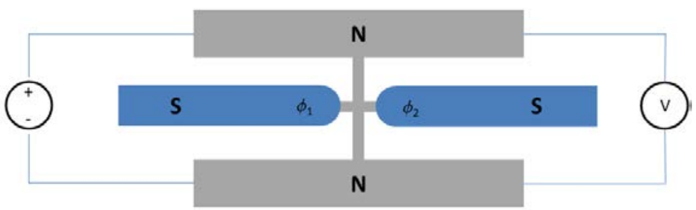
Magnetoencephalography

York instruments, Ltd, UK

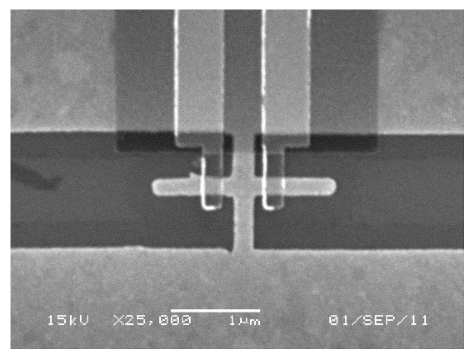


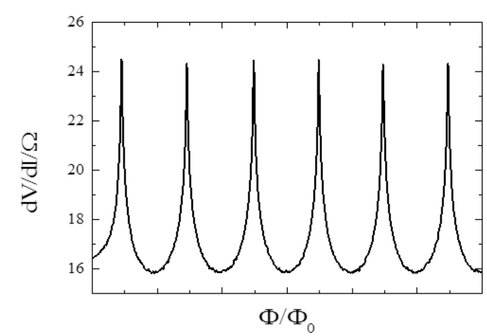
MEGSCAN

- Cooling via a vibration-free pulse tube
- 320 axial gradiometer or magnetometer sensors, 32 reference channels
- HyQUID sensor based on Andreev interferometer[1] with two SN contacts
- Current biased, dV/dI output is periodic with Φ



$$\Delta R \propto 1 - \cos\phi$$





[1]V T Petrashov, V N Antonov, P Delsing, and T Claeson; Phys Rev Lett **74**, 5268 (1995); JETP Lett **59**, 551 (1994).

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Ultra-Low-Field MRI

NMR of Protons

- For ensemble of N spins in field B_0, $M_0 = N\mu_p{}^2B_0/K_BT$
- Apply tipping field, spins precess with frequency $\omega_0/2\pi$, $\omega_0=\gamma B_0$ (Larmor frequency)
- Detect precessing magnetic moment using coil (Faraday) or SQUID (direct)
- M_0 relaxation times
    - Longitudinal (spin-lattice) – T_1
    - Transverse (spin-spin) – T_2; NMR linewidth $\Delta\nu=1/2\pi T_2$

SQUID NMR

- Signal scaling
    - Conventional coils: Signal $\propto \omega_0 M_0 \propto B_0{}^2$
    - SQUID: Signal $\propto M_0$ (or ω_0)
- Use of pre-polarization field B_p~100 mT, B_0 ~10-100 μT
- Inhomogeneous line broadening $\Delta\nu'=(\gamma/2\pi)(\Delta B_0/B_0)B_0$
    - Lower B_0 reduces field homogeneity requirements
- Lower system costs, greater portability

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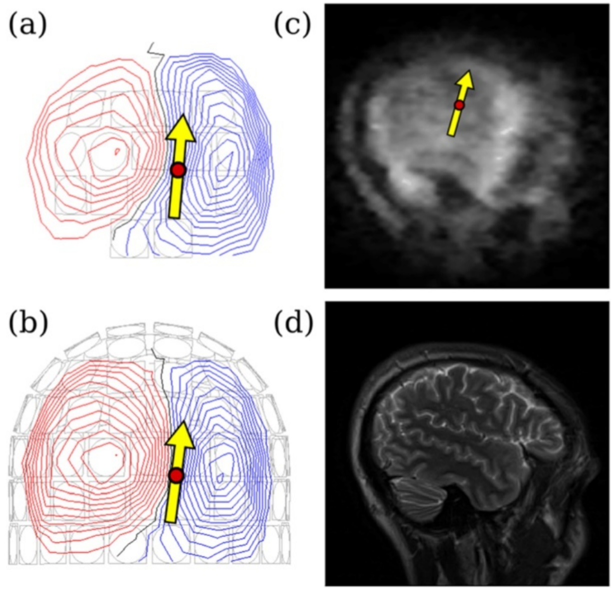
Combined ULF-MRI/MEG

Hybrid systems allow greater co-registration accuracy of MEG and MRI data

Equivalent dipoles and field patterns of visually-evoked responses using

(a) the MEG–MRI system and
(b) state-of-the-art MEG with the same stimulus protocol
(c) MRI slices at 96 μT, with the registered equivalent dipole of the auditory response overlaid
(d) Uncoregistered 3 T image acquired separately from the same subject



R. Körber et al., Supercond. Sci. Technol. **29** (2016) 113001.

Combined ULF-MRI/MEG

BREAKBEN

BREAKBEN - breaking the nonuniqueness boundary in electromagnetic neuroimaging

Combine accurate magnetic measurements of neural activity with near-simultaneous high-definition measurements of cerebral structure

Use ULF-MRI current-density imaging to provide conductivity information for improved accuracy of MEG source localization

Collaborators

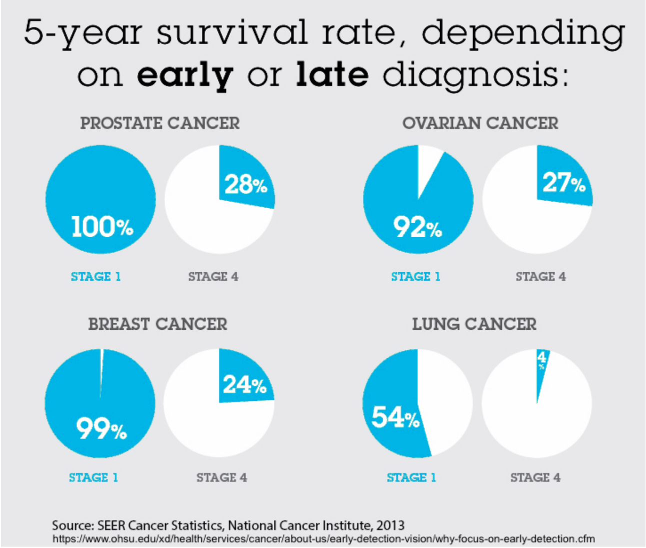
Aalto University
Hospital District of Helsinki and Uusimaa
VTT
University G. d'Annunzio of Chieti-Pescara
Elekta
PTB
TU Ilmenau

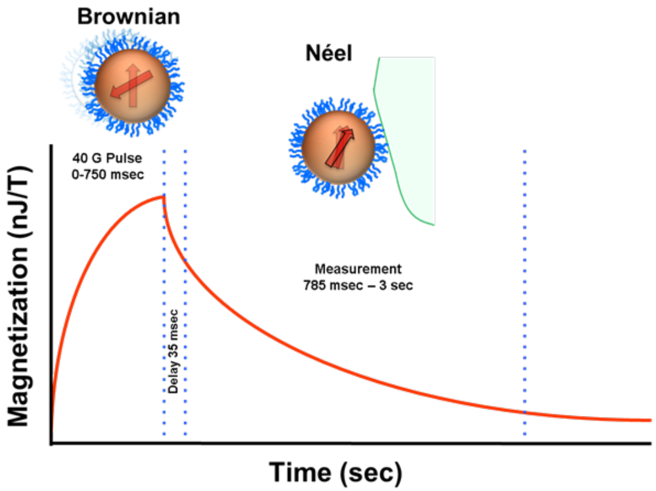
Super-Paramgnetic Relaxometry (SPMR)

- $100B global market for cancer diagnostics
- Early detection significantly reduces mortality rates

Super-Paramagnetic Relaxometry (SPMR)

- Bio-specific antibodies bound to nanoparticles cause binding to specific targeted tumor types
- Apply magnetizing pulse (e.g., ~40 G, 750 msec)
- Measure magnetization relaxation (~3 sec)
  - Unbound nanoparticles relax via Brownian motion (fast)
  - Néel relaxation of nanoparticles bound to tumor cells is slow and measurable





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Super-Paramgnetic Relaxometry (SPMR)

Imagion Biosystems, USA

- Liquid helium dewar
- Ring of six 2nd -order axial gradiometers
- Single central magnetometer for background elimination

- Potential for sub-millimeter size tumor resolution
- 1000x more sensitive than current imaging methods

Method	MagSense Magnetic Relaxometry	MRI Magnetic Resonance Imaging	PET Positron Emission Tomography	Ultrasound	X-Ray/CT
Detection Threshold	< 1 million cells	millions of cells	NA	4 billion cells	NA
Quantitative	Yes	Yes	No	No	No
Specificity	Yes	No	No	No	No

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Immunoassay

MagQu, Taiwan

XacPro-S361

- AC magnetosusceptometer for ultra-sensitive immunoassay
- High-Tc SQUID magnetometer
- Clinical Application -Diagnosis of Alzheimer's Disease
- Four installations
  - National Taiwan University Hospital
  - National Taiwan Normal University
  - Arizona State University
  - Bio-Check Biotech Co., Ltd.

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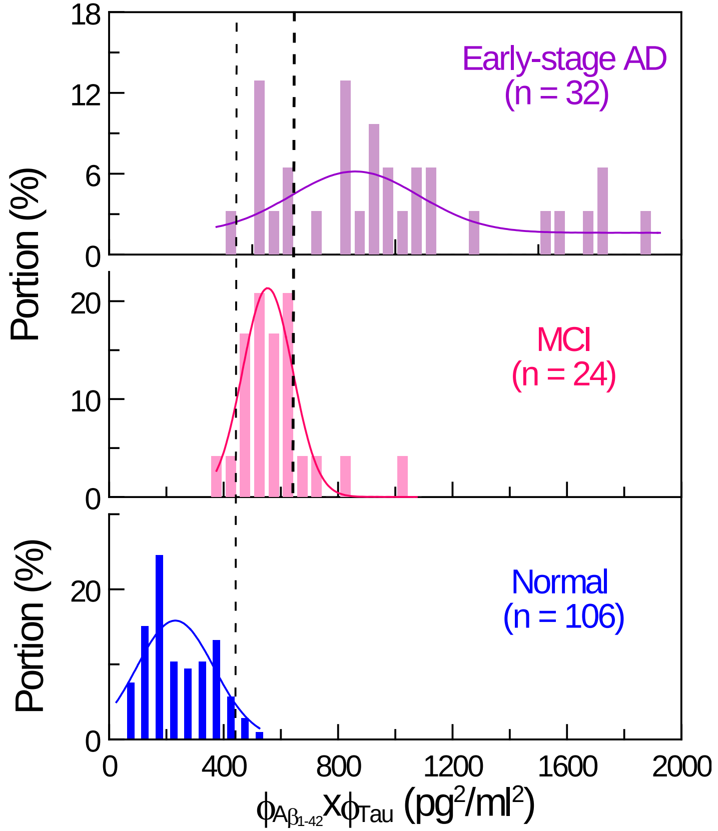
Immunoassay

$A\beta_{1-42}$ x Tau in plasma: Normal vs. MCI vs. Early-stage AD



Normal vs. patient:

Cut-off value = 455.49 $(pg/ml)^2$
Sensitivity = 0.96
Specificity = 0.97

MCI vs. Early-stage AD:

Cut-off value = 642.89 $(pg/ml)^2$
Sensitivity = 0.82
Specificity = 0.84

Early-stage diagnosis!

MCI: mild cognitive impairment

MagQu

Curr. Alzheimer Res. **9**, 1142 (2012)
ACS Chem. Neurosci. **4**, 1530 (2013)

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New Technology Trends for Biomagnetism

Sensor and Dewar Technology Developments

- Development of ultra-sensitive magnetometers with resolution ~0.1 $fT/Hz^{1/2}$, comparable to the Nyquist noise of the human body
  - Improved thermal shielding to reduce background noise of LHe dewar (e.g., PTB magnetometer with alumina thermal shields, aluminized polyester textile MLI, 45-mm diameter pickup loop, ~150 aT/Hz)
  - Development of low capacitance, submicron junctions (e.g., IPHT cross-type junctions)
- Development of HTS magnetometers/gradiometers for MEG
  - HTS will reduce thermal shielding requirements; shorten sensor standoff distance
  - Sensor array can be better matched to head size (male/female, adult/child/newborn)
  - Development of wafer-scale processes for high-quality junctions and multilayer flux transformers needed
- Development of microcoolers
  - Enabling the development of low-cost, portable tools for immunoassays

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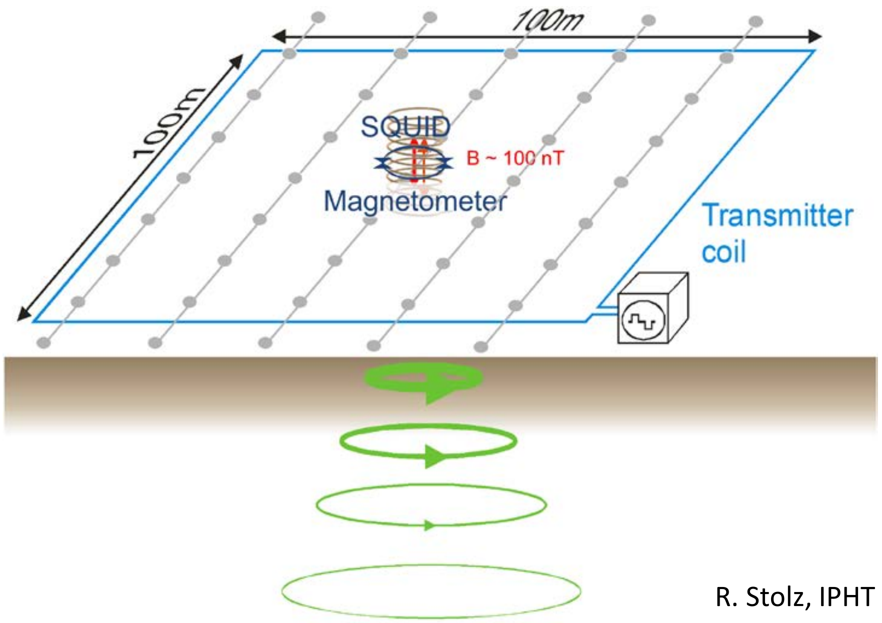
Applications

- Biomagnetism
- **Geophysics**
  - Transient Electromagnetics (TEM) for Mineral Exploration
  - Ionospheric Detection
  - (HTS Borehole Logging - T. Hato et al., SUSTERA, Japan)
- Nondestructive Testing

Transient Electromagnetics (TEM)

- Measurement of the electric resistivity of the subsurface for mineral exploration
- SQUID-based systems can distinguish between ore and conductive overburden with sharper contrast, greater depth sensitivity than achievable using induction coils
- Discovery and localization of large ore deposits worth billions of dollars using SQUID-based systems since 2001



R. Stolz, IPHT

Transient Electromagnetics (TEM)

- LANDTEM (2001)
  - CSIRO (Australia) HTS RF SQUID system
  - Commercial collaboration with Outer-Rim Exploration Services
  - Localization of large deposits of nickel sulphide and silver worth hundreds of millions of dollars

- JESSY DEEP (2003)
  - IPHT/Supracon (Germany), LTS and HTS SQUID systems
  - more than 20 systems in worldwide operation

- SQUITEM-3 (2013)
  - SUSTERA (Japan)
  - Ramp-edge junctions ($La_{0.1}Er_{0.95}Ba_{1.95}Cu_3O_y$ / $SmBa_2Cu_3O_y$) HTS multi-layer process
  - 30 $fT/Hz^{½}$ white noise (f > 1 kHz)

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Ionospheric Detection

Low Noise Underground Laboratory of Rustrel (France)

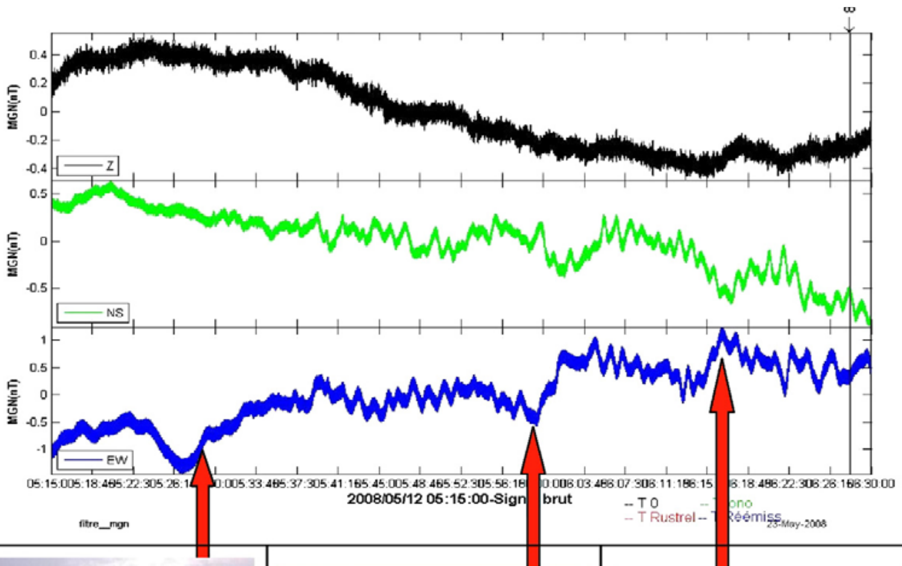
- [SQUID]^2 = SQUID with Shielding Qualified for Ionosphere Detection
  - Housed in underground former missile control center capsule
  - LTS vector magnetometer, <3 fT/Hz$^{1/2}$ for f > 40Hz
- Detection of magnetic storms, TLE sprites, ELVES, solar eruptions, mesopause excitations, Earth breathing modes, …
- Possible observation of earthquake precursors

LSBB Rustrel – located 518 meters under mountain

[SQUID]^2 System

Ionospheric Detection

Low Noise Underground Laboratory of Rustrel (France)



60 minutes ago Baoji, 500km from epicenter	30 minutes ago Tian-Shui, 450km from epicenter	10 minutes ago Mei-Xian, 550km from epicenter

M 8.1 Sichuan-Wenchuan Quake
May 12, 2008

- Jumps in EW trace 60, 30 and 10 minutes before quake
- Electric field produced by precursor piezo-electric effects
- Time coincident “Rainbow clouds” observed away from epicenter

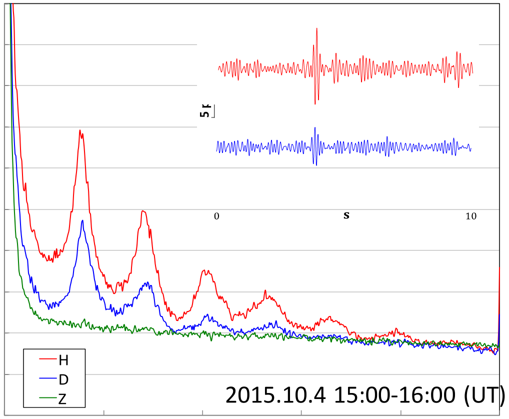
G. Waysand et al., C. R. Physique **12**, (2011) 192.

Ionospheric Detection

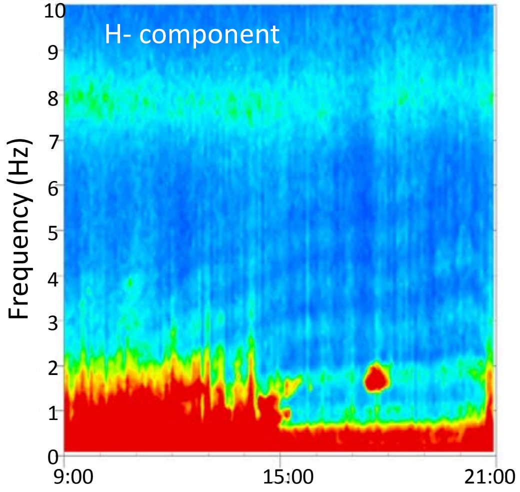
Kanazawa Institute of Tech. (Japan)

- Three LTS magnetometers
  - $2.2 \times 2.2\ mm^2$ pickup loop
  - 30 fT/Hz$^{1/2}$ white noise
  - Direct readout electronics
  - 33L LHe dewar, 30-day operation

Schumann resonance



Ionospheric Alfvén resonance



Kawai et al 2017 *Supercond. Sci. Technol.* https://doi.org/10.1088/1361-6668/aa733f

STAR CRYOELECTRONICS

Applications

- Biomagnetism
- Geophysics
- **Non-Destructive Testing**
  - Materials Characterization
  - Integrated Circuit Inspection
  - Defect and Failure Analysis
  - (Food Inspection – S. Tanaka, Toyohashi Univ., Japan)

IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), No. 41, July 2017.
This keynote presentation Tu-KEY-02 was given at ISEC 2017.

Materials Characterization

SQUID-based measurements of magnetic properties as a function of magnetic field and temperature

Over 1,000 SQUID magnetometers sold since 1984 (>$200M in commercial revenues)

CRYOGENIC
CRYOGENIC LIMITED

QuantumDesign

S700X SQUID Magnetometer

Magnetic Property Measurement System (MPMS®3)

IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), No. 41, July 2017.
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Rock Magnetometry

William S Goree, Inc (USA)

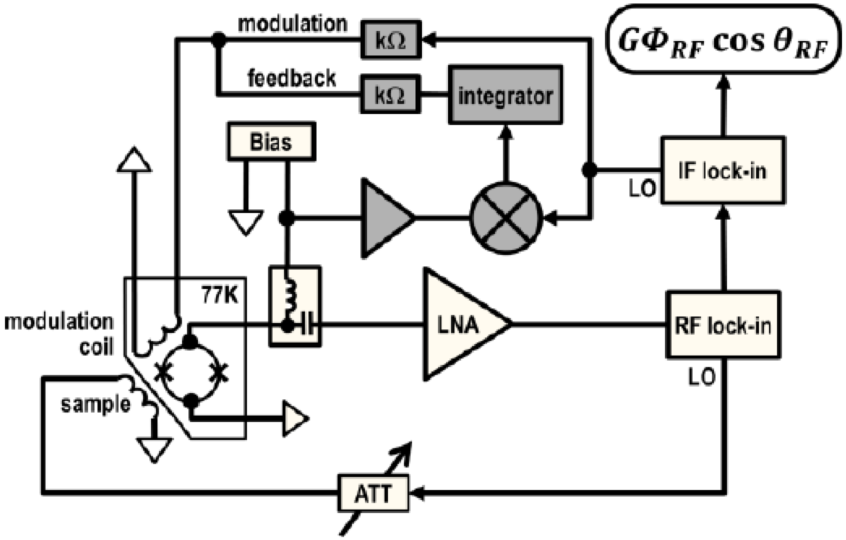
- Rock magnetometer for palaeomagnetism – studies of the record of the Earth's magnetic field in rocks, sediments, or archeological materials
- Originally produced by 2G Enterprises, Inc.
- LTS SQUID system with PT cryocooler
- Magnetic Dipole Moment Noise <10^{-12} A/m^2
- More than 135 systems installed since ~1984

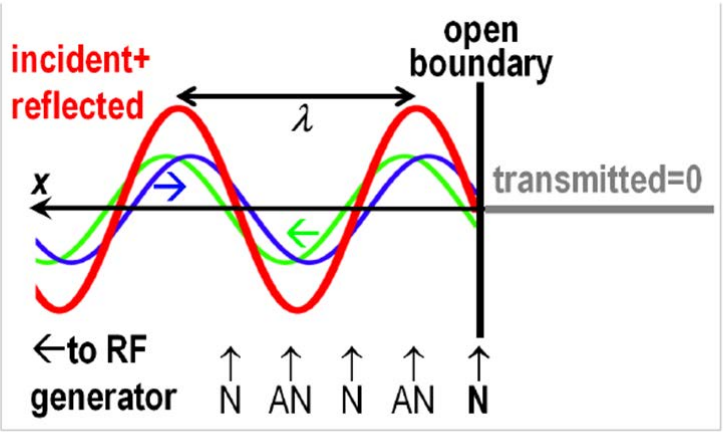
MODEL 755 & 760-4K
Rock Magnetometer

Circuit Inspection

Neocera LLC, USA

- Scanning SQUID microscope with HTS DC SQUID
- Readout electronics sense coherent magnetic fields up to 2 GHz
- Open circuit acts as a transmission line with node at open end

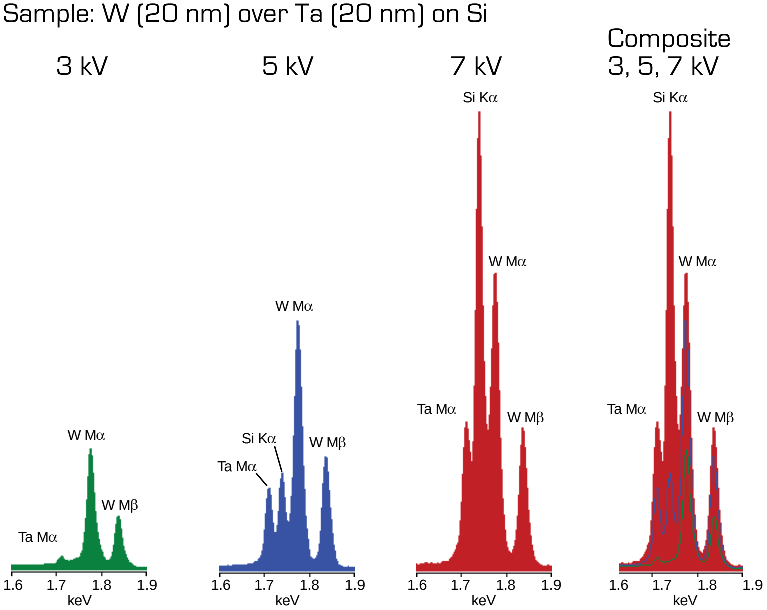


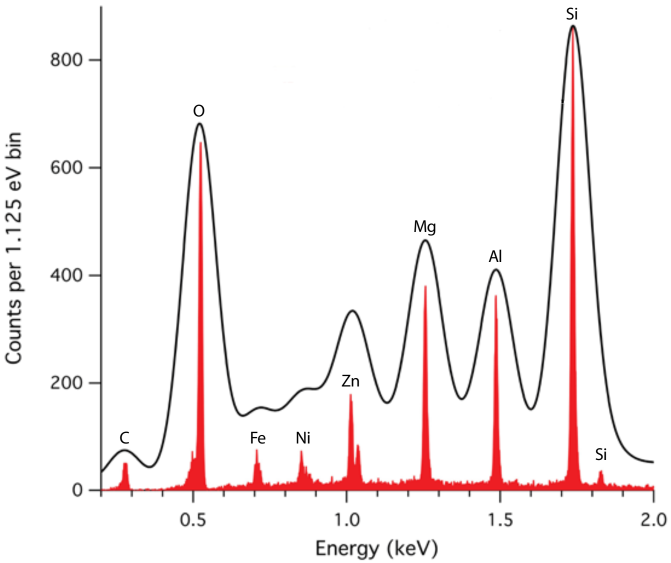


Defect and Failure Analysis

STARCryo MICA-1600 Energy Dispersive X-Ray Spectrometer

- 4x4 array of 0.5 mm^2 TES microcalorimeter detectors
- Two-stage SQUID readout for each channel, with SSAA output stage
- Energy resolution <10 eV FWHM at Si K_{α} (1.7 keV)
- Maximum count rate up to 10 kcps
- Cryogen-free, automated cryostat operation





Applications

- Biomagnetism
- Geophysics
- Non-Destructive Testing
- **Basic Research**
  - Astrophysics – Cosmic Microwave Background (CMB) and X-Ray Observatories
  - (SQUID-Based Magnetic Microscopy)

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Astrophysics Research

Cosmic Microwave Background "Stage-4" Experiments (CMB-S4)

- New instruments planned for astrophysical surveys having large focal plane arrays of ~100,000 superconducting detectors
- Tens of thousands of low-noise cryogenic amplifiers are required for frequency domain multiplexed readouts

- Detection of B-mode CMB polarization to test inflation
- Determine limits on neutrino mass
- Constraints on the nature of dark energy
- Tests of general relativity on large scales

POLARBEAR on 3.5 m Huan Tran Telescope, Chile

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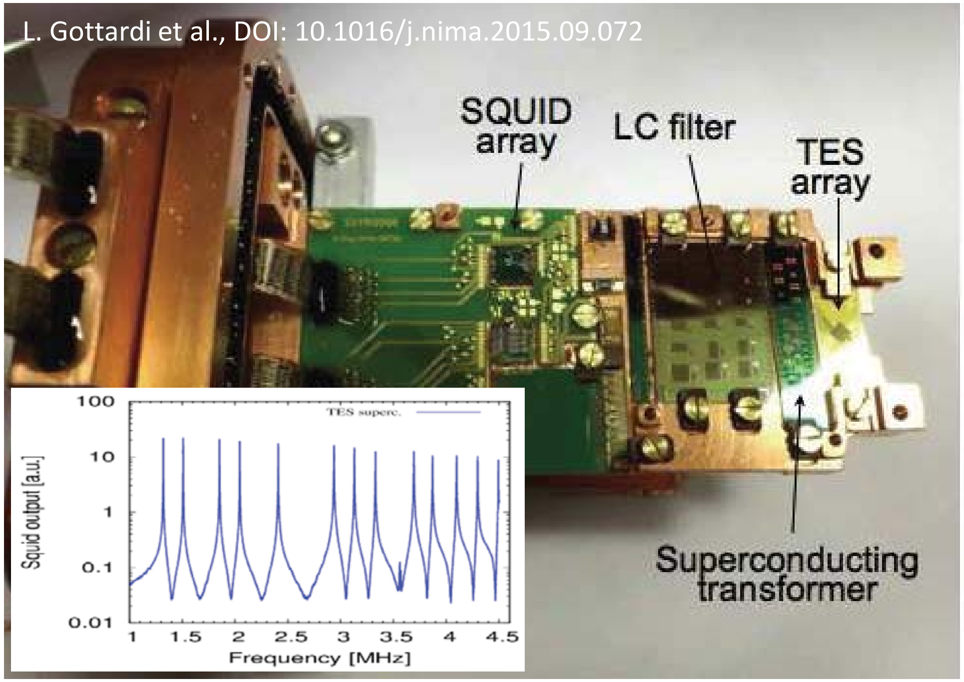
Astrophysics Research

X-Ray Observatories

Advanced Telescope for High-Energy Astrophysics (Athena)

3,840 TESs coupled to X-ray absorbers and read out in 1-5 MHz bandwidth using Frequency Domain Multiplexing (FDM)

L. Gottardi et al., DOI: 10.1016/j.nima.2015.09.072



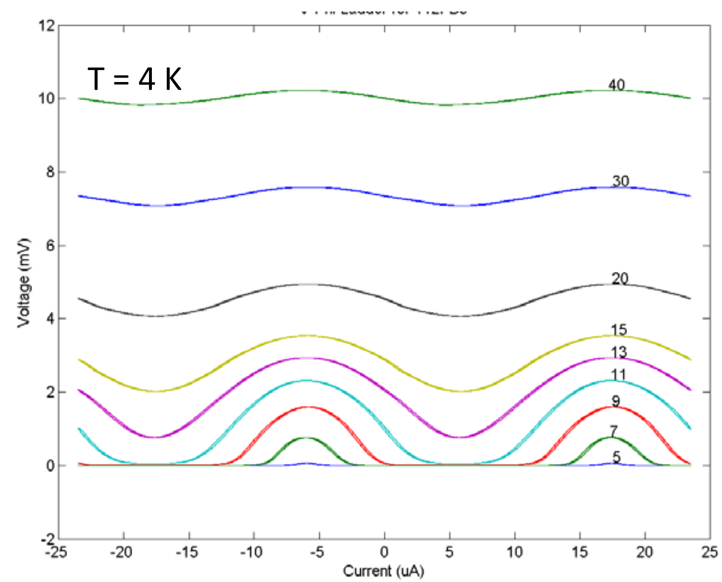
X-ray Integral Field Unit (X-IFU)
SRON/VTT and NASA-GSFC/NIST

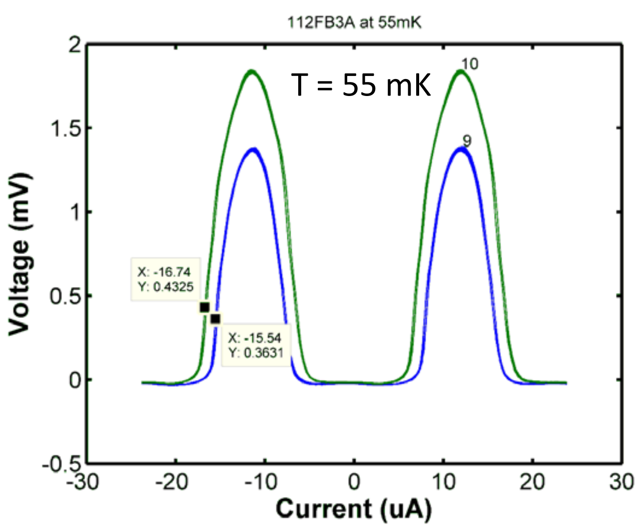
- Each pixel is separated in frequency space by high-*Q* superconducting LC filter
- Requires amplifiers with low input inductance, low flux noise, high-dynamic range and low power consumption.

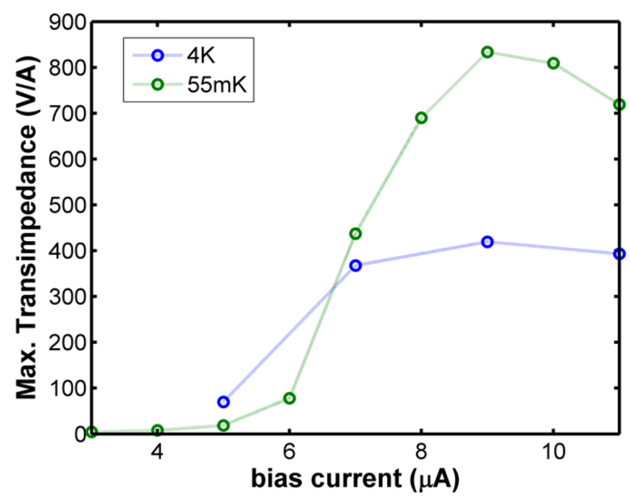
Cryogenic Amplifiers for Detector Readouts

Series SQUID Array Amplifiers

- 112-SQUID Array with 11 nH input inductance, 23.6 µA/Phio input coupling
- 2.4 mV voltage swing, 400 V/A transimpedance at 4 K, ~800 V/A at 55 mK
- 5.9 pA/Hz^{½} current noise referred to input (4 K)
- <5 nW power dissipation at 55 mK, enables integration on focal plane array







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Summary

- The market outlook for LTS SQUIDs is strong, with compelling applications in biomagnetism and key scientific applications in astrophysics research
- State-of-the-art HTS SQUIDs are well-suited for high-impact applications in geophysics and immunoassays
- The market for HTS SQUIDs will likely expand, if reliable, high-yield, wafer-scale procesess can be developed for multilayer SQUIDs with <<50 ft/Hz at frequencies <<1 kHz

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