CAPP

Center for Axion and Precision Physics Research

Beam Position Monitoring SQUID array

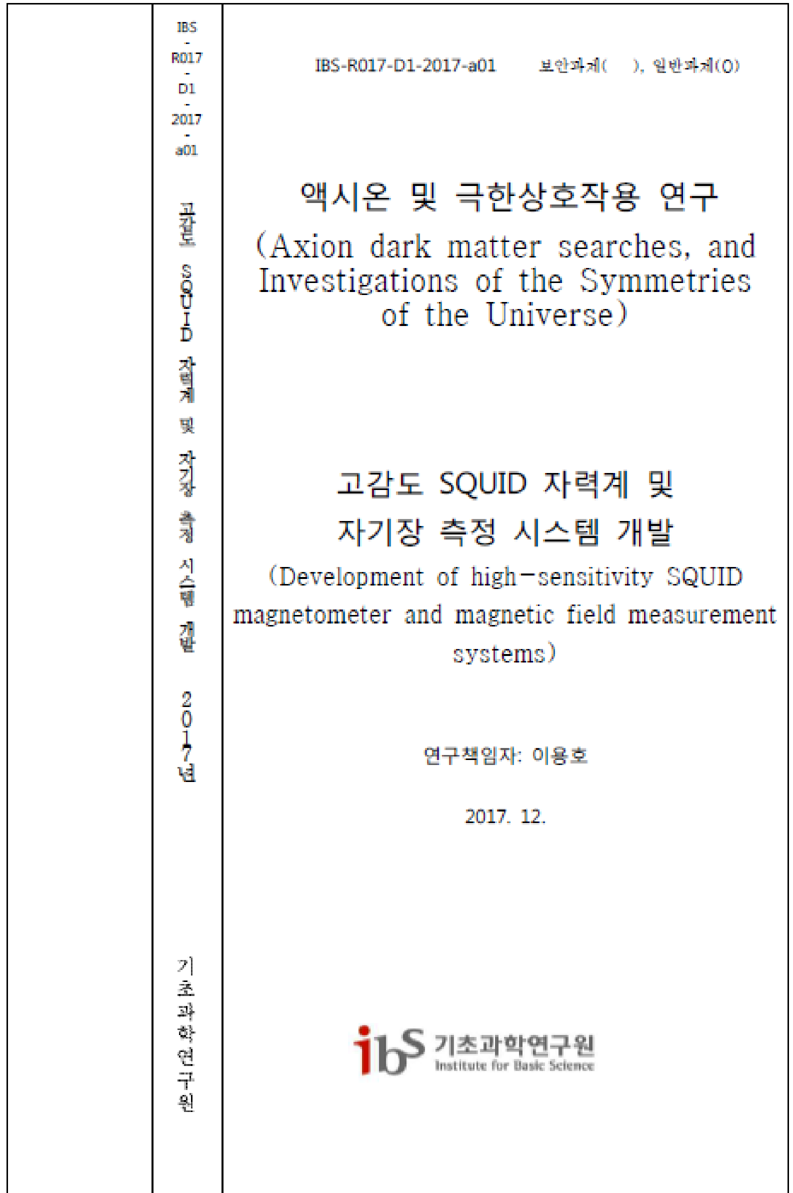
Andrei Matlashov,[A] Selcuk Haciomeroglu,[A] Yong-Ho Lee,[B]

[A]IBS/Center for Axion and Precision Physics, [B]KRISS

Daejeon, Korea

andrei@ibs.re.kr

IBS/CAPP and KRISS Collaboration



IBS-R017-D1-2017-a01 고감도 SQUID 자력계 및 자기장 측정 시스템 개발 2017년 기초과학연구원

IBS-R017-D1-2017-a01 보안과제( ), 일반과제(O)

액시온 및 극한상호작용 연구

(Axion dark matter searches, and Investigations of the Symmetries of the Universe)

고감도 SQUID 자력계 및
자기장 측정 시스템 개발

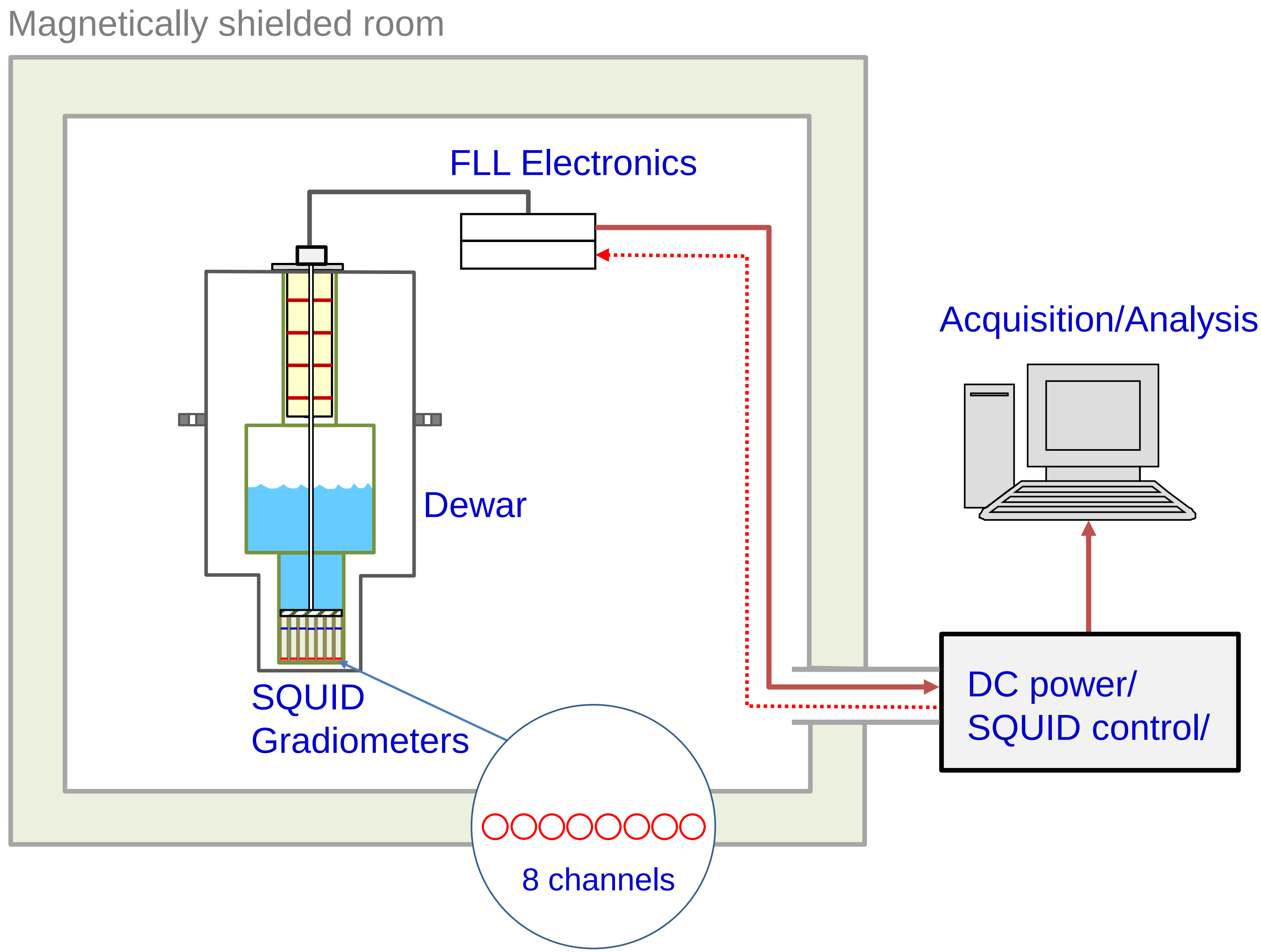
(Development of high-sensitivity SQUID magnetometer and magnetic field measurement systems)

연구책임자: 이용호

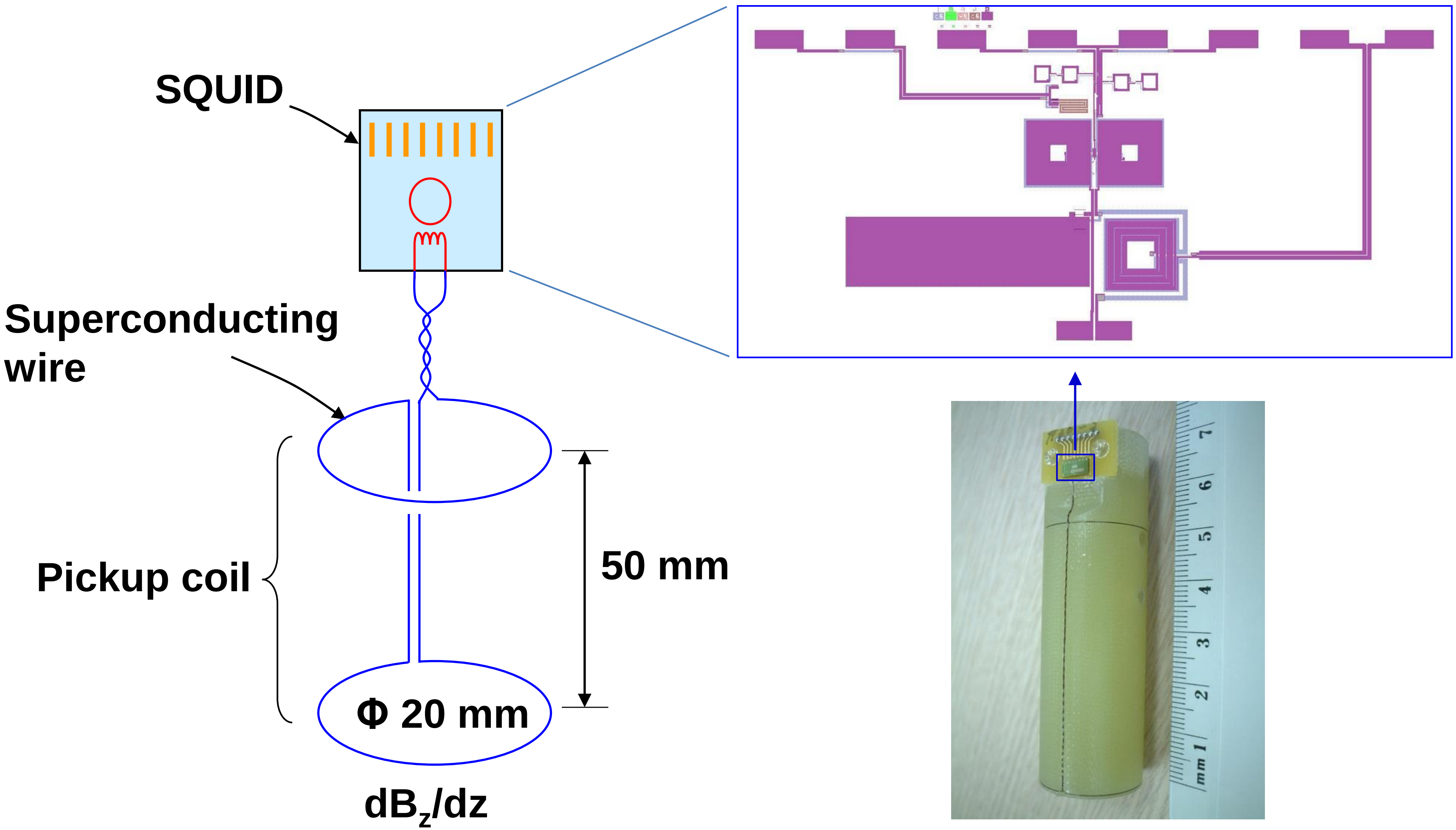
2017. 12.

ibS 기초과학연구원 Institute for Basic Science

G1 Beam Position Monitoring SQUID system



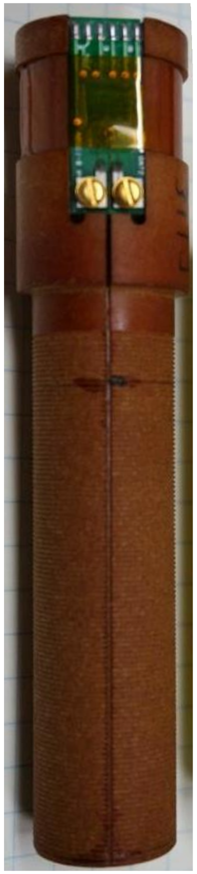
Axial Wire-Wound First-Order Gradiometers

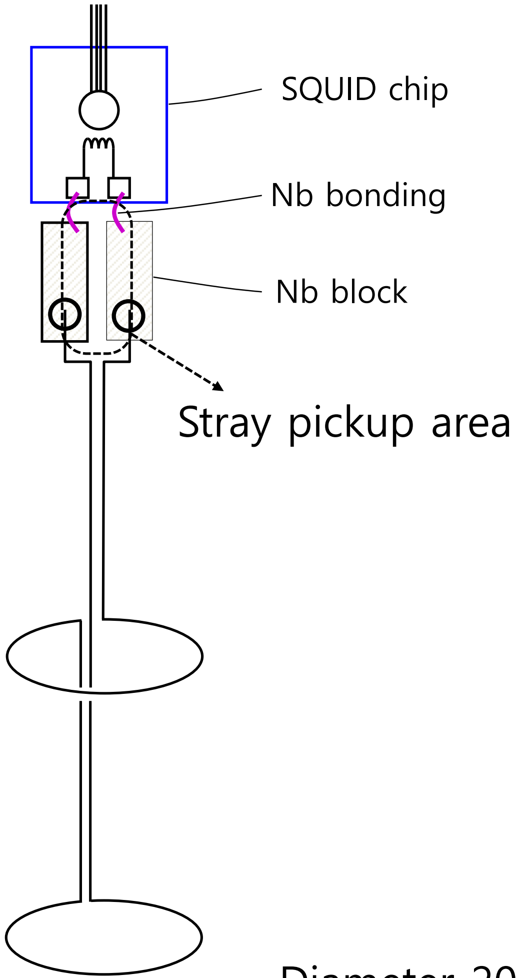


Pickup coil: Diameter 20 mm, baseline 50 mm

Wire-wound Pick-up Coils Bonding

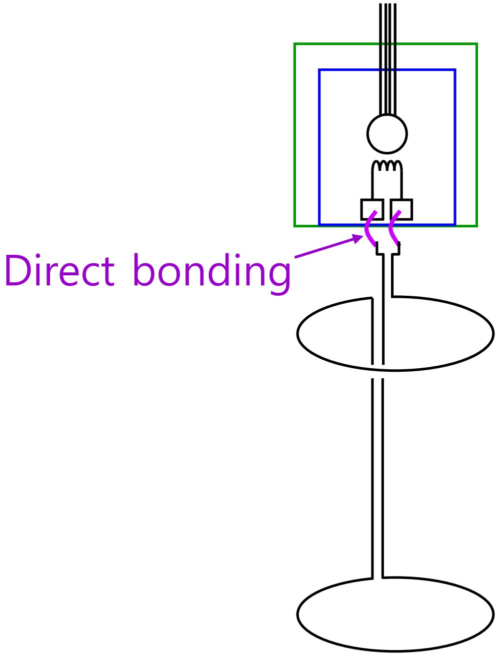
Conventional bonding (Star Croelectronics)

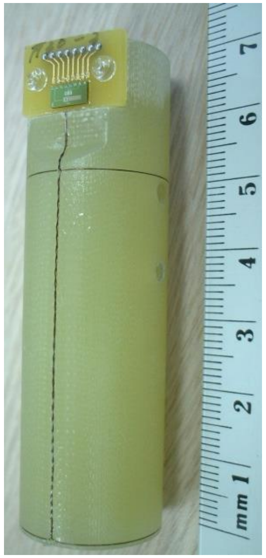




Diameter 20 mm: $A = 628\ mm^2$

KRISS method



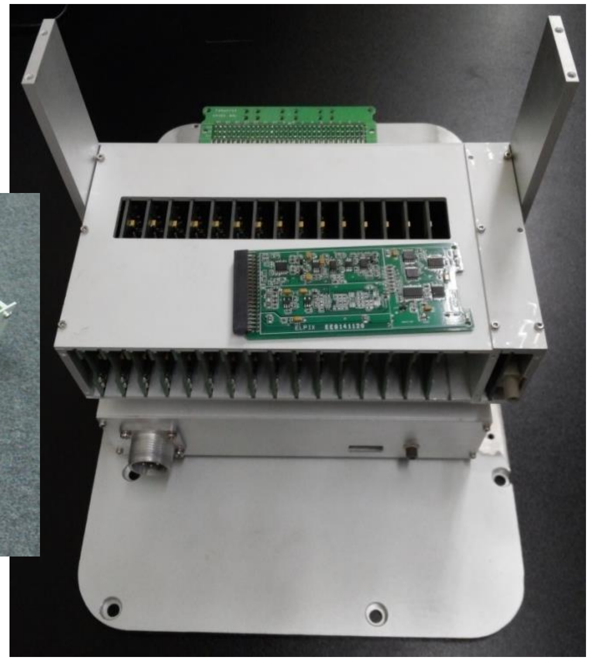


Stray pickup area:
≈ 0.3 mm x 2 mm = 0.6 mm^2
→ Imbalance = 0.1 %
→ Better SNR or lighter MSR

3-Layer Magnetically Shielded Room at CAPP

SQUID Electronics

Flux-lock loop circuits



DC-power and acquisition

High-pass filter: 200 Hz
Low-pass filter: 2 kHz
Sensitivity: 1.0 nT/V and 0.01 nT/V with Gain = 100
LSB: 15 × 10^{-15} T and 0.15 × 10^{-15} T with Gain = 100

G2 Beam Position Monitoring SQUID system

Number of SQUID magnetometers: 2 × 8

Pickup coil: 2-turn wire-wound magnetometer, Ø 17 mm

SQUIDs-in-Vacuum Design

Superconductive Shielding

Superconducting Imaging Surface → the First-Order Gradiometers

Horizontal Cylindrical Dewar

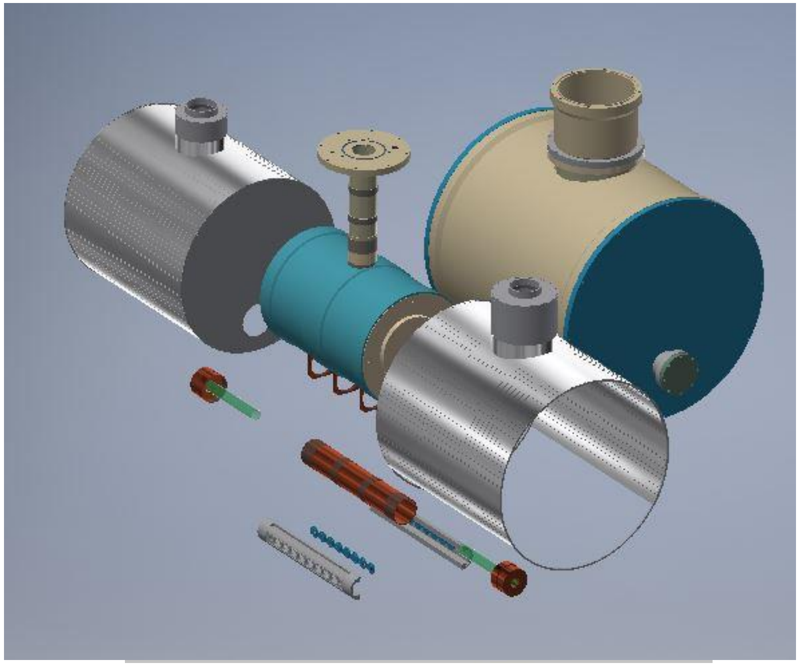
System Field Resolution: 1.2 fT/√Hz @1 kHz

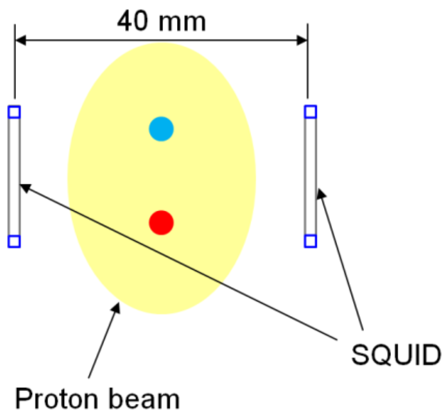
Superconductor imaging surface magnetometry

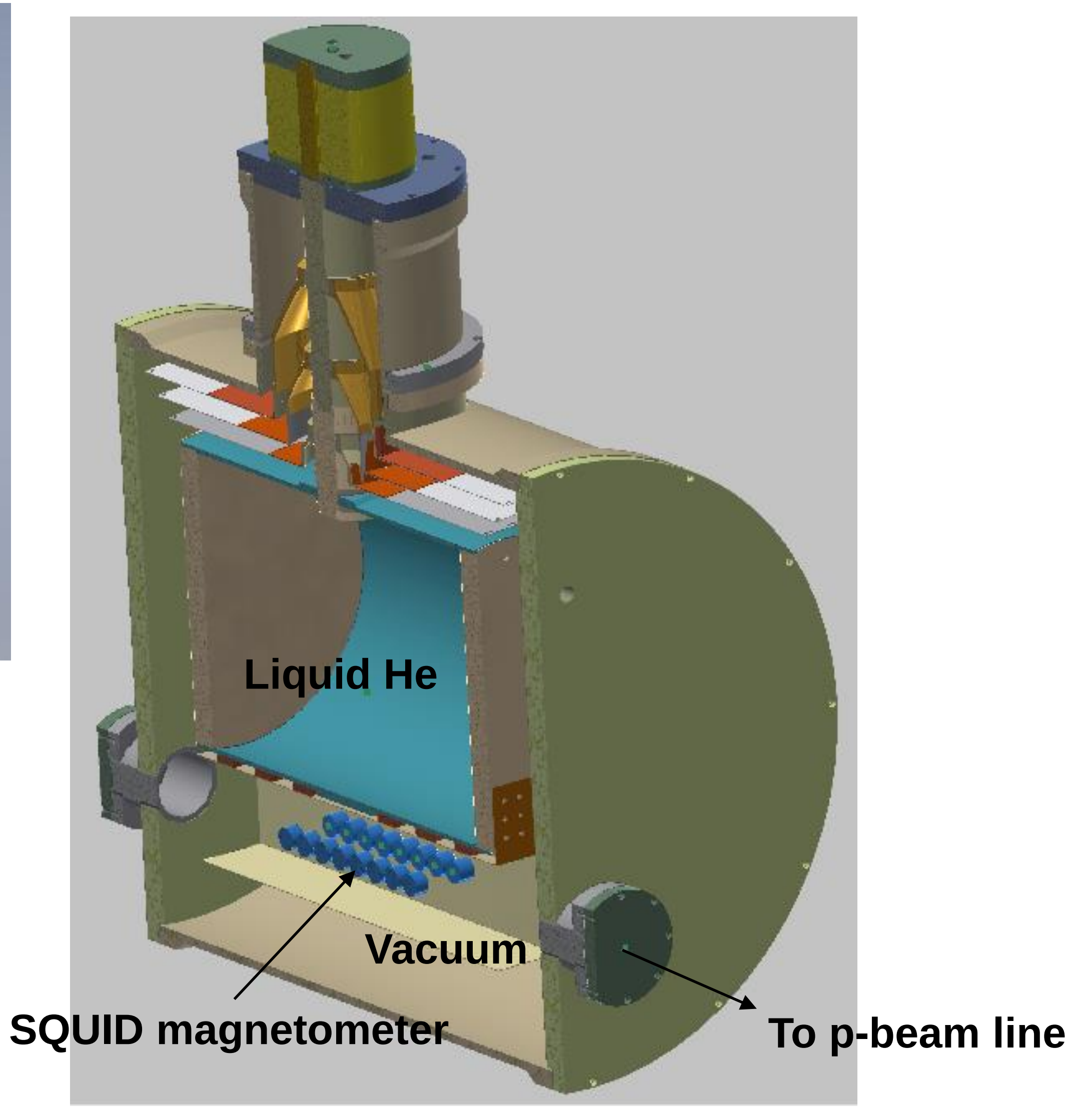
David B. van Hulsteyn, Albert G. Petschek, Edward R. Flynn,
and William C. Overton, Jr.
Los Alamos National Laboratory, Physics Division, Los Alamos, New Mexico 87544

(Received 14 November 1994; accepted for publication 24 March 1995)

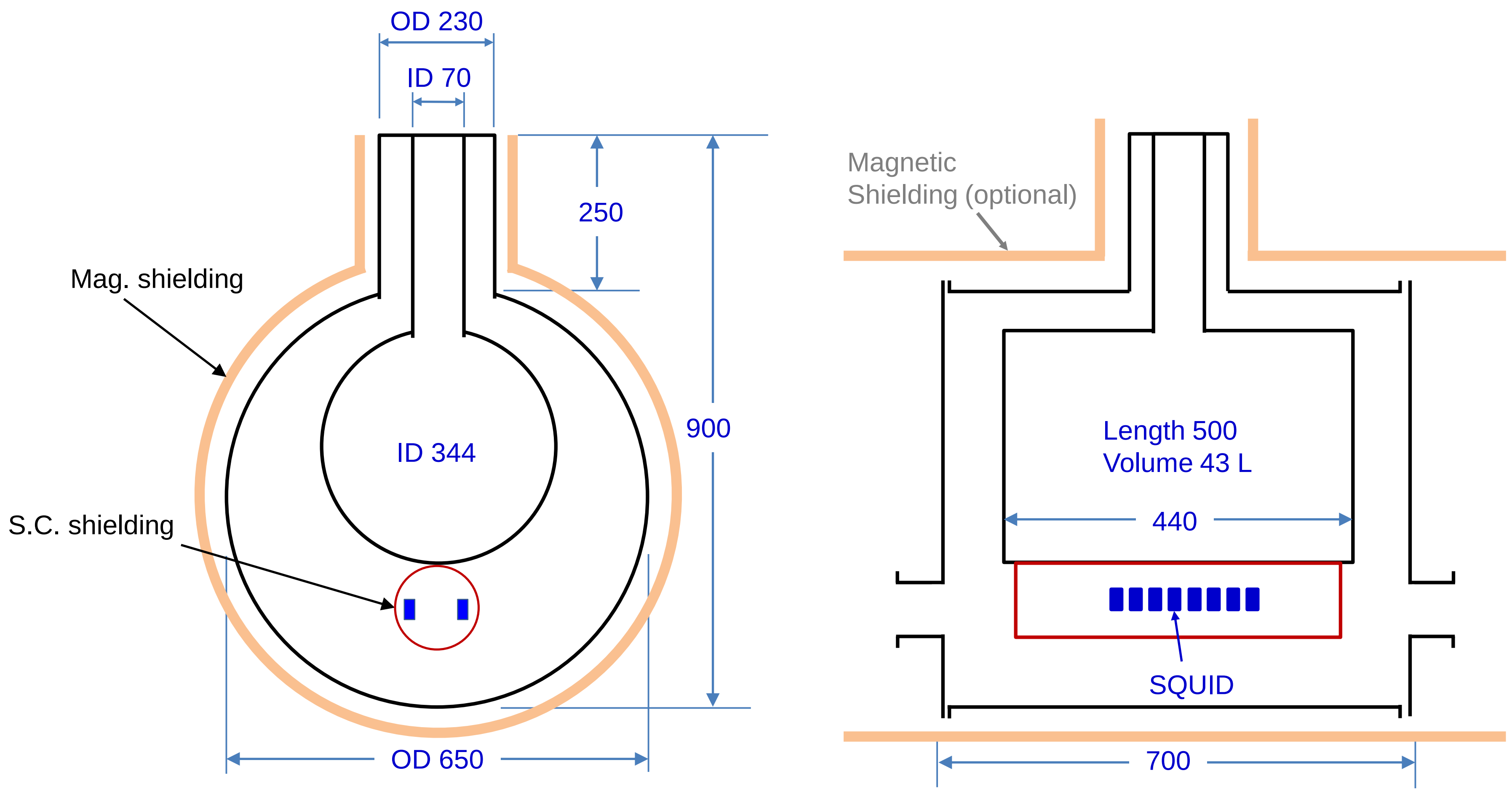
G2 Beam Position Monitoring SQUID system



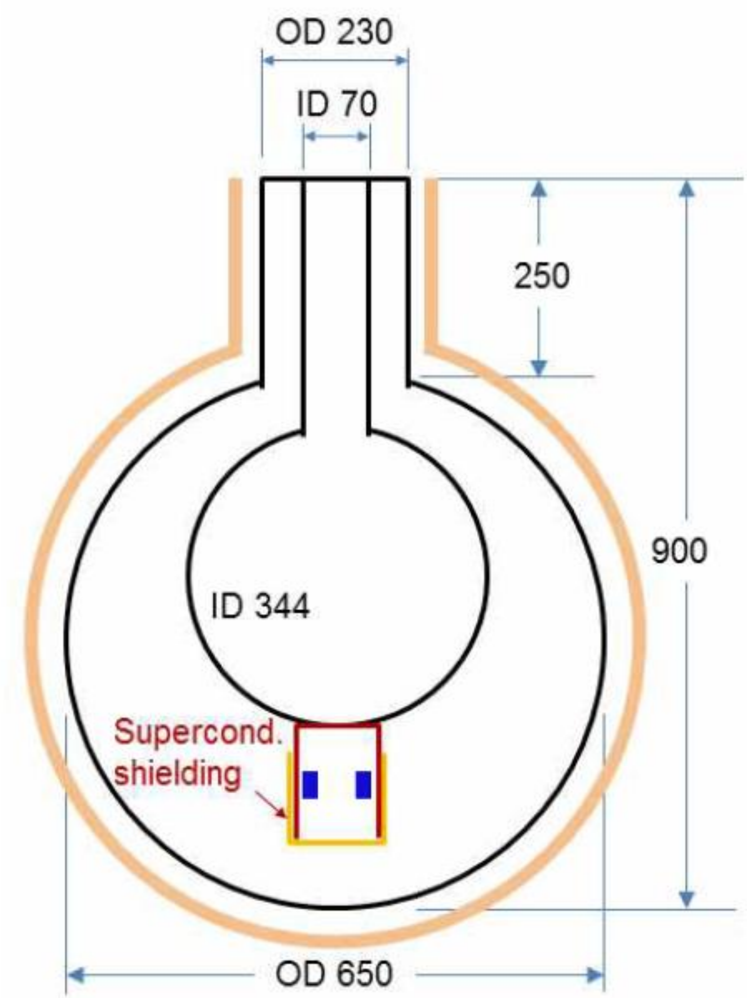


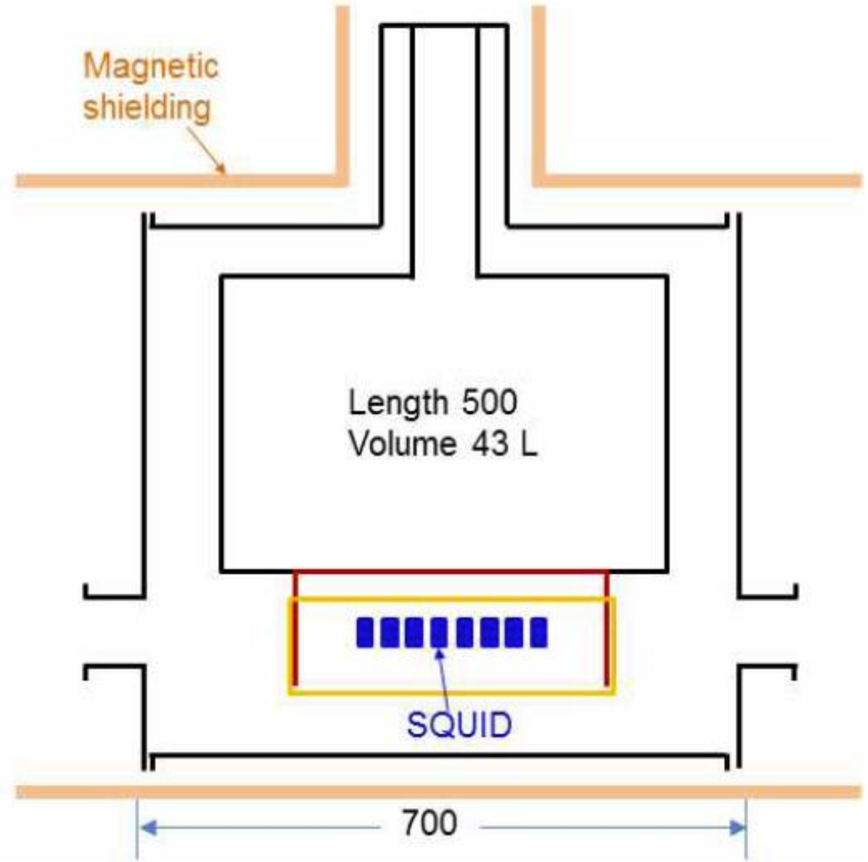


Cylindrical Dewar: Schematic



Superconducting Imaging Surface



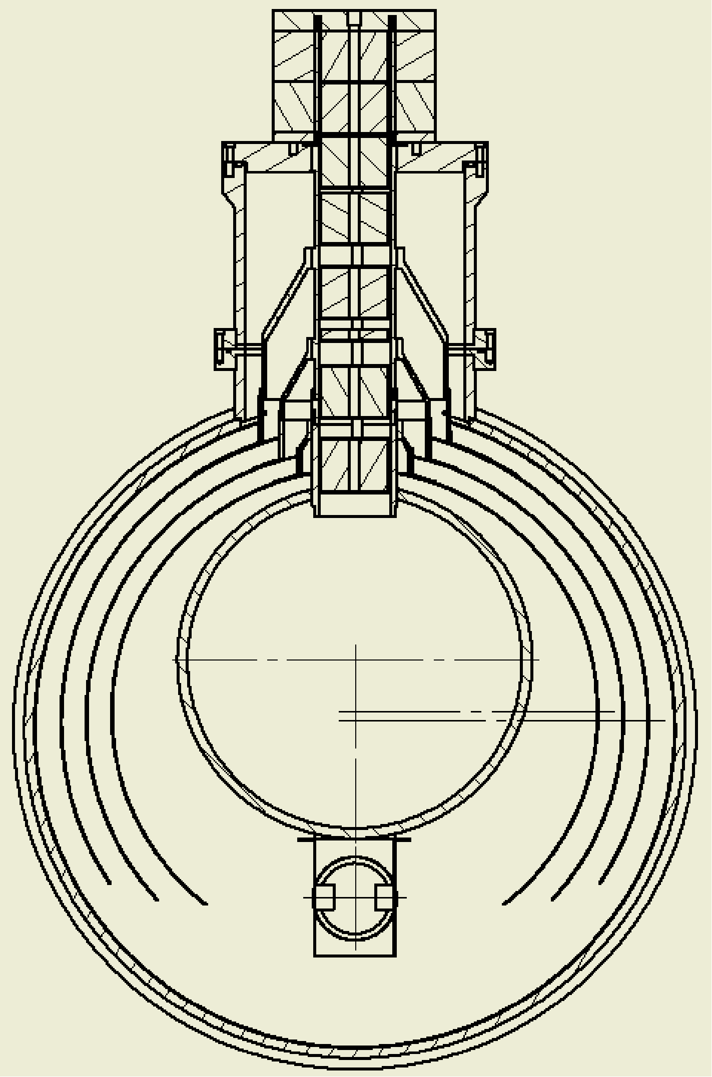


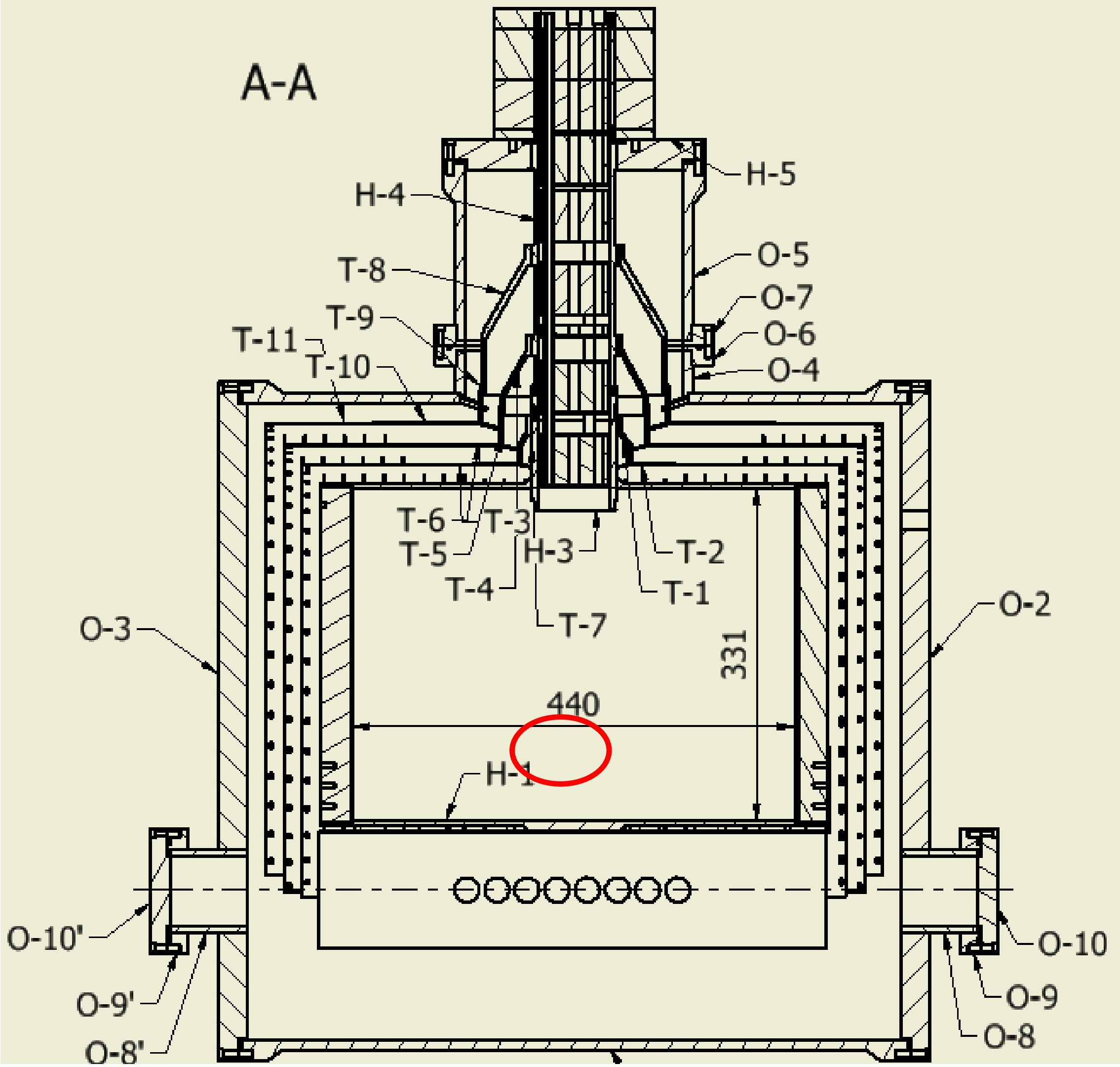
Superconductor imaging surface magnetometry

David B. van Hulsteyn, Albert G. Petschek, Edward R. Flynn, and William C. Overton, Jr.
Los Alamos National Laboratory, Physics Division, Los Alamos, New Mexico 87544

(Received 14 November 1994; accepted for publication 24 March 1995).

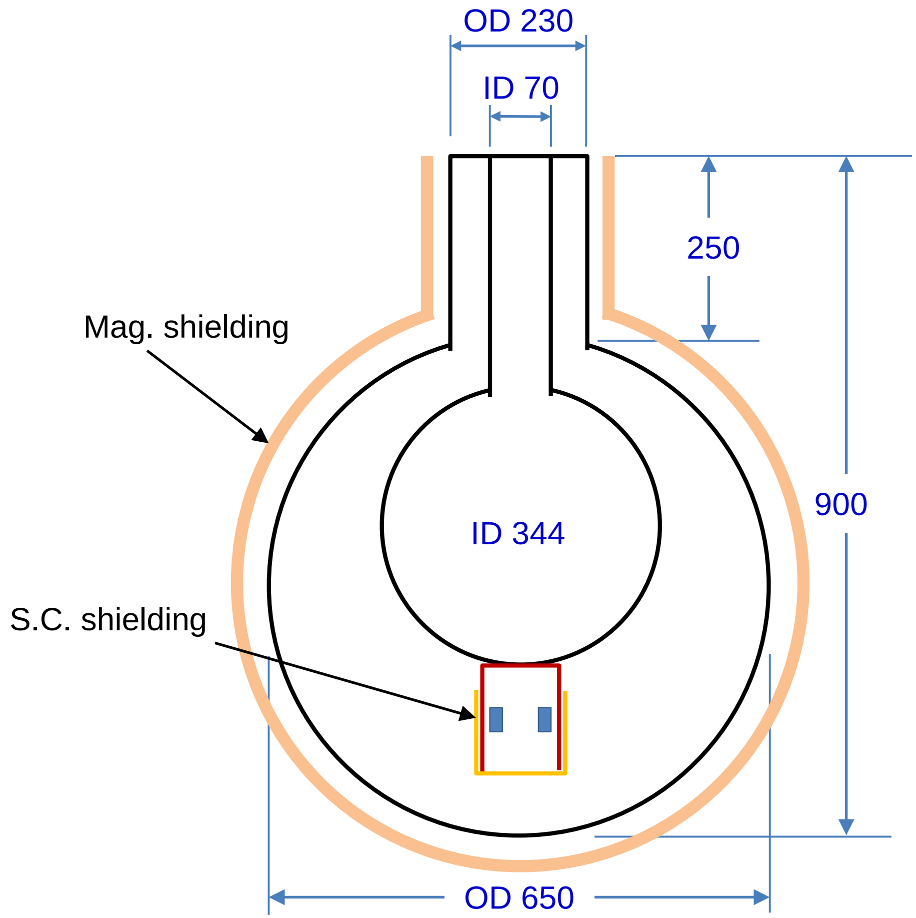
Cylindrical Dewar: Cross-section

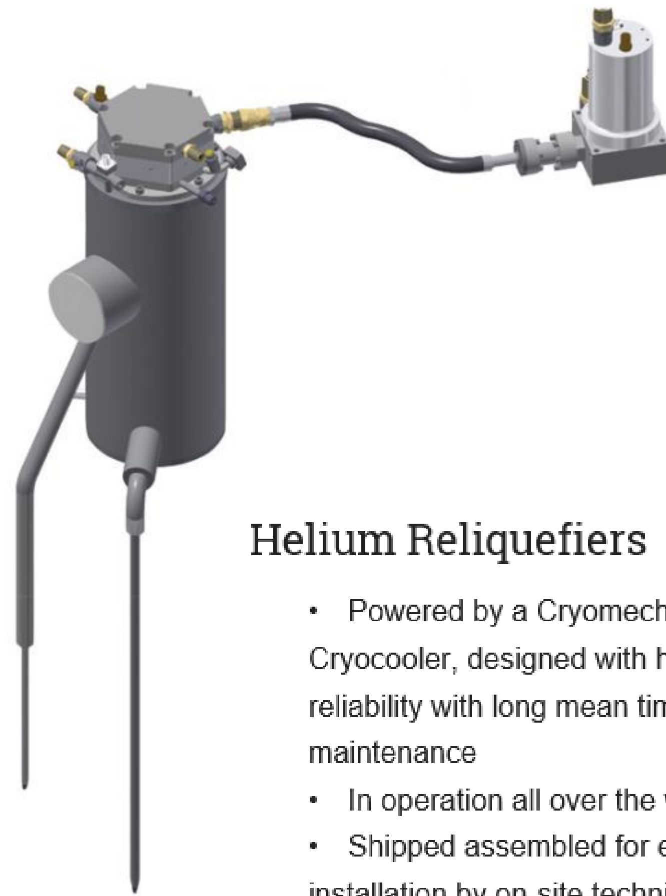




Cylindrical Dewar: Assembly

Cylindrical Cryostat: Re-Liquefier

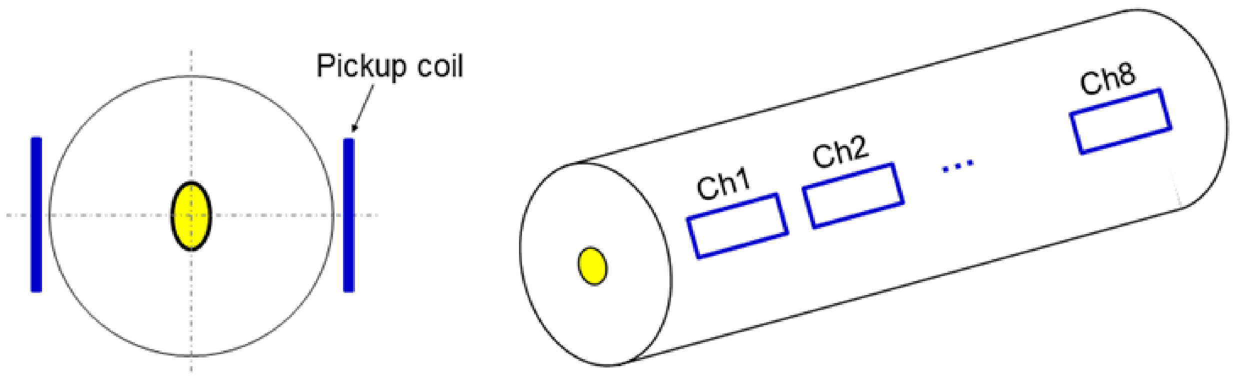




Helium Reliquefiers

- Powered by a Cryomech Pulse Tube Cryocooler, designed with high reliability with long mean times between maintenance
- In operation all over the world
- Shipped assembled for ease of installation by on-site technician
- Operate 24 hours a day, 7 days a week reliably, automatically and safely
- Customized design for each application

16 channel SQUID Magnetometers Array



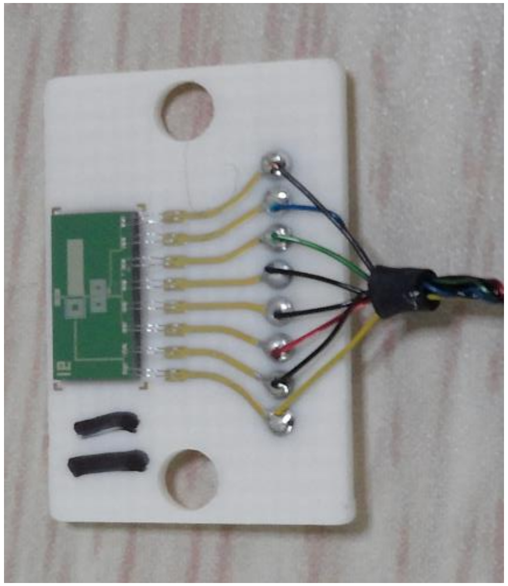
(a) (b)

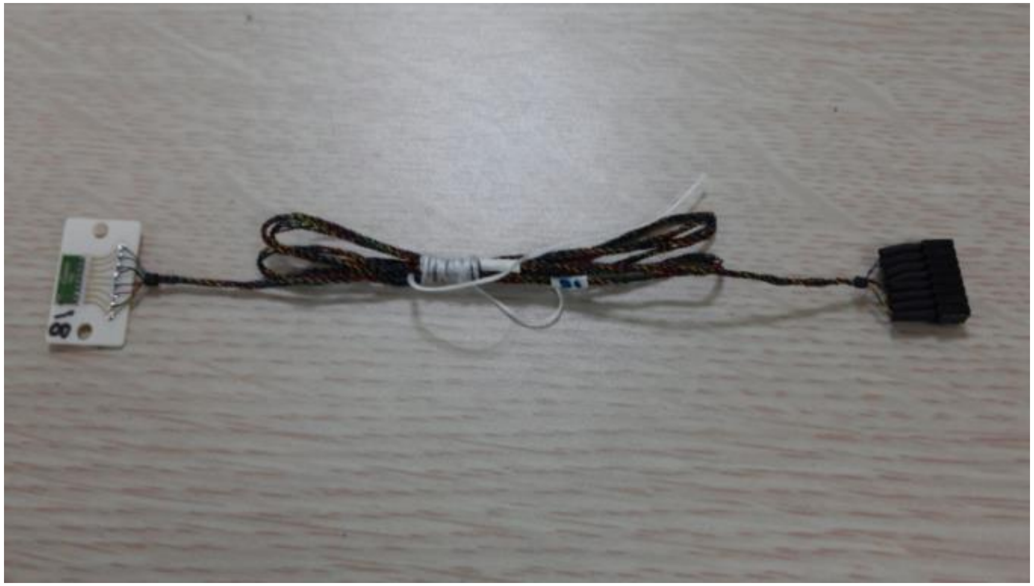
Fig. 21. Arrangement of the pickup coils. Blue lines are pickup coils, and yellow oval is the hypothetical proton beam shape. (a) Two pickup surfaces facing each other to measure two radial field components, and (b) 8 pickup coils are arranged along the beam propagation direction.

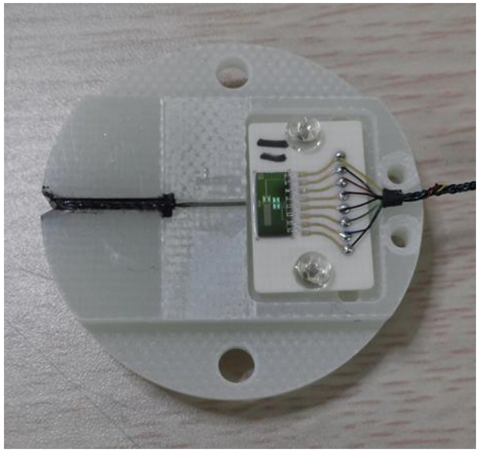
Main configuration of the SQUIDs and dewar are as following:

- Inter-coil distance: about 40 mm
- Rectangular coil: 15 mm x 40 mm
- Interval between pickup coils: about 50 mm
- 8 channels/side: 16 channels/dewar
- Either thin film or wire-wound pickup coil

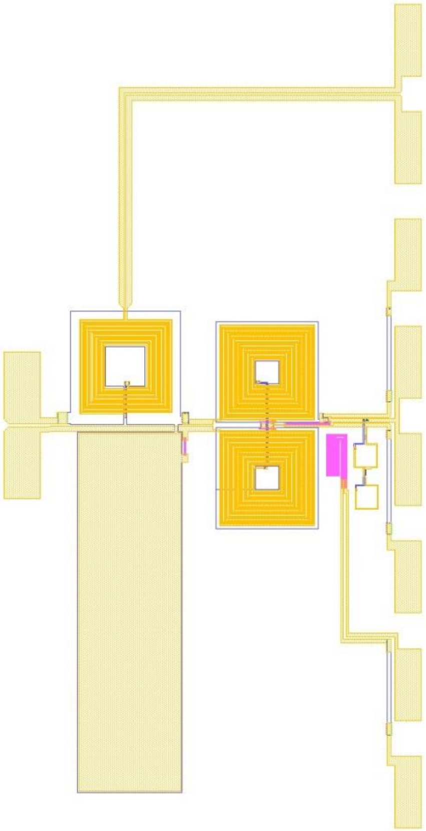
Magnetometer Design

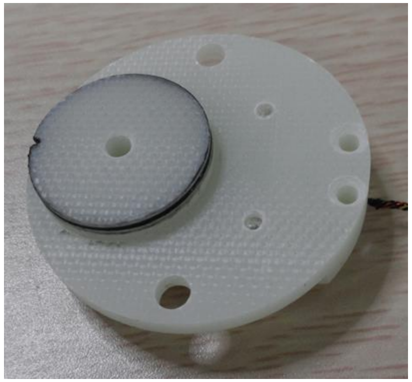


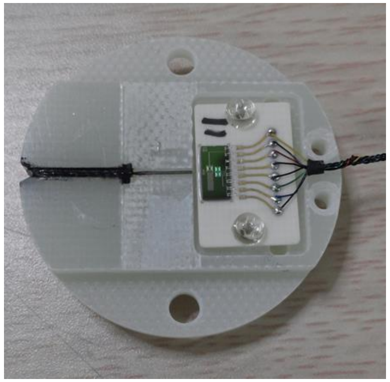




Magnetometer Parameters







Parameter	Value	Unit
Number of pickup-coil turn	2	Turn
Nb wire diameter	0.13	mm
Pickup coil diameter	**17**	**mm**
Pickup coil inductance L_p	213	nH
Input coil inductance L_i+L_f	202	nH
Mutual inductance Mi (L_s: L_i)	4.78	nH
Pickup area A_p	454	mm^2
Transfer coefficient (B/Φ)	0.4	nT/Φ_0
Flux noise	3.0	$\mu\Phi_0/\sqrt{Hz}$
Field resolution	**1.2**	**$fT/\sqrt{Hz}$**

New Generation SQUID Magnetometers

Device name	ML2A	ML2B	ML4.5	ML7	ML12
Number of loops	8	4	8	10	12
Chip size (mm^2)	2.5 × 2.5	2.5 × 2.5	5.0 × 5.0	7.5 × 7.5	12.5 × 12.5
Outer pickup coil dimension (mm)	2.0	2.0	4.5	7.0	12.2
Transfer function, $1/A_{eff}$, (nT/Φ_0):					
Measured	5.55	3.03	1.09	0.57	0.25
Calculated	5.54	2.48	1.10	0.56	0.26
Junction size (μm × μm)	0.8 × 0.8	0.8 × 0.8	0.8 × 0.8	0.8 × 0.8	0.6 × 0.6
Junction critical current, I_c, (μA)	9.3	11.9	8.0	7.5	2.3
Damping resistance, R_n, (Ω)	19.8	16.0	19.8	18.6	47.8
Calculated SQUID inductance L (pH)	130	375	270	325	300
β_L	1.19	4.30	2.10	2.34	0.67
β_C	0.44	0.37	0.38	0.31	0.36
Voltage swing (μV_{pp}):					
Measured	170	145	135	110	100
Calculated	175	150	135	115	110
SQUID noise					
Intrinsic flux noise ($\mu\Phi_0$ $Hz^{-1/2}$) :					
Measured	0.63	1.50	1.10	1.23	1.34
Calculated	0.42	1.21	0.82	1.00	0.75
Measured intrinsic field noise (fT $Hz^{-1/2}$)	3.5	4.5	1.2	0.7	0.33
Energy resolution:					
Measured (h)	9.7	19.5	14.5	15.1	19.3
Calculated (h)	4.4	12.7	8.0	10.0	5.8

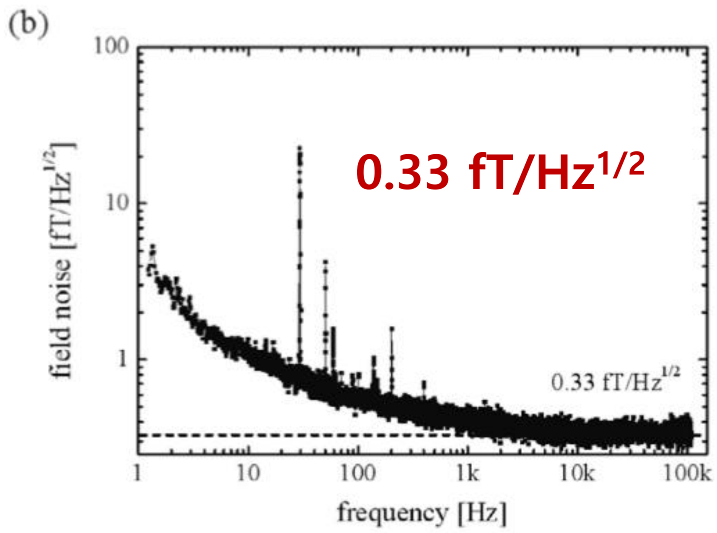


Figure 2. Typical noise spectra of two multi-loop SQUID magnetometers; (a) magnetometer of type ML7 with 0.8 μm × 0.8 μm Josephson junctions and (b) of type ML12 with 0.6 μm × 0.6 μm Josephson junctions.

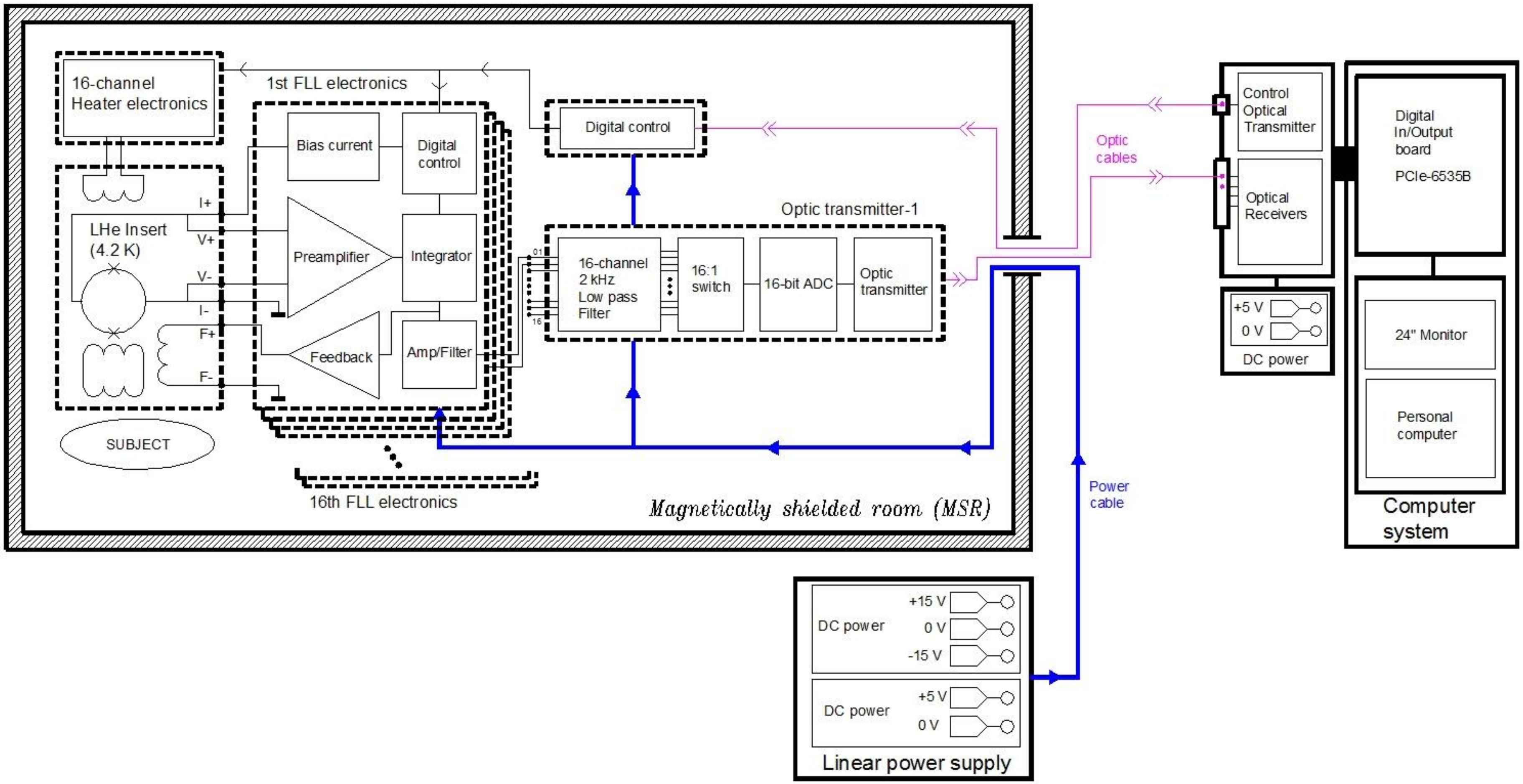
Pick-up Loop: 12 × 12 mm^2
Noise = 0.33 $fT/Hz^{1/2}$

→

Pick-up Loop: 24 × 48 mm^2
Noise = 0.11 $fT/Hz^{1/2}$

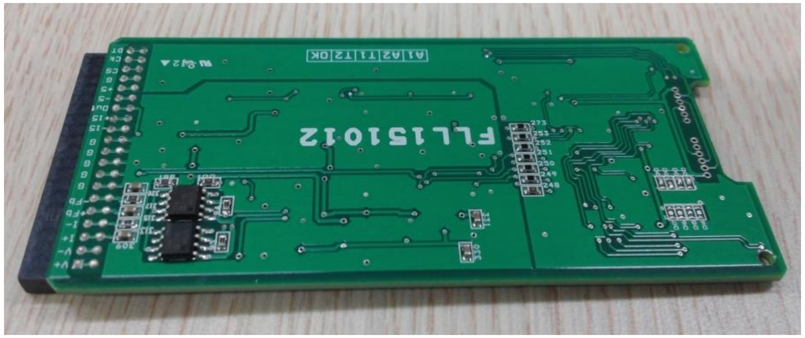
IPHT, Jena, Germany (2011)
Supercond. Sci. Technol. 24 (2011) 065009(5pp)
doi:10.1088/0953-2048/24/6/065009

SQUIDs Control Electronics and PS

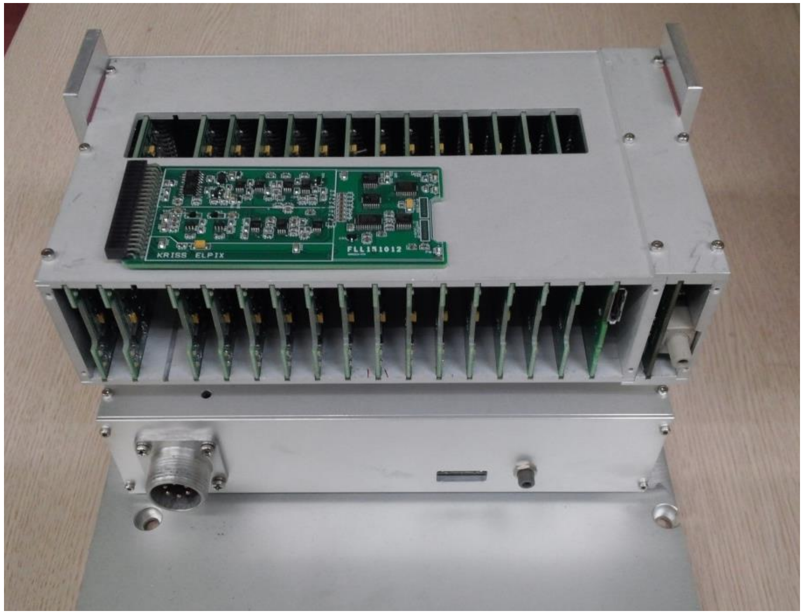


16 channel SQUID Electronics

Flux-lock loop circuits



DC-power and acquisition



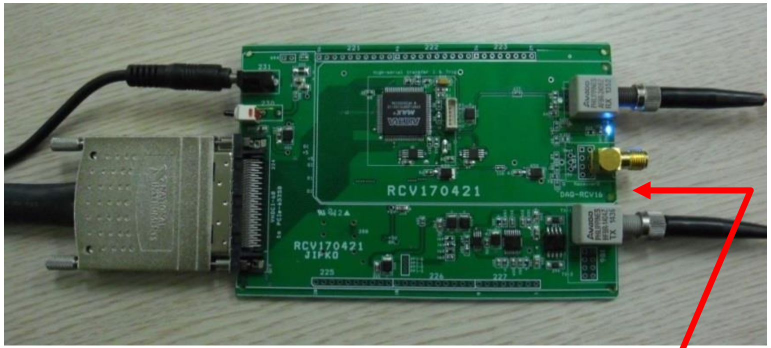
Output: Digital, optical
High-pass filter: 200 Hz
Low-pass filter: 2 kHz
Optimum signal frequency range: 500 ~ 1,000 Hz

SQUID Read-out and Control Electronics

Flux-Lock-Loop box

Analog-to-digital converter

Control

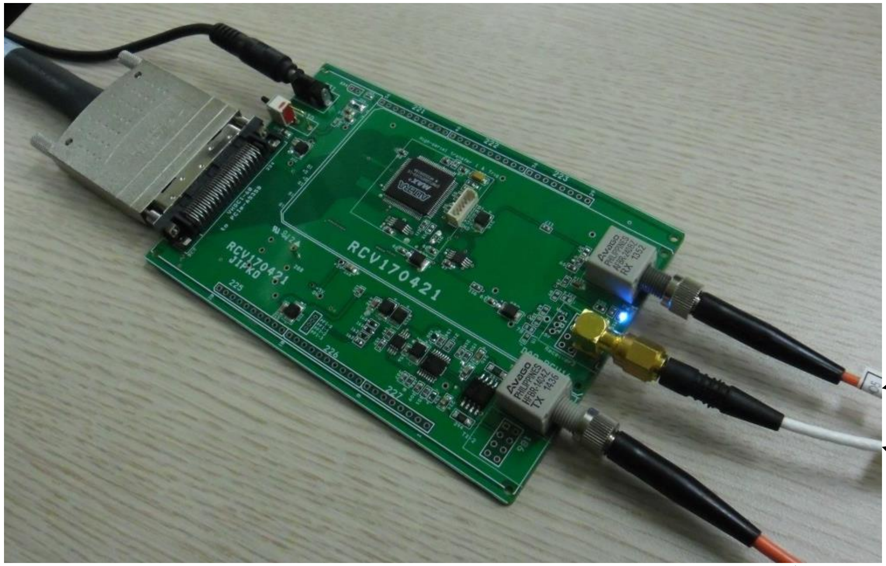


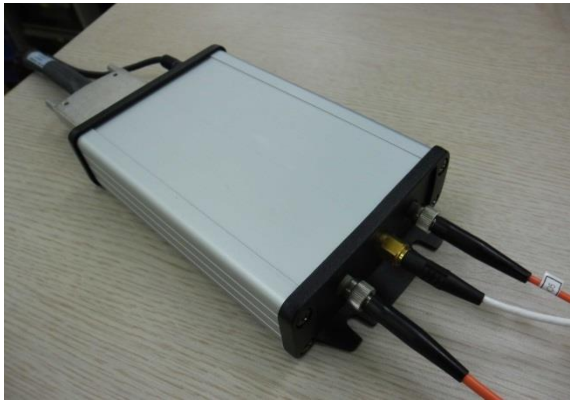
External trigger port

24-bit resolution
10 kSample/s

Optical Controls and Read-outs

Computer (Digital I/O)





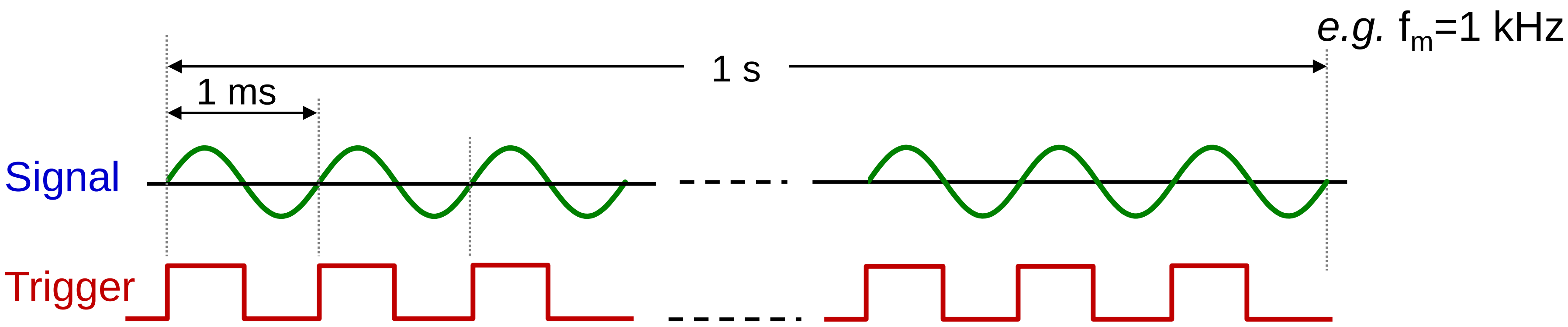
FLL input (digital/serial)

Trigger input (Electrical or optical)

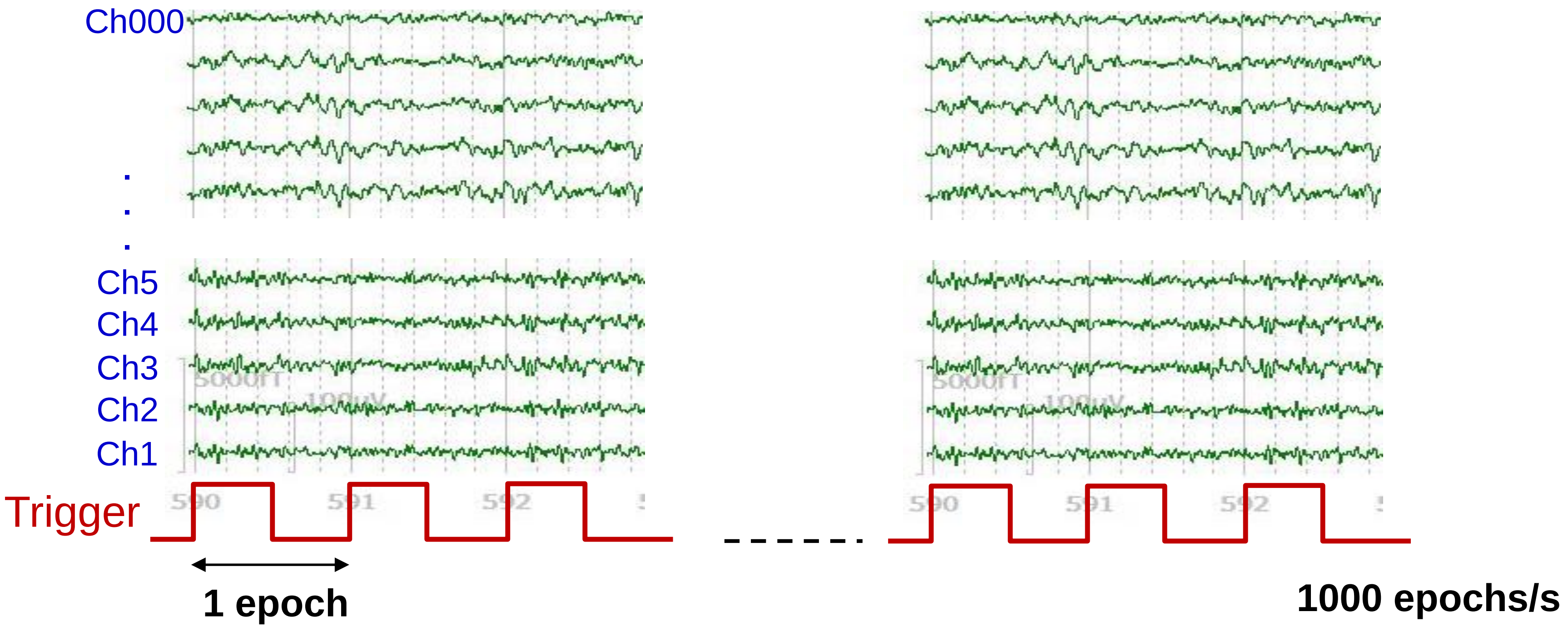
FLL control output

16 bit resolution
10 kSample/s per channel
FLL output: Optical signal

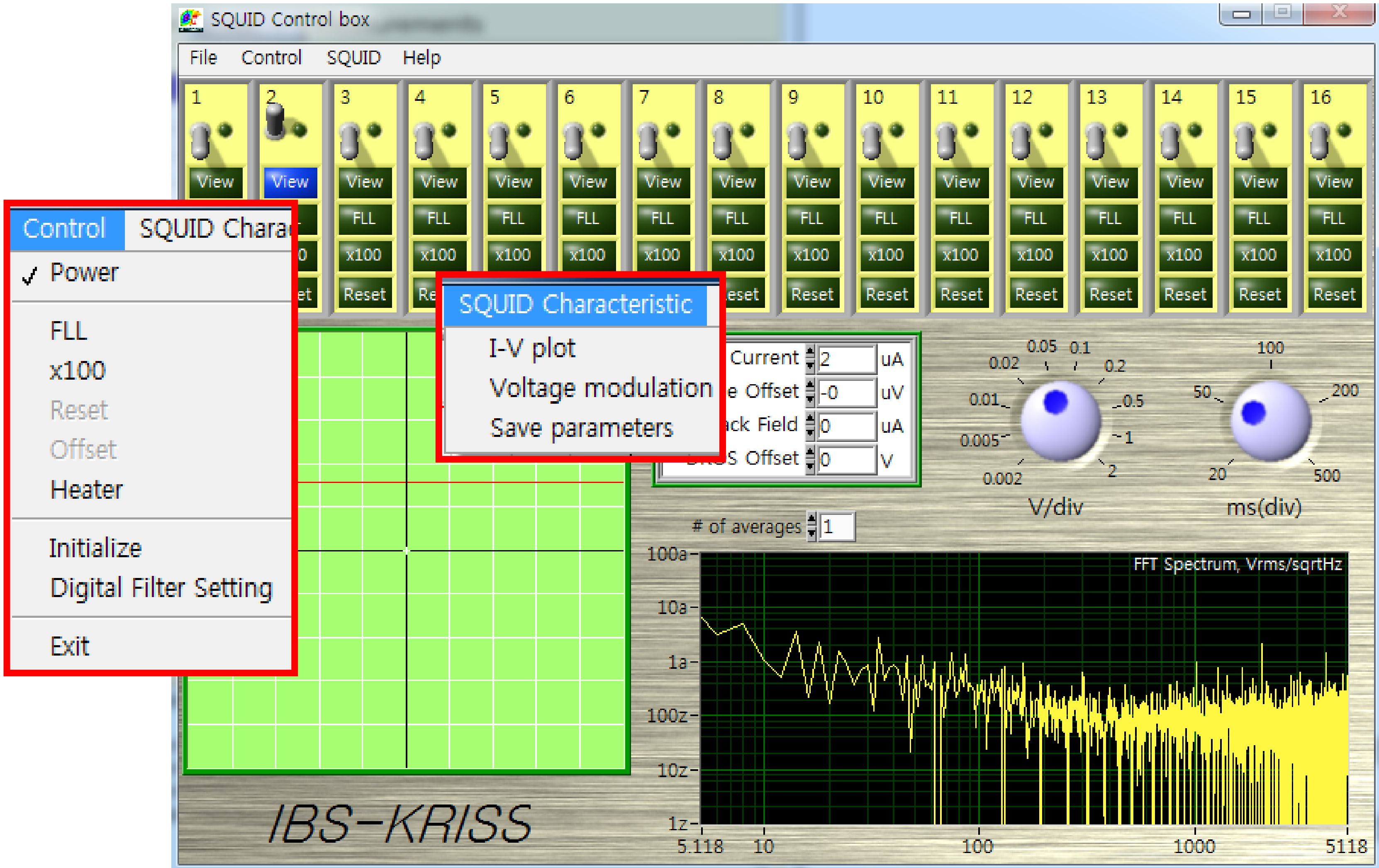
BMP Signals Triggering and Averaging



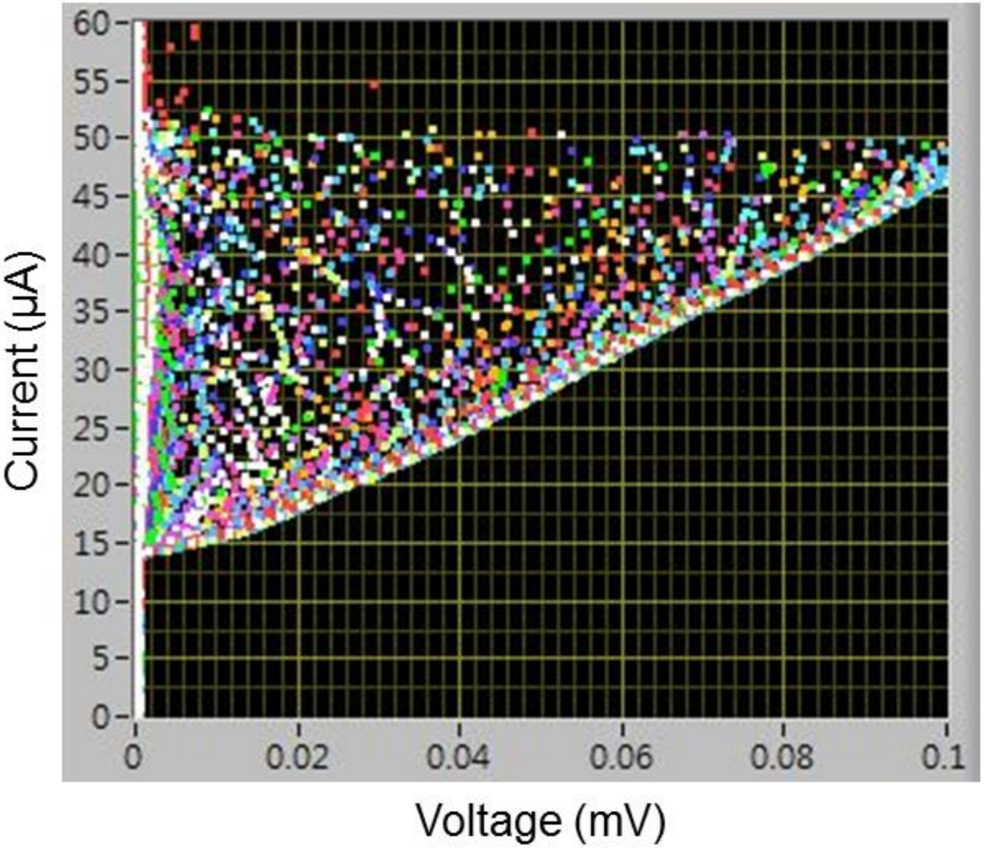
<Measured data>

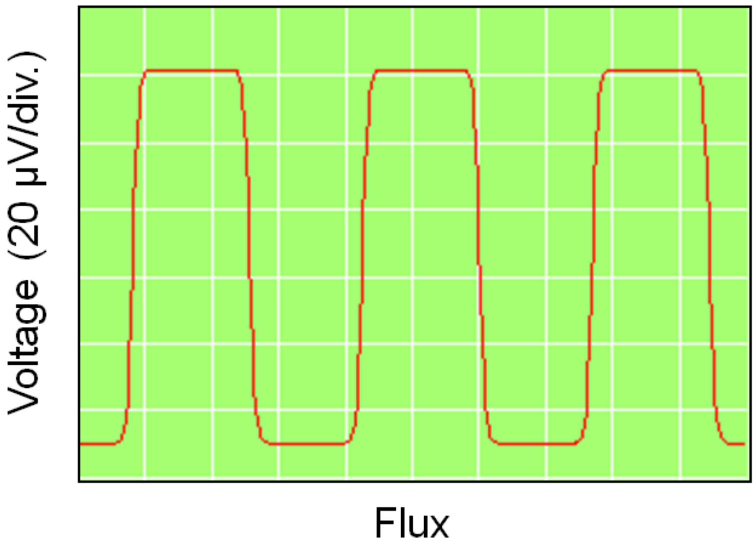


SQUIDs Control Software



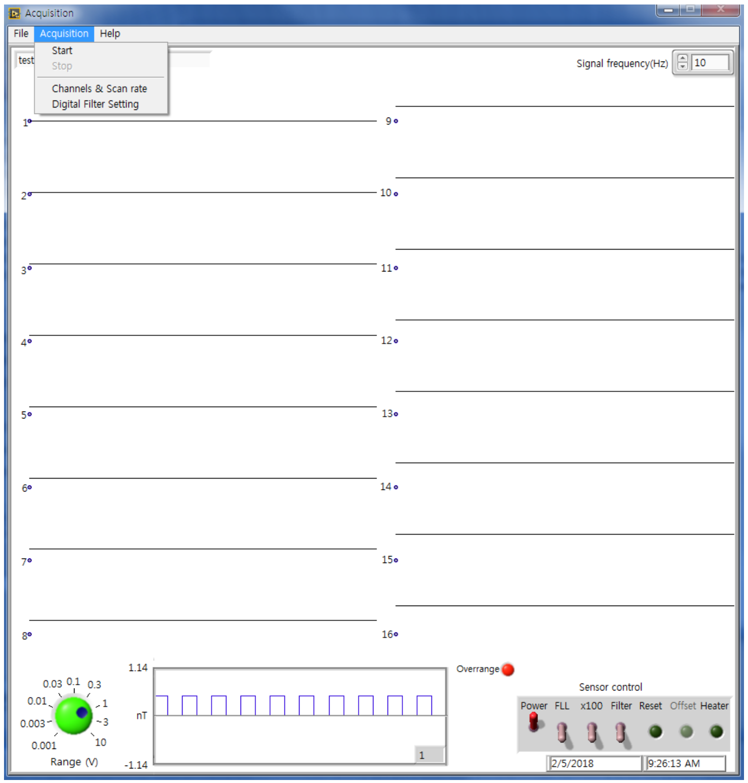
SQUIDs I-V and V-Φ monitoring and adjustment



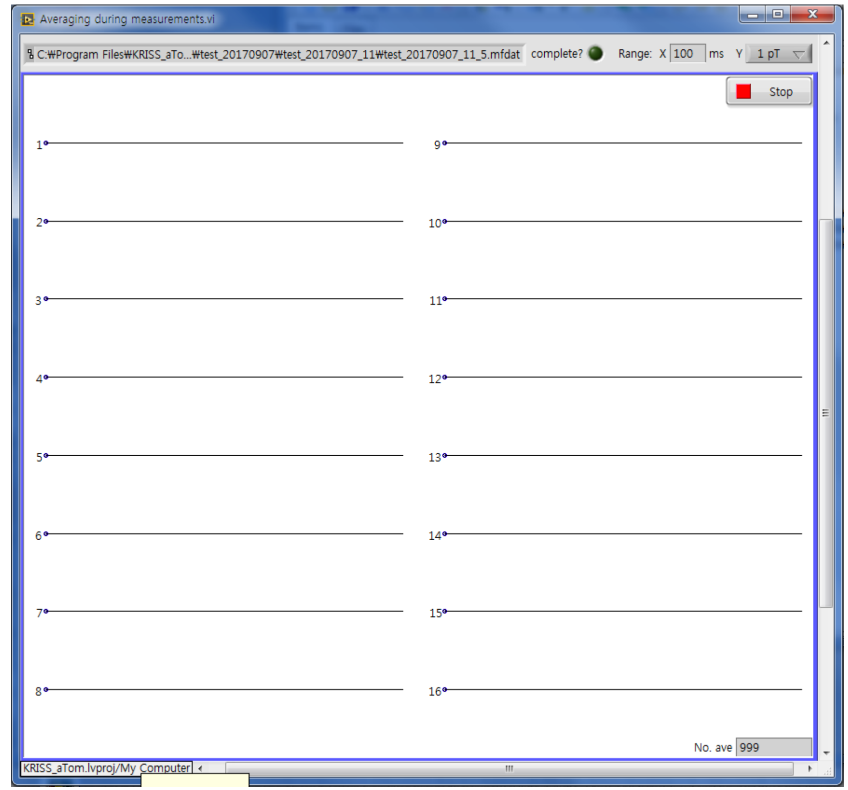


Data Acquisition and Averaging

Acquisition (Saving) window

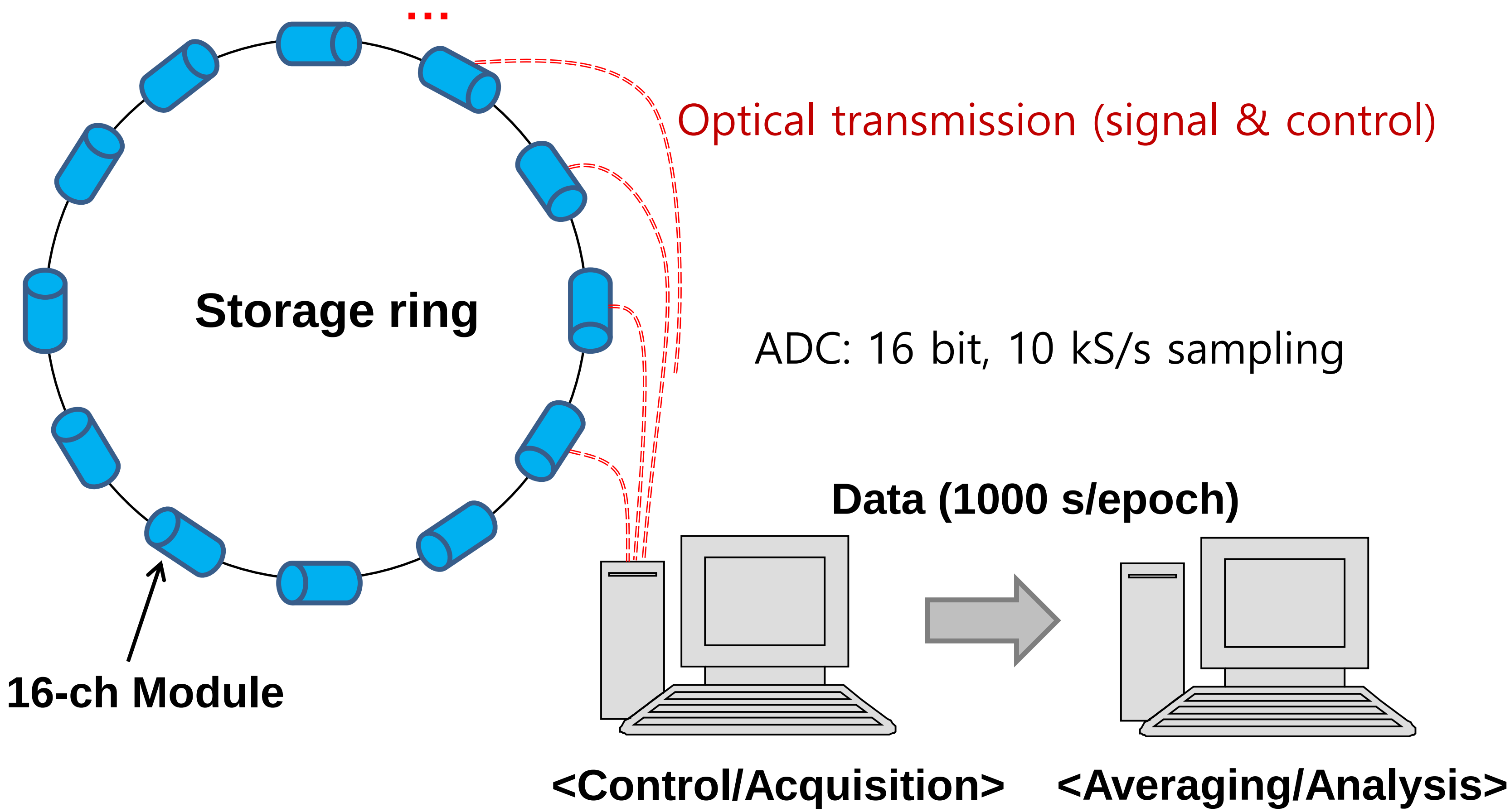


Real time averaging window



During data saving, real time averaging window appears.
Data are saved every 20 s (default value).

BMP Systems in the Storage Ring



Interference-free control

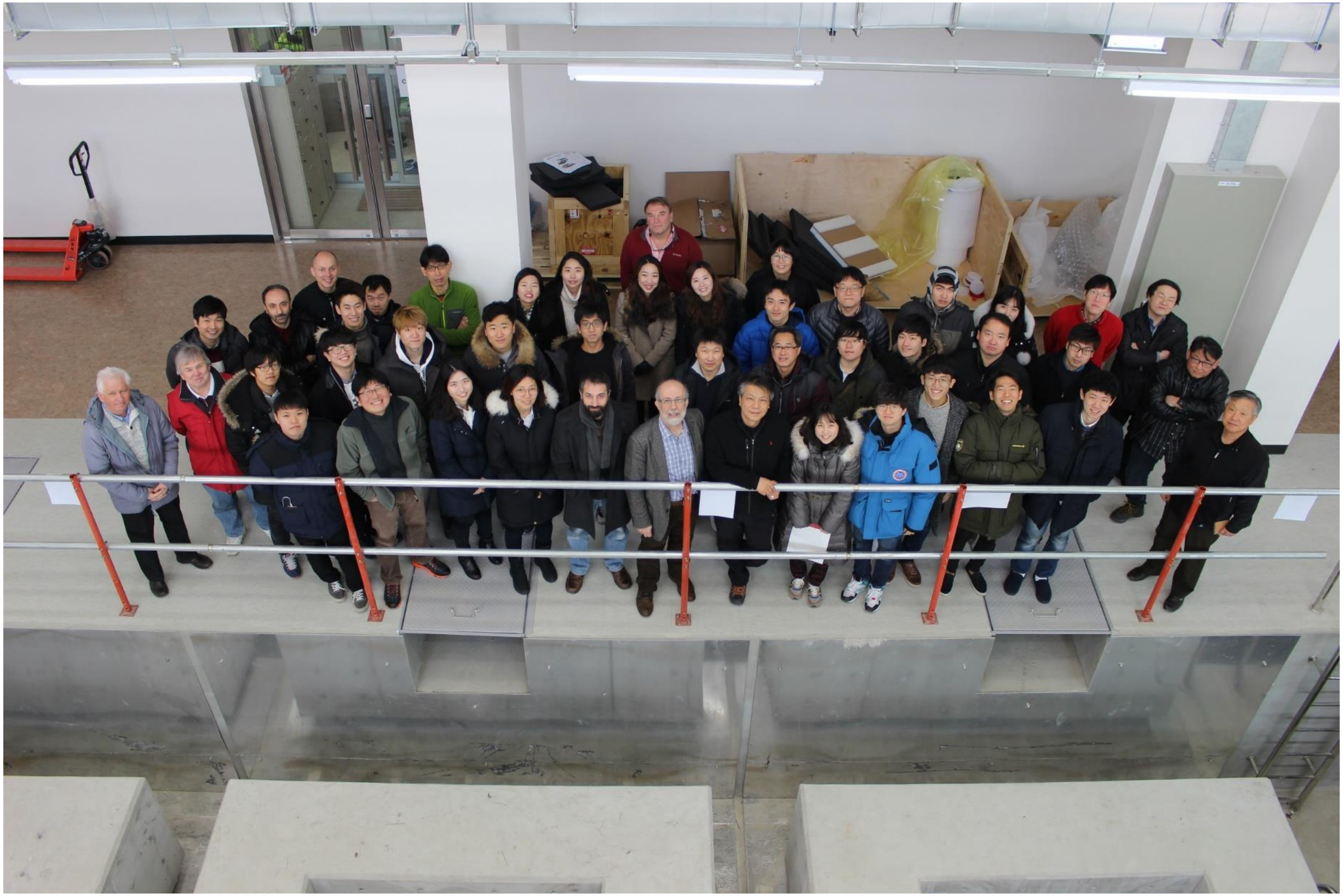
Noise-free acquisition

No time-delay bet. modules

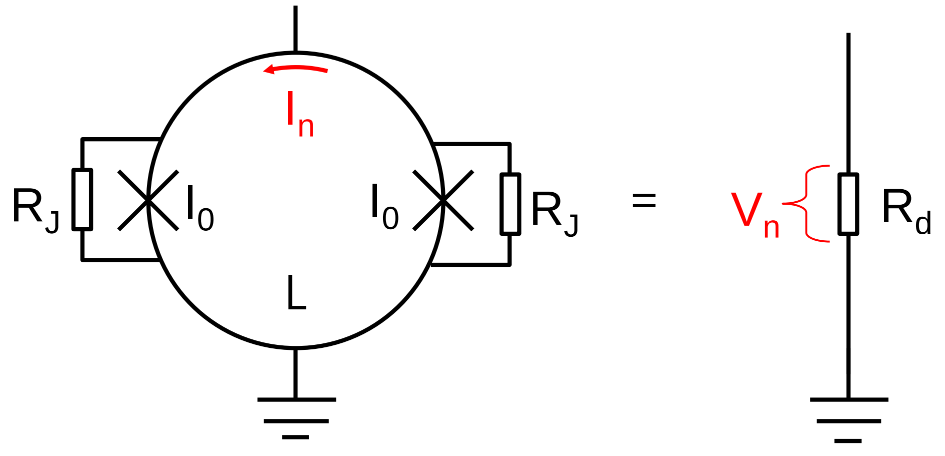
SUMMARY

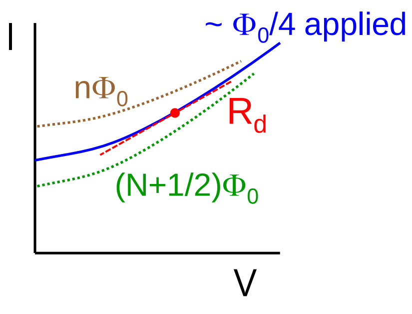
- ❖ **The First generation (G1) of BMP system: tested at KRISS and moved to CAPP for further tests and research.**
- ❖ **The Second generation (G2) of BMP system: designed, all key components manufactured; it will be assembled in May 2018.**
- ❖ **Field Resolution: current G1 system → 3.5 fT/√Hz @1 kHz**
- ❖ **Field Resolution: under construction G2 system → 1.2 fT/√Hz @1 kHz**
- ❖ **Field Resolution: new generation SQUIDs → 0.15 fT/√Hz @1 kHz**

THANKS FOR YOUR ATTENTION !



DC SQUID Noise





1. Circulating current noise due to $2R_J$: $I_n=(4k_BT/2R_J)^{0.5}$
   SQUID inductance: L
   Flux noise=$I_n \times L=\{4k_BT(L^2/2R_J)\}^{0.5}$

2. Voltage noise due to SQUID dynamic resistance R_d: $V_n=(4k_BTR_d)^{0.5}$
   Flux-to-voltage transfer: V_Φ
   Flux noise: $V_n/V_\Phi=(4k_BTR_d/V_\Phi{}^2)^{0.5}$

Total flux noise (intrinsic): $\Phi_n=\{4k_BT(L^2/2R_J + R_d/V_\Phi{}^2)\}^{0.5} = \sim L/R_d{}^{0.5}$

Single-chip Magnetometers from IPHT, Jena

Sub-micrometer Josephson junctions

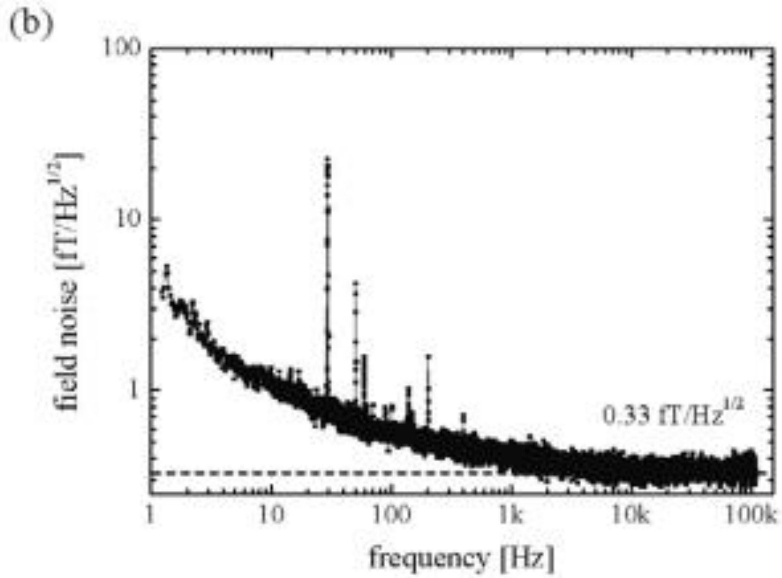


Figure 2. Typical noise spectra of two multi-loop SQUID magnetometers; (a) magnetometer of type ML7 with 0.8 μm × 0.8 μm Josephson junctions and (b) of type ML12 with 0.6 μm × 0.6 μm Josephson junctions.

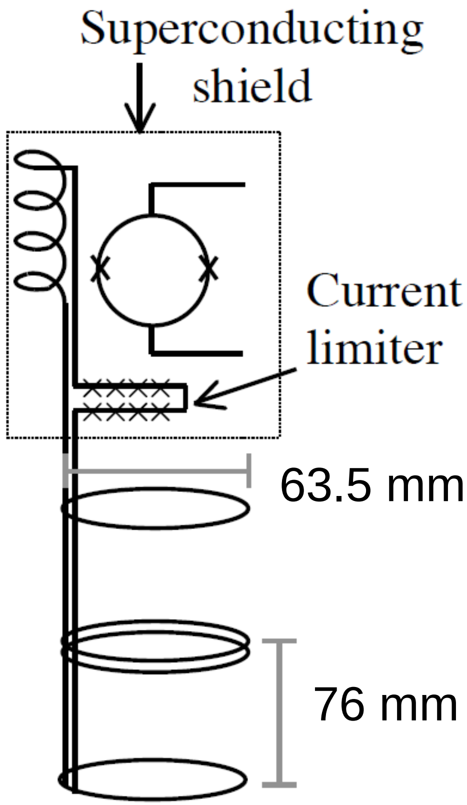
Device name	ML7	ML12
Number of loops	10	12
Chip size (mm^2)	7.5 × 7.5	12.5 × 12.5
Outer pickup coil dimension (mm)	7.0	12.2
Transfer function, $1/A_{eff}$, (nT/Φ_0):		
Measured	0.57	0.25
Calculated	0.56	0.26
Junction size (μm × μm)	0.8 × 0.8	0.6 × 0.6
Junction critical current, I_c, (μA)	7.5	2.3
Damping resistance, R_n, (Ω)	18.6	47.8
Calculated SQUID inductance L (pH)	325	300
β_L	2.34	0.67
β_C	0.31	0.36
Voltage swing (μV_{pp}):		
Measured	110	100
Calculated	115	110
SQUID noise		
Intrinsic flux noise ($\mu\Phi_0$ $Hz^{-1/2}$) :		
Measured	1.23	1.34
Calculated	1.00	0.75
Measured intrinsic field noise (fT $Hz^{-1/2}$)	0.7	0.33

Intrinsic noise: 0.33 fT/√Hz

UC Berkeley Ø63.5 mm Gradiometer

Single-channel dewar

ez-SQUID



Sensitivity: 0.7 fT/√Hz

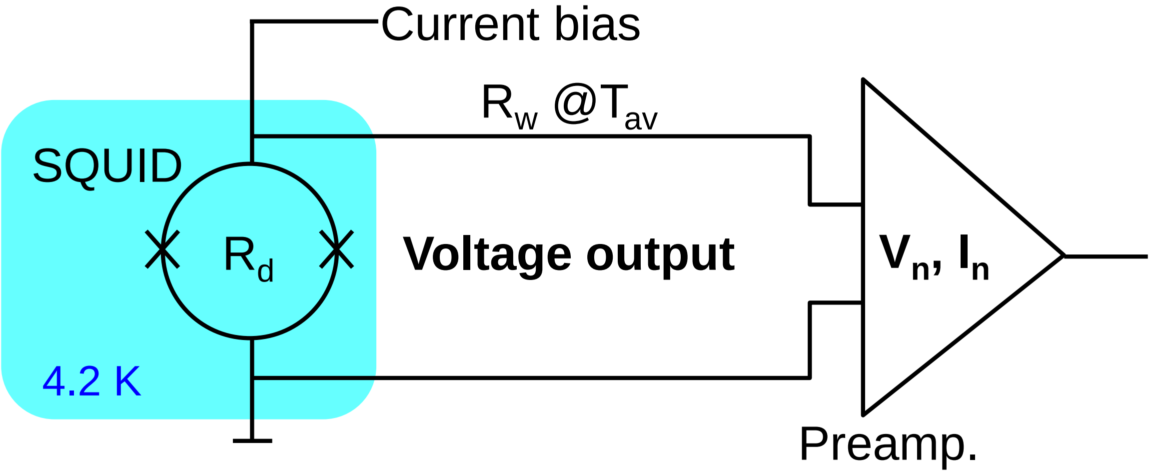
LANL Ø60 mm Gradiometers

2nd-order gradiometer 1
d=37 mm, b=60 mm,
Noise: 1.2-2.8 fT/√√Hz at 1 kHz

2nd order gradiometer 2
d = 90 mm, b= 90 mm,
Noise < 0.5 fT/√Hz

Preamplifier Noise Contribution

In direct readout mode



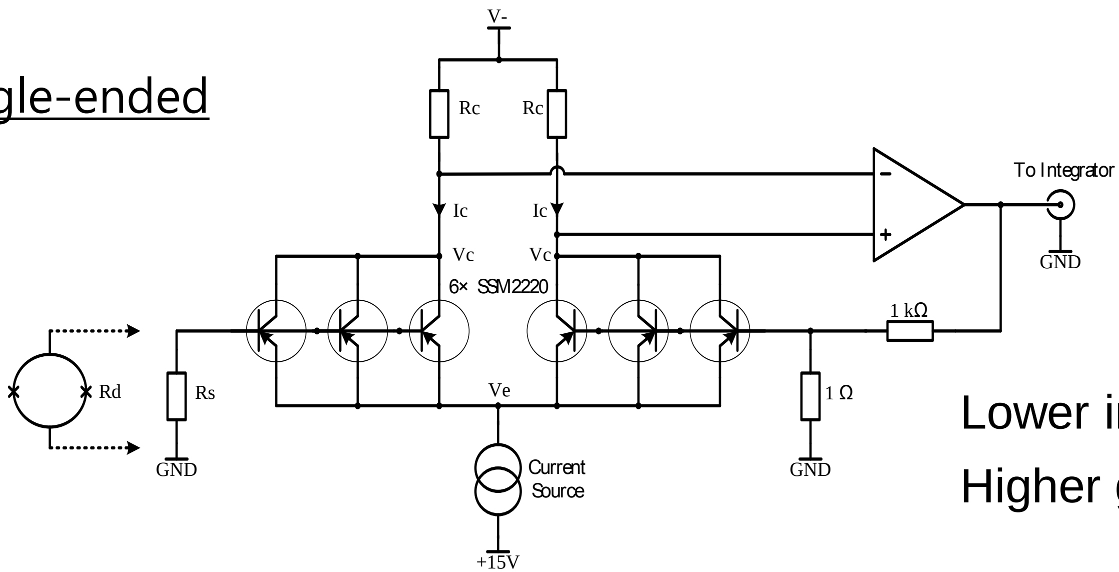
Noise of SQUID system: $\Phi^2_{intrinsic} + \Phi^2_{preamp}$

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

$$V_{n,tot} = \{V_n^2 + I_n^2(R_d+R_w)^2 + 4k_BT_{SQ}R_d + 4k_BT_{av}R_w\}^{0.5}$$

Low-noise Preamplifier

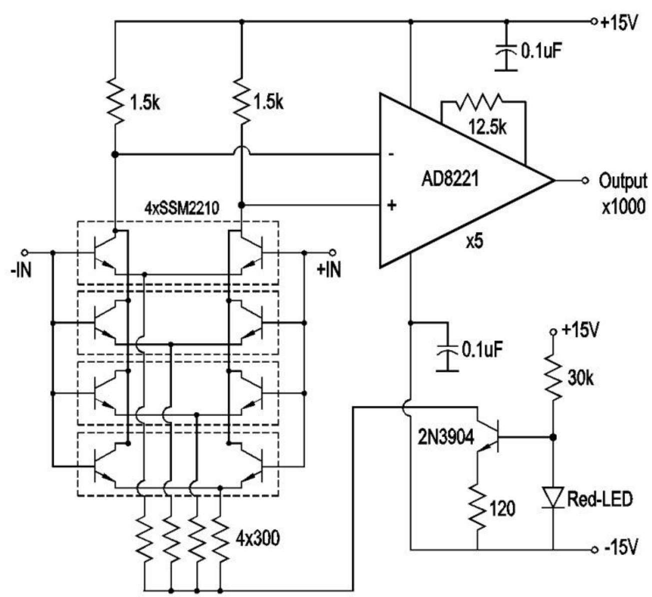
Single-ended



Lower input noise

Higher ground noise

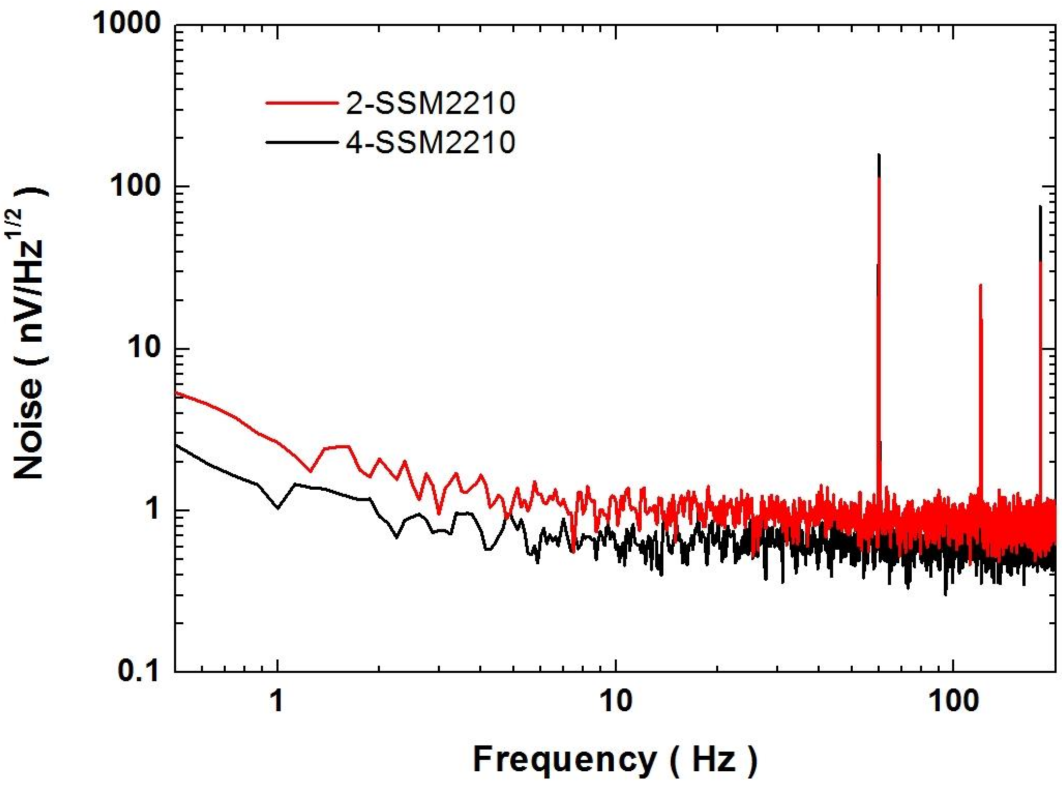
Differential



Higher input noise

Less ground noise

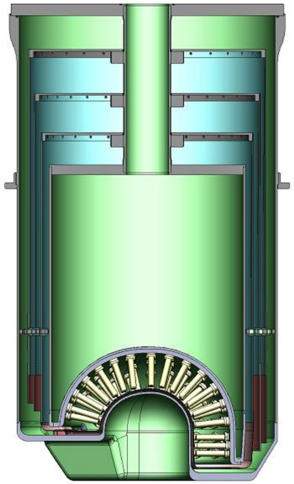
Preamplifier Noise

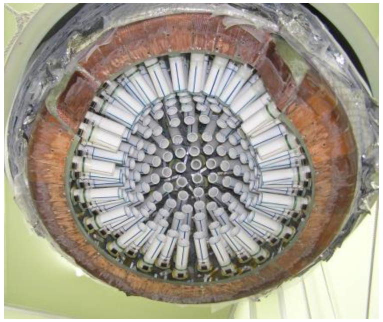


Moderate input voltage noise
Moderate input current noise

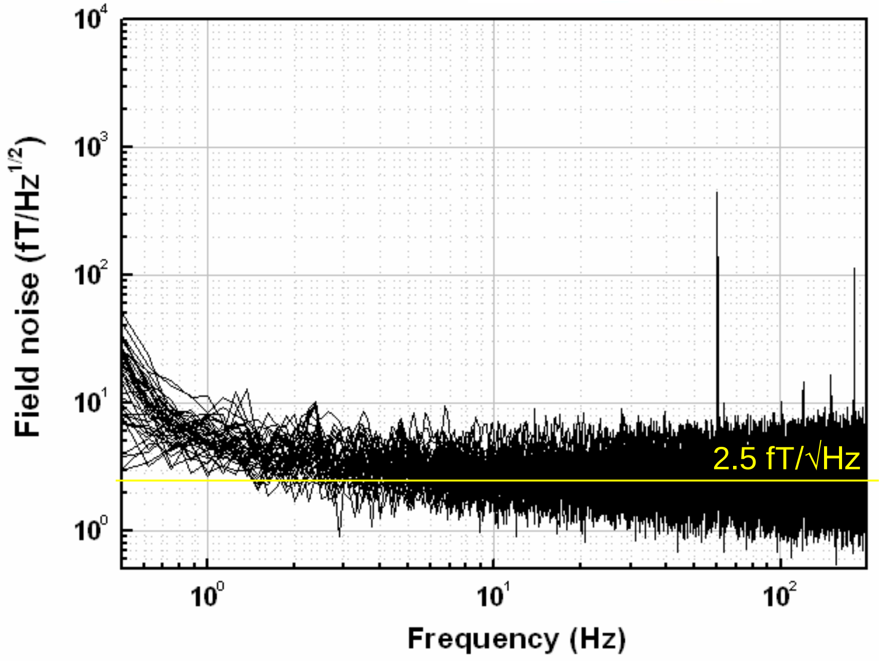
cf)
Low input voltage noise → High input current noise
Large R_d: $I_n R_d > V_n$

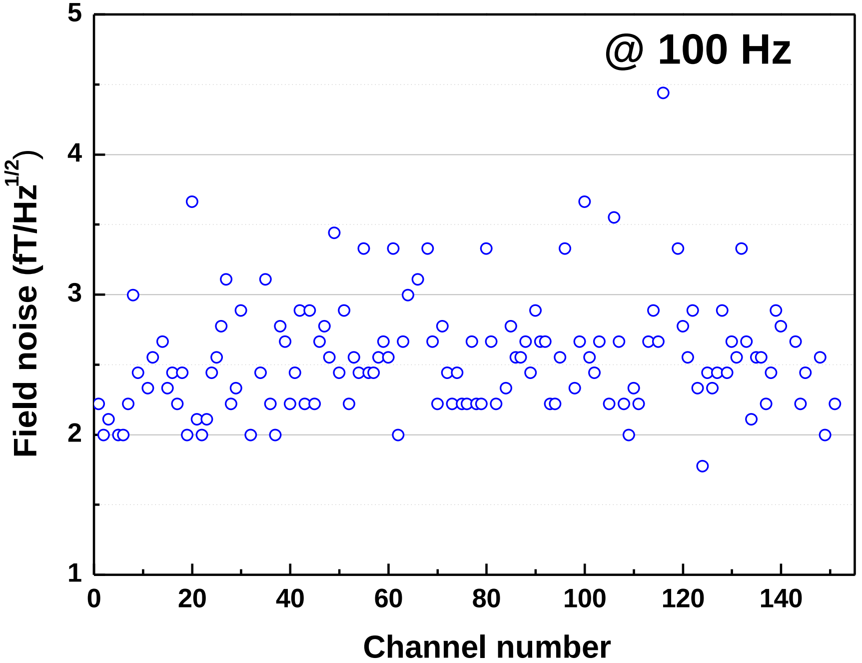
KRISS Whole-head MEG System





B/Φ: 0.46 nT/Φ_0





Subjects	Category	2014	2015	2016	2017	2018	2019
Low-noise SQUID system for pEDM	Research outcome			SQUID magnetometer and control electronics system		Ultra-low-noise SQUID magnetometer and control electronics system	
			Pretest SQUID system		Hollow cylindrical dewar, Superconductive shielding, optimization		
			8-ch SQUID system, 3 fT/Hz	16ch SQUID system, system noise 3 fT/√Hz (@ 1 kHz)		16ch SQUID system optimization	
						System noise 2 fT/√Hz (@ 1 kHz)	System noise 1.5 fT/√Hz (@ 1 kHz)