ISEC2019 (Riverside, CA, USA)
2019/7/30

Evolution of HTS Josephson junction technology and its application in Japan

Keiichi Tanabe

Superconducting Sensing Technology Research Association

SUSTERA

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), September 2019.
Distinguished presentation 2-FA-D-1 given at ISEC, 28 July-1 August 2019, Riverside, USA.

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2019/7/30

Evolution of HTS Josephson junction technology and its application at ISTEC and SUSTERA

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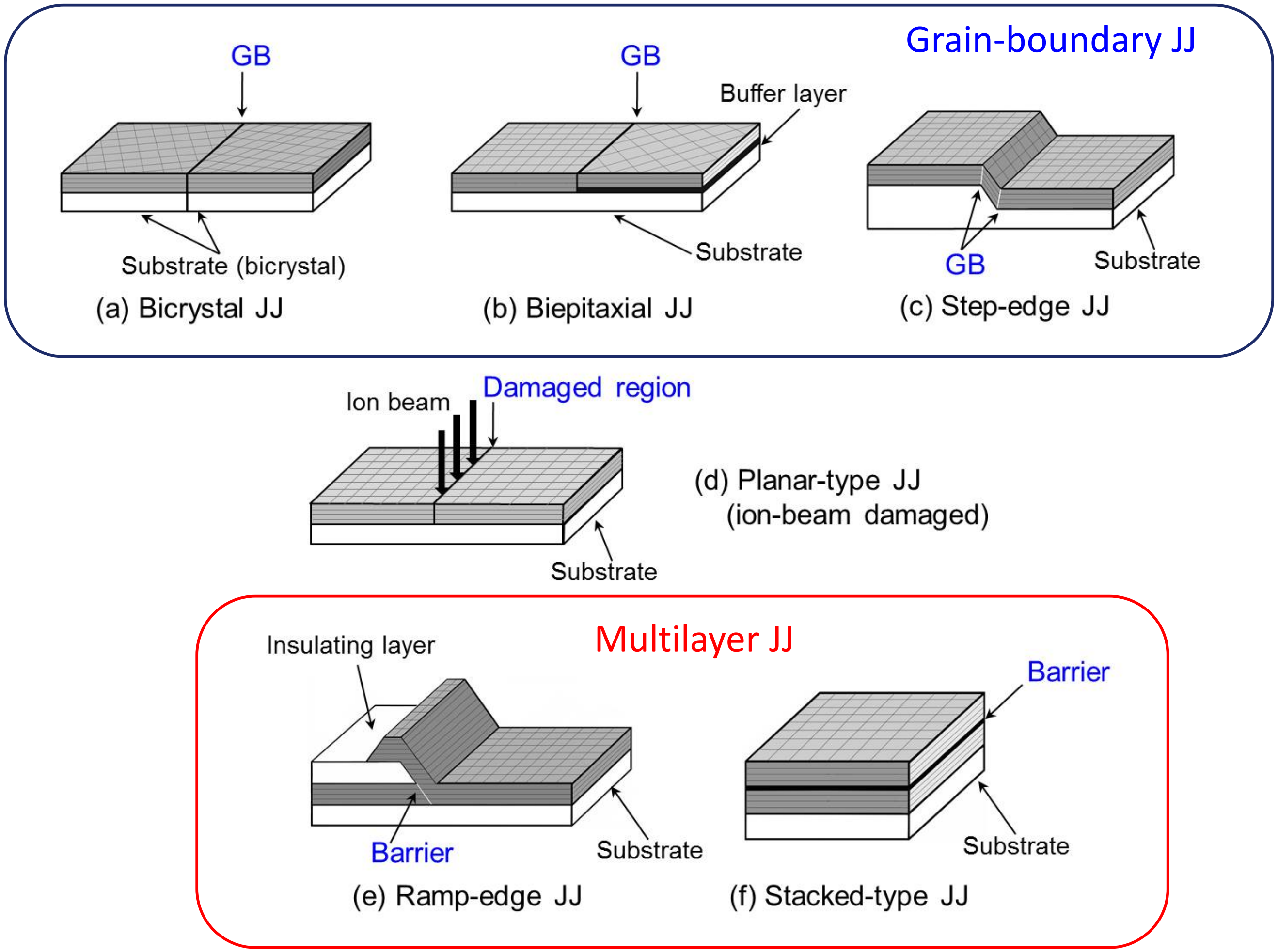
SUSTERA

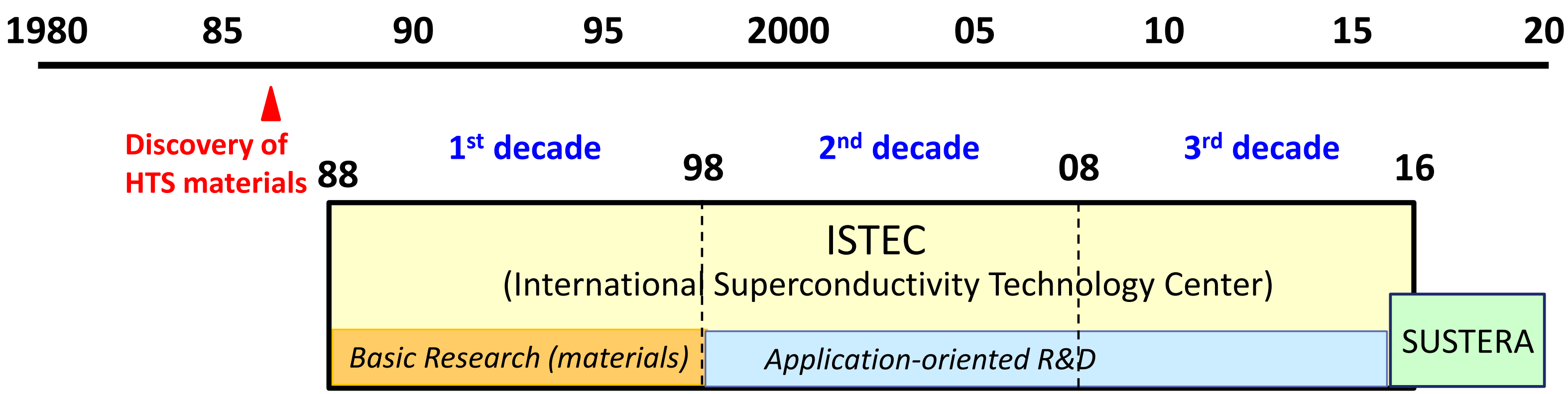
Introduction: HTS JJ



K. Tanabe, "HTS Josephson Junctions," in Applied Superconductivity, vol. 1, P. Seidel, Ed. Wiley-VCN, 2015, pp. 306-327.

Introduction and Outline

History of ISTEC and SUSTERA



HTS JJ technology	*Grain-boundary (GB) JJ*	*Ramp-edge JJ (IEJ)*	*Ramp-edge JJ (modified)*
Devices		*HTS-SFQ devices*	*Multilayer HTS SQUIDs*
Systems			*SQUID systems for field use*

Outline

(1) 1st decade: GB JJ
(2) 2nd decade: Ramp-edge JJ, HTS SFQ devices
(3) 3rd decade: Multilayer HTS SQUIDs
(4) Application of multilayer HTS SQUIDs (field use)

(1) 1st decade: GB JJ

Superconducting Sensor Laboratory

(founded by Japan Key Technology Center , Hitachi, SEI, Yokogawa, SII, Shimadzu, ….)

LTS SQUIDs → 64 ch MCG system (Hitachi) in 2nd decade

HTS SQUIDs using step-edge junctions

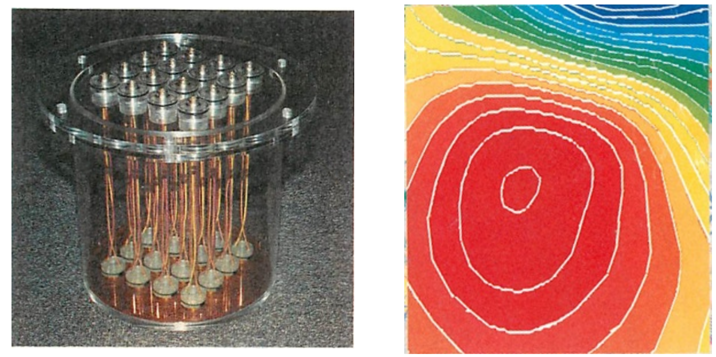
demonstration of 16 ch MCG

↓

SQUITEM 1,2 (JOGMEC, SEI)

Metallic contaminant detection (TIT)

51 ch MCG system (Hitachi, Bicrystal JJ)



H. Itozaki *et al*

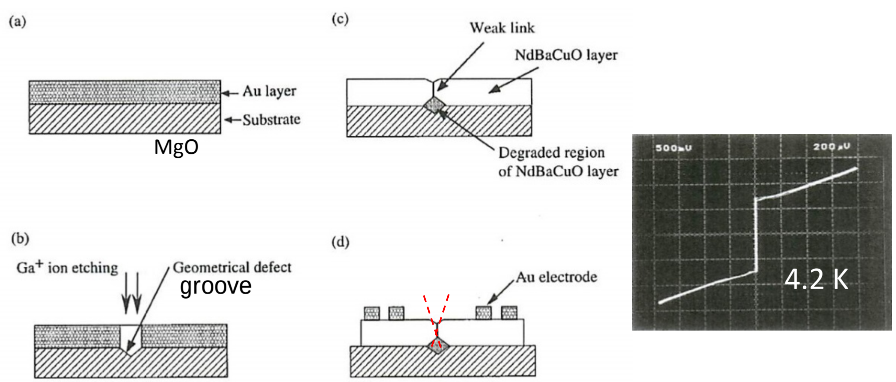
ISTEC

Materials research

GB junctions using FIB technique

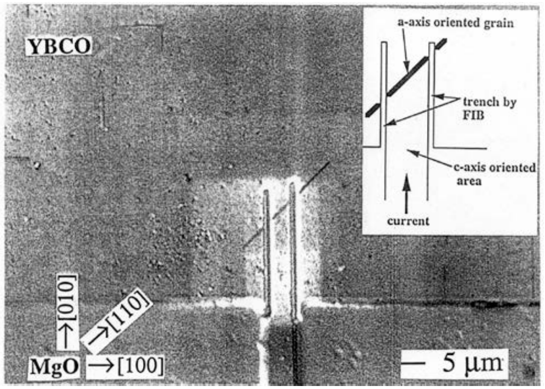
weak-link, *a*/*c* GB junction

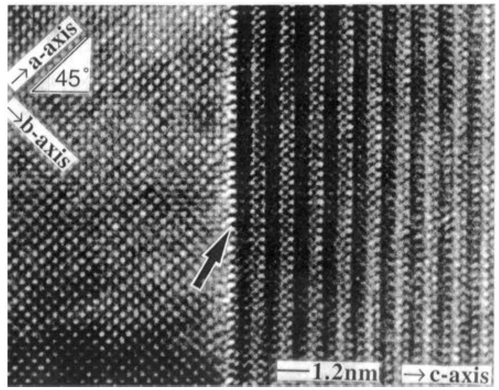
Hg-1212 bicrystal JJ and SQUIDs



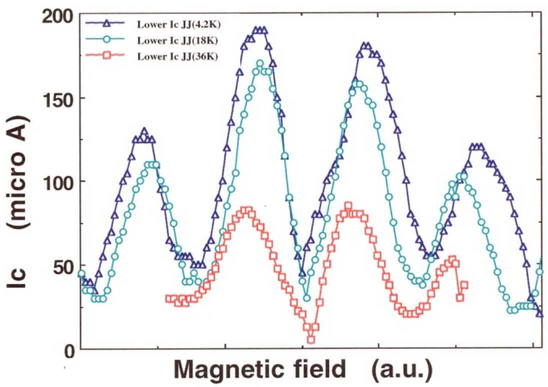
S. Morohashi *et al*., Jpn. J. Appl. Phys. **38**, 698 (1999).

(1) 1st decade: GB JJ

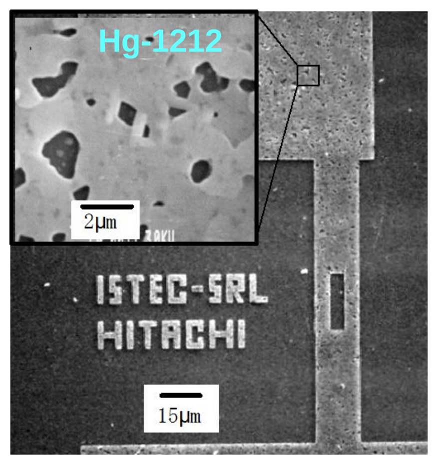


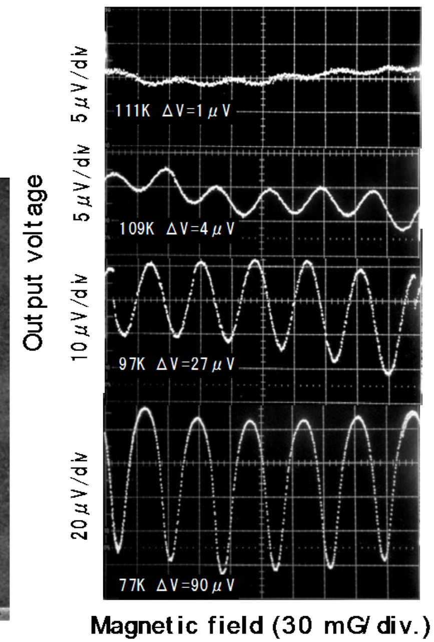


a/*c* grain boundary



Y. Ishimaru *et al.*, Phys. Rev. B **55**, 11851 (1997).





A. Tsukamoto *et al.*,
Appl. Phys. Lett. **73**, 990 (1998).

(2) 2nd decade: Ramp-edge JJ

- **Developments of HTS multilayer structures with ramp-edge JJs for HTS SFQ devices (supported by New Energy and Industrial Technology Development Organization)**

  NEDO project "Fundamental technologies for superconductivity applications" (FY98-03)

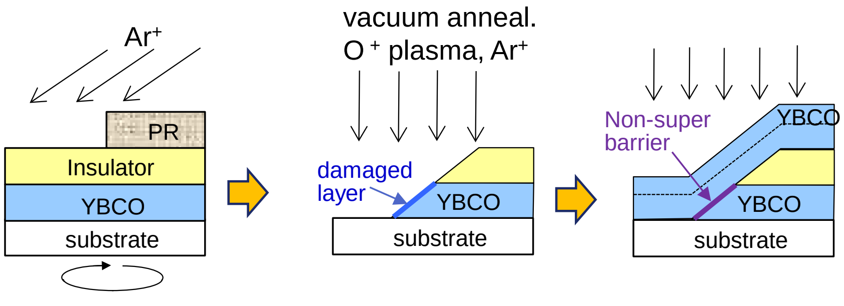
  ISTEC, Hitachi, Toshiba, Fujitsu, NEC, Sanyo, DuPont, AIST

  NEDO project "Superconductor Network Device" (FY03-06)

  ISTEC, Hitachi, Fujitsu, Advantest

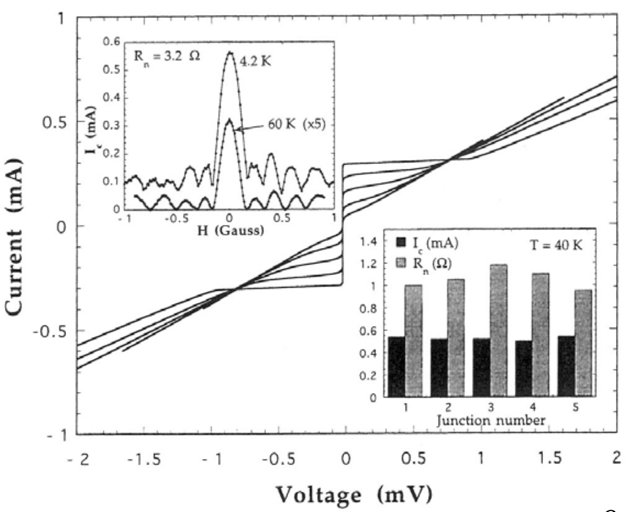
- **Interface-engineered junction (IEJ)**

B. H. Moeckly and K. Char, *Appl. Phys. Lett.* ***71****, 2526 (1997).*



T. Satoh *et al.*, *IEEE trans. Appl. Supercond.* ***9****, 1549 (1999).*
J. G. Wen *et al.*, *Appl. Phys. Lett.* ***75****, 2470 (1999).*

Small I_c spread preferable to SFQ circuits

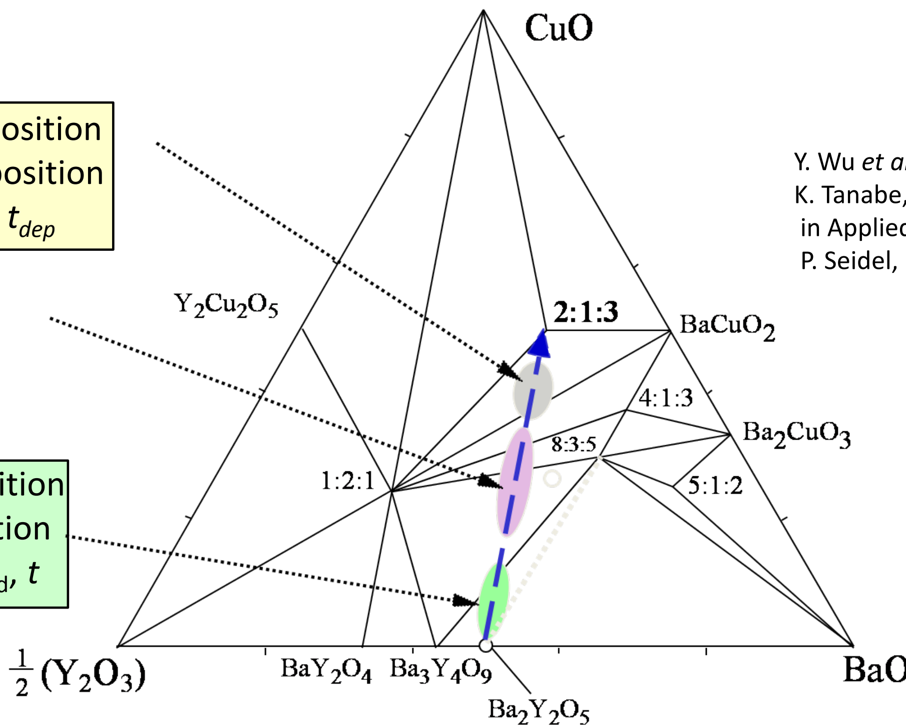


(2) 2nd decade: Ramp-edge JJ

IEJ: Formation mechanism

Interface composition after YBCO deposition *depends on* T_s, t_{dep}

Surface composition after Ar^+ irradiation *depends on* V_{irrad}, t

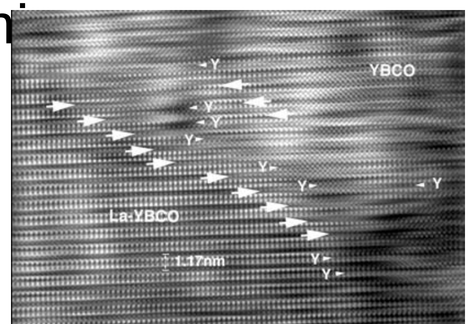


Y. Wu *et al.*, J. Appl. Phys. **92**, 4571 (2002).
K. Tanabe, "HTS Josephson Junctions," in Applied Superconductivity, vol. 1, P. Seidel, Ed. Wiley-VCN, 2015, pp. 306-327.

Triangular Phase Diagram for YBCO system

(2) 2nd decade: Ramp-edge JJ

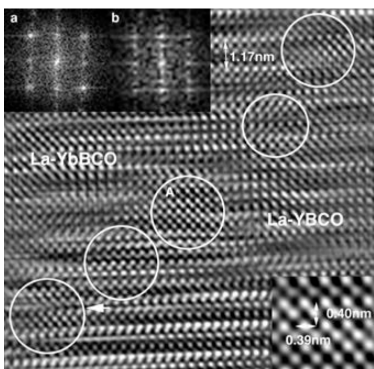
IEJ: Formation mechani

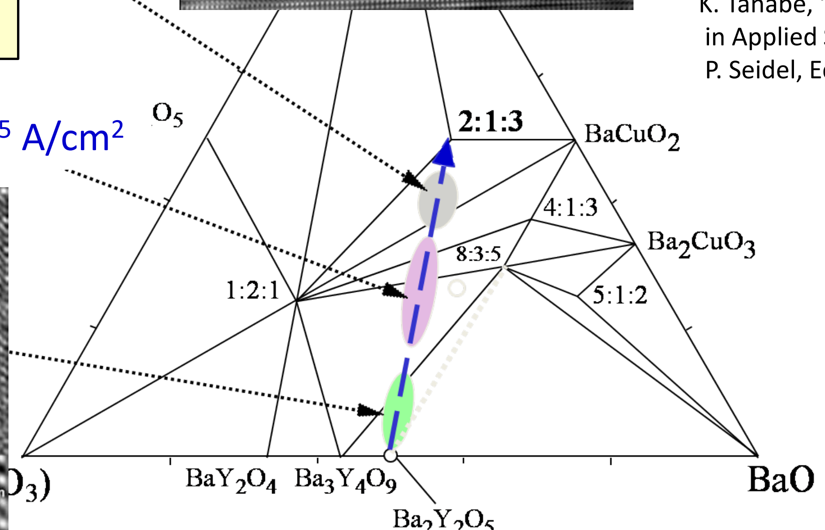


High T_s
J_c : >10^5 A/cm^2

Interface composition after YBCO deposition *depends on T_s, t_{dep}*

Low T_s
J_c :10^4-10^5 A/cm^2





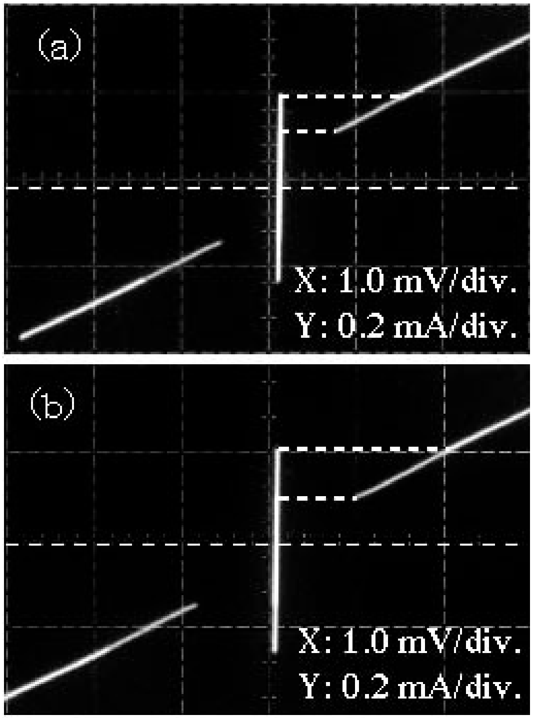
Y. Wu *et al*., J. Appl. Phys. **92**, 4571 (2002).
K. Tanabe, "HTS Josephson Junctions," in Applied Superconductivity, vol. 1, P. Seidel, Ed. Wiley-VCN, 2015, pp. 306-327.

Triangular Phase Diagram for YBCO system

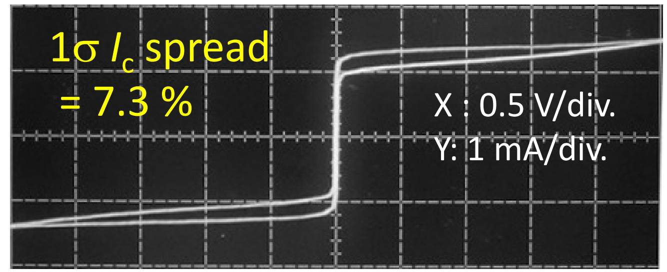
Mutual atomic diffusion at the interface has a significant role
Precise control of deposition conditions required, but actually possible

(2) 2nd decade: Ramp-edge JJ

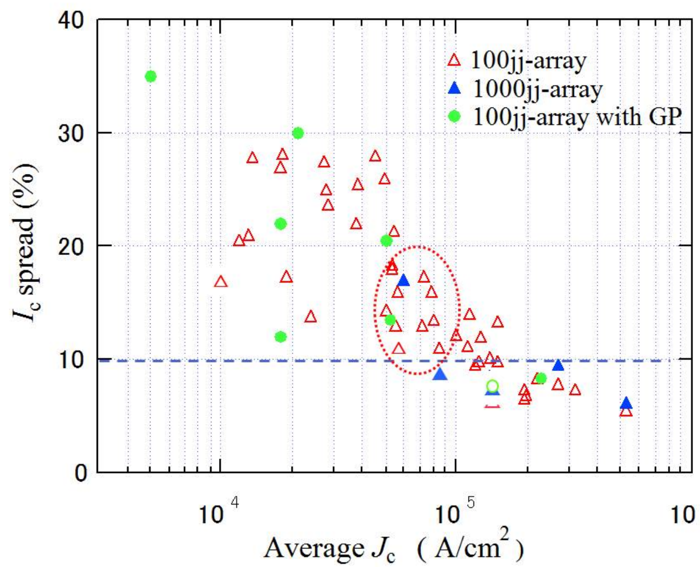
IEJ: Properties



***I-V* characteristics at 4.2 K**
I_cR_n product = 1.5-2 mV

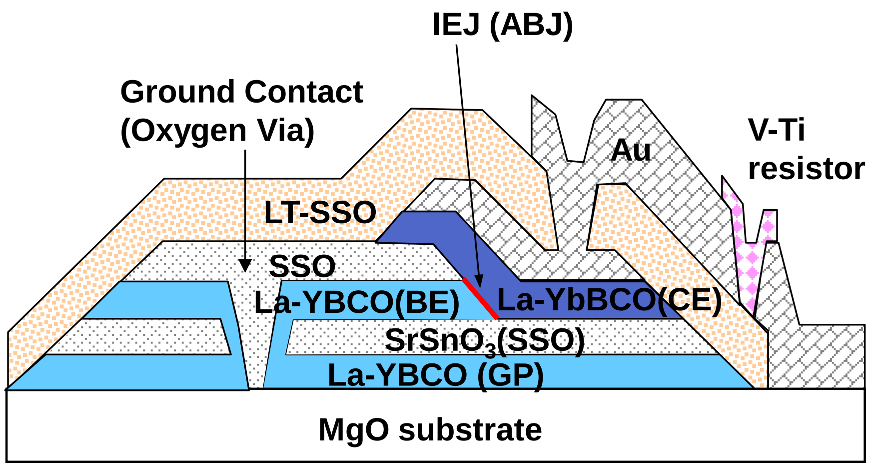


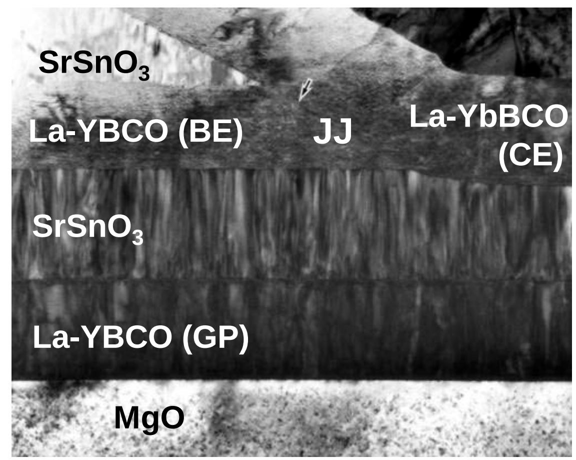
***I-V* characteristics for 1000-JJ array at 4.2 K**



(2) 2nd decade: Ramp-edge JJ

Multilayer structure



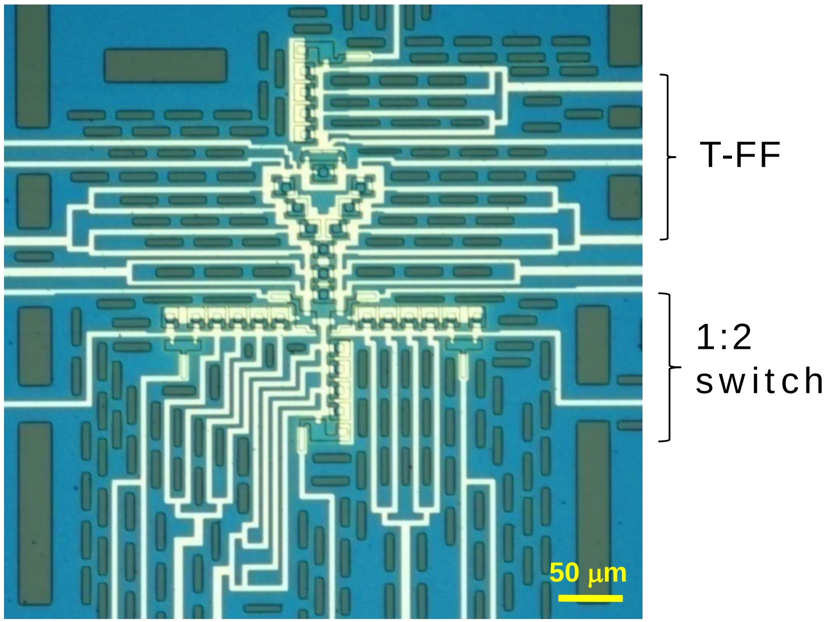


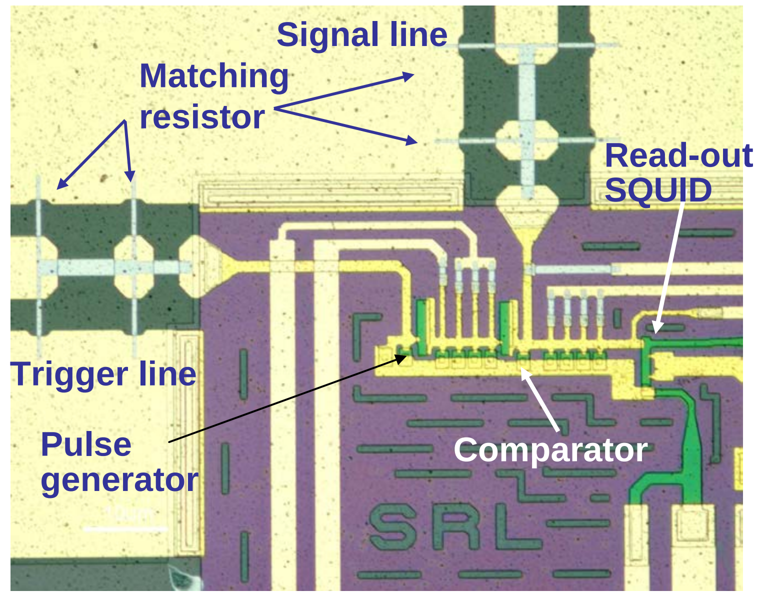
Features

- 3 La-substituted RE-123 layers with $SrSnO_3$ (SSO) insulator
  R_a of SSO/HTS/SSO/HTS sputtered multilayer < 2 nm
- Ramp-edge-type JJs (modified barrier) with 1σ I_c spread 5-10 %
- Minimum junction width of 1.5 μm
- Oxygenation of GP through via holes (550 ℃, 10 h, slow cool down)
- GP patterning, LT-SSO insulator, Au CPW lines for sampler
- V-Ti resistor with sheet resistance of 5-25 Ω.

ISTEC

(2) 2nd decade: HTS SFQ devices



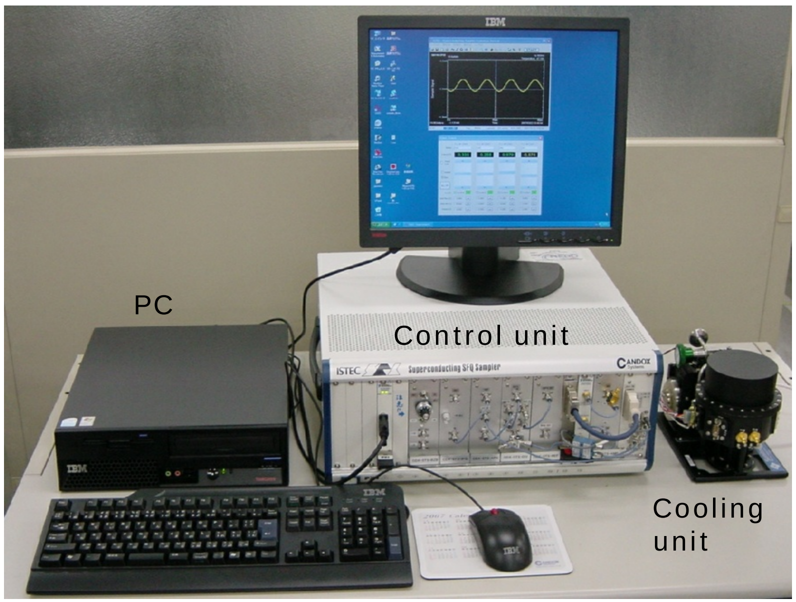


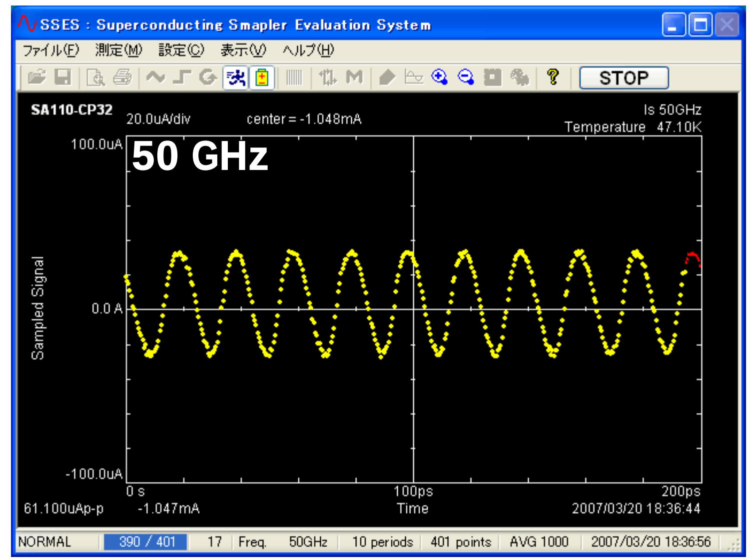
HTS SFQ 1:2 de-multiplexer (50 JJs integrated)

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

K. Tanabe *et al.*, IEICE Trans. Electron **E91-C**, 280 (2008).

(2) 2nd decade: HTS SFQ devices





Demonstration of desk-top sampler system at ISTEC (40 K operation)

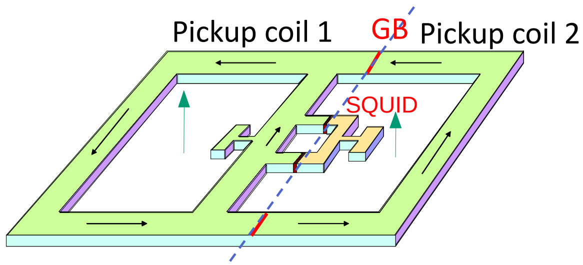
(H. Suzuki *et al*., ISEC2007, Washington DC)

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

(3) 3rd decade: Multilayer HTS SQUIDs

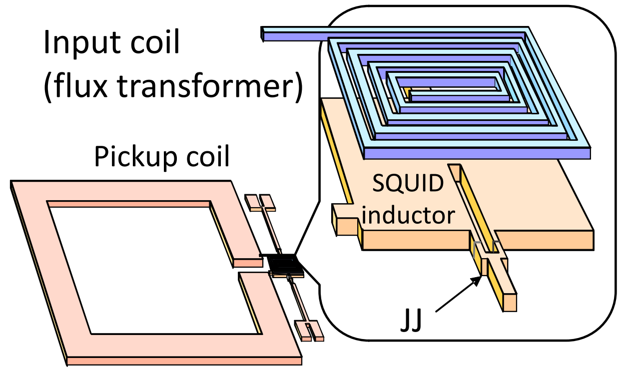
▪Why multilayer HTS SQUIDs?

- All commercial HTS SQUIDs consist of single HTS layer and GB JJs.
- By multilayer structure such as in LTS SQUIDs, higher performance is expected.



Gradiometer with GB junctions

Without high-angle GB, higher tolerance against application of magnetic field expected
Lower probability of flux trapping

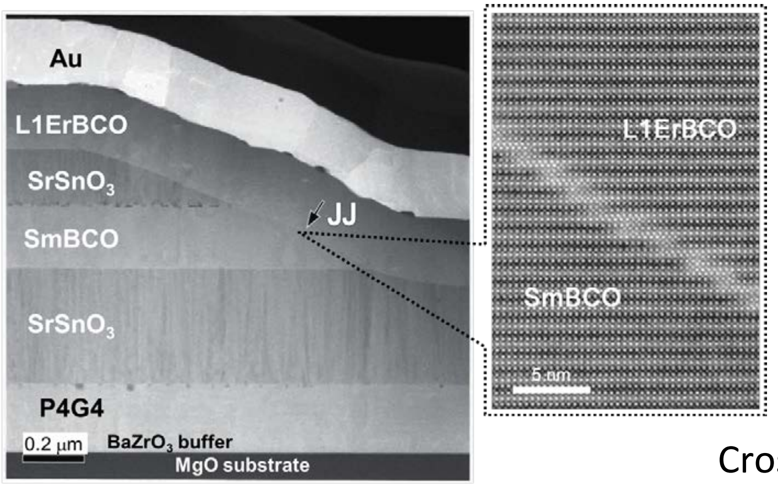


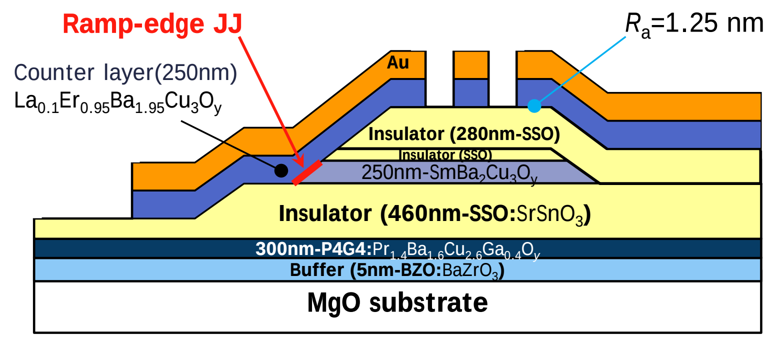
Magnetometer with integrated input coil

Higher sensitivity (>x 5) expected

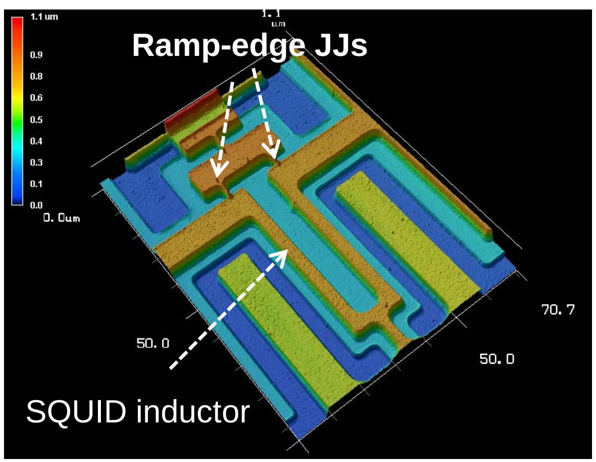
- More complicated devices such as multichannel SQUID array can be easily fabricated using cross-over structure and ramp-edge JJs.

(3) 3rd decade: Multilayer HTS SQUIDs





Cross-section of multilayer HTS SQUIDs



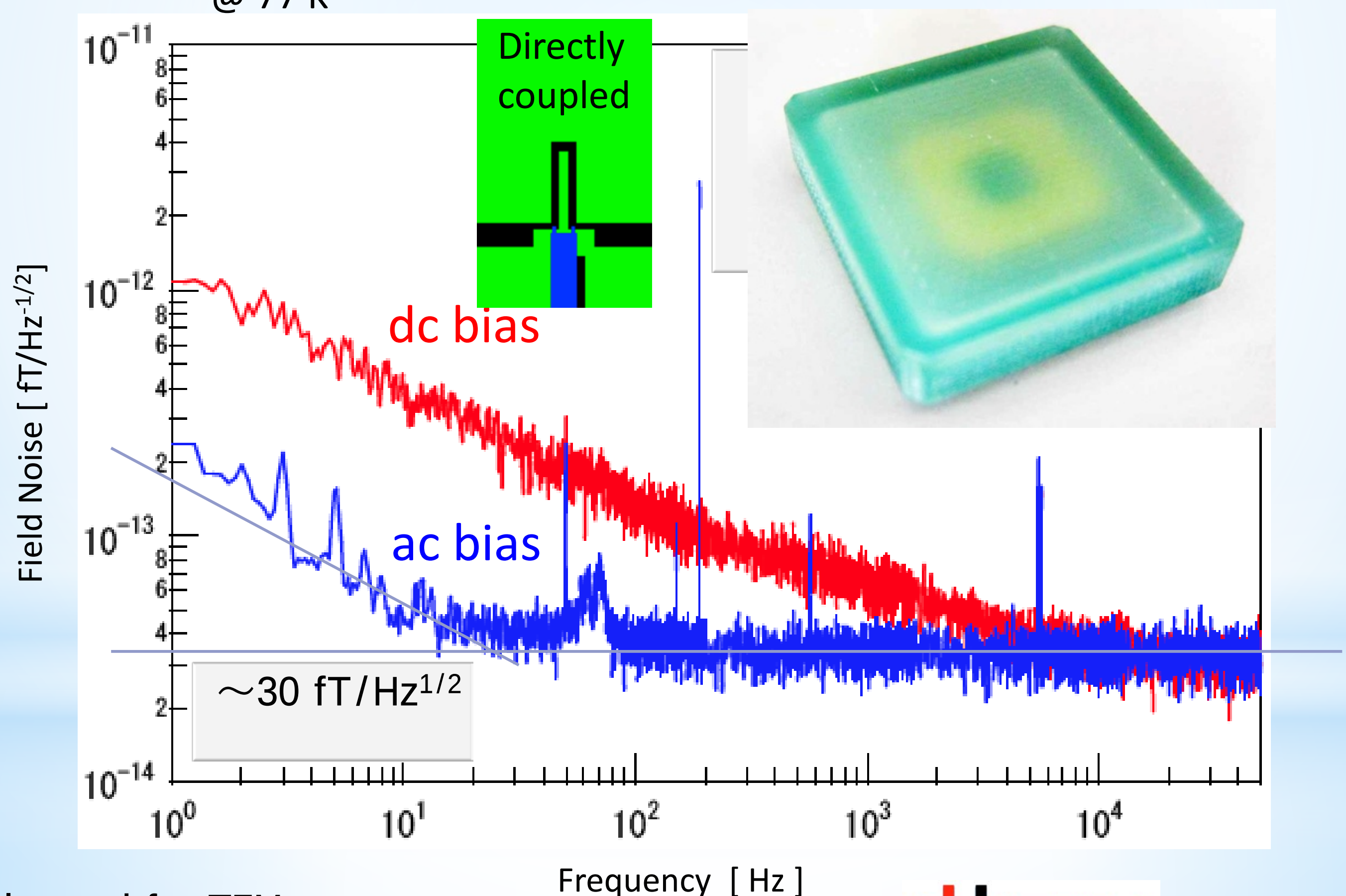
- SmBCO and La-ErBCO (T_c > 90 K) electrodes
- Deposition of thin Cu-deficient layer on ramp surface before upper HTS deposition
  ➡ Stable operation at 77 K

- Lower black-color insulating layer (Ga-PrBCO)
  ➡ Higher uniformity of JJ properties on chip

Standard directly-coupled magnetometer

@ 77 K

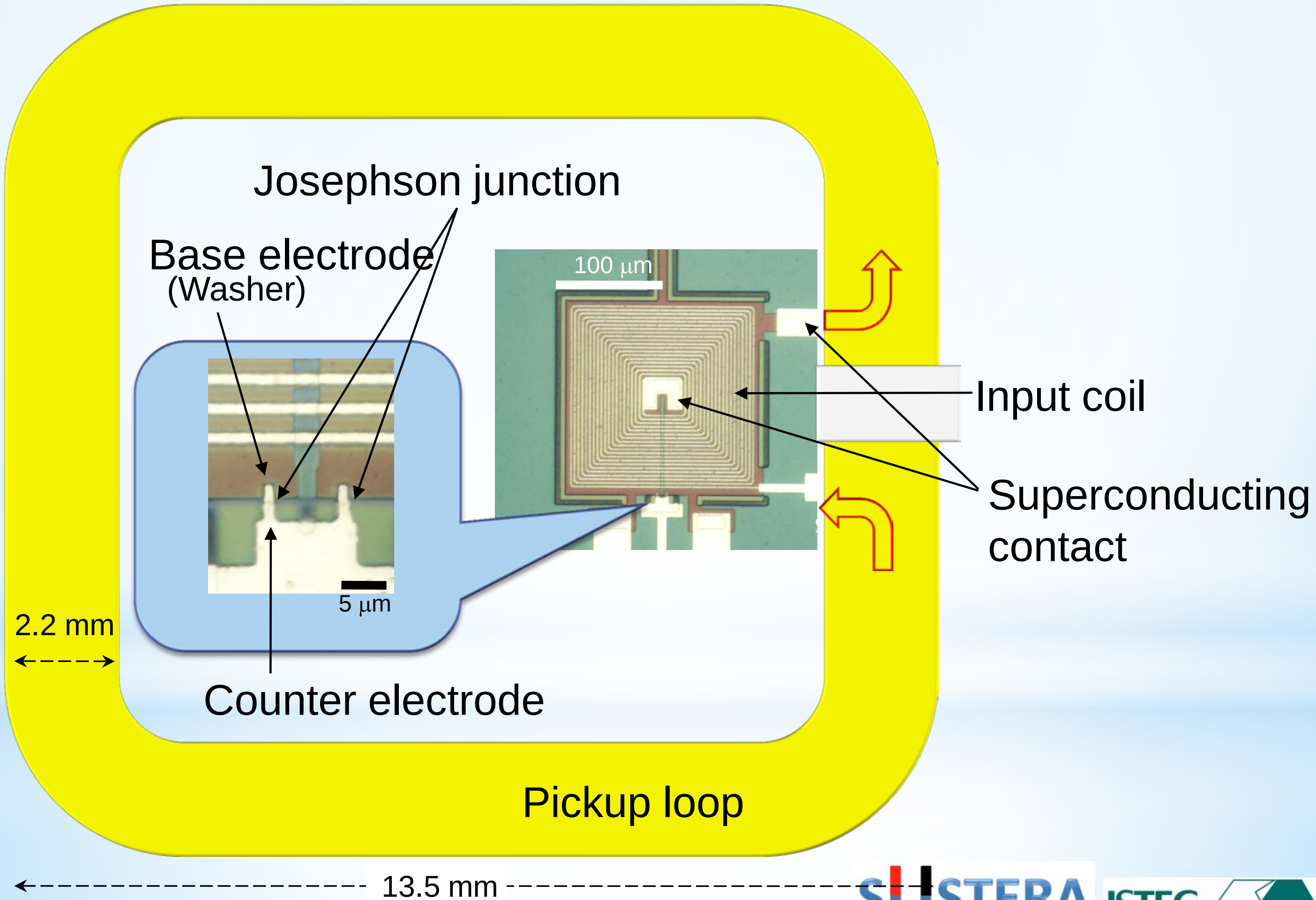
Magnetometer (Module)



+ mostly used for TEM systems
for exploration of metal, geothermal, oil resources

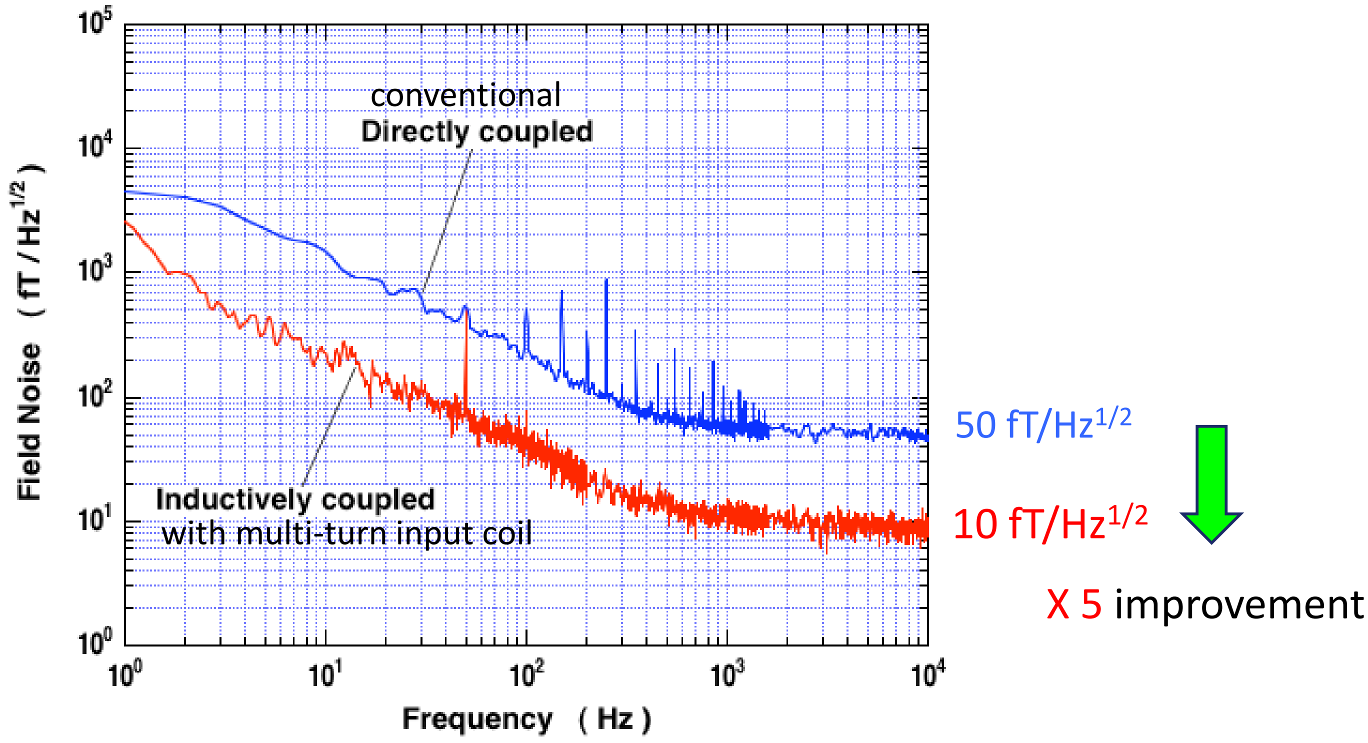
SUSTERA ISTEC

Magnetometer with integrated input coil



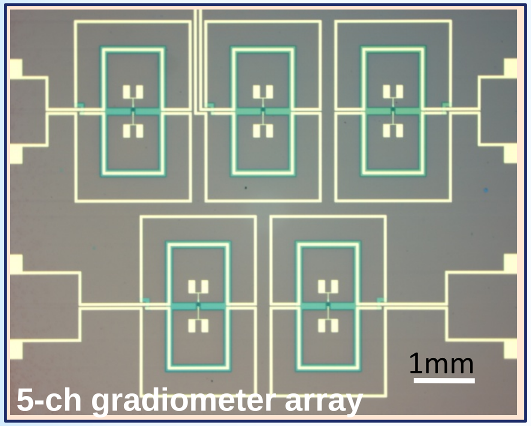
H. Wakana *et al*., IEEE Trans. Appl. Supercond. **19** (2009) 782.

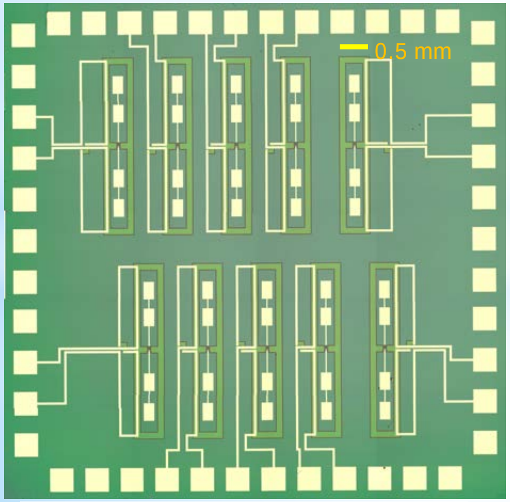
Magnetometer with integrated input coil



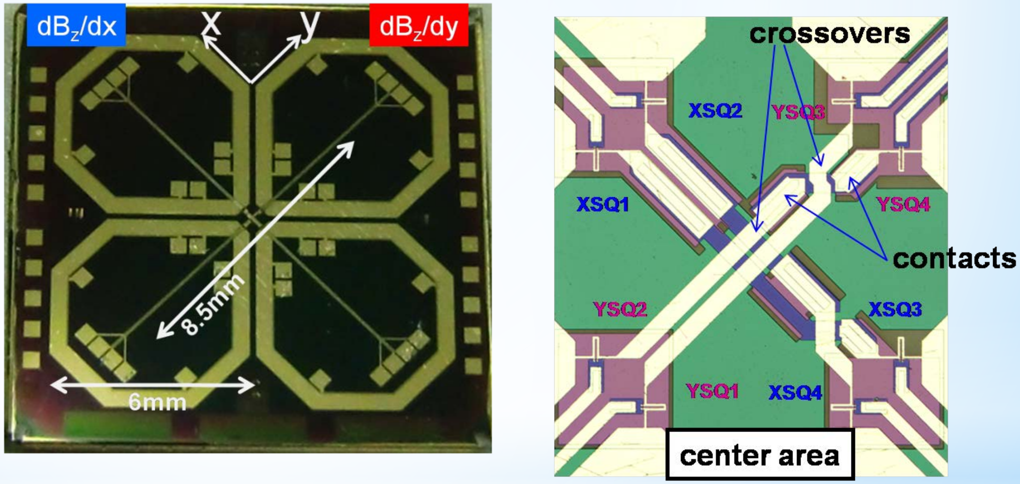
H. Wakana *et al.*, IEEE Trans. Appl. Supercond. **19** (2009) 782.

Gradiometers





10-ch gradiometer array

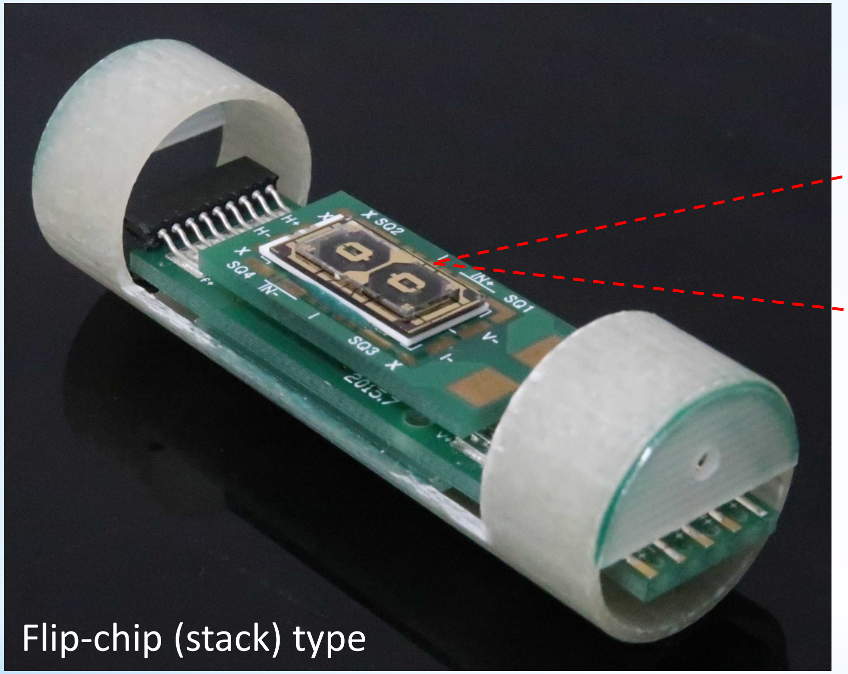


Two-axis gradiometer

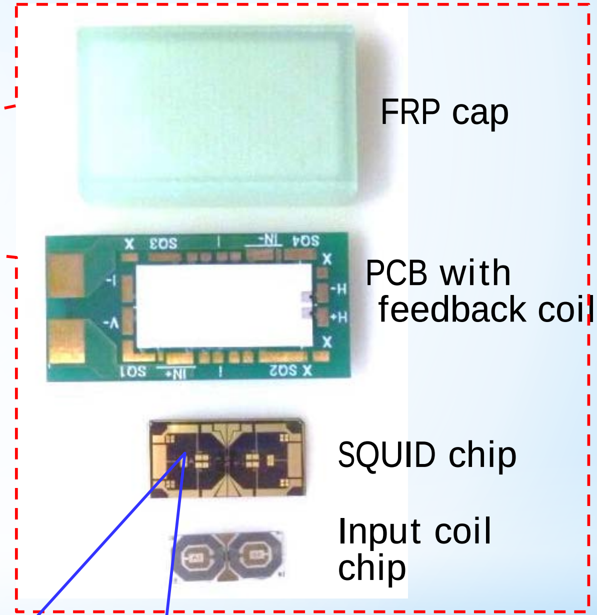
A. Tsukamoto *et al.*, IEEE Trans. Appl. Supercond. **21** (2011) 363.

SUSTERA ISTEC

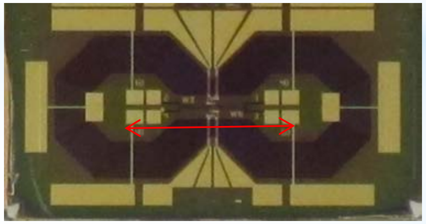
Gradiometer for use with external pickup coil



Gradiometer module



+ enable flexible system design
+ mostly used for NDT systems
  magnetic immunoassay system



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

(4) Application of Multilayer HTS SQUIDs

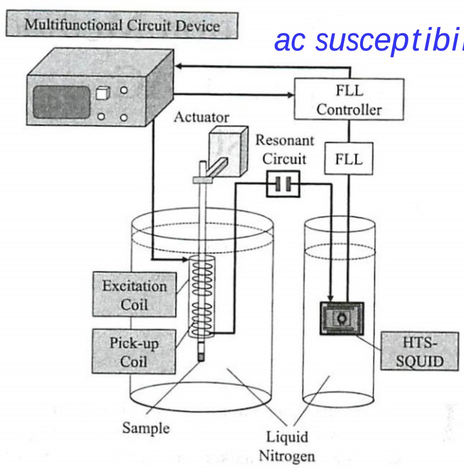
- Non-destructive testing (NDT)
  multi-filamentary coated conductor, infrastructure (expressway bridge)

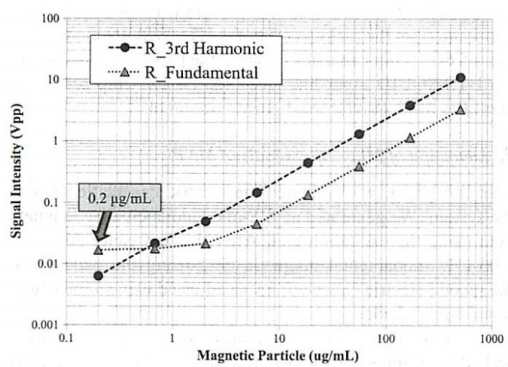
- Exploration/Monitoring of natural resources (ground TEM)
  metal deposit, geothermal reservoir, oil reservoir

- Monitoring of CO_2 EOR (borehole TEM), CCS

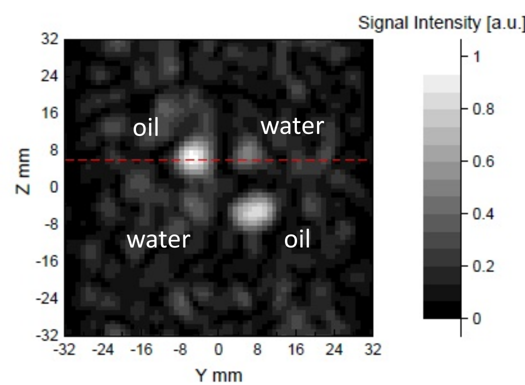
- Liquid-phase assay using magnetic nanoparticles, ULF-NMR/MRI

ac susceptibility measurement system





T. Mizoguchi *et al.*, IEEE Trans. Appl. Supercond. **26**, 1602004 (2016).



T_1-waited image

K. Demachi *et al.*, IEEE Trans. Appl. Supercond. **29**, 1600905 (2019).

Highly-sensitive magnetic nondestructive testing
for deterioration diagnosis and maintenance of infrastructure

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

Member: K. Tsukada (Okayama Univ.)	compact NDT system with MR sensor
K. Tanabe (SUSTERA)	highly-sensitive NDT system using SQUIDs
T. Furukawa (JAPEIC)	simulation, pulse ECT method with MR sensor
T. Sasayama (Kyushu Univ.)	inverse problem

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

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

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

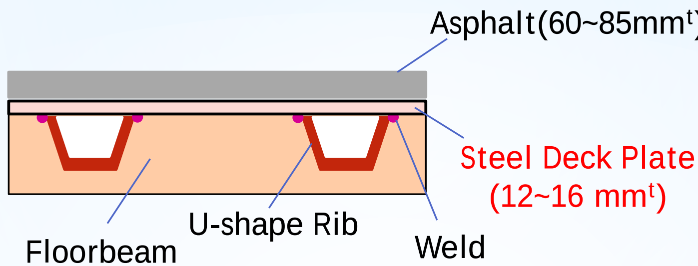


700,000 bridges, 100,000 tunnels many of them older than 50 years
huge maintenance cost has to be saved by technologies

Highly-sensitive magnetic nondestructive testing
for deterioration diagnosis and maintenance of infrastructure

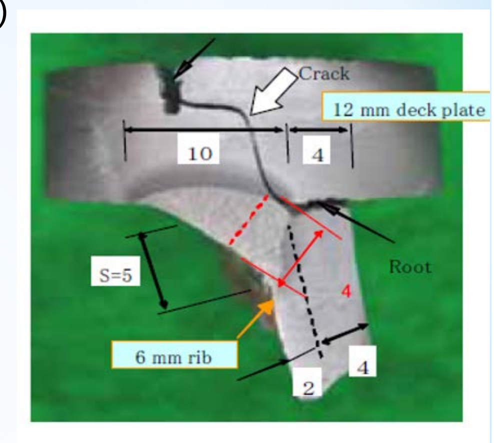
Target of NDT system with HTS-SQUIDs: Fatigue crack in steel deck plate

Orthotropic steel deck bridge (Hanshin expressway)



Orthotropic steel deck (OSD) structure

OSD consists of a flat, thin steel deck plate, stiffened by a series of closely spaced longitudinal ribs which are supported by orthogonal transverse floor beam.



Fatigue crack [1]

- We have developed an HTS-SQUID eddy current testing (ECT) system to detect fatigue cracks through asphalt pavement.
- SQUID has high sensitivity even at low frequencies

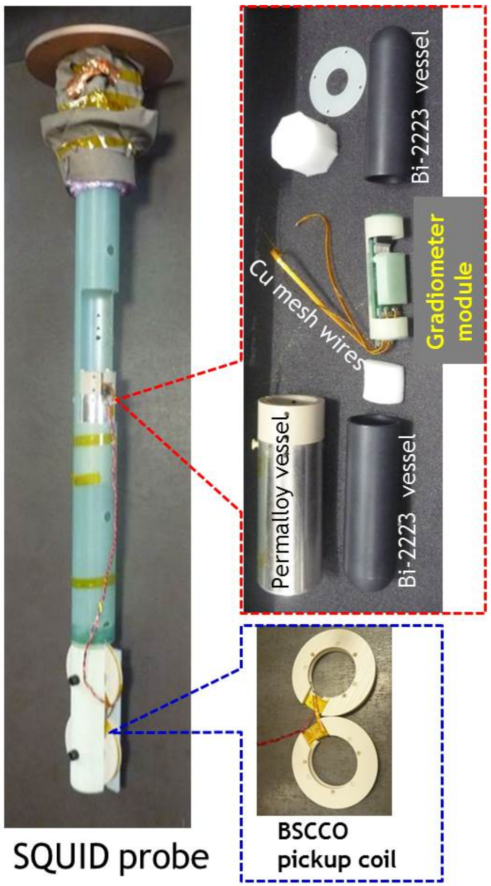
→ detection at larger lift-off
detection of non-through crack (skin depth, $\delta = (2/\mu\sigma\omega)^{1/2}$) expected

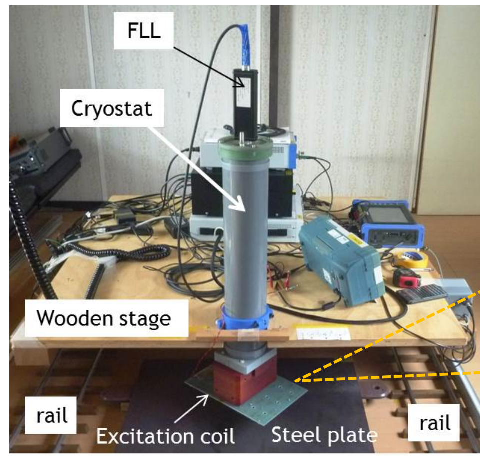
[1]: A. Tabata *et al.*, "Inspection and reinforcement for fatigue damages on orthotropic steel deck bridge", Hanshin Expressway Company Limited, Japan

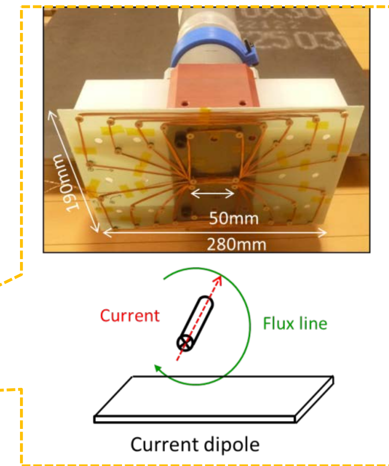
IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), September 2019.
Distinguished presentation 2-FA-D-1 given at ISEC, 28 July-1 August 2019, Riverside, USA.

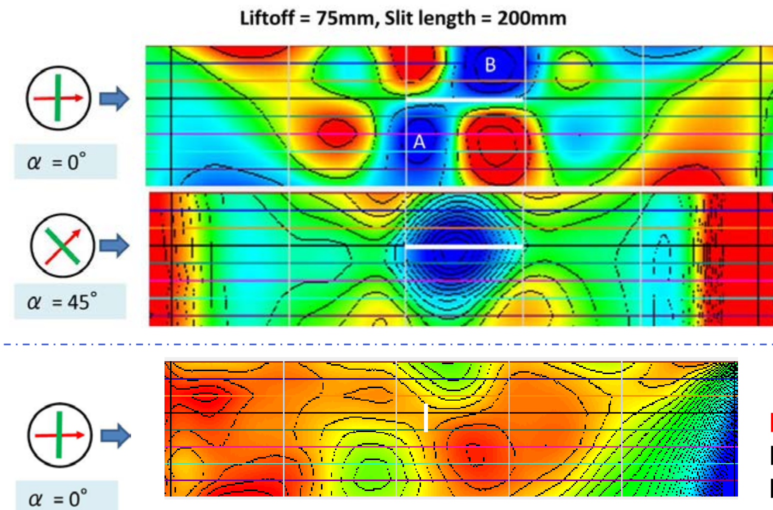
Highly-sensitive magnetic nondestructive testing

for deterioration diagnosis and maintenance of infrastructure









Im signal
Red : positive
Blue : negative

Detection of 50 mm slit at 100 mm lift-off possible

Re signal
Non-through slit
Length = 50 mm
Depth = 2 mm

A. Tsukamoto *et al.*, IEEE Trans. Appl. Supercond. **27**, 1600505 (2017).

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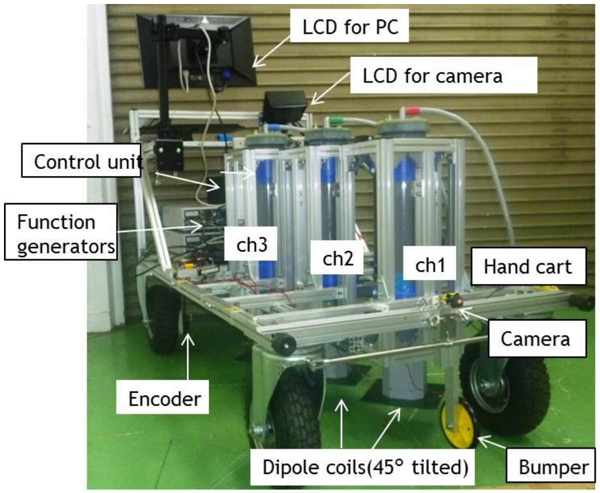
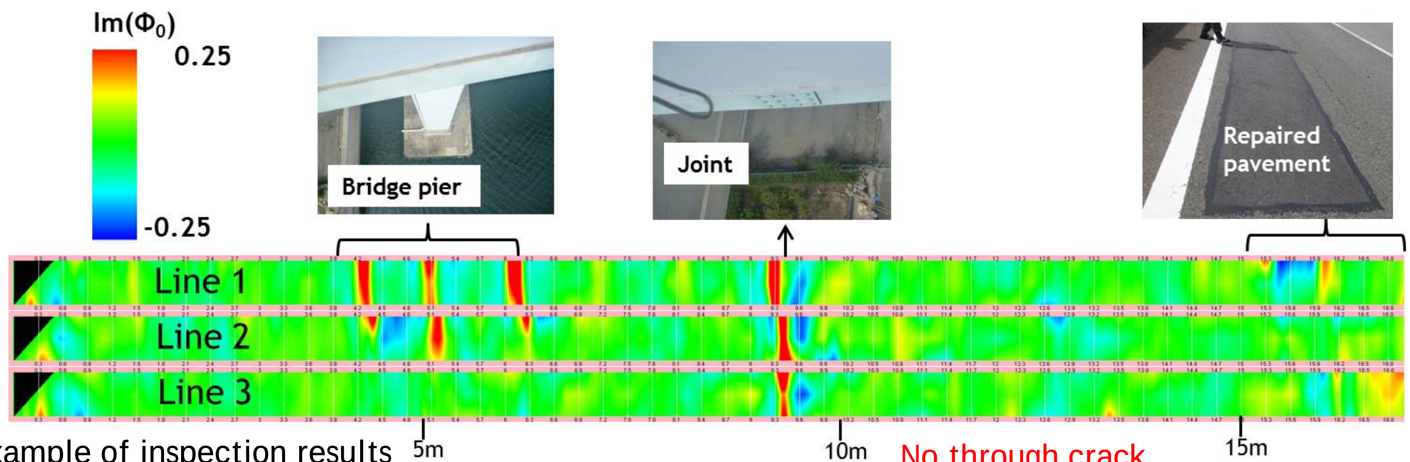
Highly-sensitive magnetic nondestructive testing

for deterioration diagnosis and maintenance of infrastructure



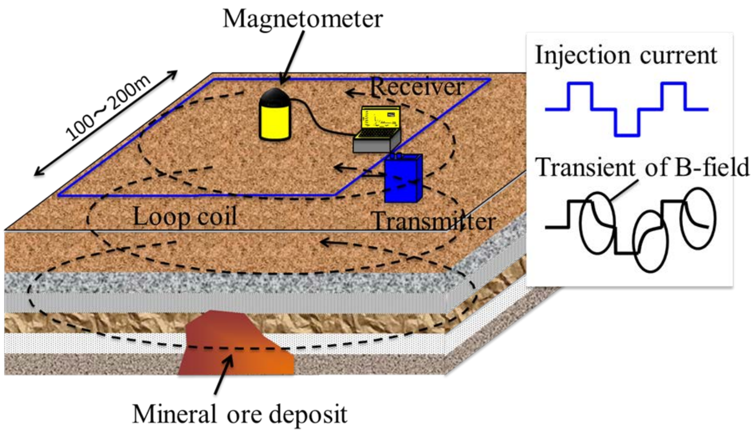
Prototype road inspection system

Field test on expressway bridge (Oct. 2018)

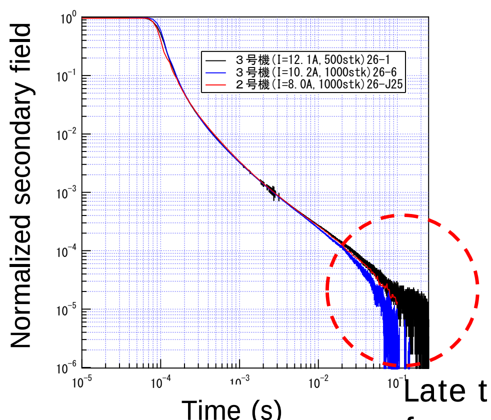


Example of inspection results

SQUITEM-III
for exploration of metallic deposit

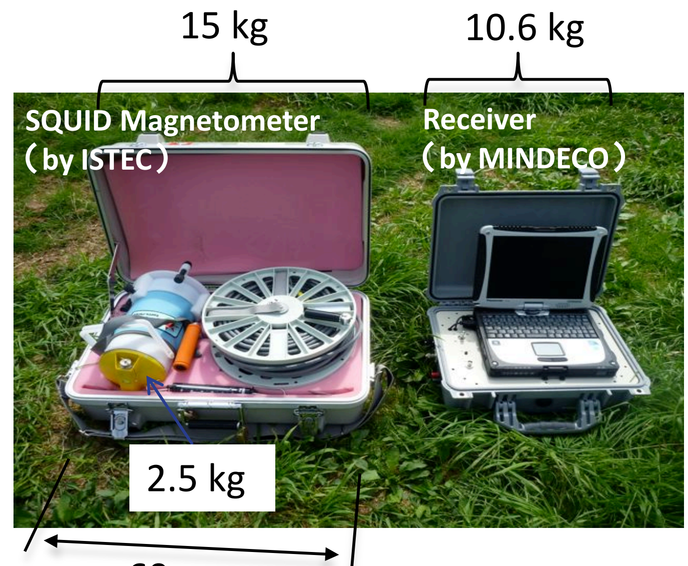


Transient electromagnetic (TEM) method



Late time data
from deeper underground

TEM system using multilayer HTS SQUID



Compact design
Vacuum maintenance free
Keep LN_2 for 17 h
> x 10 higher slew rate (10.5 mT/s)
(> x 20 higher S/N)

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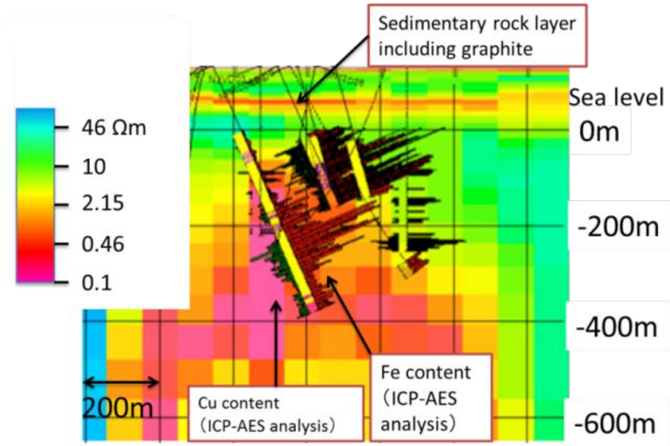
T. Hato *et al.*, Supercond. Sci. Technol. **26**, 115003 (2013).

SQUITEM-III

for exploration of metallic deposit



Field test result in Australia

Actual exploration in Peru

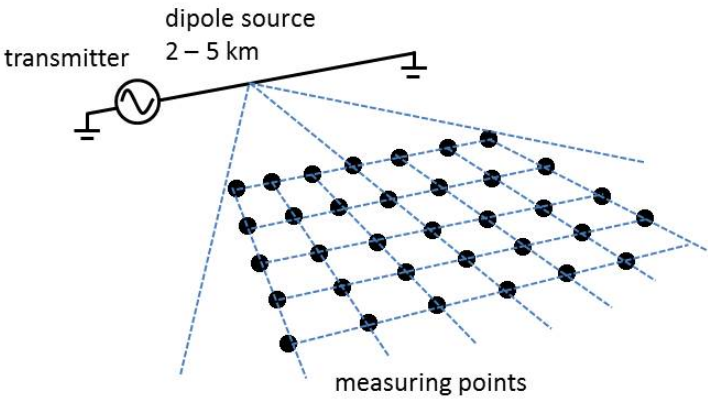
Development of improved SQUITEM-III (FY2015-FY2016)
- x, y, z 3-component SQUID sensors tested in Australia field

SUSTERA has two SQUITEM-III systems for new application

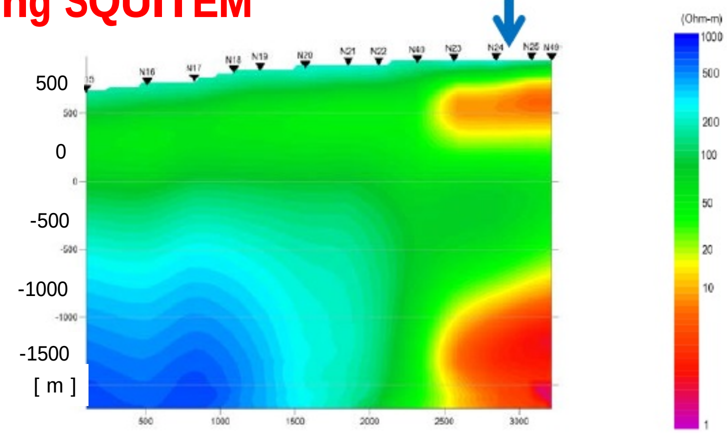
JOGMEC ISTEC MINDECO SUSTERA

Exploration of geothermal reservoir

LOTEM(Long-offset TEM) using SQUITEM



Boundary found by Gravity survey



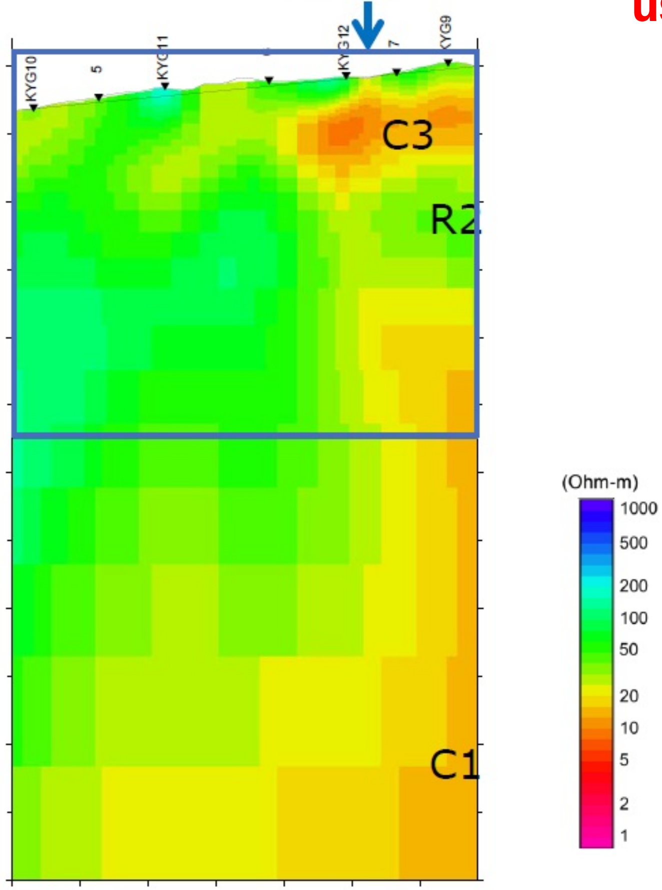
C: conductive zones
R: resistive zones

NEDO results briefing meeting
http://geothermal.jogmec.go.jp/report/event_180618.html

Exploration of geothermal reservoir

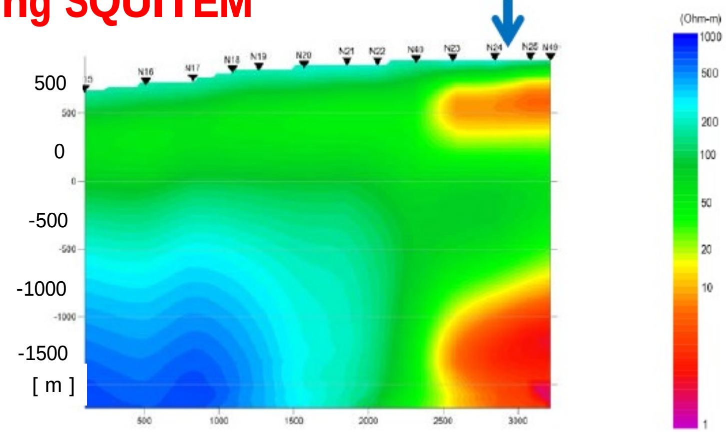
MT
(Magnetotelluric)

Boundary found by Gravity survey



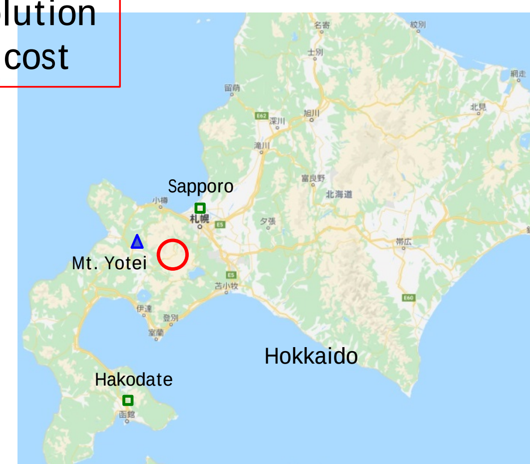
LOTEM(Long-offset TEM) using SQUITEM

Boundary found by Gravity survey



Higher spatial resolution
Lower exploration cost

C: conductive zones
R: resistive zones



NEDO results briefing meeting
http://geothermal.jogmec.go.jp/report/event_180618.html

Monitoring of oil reservoir

Field test using SQUITEM was performed in November 2017.
Collaboration between PTTEP and JOGMEC (MINDECO and SUSTERA joined.)

Figure 1. Location of the Phitsanulok Basin and other Cenozoic basins in northern Thailand. Modified from Morley and others (2001), Morley (2009), and Palin and others (2013).

Sirikit oil field
(Thailand)

Oil reservoir at -2000 m
EOR by water flooding

Transmitter Site (2000 m long dipole source was used.)

Arrangement of the transmitter

Signals for operating the generator

confirmation of transmission waveform

Reciever Site

Sugarcane

Rice field

Moving the receiver

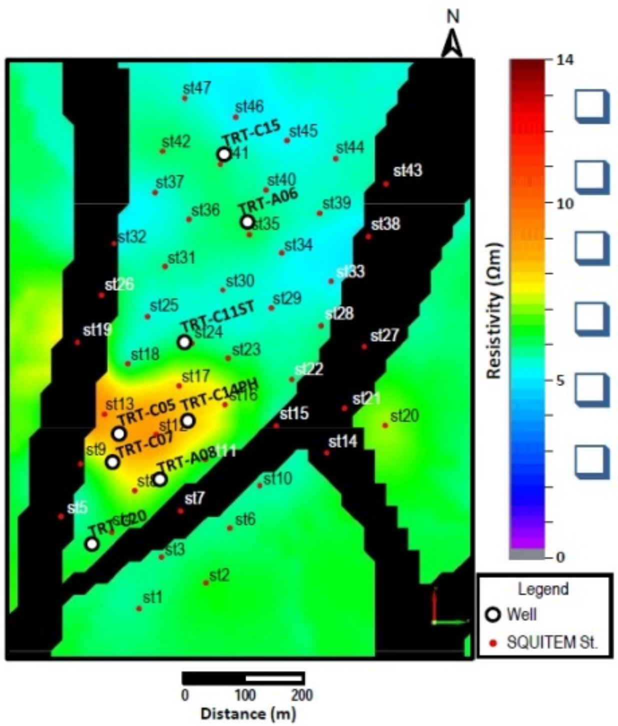
V. Hansamuit (PTTEP) @JOGMEC Techno Forum 2018

http://techno-forum.jogmec.go.jp/2018/detail/index.html

Monitoring of oil reservoir

Field test using SQUITEM was performed in November 2017.
Collaboration between PTTEP and JOGMEC (MINDECO and SUSTERA joined.)

PTTEP

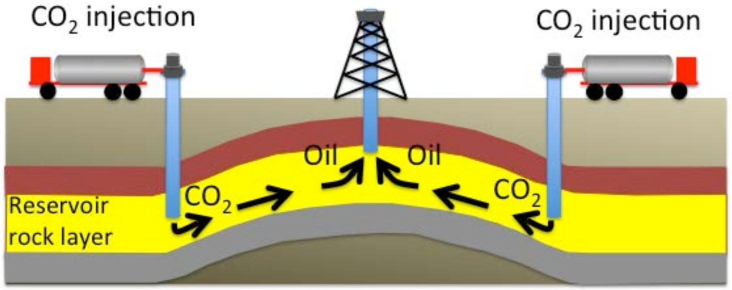


Resistivity Map of SQUITEM 1D inversion

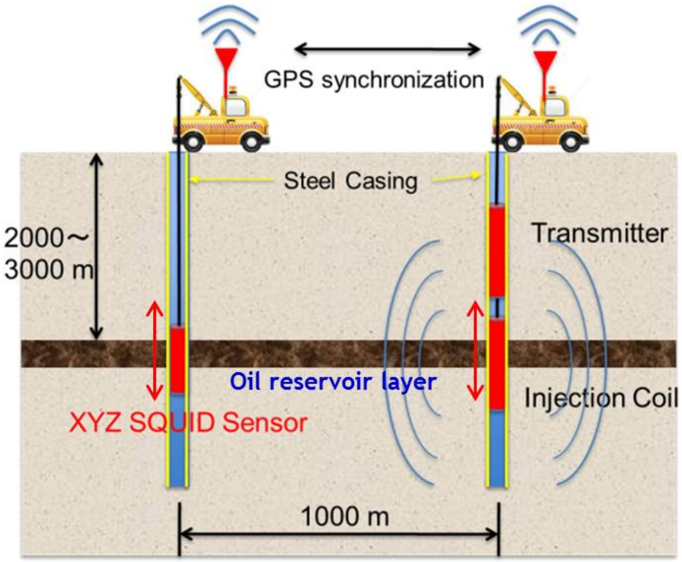
- Promising Outcome
- 2nd Survey is planned
- Extend to 3D model

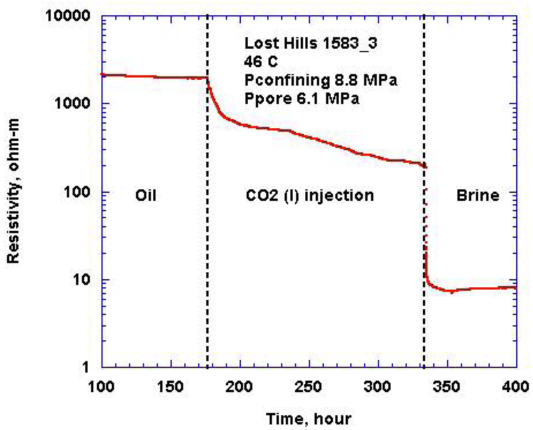
V. Hansamuit (PTTEP) @JOGMEC Techno Forum 2018
http://techno-forum.jogmec.go.jp/2018/detail/index.html

Monitoring of CO_2 EOR (Borehole TEM)



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





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

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

EM in wells with steel casing and the distance > 1000 m expected

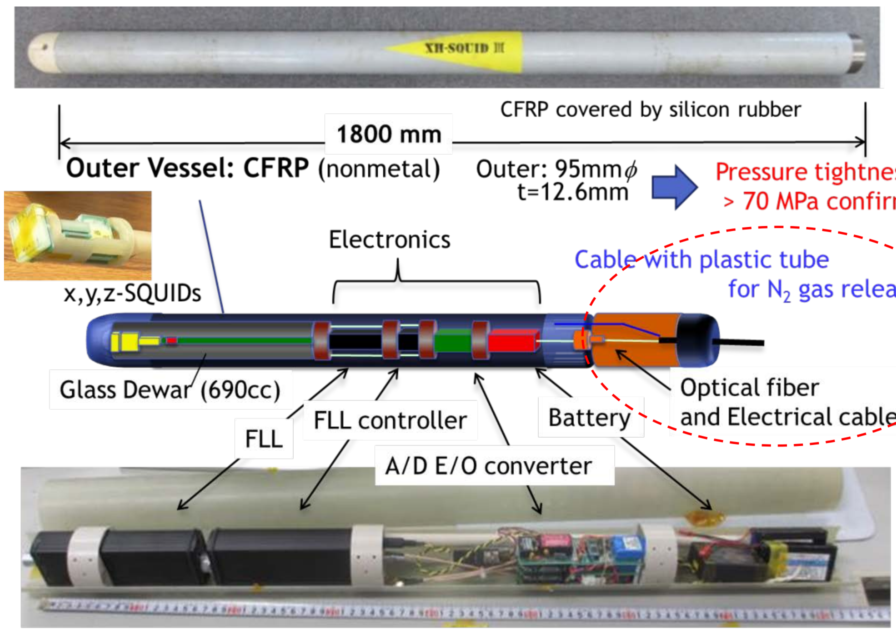
Technical challenges:

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

Monitoring of CO_2 EOR (Borehole TEM)

Development of elemental technologies

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



Control of SQUIDs through 3 km long optical fiber confirmed

SQUID receiver system for use in a test well

JOGMEC Kashiwazaki test field

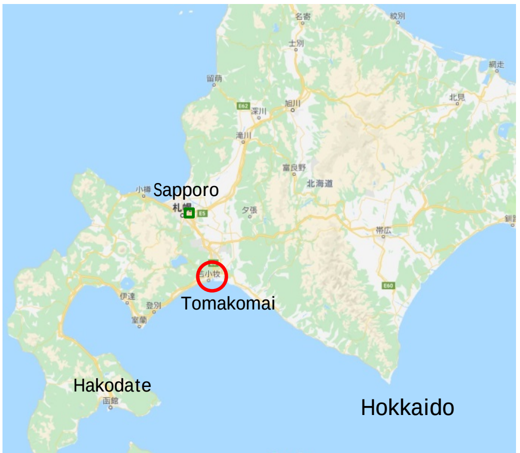
Stable operation in borehole filled with oily water at ∼300 m confirmed.

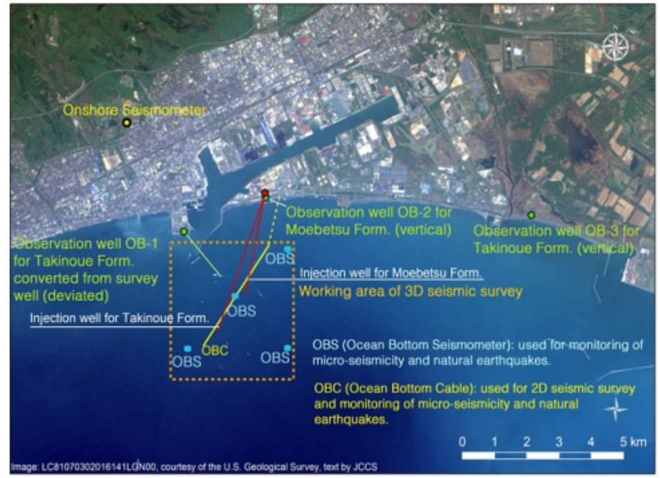
Test results indicated a possibility of long distance EM logging > 1000m.

ISTEC MINDECO JOGMEC

T. Hato *et al*., IEEE Trans. Appl. Supercond. **27**, 1600705 (2017).

Monitoring of CCS (CO_2 capture and storage)

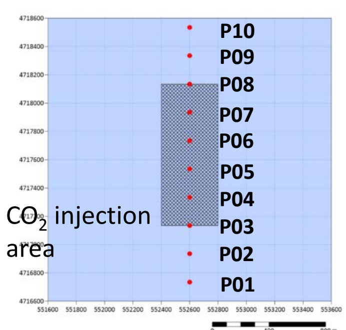


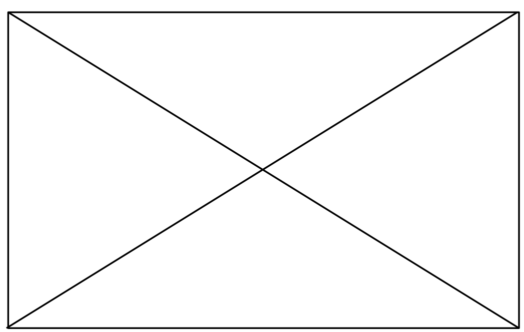


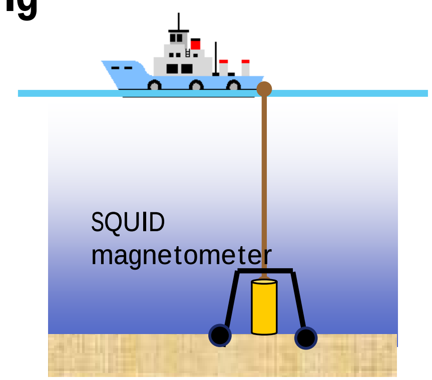
Reservoir1:
Moebetsu fm.
1000-1200 m
below Sea level

Tomakomai CCS Demonstration Project (https://www.japanccs.com/en/business/demonstration/deploy.php)

Possibility of applying TEM (LOTEM) to monitoring



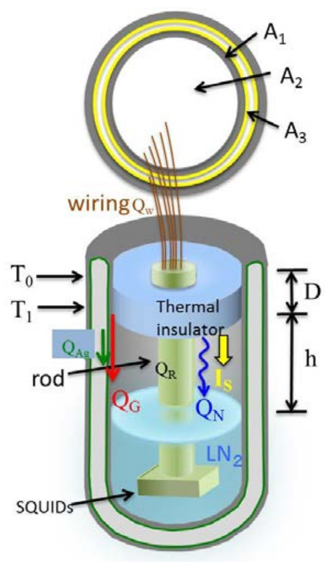


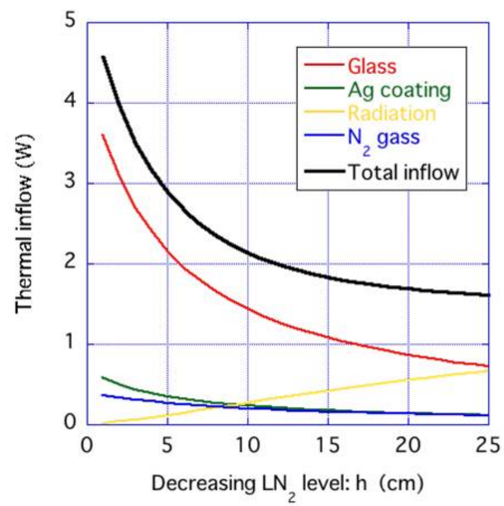


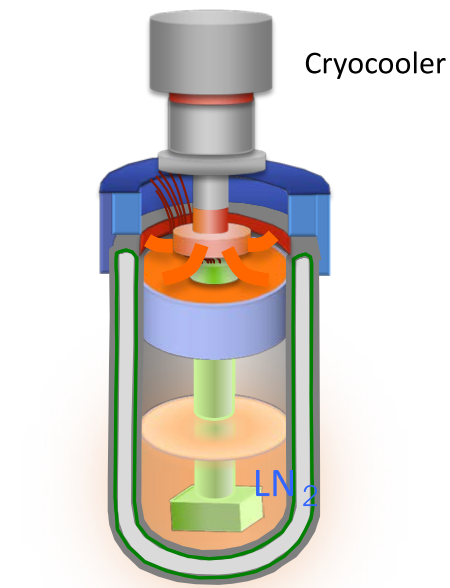
Difference of transient curves (numerical simulation)
(with and without CO_2) 100A transmitter current

Image of TEM observation

New development of cooling technique







Cooling with liq. N_2 in a glass Dewar

T. Hato and K. Tanabe, IEEE Trans. Appl. Supercond. **28**, 1601404 (2018).

+ Heat inflow determines holding time of LN_2.
+ Heat inflow due to thermal conduction trough glass wall and radiation from thermal insulator is dominant .

Hybrid cooling system

+ enables long-time operation in the sea

Issues:

+ How to remove cooler heat
+ good thermal contact
+ vibration & noise

SUSTERA

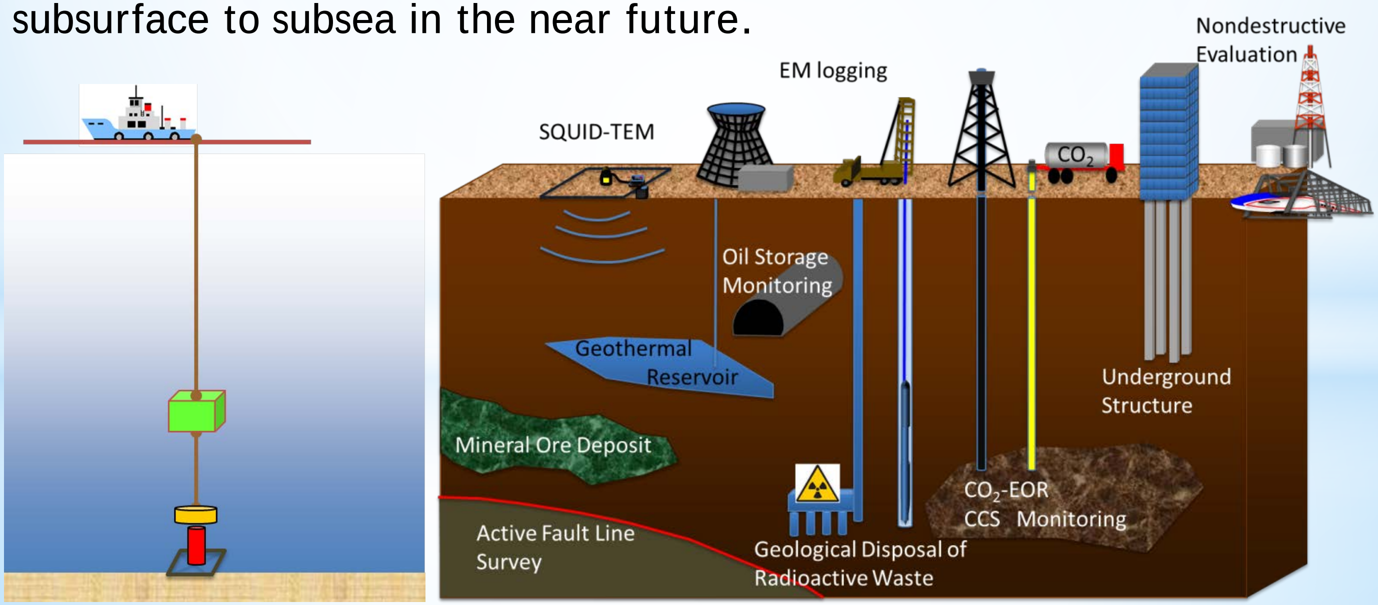
Initial results will be presented by T. Hato at EUCAS2019

Summary

HTS multilayer and ramp-edge junction technologies developed for HTS SFQ circuits were successfully applied to the development of multilayer HTS SQUIDs with relatively high tolerance against application of magnetic field.

Using such multilayer HTS SQUIDs, a variety of systems for use on the ground or road, and in a borehole have been developed and demonstrated.

At SUSTERA, we will try to further expand HTS-SQUID application, for example, from subsurface to subsea in the near future.



Collaborators

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