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Oral presentation at IWSSD 2016. No manuscript was submitted for hardcopy journal publication.

IWSSD2016 (AIST, Tsukuba)
2016/11/14-17

Application of SUSTERA high-T_c SQUIDs at and under the ground

Keiichi Tanabe

Superconducting Sensing Technology Research Association

Collaborators

SUSTERA T. Hato, A. Tsukamoto, Y. Oshikubo, S. Adachi

Mitsui Mineral Development Engineering Co., Ltd. (MINDECO):
H. Watanabe, H. Ishikawa, C. Okada

MINDECO

Japan Oil, Gas and Metals National Corporation (JOGMEC) :
M. Harada, K. Yoshimatsu, Y. Kunishi, A. Kato

JOGMEC

Okayama University: K. Tsukada, K. Sakai

OKAYAMA UNIVERSITY

Kyushu University: K. Enpuku, T. Sasayama

KYUSHU UNIVERSITY

Japan Power Engineering and Inspection Corporation (JAPEIC):
Weiying Cheng

JAPEIC JAPAN POWER ENGINEERING AND INSPECTION CORPORATION

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Introduction of SUSTERA

ISTEC (founded in 1988) → dissolved in June, 2016

HTS Conductor Processing & Power Application Division → merge (April, 2016) → **AIST** Research Institute for Energy Conservation

Superconductivity Research Laboratory

Materials/Physics & Electronic Devices Division (HTS-SQUIDs) → transfer → **SUSTERA** (founded in February, 2016)

SUSTERA is the mutual aid organization (nonprofit organization) in which members conduct collaborative research on the sensing technology based on HTS-SQUIDs.

Initial members:
+ Fujitsu Ltd.
+ The Chugoku Electric Power Co., Inc.
+ MINDECO
+ ISTEC (until June, 2016)

Products: HTS-SQUID chip (module), compact cryostat

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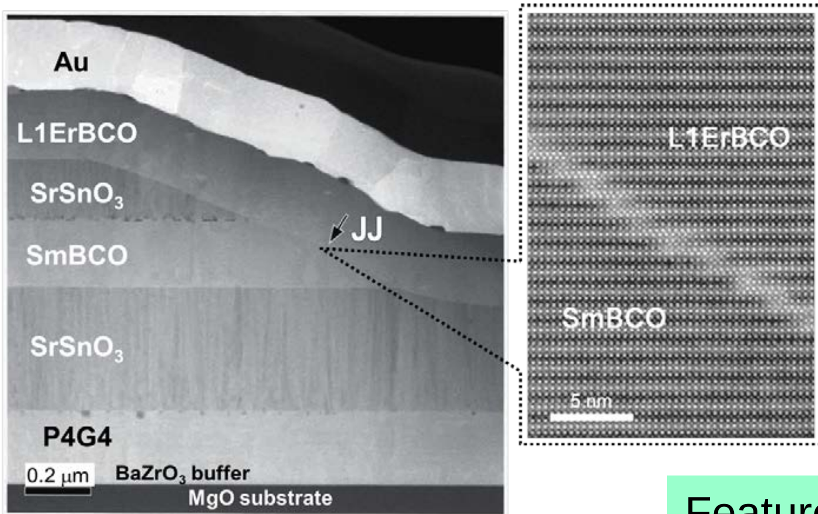
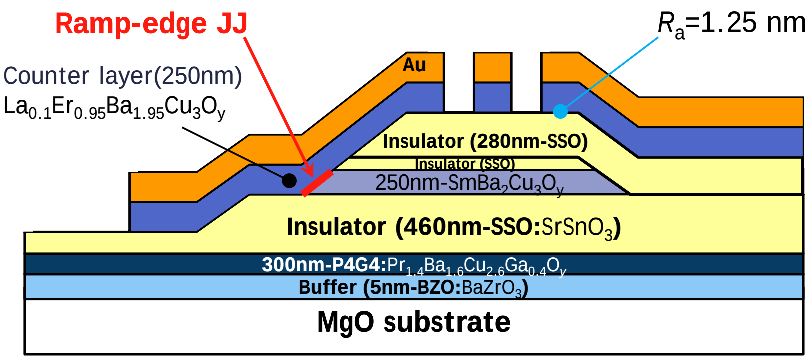
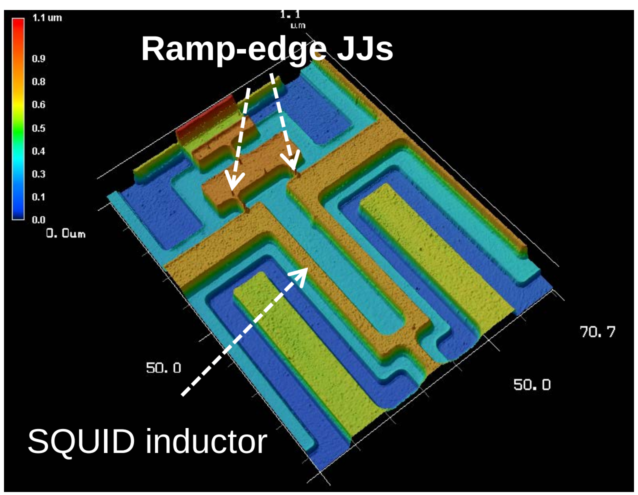
HTS SQUIDs with multilayer structure and ramp-edge JJs (2007～)







Features

*Integrated circuit structure with several oxide layers
*High-angle GB is eliminated from JJs and coils

Advantages

*Stable operation at 77 K
*Easy to fabricate multi-channel array sensor
*Robust against application of magnetic field
*High field sensitivity approaching LTS SQUIDs

SUSTERA ISTEC

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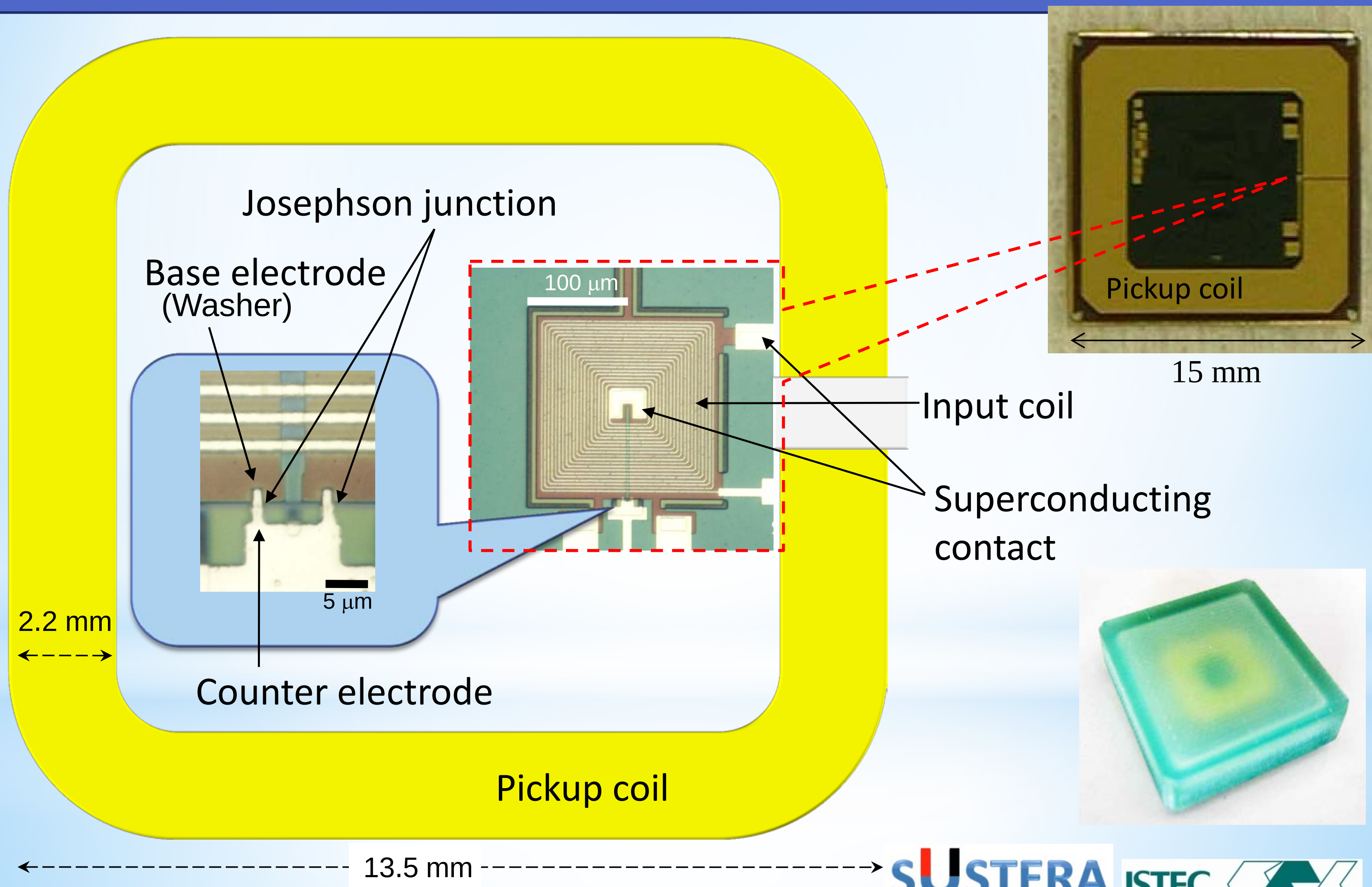
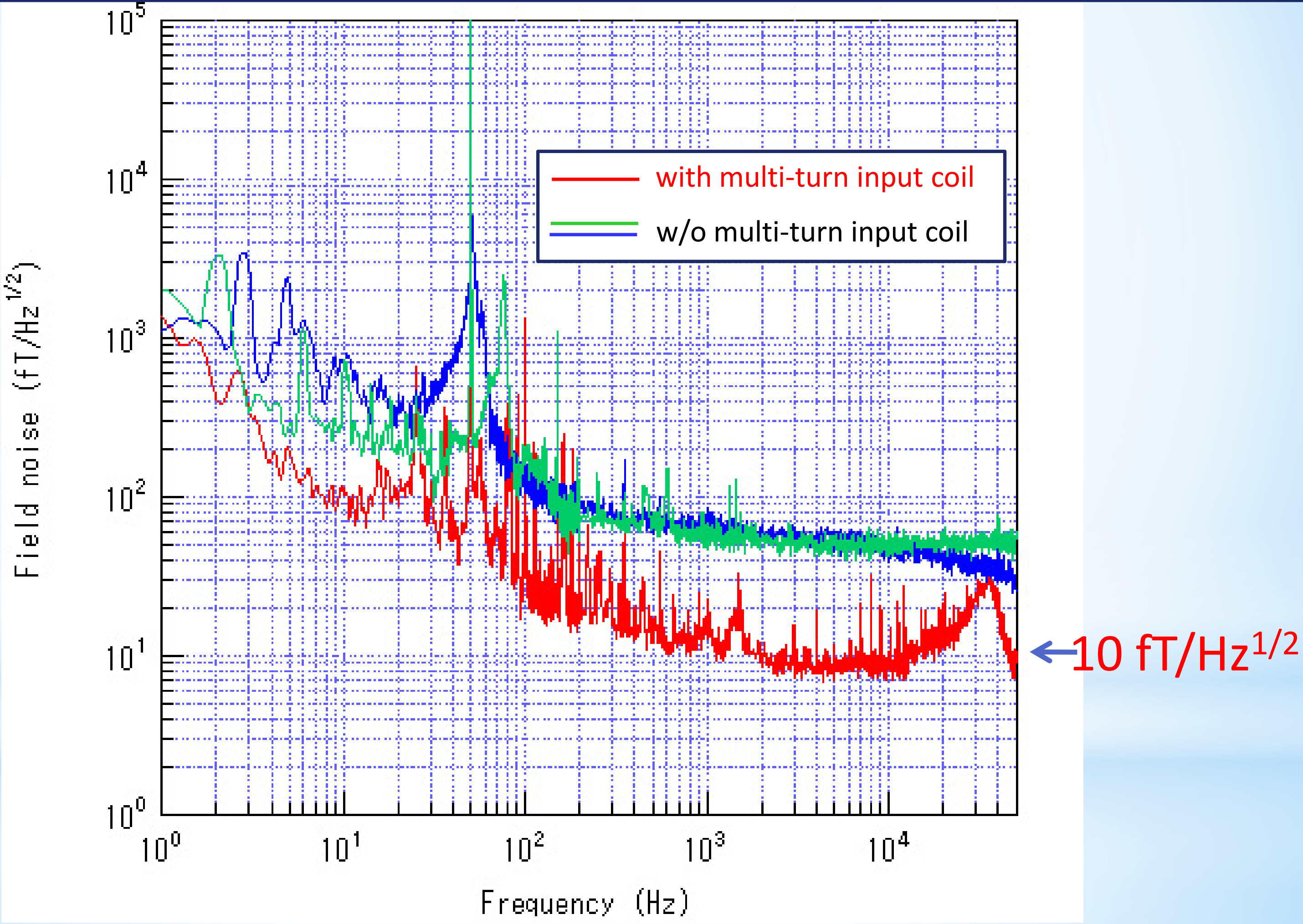
Magnetometer with multi-turn input coil



Magnetometer with multi-turn input coil



Field noise spectra in Earth's magnetic field

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SQUITEM-III system

for exploration of metal resources

\# Compact design

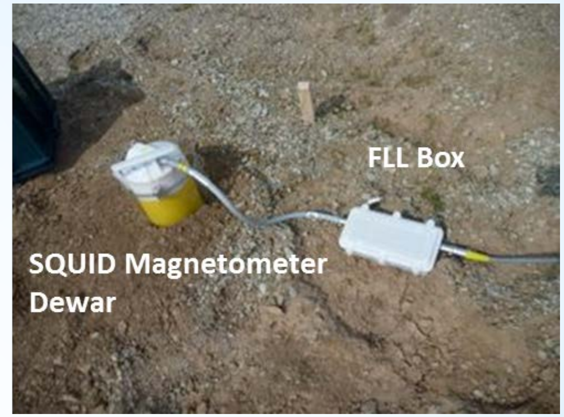
\# Vacuum maintenance free

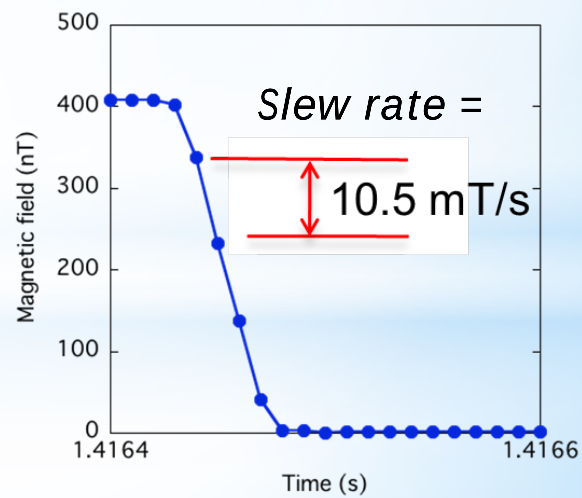
\# Keep LN_2 for 17 h

\# > x 10 higher slew rate

(> x 20 higher S/N)

Commissioned by JOGMEC





JOGMEC ISTEC MINDECO

T. Hato *et al.*, Super. Sci. Tech. **26** (2013) 115003.

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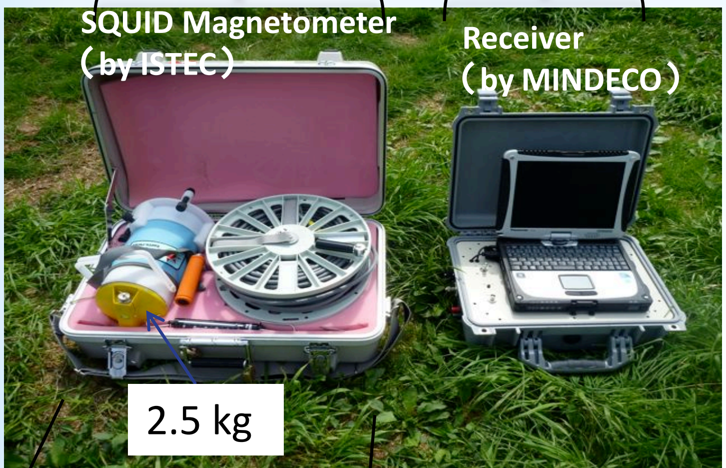

Compact design
Vacuum maintenance free
Keep LN_2 for 17 h
> x 10 higher slew rate
(> x 20 higher S/N)

Actual exploration in Peru

JOGMEC ISTEC MINDECO

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Commissioned projects at SUSTERA

- Development of advanced bio-sensing technology using HTS-SQUID
  (JST S-innovation program; FY2009～)

- Development of highly-sensitive magnetic NDE for deterioration evaluation and maintenance of infrastructure
  (JST SIP program; FY2014～)

- Development of next-generation SQUITEM system
  (JOGMEC project; FY2010～FY2012, FY2014～FY2016)

- Development of SQUITEM system for exploration of geothermal reservoir
  (JOGMEC project; FY2016～)

- Development of long-distance EM logging system using SQUID sensors
  (JOGMEC project; FY2012～)

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

R&D Leader: Prof. Keiji Tsukada (Okayama University)

Member: K. Tsukada (Okayama Univ.) compact NDE system with MR sensor
K. Tanabe (SUSTERA) highly-sensitive NDE system using SQUIDs
T. Furukawa (JAPEIC) simulation, pulse ECT method with MR sensor
T. Sasayama (Kyushu Univ.) inverse problem
Supporting Member: Mitsui Engineering & Shipbuilding Co., Ltd.
Chugoku Electric Power Co., Inc.

Cross-ministerial SIP (Strategic Innovation Promotion Program) FY2014-2018
operated by Council for Science, Technology and Innovation, Cabinet Office

"Technology for maintenance, renewal, management of infrastructure" program



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

44 R&D subjects (NDE techniques, materials, robotics, ICT, asset management)
supported by JST and NEDO

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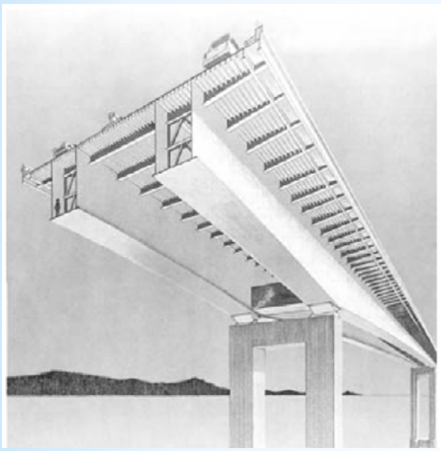
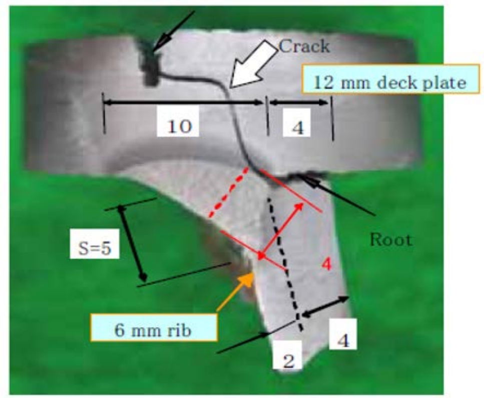
Highly-sensitive magnetic nondestructive evaluation for deterioration evaluation and maintenance of infrastructure

Target of NDE system with HTS-SQUIDs: Steel deck plate

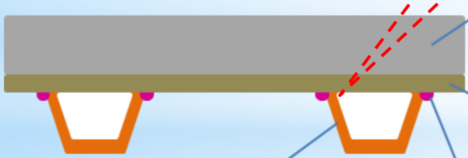


The San Mateo-Hayward Bridge



Fatigue crack in deck plate

A. Tabata, *et al*,
Hanshin Expressway Company Limited, Japan



Asphalt pavement (65~85mm^t)

Steel deck plate (12~16 mm^t)

U-shaped rib

Rib-to-deck weld

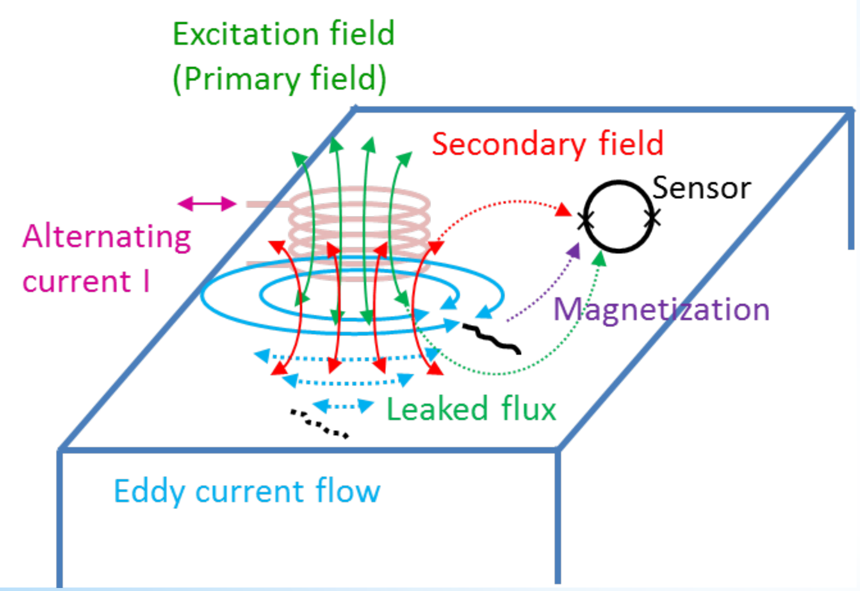
Structure of steel deck plate used in bridge or highway

Fatigue crack usually starts along a welding line inside a rib, and finally penetrates to the top surface of the deck plate.

An electromagnetic inspection technique is expected to detect fatigue cracks through an asphalt pavement.

By using HTS-SQUIDs with high sensitivity even at low frequencies, detection of non-through cracks as early-stage diagnosis is expected.

Issue of eddy current testing (ECT) of ferromagnetic material (ex. steel)



Principle of ECT

+ Distortion of eddy current flow around a crack changes the secondary field distribution which is detected by a sensor.

+ For the case of a ferromagnetic material, high permeability makes skin depth ($\delta = (2/\mu\sigma\omega)^{1/2}$) very short.
+ Leaked flux through a test object and a magnetic field generated by a magnetization also link to the sensor.
+ Permeability changes generally have a much greater effect on eddy current response than conductivity variations [1] and would make crack detection difficult.

SQUID-ECT method using low frequency excitation may be advantageous.

[1] Javier Garcia-Martin, et al, “Non-destructive techniques based on eddy current testing”, Sensors 2011, **11**,2525-2565.

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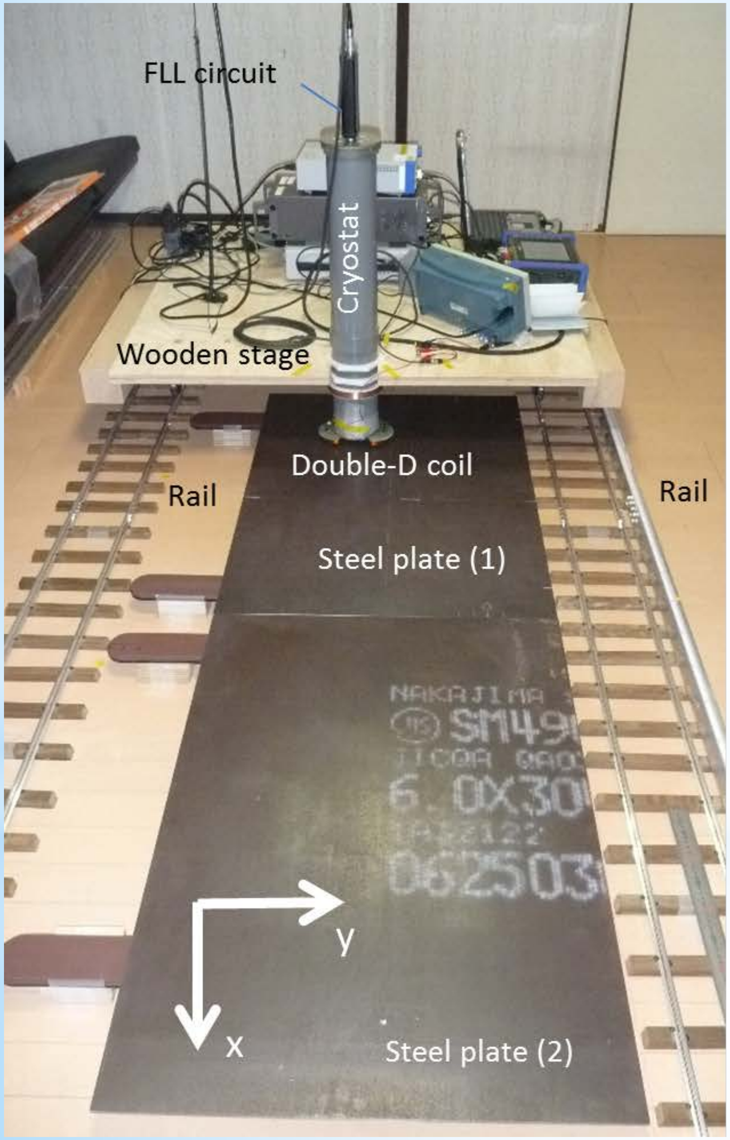
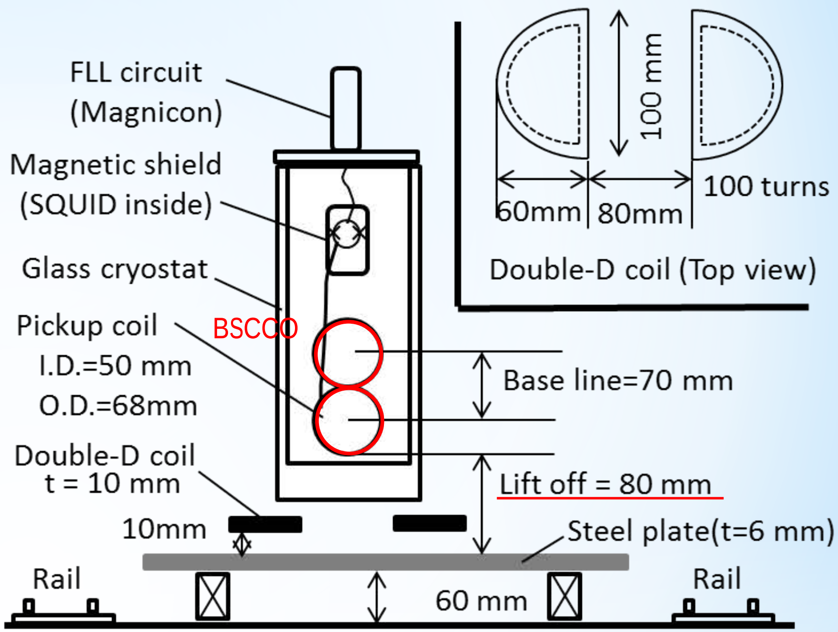
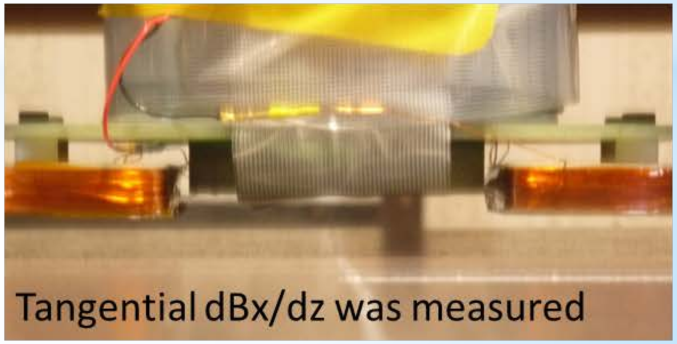
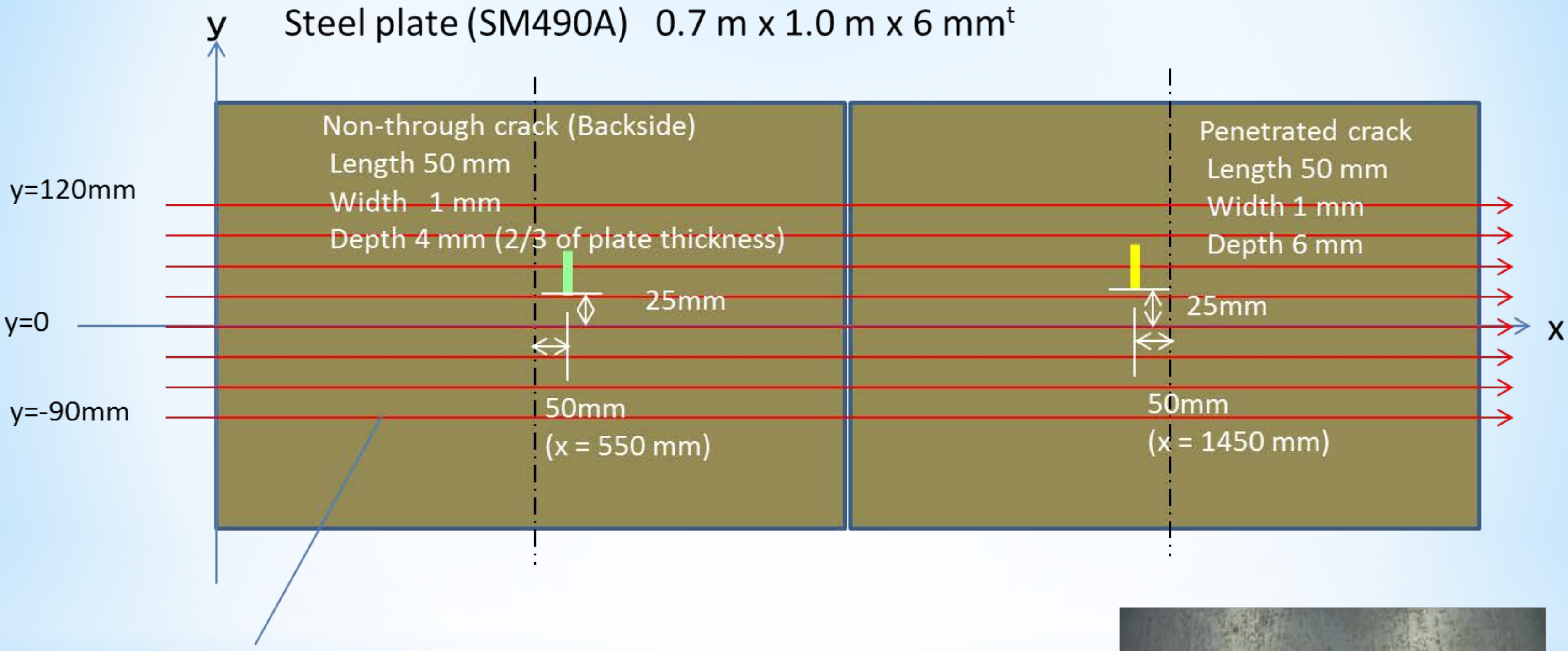
Trial fabricated SQUID-ECT system







Test steel plate with simulated crack (slit)



Scan lines (8 lines with 30 mm interval)

Averaging every 2 mm of moving using encoder signal

2D contour map

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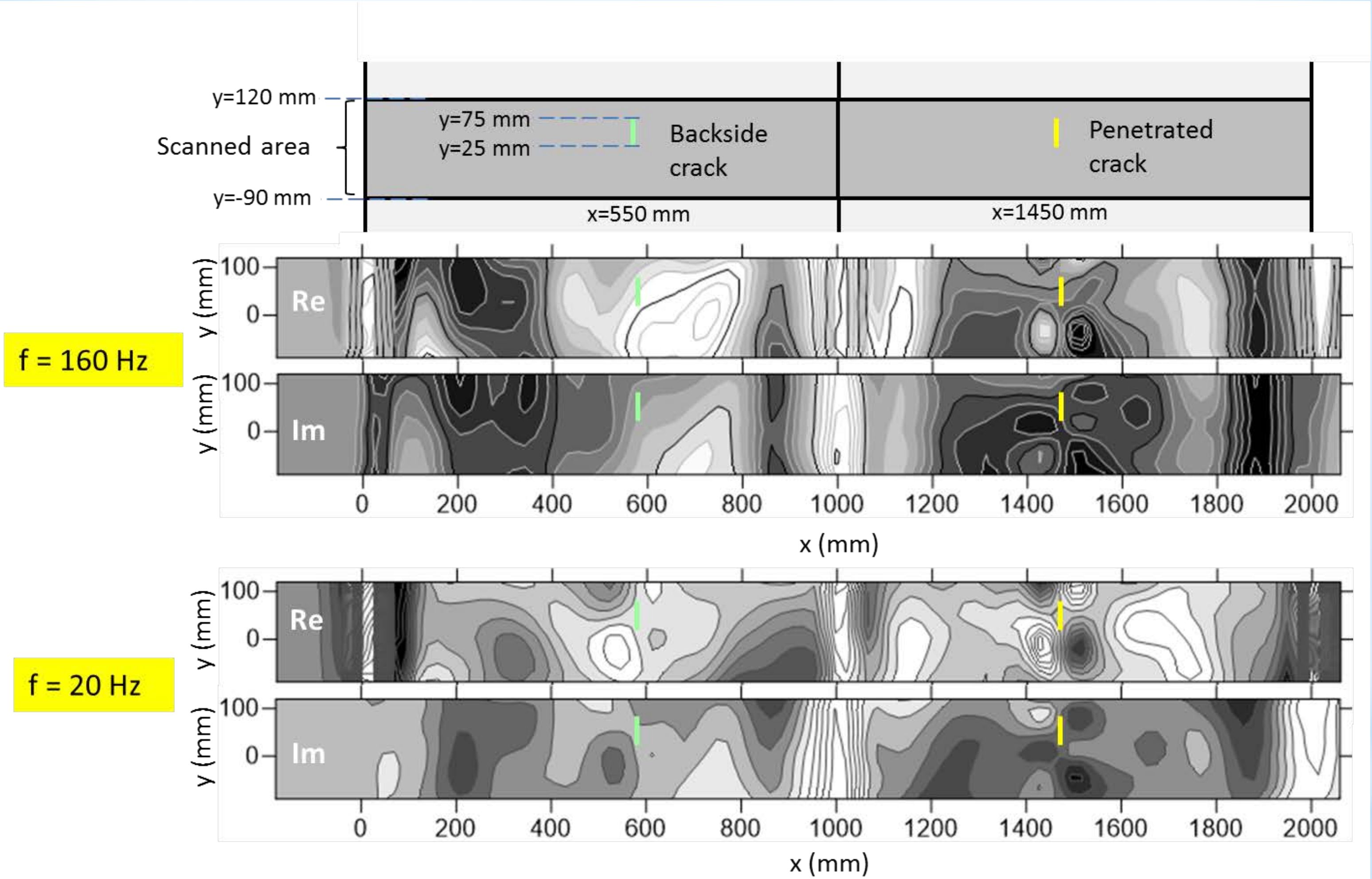
NDE results



- Quadrupole pattern from penetrated crack is observed in **Re** data at both 20 and 160 Hz.
- Due to a longer δ, quadrupole pattern from backside crack can be observed in 20 Hz **Re** data.
- **Re** and **Im** components have different origins (flux leakage, eddy current).
- Background signal due to magnetization is reduced by decreasing the excitation frequency.

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NDE system using a cart for field test

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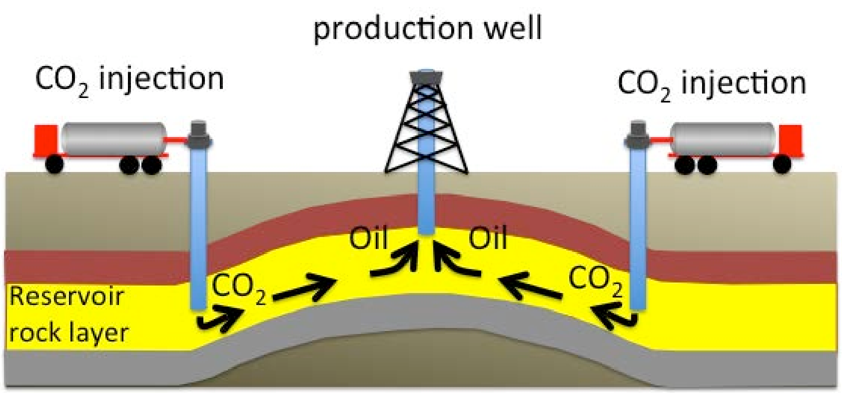
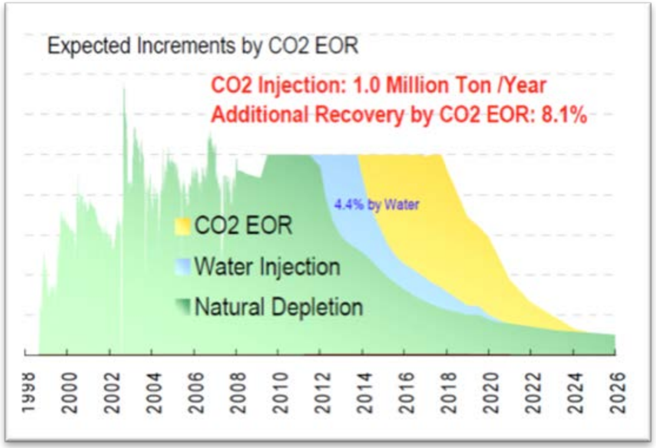
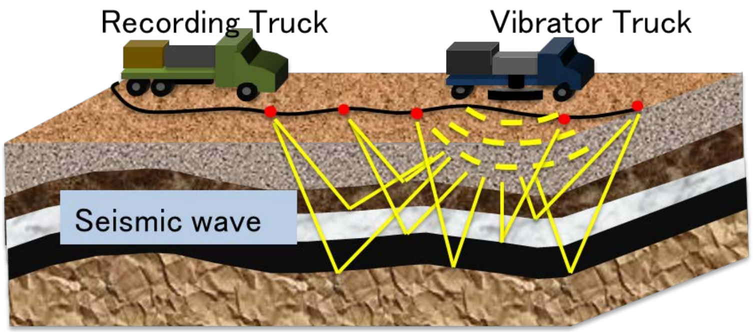
Development of long-distance EM logging system - Application to oil field -



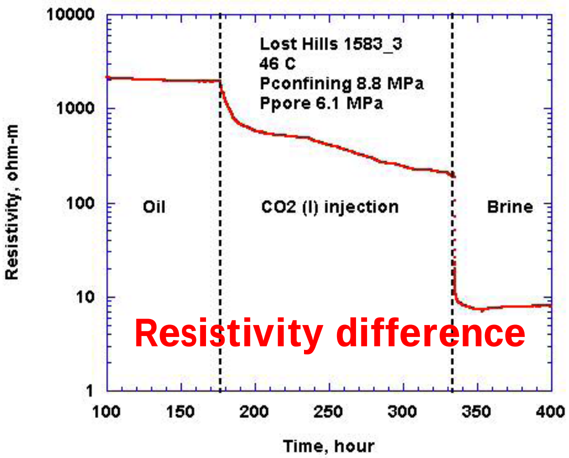
Schematic of enhanced oil recovery (EOR) technology utilizing CO_2



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 long-range EM logging system - Application to oil field -

ISTEC MINDECO JOGMEC

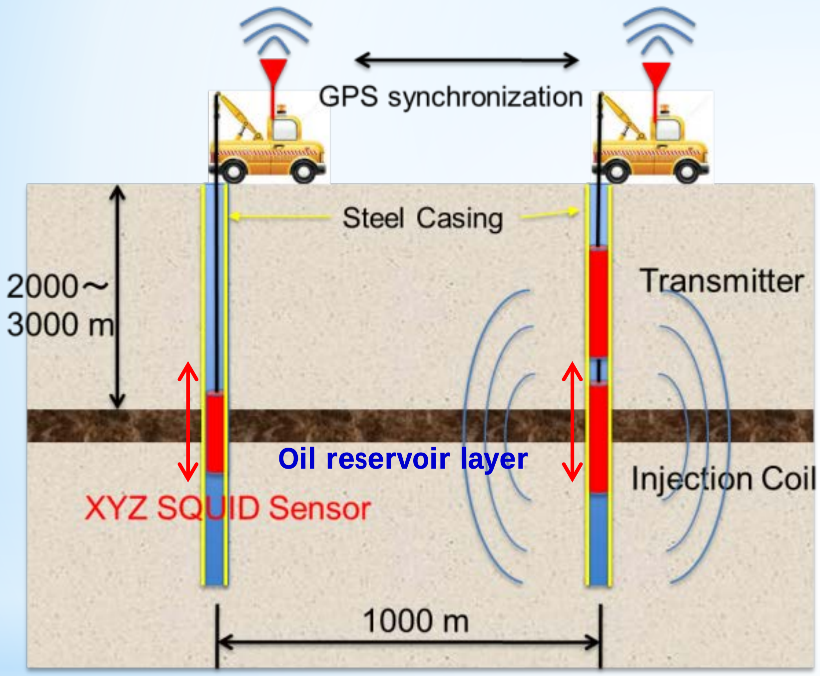


Image of crosshole EM (logging) system with HTS-SQUID magnetometer (Resistivity tomography between two wells)

- 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 receiver (magnetometer) usable in high pressure (30-70 MPa) and high temperature (200 ºC) environment
- Remote control of SQUID magnetometer

Development of elementary technologies started in 2012

FY2012 JOGMEC "Innovative technology in oil and gas development field" program
FY2013-2015 JOGMEC "Technical solution project"

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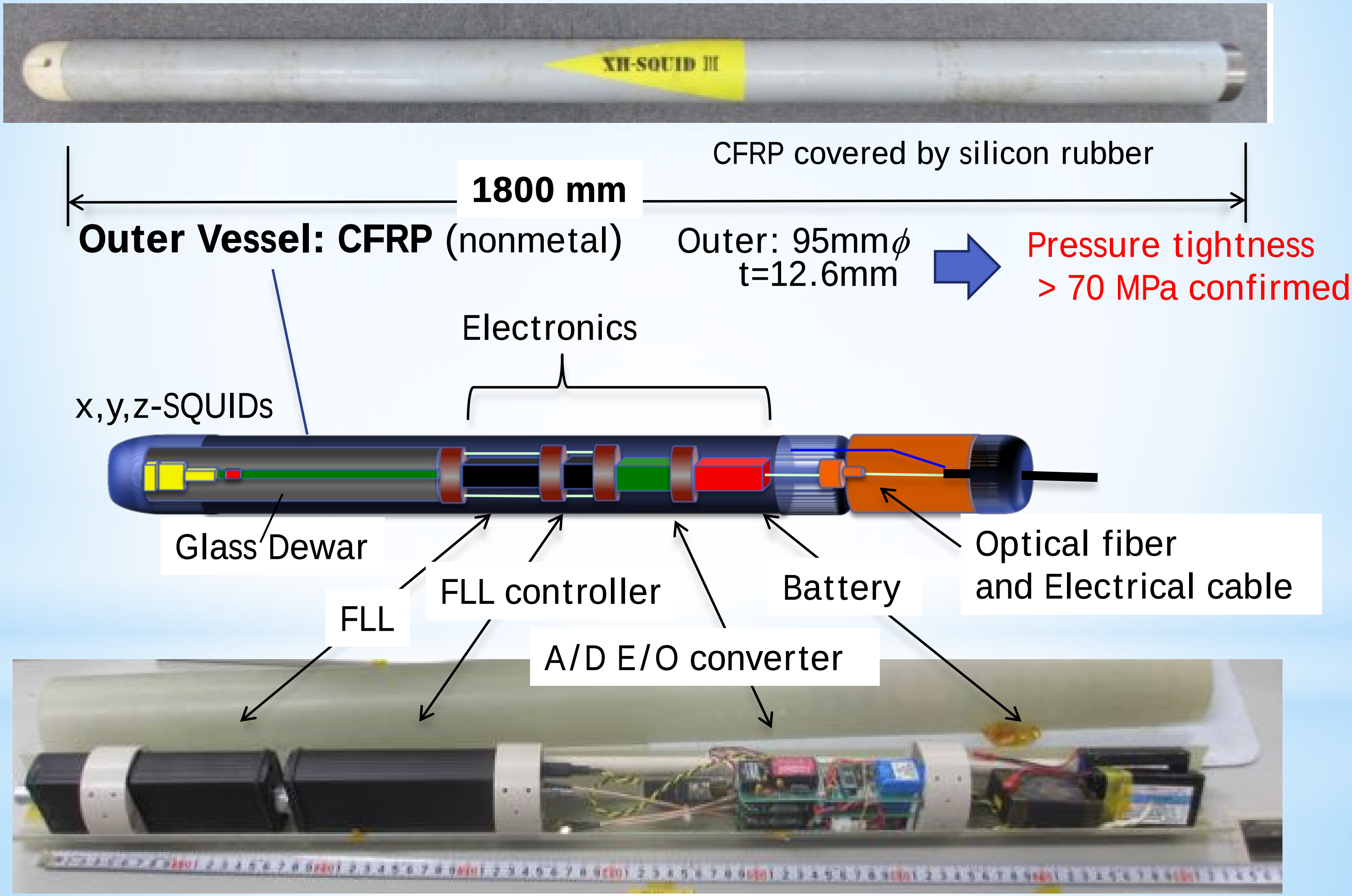
SQUID receiver system for use in a test well



Control of SQUIDs through 3 km long optical fiber confirmed

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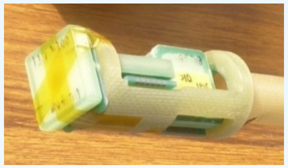
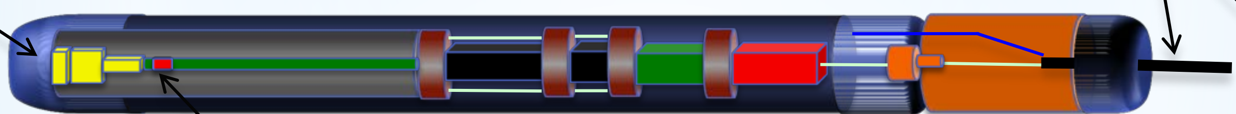
SQUID receiver system for use in a test well



Cable with plastic tube
for N_2 gas release

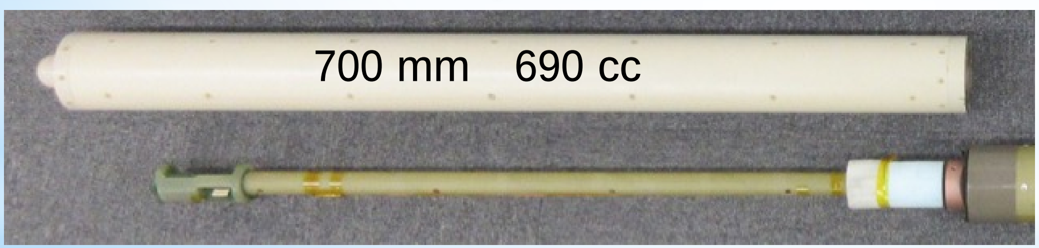
XYZ-SQUID

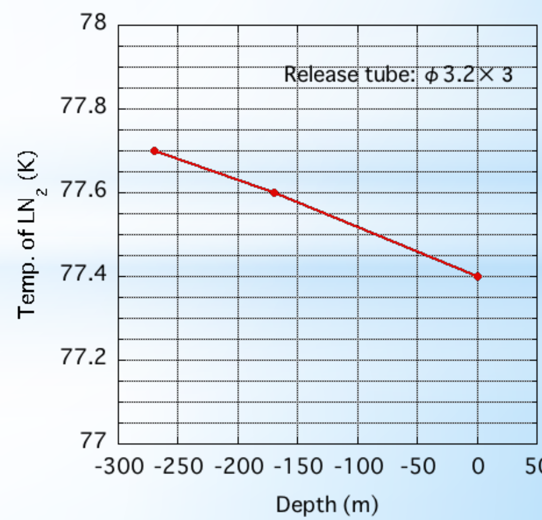
Inner diameter: 3.2 mmϕ x 3



Thermal sensor

Outer diam. of cable: 17.8 mmϕ





LN_2 holding time: 40 h

Temperature rise: 0.3 K at -270 m
caused only by difference of elevation

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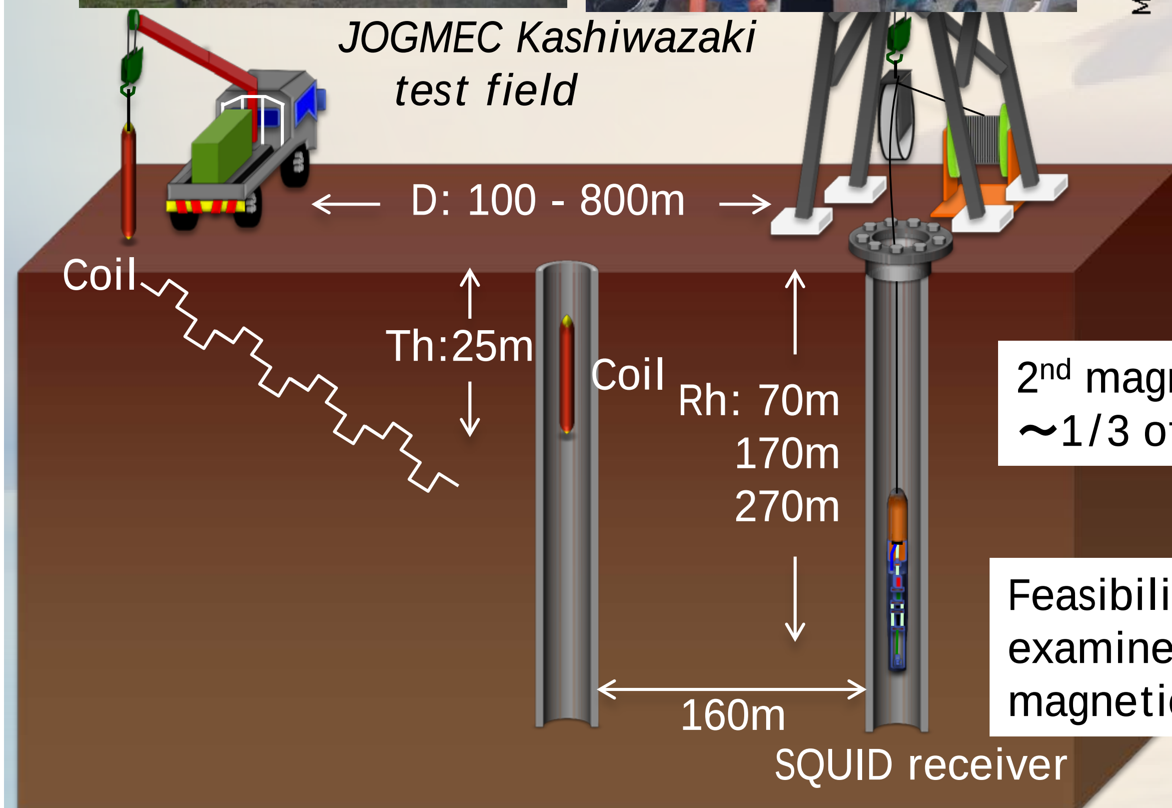
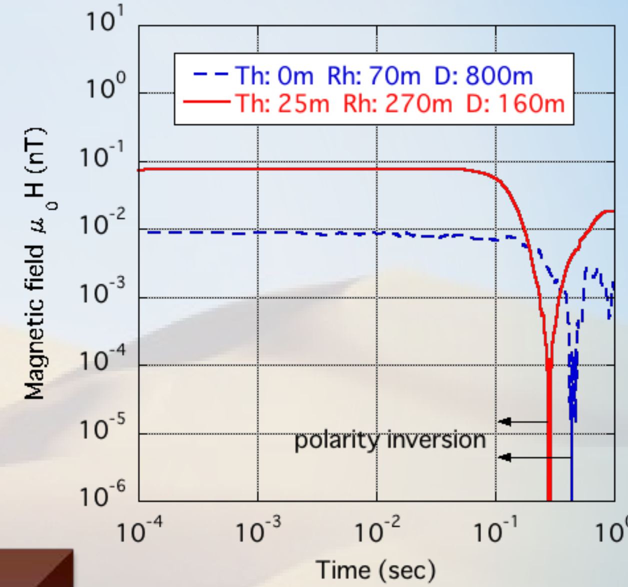
Field test (real measurement in a borehole with steel casing)





2nd magnetic field
∼1/3 of primary magnetic field.

Feasibility of induction logging was examined by detecting primary magnetic field.

SUSTERA

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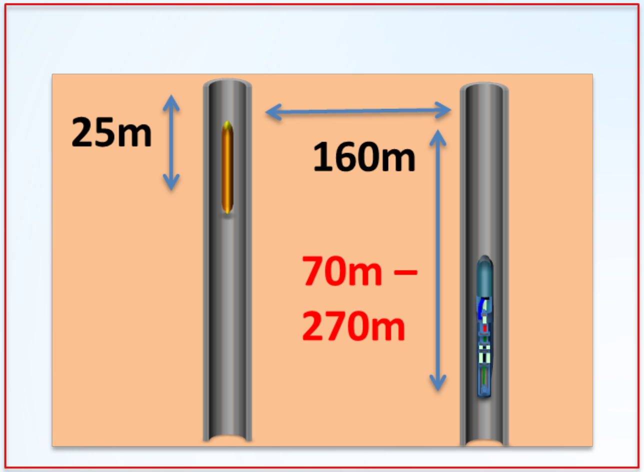
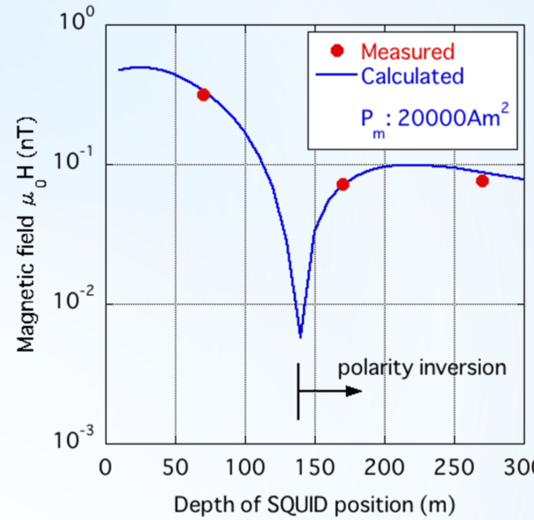
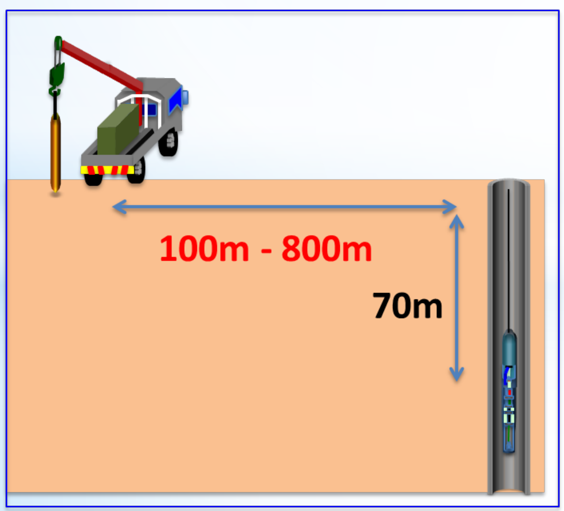
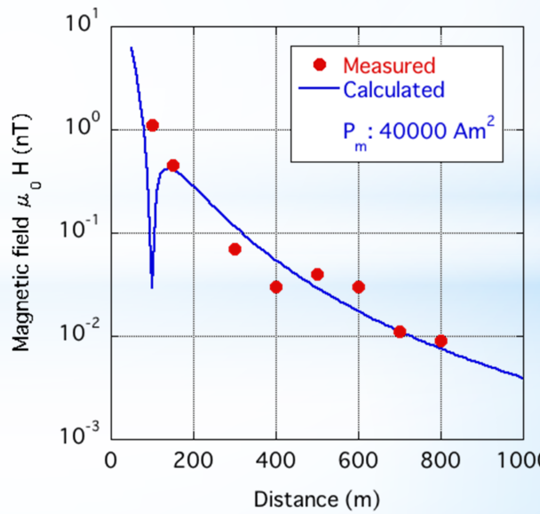
Test results





Stable operation in borehole filled with oily water at ∼300 m confirmed.





4 pT at 1000 m

Indicating possibility of long distance EM logging : > 1000m

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Summary

- At SUSTERA, HTS-SQUIDs with the multilayer structure and ramp-edge junctions are routinely fabricated using the facility transferred from ISTEC.

- These multilayer HTS-SQUIDs have been applied to various systems for use at and under the ground including TEM systems for exploration of metal and geothermal resources, EM logging system for monitoring of oil layer, and NDE system.

- Detection of backside crack-like defects in a steel plate at 80 mm lift-off has been demonstrated, indicating a possibility of application of HTS-SQUIDs to NDE of infrastructure.

- A SQUID receiver system for cross-hole EM logging has been developed. Stable operation of SQUIDs at about 300 m depth in a steel-cased well and observation of transient magnetic field from a coil placed at 800 m distance have been demonstrated, indicating possibility of application to long-distance EM logging.

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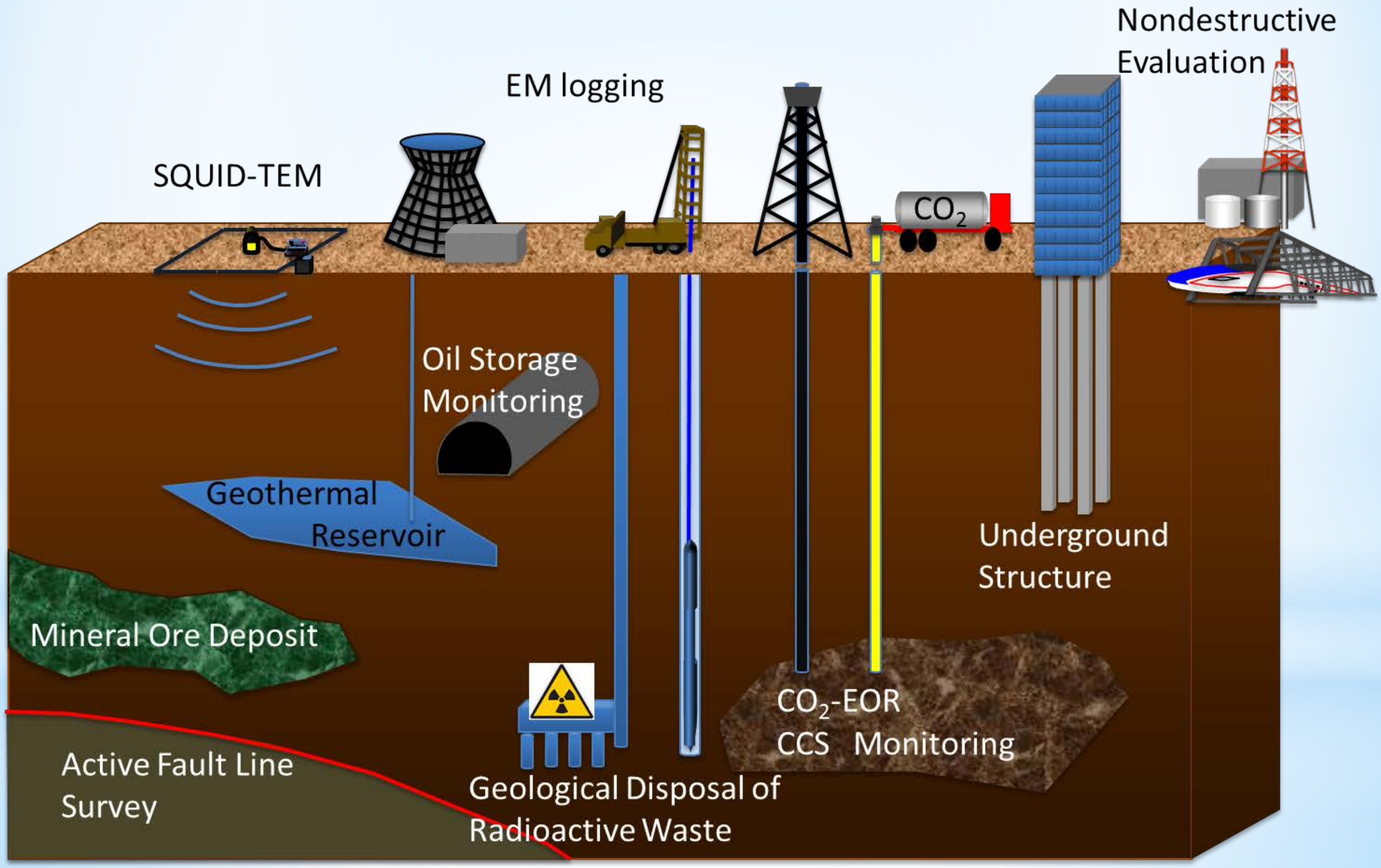
Possibilities of HTS-SQUIDs for use at and under the ground in the near future



Seabed resources survey (hydrothermal polymetallic ore, methane hydrate)

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SUSTERA Products

SUSTERA Catalog No.0001

HTS SQUID gradiometer chip

DL35

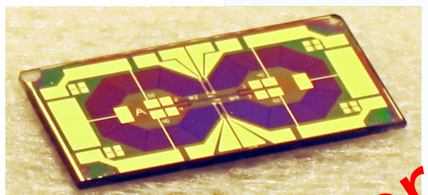
http://www.sustera.or.jp/

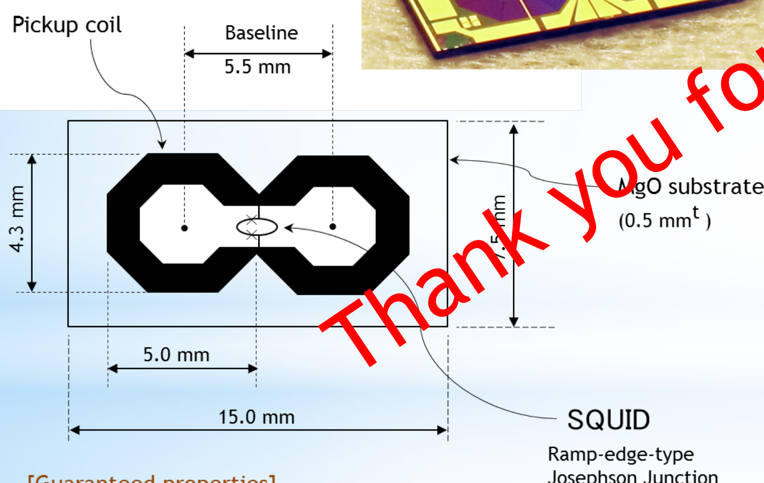
High sensitivity chip to detect minute magnetic field gradient

<<< General-purpose SQUID gradiometer chip utilized by any users>>>

Design: 1st order planar gradiometer (directly coupled)

Working Temp.: 77 K (Liq. N_2 Temp.)





[Guaranteed properties]

- Critical current $2I_c$: > 15 μA
- Modulation voltage ΔV: > 15 μV
- Flux noise Φ_n (white) : <10 $\mu\Phi_0/\mathrm{Hz}^{1/2}$
- Effective area A_{eff} (for one pickup coil) : ~ 0. 1 mm^2

(2016.10.31)

SUSTERA Catalog No.0002E

Portable cryostat for HTS devices

CD1

http://www.sustera.or.jp/

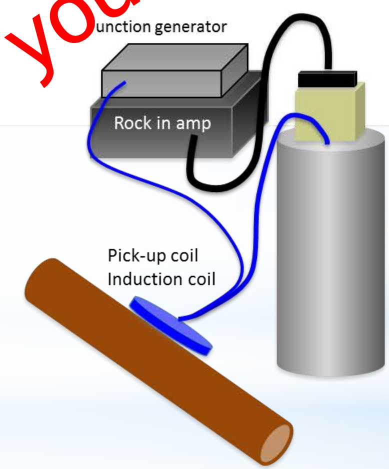
For easy testing using HTS-SQUID sensor

<<< For use of external pickup coil, suitable for outdoor use>>>

Specifications: Aluminum outer container, Inner glass Dewar

Cooling Temp.: 77 K (with liquid N_2)

Example of usage



D: 140 mmϕ H: 370 mm
Weight: 4.2 kg (incl. probe)

[Features]

- Liq. N_2 keeping time: > 14 hours (with SQUID probe inserted)
- Magnicon and STARCryo FLL attachable
- Permalloy shield installable (option)
- Flange, port, connectors can be customized

(2016.11.1)

Thank you for your attention.