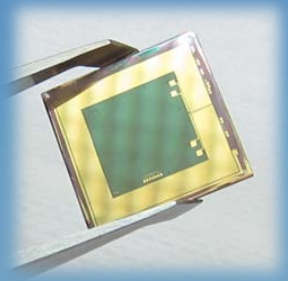
IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January 2015.
Plenary presentation PL-6-INV was given at ISS 2014, Tokyo, November 25 - 27, 2014.

ISS2014 (Nov. 25-27, 2014)
Funabori, Tokyo



Recent Progress of HTS SQUID Application in Japan

Keiichi Tanabe

Director General
Director of Materials/Physics & Electronic Devices Div.
Superconductivity Research Laboratory - ISTEC

IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January 2015.
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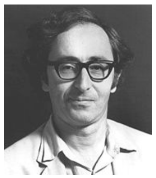
50th anniversary of SQUID

Theoretical prediction by B. D. Josephson



Physics Letters ***1****, 251 (1962).*

Josephson effect

Experimentally confirmed by
P. W. Anderson and J. M. Rowell

Phys. Rev. Lett. ***10****, 230 (1963).*

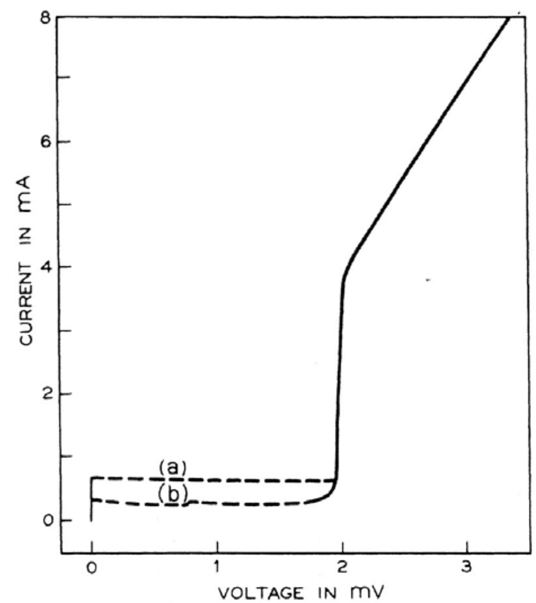
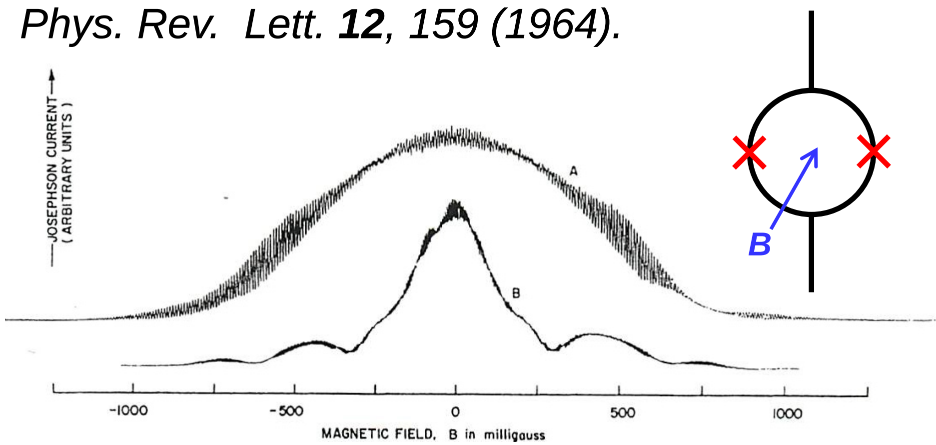


FIG. 1. Current-voltage characteristic for a tin-tin oxide-lead tunnel structure at ~1.5°K, (a) for a field of 6×10^{-3} gauss and (b) for a field 0.4 gauss.

First observation of quantum interference
R. C. Jaklevic, J. Lamble, A. H. Silver, and
J. E. Mercereau

Phys. Rev. Lett. ***12****, 159 (1964).*

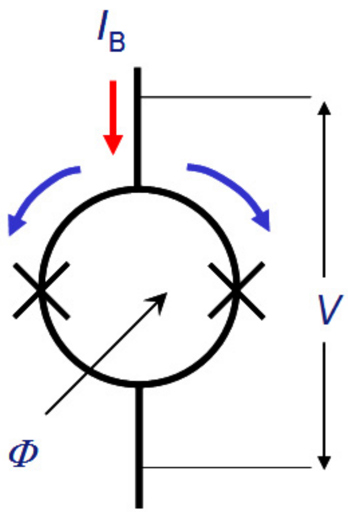


Superconducting Quantum Interference Device (SQUID)

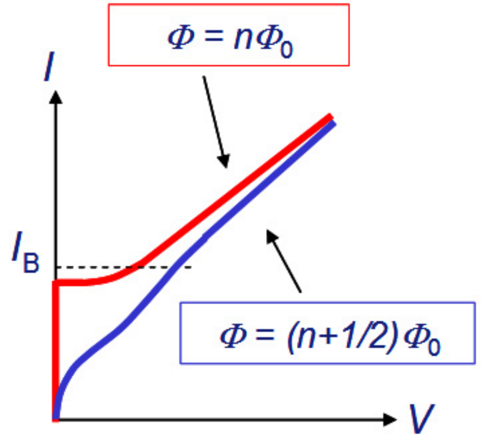
Outline

1. Fundamentals of SQUID
   - operation principle, representative applications of LTS/HTS-SQUIDs
2. Multilayer HTS-SQUID developed at ISTEC
   - structure, features, previous applications
3. Recent progress of application in Japan
   - metallic contaminant detection system, SQUID microscope
   - bio-sensing system (JST S-innovation project)
   - SQUID-TEM, magnetic prospecting, crosshole EM systems (JOGMEC projects, exploration and monitoring of underground resources)
   - nondestructive evaluation of infrastructure (JST SIP project)
4. Summary and future prospects

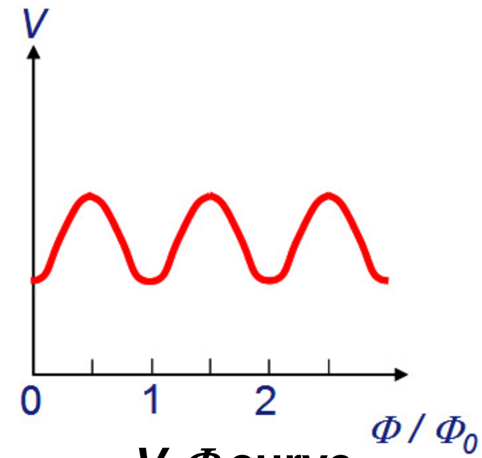
1. Fundamentals of SQUID
Structure and operation principle



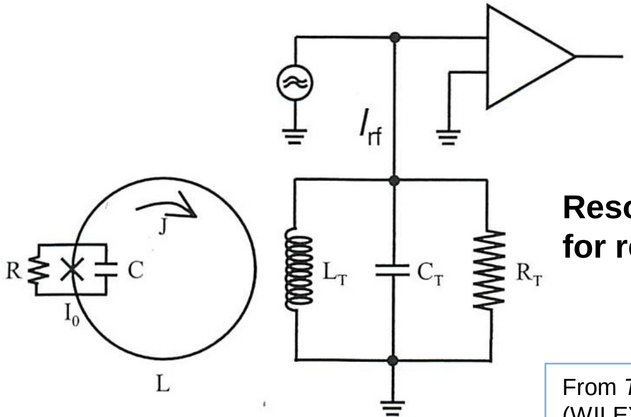
dc-SQUID



***I-V* curve**



***V-Φ* curve**



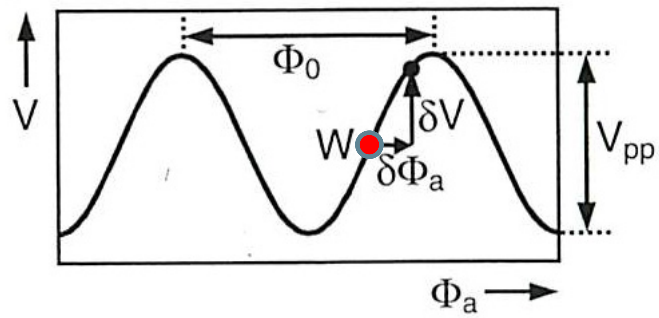
Resonant circuit for readout

From *The SQUID Handbook* (WILEY-VCH)

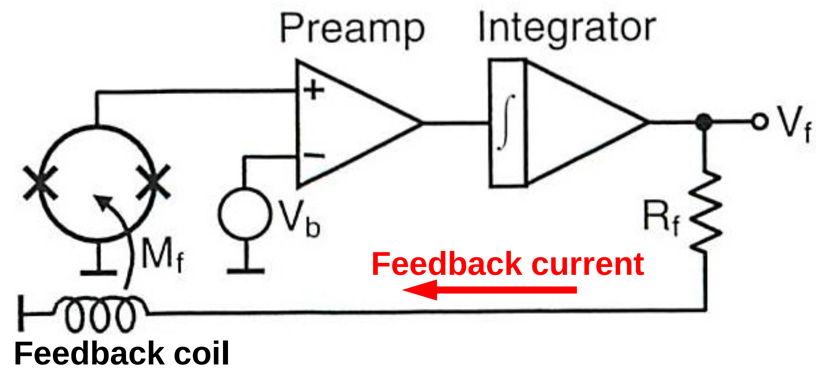
rf-SQUID

1. Fundamentals of SQUID
SQUID magnetic sensor

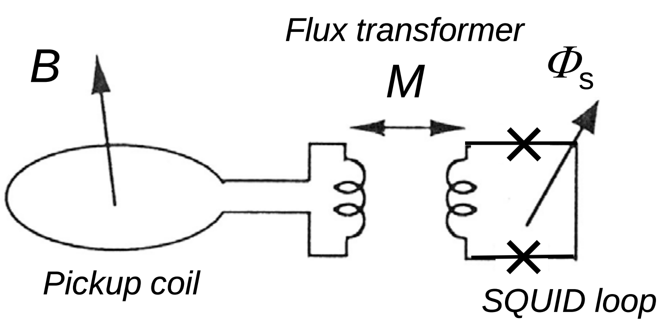
From *The SQUID Handbook* (WILEY-VCH)



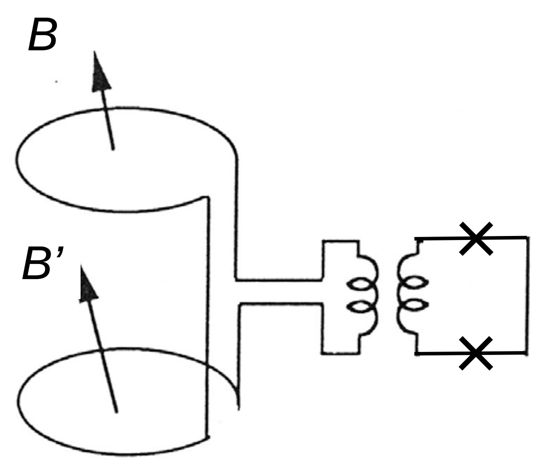
***V-Φ* curve**



Flux-Locked Loop (FLL) circuit



Magnetometer (B_z, ...)

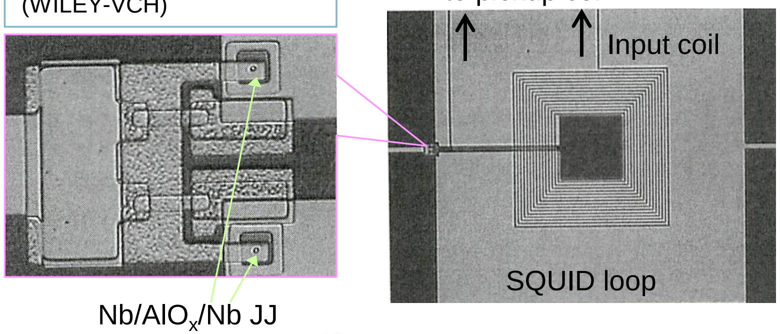


Gradiometer (dB_z/dz, ...)

1. Fundamentals of SQUID

Nb-based LTS SQUID

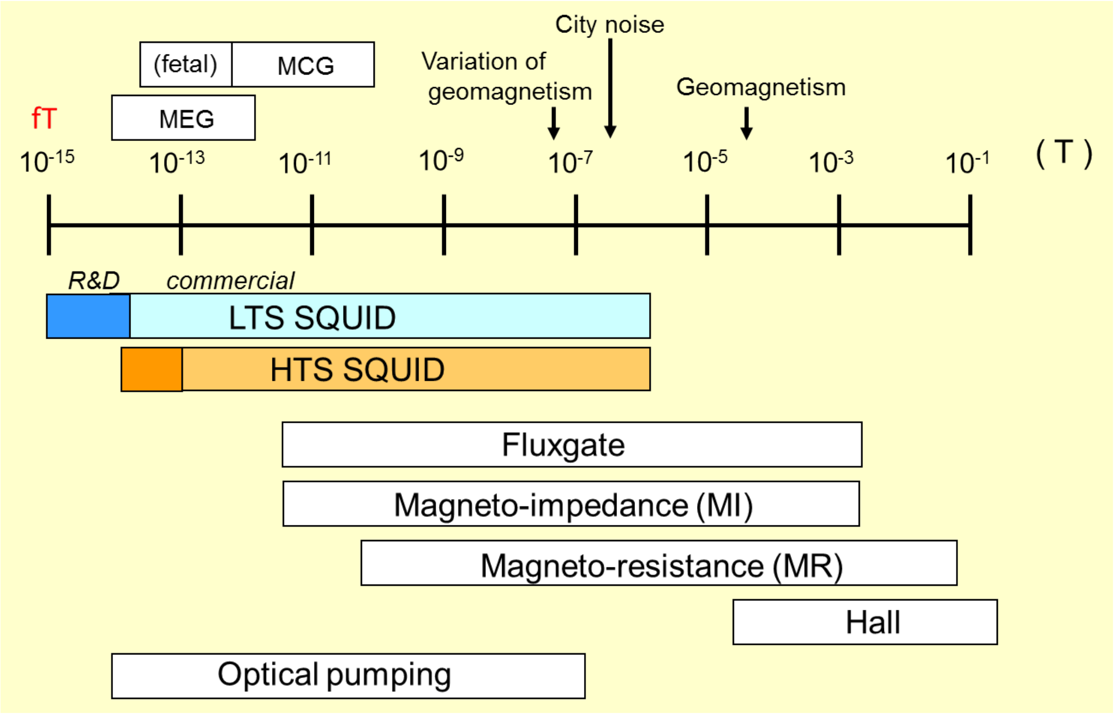
From *The SQUID Handbook* (WILEY-VCH)



160 ch Magnetoencephalography (MEG) system
Yokogawa Electric Corporation
(http://yokogawa.co.jp)

64 ch Magnetocardiography (MCG) system
Hitachi Ltd.

1. Fundamentals of SQUID
Features



- Higher sensitivity (Lower field noise)
- Wideband (constant sensitivity from dc to high frequency)
- Compact vector sensor
- Stable sensitivity
- Easy cooling with liq. N_2 <HTS SQUID> suitable to field use

IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January 2015.
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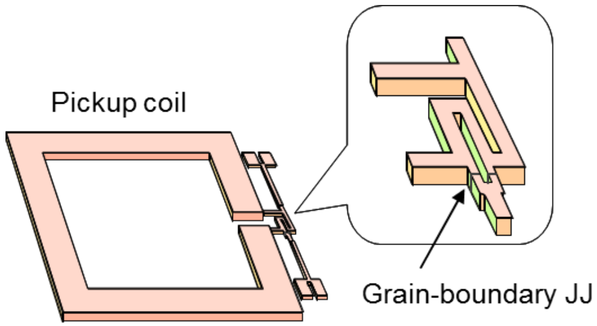
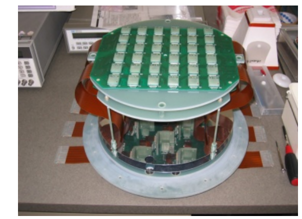
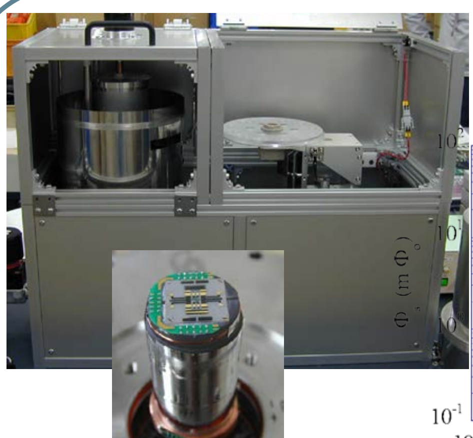
1. Fundamentals of SQUID
HTS SQUID; previous applications in Japan

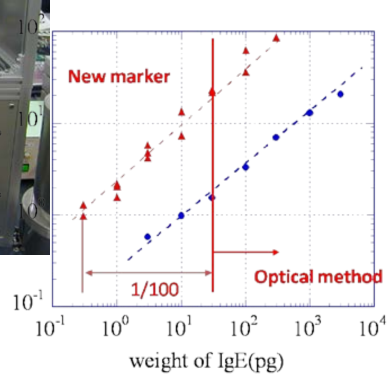


Conventional single-layer HTS SQUID



51 ch HTS MCG (Hitachi)





Magnetic immunoassay (Kyushu U, Hitachi)

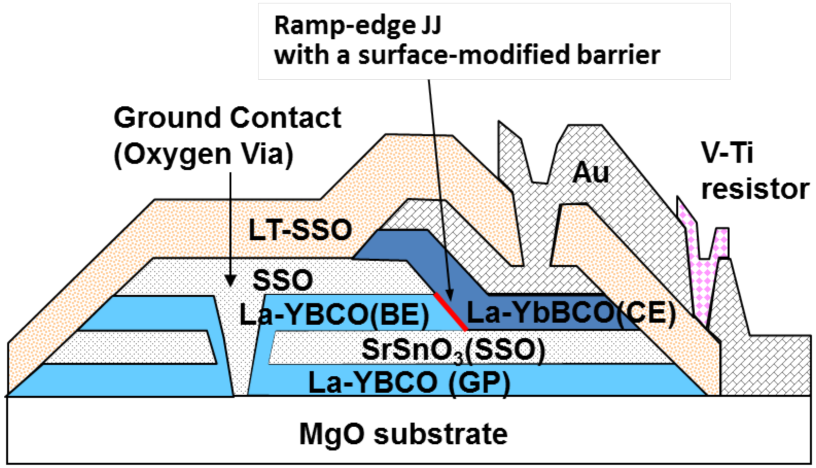
In marketplace!

Magnetic alien detection (TUT, SEI, AFT)

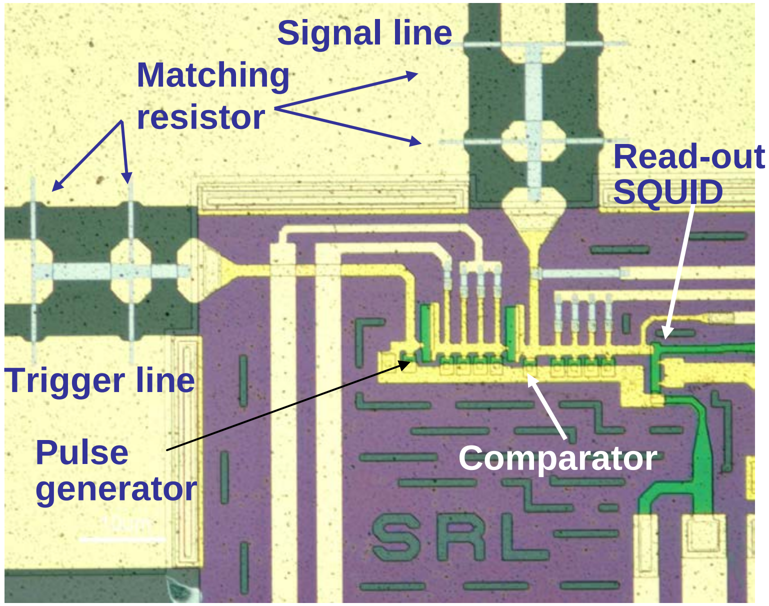
ULSI inspection system (NEC, Hamamatsu)

2. Multilayer HTS-SQUID developed at ISTEC
Underlying technology

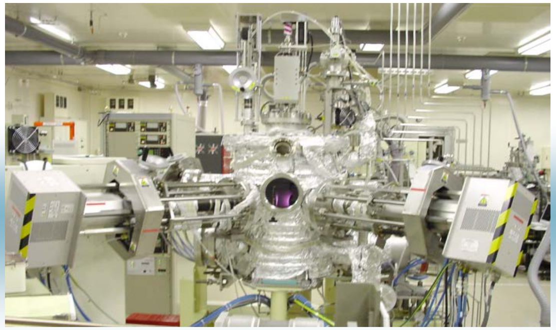
ISTEC



- 3 RE-123 layers with $SrSnO_3$ (SSO) insulator
  R_a of sputtered multilayer < 2 nm
- Ramp-edge-type JJs with 1σ I_c spread 5-10 %
- Minimum junction width of 1.5 μm



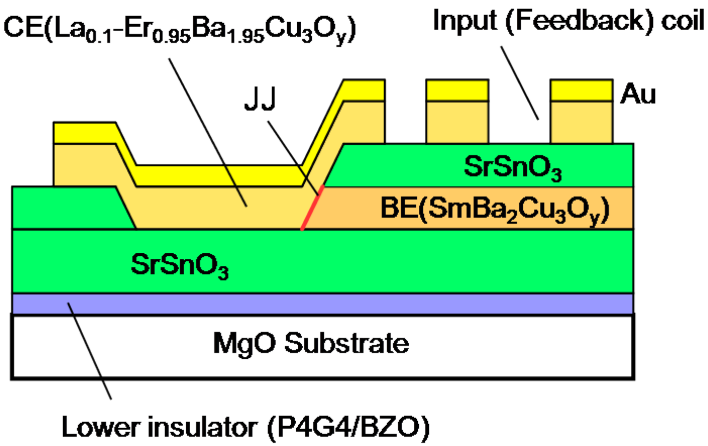
HTS Sampler circuit with a potential bandwidth over 100 GHz
(15 JJs integrated)



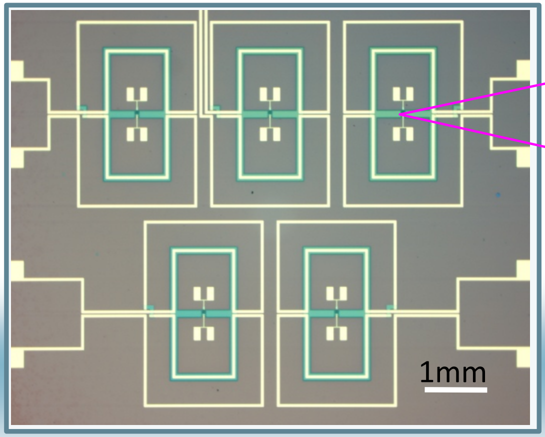
2. Multilayer HTS-SQUID developed at ISTEC
Structure and features

- **Modified multilayer process for HTS SQUIDs**

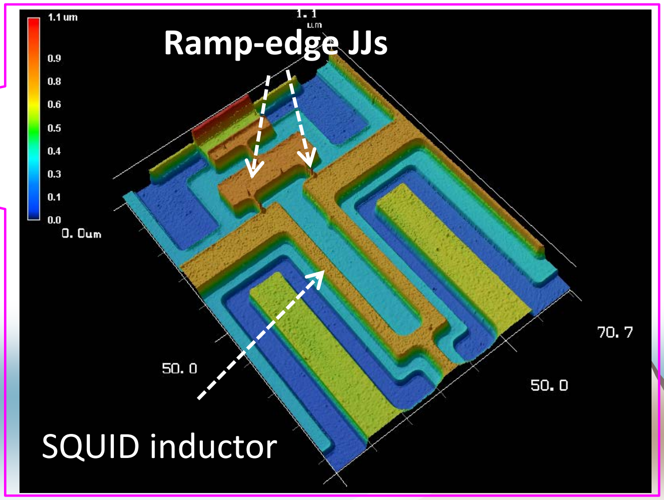
ISTEC



- SmBCO and La-ErBCO (T_c > 90 K) electrodes
- Deposition of thin Cu-deficient layer on ramp surface before upper HTS deposition
  ⇒ Stable operation at 77 K
- Lower black-color insulating layer (Ga-PBCO)
  ⇒ Higher uniformity of JJ properties on chip



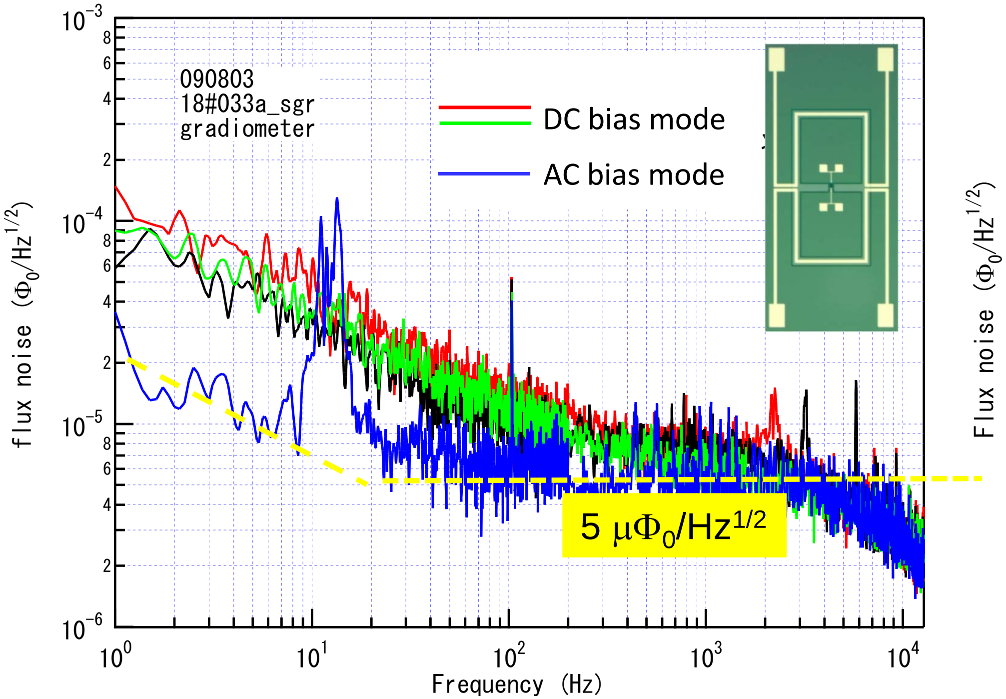
5-ch gradiometer array for NDE of CCs



2. Multilayer HTS-SQUID developed at ISTEC

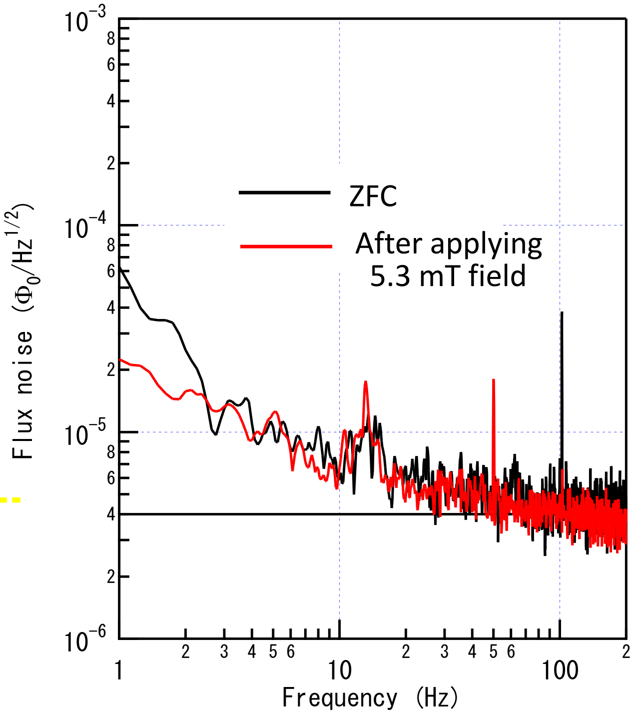
Performance

- Lower flux and field noise (higher sensitivity)
- Higher tolerance against application of magnetic field



Flux noise spectra taken with DC and AC bias mode

Flux noise (@ 1 kHz, 77 K) = 3 – 10 $\mu\Phi_0/Hz^{1/2}$

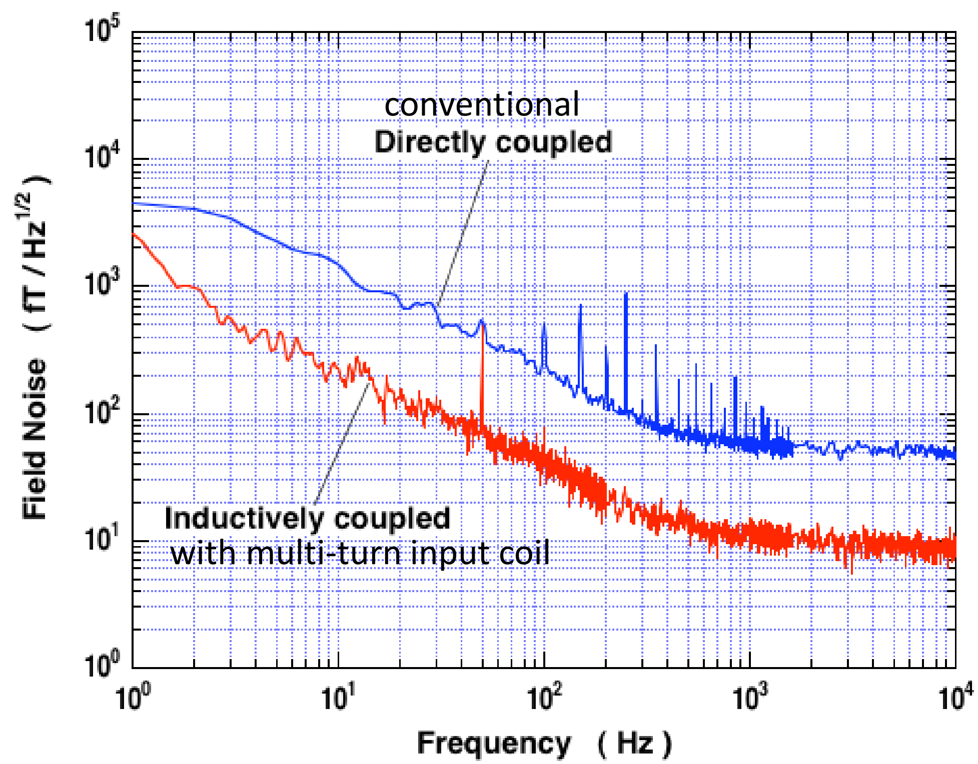


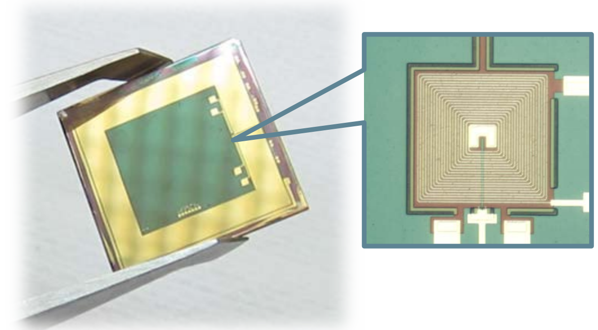
Flux noise spectra before and after applying AC magnetic field

No flux trapping after applying several mT field

2. Multilayer HTS-SQUID developed at ISTEC

Performance





50 fT/Hz$^{1/2}$

10 fT/Hz$^{1/2}$

X 5 improvement

3. Recent progress of application in Japan

(1) Applications using commercial rf SQUIDs

- Metallic contaminant detection (*Toyohashi University of Technology*)
- STM/SQUID microscope (*Osaka University*)

(2) JST S-innovation project

- Bio-sensing system

(3) JOGMEC projects

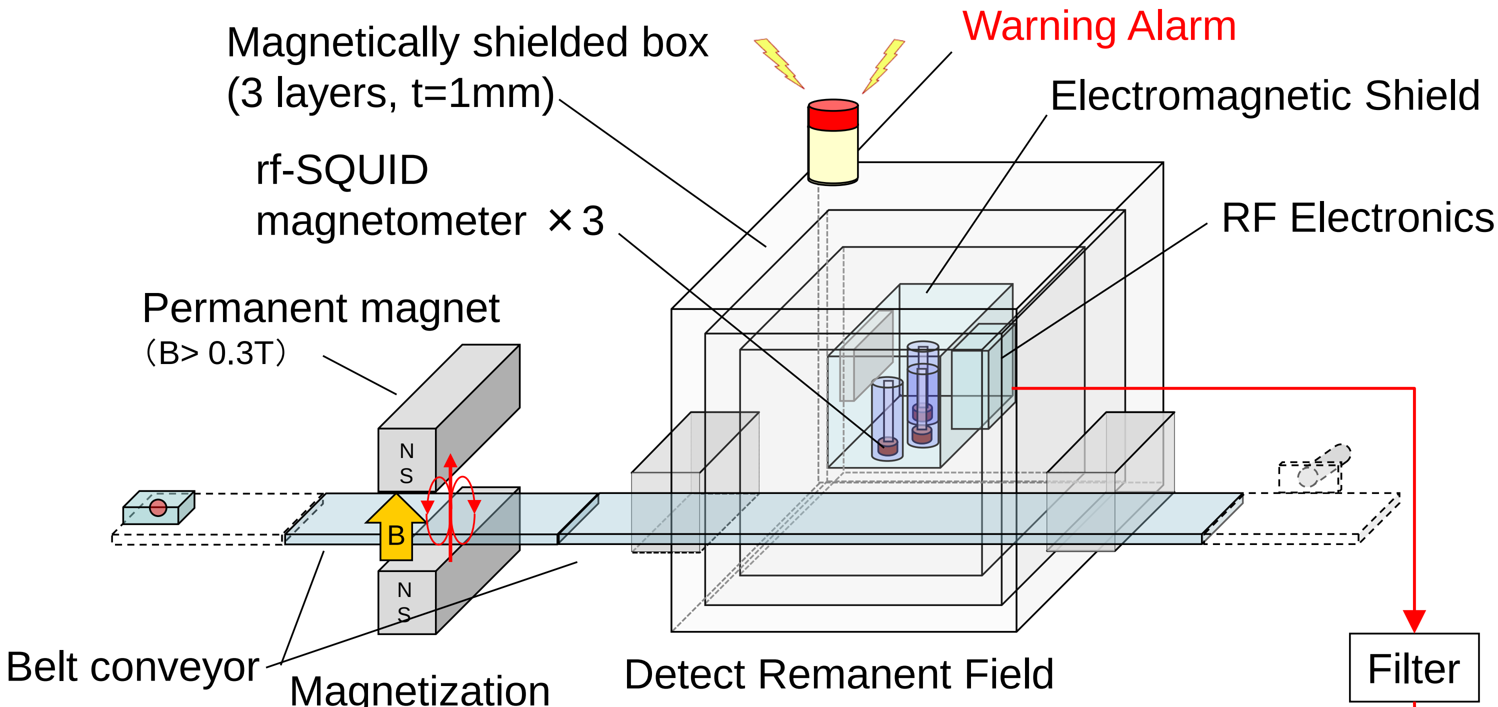
- SQUID-TEM system
- Magnetic survey system (gradiometer)
- Crosshole EM logging system

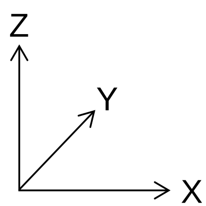
(4) JST SIP project

- Nondestructive evaluation system for infrastructure

(2)–(4): ISTEC dc SQUIDs

Metallic contaminant detection system for food inspection (Prof. S. Tanaka, TUT)

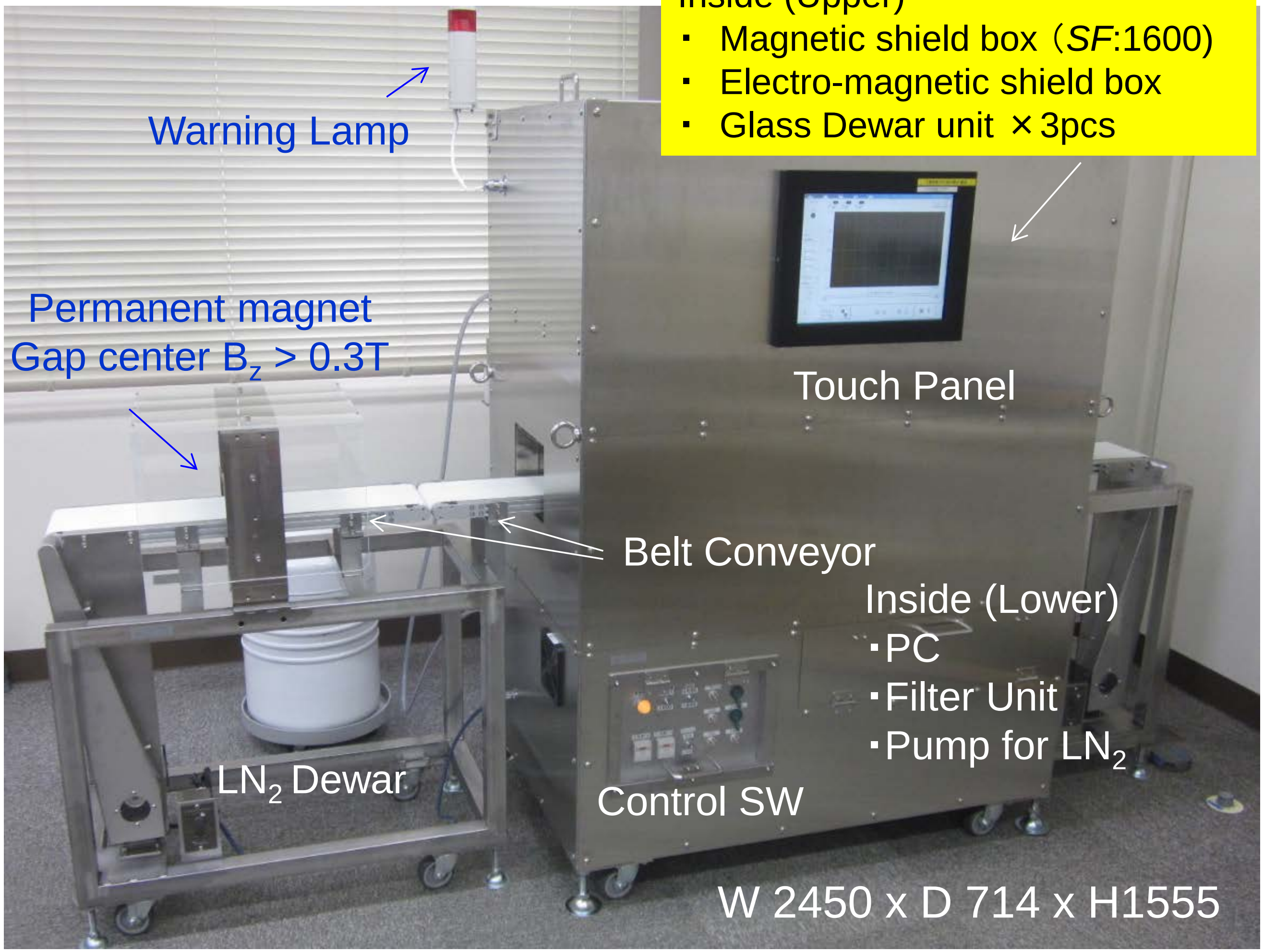




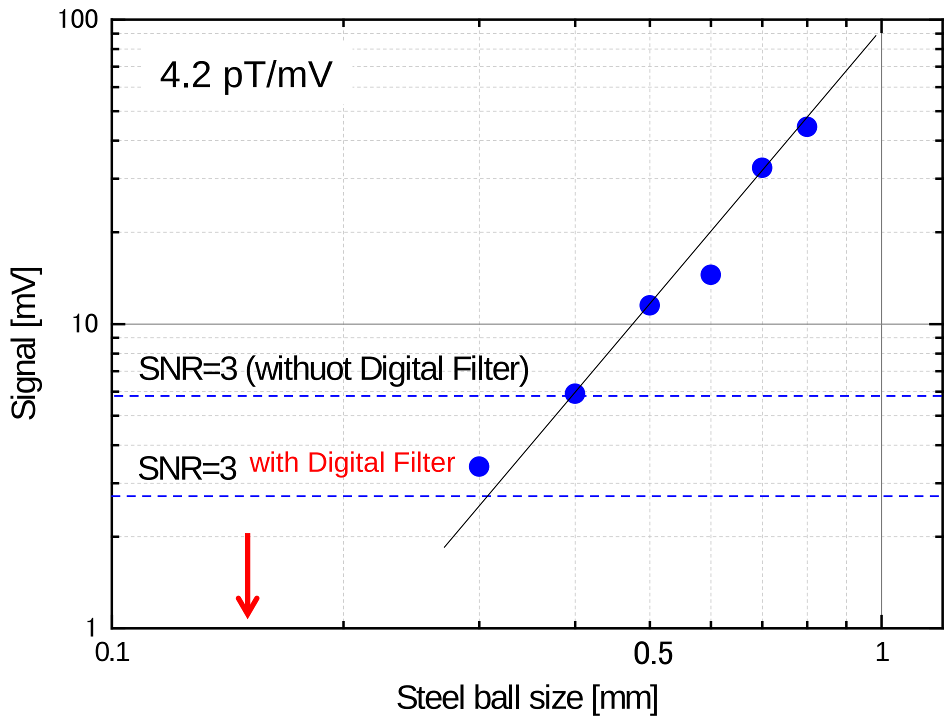
Targets of the development
- Detect metallic ball of less than ϕ0.5 mm (if possible ϕ0.3 mm).
- Stand-off Distance: > 100 mm for a thick package
- Automatic controlled.

PC / AD Board
Auto-adjustment program
Automatic detection program

Picture of the system

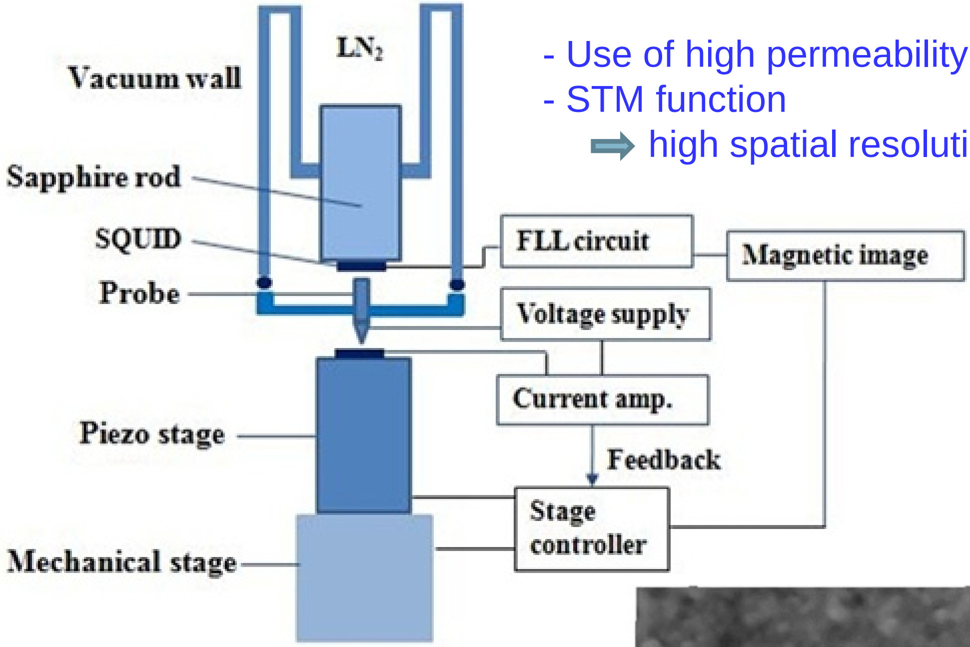


Signal – Steel Ball Size Relationship

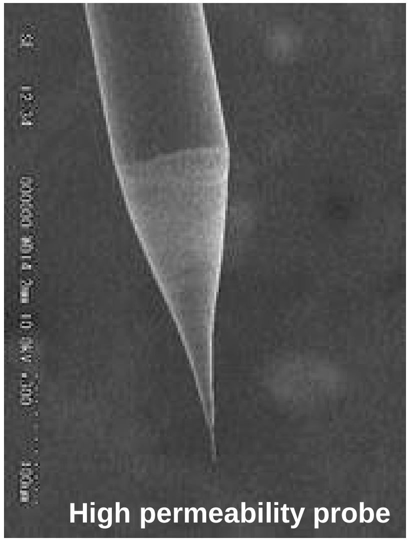


- A steel ball with a diameter as small as ϕ0.5 mm with a stand-off distance of 117 mm and a speed of 20 m/min was successfully detected with a SNR15.
- A steel ball with a diameter as small as ϕ0.3 mm was successfully detected with an SNR 4.5.

STM-SQUID magnetic microscope
Osaka University (Prof. Itozaki)

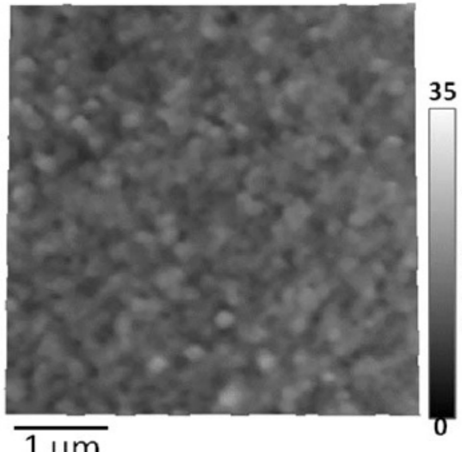


- Use of high permeability probe
- STM function
  ⇨ high spatial resolution

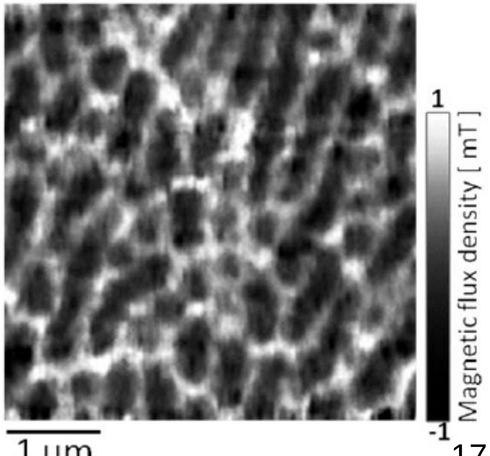


http://www.sup.ee.es.osaka-u.ac.jp/squid_4.html

OSAKA UNIVERSITY



STM image of Ni film



Magnetic image

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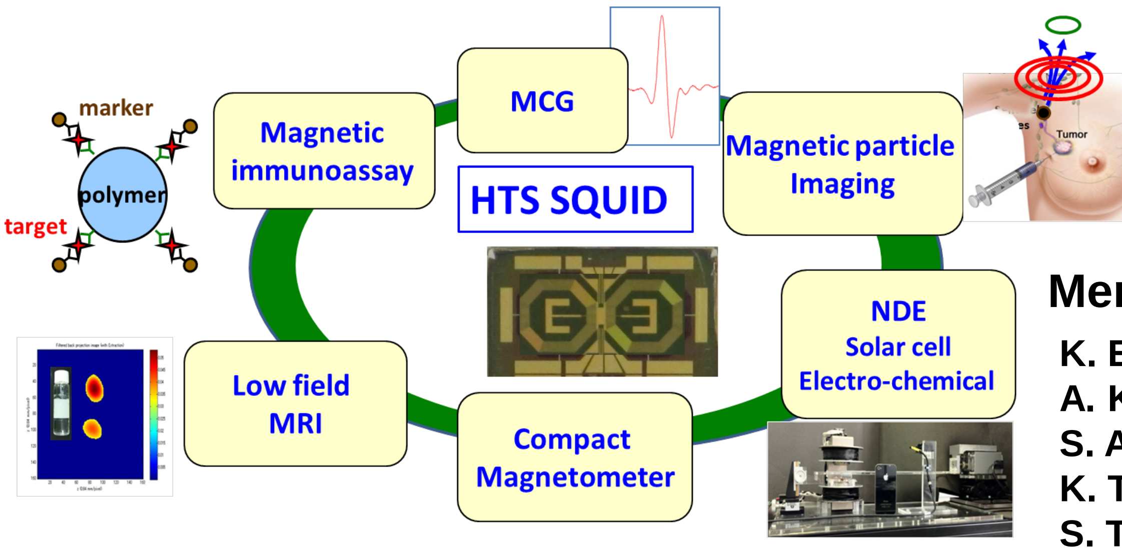
S-innovation SQUID project

- HTS SQUID systems for biomedical and NDE application -

Research Leader: K. Enpuku (Kyushu Univ.)

Development Leader: A. Kandori (Hitachi, Ltd.)



Foundation from JST

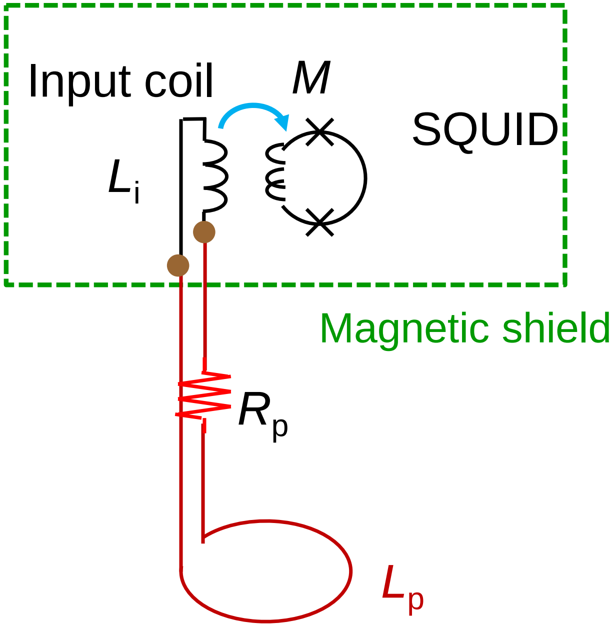
Total Budget: $8M

Member:

- K. Enpuku (Kyushu Univ.)
- A. Kandori (Hitachi, Ltd.)
- S. Adachi (ISTEC)
- K. Tsukada (Okayama Univ.)
- S. Tanaka (Toyohashi Univ. Tech.)

FY	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
STAGE		STAGE I (2010–2011) Elemental Technologies		STAGE II (2012–2015) Applications				Products STAGE III (2016–2018)		

HTS-SQUID module for use with external pickup coil



- Flexible system design possible (use of normal metal pickup coil)
- High sensitivity expected at

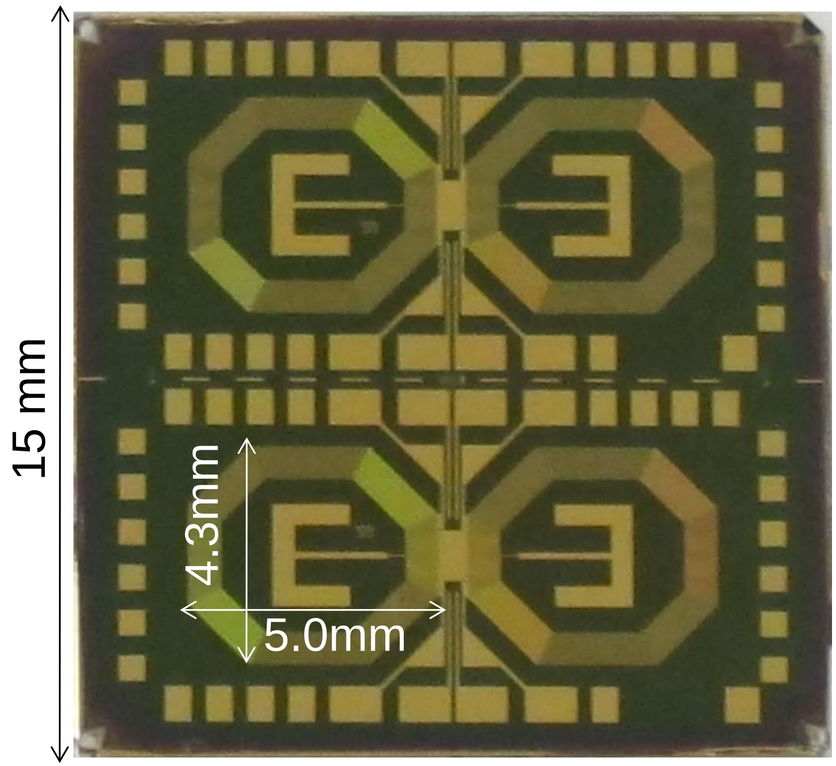
$$f > f_{cutoff} = R_p/2\pi(L_p+L_i)$$

- Higher field tolerance (use of magnetic shield for the module)

A. Tsukamoto *et al.*, Supercond. Sci. Technol. **26**, 015013 (2013).

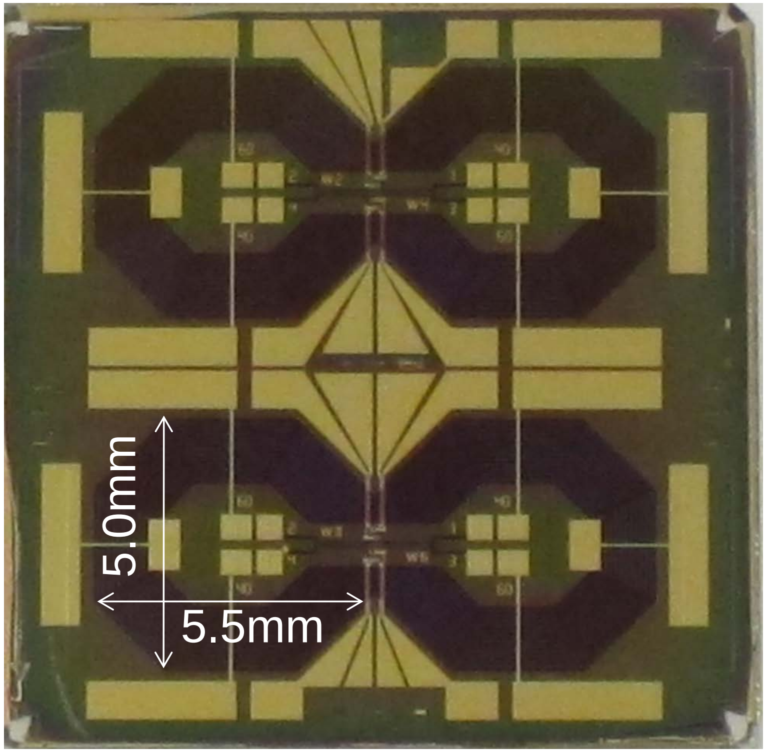
HTS-SQUID module for use with external pickup coil

ISTEC



Input coil chip

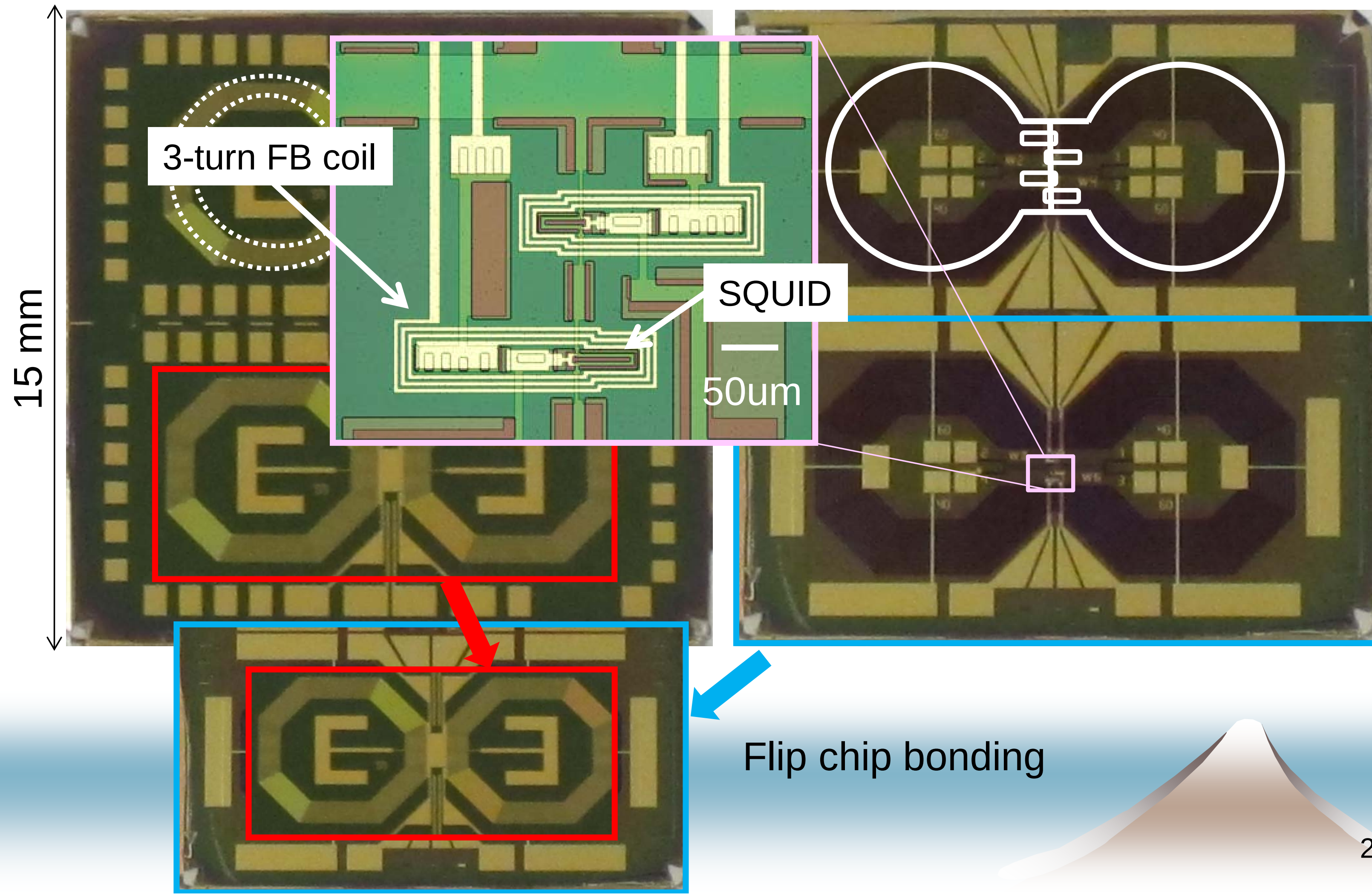
Number of turns(N_i)= 26 or 59 turns



SQUID chip

SQUID inductance(L_{SQ})=40 or 60 pH

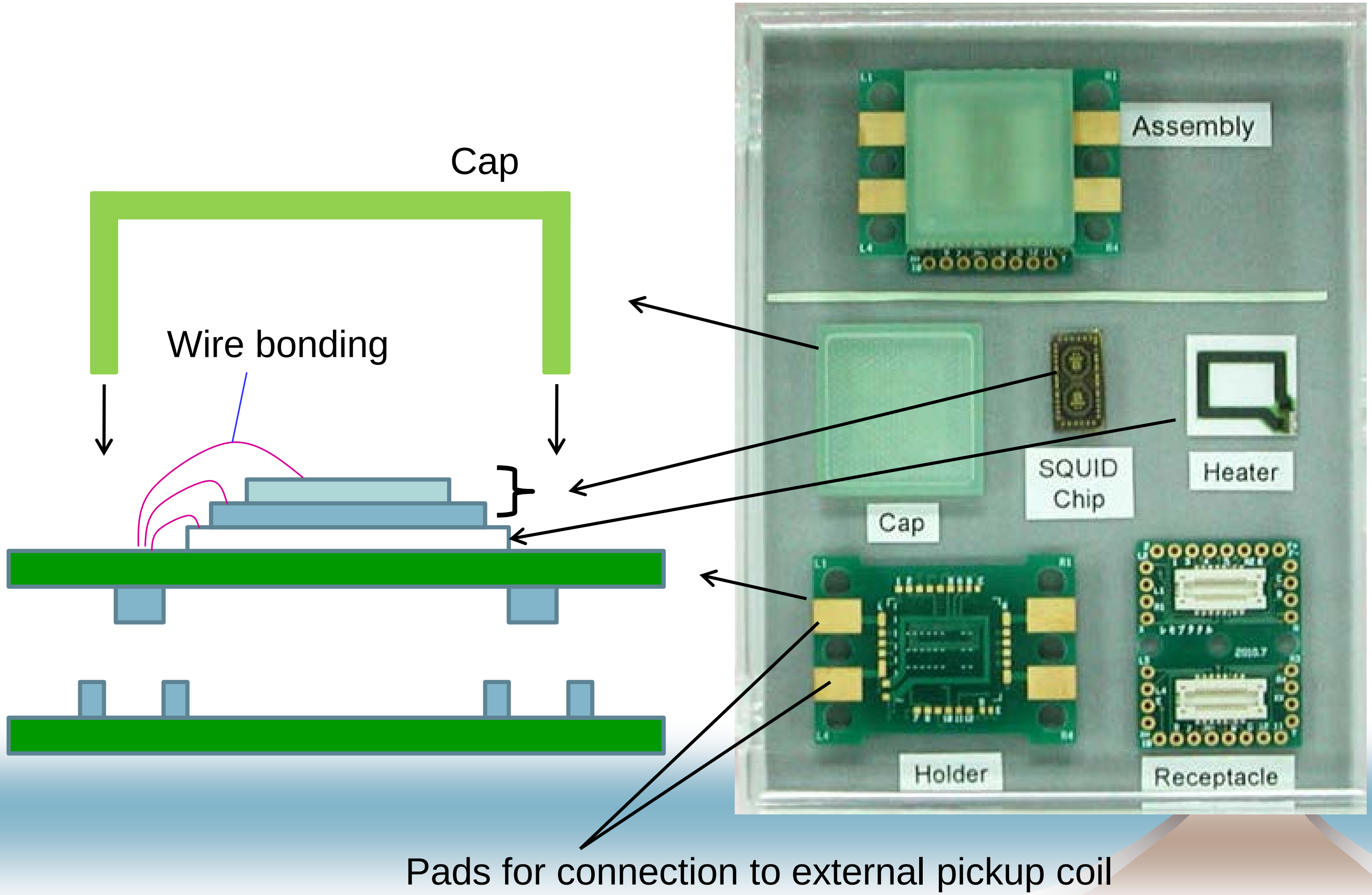
HTS-SQUID module for use with external pickup coil



Flip chip bonding

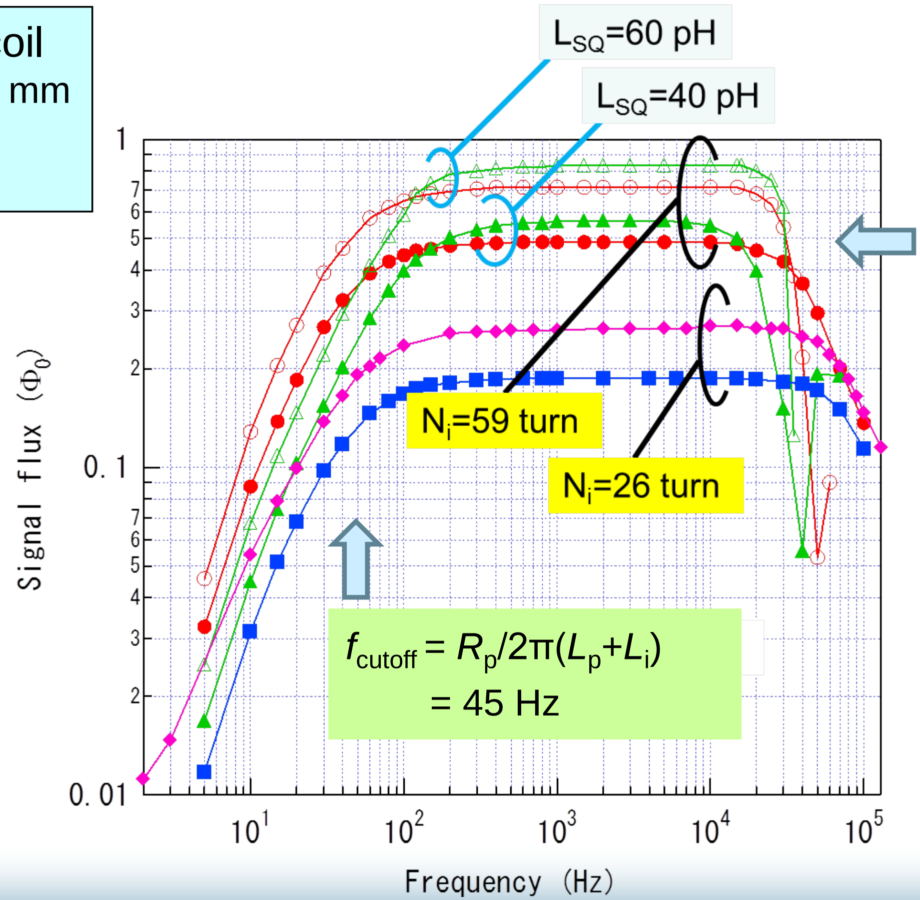
HTS-SQUID module for use with external pickup coil

ISTEC



HTS-SQUID module for use with external pickup coil

Litz wire pickup coil
N_p=150、D_{in}=Φ 40 mm
R_p= 0.28 Ω @77K
L_p= 968 μH @77K

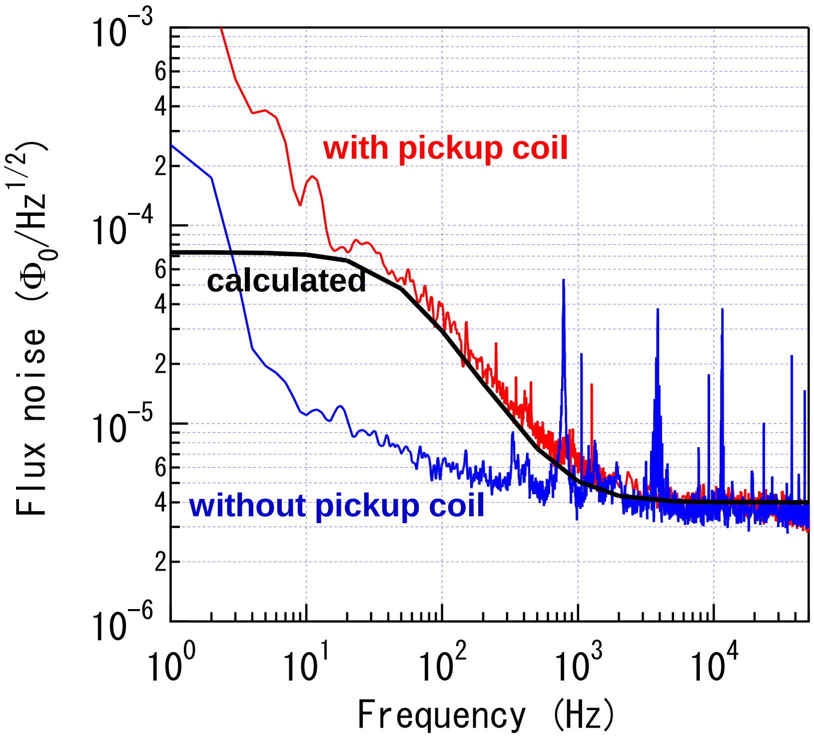


M_i = 1.38 nH
A_{eff} = 0.25 mm²

A. Tsukamoto *et al.*, Supercond. Sci. Technol. **26**, 015013 (2013).

Frequency dependence of observed signal flux for sensor with normal metal pickup coil

HTS-SQUID module for use with external pickup coil



35 fT/Hz$^{1/2}$

A. Tsukamoto *et al.*, Supercond. Sci. Technol. **26**, 015013 (2013).

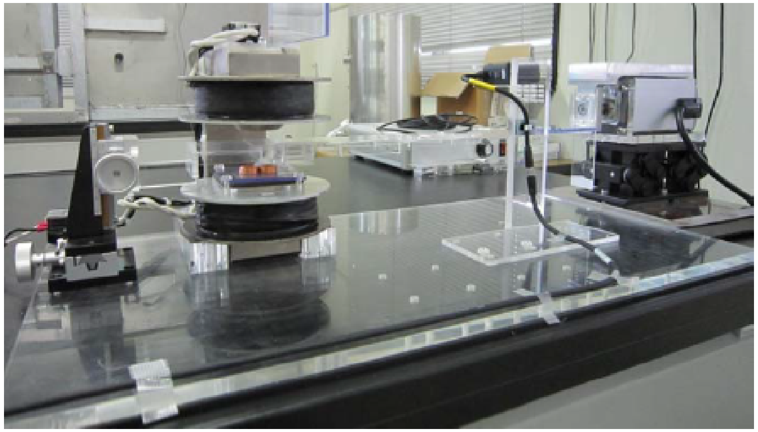
Flux noise spectrum for sensor with normal metal pickup coil

$$\sqrt{S_{\Phi(\mathrm{total})}}=(M_i^2\cdot(4k_BTR_p)/(R_p^2+(\omega(L_p+L_i))^2)+S_{\Phi(\mathrm{SQUID})})^{1/2}$$

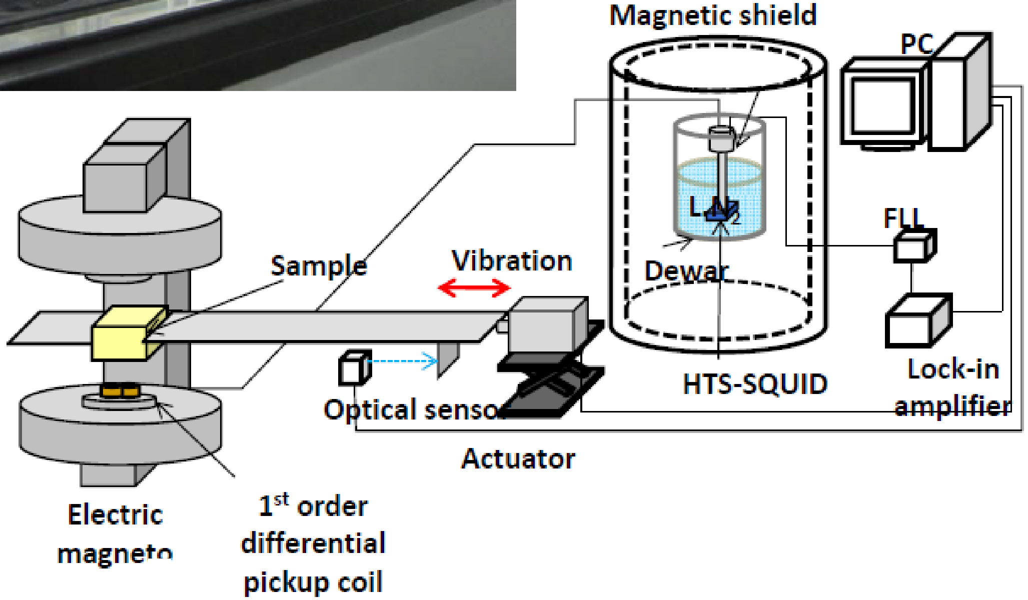
Parameters of calculation: R_p=0.28 Ω and $\sqrt{S_{\Phi(\mathrm{SQUID})}}$ = 4 μΦ_0/√Hz

Application of HTS-SQUID module
Compact dc magnetometer

OKAYAMA UNIV.



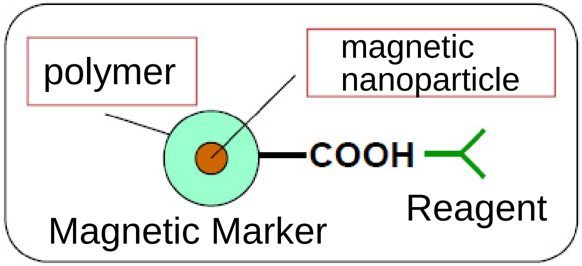
Sensitivity: 10^{-7} emu (vibration type)
x10 better than VSM
7×10^{-9} emu (rotation type)
x 100 better than VSM

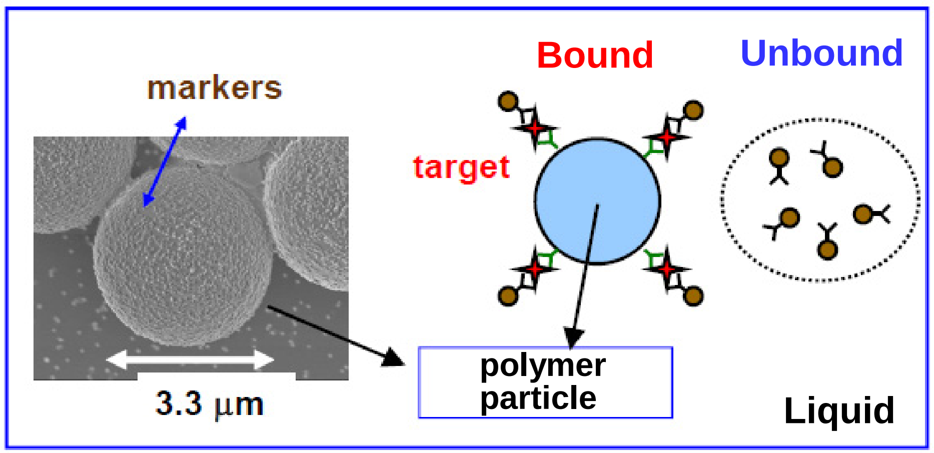


M. M. Saari, et al. IEEE Appl. Supercond. Vol. 23, No. 3 (2013)

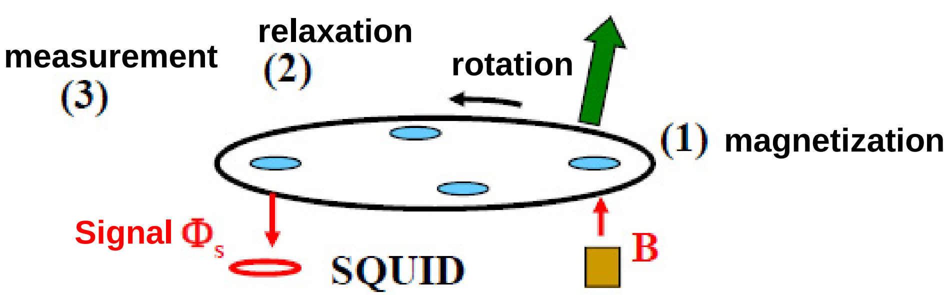
Application of HTS-SQUID
Magnetic immunoassay

KYUSHU UNIVERSITY



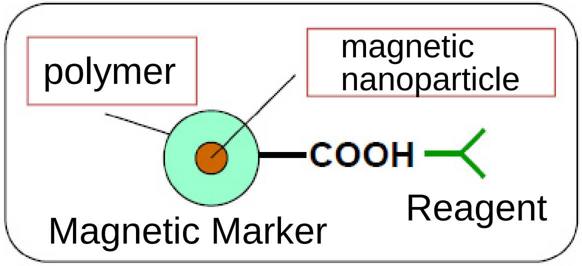


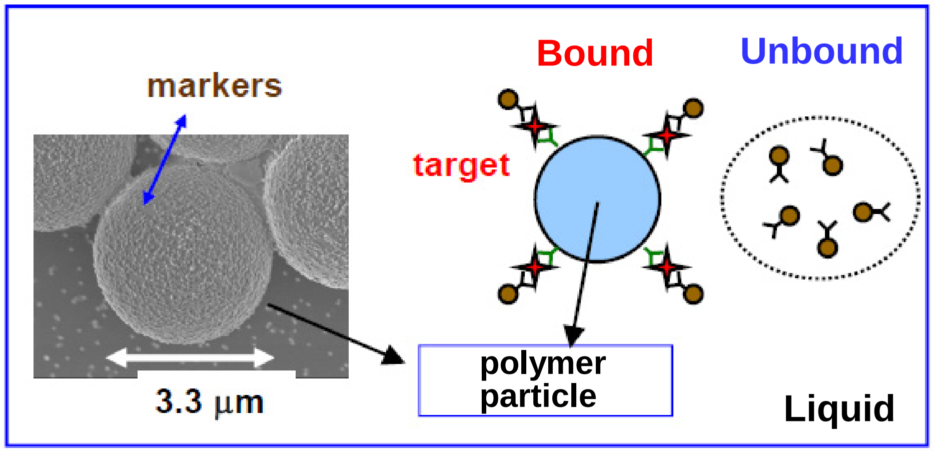
targets:
disease-related protein
bacteria
cancer cell
environmental toxin
DNA

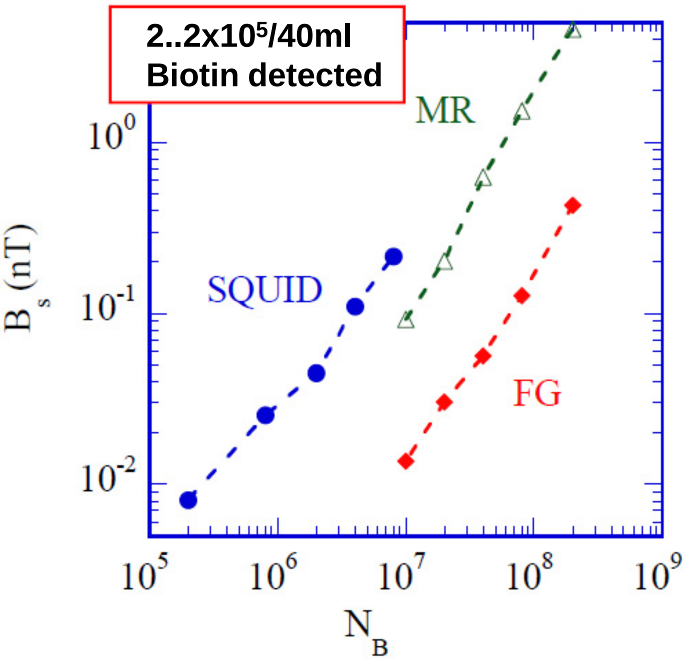


Application of HTS-SQUID
Magnetic immunoassays

KYUSHU UNIVERSITY





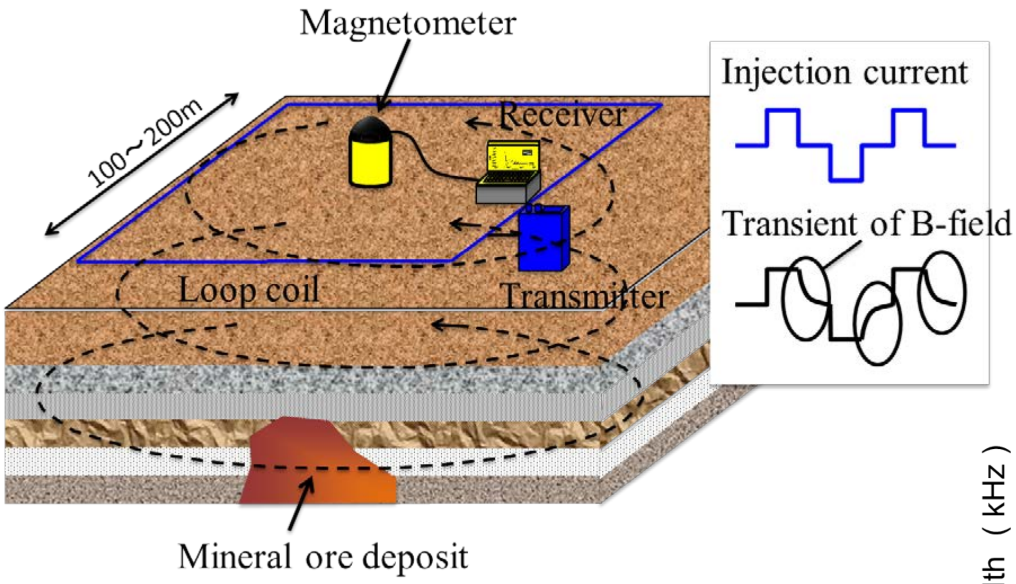


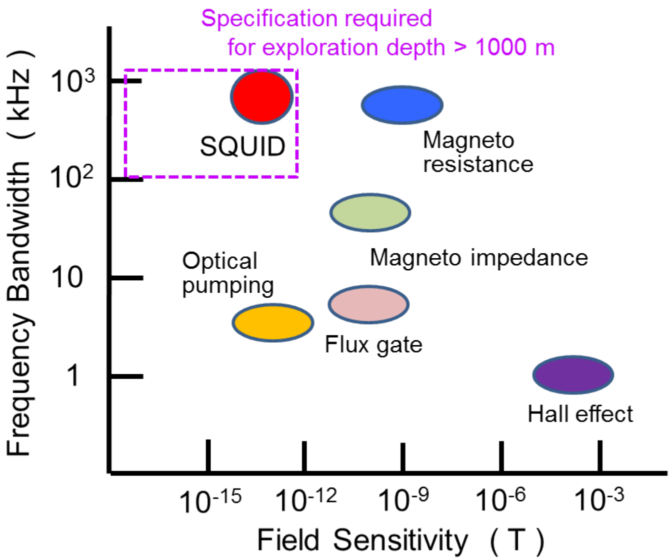
Detected signal vs. number of biotin

Prototype system using HTS-SQUID module is being developed by Hitachi, Kyushu Univ., and ISTEC.

JOGMEC Next-generation SQUITEM project

- SQUID-TEM system for exploration of metal resources-





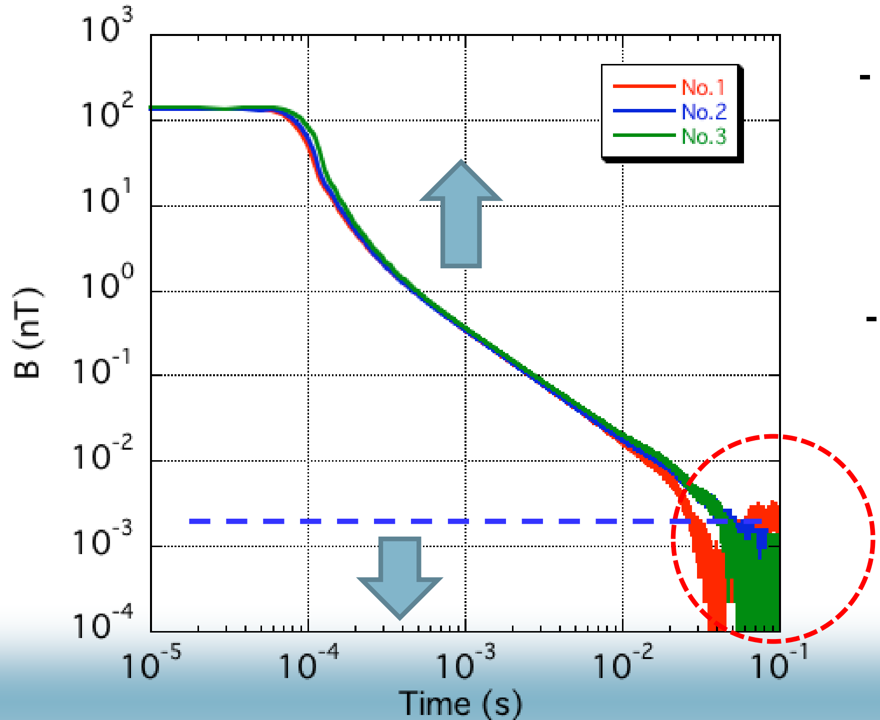
Transient Electro-Magnetic (TEM) method

- Conventional TEM: induction coil as a sensor
- Direct measurement of field (not d*B*/d*t*) by SQUID with higher sensitivity and wide bandwidth enables exploration of deeper mineral ore body

JOGMEC Next-generation SQUITEM project

- SQUID-TEM system for exploration of metal resources-

- SQUITEM2 system previously developed by JOGMEC and Sumitomo SS.
- Development of next-generation system (SQUITEM3) FY2009-2012
  better exploration depth, more compact



- Increase signal level by applying higher loop current

higher tolerance against d*B*/d*t* (slew rate) required

- Decrease sensor noise level

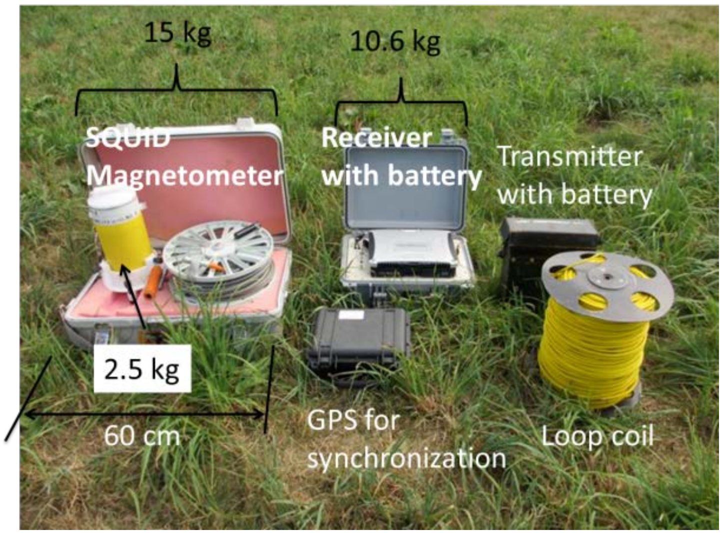
Multilayer HTS SQUID

JOGMEC Next-generation SQUITEM project

- SQUID-TEM system for exploration of metal resources-

Details: FD-3, T. Hato (Tuesday afternoon)

ISTEC MINDECO JOGMEC



SQUITEM3 system

SQUID magnetometer: ISTEC

Receiver: MINDECO

SQUID type:	DC-SQUID 1 channel
Environment for use:	Sea level 0m～6000m Temp. -20℃～55 ℃
Max loop current（100m square loop）	>40A
Frequency band:	DC～ 50kHz (100kHz 24bit sampling)
Slew rate:	10.5mT/s
Field noise:	30fT/√Hz @10kHz
Electricity consumption:	0.96W
Duration of battery:	17h
Capacity of LN_2:	1L
Duration of LN_2:	17h（Standing） >8h（Field operation）
Size of magnetometer:	134mmϕ 300mmH 2.5kg
Total weight :	25.6kg
(Magnetometer, FLL, Receiver, Connecting cable)	

Specification of SQUITEM3 system

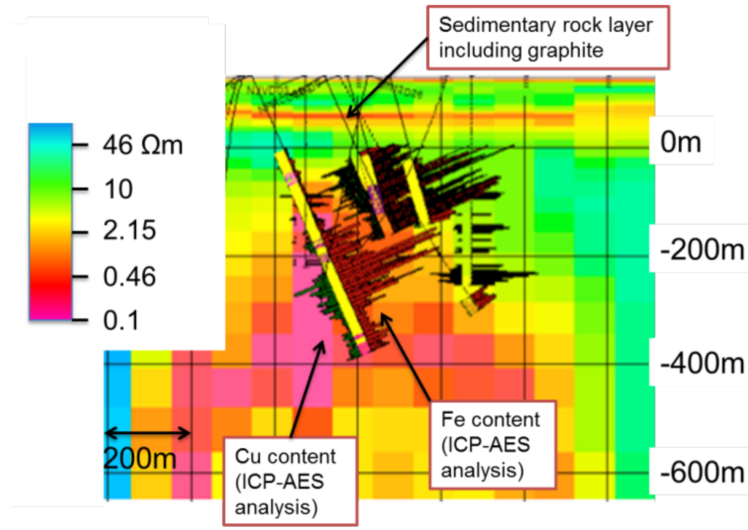
- One person can carry the SQUID magnetometer and receiver
- Full day use with 1L liq. nitrogen
- Slew rate (10.5 mT/s) x10 better than SQUITEM2
  owing to ISTEC multilayer SQUID, optimization of feed-back circuit,
  optimized rf shielding

JOGMEC Next-generation SQUITEM project

- SQUID-TEM system for exploration of metal resources-

ISTEC MINDECO JOGMEC

Field test in Australia (2012.10)



Resistivity distribution map

T. Hato *et al.*, Supercond. Sci. Technol. **26**, 115003 (2013).

Exploration in Peru (2014.1)

- Exploration performance better than conventional TEM confirmed
- Used in actual exploration of metal resources and geothermal reservoir
- Development of improved system (3-channel) started FY2014-2015

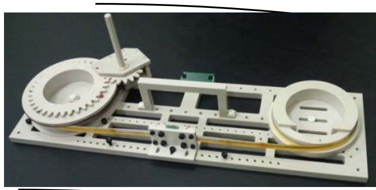
METI-JOGMEC SQUID gradiometer project

for magnetic prospecting of metal resources

Continuous measurement of gradient of the earth's magnetic field to find anomaly due to mineral ore body

ISTEC JOGMEC

Commissioned by METI and JOGMEC



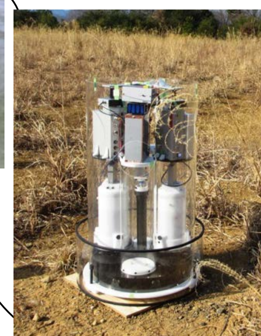
FY2010

Gradiometer using coated conductor coil

FY2011

Electronic gradiometer

FY2012



FY2013

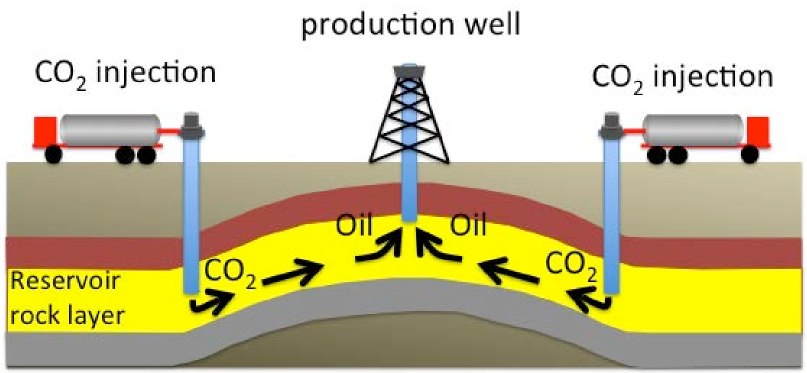
Electronic gradiometer
Thin-film gradiometer

FY2014

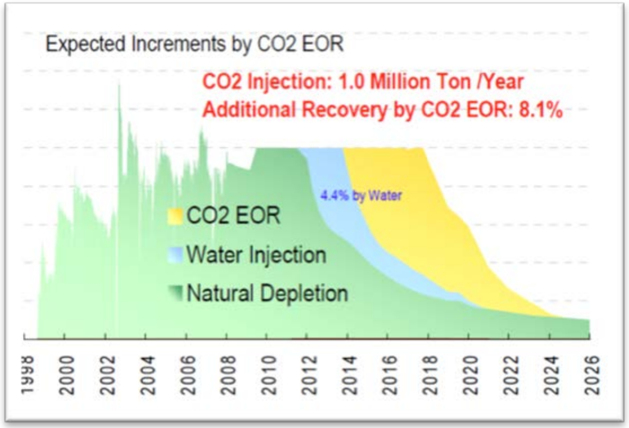
Compact mobile system

FY	2009	2010	2011	2012	2013	2014	2015	2016
STAGE		STAGE I **Elemental Technologies**			STAGE II **Practical system**			

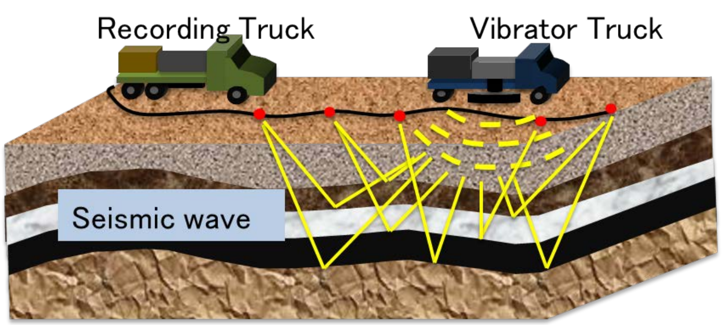
Development of crosshole EM system
- application to oil field -



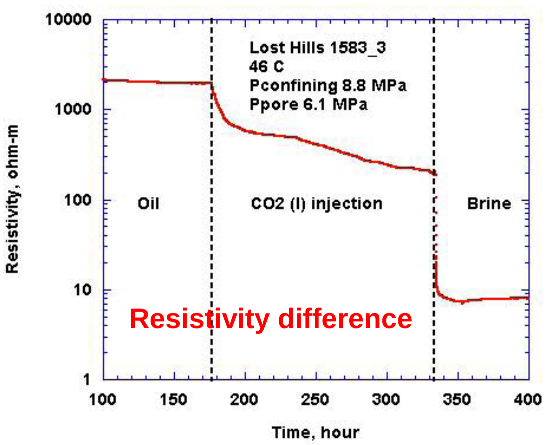
Schematic of enhanced oil recovery (EOR) technology utilizing CO_2.



Expected increments of oil production by CO_2 EOR



Combination of electromagnetic (EM) method with seismography and gravity survey could significantly Improve monitoring of CO_2 EOR.



B. Kirkendall, J. Roberts 2004
Lawrence Livermore National Lab.

Development of crosshole EM system
- application to oil field -

ISTEC MINDECO JOGMEC

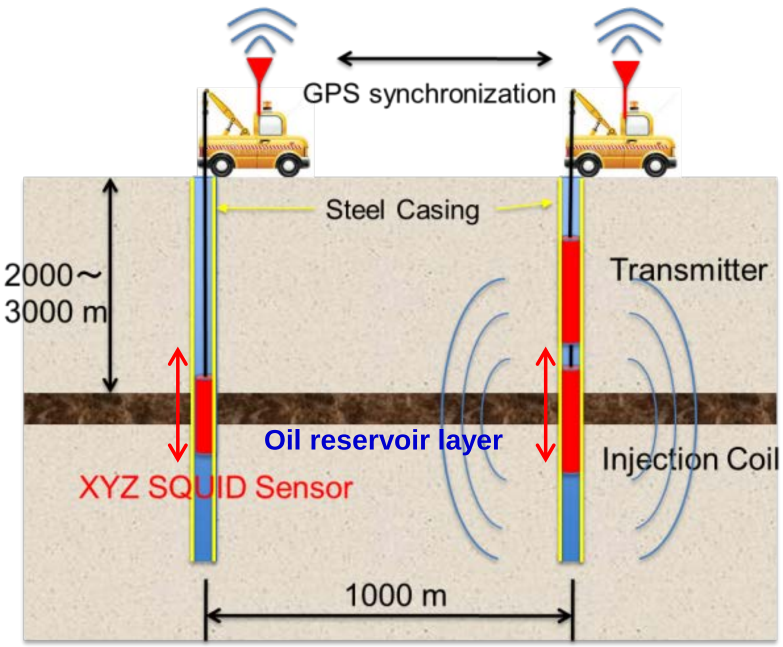


Image of crosshole EM (logging) system with HTS-SQUID magnetometer (Resistivity tomography between two wells)

- Insufficient sensitivity of conventional induction coil sensor ⟹ short distance
- Owing to high sensitivity of SQUID even at low frequencies

EM in steel-cased wells
with the distance > 1000 m expected

Technical challenges:

- Analysis technique to compensate influence of steel casing
- High-power transmitter & injection coil
- HTS-SQUID magnetometer usable in high pressure (30-70 MPa) and high temperature (250 ^{o}C) environment
- Remote control of SQUID magnetometer

Development of elementary technologies started in 2012
JOGMEC "Innovative technology in oil and gas development field" program

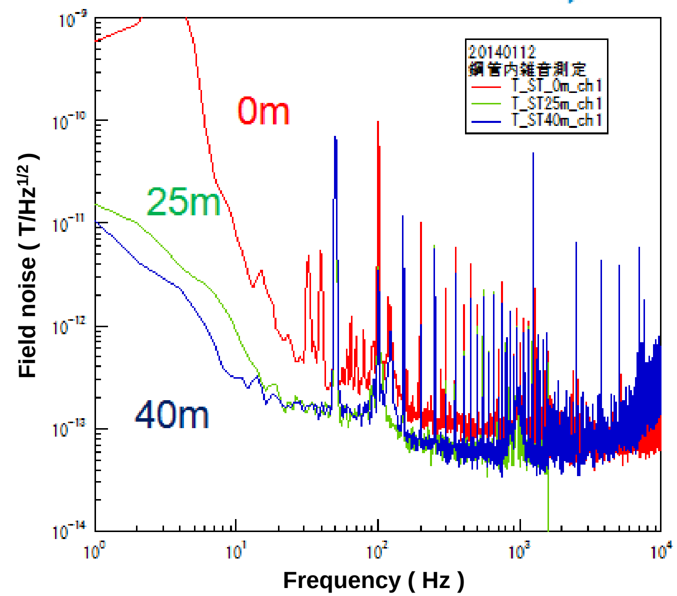
IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January 2015.
Plenary presentation PL-6-INV was given at ISS 2014, Tokyo, November 25 - 27, 2014.

Development of crosshole EM system

- Preliminary field test-

ISTEC MINDECO JOGMEC

At JOGMEC Kashiwazaki TF (Niigata Prefecture)



Noise spectra of SQUID in steel-cased well filled with water (at 0, 25, 40 m depth)

Field test in 1000 m-depth-class well scheduled next spring.

Cross-ministerial SIP (Strategic Innovation Promotion Program) FY2014-2018

operated by Council for Science, Technology and Innovation, Cabinet Office

10 selected important issues FY2014 Budget: 450 M$

next-generation power electronics, innovative structural materials, energy carrier,
next-generation survey technology for marine resources, automatic driving,
technology for maintenance, renewal, management of infrastructure, etc.

Program Director: Prof. Yohzo Fujino (Yokohama National University)

700,000 bridges, 100,000 tunnels many of them older than 50 years
huge maintenance cost has to be saved by technologies

44 proposals (NDE techniques, materials, robotics, ICT, asset management) adopted
supported by JST, NEDO

“Highly sensitive magnetic non-destructive evaluation
for deterioration evaluation and maintenance of infrastructure”

Highly sensitive magnetic nondestructive evaluation for deterioration evaluation and maintenance of infrastructure

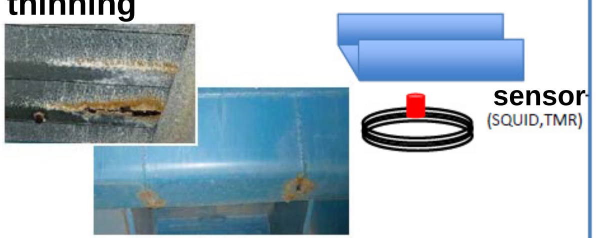
Project Leader: Prof. Keiji Tsukada (Okayama University)

Member: K. Tsukada (Okayama Univ.) remote pulse method, prototype system with TMR
K. Tanabe (ISTEC) SQUID-NDE system
T. Furukawa (JAPEIC) simulation, pulse ECT method with TMR
T. Sasayama (Kyushu Univ.) inverse problem

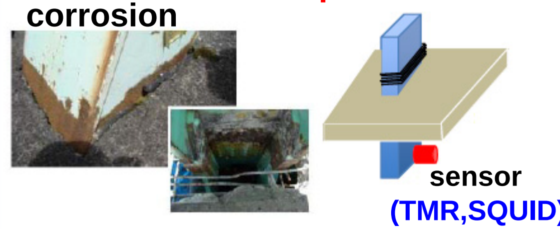
Supporting Member: Mitsui Engineering & Shipbuilding Co., Ltd.
Chugoku Electric Power Co., Inc.

NDE technique for thick steel, reinforcing rods under concrete , pipe

corrosion thinning — **pulse ECT method**



remote pulse method — **corrosion**



magnetic leakage flux method

invisible cracking — **sensor**

automatic scanning using robot

Development of compact SQUID-NDE system (ISTEC)

4. Summary and future prospects

- HTS-SQUID can be operated easily with liquid nitrogen. In particular, multilayer SQUID developed at ISTEC has higher sensitivity and tolerance to field application. These features are suitable to underground exploration and NDE.

- Recently many prototype or practical systems using HTS-SQUIDs have been developed in Japan. For example, SQUID-TEM system (SQUITEM3) has been used for actual exploration.

- Development of elementary technologies with the aim of application to oil field (monitoring of CO_2 EOR) and compact NDE system for infrastructure has started.

HTS-SQUID has almost reached a new stage where various field applications are viable.

4. Summary and future prospects

Possibilities of SQUID as a highly-sensitive magnetic sensor for underground resources

Technologies of
SQUID-TEM
EM logging

→

In the near future
- Survey of geothermal reservoir
- Oil storage monitoring
- CCS (CO_2 Capture and Storage) monitoring
- Geological disposal of radioactive waste
- Underground structure of architectures

In the future
- Survey of seabed resources
  - hydrothermal polymetallic ore
  - methane hydrate

Acknowledgments

ISTEC: T. Hato, A. Tsukamoto, S. Adachi, Y. Oshikubo, Y. Moon

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JOGMEC: M. Motoori, M. Sugisaki, T. Mouri, A. Kato, Y. Kunishi

Kyushu Univ.: K. Enpuku

Toyohashi UT: S. Tanaka

Okayama Univ.: K. Tsukada

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JOGMEC (Japan Oil, Gas and Metals National Corporation)
JST (Japan Science and Technology Agency)
NEDO (New Energy and Industrial Technology Development Organization)