IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January 2017.
Plenary presentation AT-2 given at 1st Asian ICMC – CSSJ 50th Anniversary Conference; Kanazawa, Japan, November 7 - 10, 2016.

Overview of HTS Large Scale Application in Japan

1st Asian ICMC and CSSJ50

November 8, 2016@Kanazawa

Kenichi Sato
Japan Science and Technology Agency (JST)

Japan Science and Technology Agency

Typical Superconductivity Projects

Ministry	Funding Agency	Superconductivity Project
MEXT	JST (Total FY2015 Budget: 1,207 M$) (100¥/$)	SENTAN (1.03 GHz NMR, 3T/MRI) S-Innovation ALCA
Science Council of Japan		High Magnetic Field Collaboratory
METI	NEDO (Total FY2015 Budget: 1,298 M$) (100¥/$)	Promotion of Commercialization of HTS Cable and Magnet (2016-) Yokohama HTS Cable / Safety & Reliability of HTS Cable Ishikari HTS/DC Cable CC Magnet (METI - AMED) 300kW Flywheel M-PACC 3MW Ship Propulsion Motor 100kW Motor for Bus

MEXT: Ministry of Education, Culture, Sports, Science and Technology
JST: Japan Science and Technology Agency
METI*: Ministry of Economy, Trade and Industry
NEDO: New Energy and Industrial Technology Development Organization
AMED: Japan Agency for Medical Research and Development

Japan Science and Technology Agency

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NEDO: New Energy and Industrial Technology Development Organization
AMED: Japan Agency for Medical Research and Development

Japan Science and Technology Agency

JST Program "S-Innovation" on Superconducting Systems Launched in 2009FY

Basic Research

- Understanding of Essentials
- Breakthrough

Applied Basic Research
Components Technology
Application Model

- Bridging Research —
<Industry / Academia>

- **System Concept**
- **HTS Key Technology**
- **Components**
- **Cryogenics**

Application Development Research

- Implementation
- Manufacturing Technique
- Cost Down

Japan Science and Technology Agency

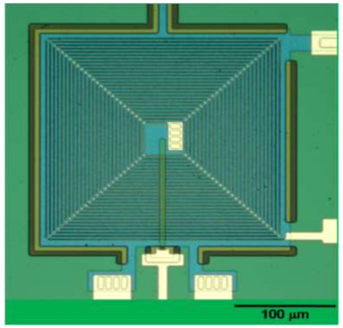
Features of Superconducting Systems in S-Innovation

- **Focus on HTS**
- **Select 5 Teams thorough Peer Screening**
- **Plural Teams do Information Exchange**
- **Academia and Industry Collaboration**
- **Max. 10 Years Seamless Funding (FY 2009 – FY 2018)**

(Program Officer: K. Sato)

Five Teams Developing HTS System

HTS SQUID System

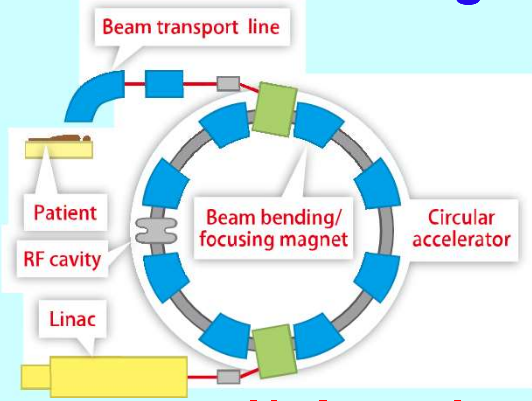


K. Enpuku

20 MW HTS Motor (2009-2013)

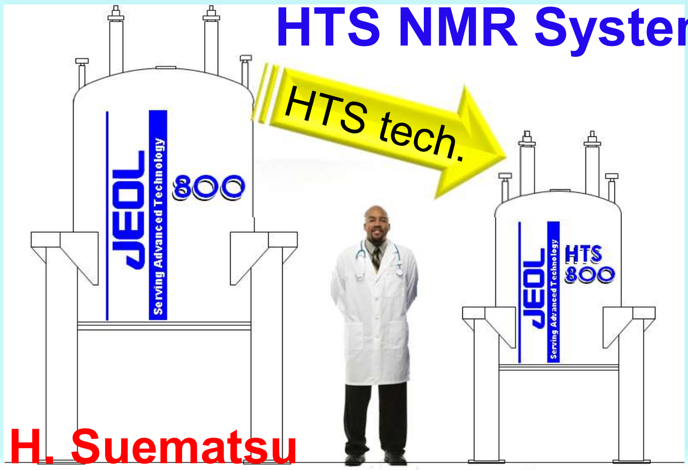
T. Yanamoto

HTS Accelerator Magnet



N. Amemiya

HTS NMR System



H. Suematsu

Next Generation Railway System

M. Tomita

Applied Basic Research, Component Technology, Application Model FY 2009 – FY 2018

Japan Science and Technology Agency

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IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January 2017.
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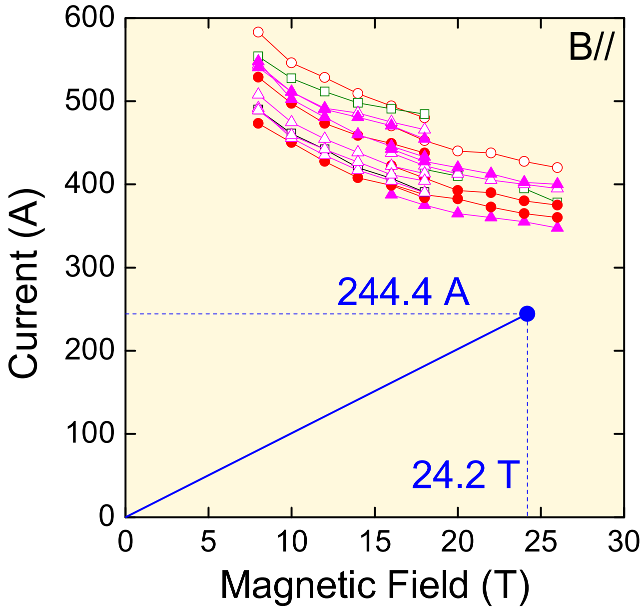
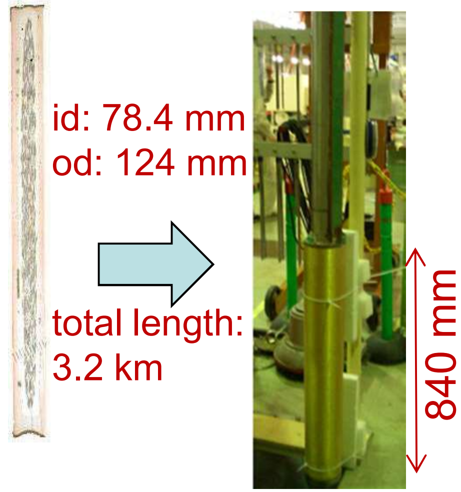
Magnets

-Sentan-
1,020MHz (24 T) Achieved on Oct. 30, 2014

- NbTi + Nb_3Sn + DI-BSCCO
- A Half Year Continuous Run
- Next Stage Plan: ~1.3 GHz (30.6 T)



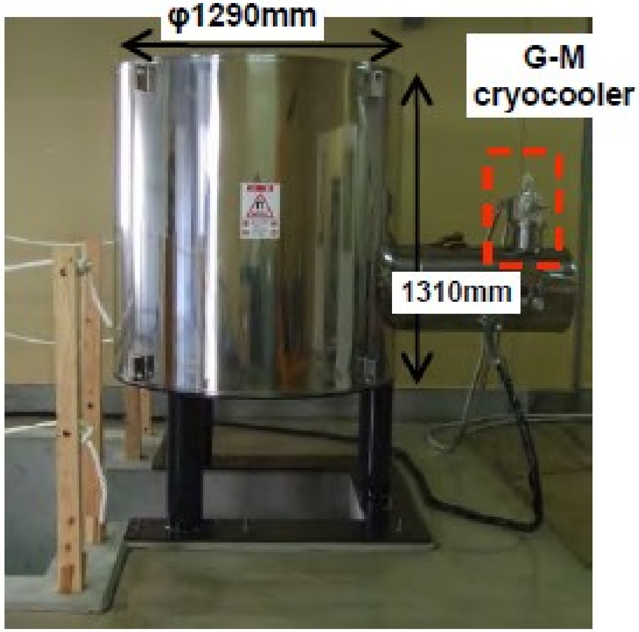


2015.7.1 http://www.nims.go.jp/news/press/2015/07/201507010.html

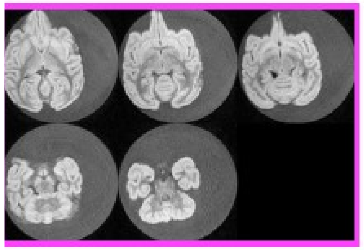
H. Maeda and T. Shimizu: J. Cryo. Super. Soc. Jpn. Vol.51(2016) p.324

-Sentan-
3T/MRI (DI-BSCCO) for Human Brain

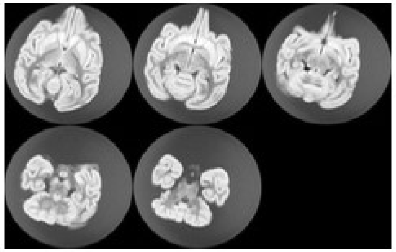
Diameter of RT bore	φ514mm with iron shims
Field strength	3T
Maximum Field strength	B_{axial}: 5.0T B_{radial}: 3.6T at coil#1,5
Field homogeneity	5ppm in r250mm×z200mm
Operation temperature	20K
Ic/Iop@20K	0.77
Stored energy	2.3MJ



Our HTS-MRI

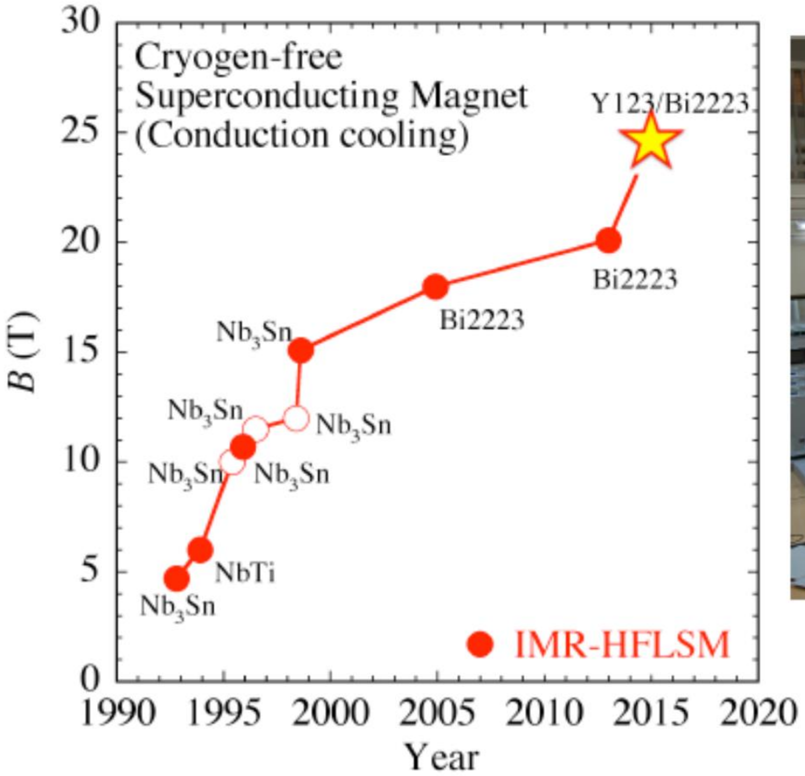


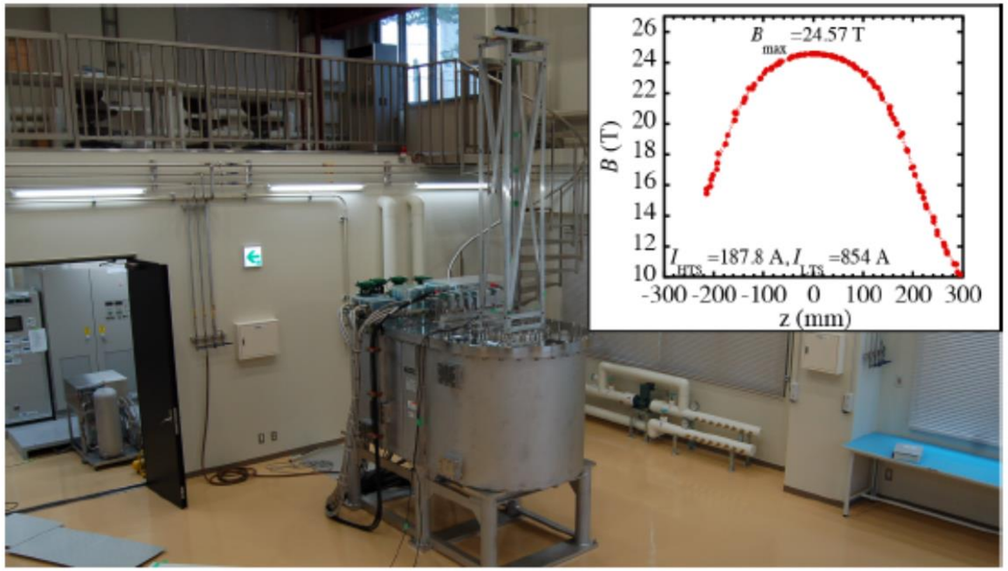
Siemens 1.5T(Sonata)



Japan Science and Technology Agency

- High Magnetic Field Collaboratory - 25 T Superconducting Magnet





NbTi + Nb_3Sn + Bi-2223 NX: 24.6 T
(14 T @ 5 K) (10.6 T @ 7.5K)

High Field Laboratory for Superconducting Materials (HFLSM),
Institute for Materials Research, Tohoku University

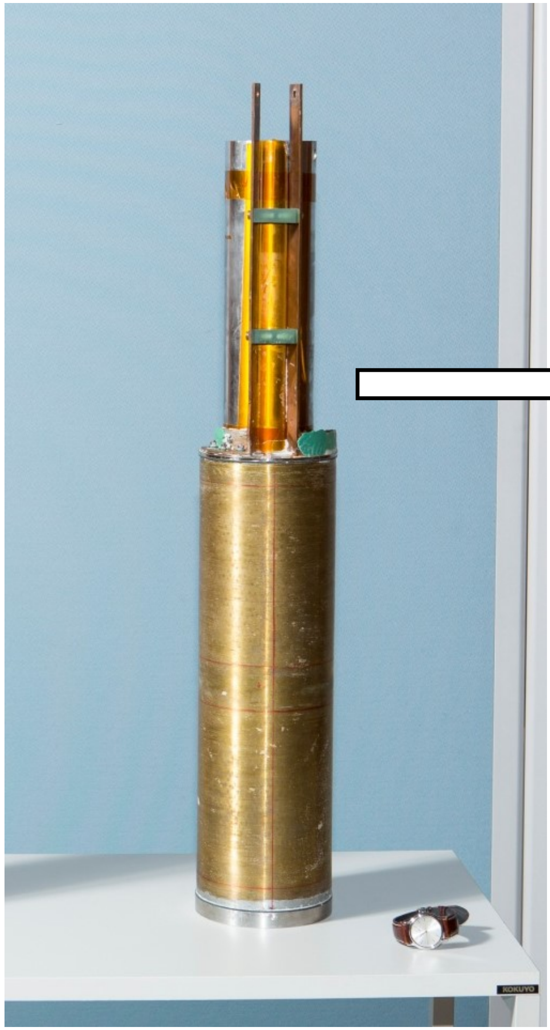
S. Awaji et al.: http://snf.ieeecsc.org/abstracts/sth41-achievement-246-t-cryogen-free-superconducting-magnet-sendai-hflsm

Japan Science and Technology Agency

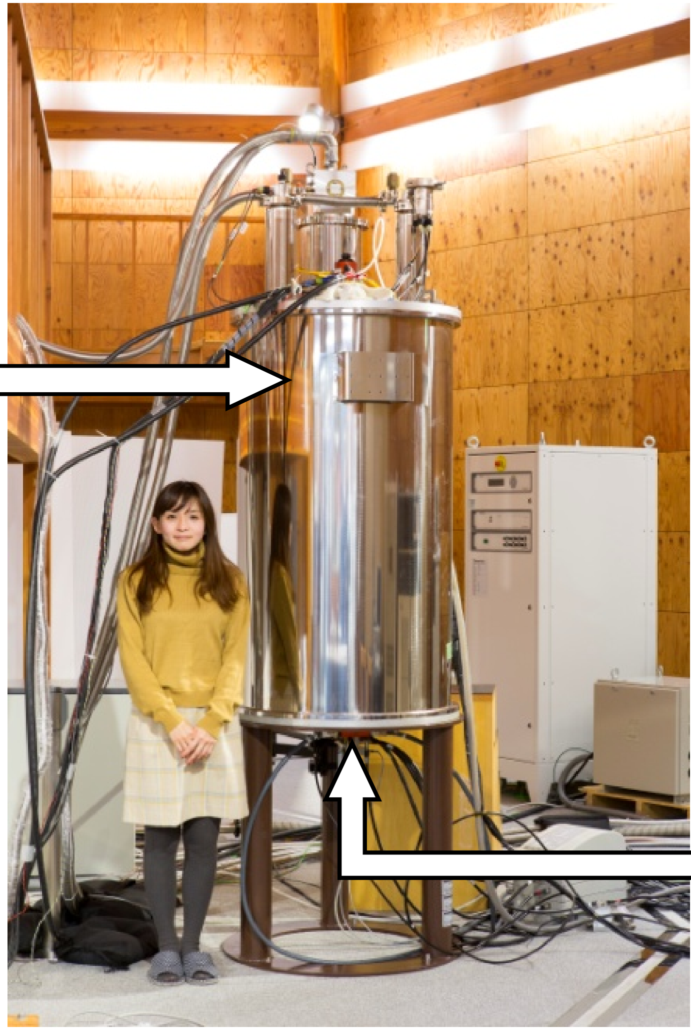
- S-Innovation -

High-resolution NMR measurement for a 400 MHz LTS/REBCO NMR magnet

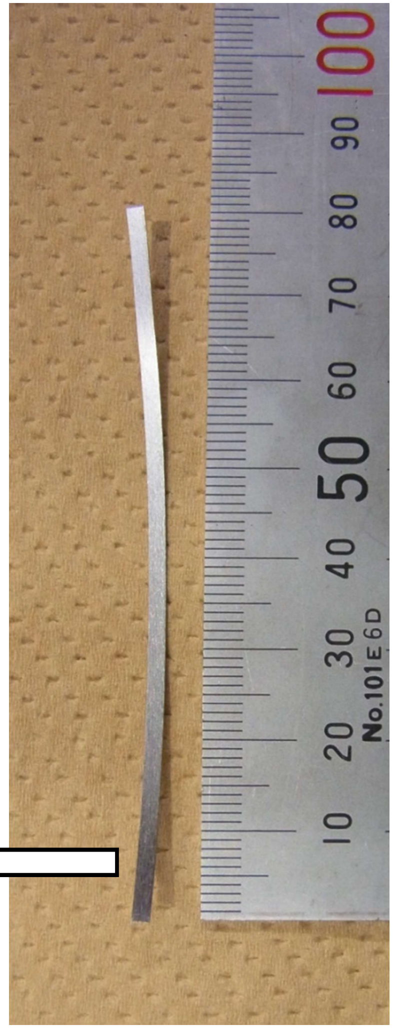
REBCO coil



400 MHz NMR



Simple ferromagnetic shim



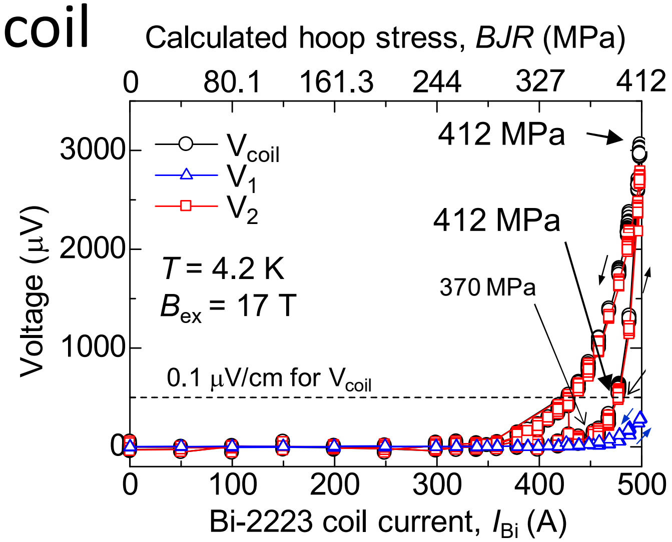
- S-Innovation -

Combination of a high hoop stress tolerance and a small screening current-induced field for a Bi-2223 NX coil in a high field

Bi-2223 NX layer-wound coil

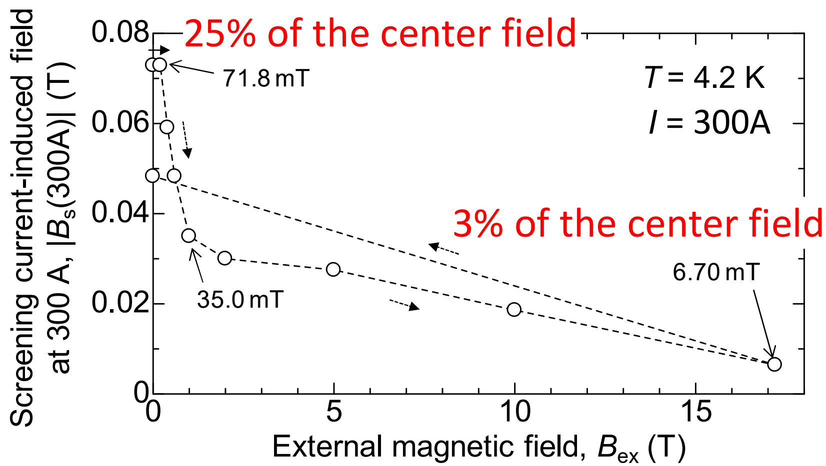
Ni-alloy reinforced conductor

Hoop stress test



Hoop stress tolerance >370MPa

Screening current-induced field



Small screening current-induced field in an external field >1 T

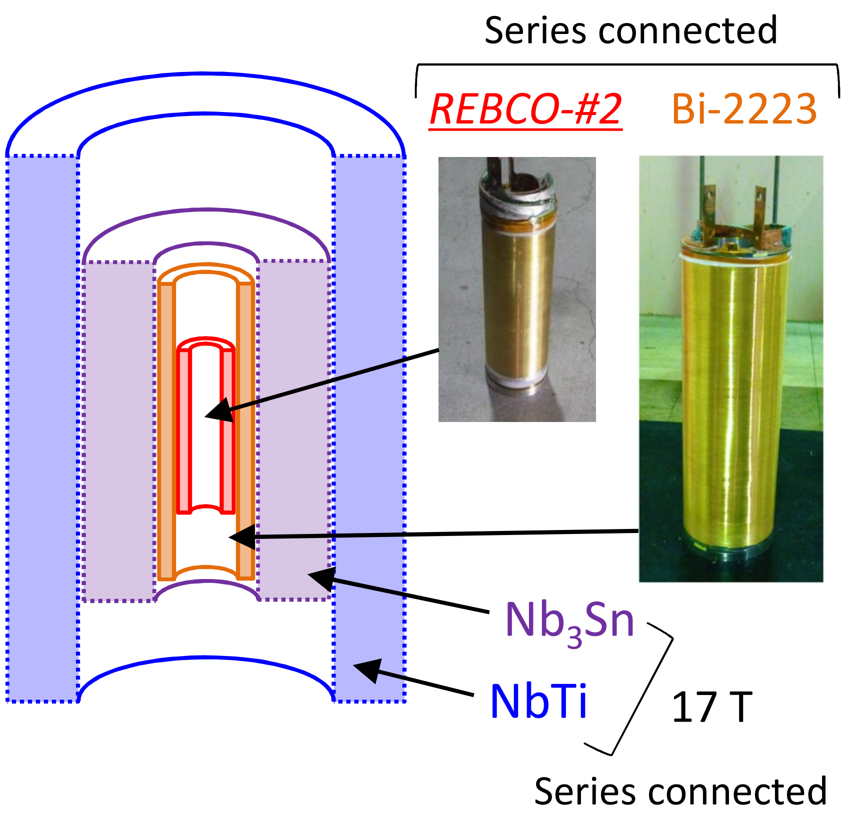
Yanagisawa et al. SuST 28, 125005 (2015)

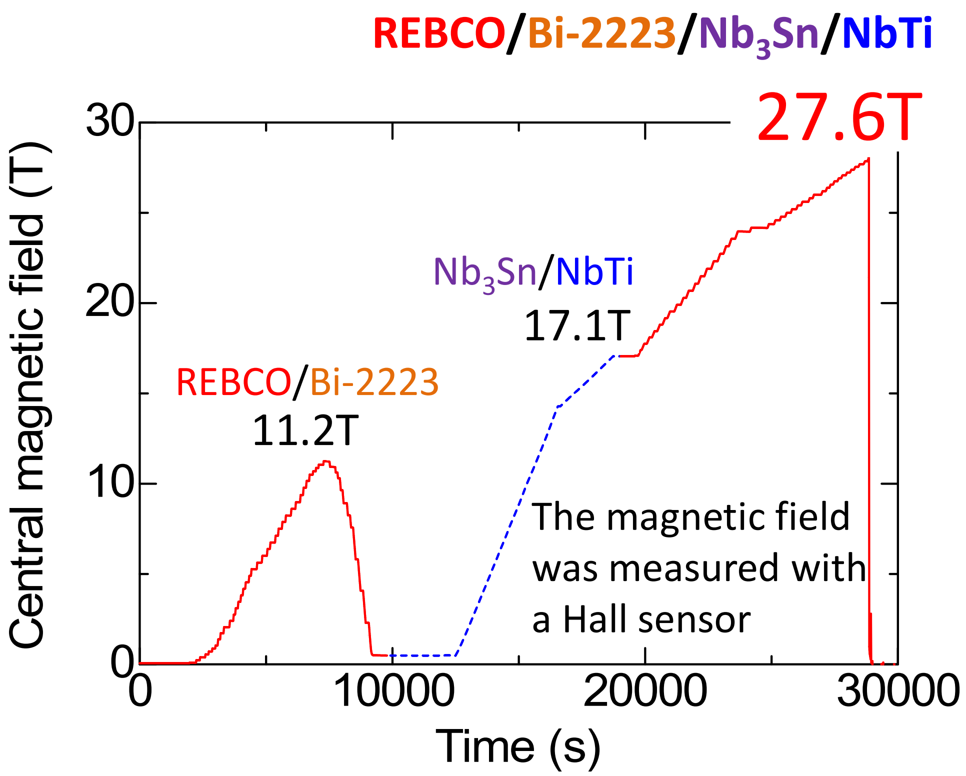
- S-Innovation -

A 28 T REBCO-Bi-2223-Nb_3Sn-NbTi coil; 27.6 T generation

Yanasawa et al. IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), July 2016.

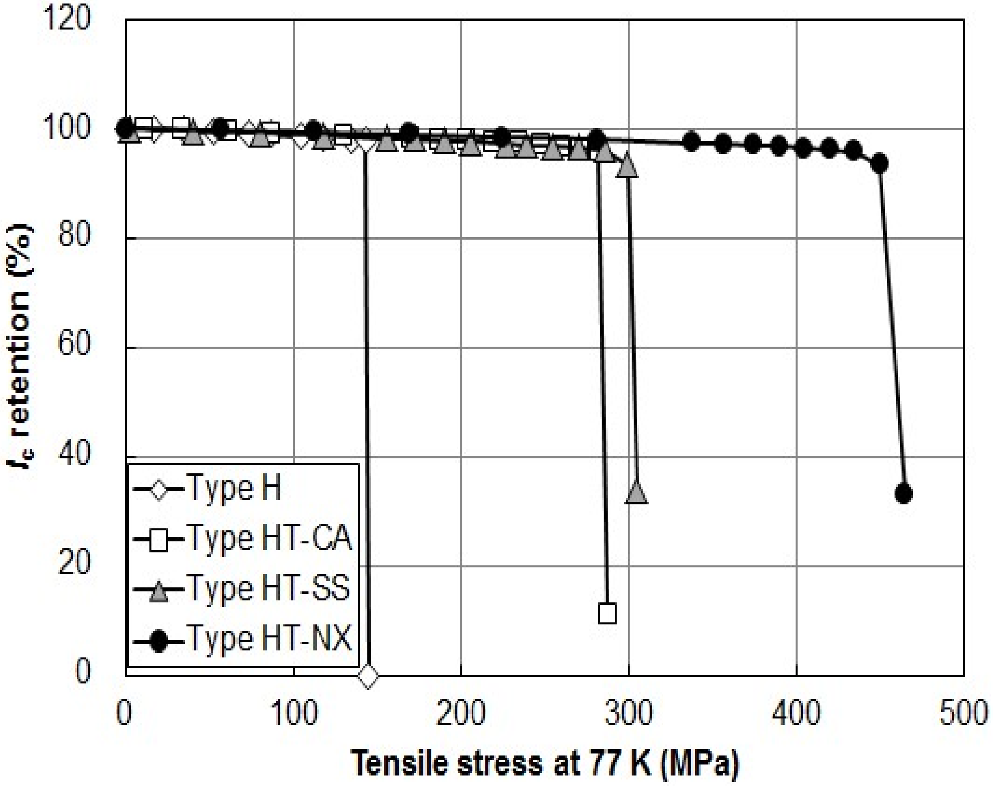
The second REBCO coil was fabricated with methods to reduce the degradation (outer binder and external joint)

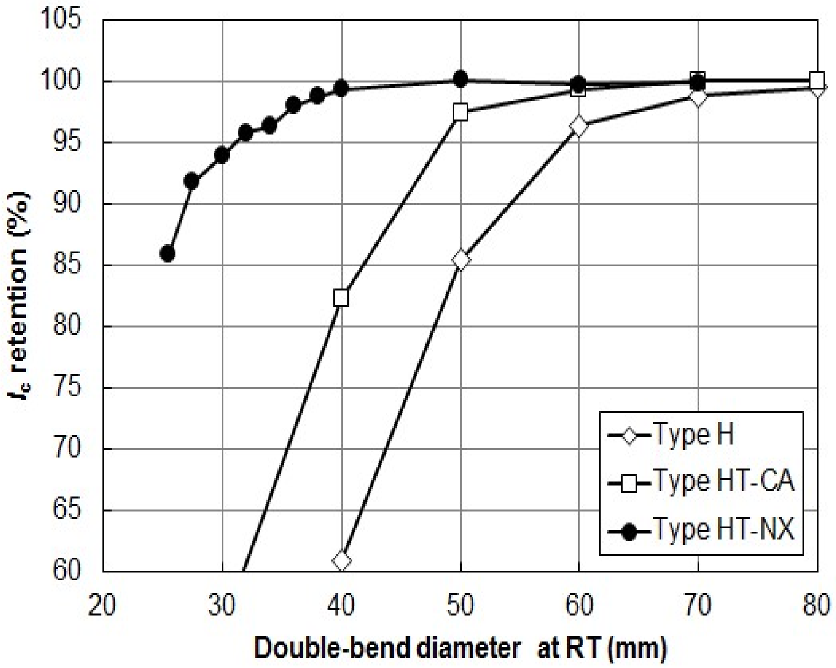




An increment of the world record of a magnetic field intensity for fully superconducting magnets operated at 4.2K

Application Driven Materials Development





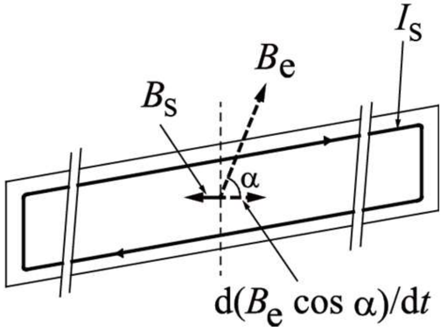
- High Strength HTS Wire for Super-High Field (Bi-2223 HT/NX) -

Ch. 2.1 S. Kobayashi and Ch. 2.3 A. Otto in "Research, Fabrication and Applications of Bi-2223 HTS Wires", Ed. Kenichi Sato, World Scientific 2016

Japan Science and Technology Agency

- S-Innovation -
What is particularly required for accelerator magnets and their fabrication?

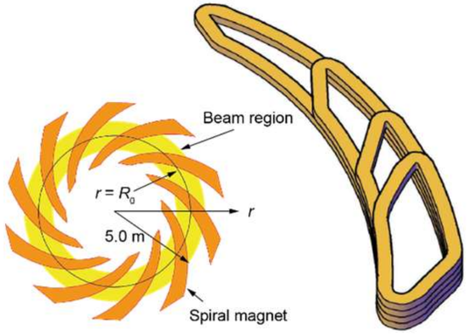
Generation of precise magnetic fields



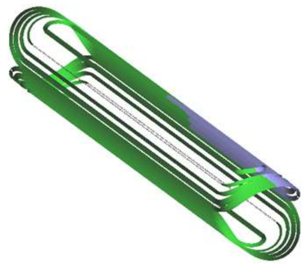
Screening current

- **Predicting the influence of screening current and, then, designing a magnet taking it account**
- **Suppressing its influence by appropriate design of coils**

Winding technology to make coils with complicated geometry



Magnet for spiral sector FFAG accelerator

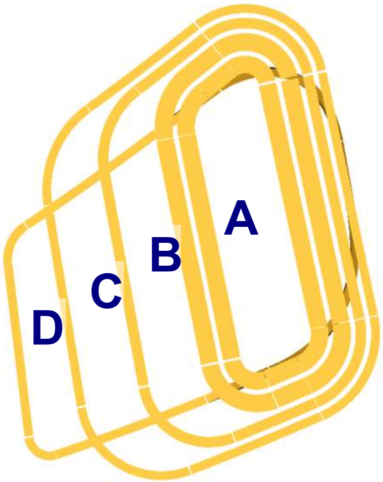


Beam-line magnet

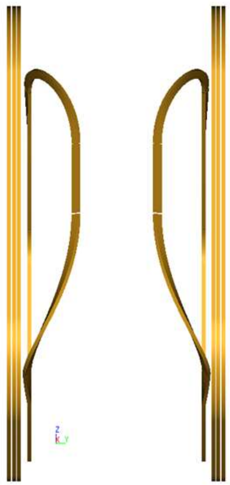
- **Coils with negative bends**
- **Coils with 3D shapes**

With little dimensional error!

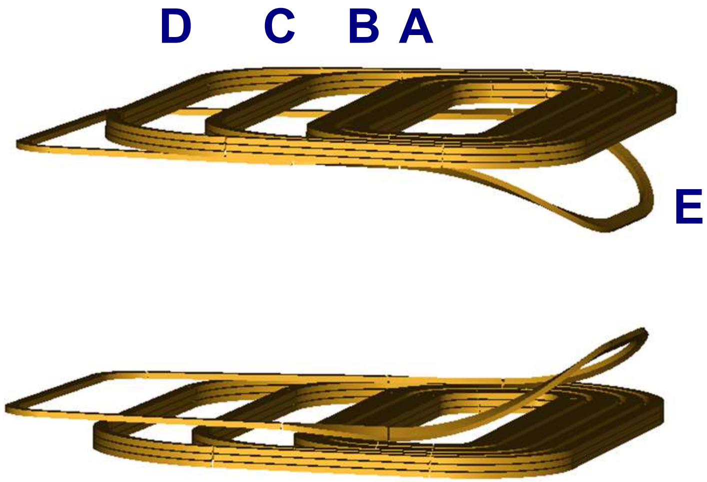
- S-Innovation -
Coils composing model magnet



Top view



Side view



Isometric view

Front view

Coil parameter	A	B	C	D	E
Outside dimension, x-axis, mm	93	139	228	308	250
Outside dimension, y-axis, mm	100	146	185	215	100
Minimum bending radius, mm	20	58	98	130	26
negative-bend radius, mm	3262	3186	3035	2884	2700
Radius of the duct curvature, mm	-	-	-	-	150
Number of turns	100	100	60	50	50
Total tape length / coil, m	79.5	94.0	70.6	68.4	75.0
Number of coil	6	6	6	6	2

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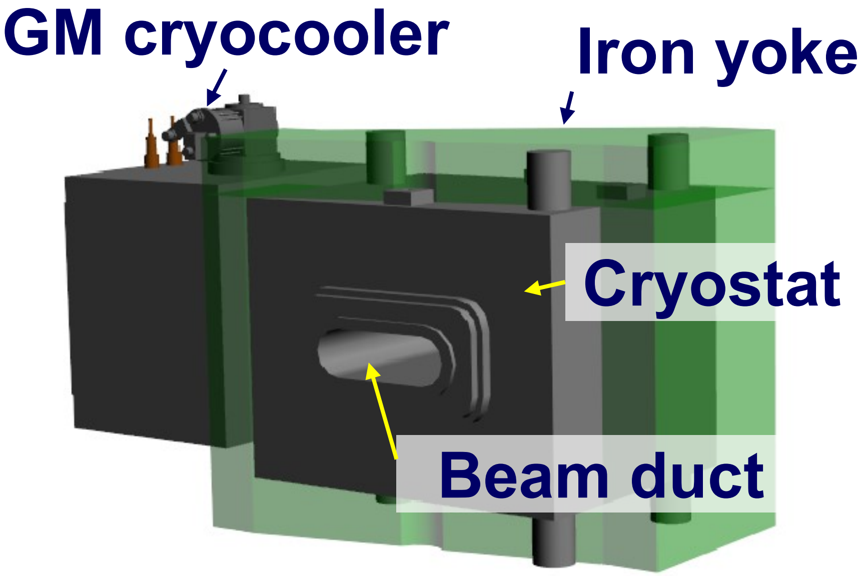
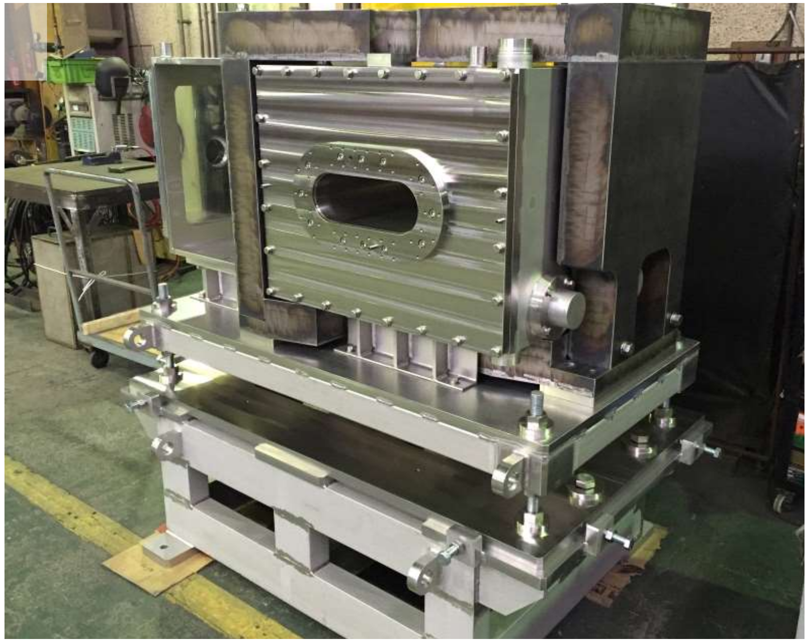
- S-Innovation -
Model Magnet for Accelerator





Japan Science and Technology Agency

- METI - AMED -
Development of Fundamental Technology Applicable to High-temperature Superconducting Coils (CC Magnets)

Future Target	Project R&D (2013 – 2015)	
	Coil Dia. (mm)	Bo
Ultra-High-Field MRI (Toshiba)	ID: 500 OD: 520 - 548	1.5 T@192A 4.1 ppm, 0.8 ppm/hr @200mmϕ
	ID: 50 OD: 130	10 T
Very-Stable-Field MRI (Mitsubishi Electric)	ID: 320 OD: 471	2.9 T@125A Jcoil: 110A/mm^2 2 ppm@25mmϕ
	ID: 850 OD: 950	Trial for ~1m Dia. Coil

Japan Science and Technology Agency

Project Period: 3 years (2013-2015)

- 300kW Flywheel -
Demonstration Machine of Flywheel Energy Storage System

- 2010-2015
- Output power / Storage capacity: 300 kW / 25 kWh
- Superconducting Magnetic Bearing (CC Coil and YBCO Bulk)
- CFRP Flywheel: 2m Dia., 4,000 kg, 3,000 rpm
- Connected with 1MW Photovoltaic Plant

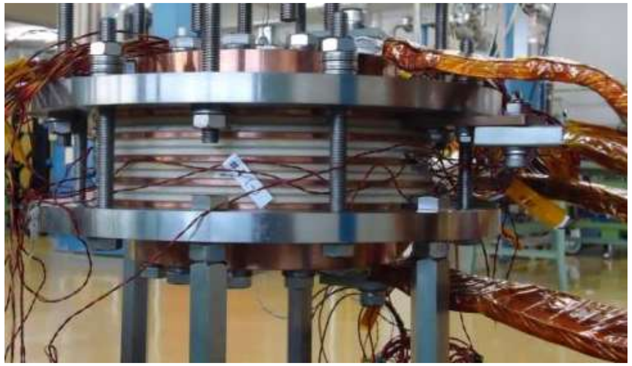
T. Yamashita et al.; Abstracts of CSSJ Conference, Vol.93(2016) p.127 (RTRI, KUBOTEK, Furukawa, MIRAPRO, Yamanashi Pref.)

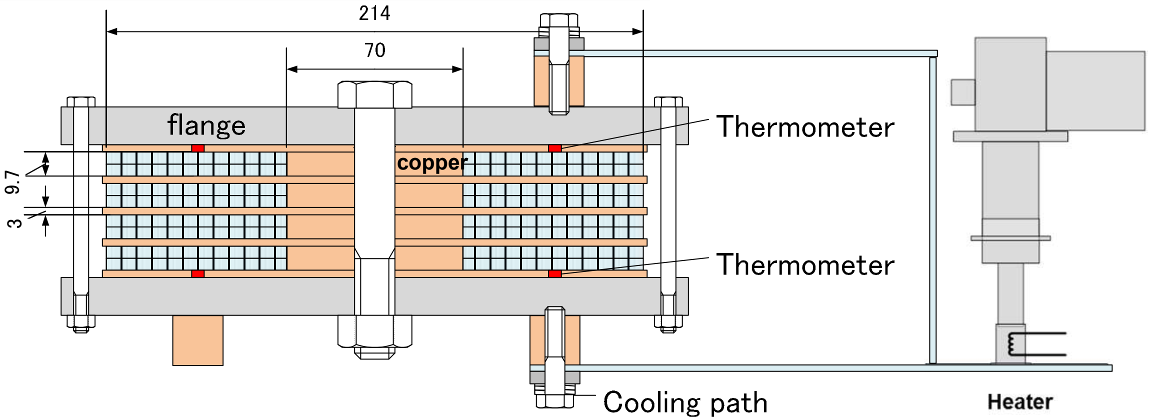
Japan Science and Technology Agency

Rotating Machines

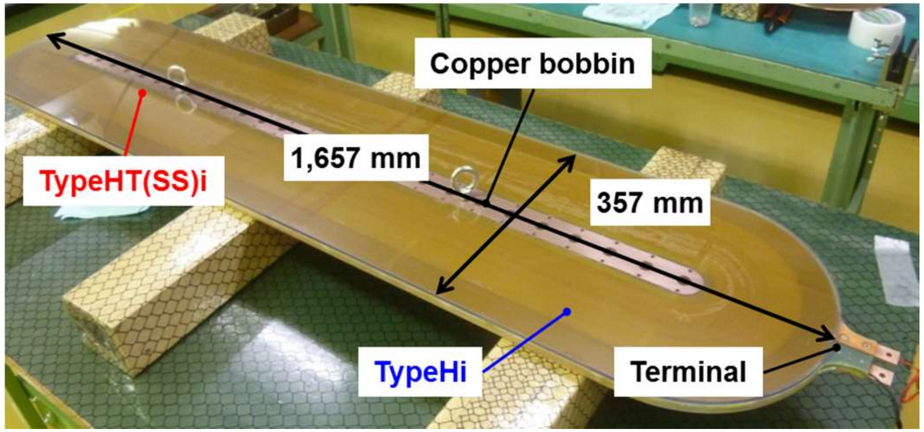
- S-Innovation -
Quench Protection: Coil for 20 MW Motor

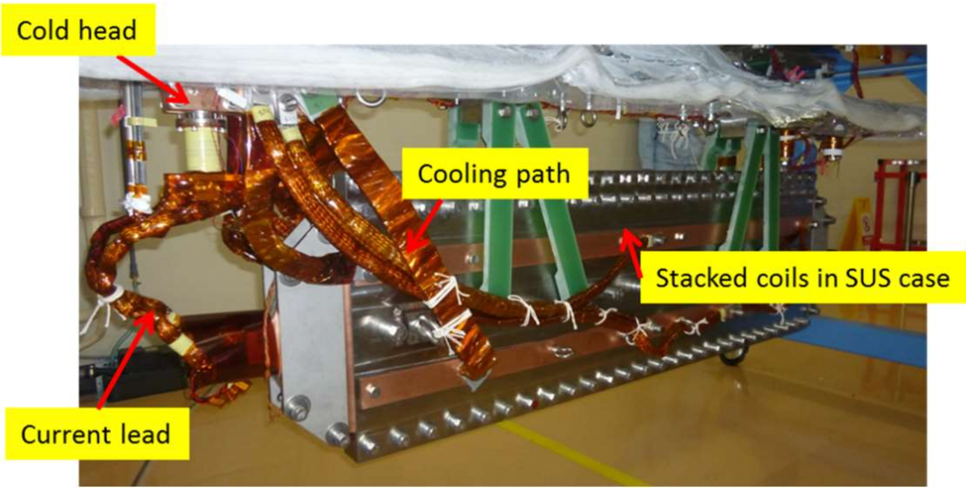
Small Coil: 0.4H, 8KJ@200A





Large Coil for 20 MW Motor: 15H, 300KJ@200A





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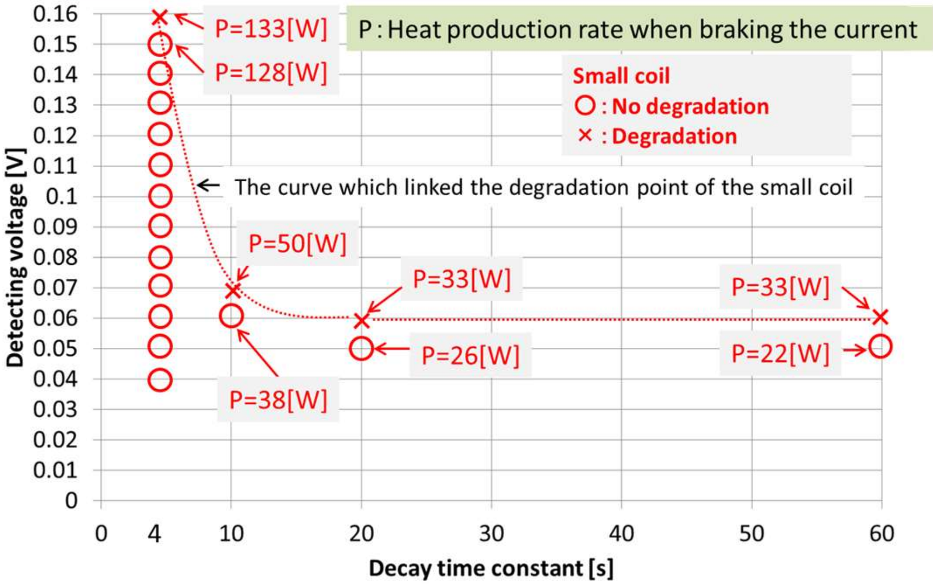
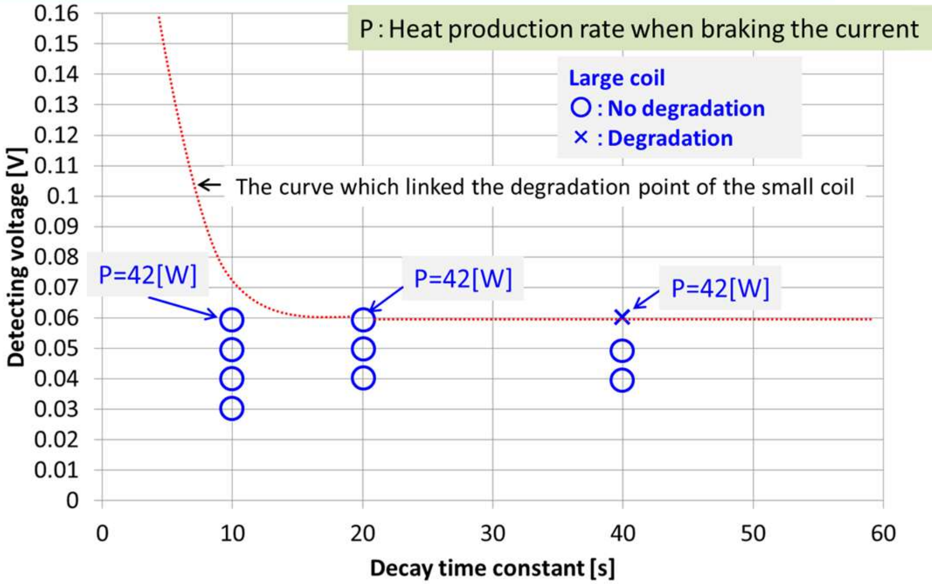
- S-Innovation -
Results: Small Coil & Large Coil



Small coil



Large coil

・DI-BSCCO coil can be protected by Detect & Dump technique in 200A(Je=202A/mm²).

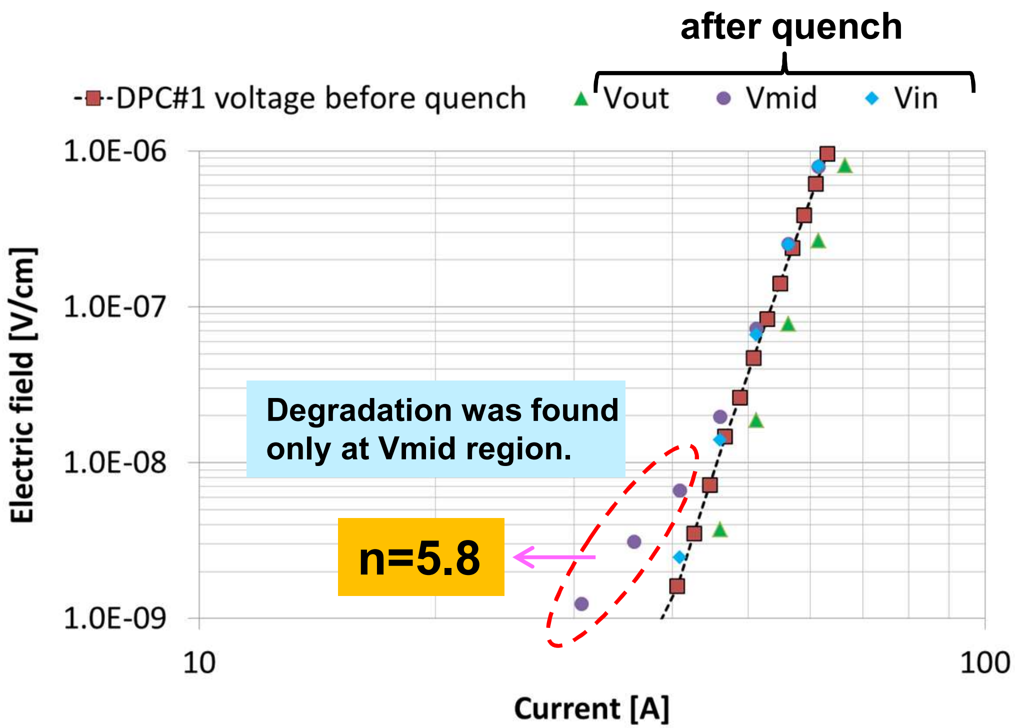
・There was not great difference between the results of the small coil and that of the large coil.

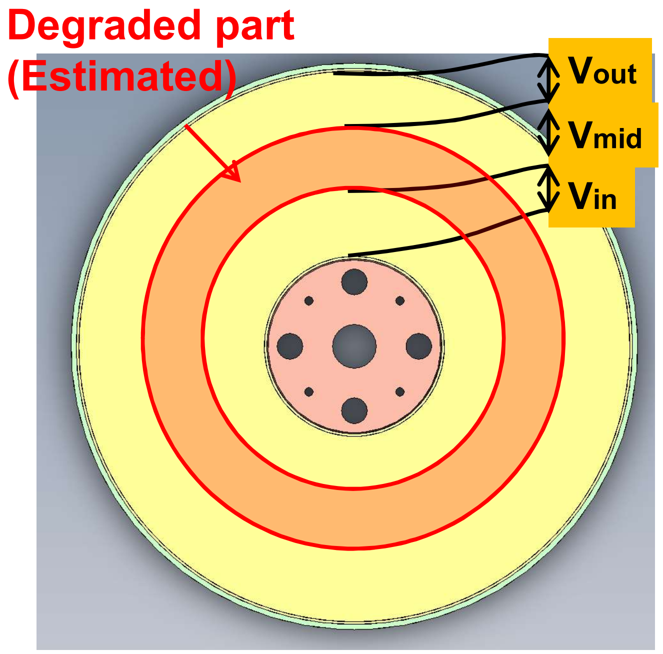
⇒Heat production rate in hotspot are similar.

⇒Coil protection depends on heat production rate in the hotspot, but not on the size of coil.

- S-Innovation -
Degraded Part

The coil did not burned out. Degraded part was investigated.



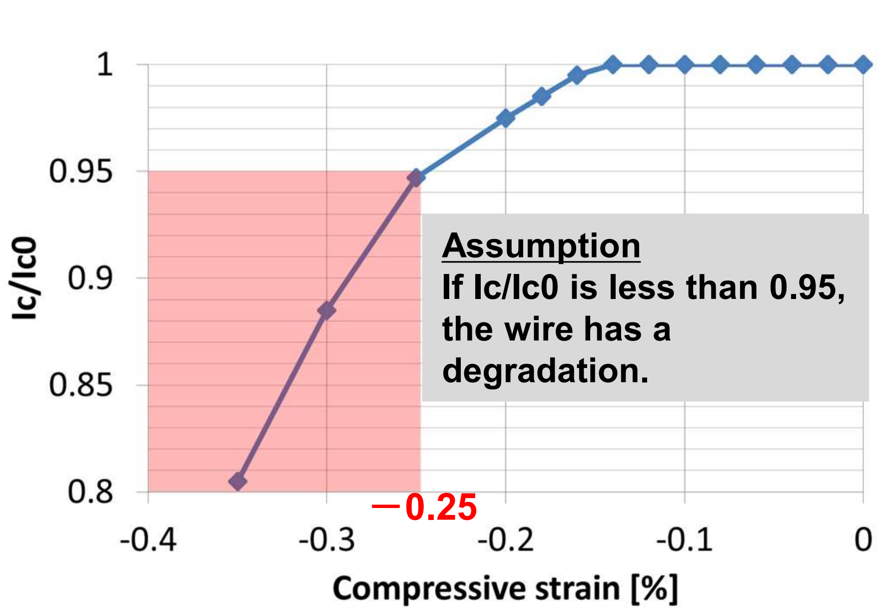


The degraded part is estimated to be red colored area.
Ic@10^{-9}V/cm decreased from 40A to 30A.

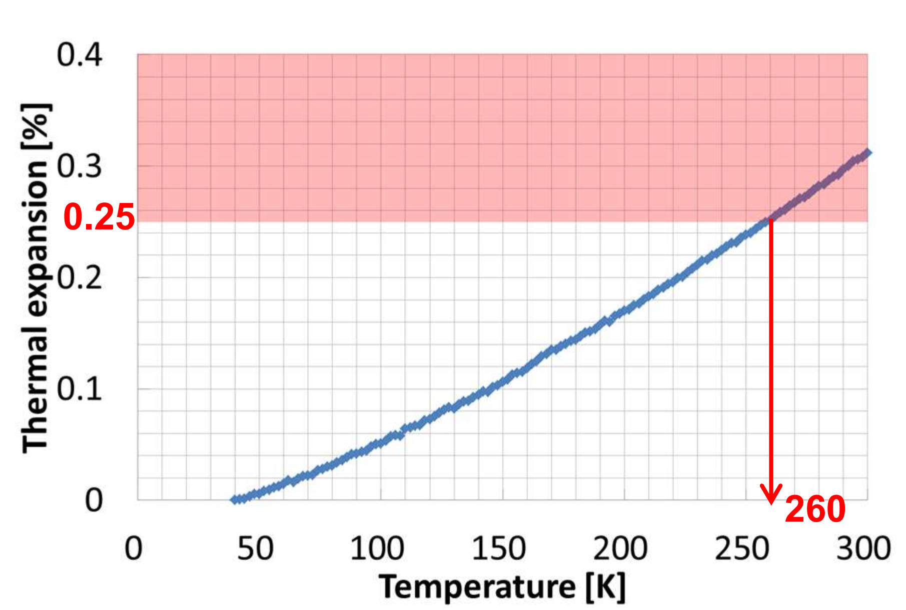
- S-Innovation -
Origin of Degradation

A degradation of the wire was caused by stress induced by difference in the thermal expansion coefficient as the temperature increased.

Compression characteristics by Dr. Osamura



Thermal expansion characteristics



Compressive strain > 0.25%, Ic/Ic0 < 0.95.

Thermal expansion > 0.25 %, temperature > 260 K.
⇒It is estimated that hotspot's temperature is more than 260 K.

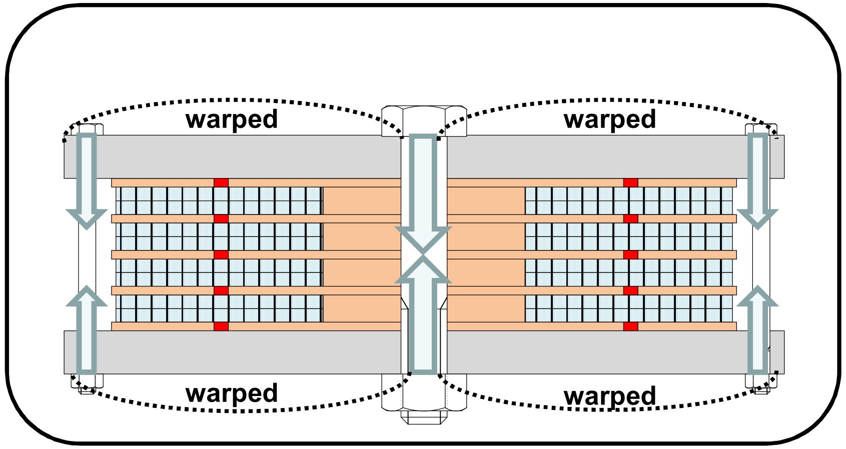
Japan Science and Technology Agency

- S-Innovation -
Better Thermal Conduction

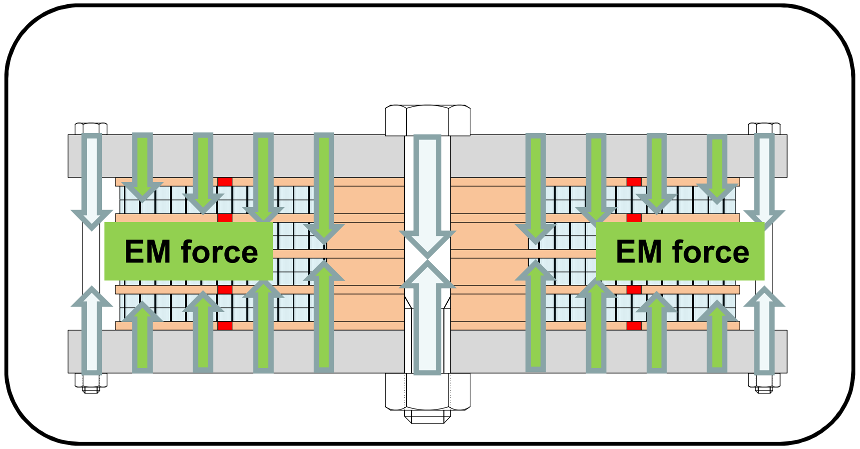
●Proposed measures

・With magnetic flange, the electromagnetic force is used.
⇒The flange is not warped and the contact pressure is uniform. Low thermal resistance is achieved.

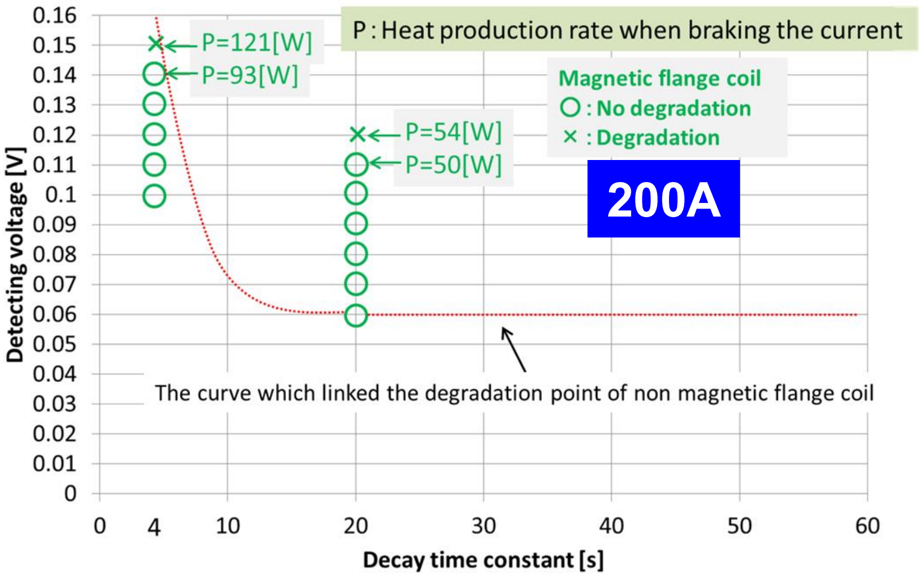
Nonmagnetic flange coil



Magnetic flange coil



- S-Innovation -
Results: Magnetic Flange Coil



Magnetic flange coil 200A

Magnetic flange coil 200A,250A,300A

・The left graph shows that when the decay time constant is 20s, an effect of the magnetic flange is found.
・When the **operating current is increased**, the lines which linked the degradation points shift to the **lower left**.
・DI-BSCCO coil can be protected by **Detect & Dump technique** even if **Je=266A/mm^2**.

Japan Science and Technology Agency

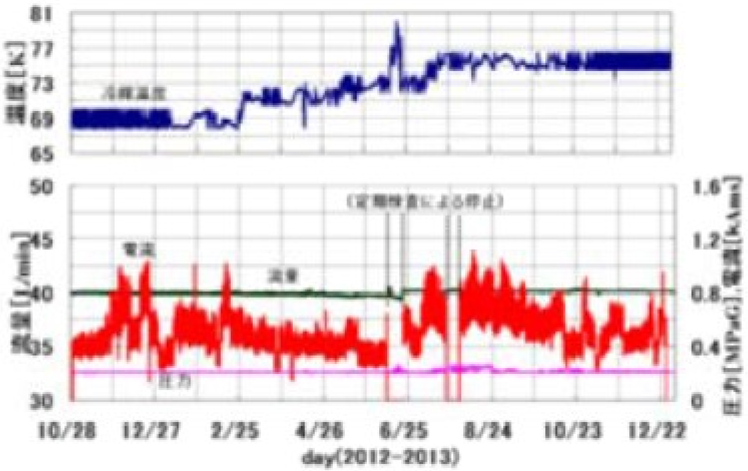
100 kW Motor for Bus (FY2012-2014)

- **Permanent Magnet Synchronous Motor (Superconducting Armature Type) with Liq. N_2 Cooling System**
- **Saddle coil with DI-BSCCO for Armature**
- **On Board Refrigerator: Split Stirling Cryocooler 151W@70K, COP=0.07 (Input: 2.15 kW)**

H. Oyama et al.; Abstracts of CSSJ Conference, Vol.90(2014) p.69
K. Nakano et al.; Abstracts of CSSJ Conference, Vol.90(2014) p.70
K. Nakano et al.; Abstracts of CSSJ Conference, Vol.92(2015) p.237

Cables (AC, DC)

Yokohama HTS Cable Project:
Go to Grid October 29, 2012



Voltage – Current		66kV – 3,000A
Cable capacity		300MVA (Line capacity : 200MVA)
HTS cable	Shape	3-core in one Cryostat
	Length	250m (in 170mm duct)
	Accessories	2 End Boxes in Air and Joint
	Wire	***DI-BSCCO***
Fault Current Condition		31.5 kA X 2 sec
Members		*Tokyo Electric Power Company,* *MAYEKAWA, NEDO, Sumitomo Electric*

- ***Over 1 year operated without trouble @ December 2013***
- ***Continue with newly developed 5kW Cooler (30% Carnot)***
- ***Cryocooler maintenance was done without the system shut down***

Japan Science and Technology Agency

Outline of New National Project

Project :

Verification Tests and Study on Safety and Reliability of HTS cable

Purpose:

- **To verify the Safety and Reliability of HTS Cables at Accidents by conducting model tests with actual dimension cable for 22 kV, 66kV and 275 kV class.**
- **To develop 5 kW class Brayton Refrigerator System with higher performance and to confirm its stable operation in the grid at Asahi SS.**

Period : From July 2014 to March 2019

Members :

NEDO (Project management)
Tokyo Electric Power Company (Utility , Project leader)
Sumitomo Electric, Furukawa Electric, Fujikura (Cable manufacturer)
Mayekawa Co. (Refrigerator manufacturer)

Testing Items on Safety Evaluations

	Assuming accidents	Evaluating items
a) Short Circuit Current Test	Passing amount of fault current caused by accidents at the outside of HTS cable	• LN2 T and P rising level • Damage for HTS cable • Possibility of rapid restart operation
b) Ground Fault Test	Ground fault of HTS cable itself caused by dielectric breakdown	• LN2 T and P rising level • Damage for HTS cable
c) Penetrating Damage Test	c-1) Damage on outer cryostat pipe followed by degradation of Vacuum rate	• Vacuum rate degradation • T and P rising level caused by increasing heat invasion
	c-2) Penetration damage on inner cryostat pipe followed by leakage and blow out of LN2	• Influence on its circumference such as soil, surrounding apparatus, other cables. • Lack of oxygen in case of tunnel or joint vault

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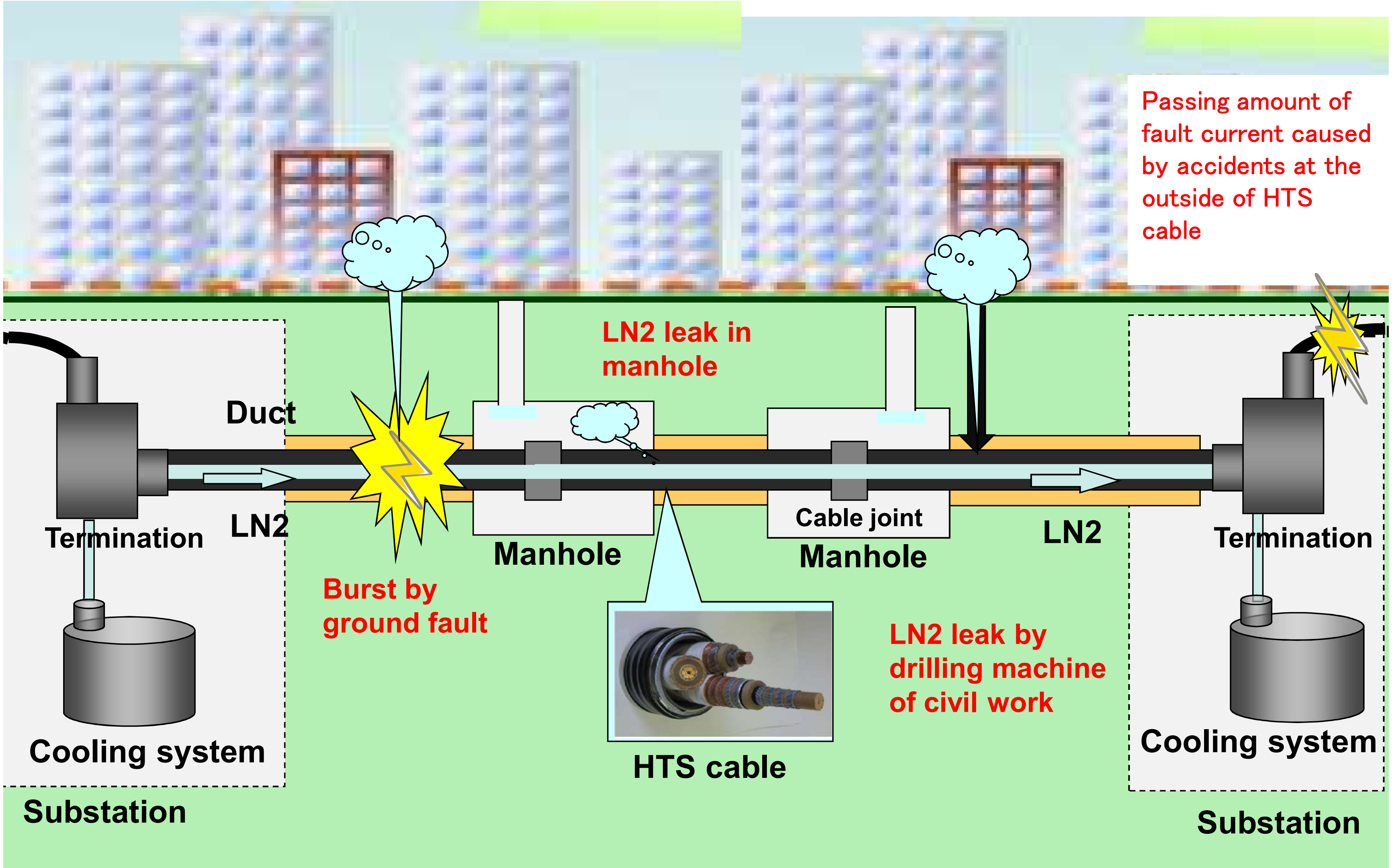
Image of HTS Cable System and its Accident



Japan Science and Technology Agency
SUMITOMO ELECTRIC
FURUKAWA ELECTRIC GROUP
TEPCO

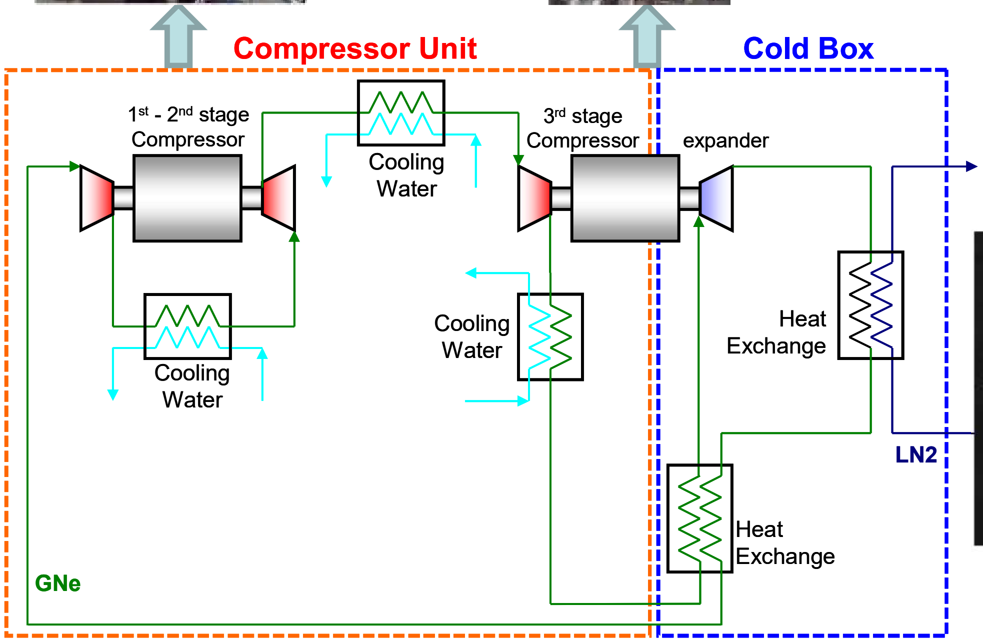
MAYEKAWA

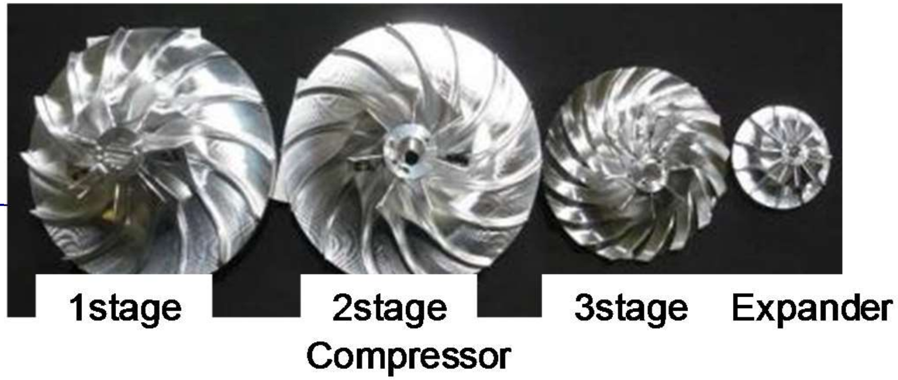
■Specifications

Large capacity ･･･ **Cooling Capacity: 5 kW**

High efficiency ･･･ **COP: 0.1**

Long maintenance interval ･･･ **30,000 hours**





High performance impeller

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IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January 2017.
Plenary presentation AT-2 given at 1st Asian ICMC – CSSJ 50th Anniversary Conference; Kanazawa, Japan, November 7 - 10, 2016.

HTS DC Cable – Ishikari Project(1)

2013	2014	2015～	2020～
Demonstration		Operation Research	Utilization
Design, Production, Installation	Production, Installation, Operation		

Cable Capacity	50 MW
Length	(1) 500m, (2) ~1 km
Members	*Chiyoda, Corporation, Chubu University, SAKURA Internet, METI, Sumitomo Electric*

PV

DI-BSCCO

HTS Cable

← 500 m →

Ishikari Data Center (SAKURA Internet)

石狩湾新港地域

N. Chikumoto et al.; Abstracts of CSSJ Conference, Vol.90(2014) p.23

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HTS DC Cable – Ishikari Project(2)

	Line 1	Line 2
Current	5 kA	2.5 kA
Voltage	20 kV	20 kV
Number of Tape (Inner Conductor)	37 (DI-BSCCO Type CA, Ic>180 A)	24 (DI-BSCCO Type CA, Ic>180 A)
Number of Tape (Outer Conductor)	35 (DI-BSCCO Type CA, Ic>180 A)	15 (DI-BSCCO Type CA, Ic>220 A)
Cable Length	500 m	1,000 m
Layout	Connected with PV and Data Center	Hairpin Shape
Refrigherator	1kW Stirling & 2kW Turbo-Bryton	2 x 1kW Stirling & 2 x 2kW Turbo-Bryton

N. Chikumoto et al.; IEEE Trans. Appl. Supercond. 26, 5402204 (2016)

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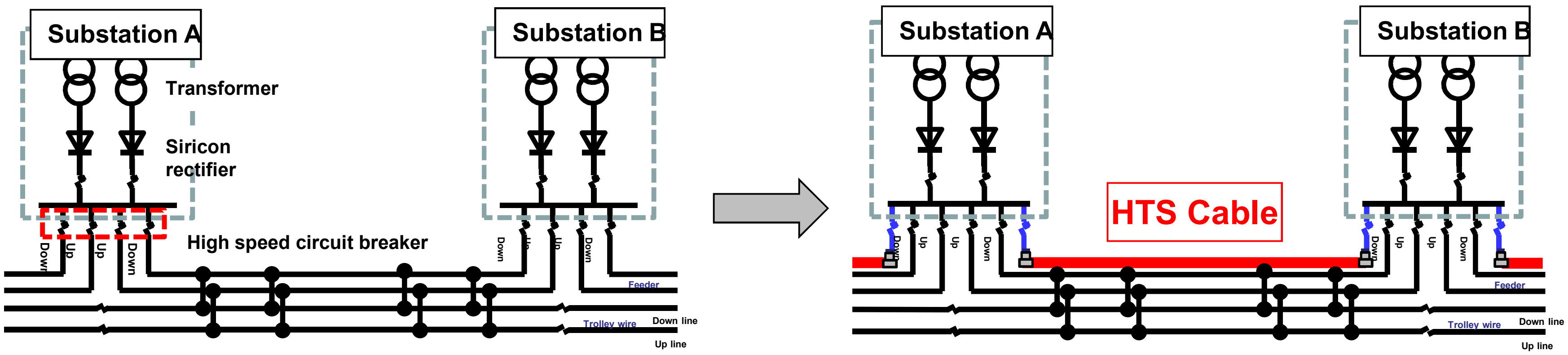
- S-Innovation -
Effects of Superconducting Feeder System of Railway



Energy saving

Reduction of failure of the regenerative brake > Energy loss by cooling systems

Reduction of energy loss of electric power transmissions

Load leveling of substations

Without enhancing substation power
- Fulfillment of enhancing transport capacity
- Fulfillment of reducing the number of the substations

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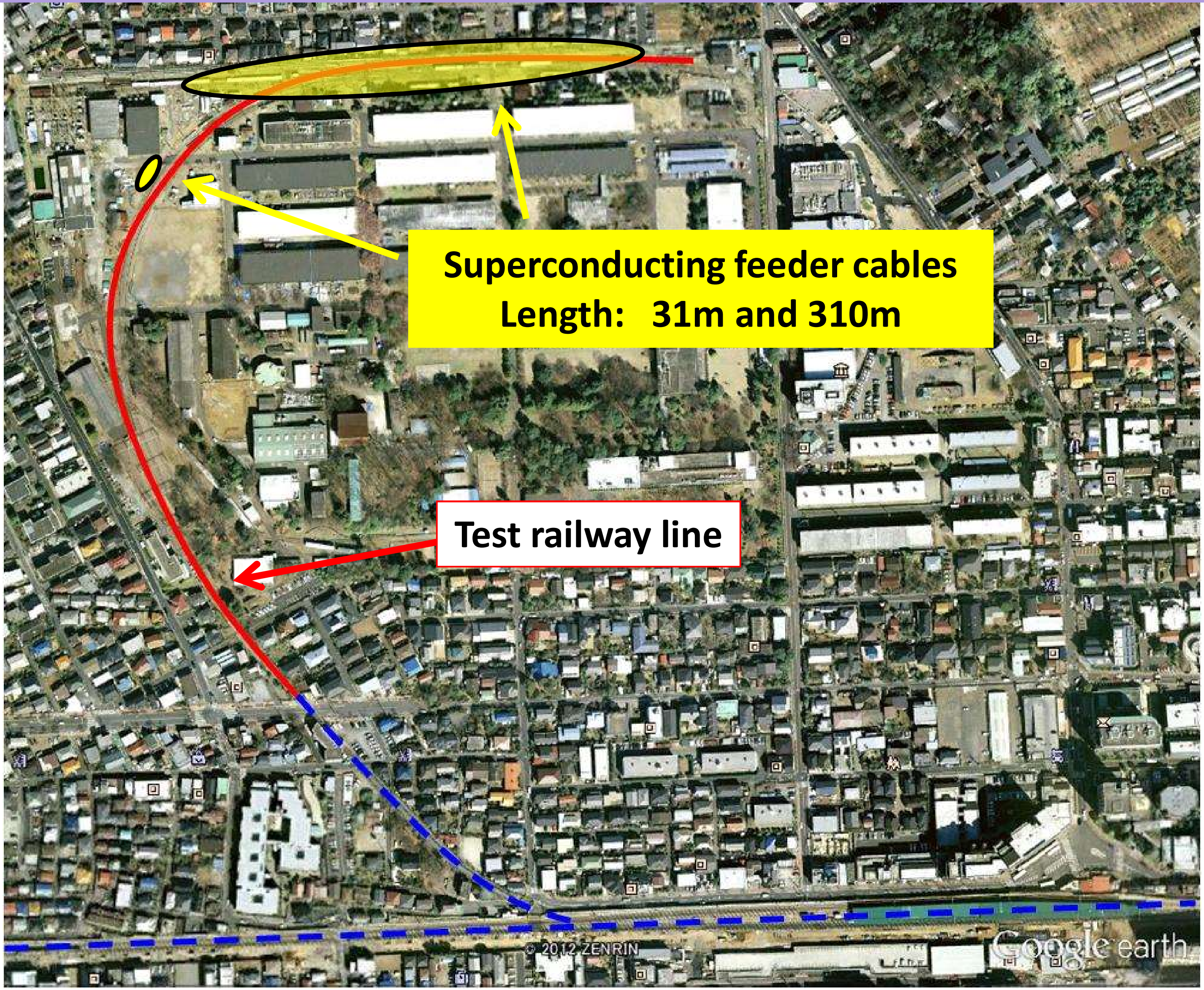
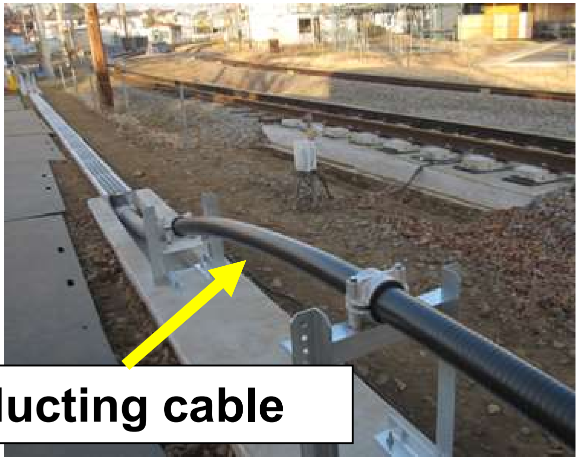
Train test truck in Railway Technical Research Institute (JPN)



- S-Innovation -
Superconducting feeder cable system

Superconducting feeder cable system

- 30 meter class superconducting cable
- Indirect cooling system
- Go & Return system



Superconducting cable

Cooling system

- GM cryocooler ：150 W (@77 K)×2
- Sub cooler： 300 W(@77 K)
- LN_2 pump： max 30L/min

Test results

- Cooling test → Heat transfer coefficient between go & return flow was 1 W/(m･K)
- Cooling force measurement → 700 kgf at 77 K
- Current test → Ic : 6960 A at 77 K
- Succeed in train running test using the superconducting cable; the first case in the world

➡ Commercial train running test in *Izuhakone Railway*

Cooling system

- S-Innovation -
Commercial Train Running Test at Actual Railway Line

News Release

超電導き電ケーブルを用いた列車走行実験について

—営業線における試験列車の走行実験に成功—

平成２７年４月３０日
公益財団法人鉄道総合技術研究所
伊豆箱根鉄道株式会社

公益財団法人鉄道総合技術研究所（以下、鉄道総研）は、去る平成27年(2015年)3月27日、伊豆箱根鉄道株式会社（以下、伊豆箱根鉄道）の協力の下、超電導き電ケーブルを用いた営業線における試験列車の走行実験に成功しましたのでお知らせします。

直流電気鉄道は、変電所から架線に電気を送り届けるき電線の電気抵抗に起因する回生失効や送電損失、変電所間での電圧降下などといった課題があります。鉄道総研では、これらの課題の解決に向け、超電導材料をき電線に適用して電気抵抗ゼロで送電できる、「超電導き電ケーブル」の研究開発を進めてまいりました。本技術の実用化によって、回生失効や送電損失の低減による省エネルギー化に加え、電圧補償、変電所の負荷平準化など様々な効果が期待されます。

鉄道総研では、鉄道現場で求められる仕様を満たす超電導き電ケーブルの実現に向け、超電導材料から機器まで、基礎から応用に至る研究開発に取り組んでいます。これまで、鉄道総研・国立研究所内の試験線路に、平成25年には31 m、平成26年には310 m長の超電導き電ケーブルを敷設し、実車両走行試験により超電導き電ケーブルが直流電気鉄道へ適用できることを確認してきました。

この度、営業線における実際の設備への接続や超電導き電システムとしての動作確認など、実用化に向けた基礎的な技術検証を主な目的とし、去る平成27年3月27日に伊豆箱根鉄道・駿豆線において、超電導き電ケーブルを用いた列車走行実験を実施しました。使用した超電導き電ケーブルは、長さ6m、電流容量2,080 Aで、駿豆線の変電所に敷設し、き電回路に組み込みました（写真１）。今回の試験では、超電導き電ケーブルを液体窒素により冷却（-196℃）し、超電導送電を行いました。

3月27日未明、田京～修善寺間（5.5km）を往復する試験列車（伊豆箱根鉄道3000系電車、3両編成）に超電導き電ケーブルを通して電気を供給し、国内外で初めて営業線における超電導送電による列車走行実験に成功しました（写真２）。鉄道総研では、今後、より実用的な条件で営業線での走行試験を行うとともに、ＪＲ、民鉄等への導入を目指し、超電導き電システムの開発を進めてまいります。

なお、超電導き電ケーブルの開発は、鉄道総研が、国立研究開発法人 科学技術振興機構（JST）の研究成果展開事業「戦略的イノベーション創出推進プログラム（S-イノベ）」および国土交通省の鉄道技術開発費補助事業の一環として行っております。

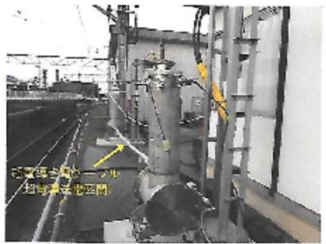


写真１　敷設した超電導き電ケーブル

写真２　列車走行試験の様子

公益財団法人 鉄道総合技術研究所
〒185-8540 東京都国分寺市光町 2-8-38

- First Trial to introduce HTS Cable to Actual Train Line
- March 27, 2015 in Izuhakone Railway Co.,LTD.
- HTS Cable: 6m length

(http://www.jst.go.jp/s-innova/index/press_20150430-hakone.pdf)

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Summary

1. **HTS Application Programs including Power Cables (AC/DC), compact NMR & Accelerator, High Field Magnets over 24T, Flywheel and Motors**

2. **Application Driven Materials and High Efficient Cryocoolers Development**

3. **Quench Protection of HTS Magnets**

4. **Noble Applications:**
   Cables to Railway
   Super High Field Magnets to NMR
   Compact Accelerator
   Motors to Automobiles

Thank you for your attention!

Japan Science and Technology Agency