Title: Low-noise SQUID systems for ARIADNE and pEDM; SQUIDs, magnetic shielding and cooling

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Abstract:

SQUIDs for ARIADNE, pEDM and Axion

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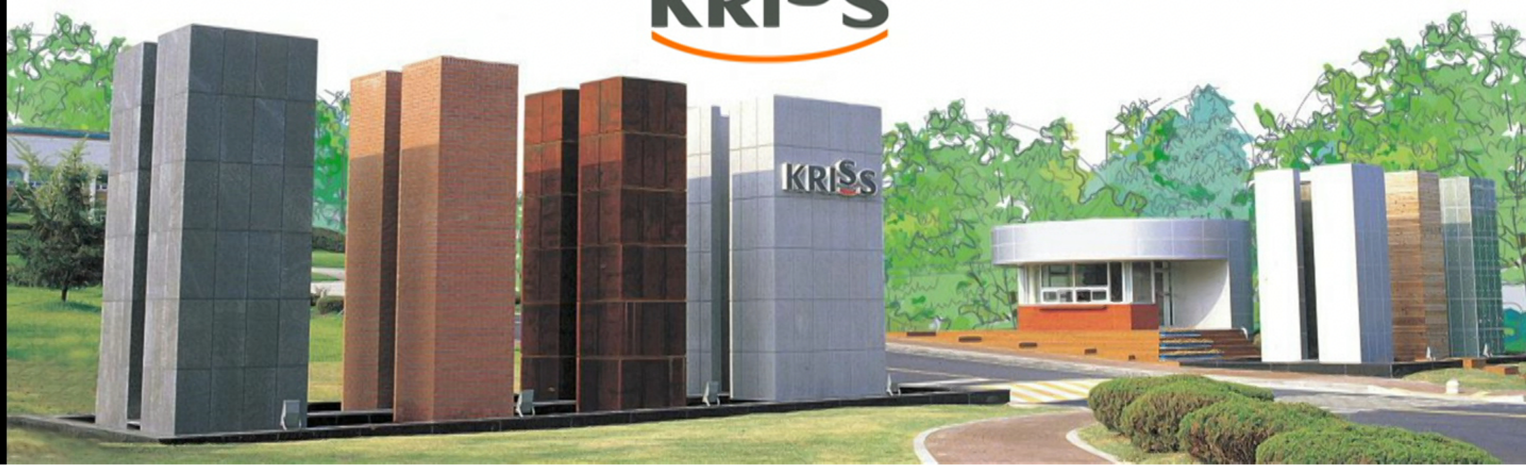
Korea Research Institute of Standards and Science (KRISS)



Content

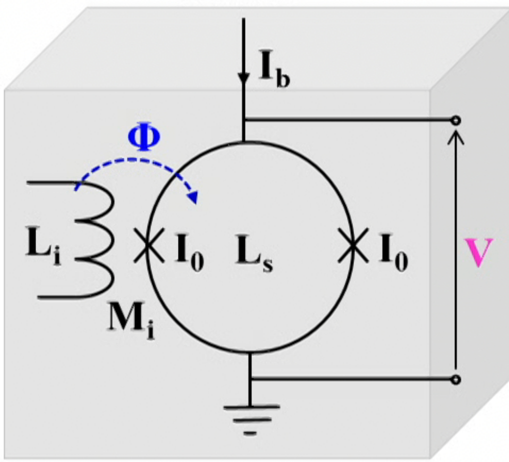
SQUID system engineering in KRISS

SQUIDs for ARIADNE, pEDM and Axion

High sensitivity sensor - SQUID

SQUID (Superconducting Quantum Interference Device)

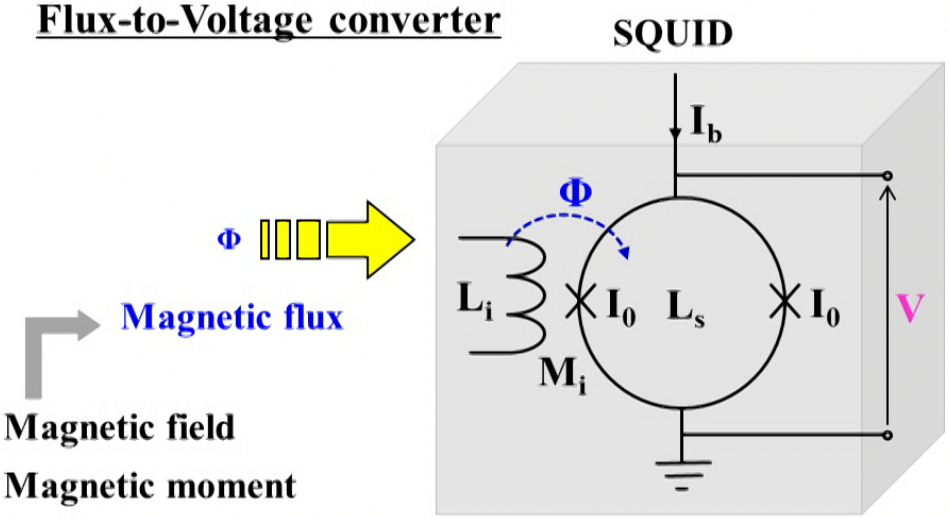
Flux-to-Voltage converter



High sensitivity sensor - SQUID

SQUID (Superconducting Quantum Interference Device)

Flux-to-Voltage converter



Magnetic field

Magnetic moment

Current

RF power

Displacement

…

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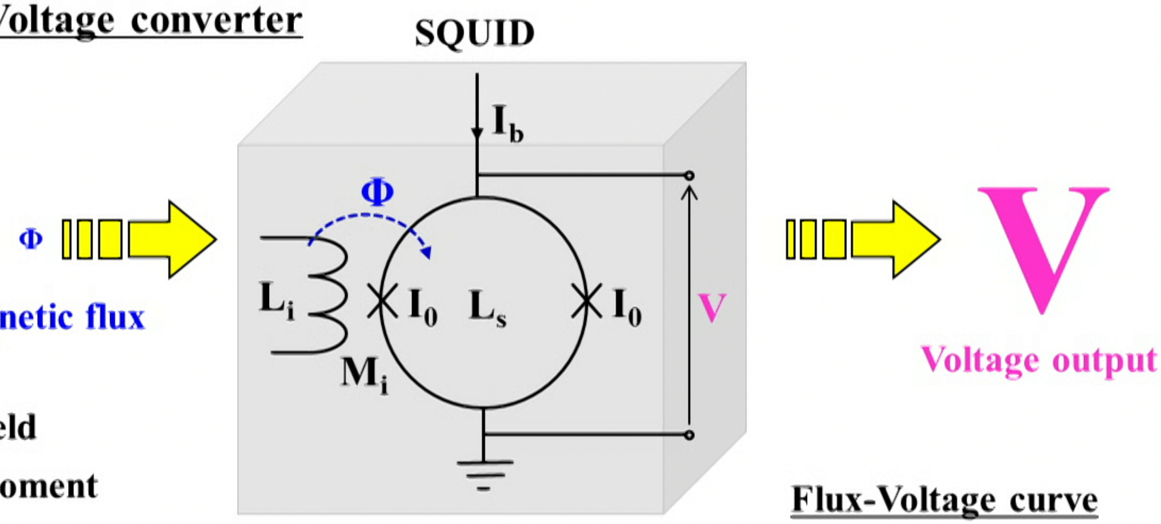
High sensitivity sensor - SQUID

SQUID (Superconducting Quantum Interference Device)

Flux-to-Voltage converter



Magnetic flux

Magnetic field

Magnetic moment

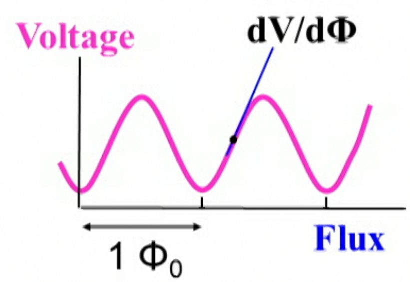
Current

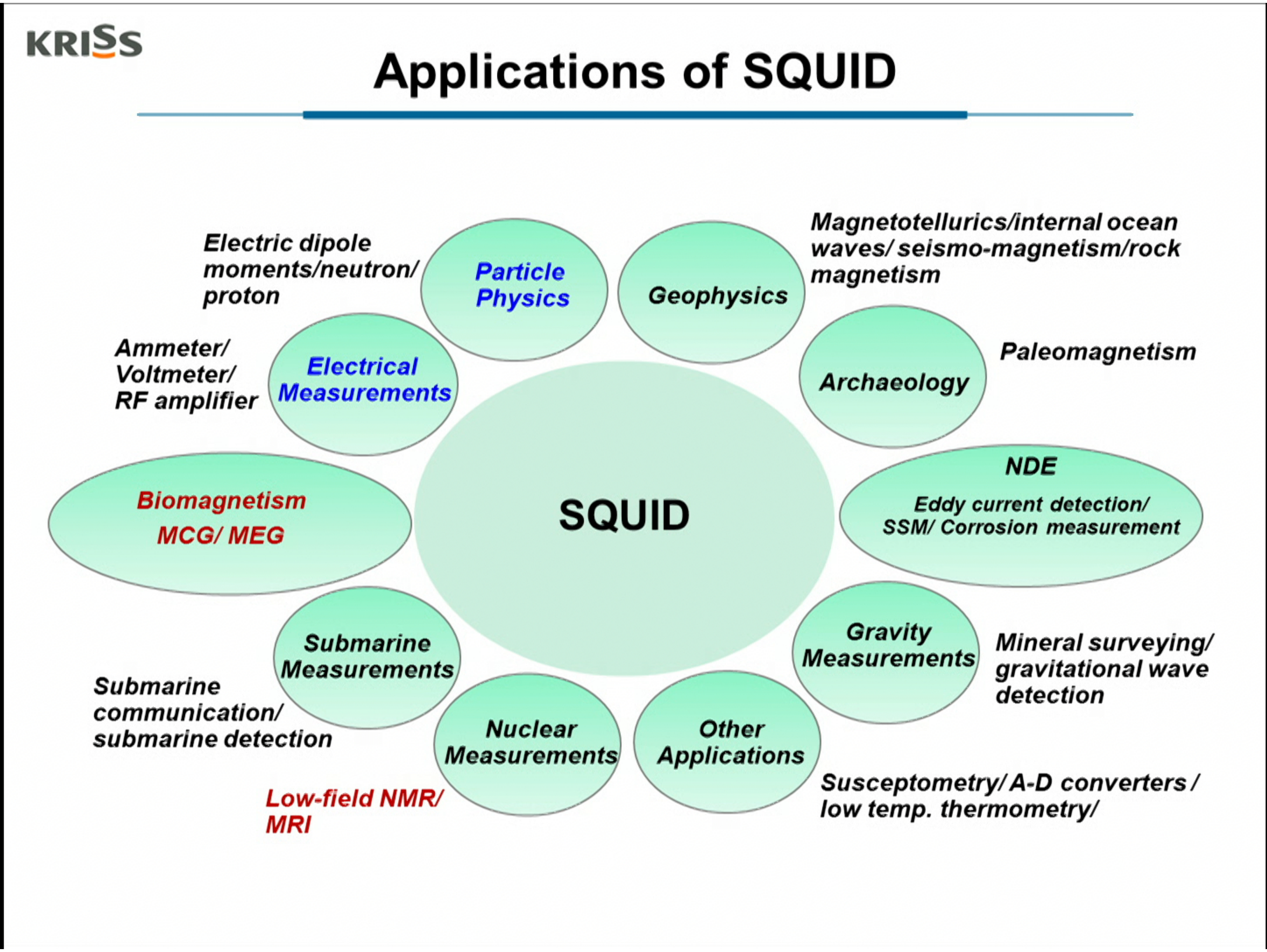
RF power

Displacement

…

Flux-Voltage curve





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Applications of SQUID
SQUID
Particle Physics
Electric dipole moments/neutron/ proton
Geophysics
Magnetotellurics/internal ocean waves/ seismo-magnetism/rock magnetism
Electrical Measurements
Ammeter/ Voltmeter/ RF amplifier
Archaeology
Paleomagnetism
Biomagnetism
MCG/ MEG
NDE
Eddy current detection/ SSM/ Corrosion measurement
Submarine Measurements
Submarine communication/ submarine detection
Gravity Measurements
Mineral surveying/ gravitational wave detection
Nuclear Measurements
Low-field NMR/ MRI
Other Applications
Susceptometry/ A-D converters / low temp. thermometry/

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Performance of SQUID system

Physical

Sensitivity (Field noise, noise temperature, etc.)

Bandwidth

Slew rate

Dynamic range

…

Engineering

Reliability of operation

Yield of fabrication

Cost of fabrication and operation

Compactness (Space for installation)

…

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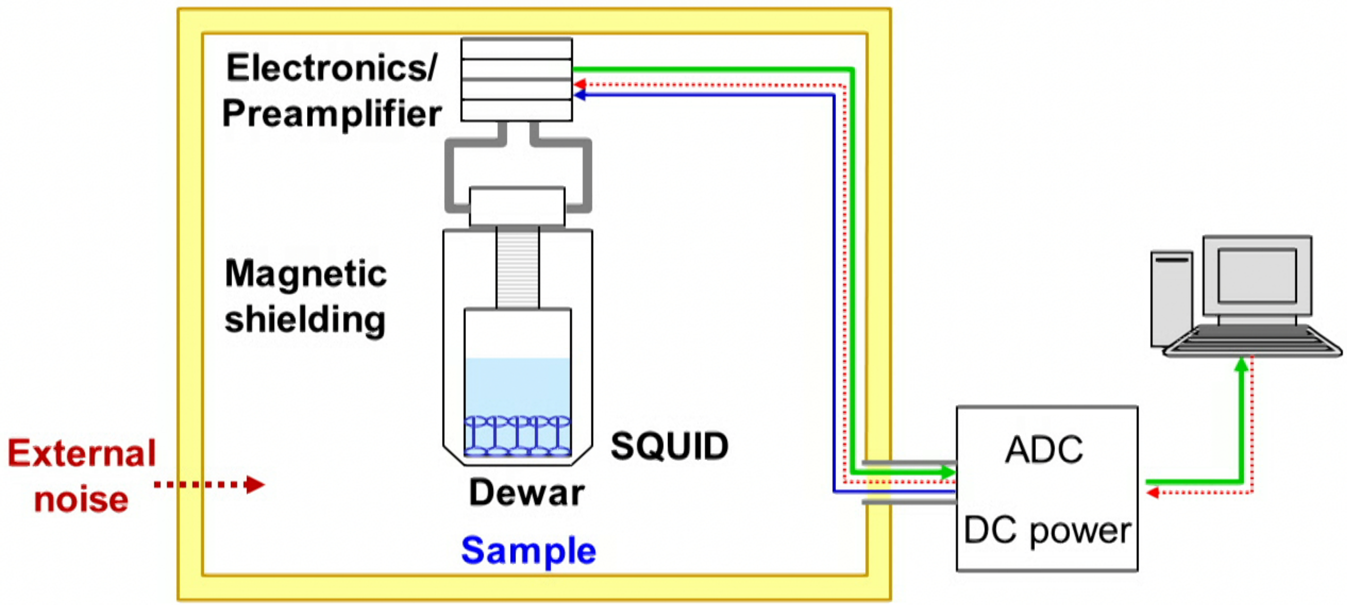
SQUID system: Component and noise sources



SQUID system noise: SQUID intrinsic noise + Electronics noise
Thermal noise of dewar (superinsulation & thermal shield)
Thermal noise of metals in shielding structure (mumetal & aluminum)
Residual environmental noise, RF interference, Digitization noise

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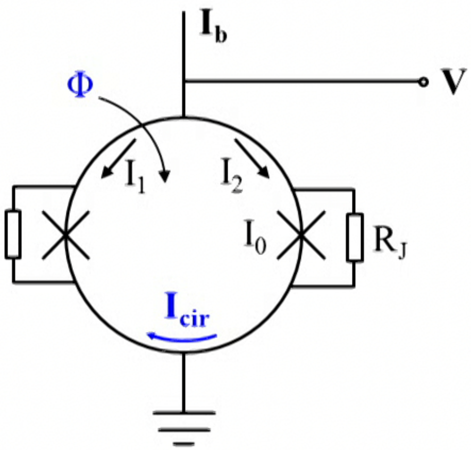
DC-SQUID

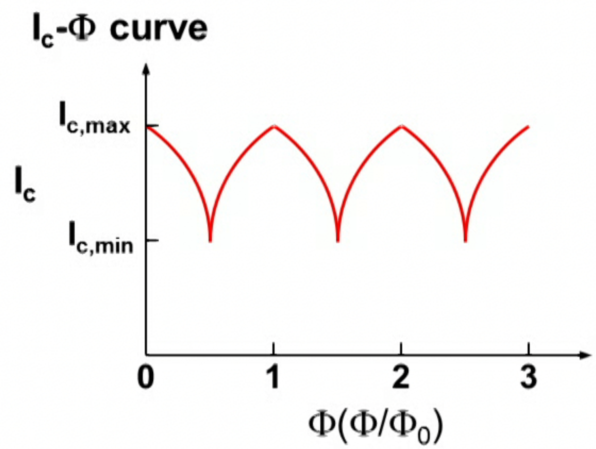
Basic structure



Screening parameter of the SQUID

$$\beta_L = \frac{2I_0 L_{sq}}{\Phi_0} = \sim 1$$

Modulation of critical current



$$\Delta I_c = Ic_{,\,max} - Ic_{,\,min} \approx \frac{1}{1+\beta_L} 2I_0$$

Optimum: $\beta_L \approx 1$

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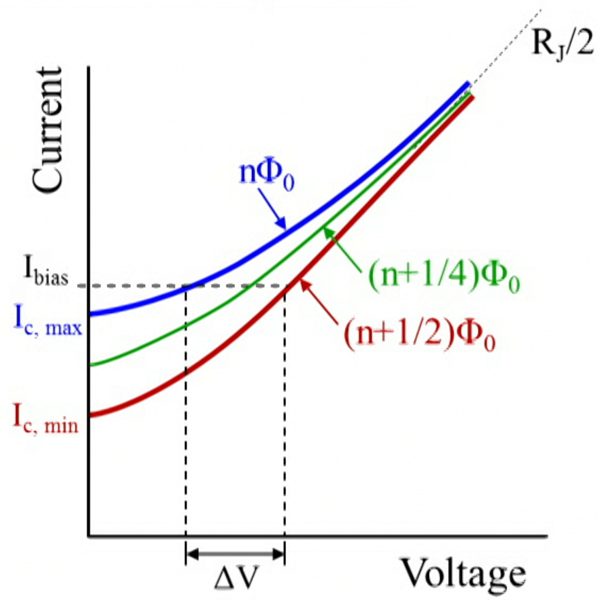
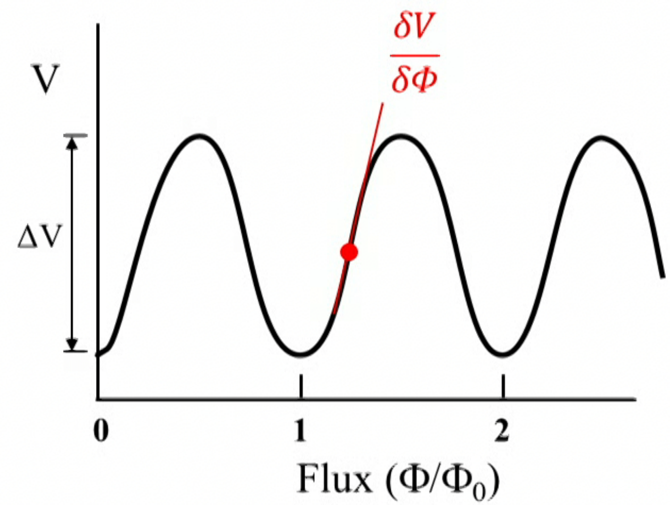
Flux modulation of DC-SQUID

Current-Voltage curve



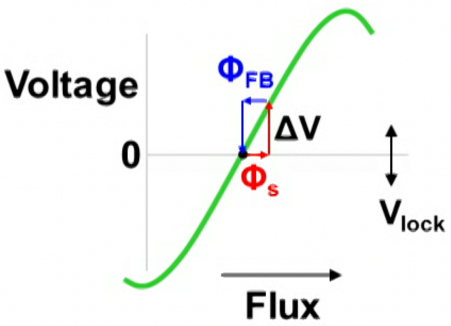
Voltage-Flux curve



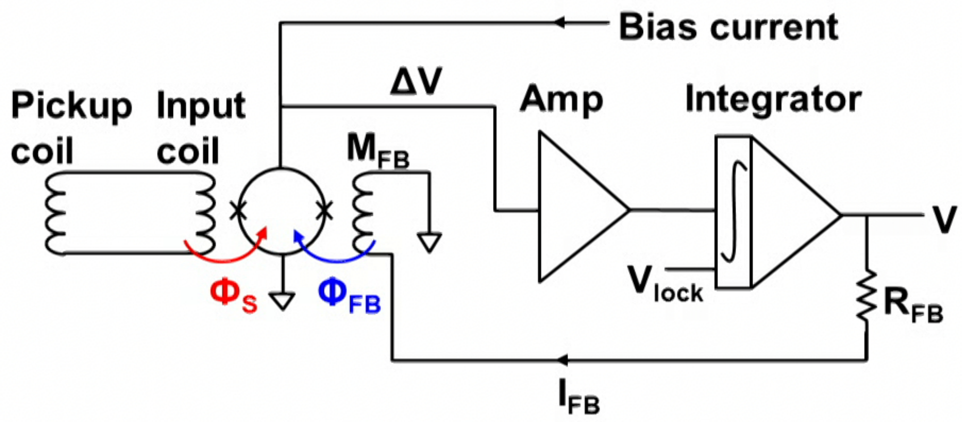
$$\frac{\delta V}{\delta \Phi} \approx \frac{2\beta_L}{1+\beta_L} \frac{R_j}{L_{sq}} \approx \frac{R_j}{L_{sq}}$$

SQUID readout: Flux-locked loop (FLL)

Negative feedback



Flux-locked loop

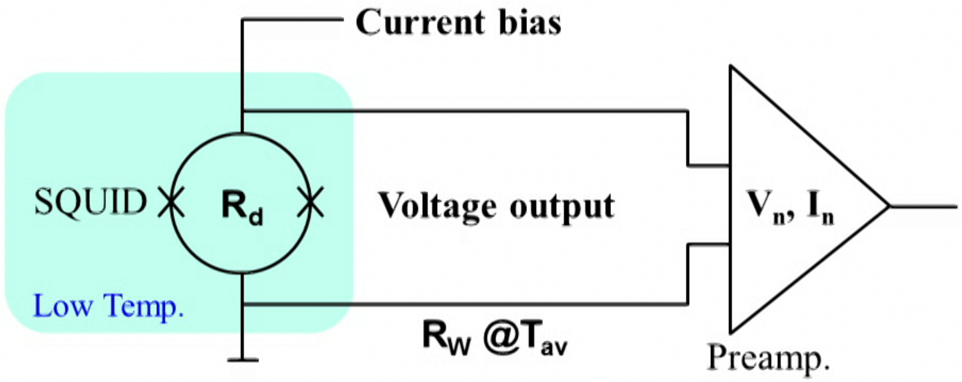


In FLL mode, the flux in the SQUID is kept constant (locked).

→ Output voltage= $I_{FB} \times R_{FB}$, $I_{FB} = \Phi_{FB}/M_{FB}$

Preamplifier noise contribution

In direct readout mode



Noise of SQUID system: $\Phi^2_{intrinsic} + \Phi^2_{preamp}$

Preamplifier noise contribution: $\Phi_{preamp} = V_{n,tot}/(\delta V/\delta\Phi)$

$$V_{n,tot} = \{V_n^2 + I_n^2(R_d+R_w)^2 + 4k_BT_SR_d + 4k_BT_{av}R_w\}^{0.5} =\sim 0.5\ \mathrm{nV}/\sqrt{\mathrm{Hz}}$$

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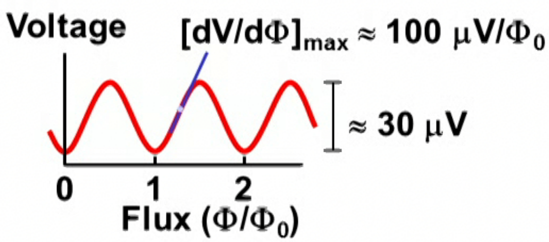
SQUID type and preamplifier input noise

Standard DC SQUID

Flux-voltage curve



$dV/d\Phi$: 100 $\mu V/\Phi_0$

If, preamplifier noise: 0.5 $nV/\sqrt{Hz}$

➔ 5 $\mu\Phi_0/\sqrt{Hz}$

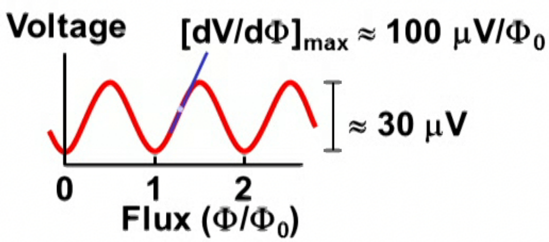
Low transfer coefficient :

⇒ Complex readout electronics

SQUID type and preamplifier input noise

Standard DC SQUID

Flux-voltage curve



$dV/d\Phi$: 100 $\mu V/\Phi_0$

If, preamplifier noise: 0.5 nV/√Hz

➔ 5 $\mu\Phi_0/\sqrt{Hz}$

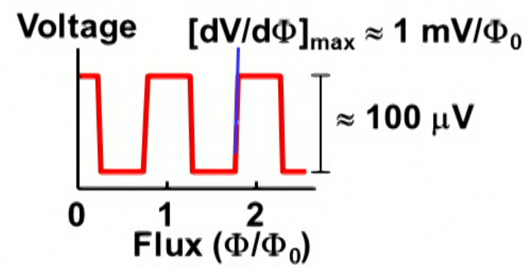
Low transfer coefficient :

⇒ Complex readout electronics

DROS

(Double relaxation oscillation SQUID)

Flux-voltage curve



High flux-to-voltage transfer

⇒ Compact readout electronics

Large modulation amplitude

⇒ Stable against offset drift

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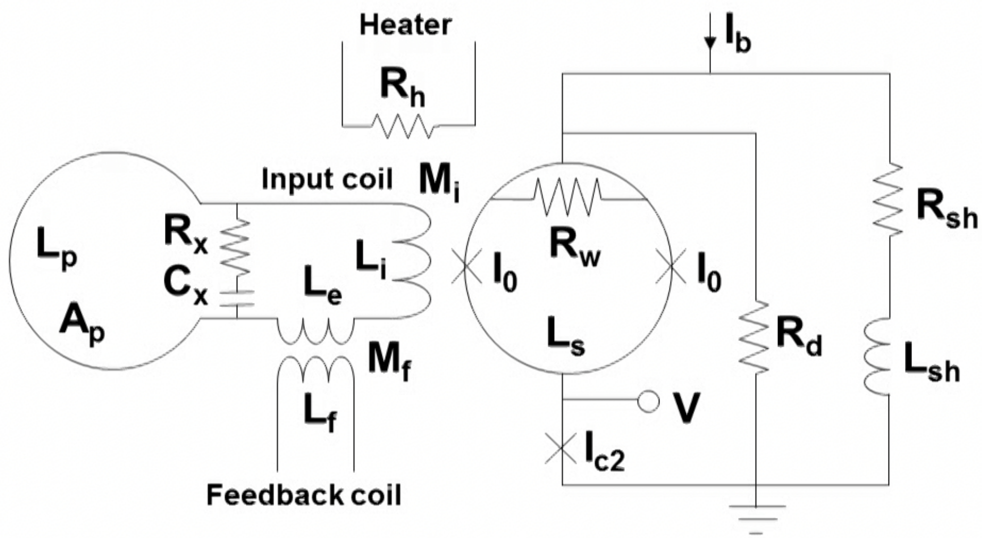
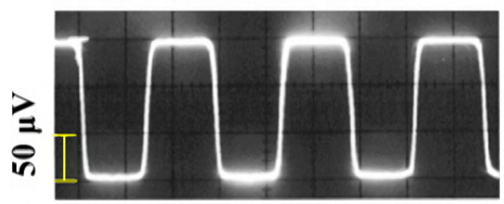
DROS: Circuit diagram



Typical flux-voltage curve



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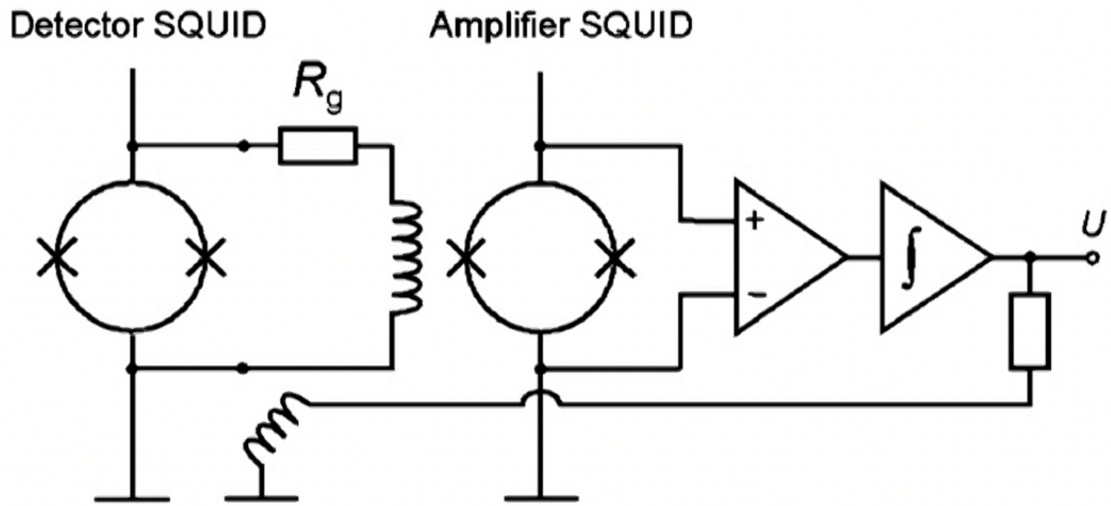
2-stage SQUID



Use a second SQUID as the amplifier of the first (detector) SQUID

→ Noise contribution of room-temperature electronics is negligible

Low system noise: < 1 $\mu\Phi_0/\sqrt{Hz}$

Control electronics

Others

- Installation space
- Fabrication cost
- Electricity consumption
- Reliability (maintenance) issue
- Power-line (Ground) noise

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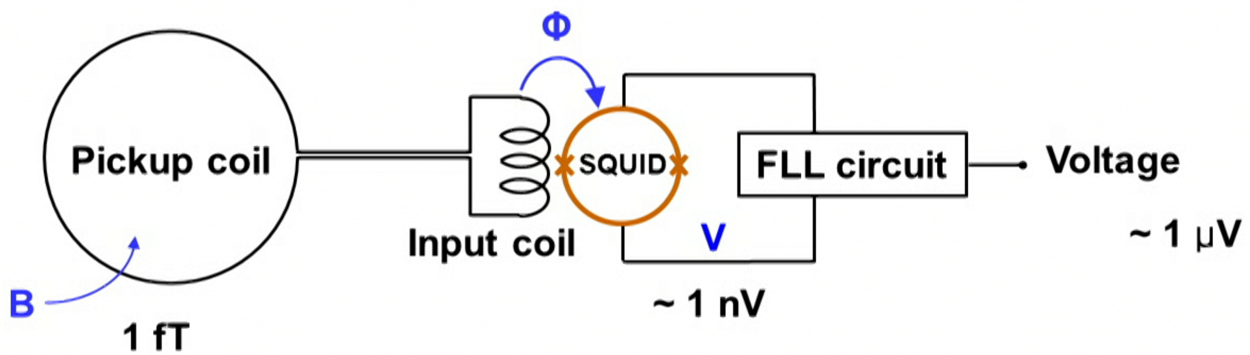
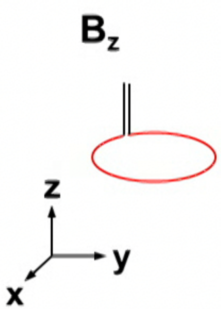
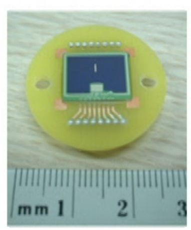
Pickup coils for field detection

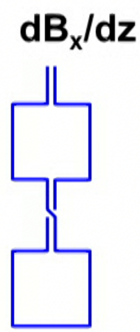


Magnetometer

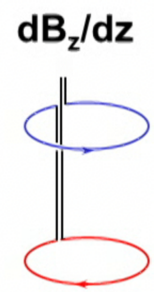




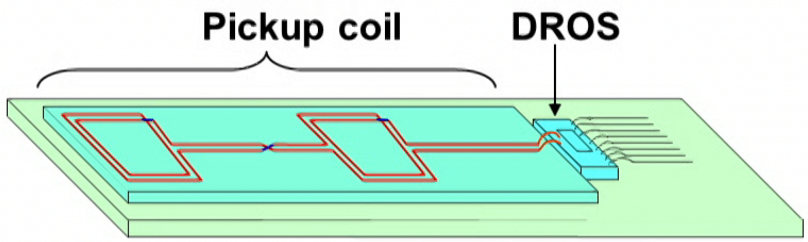
Planar gradiometer

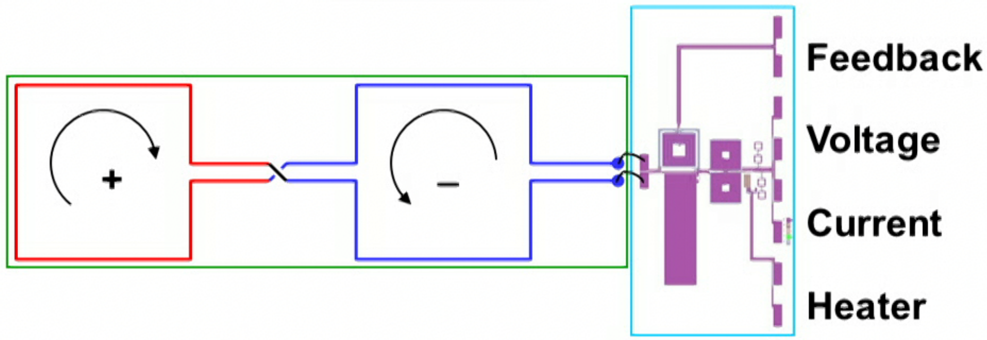


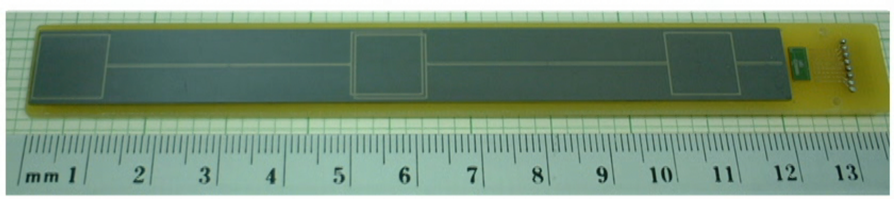
Axial gradiometer



Planar gradiometer



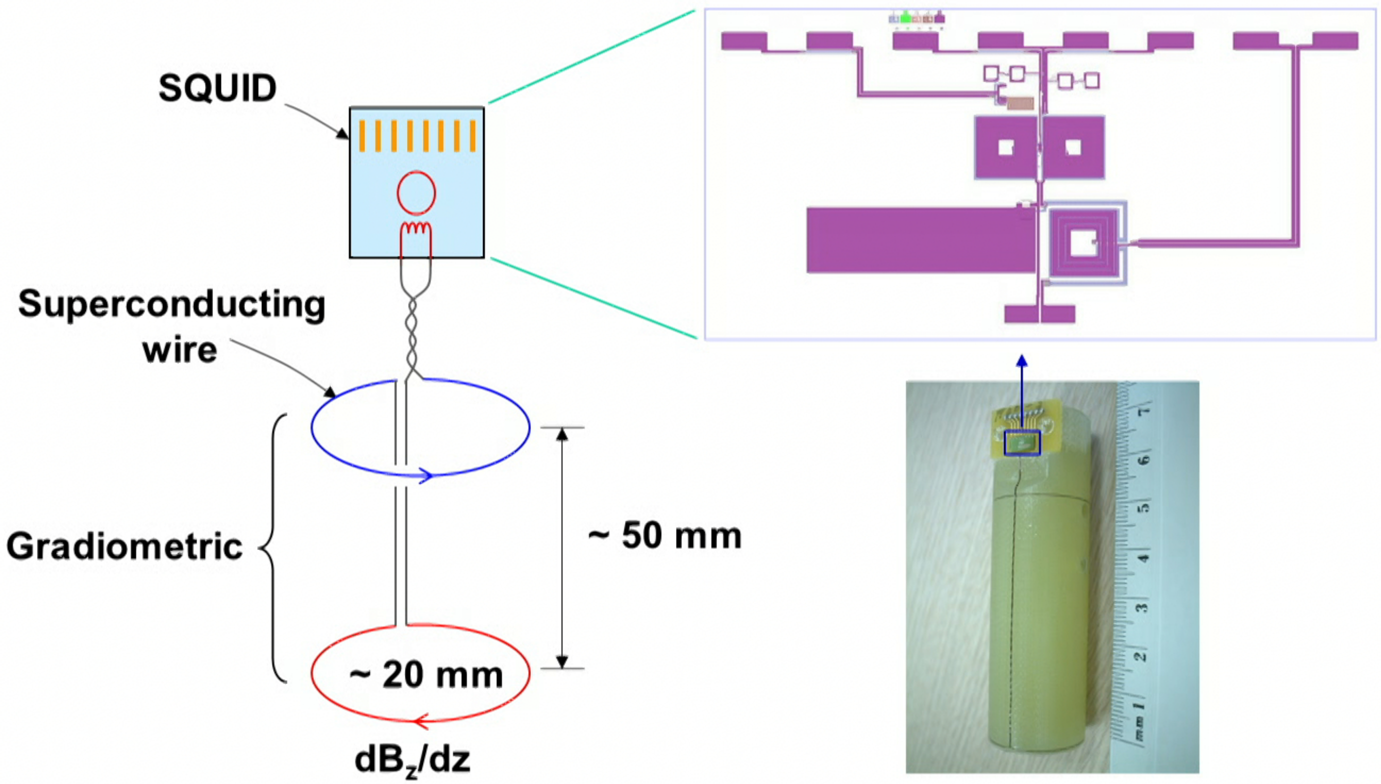




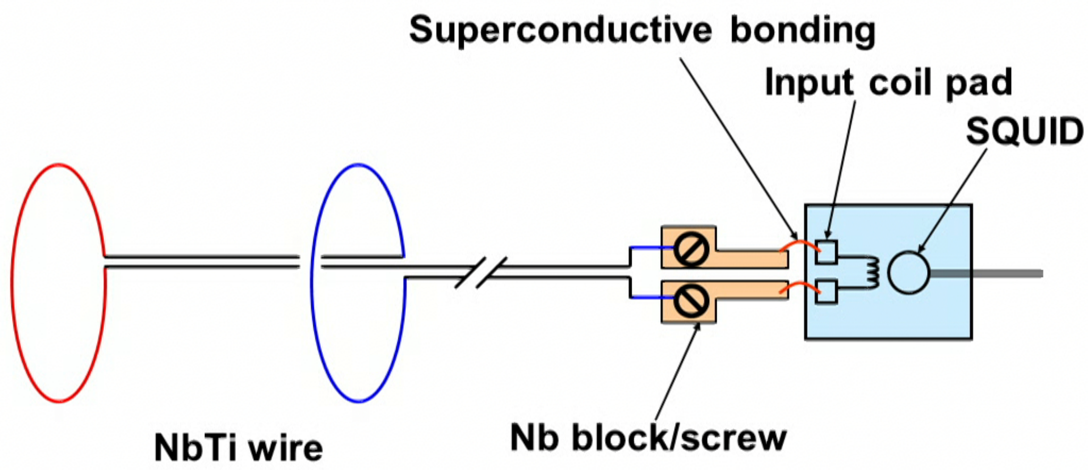
+ Higher balancing using photolithography

– Stress-free mounting of wafer on the substrate needed

Axial gradiometer

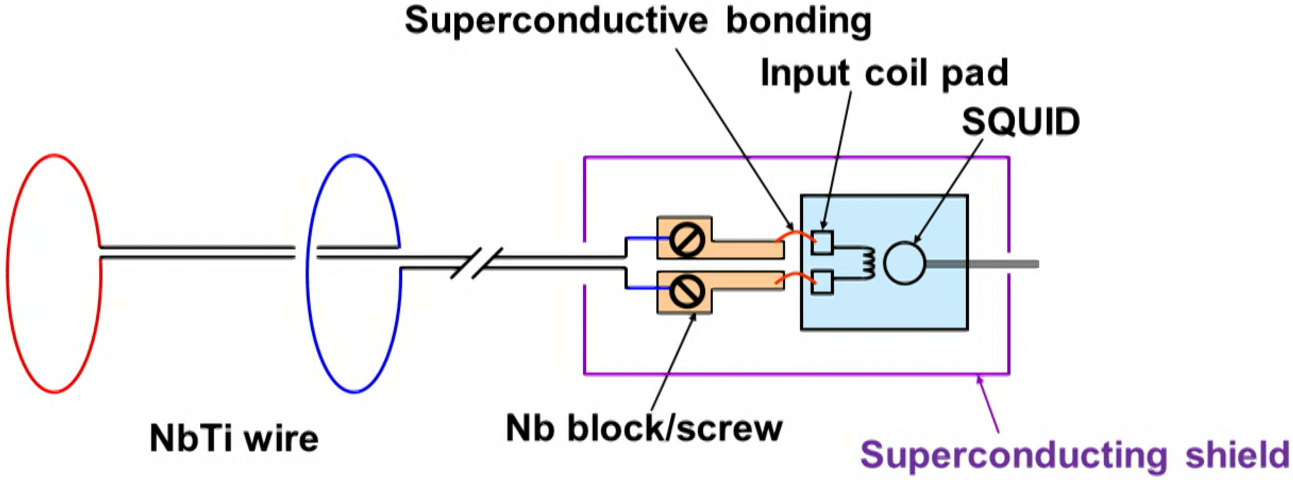


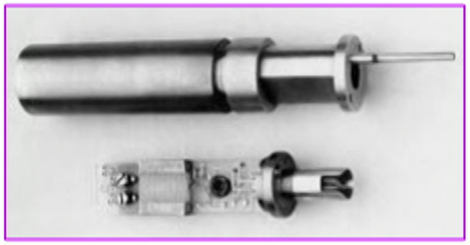
Conventional gradiometer bobbin



- Bulky
- Increased stray inductance
- Superconductive shielding (→ Field distortion)
- Long distance between SQUID and pickup coil
  (More frequent liquid-He refill)

Conventional gradiometer bobbin

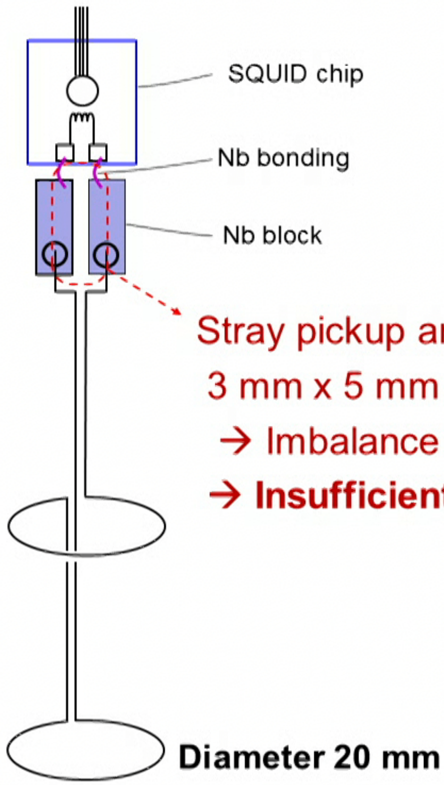




- Bulky
- Increased stray inductance
- Superconductive shielding (→ Field distortion)
- Long distance between SQUID and pickup coil (More frequent liquid-He refill)

Axial gradiometers

Conventional-2



Stray pickup area :
3 mm x 5 mm = 15 mm^2
→ Imbalance = 2.4 %
→ **Insufficient noise reduction**

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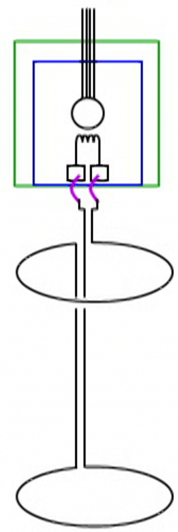

Stray pickup area :
0.3 mm x 2 mm = 0.6 mm^2
→ Imbalance = 0.1 %

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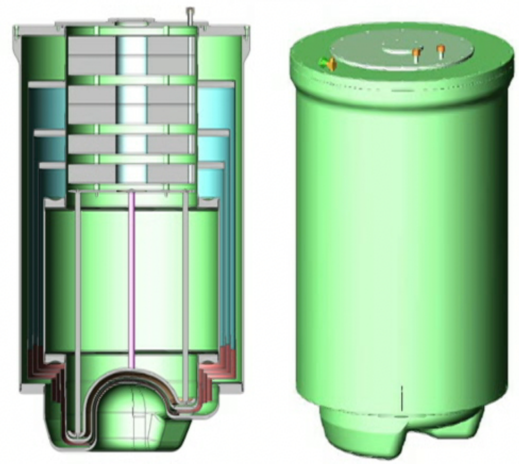
Standard insert and dewar

Gradiometer

Sensor helmet

Insert

Dewar



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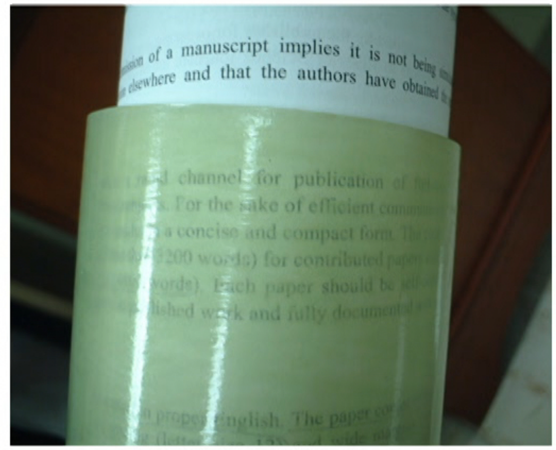
High quality fiberglass reinforced plastic

Conventional tube

- Poor vacuum sealing
- Lamination

Transparent FRP tube (KRISS)



Dewar:

- Multiple layers of superinsulations (~ 70 layers): large surface area
- Plastic, Nylon, cryogenic getter, etc: high-vacuum is difficult (~ 10^{-3} Pa)

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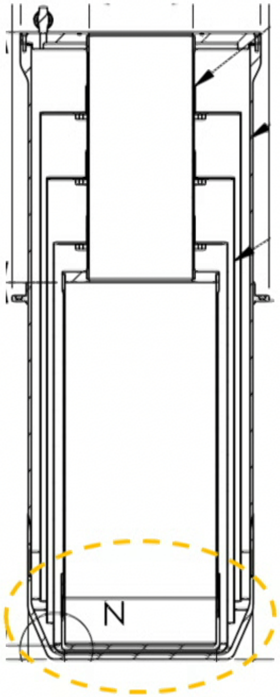
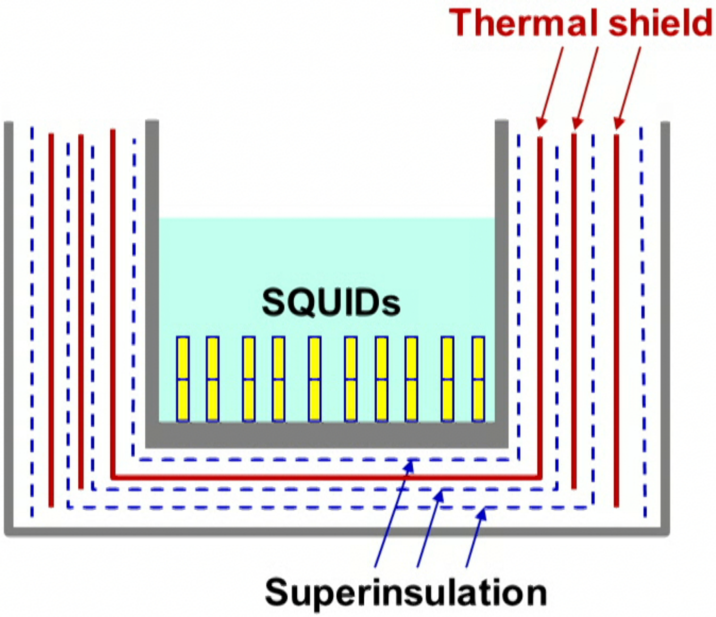
Eddy current noise





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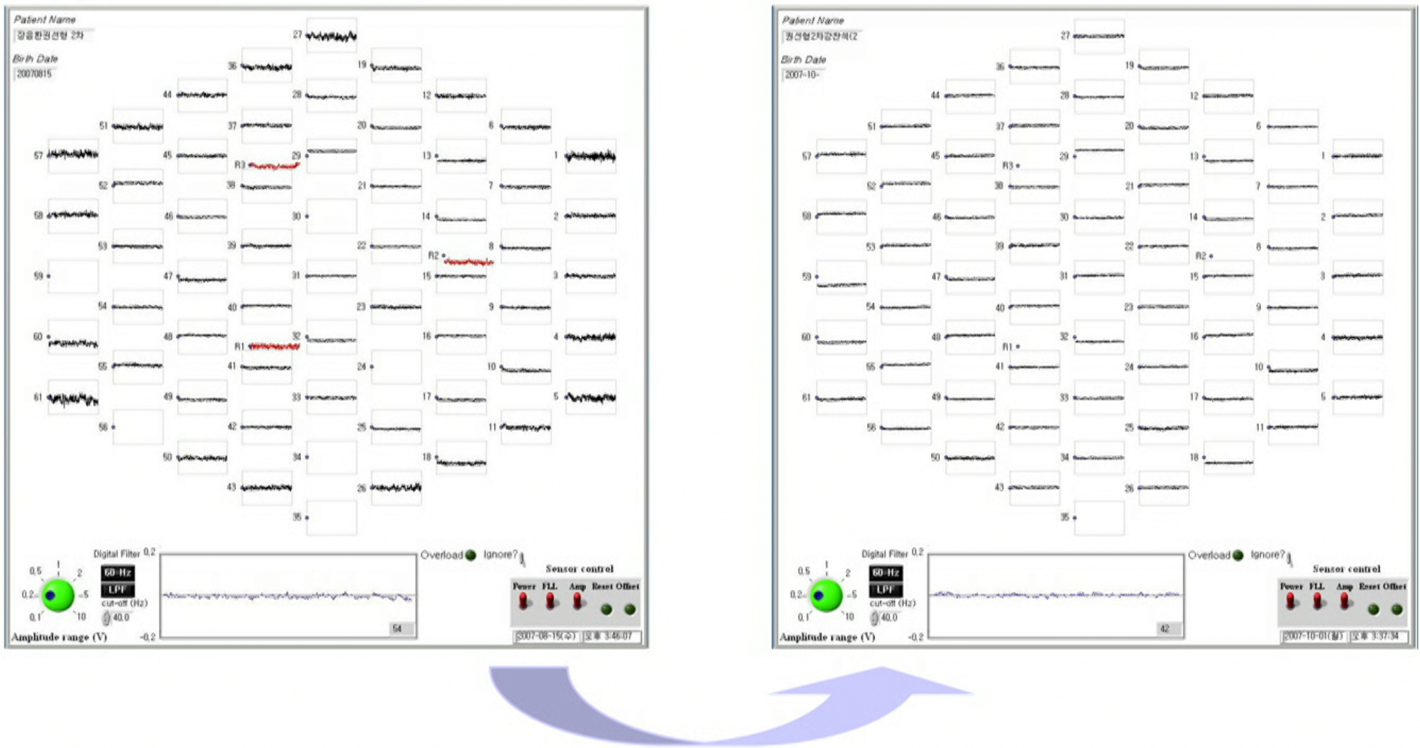
Eddy current noise by thermal shield



Reduction of thermal noise

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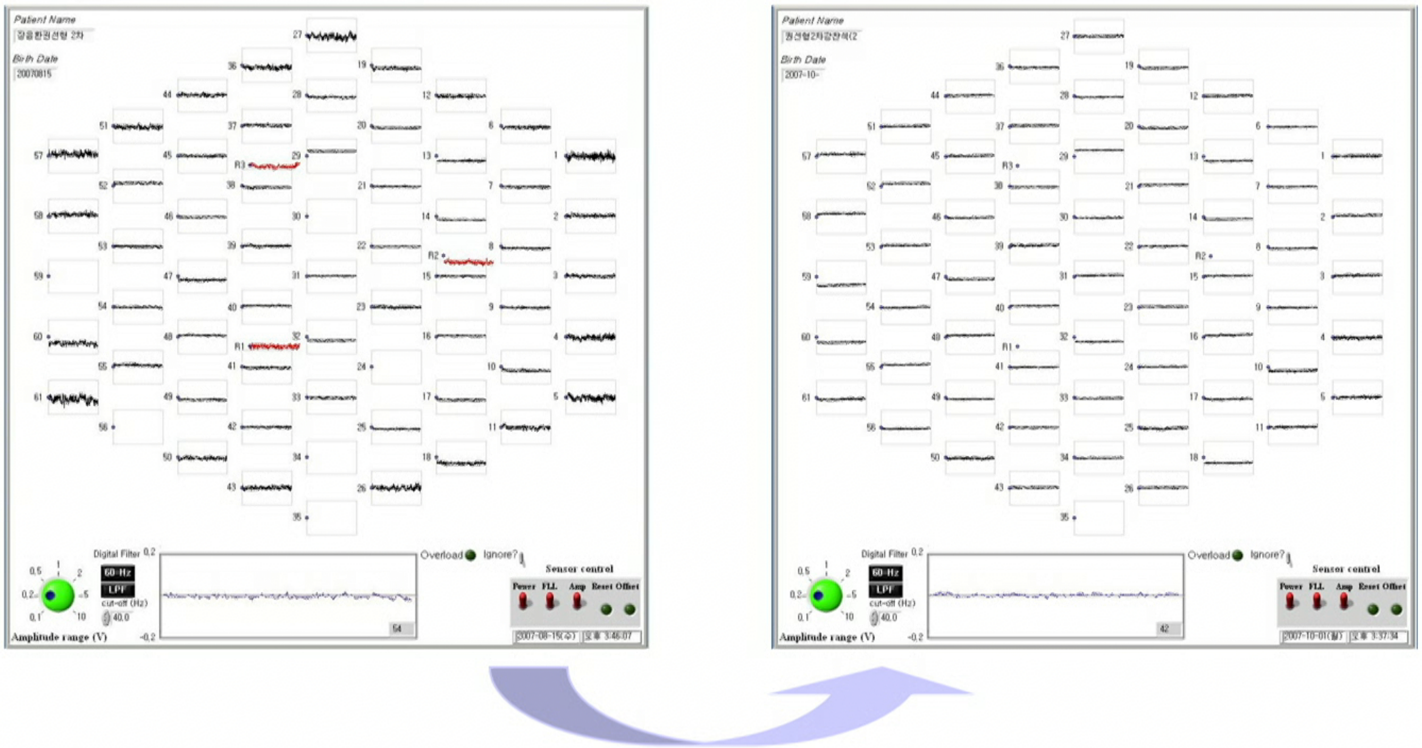
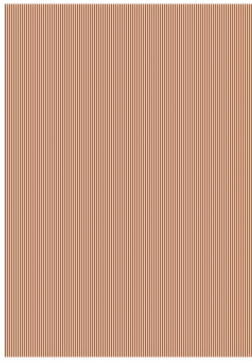
Eddy current noise by thermal shield



Reduction of thermal noise

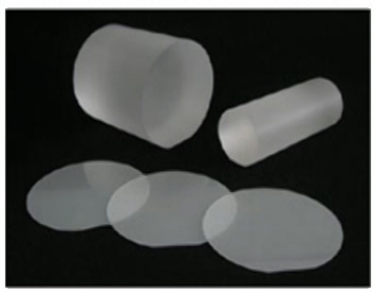
Thermal noise in thermal shield

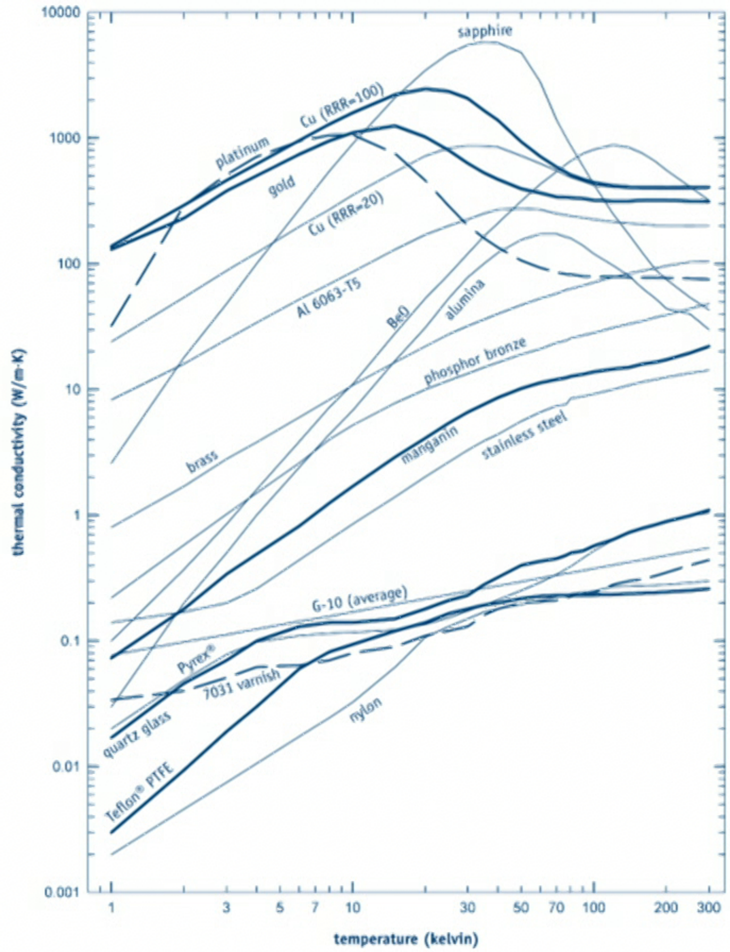
Thermal shield



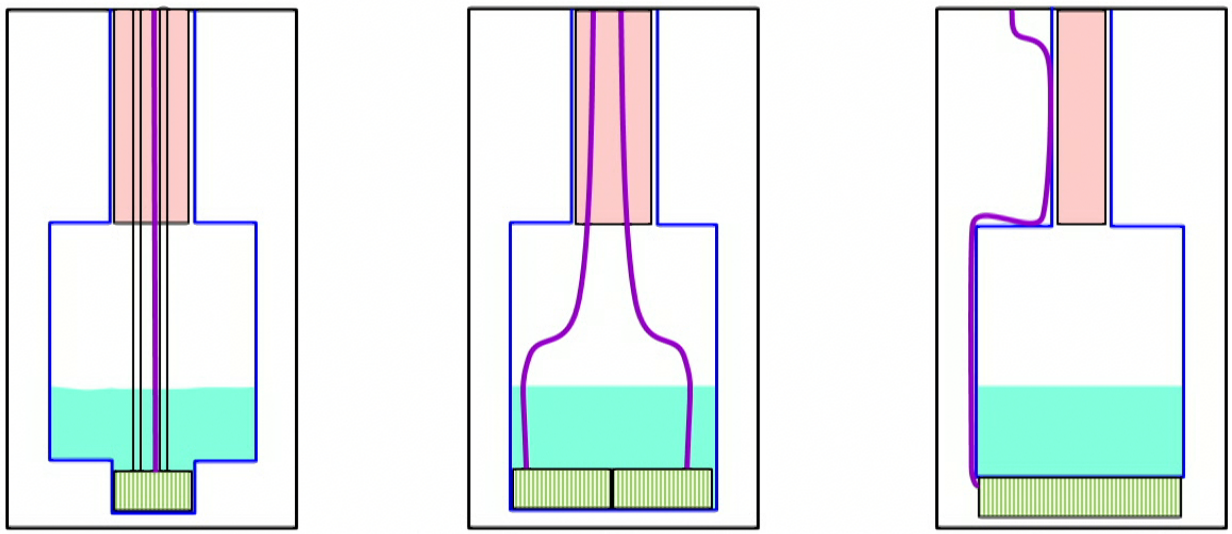
Insulated Cu wire
(Coil foil or Mesh)

Non-metallic thermal shield





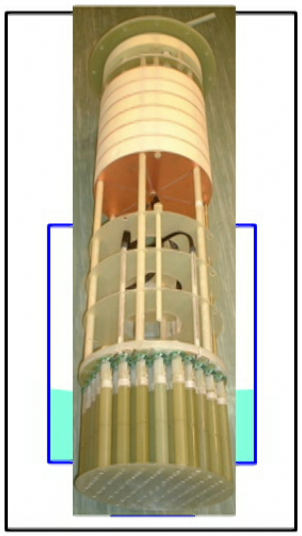
Dewar: Low thermal input



Standard dewar	Reduced neck	SQUID-in-vacuum
Insert structure Vibration Large neck diameter	Low thermal input from neck Less insert vibration	Low thermal input from neck No insert vibration Chemically stable Closer to sample

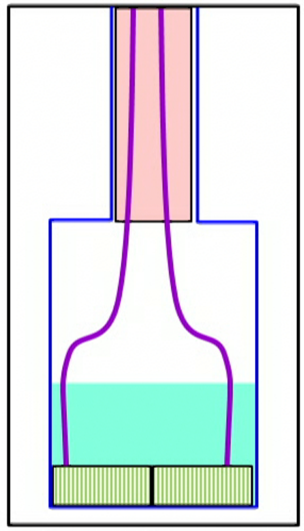
Dewar: Low thermal input

Standard dewar



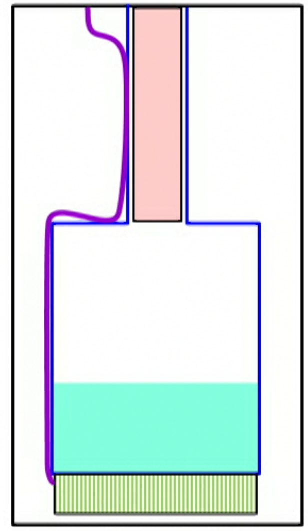
Insert structure
Vibration
Large neck diameter

Reduced neck



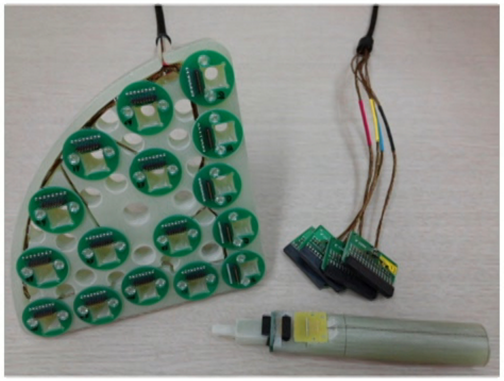
Low thermal input from neck
Less insert vibration

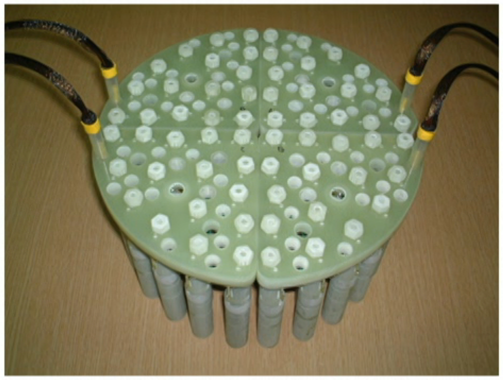
SQUID-in-vacuum



Low thermal input from neck
No insert vibration
Chemically stable
Closer to sample

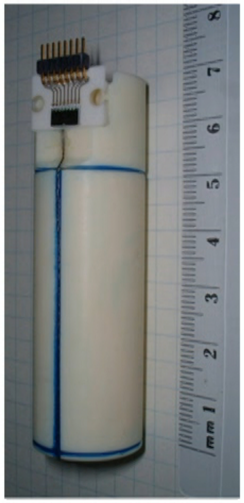
Divided 64-channel axial gradiometers

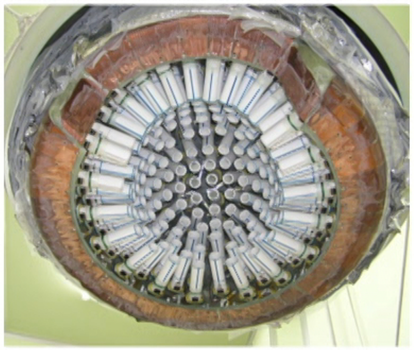




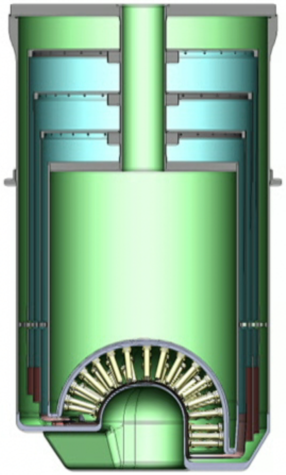
Fixed directly into inner bottom

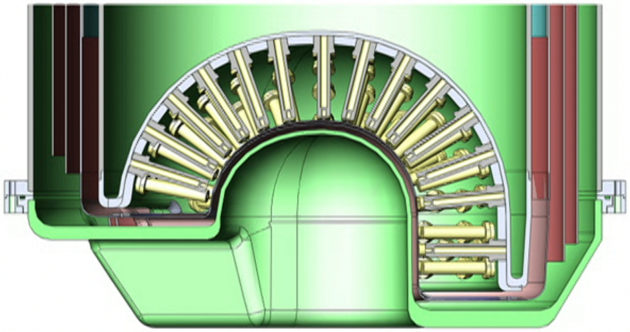
SQUID-in-vacuum helmet system





Axial first-order gradiometer





Lower boil-off of LHe
Closer distance bet. SQUID and room temp.
Magnetic contamination free from L-He

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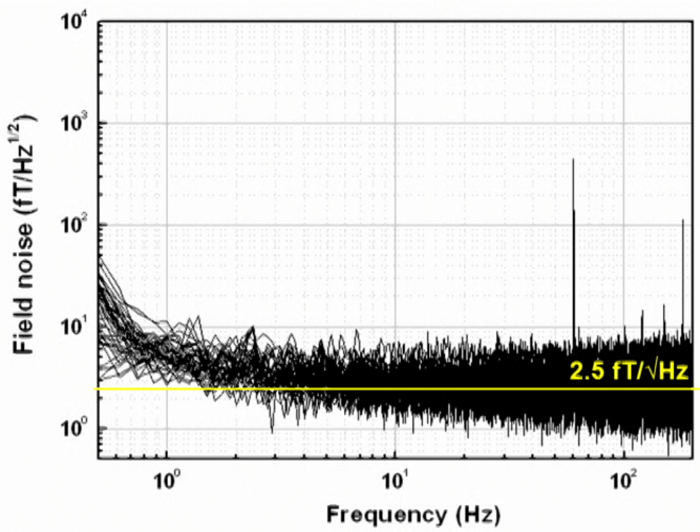
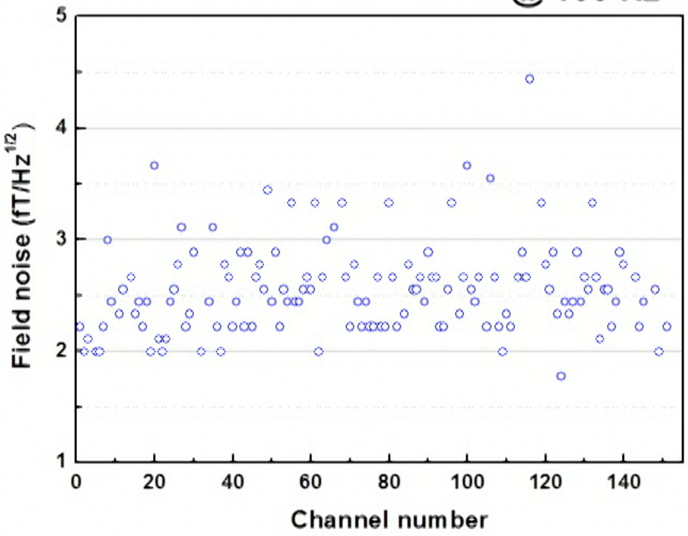
Magnetic field noise of SQUID-in-vacuum

<SQUID-in-vacuum>
Conductive cooling, 1AG



@ 100 Hz



No vibration peak from boiling of liquid helium

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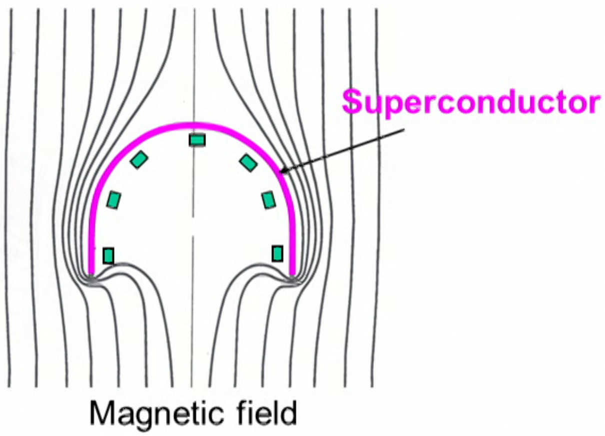
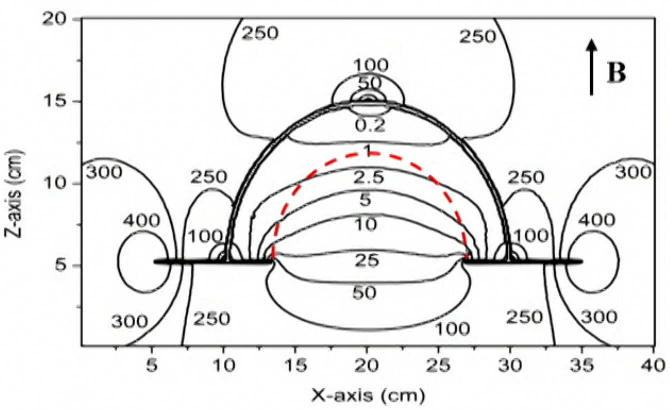
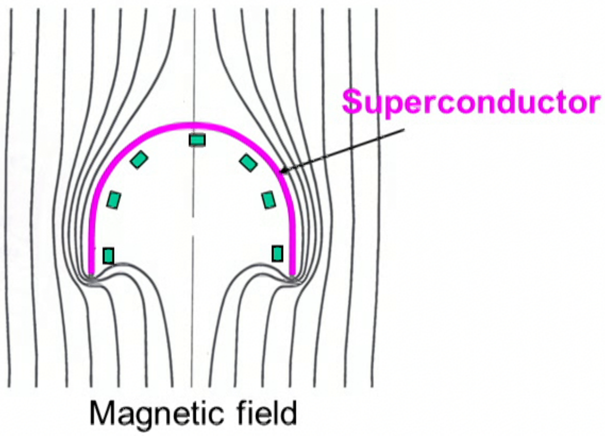
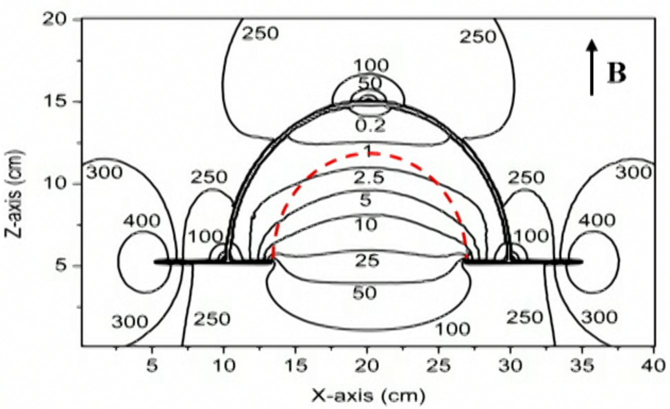
Superconductively-shielded magnetometer

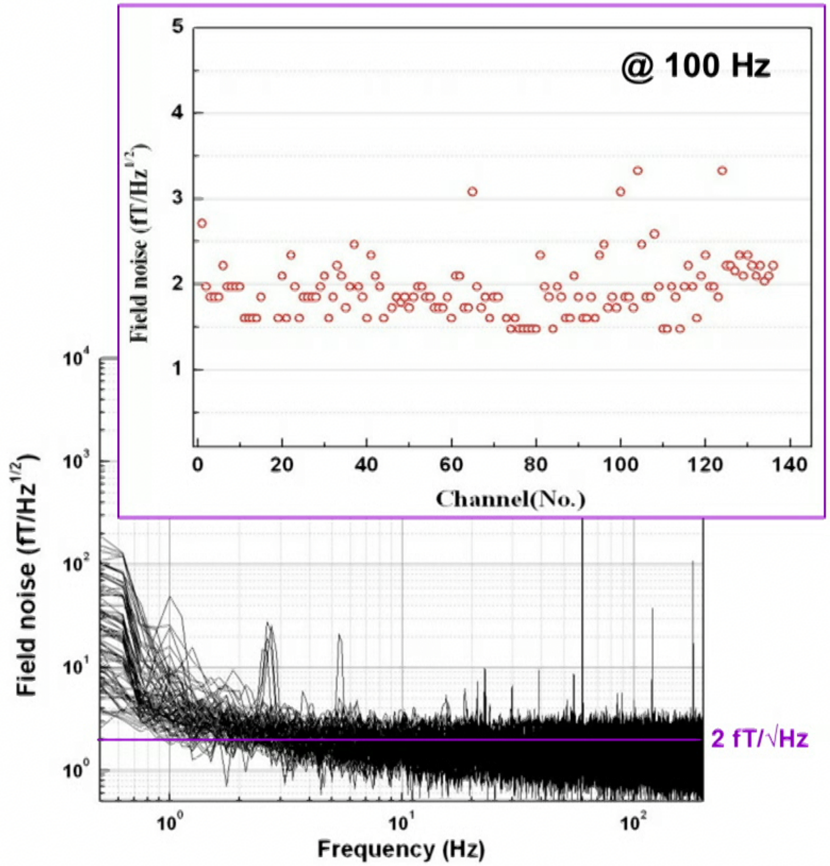




Superconductively-shielded magnetometer







Shielding of dewar thermal noises

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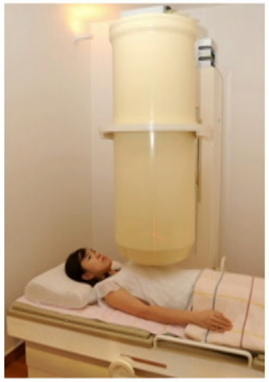
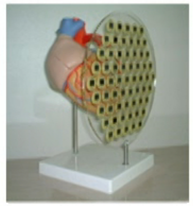
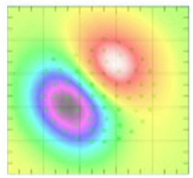
SQUIDS for Biomagnetism

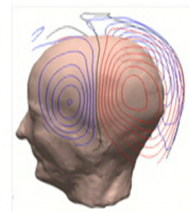
Magnetocardiography



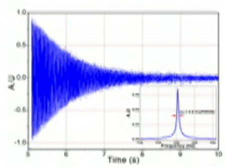


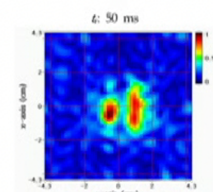


Magnetoencephalography



MRI at ultra low field





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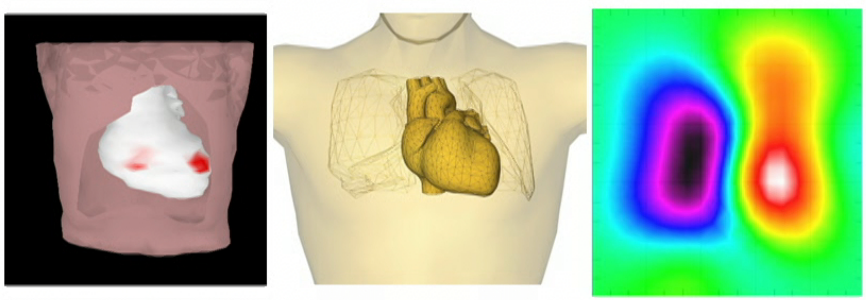
Magnetocardiography (MCG)

System

Dewar/Gantry

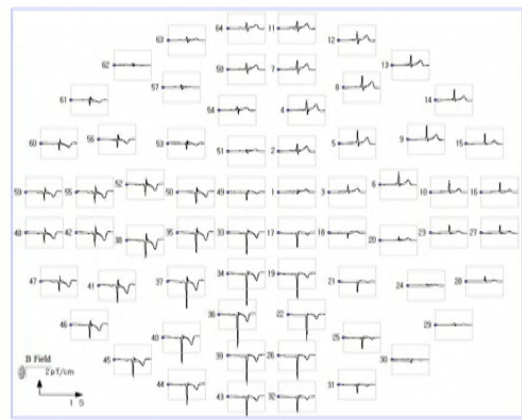
64-ch sensor

Analysis



Ischemic heart disease
Arrhythmia

Signals



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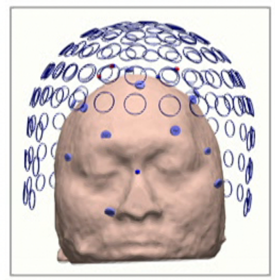
Magnetoencephalography (MEG)

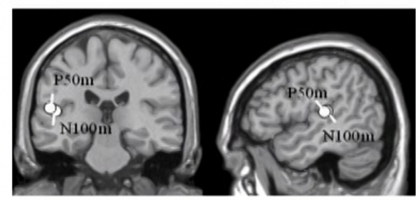
MEG system

Sensor helmet



Signals

Source analysis



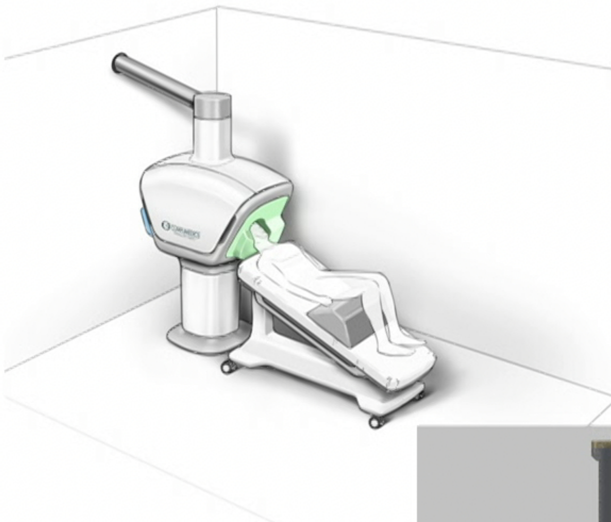
- High temporal & spatial resolution
- Non-contact & Non-invasive
- Measure neural activity

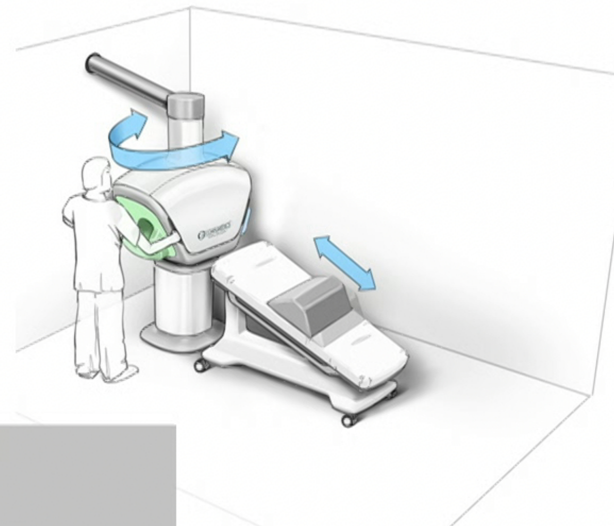
  → Study and diagnosis of brain function

  (Pre-surgical mapping, localization of epileptic sources, Brain development, Autism, diagnosis of Alzheimer's disease, cognition study, fetal diagnosis, etc)

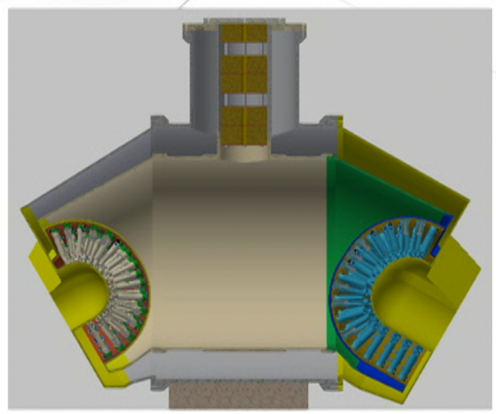
Next-generation MEG system

LifeSpan MEG: From baby to elderly (two helmets in one dewar)





Pediatric helmet
144 channels



Adult helmet
192 channels

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Method of cooling

- Liquid helium refill (weekly)
- Cyrocooler (pulse tube)
- Reliquefier

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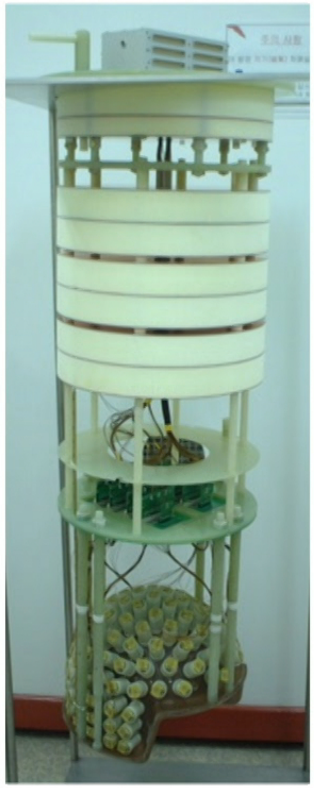
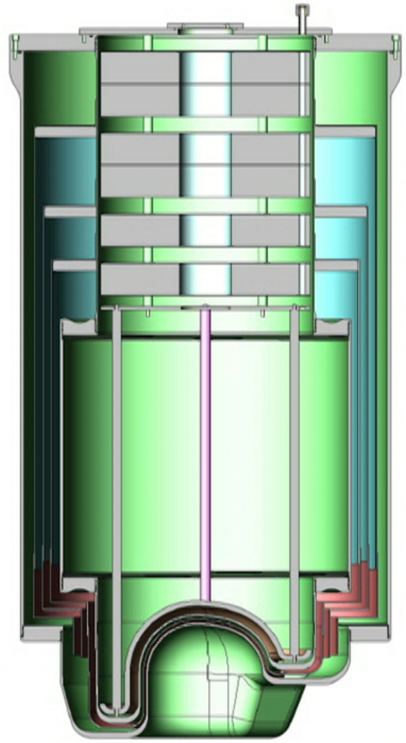
Liquid He cooled SQUID system





Liquid volume: ~ 90 L
Boil-off rate: ~ 12 L/d
Refill weekly
(~ $1,500/week)

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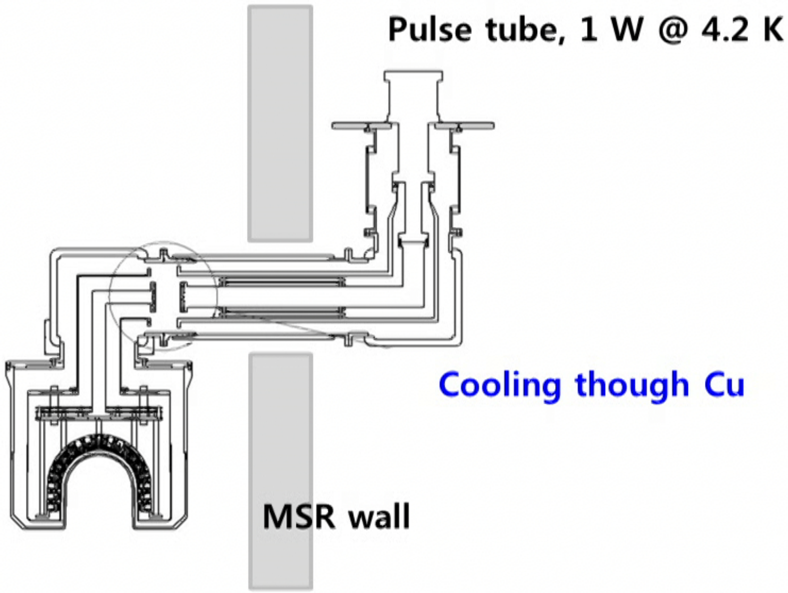
Cryocooler operated SQUID system



Trade off:

- Reduction of vibration and cryocooler magnetic noise
- Cooling effectiveness though a conductor

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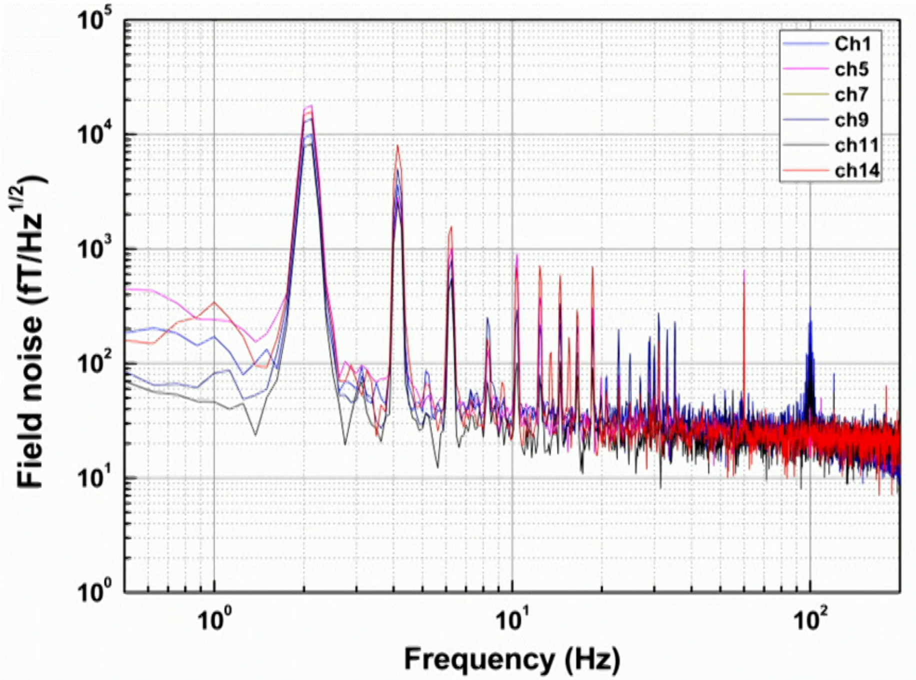
Noise of cryocooler cooled SQUID

Magnetic field noise



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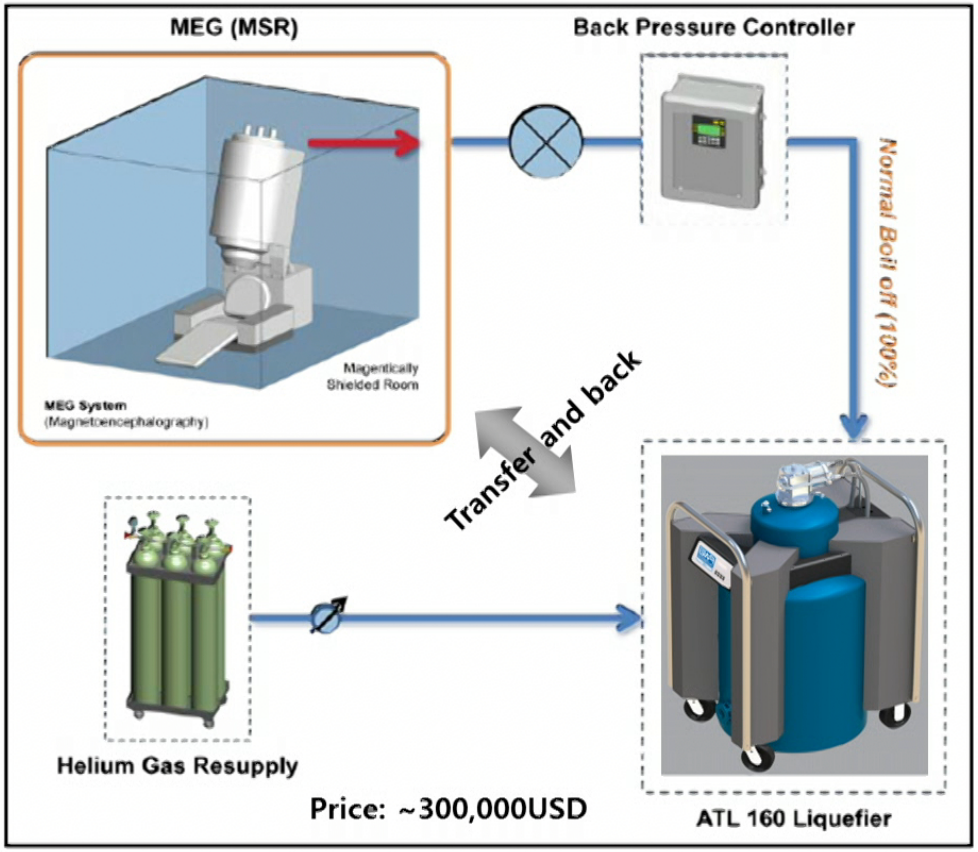
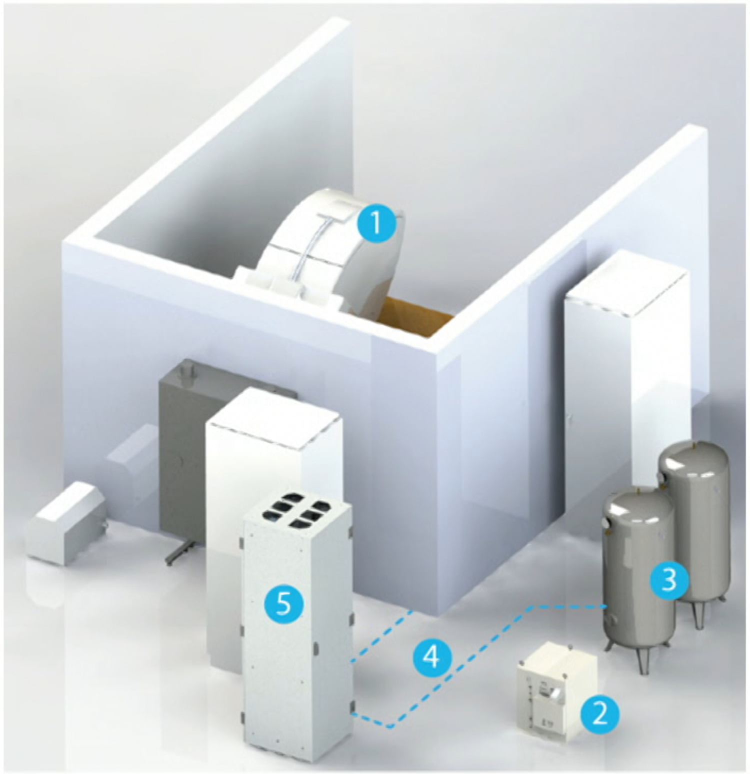
Quantum Design approach



Inconvenience (Moving the liquefier and back)
Loss

Elekta Reliquefier MEG



Reliquefier ON: Night
OFF: MEG measurement
Recovery rate: 80-85% (regeneration interval: 6~8 months)
Magnetic noise from stationary pulse tube

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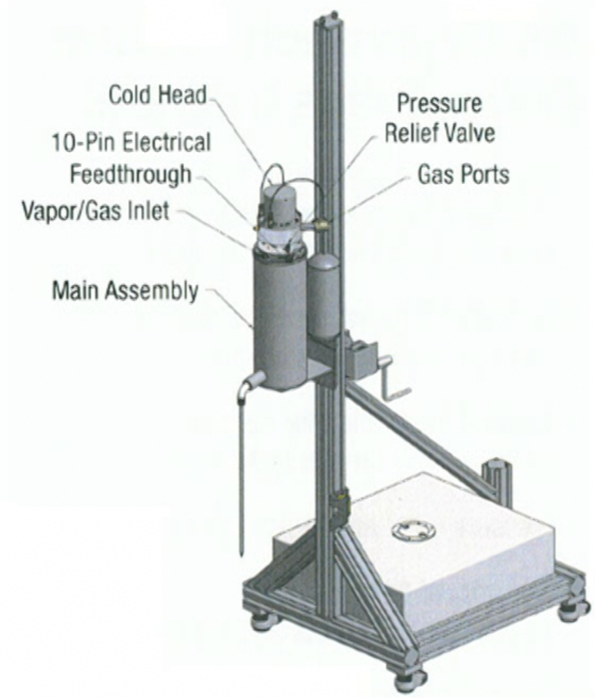
Continuous reliquefaction?



Cryomech model

Liquefaction rate?

Vibration/Magnetic noise?

Modification of the transfer tube?

Transfer loss?

Installation issue?

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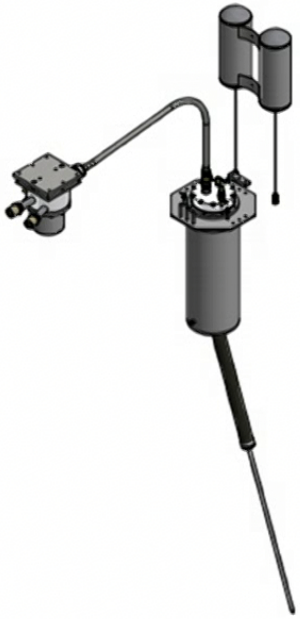
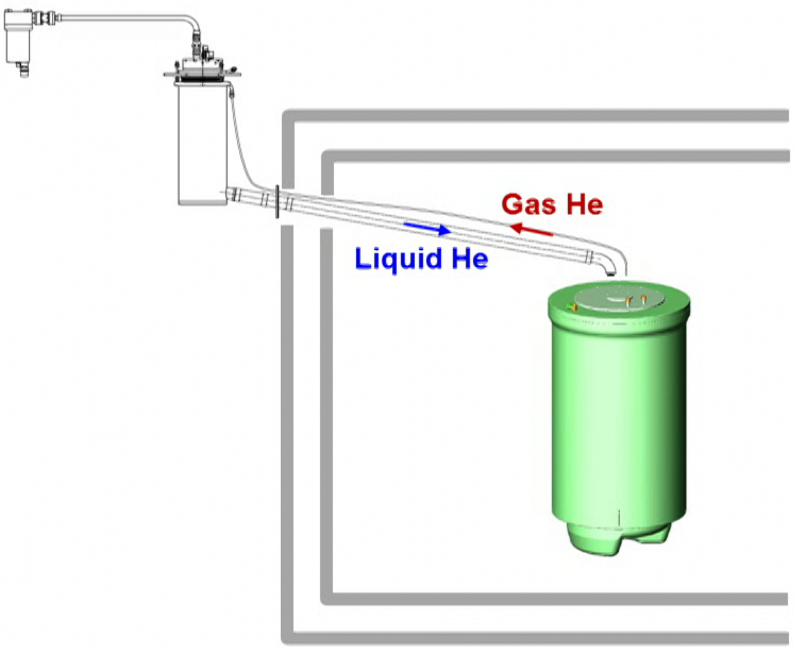
Reliquefier: Mounting type

Ceiling mounting



+ Less transfer loss
- Needs higher ceiling (+ 1 m)

Wall mounting



- Larger transfer loss
+ Lower ceiling height

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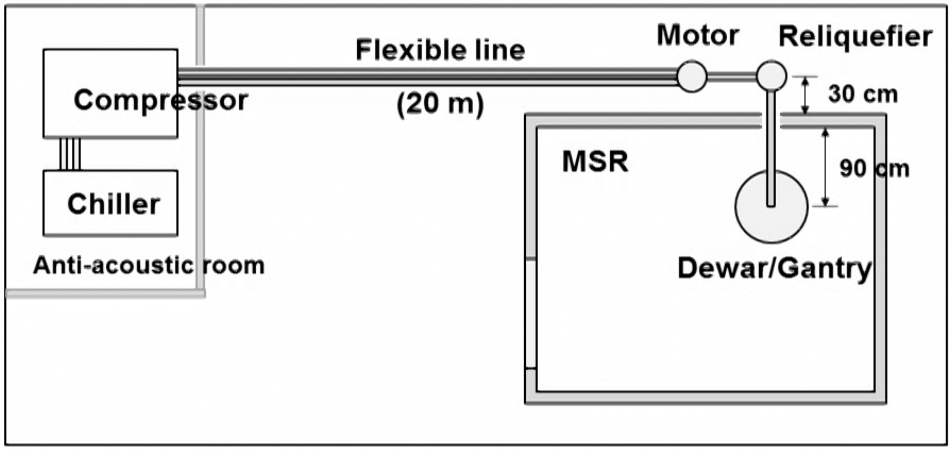
Reliquefier-based cooling



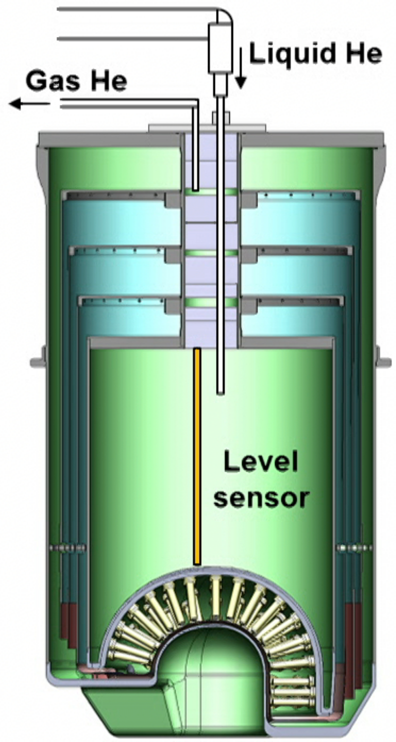
Chiller Compressor

Motor Reliquefier

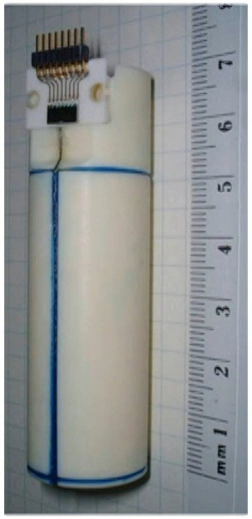
MEG Dewar

SQUID and dewar

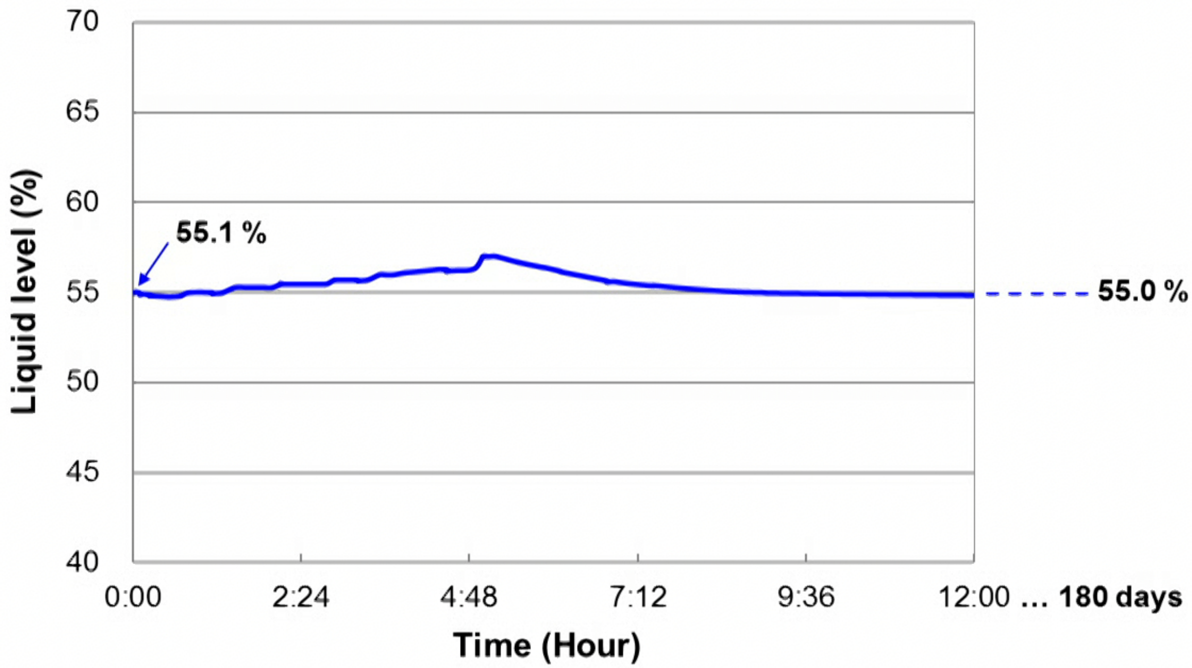
SQUID-in-vacuum



SQUID gradiometer



Liquid level change: 0% loss



During the first 6 months, 0% loss in the liquid level.
Second 6 months, 0% loss.

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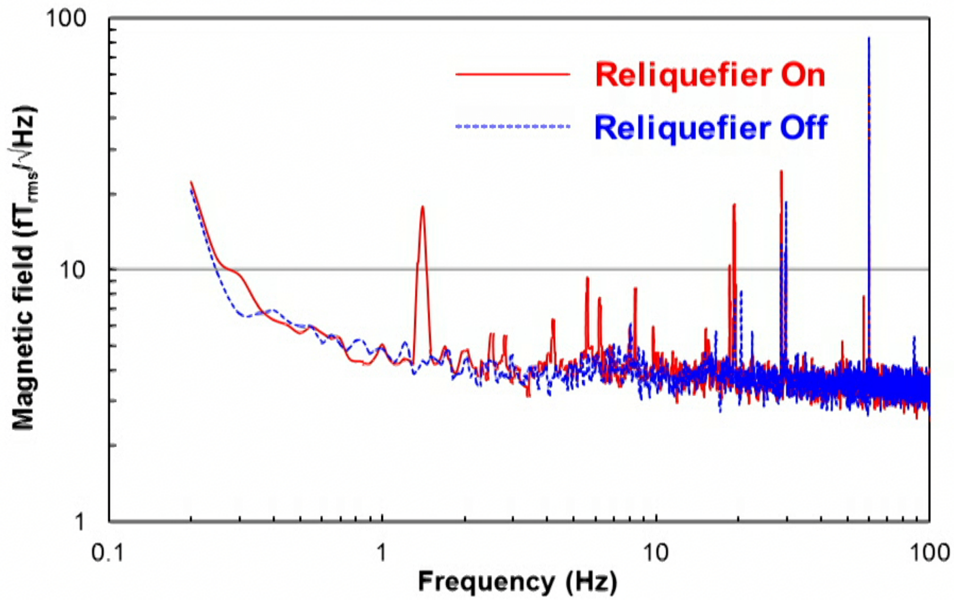
System noise: Comparison



Further optimization possible
Reference channels for common noise rejection

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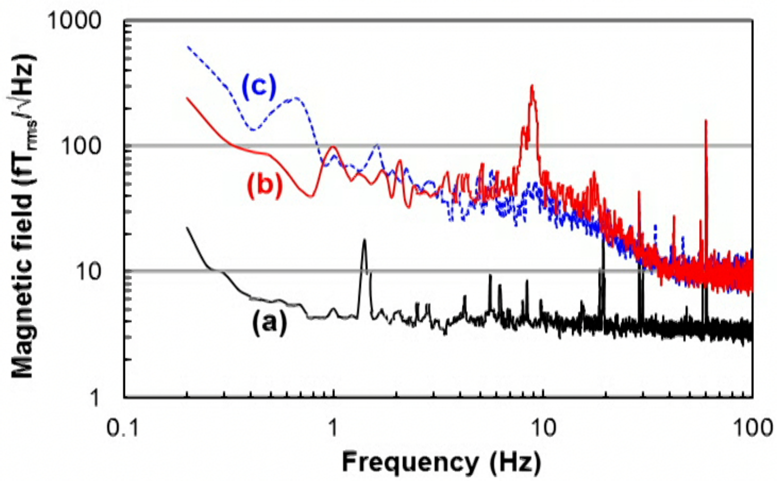
System noise: Comparison



(c) Eyes closed

(b) Eyes open

(a) Without subject

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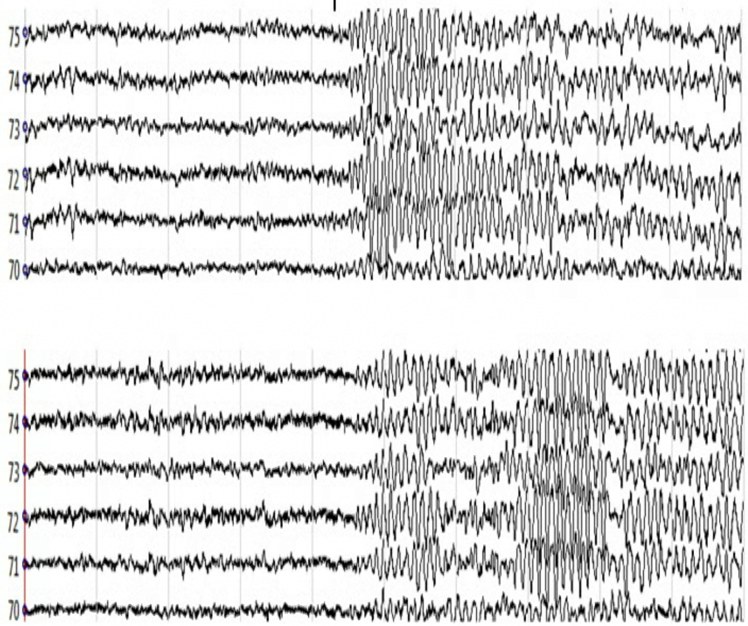
Comparison of brain signal: Reli. On vs. Off

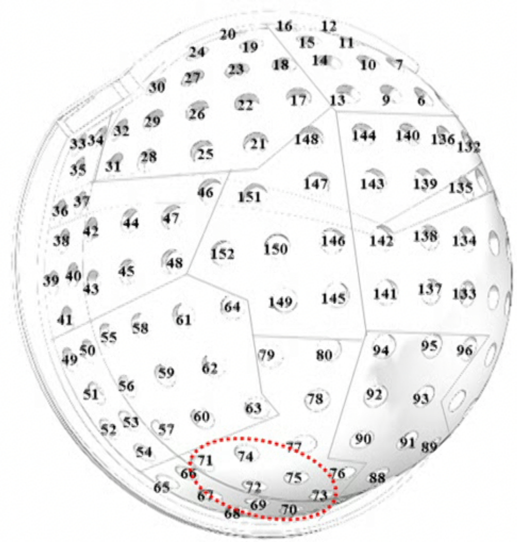
No signal processing/filtering

Eyes open | Eyes closed

Reliquefier off

Reliquefier on

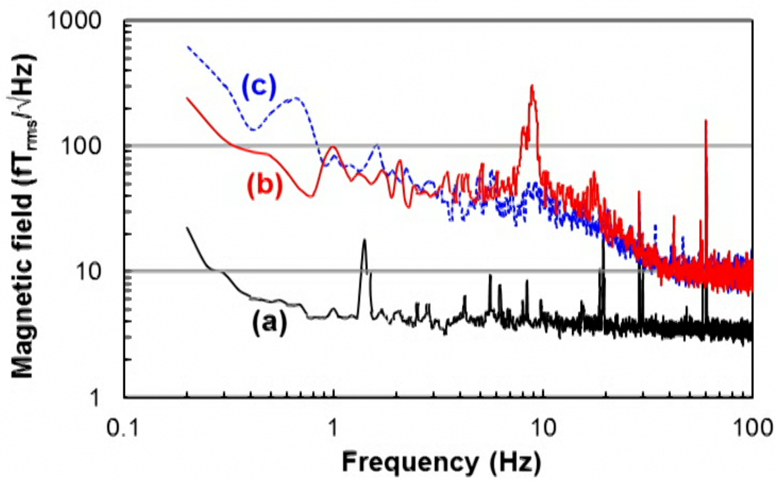




Measurement area

Reliquefier does not introduce appreciable noise on the brain signal (noise).

System noise: Comparison



(c) Eyes closed

(b) Eyes open

(a) Without subject

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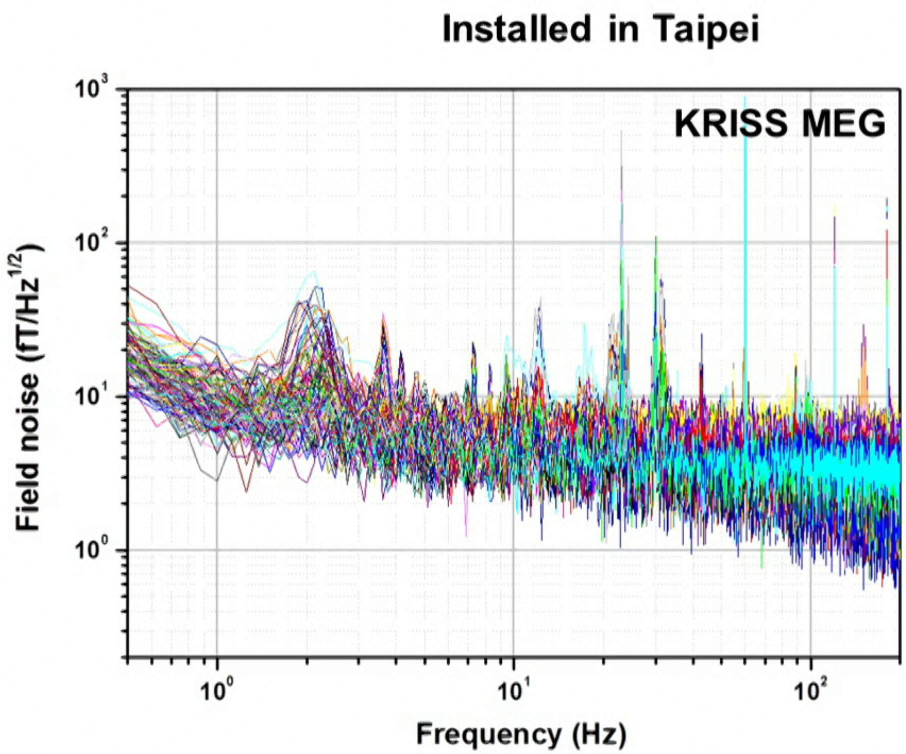
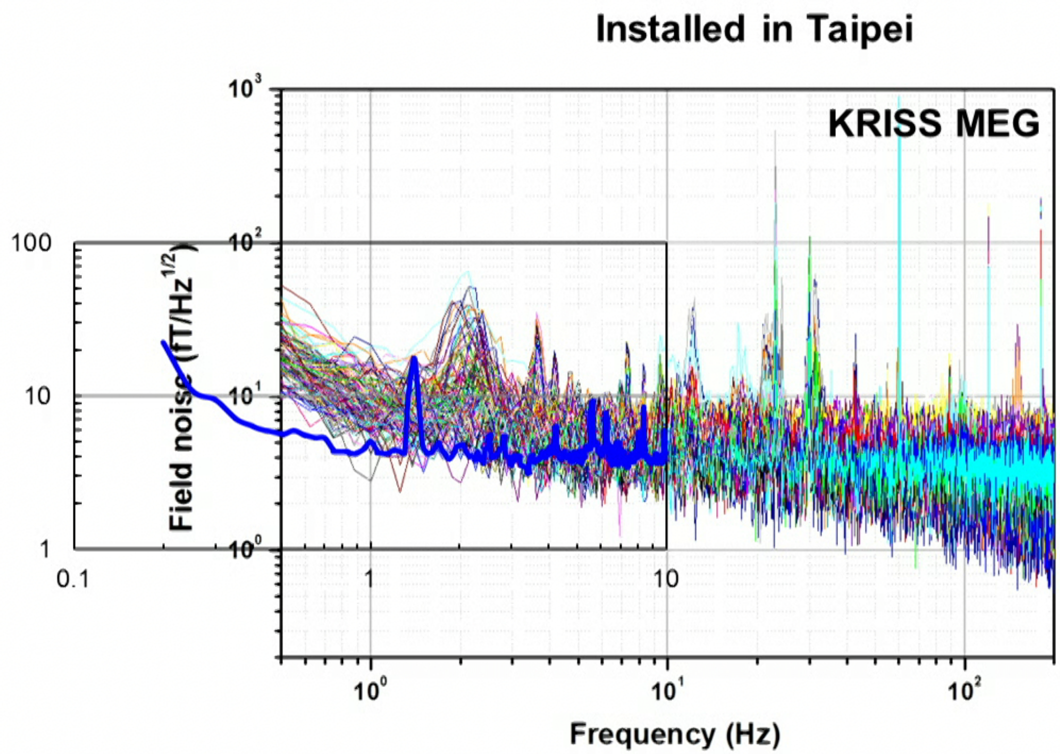
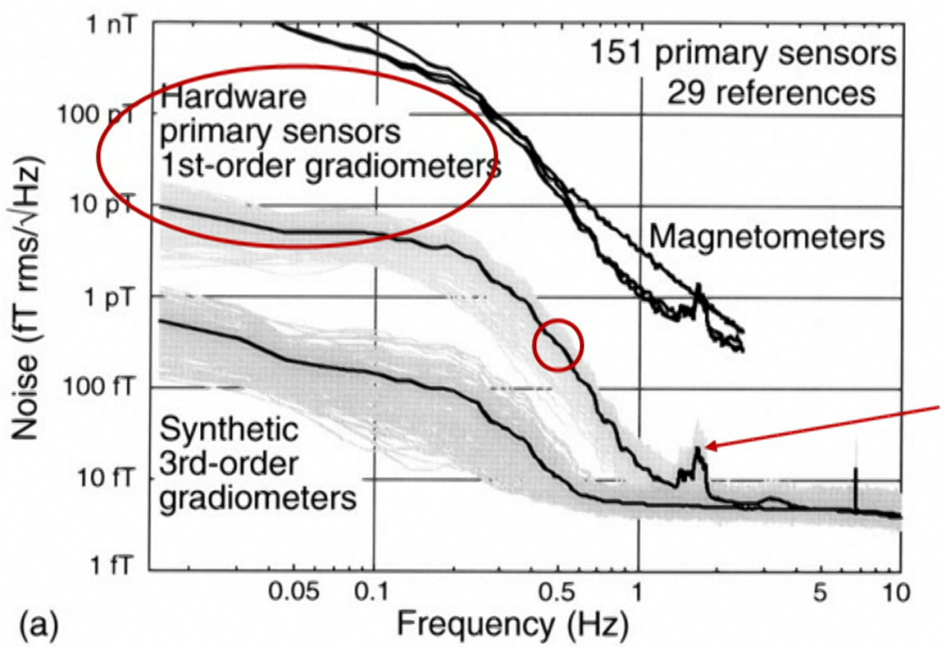
Comparison with direct liquid-He cooled MEG-1

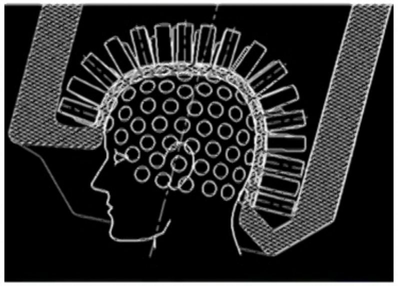


Comparison with direct liquid-He cooled MEG-1



Comparison with direct liquid-He cooled MEG-2





CTF Axial gradiometer (baseline 50 mm)

About 20 $fT_{rms}/\sqrt{Hz}$ at ~1.5 Hz (due to system vibration).

METHODS 25, 249–271 (2001)
doi:10.1006/meth.2001.1238, available online at http://www.idealibrary.com on IDEAL®

Signal Processing in Magnetoencephalography

Jiri Vrba and Stephen E. Robinson

CTF Systems Inc., A subsidiary of VSM MedTech Ltd., 15-1750 McLean Avenue, British Columbia V3C 1M9, Port Coquitlam, Canada

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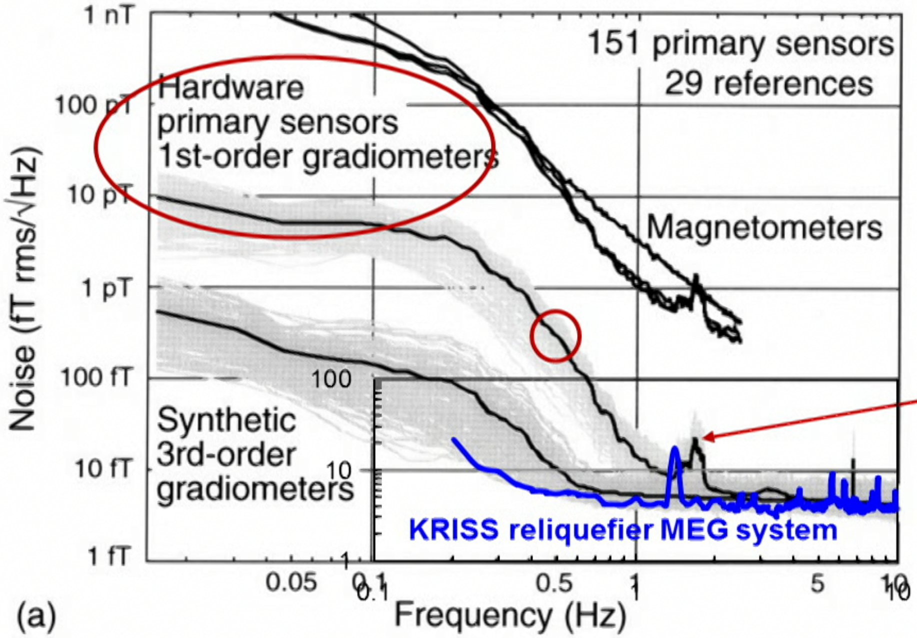
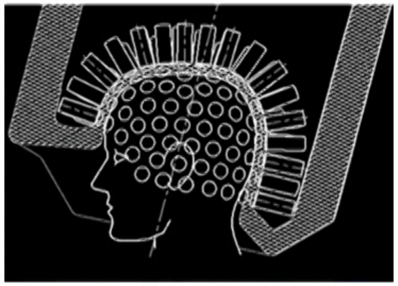
Comparison with direct liquid-He cooled MEG-2





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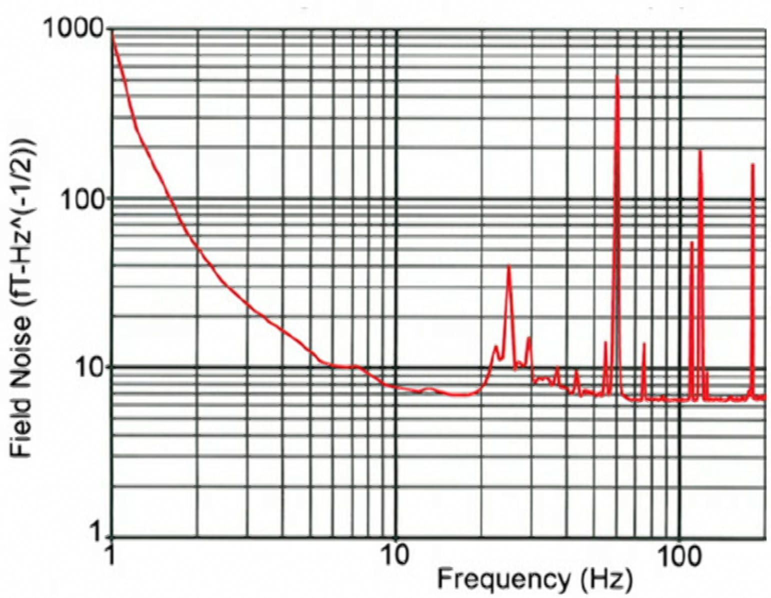
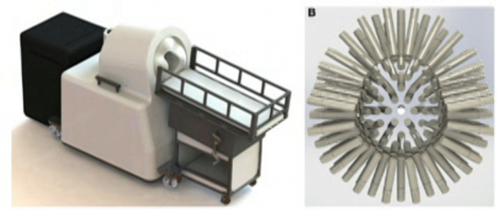
Comparison with direct liquid-He cooled MEG-3



Baby MEG (Philadelphia)



Tristan Artemis 123
Axial gradiometer
(baseline 60 mm)
L-He cooled

Much more noisy than KRISS reliquefier-MEG system (in the low frequency)

frontiers in
HUMAN NEUROSCIENCE
TECHNOLOGY REPORT ARTICLE
published: 03 March 2014
doi: 10.3389/fnhum.2014.00099

Artemis 123: development of a whole-head infant and young child MEG system

Timothy P. L. Roberts[1], Douglas N. Paulson[2], Eugene Hirschkoff[2], Kevin Pratt[2], Anthony Mascarenas[2],*

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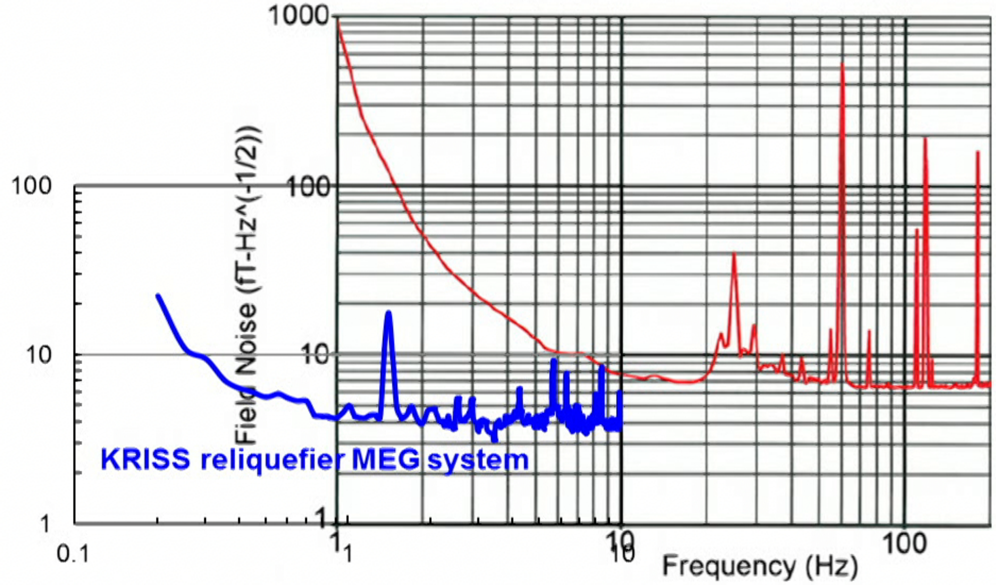
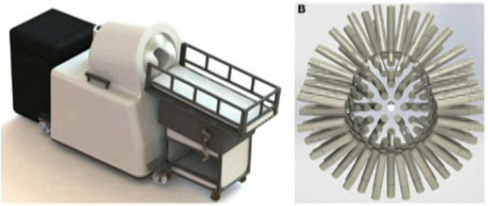
Comparison with direct liquid-He cooled MEG-3



Baby MEG (Philadelphia)



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Artemis 123: development of a whole-head infant and young child MEG system

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Reliquefier-MEG: Boston Children's Hospital

REVIEW OF SCIENTIFIC INSTRUMENTS 87, 094301 (2016)

BabyMEG: A whole-head pediatric magnetoencephalography system for human brain development research

Yoshio Okada,[1,a)] Matti Hämäläinen,[2] Kevin Pratt,[3] Anthony Mascarenas,[3] Paul Miller,[3] Menglai Han,[3] Jose Robles,[3] Anders Cavallini,[3] Bill Power,[3] Kosal Sieng,[3] Limin Sun,[1] Seok Lew,[1] Chiran Doshi,[1] Banu Ahtam,[1] Christoph Dinh,[4] Lorenz Esch,[4] Ellen Grant,[1] Aapo Nummenmaa,[2] and Douglas Paulson[3]
[1]*Division of Newborn Medicine, Department of Medicine, Boston Children's Hospital, Boston, Massachusetts 02115, USA*

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Boston Children's Hospital

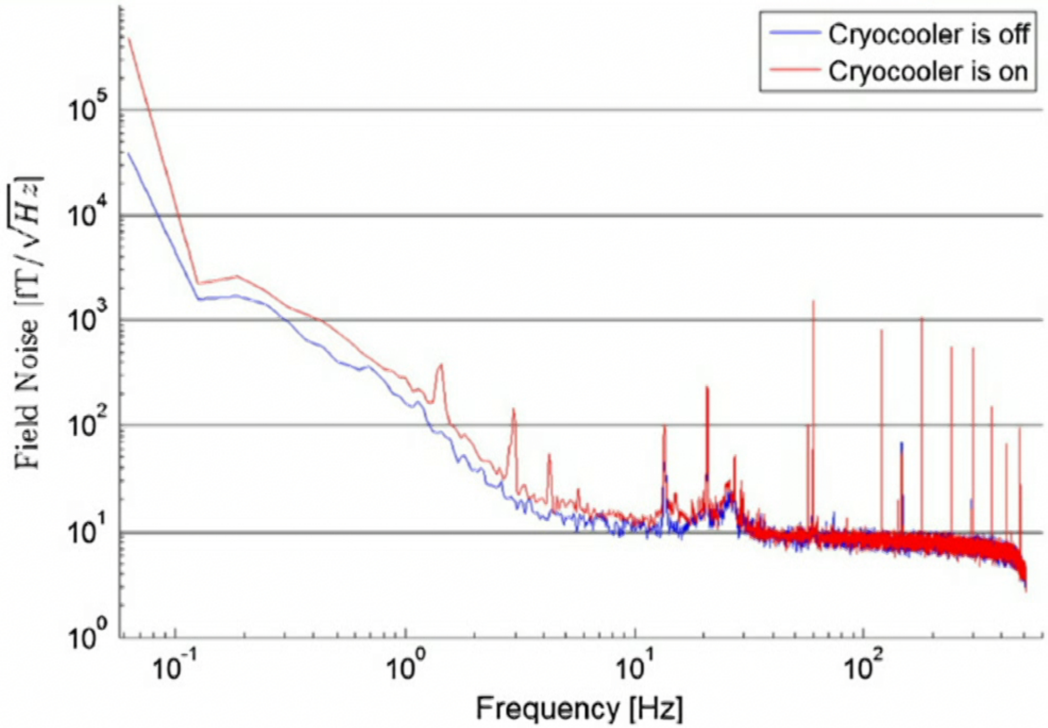

Fig. 8. Raw output of a magnetometer channel in the inner layer of the sensor array with and without the recycler on.

C. Wang, Cryogenics (2016)

Boston system noise level and peaks are much larger than KRISS system noise

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Boston Children's Hospital

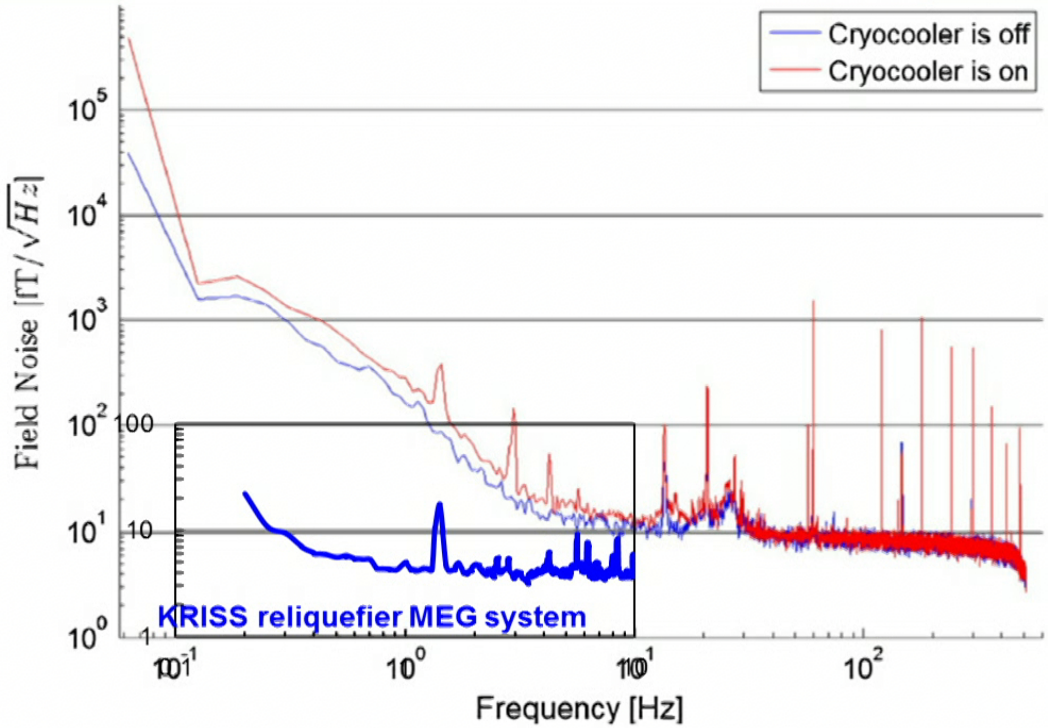

Fig. 8. Raw output of a magnetometer channel in the inner layer of the sensor array with and without the recycler on.

C. Wang, Cryogenics (2016)

Boston system noise level and peaks are much larger than KRISS system noise

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Content

SQUIDs for ARIADEN, pEDM and Axion

KRISS

Institute for Basic Science
ibs
기초과학연구원

CAPP

Center for
Axion and Precision
Physics Research

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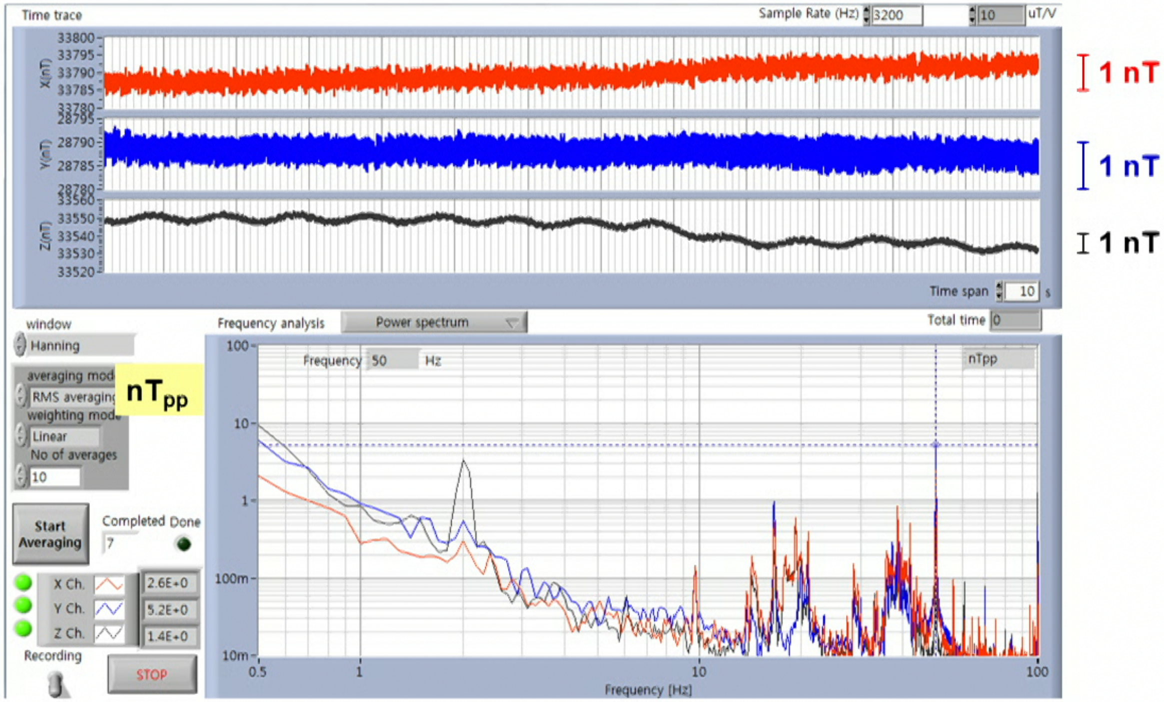
Environmental noise



MEG signal: ~ 0.0001 nT

Low-frequency drift: 100~1000 nT

Vibration noise: ~ 1 nT

60-Hz peak: 10~100 nT

Shielding

ARIADNE: Magnetic & Superconductive
- Environmental noise
- Thermal noise (Tungsten mass)
- Dewar thermal noise

pEDM: Magnetic & Superconductive
- Environmental noise
- Dewar thermal noise

Axion: Magnetic & Superconductive
- Magnet field (DC)
- Environmental noise

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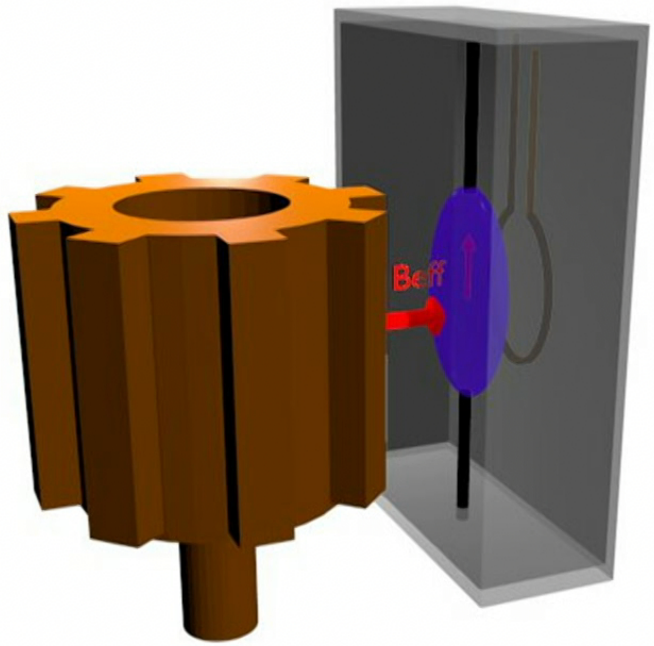
The ARIADNE axion NMR experiment

Axion Resonant InterAction Detection Experiment (ARIADNE)



$$\vec{B}_{\text{eff}} \approx \frac{1}{\hbar\gamma_N}\nabla V_a(r)(1+\cos(n\omega_{\text{rot}}t))$$

NMR signal at ~ 100 Hz

11 segments
Rotation at ~ 9 Hz

A. Arvanitaki and A. Geraci., *Phys. Rev. Lett.* 113,161801 (2014).

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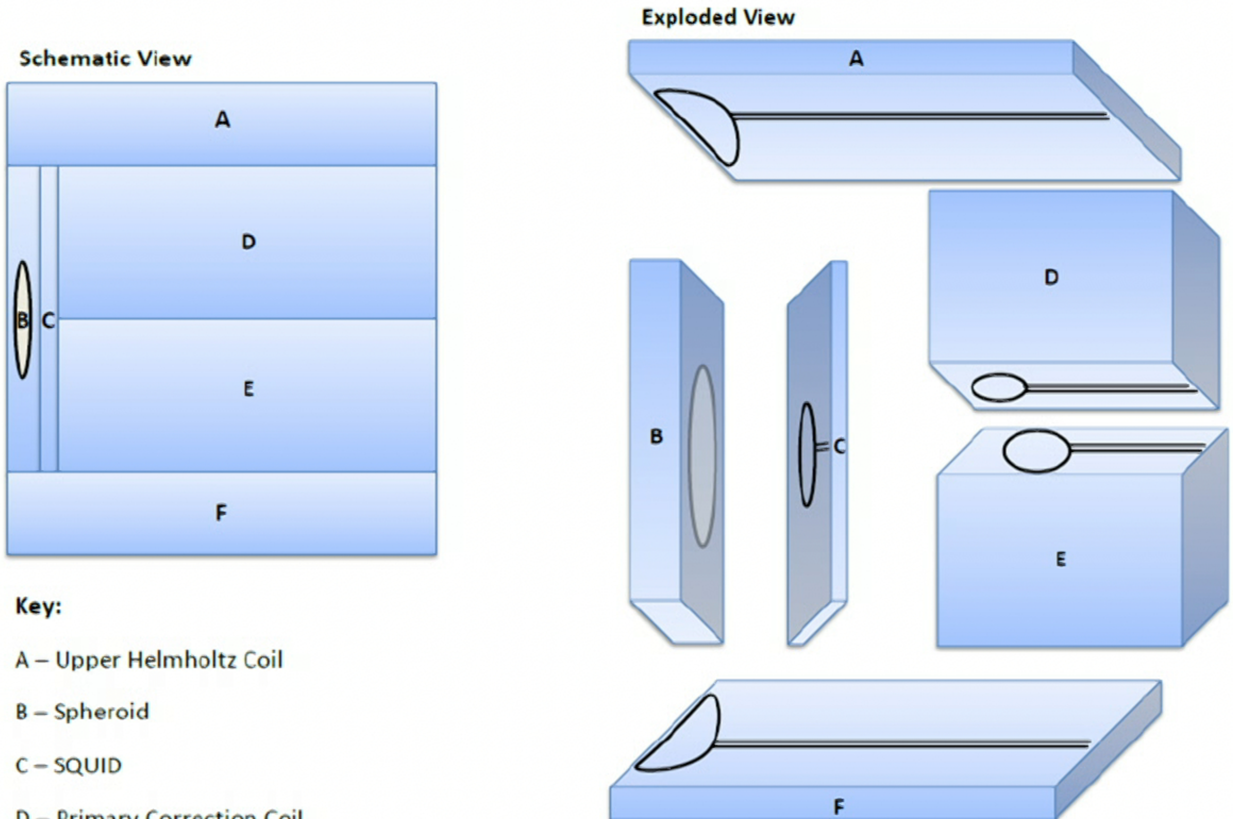
Assembly of quartz blocks



Key:

A – Upper Helmholtz Coil

B – Spheroid

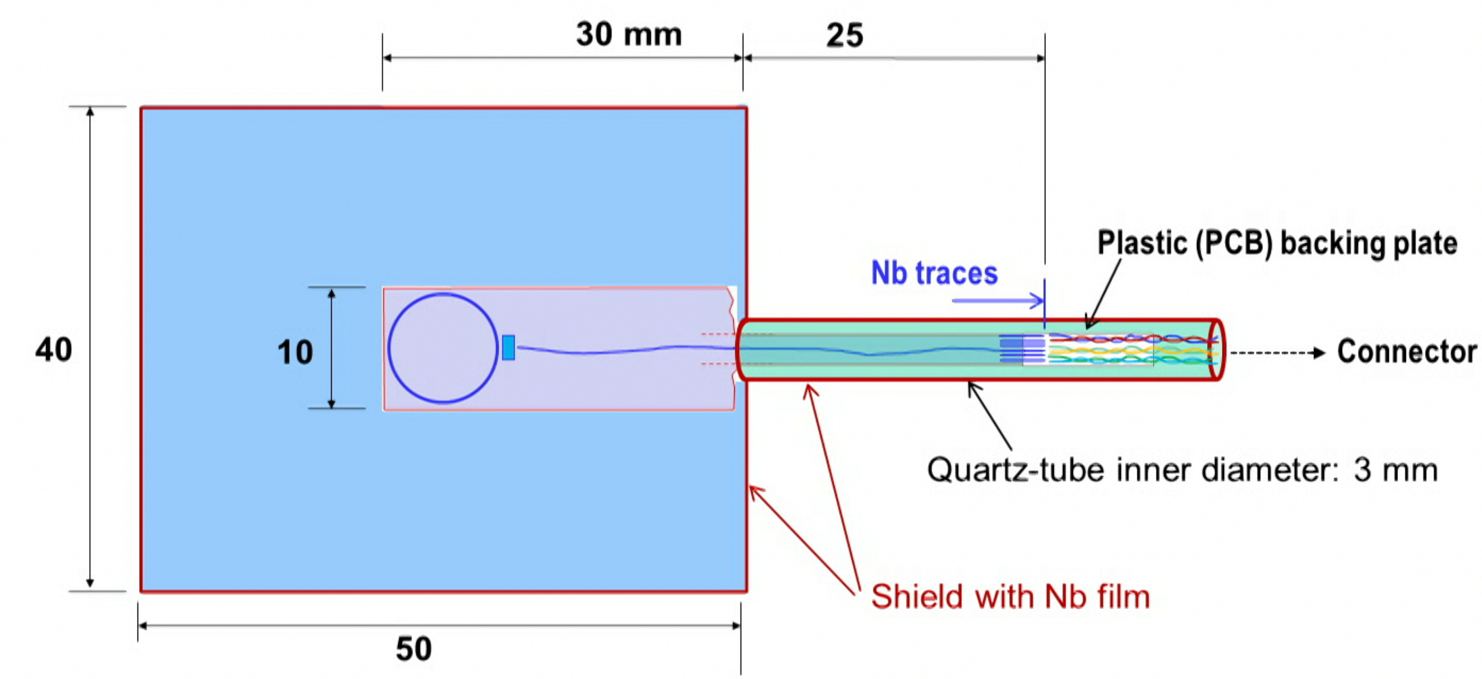
C – SQUID

D – Primary Correction Coil

E – Secondary Correction Coil

F – Lower Helmholtz Coil

Magnetometer dimensions & Wiring lines



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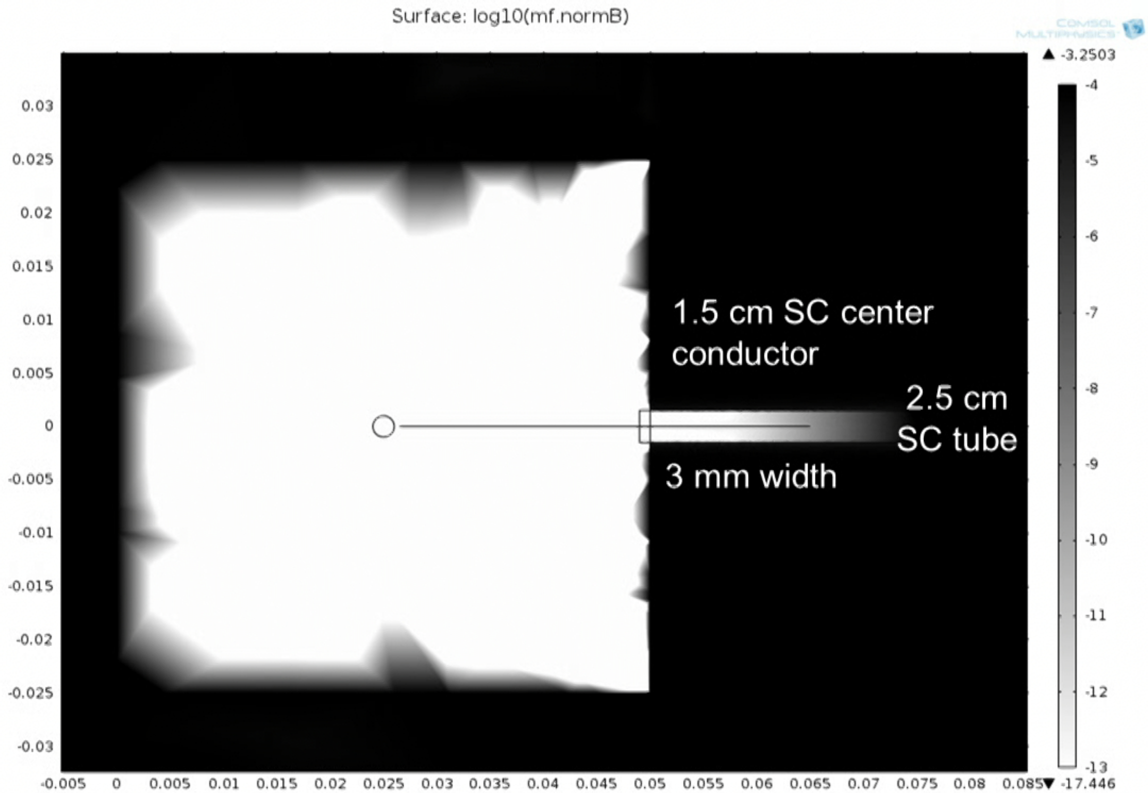
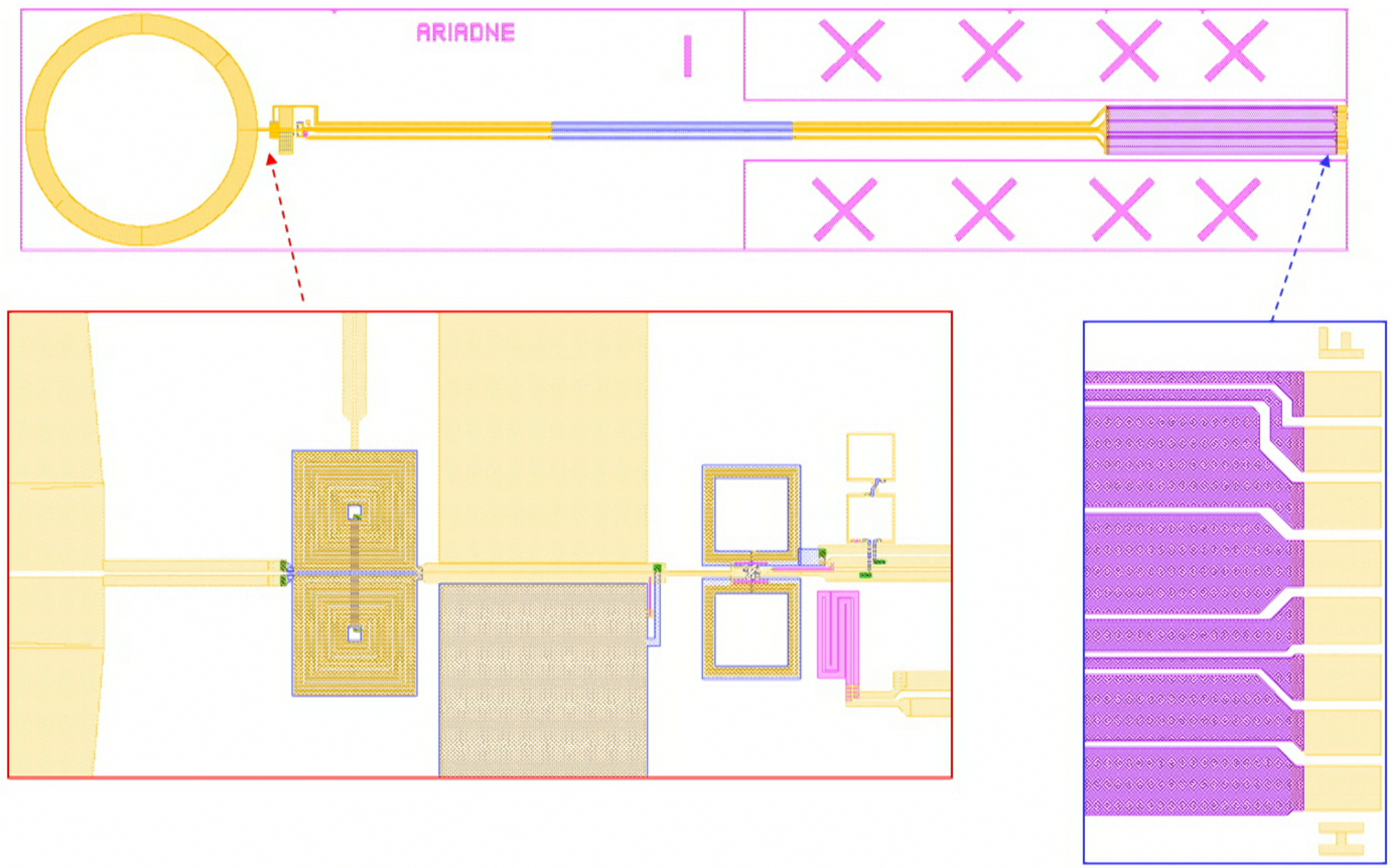
Superconductive shielding



Central field: 10^{-13} T **Applied: 10^{-4} T @ 100 Hz**

Whole layout



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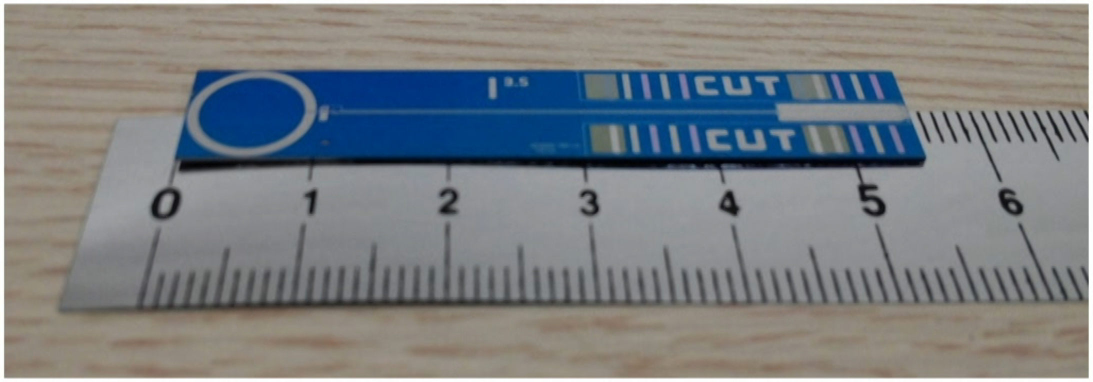
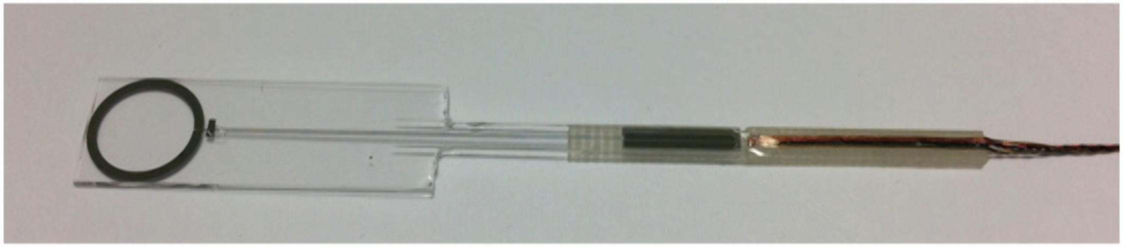
Cutting of sapphire substrate

On Si wafer



On quartz wafer



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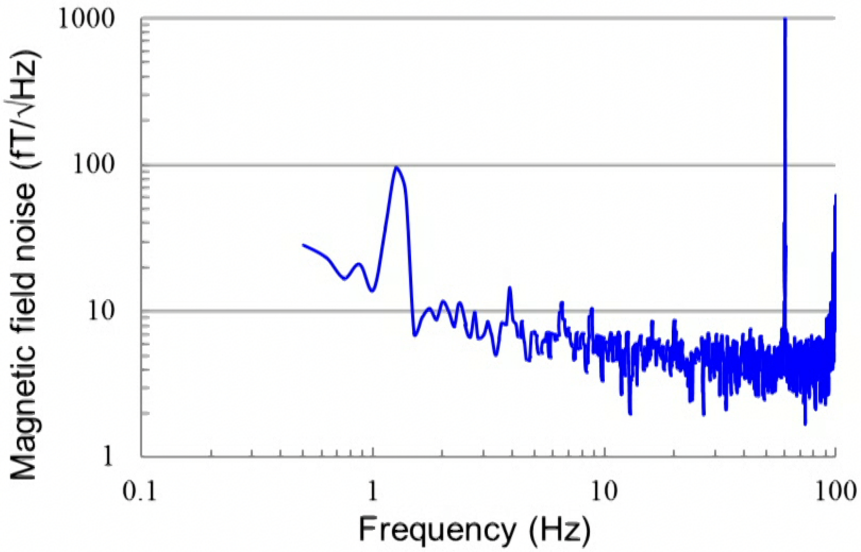
Magnetic field noise

Measured inside a 8-cm thick MSR
SQUID near the MSR floor



White noise: ~ 4.5 fT/√Hz @ 100 Hz
(sum of noises, mainly environmental noise)

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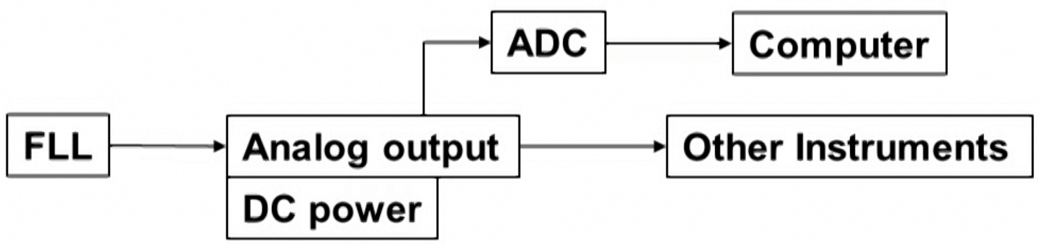
SQUID electronics (ARIADNE)

3-channel electronics

FLL
- **Preamp: SSM2210, 4 pairs, differential readout**

Measurement bandwidth: DC-1 kHz
(Optimum signal frequency: 10~100 Hz)

ADC
- **24 bit resolution**
- **10 kS/s per channel**



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Proton electric dipole moment (pEDM)

Precession of proton spin

- The electric and magnetic fields give spin precession:

$$\frac{d\vec{s}}{dt} = \frac{\vec{\mu}\times\vec{B}}{\gamma} + \vec{d}\times\vec{E}$$

- B_r=6 aT and E_r=3.5 MV/m induce same vertical spin precession for $d_p=10^{-29}$ e-cm (a few nrad/s).
- It should be shielded to 0.1nT/m and compensated, using SQUID-based BPMs.

From S. Haciomeroglu

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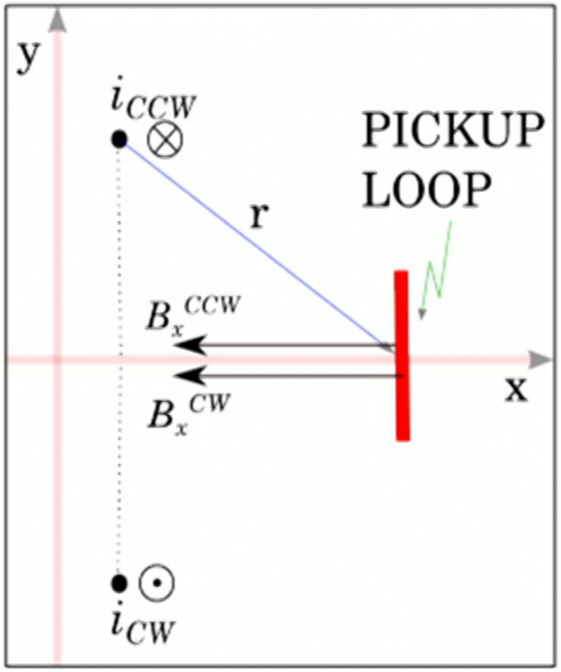
Magnetic field from proton beams

B-field sensitivity

Δy = 4pm beam separation

- 2.5 mA current,
- at r=2cm from the pickup loop
- modulated at about ω_m=1 kHz with modulation amplitude A=0.1



$$B_x(r,\omega_m)=\frac{2\mu_0 I \Delta y A\cos(\omega_m t)}{\pi r^2}\approx 2.5\cos(\omega_m t)\ \text{aT}$$

From S. Haciomeroglu

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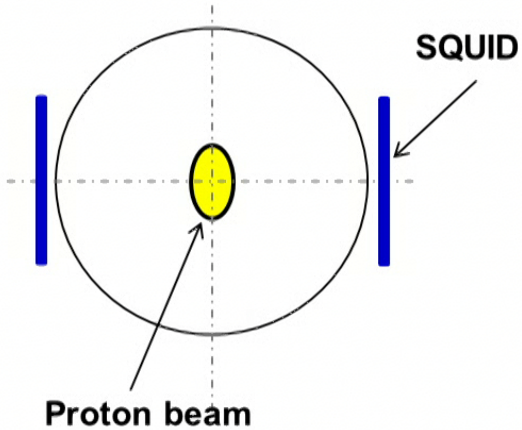
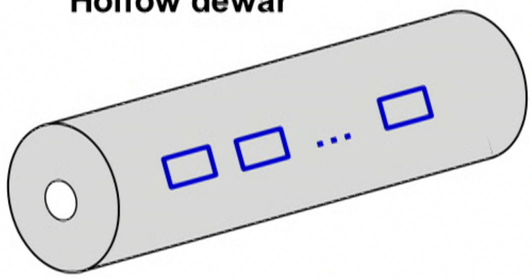
Arrangement of magnetometers





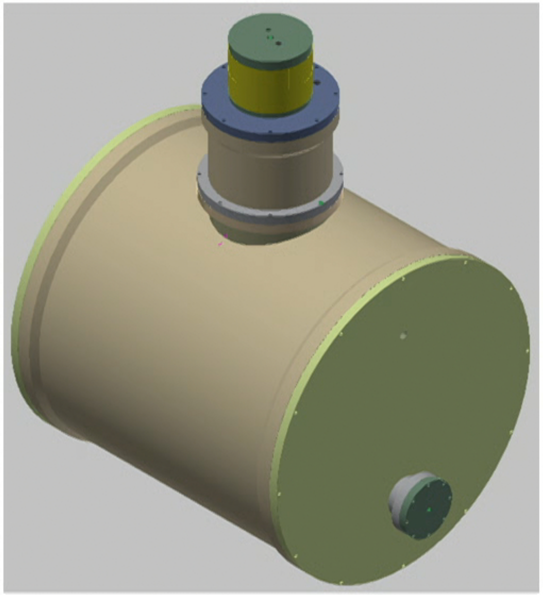
Inter-coil distance: 40 mm

8 channels/side: 16 channels/dewar

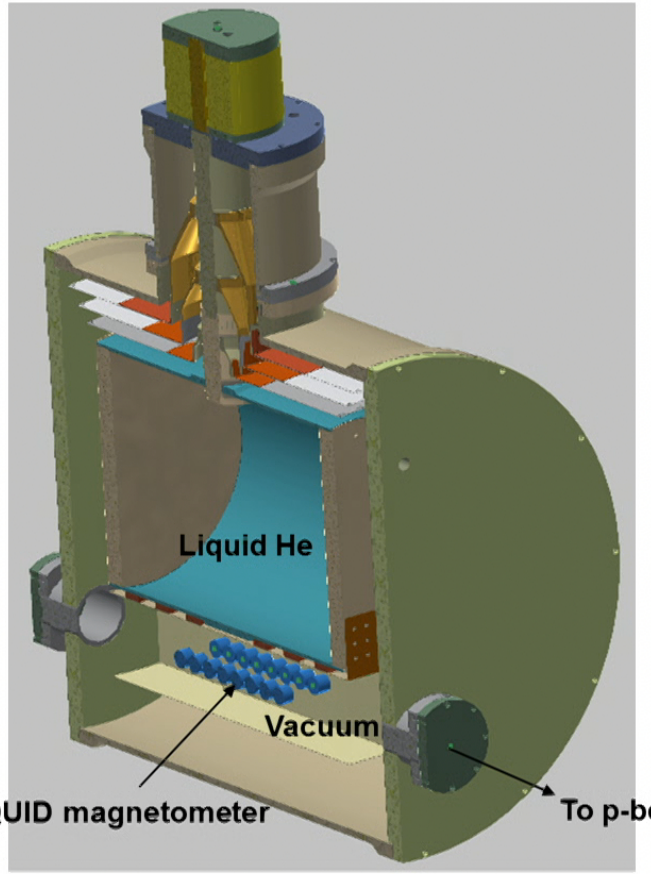
Either thin film or wire-wound pickup coil

Beam position monitoring using SQUID & Shielding
System sensitivity: ~ 0.5 fT/√Hz

Dewar



SQUID-in-vacuum



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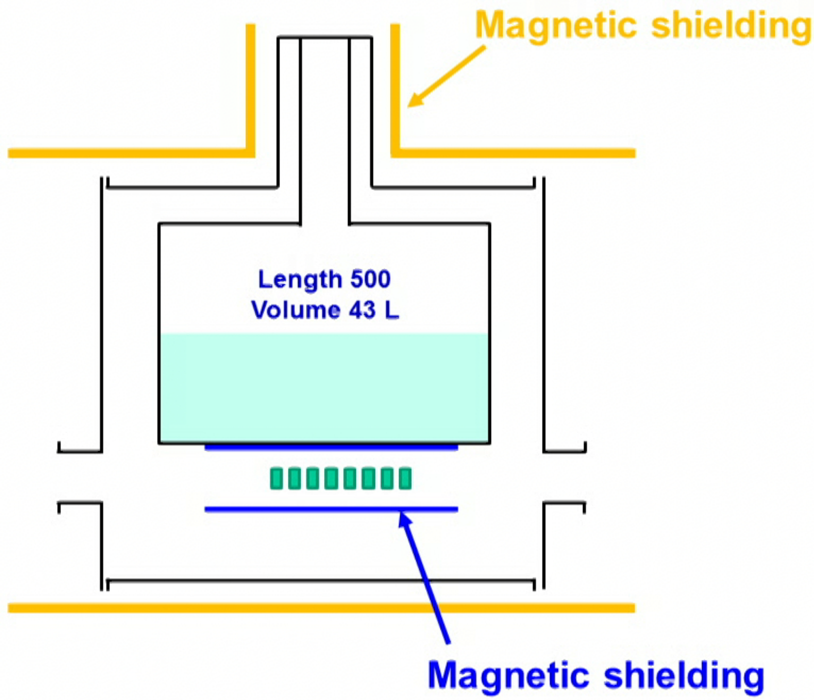
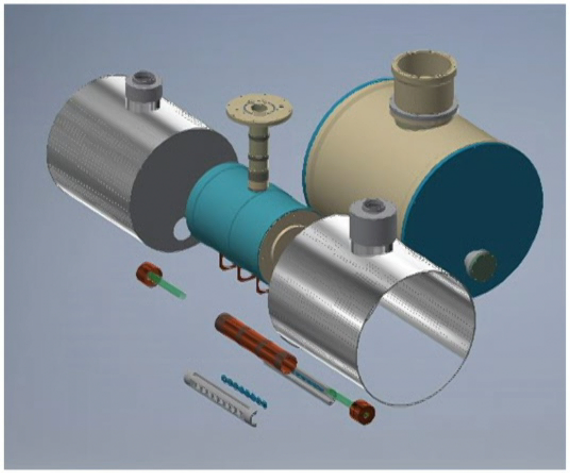
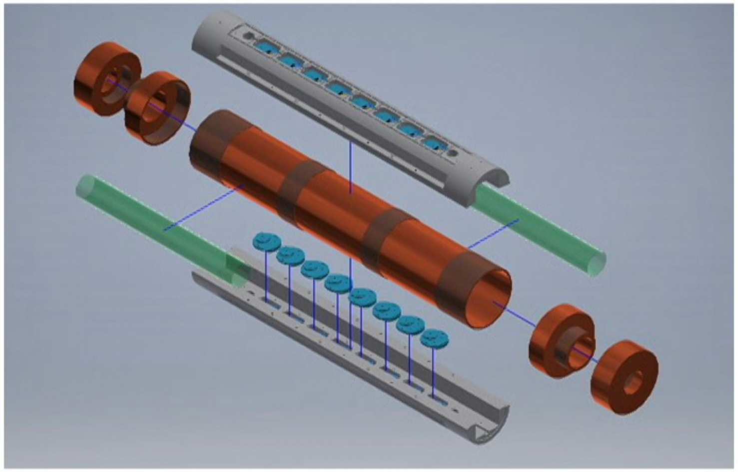
Cylindrical magnetic shielding



Beam position monitor





SQUIDs are superconductively shielded
- **Thermal noise of dewar**
- **Environmental noise**

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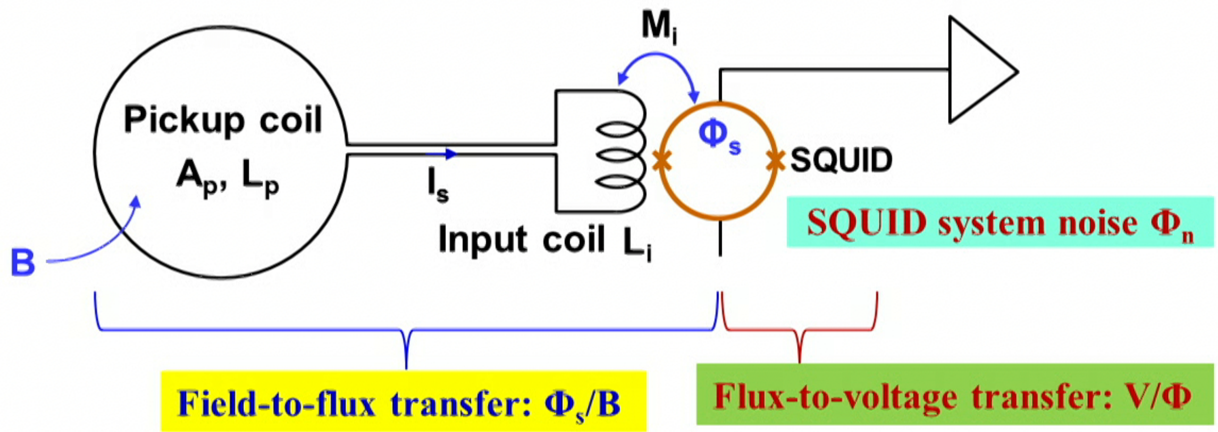
Magnetometer: SQUID and pickup coil



Field resolution at pickup coil: $B_n=\Phi_n\cdot(B/\Phi_s)$

Flux at pickup coil: $B\cdot A_p=(L_p+L_i)I_s$

Flux at SQUID: $\Phi_s=I_s\cdot M_i=B\cdot A_p\cdot M_i/(L_p+L_i)$

Field resolution at pickup coil $B_n=(L_p+L_i)\Phi_n/(M_i\cdot A_p)$

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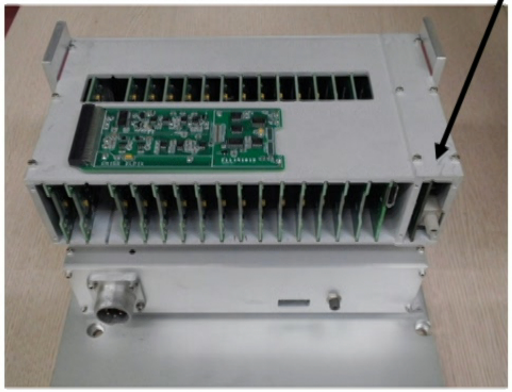
SQUID electronics (BPM)



16-channel electronics for magnetoencephalography

Optimal signal frequency range: ~1000 Hz
High-pass filter: 200 Hz
Low-pass filter: 2 kHz
Analog amplification: 100 times

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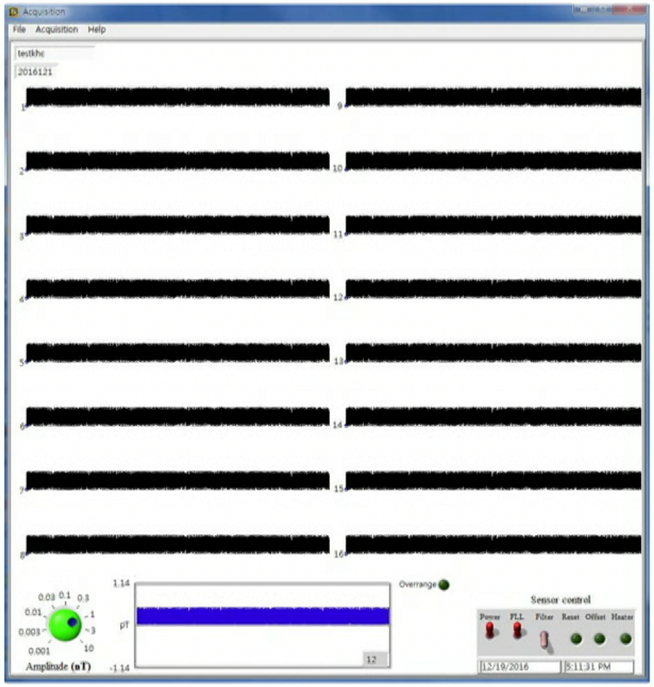
Acquisition and signal processing

Software



Control of SQUID parameters
Acquisition
Data saving in epoch unit
Signal processing: filtering, averaging

16-channel
Resolution of A/D conversion: 16 bit
Sampling rate: 10 kS/s

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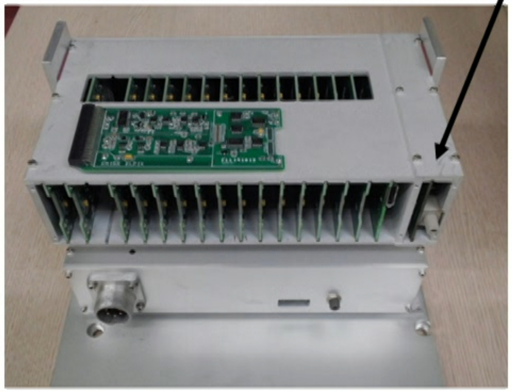
SQUID electronics (BPM)

ADC &
Optical transmitter
ADC: 16 bit, 10 kS/s sampling

Flux-lock loop circuits
(16 channels)

DC Power/Heater



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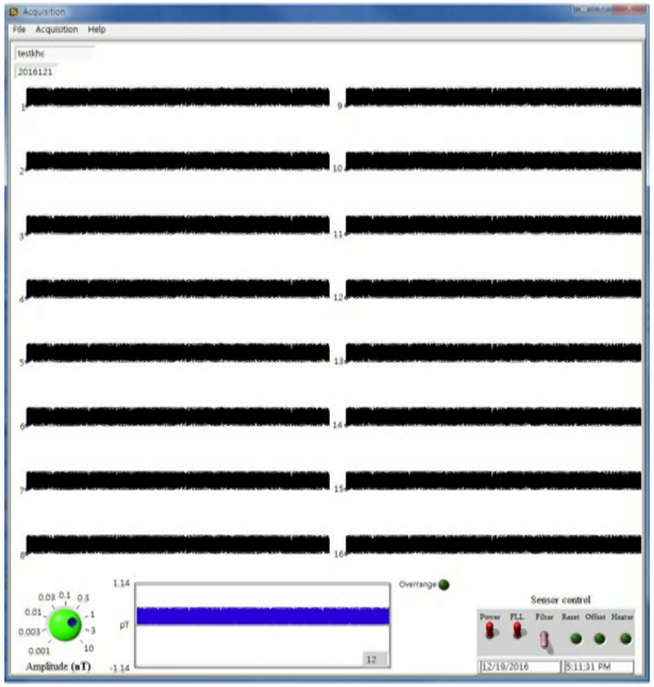


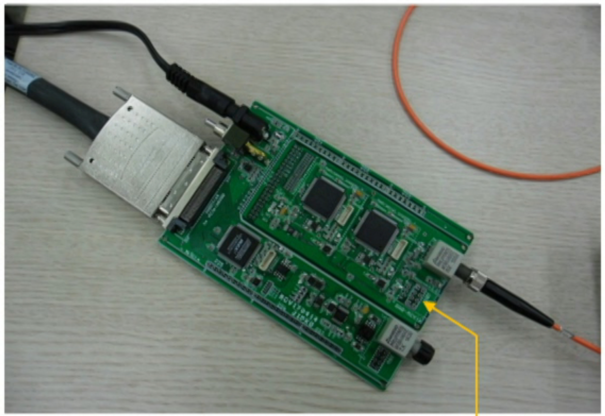
Control of SQUID parameters
Acquisition
Data saving in epoch unit
Signal processing: filtering, averaging

16-channel
Resolution of A/D conversion: 16 bit
Sampling rate: 10 kS/s

Triggered averaging

Analog trigger input for averaging

Computer



SQUID output

Trigger input

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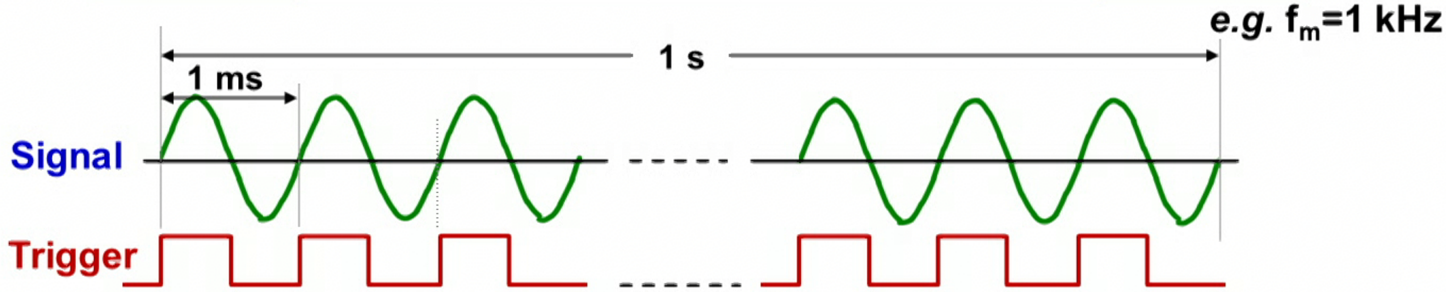
Signal averaging with triggering



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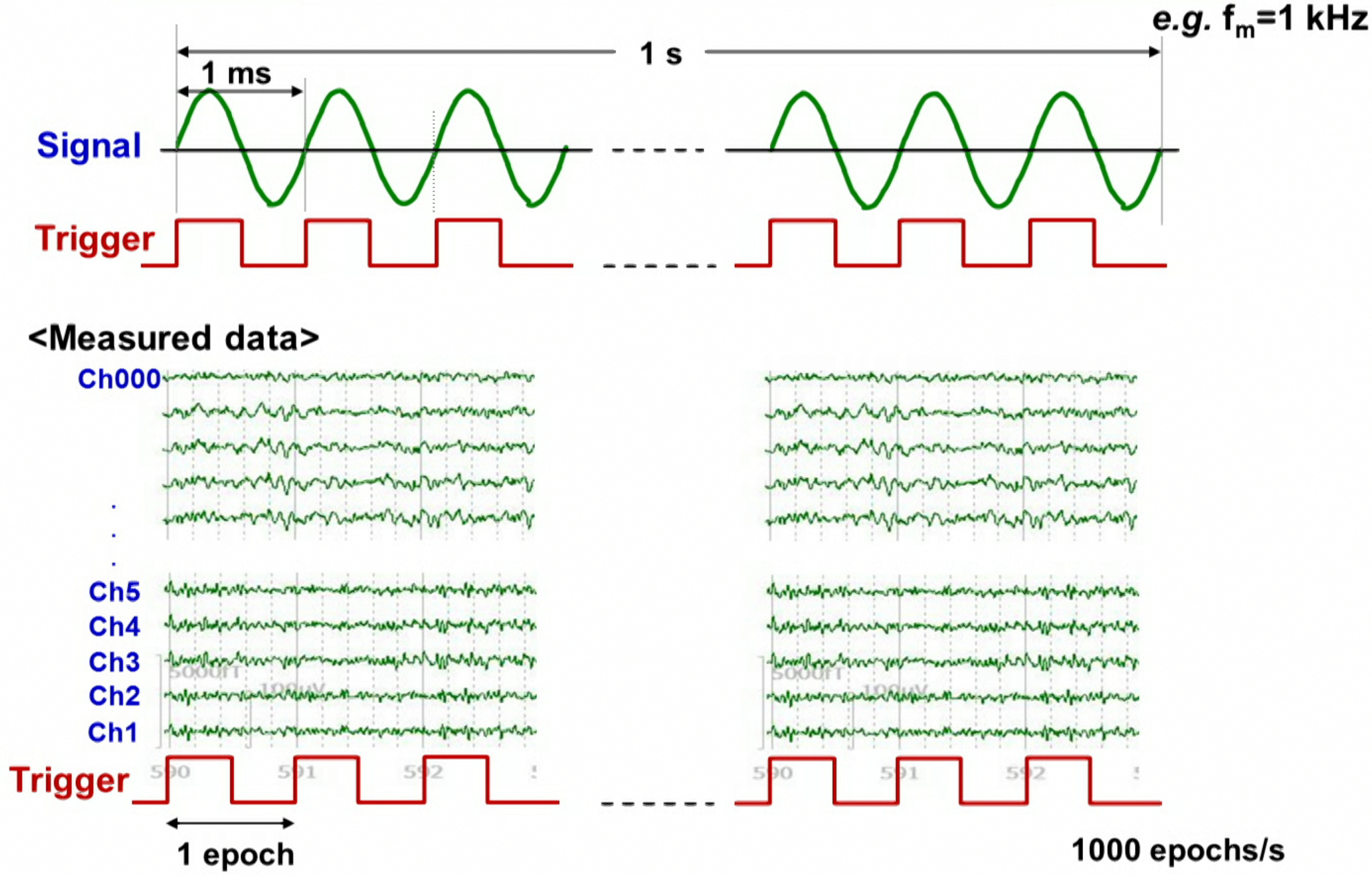
Signal averaging with triggering



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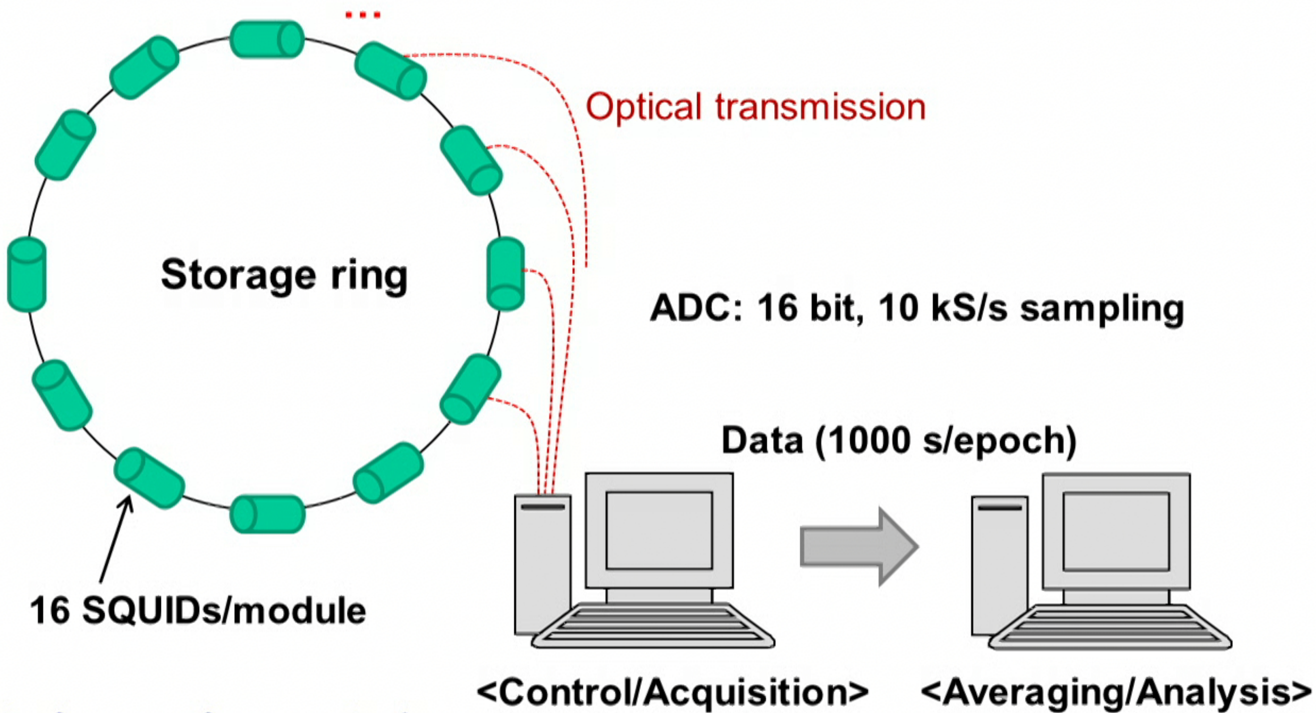
Multichannel acquisition in storage ring



Interference-free control

Noise-free acquisition

No time-delay bet. modules

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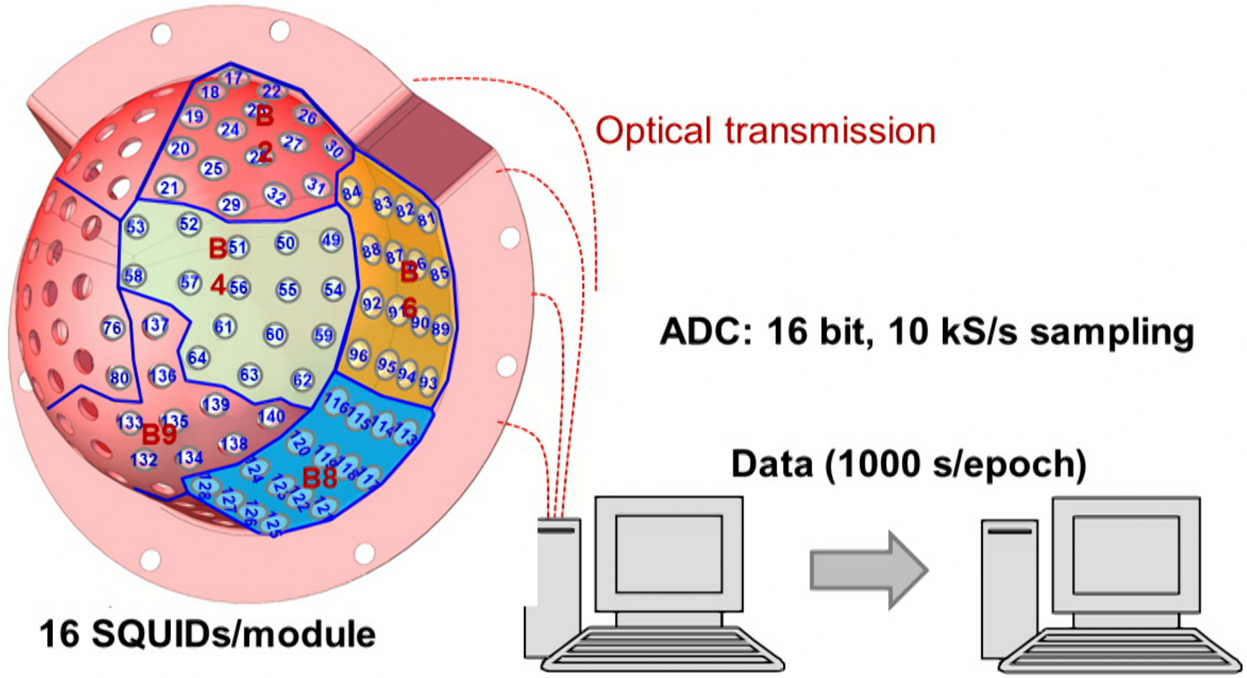
Multichannel acquisition in storage ring



16 SQUIDs/module

<Control/Acquisition> <Averaging/Analysis>

Interference-free control

Noise-free acquisition

No time-delay bet. modules

Improvement in measurement time

SNR=
(System sensitivity) x (# of SQUIDs)$^{0.5}$ x (# of averaging)$^{0.5}$

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<u>With system sensitivity of 0.5 fT/√Hz</u>

- Repetition rate: 1 kHz
- Bandwidth: 1000 Hz (500 Hz-1500 Hz)
- Noise amplitude: 0.5 fT/√Hz × √1000=16 fT (time domain)
- 16 channels/section × 22 sections=352 SQUIDs
- 352 SQUIDs × 1000 averaging/s × 1000 s/fill → Noise: 0.84 aT
- 1000 fills → noise amplitude of 27 zT

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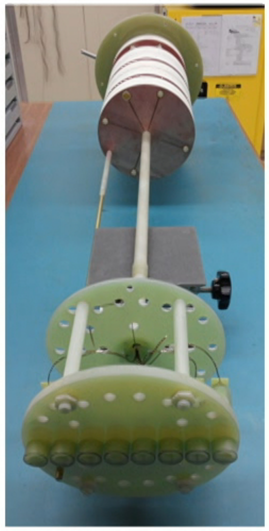
- **352 SQUIDs × 1000 averaging/s × 1000 s/fill → Noise: 0.84 aT**
- **1000 fills → noise amplitude of 27 zT**

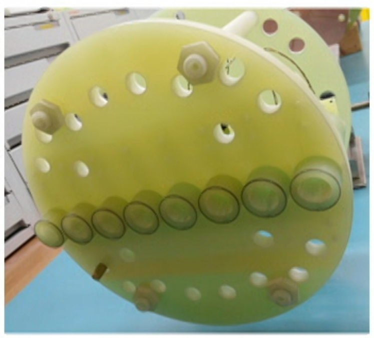
If target signal amplitude is 1 aT, SNR=37

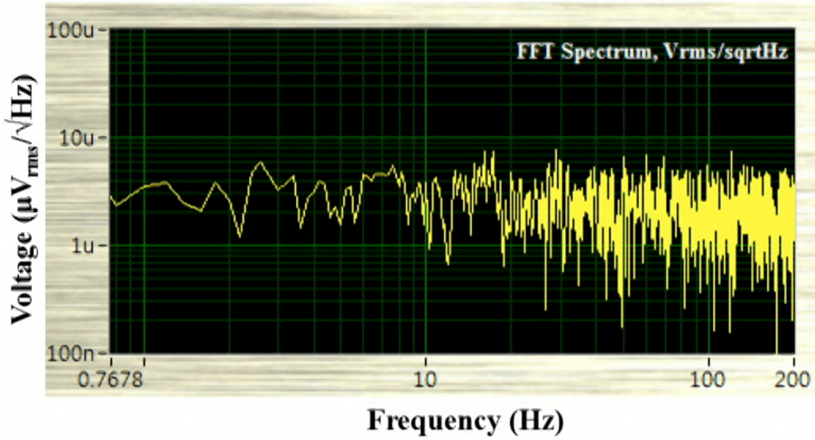
- **Measurement time: 10^6 s=11.5 days!**

***cf)* If use 3 fT/√Hz system, $(3/0.5)^2$=36 times longer time needed**

Pretest system (8-channel)

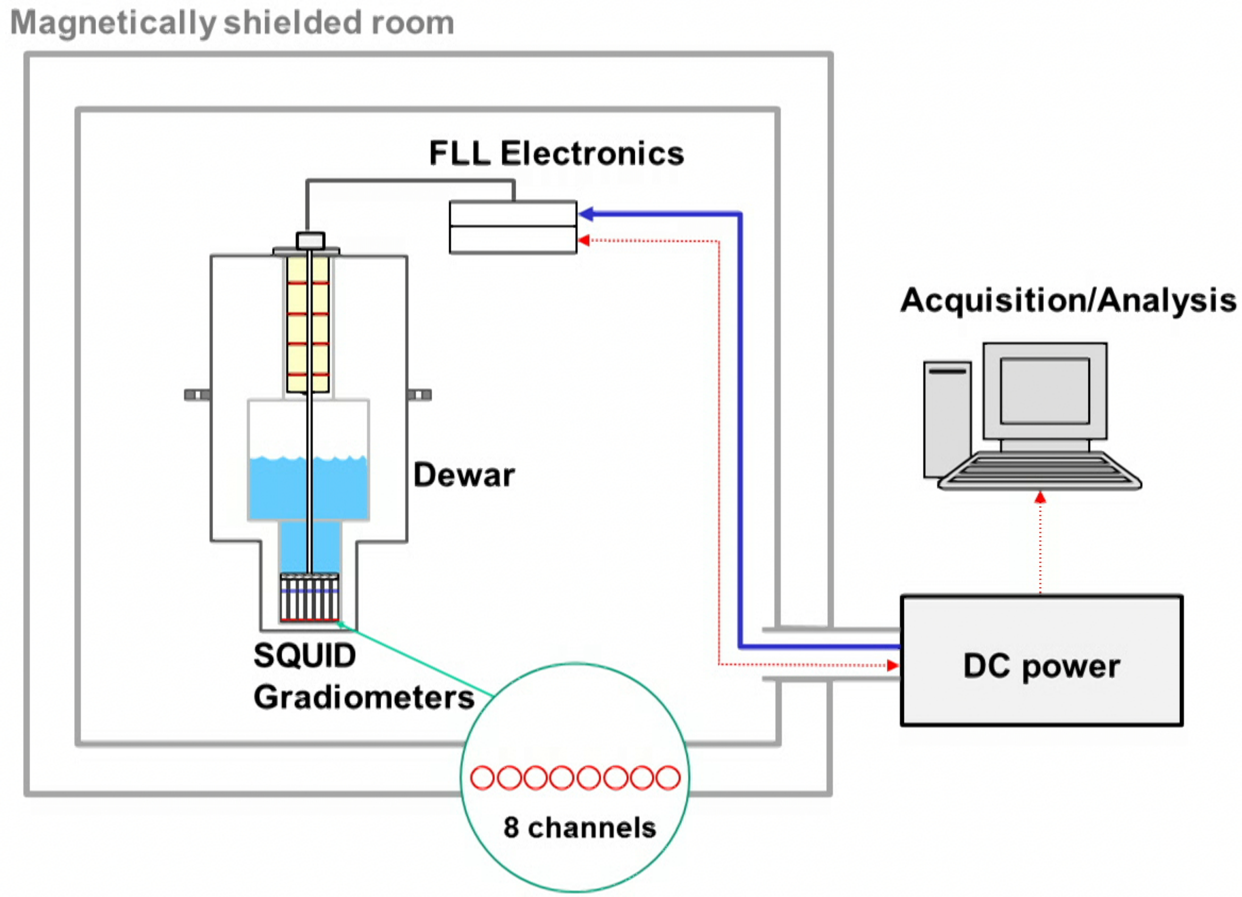




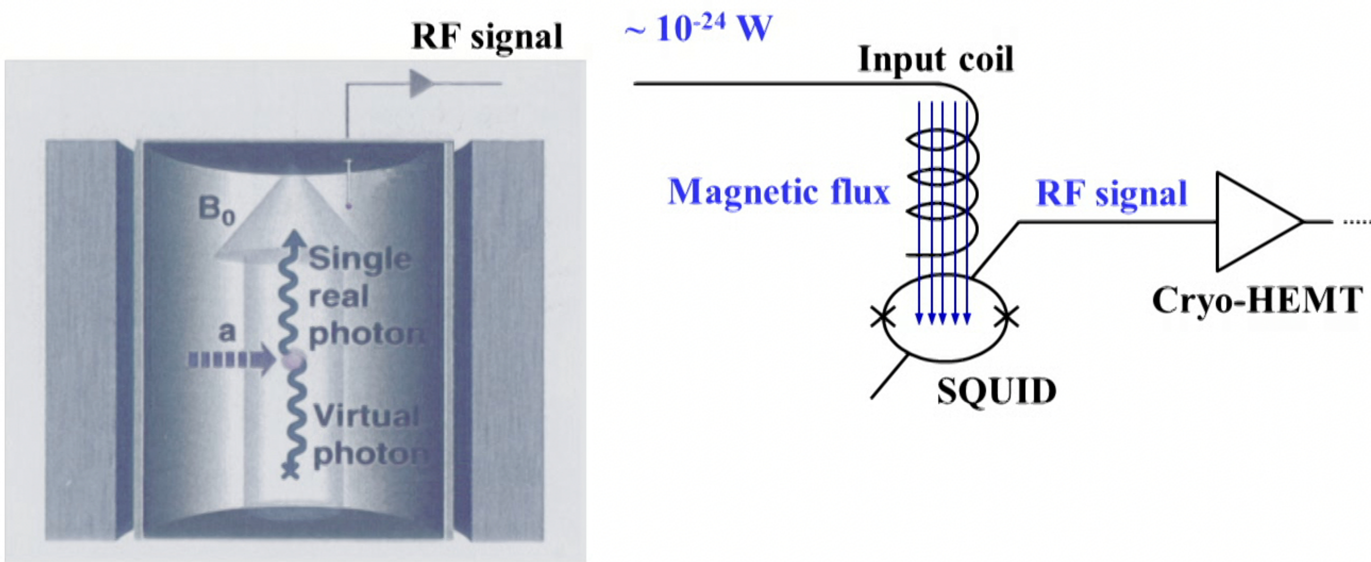


System sensitivity: 3 fT/√Hz

Pretest SQUID system



Axion search experiment



~100 mK
~10 T

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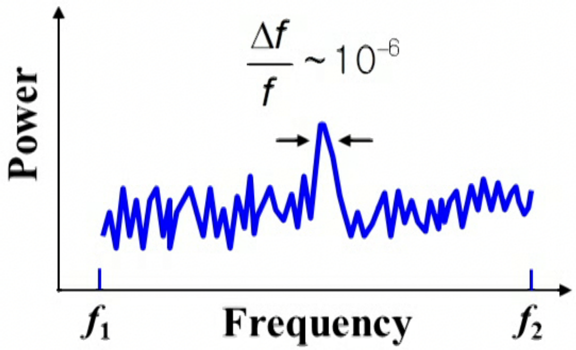
Why low-noise amplifier?

Detection of signal peak



Need to scan frequency

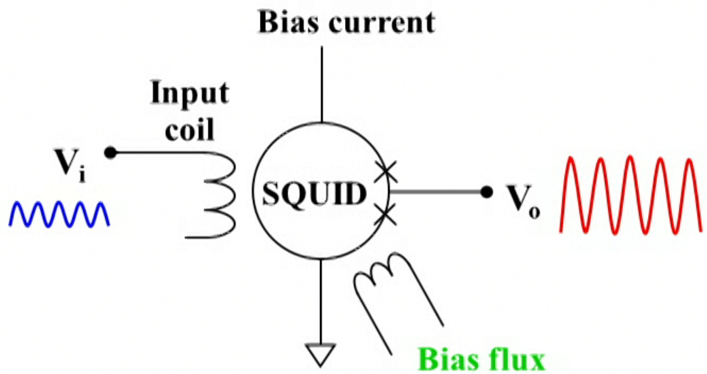
Time to scan the frequency range, $f_1 \sim f_2$
$= \sim (T_s)^2 \cdot (1/f_1 - 1/f_2)$

T_s: System noise temperature
$= T$(cavity temp.) + T_n(amp. noise temp.)

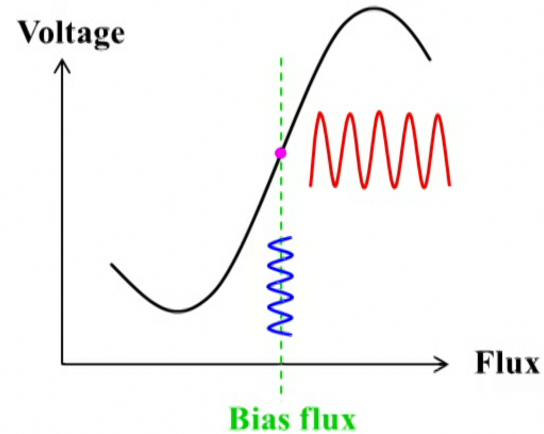
Cooling and low-noise amplifier needed.

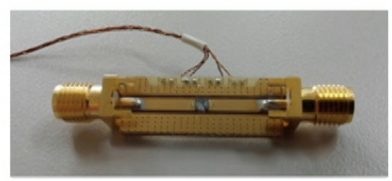
Principle of SQUID RF amplifier

<Schematic diagram>

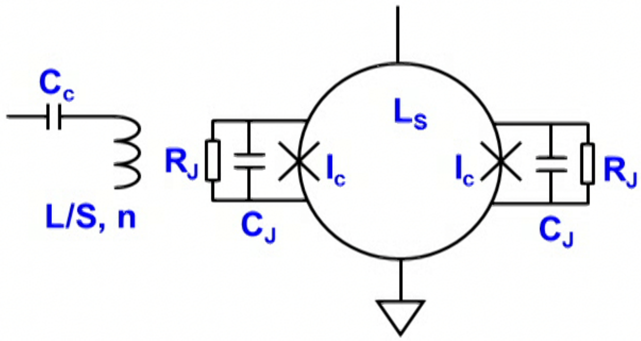


<SQUID output vs. input RF flux>

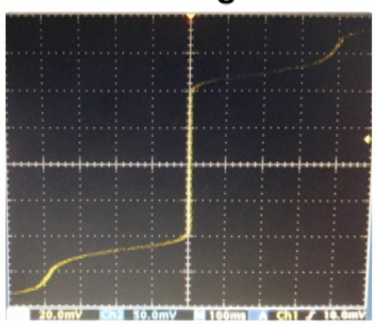




SQUID parameters



Current-Voltage



X: 20 μV/div
Y: 5 μA/div

<SQUID>

L_s: SQUID inductance

I_c or I_0: Junction critical current

R_J: Junction shunt resistance

C_J: Junction capacitance

<Input coil>

C_c: Coupling capacitance

L: Line-width, S: Space

n: Number of turns

Dielectric thickness: fixed

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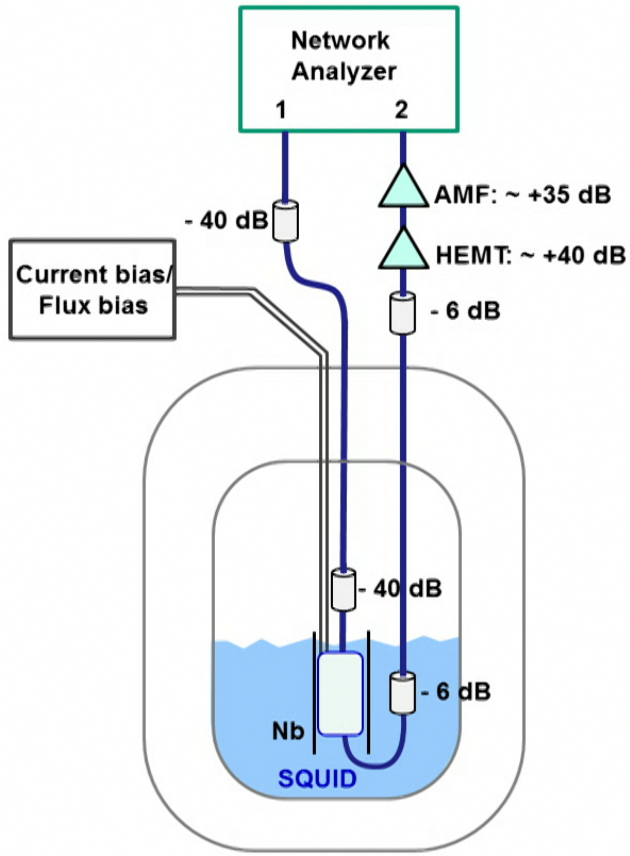
Gain measurement configuration



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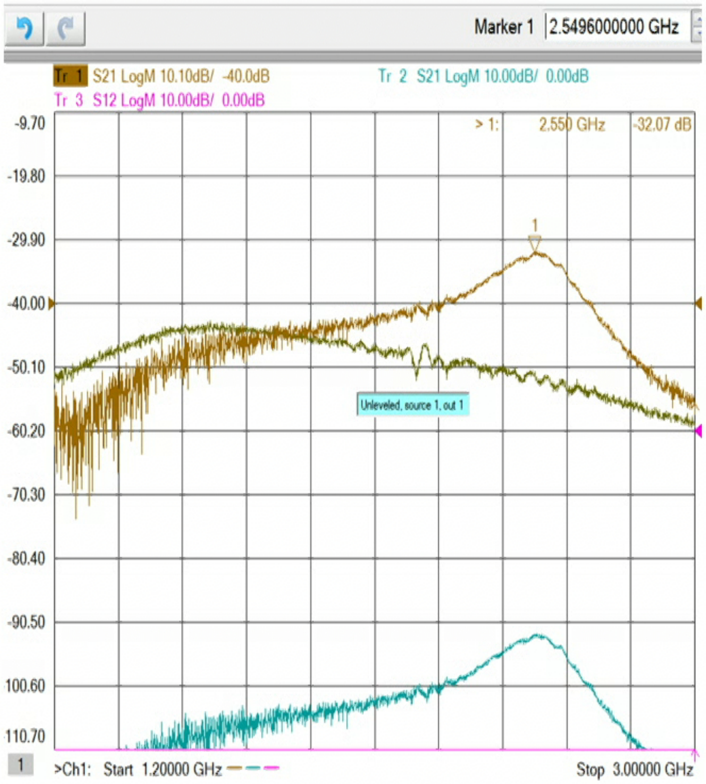
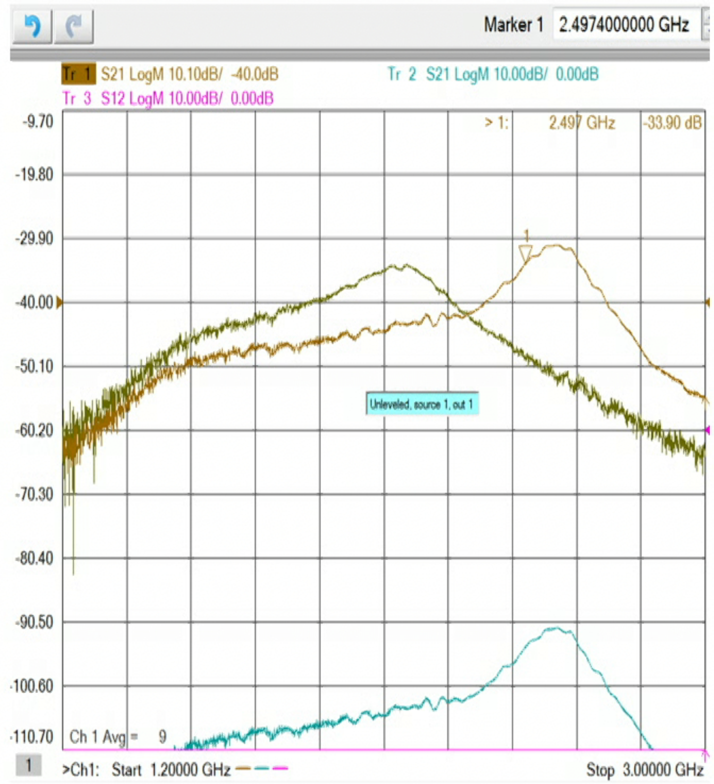
RF amplifier gain





Gain: ~ 20 dB @ 2.5 GHz, BW: ~ 200-300 MHz

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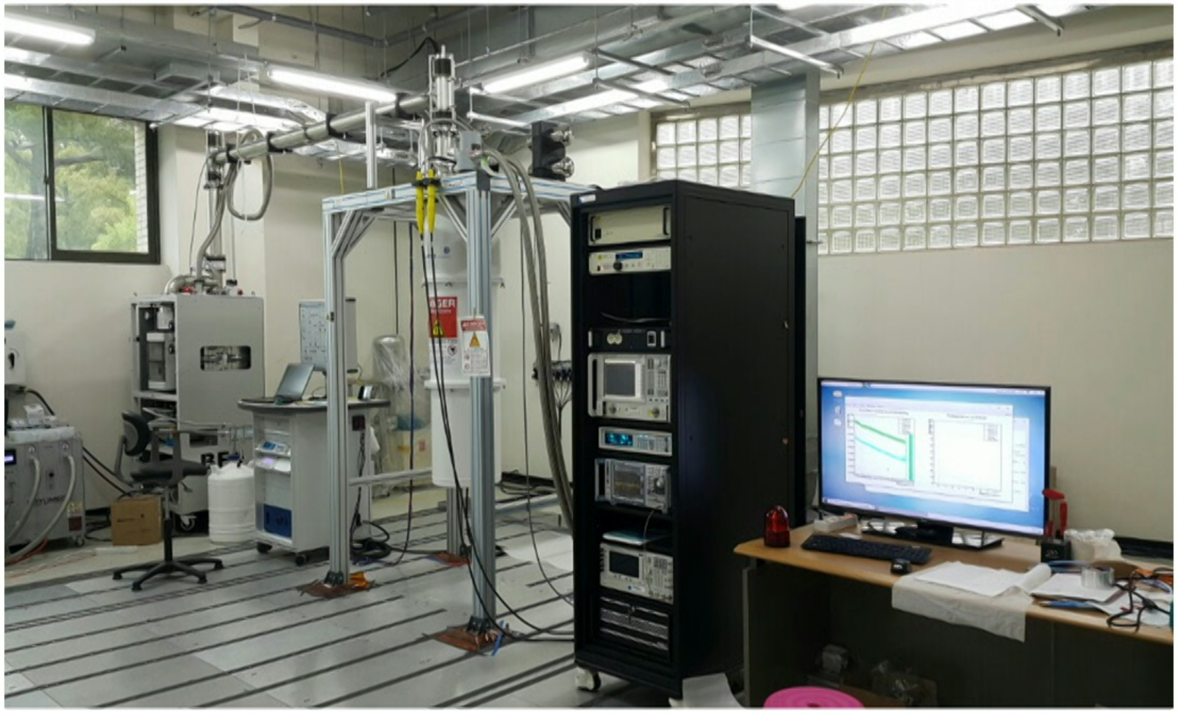
Test in a dilution refrigerator

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