PL-02 Recent Progress of Superconductivity and Cryogenic Engineering in Japan and Future Prospects as Key Technologies for Realizing Carbon Neutral Society

Central Research Institute of Electric Power Industry
and
President of CSSJ

Dr. Shirabe Akita

ACASC-Asian ICMC 2023

October 30, 2023

CRIEPI
Central Research Institute of Electric Power Industry

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 55, January, 2024. Plenary presentation given at ACASC 2023, 30 Oct. 2023, Shanghai, China

Recent Progress in Japan

R & D Direction

*Toward Actual Application by LTS
*High Magnetic Field by LTS and HTS
*High Magnetic Field Application
*Development of Precise Analyzation Method

Examples of Recent Progress

*High Magnetic Field Magnet (PL-06)
*NMR over 1 GHz
*HTS magnets for compact cyclotron
*Evaluation technology for HTS wire and magnets (A-01-SI)

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High Magnetic Field Magnet (PL-06)

by Tohoku University

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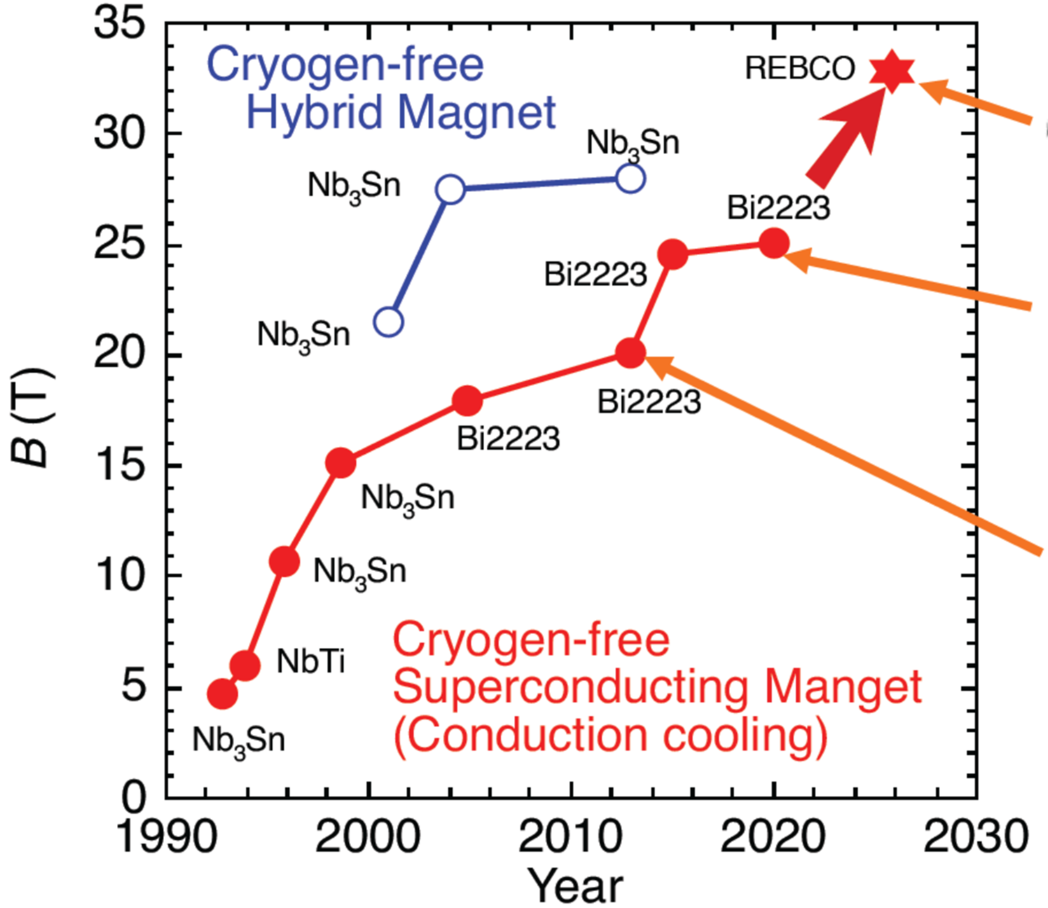
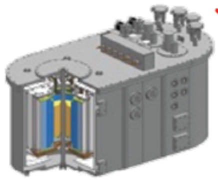
PL-06: High field superconducting magnet development with HTS
S. Awaji (Tohoku University)





33T-CSM(ϕ32RT)
ϕ320-14T-LTS
- CuNb/Nb_3Sn Rutherford, NbTi:267 MPa

ϕ96-11T-HTS
- REBCO (Robust coil concept)

25T-CSM(ϕ52RT)
ϕ300-14T-LTS
- CuNb/Nb_3Sn Rutherford, NbTi: 251 MPa

ϕ96-11T-HTS
- Ni-alloy/Ag/Bi2223 (SEI HT-Nx) : 323 MPa

20T-CSM(ϕ52RT)
ϕ196-15.57T-LTS
- CuNbTi/Nb_3Sn, NbTi: 234 MPa

ϕ90-4.45T-HTS
- Cu-alloy/Ag/Bi2223 (SEI HT-CA): 212 MPa

Lessons learned for high-field (cryogen-free) superconducting magnets will be presented!

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NMR over 1 GHz

by JST-Mirai Program

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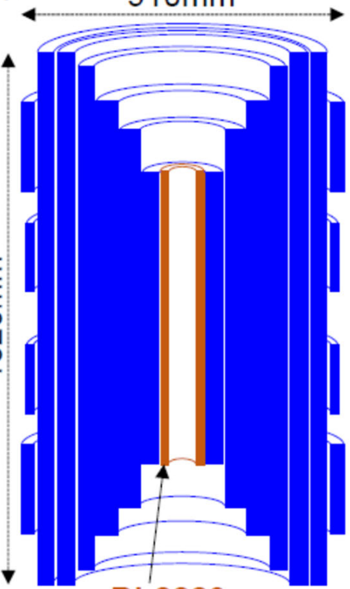
Compact >1 GHz magnet as a model of the 1.3 GHz magnet

1.02 GHz (24.0 T)

Power supply driven-mode



HTS LTS

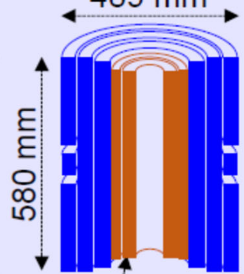
B_0 15% 85%

J: 148 A/mm^2

BJR: 189 MPa

1.01 GHz (23.8 T)

(design 1050 MHz)



Power supply driven-mode

HTS LTS

B_0 53% 47%

J: 225 A/mm^2

BJR: 291 MPa

Increased

- K Hashi *et al* 2015 *J Mag Res* **256** 30-33
- R Piao *et al* 2019 *IEEE TAS* **29** 4300407

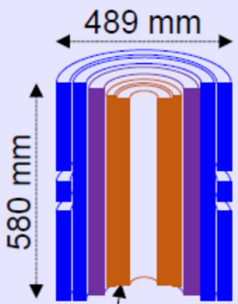
Y. Yanagisawa et al., ASC 2022 - Sir Martin Wood Memorial Session: Very High Field and NMR Magnets II -, 1LOr2D-02, Oct. 24, 2022

Compact >1 GHz magnet as a model of the 1.3 GHz magnet

R Piao *et al* 2019 *IEEE TAS* **29** 4300407

1.01 GHz (23.8 T)

(design 1050 MHz)



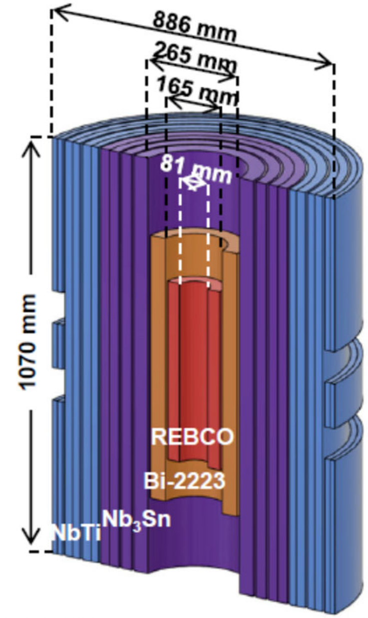
Power supply driven-mode

	HTS	LTS
B_0	53%	47%

Similar scale

HTS coil	1.01 GHz	1.3 GHz
ID (mm)	79	81
OD (mm)	208	265
Length (mm)	513	678

1.3 GHz (30.5 T)



	HTS	LTS
B_0	51%	49%

A >1 GHz magnet with a high field-contribution by HTS coils as a model of the 1.3 GHz magnet.

Y. Yanagisawa et al., ASC 2022 - Sir Martin Wood Memorial Session: Very High Field and NMR Magnets II -, 1LOr2D-02, Oct. 24, 2022

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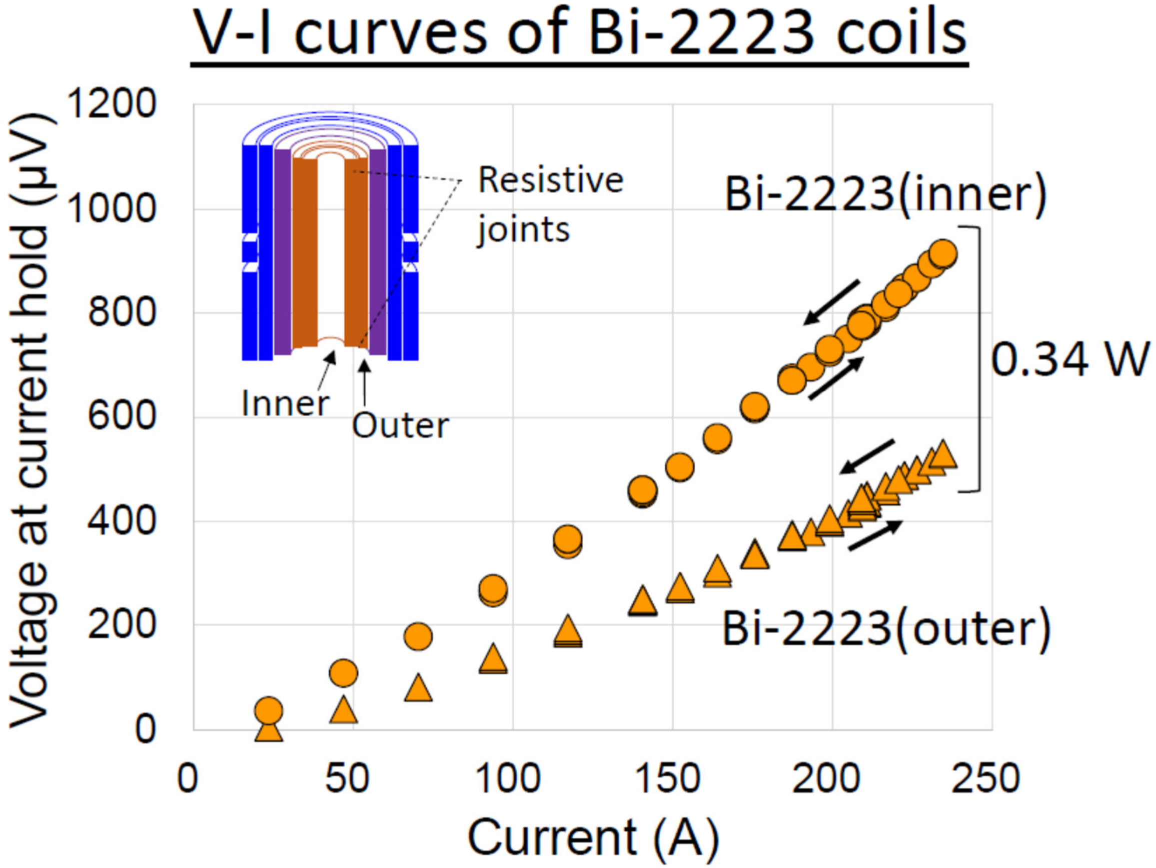
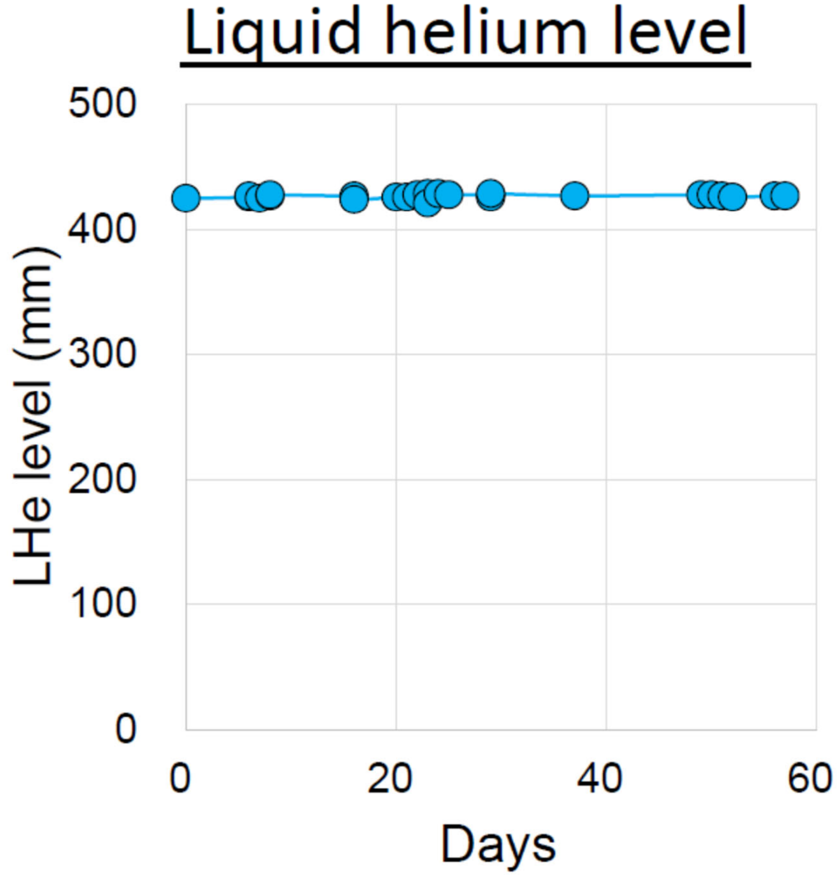
Magnet performance





- **V-I curves are reversible (no degradation and quench).**
- **No reduction in LHe level through charging and operation using cryocoolers.**

Y. Yanagisawa et al., ASC 2022 - Sir Martin Wood Memorial Session: Very High Field and NMR Magnets II -, 1LOr2D-02, Oct. 24, 2022

The 1.01 GHz magnet addressed four development issues

1. Detection of the HTS coil degradation with an infinitesimal change in coil voltage.
2. Stabilization of a temporal fluctuation of the magnetic field due to the DC power supply and screening currents.
3. Homogeneous magnetic field using shimming systems.
4. Development of a quench simulation code for an LTS/HTS magnet.

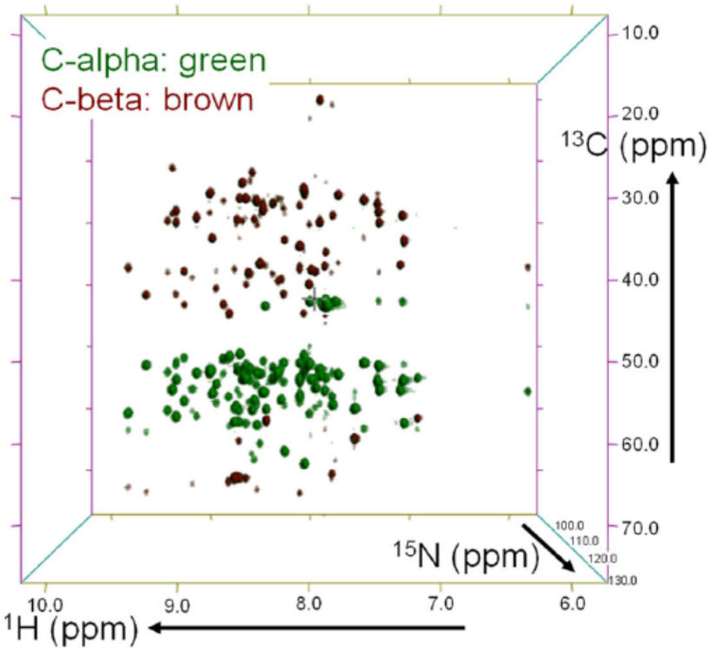
Y. Yanagisawa et al., ASC 2022 - Sir Martin Wood Memorial Session: Very High Field and NMR Magnets II -, 1LOr2D-02, Oct. 24, 2022

NMR spectra for proteins at 1.01 GHz

The authors thank Mr. Y. Endo of JEOL Ltd. for the SS NMR measurements.

Solution NMR

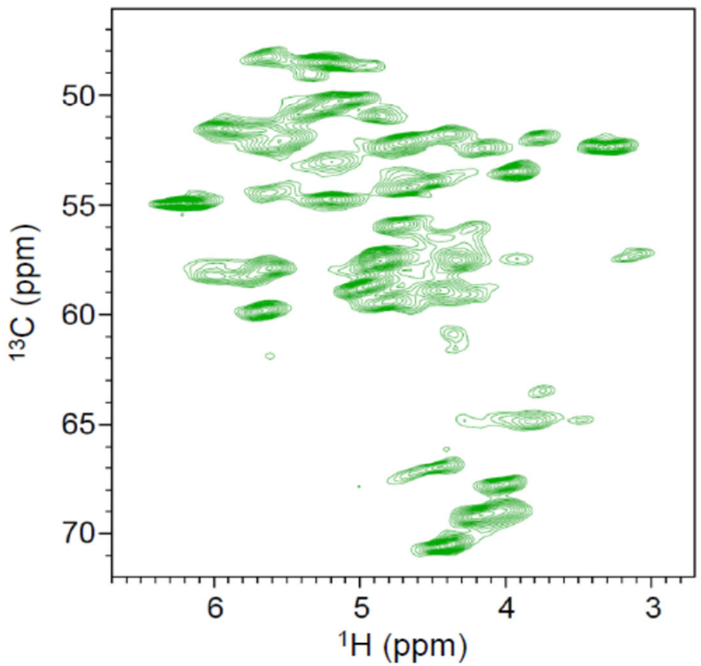
3D triple resonance NMR (HNCACB) for a protein sample (ubiquitin)



Experiment time: 1 day

Solid state NMR

2D double resonance NMR for a protein sample (GB1)



Experiment time: 20 m

Demonstrating that an LTS/HTS magnet with a high contribution of the HTS coil magnetic field (≥50%) can provide high-resolution NMR spectra.

Y. Yanagisawa et al., ASC 2022 - Sir Martin Wood Memorial Session: Very High Field and NMR Magnets II -, 1LOr2D-02, Oct. 24, 2022

HTS magnets for compact cyclotron

by Waseda University

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 55, January, 2024. Plenary presentation given at ACASC 2023, 30 Oct. 2023, Shanghai, China

ASE 先進理工学部 School of Advanced Science and Engineering

OKAYAMA UNIVERSITY

OSAKA UNIVERSITY

中部電力

住友重機械工業

Development of No-Insulation REBCO Coil system for Skeleton Cyclotron Accelerator - Next Generation Medical Application -

This work was supported by JSPS Grant-in-Aid for Scientific Research(S) from the Ministry of Education, Science, Sports, and Culture

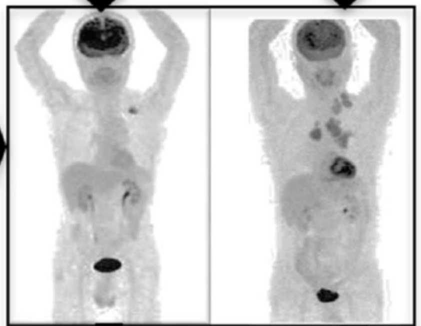
A. Ishiyama (Waseda Univ.)

Targeted α-particle therapy

One third of patients are diagnosed as "advanced cancer" at first visit: 5-year relative survival is 15% or less

Advanced Cancer

Cancer progress	Primary organ	Regional lymph node metastasis	Adjacent organ infiltrate	Distant metastasis
Ratio at first diagnosis	47%	22%	12%	19%



Surgical resection
Radiation irradiation
Chemical treatment
Immunotherapy

Chemical treatment
Immunotherapy

5-year relative survival	74.5%	47.2%	17.9%	6.1%

Applying targeted α-particle therapy

Suppression of refractory cancer

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Magnetic field required for cyclotron accelerator

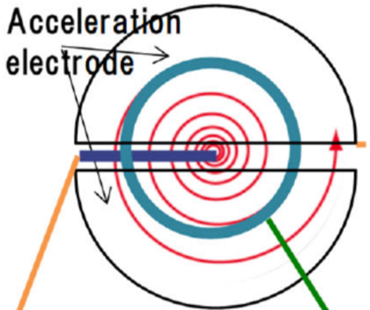
Isochronism

It takes the same time that particle takes one round.

The orbit radius of accelerated particle is getting larger, and the mass is also getting heavier.

Isochronous field

Keep isochronism by radially increasing magnetic field



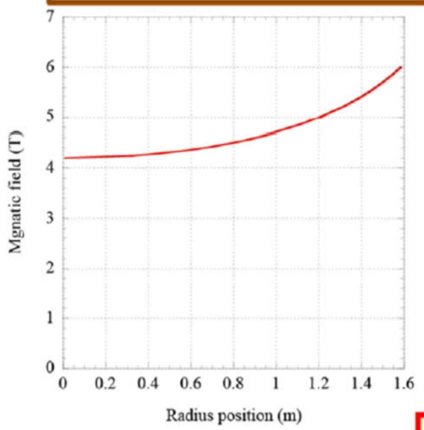
Beam trajectory stability

Maintain particles in orbit.

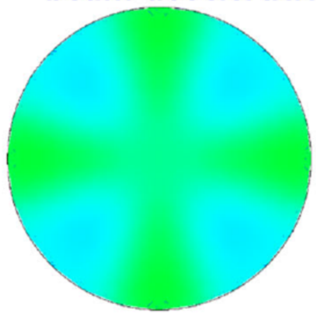
Particles off the mid-plane diverge.

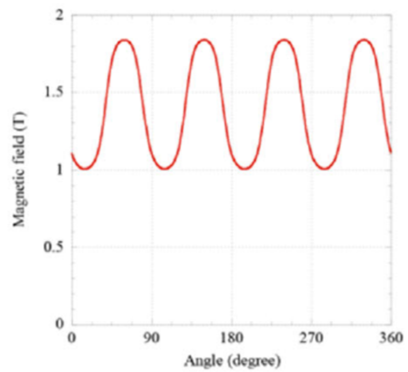
AVF(Azimuthally Varying Field)

Magnetic field with a periodical strength in the circumferential direction places particles in orbit.



Field distribution on beam acceleration plane





Coil-azimuthal direction

Necessary to generate highly accurate field (0.01-0.1%)

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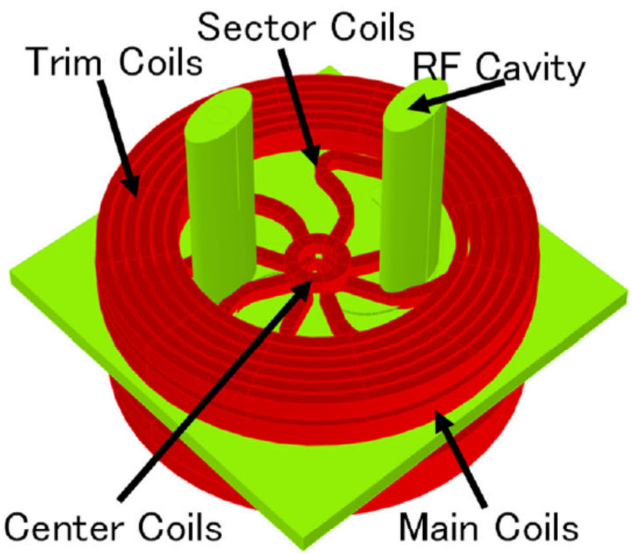
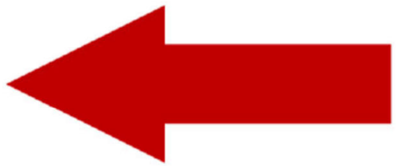
World's First HTS "Skeleton Cyclotron"

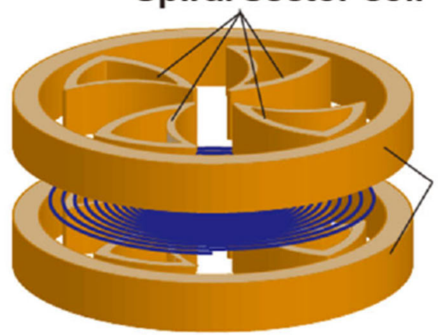
HTS-SC(HTS Skeleton Cyclotron)

H.Ueda, M.Fukuda, A.Ishiyama, S.Noguchi, S.Nagaya et al., "Conceptual Design of Next Generation HTS Cyclotron", IEEE Trans. on Applied Supercond., Vol.23, No.3, 4100205, 2013

Only an HTS multi-coil system without iron core produces a high magnetic field with high precision necessary for beam acceleration.







Compact, lightweight, & high power!

^{211}At **Mass** production (36MeV, **500μA**)

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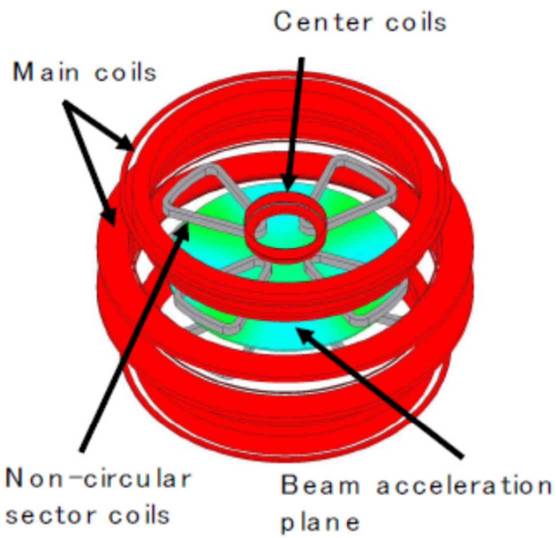
World's First output energy-variable cyclotron accelerator

Due to Iron-Coreless

✔Compact, lightweight, and energy-variable cyclotron accelerator



1) ^{211}At Production (targeted α-particle therapy)
Energy: 36 MeV, Avg. Field: 1.73 T

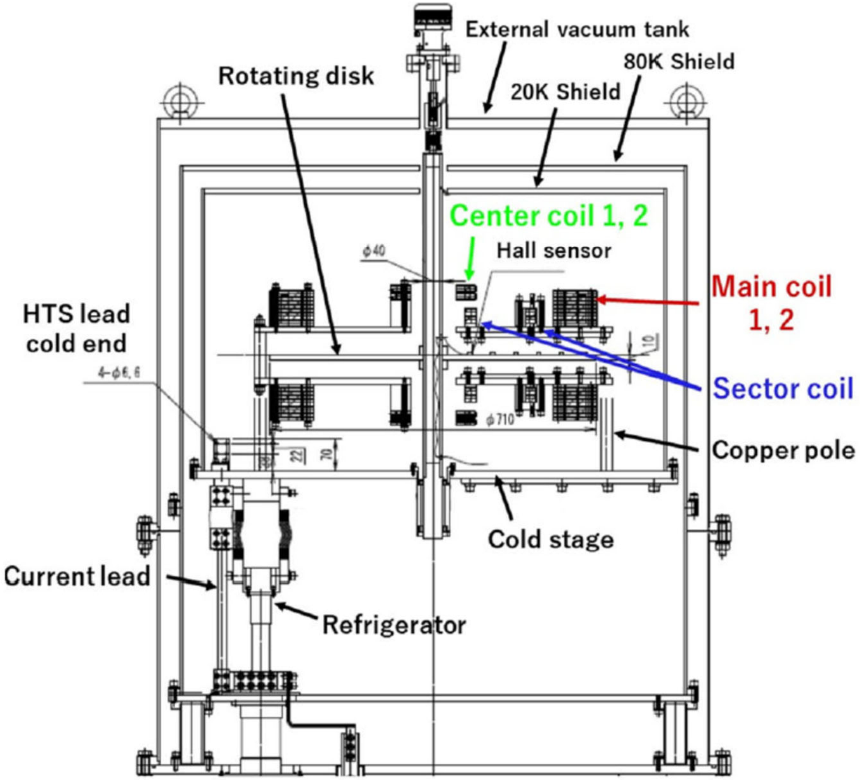
2) RI Production for PET (high output desired)
Energy: 18 MeV, Avg. Field: 1.23 T

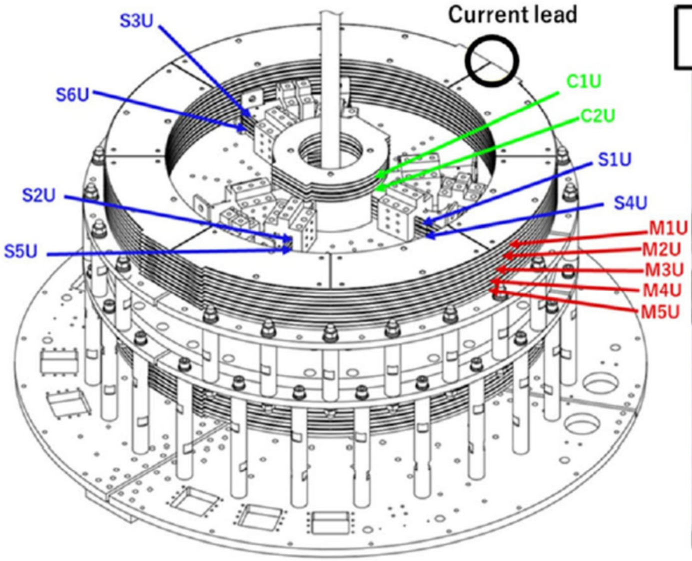
3) BNCT (Boron Neutron Capture Therapy)
Energy: 40 MeV, Avg. Field: 2.59 T

4) ^{225}Ac, RI Production (α-ray)
e.g.) Energy: 16 MeV

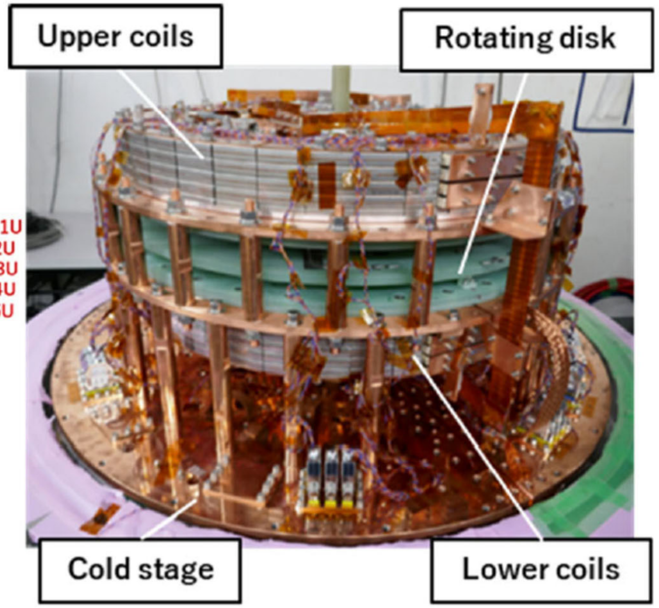
We are developing an HTS skeleton cyclotron system with the above functions by changing the magnetic field.

½-scele REBCO coil system





M : Main coil C : Center coil S : Sector coil
U : Upper col L : Lower coil



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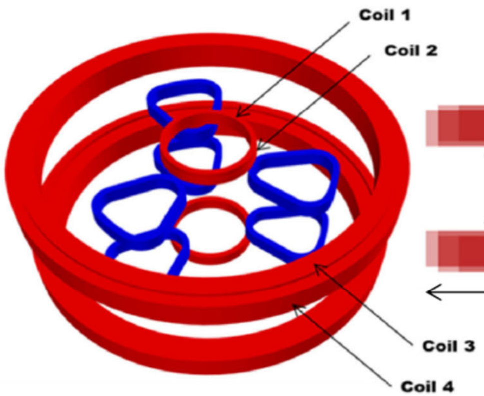
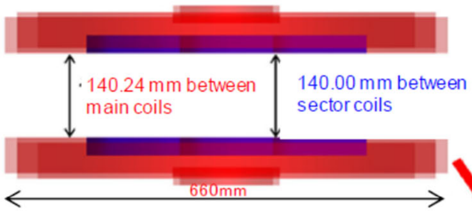
½-scele REBCO coil system

★ Experiments started at FY 2022.

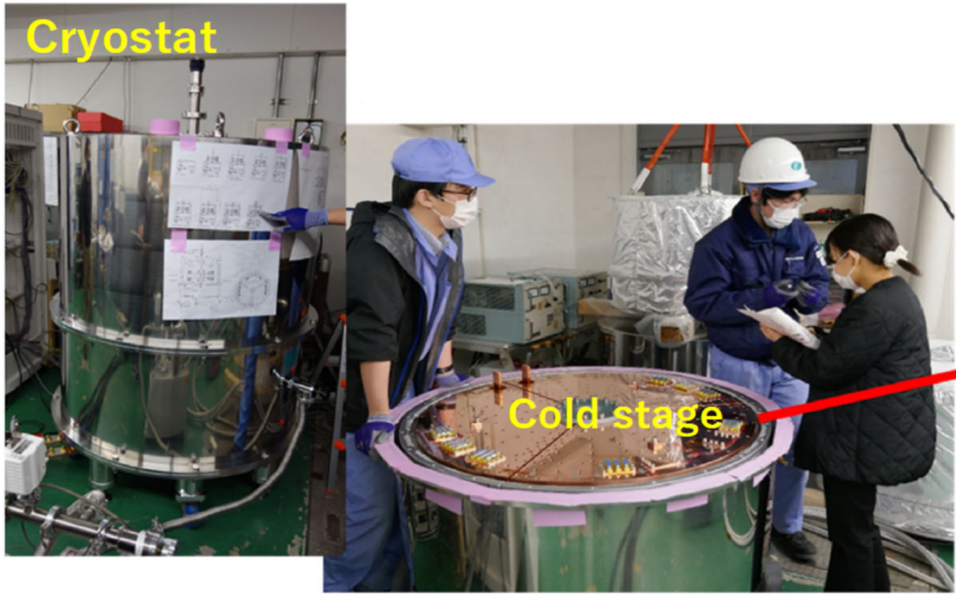


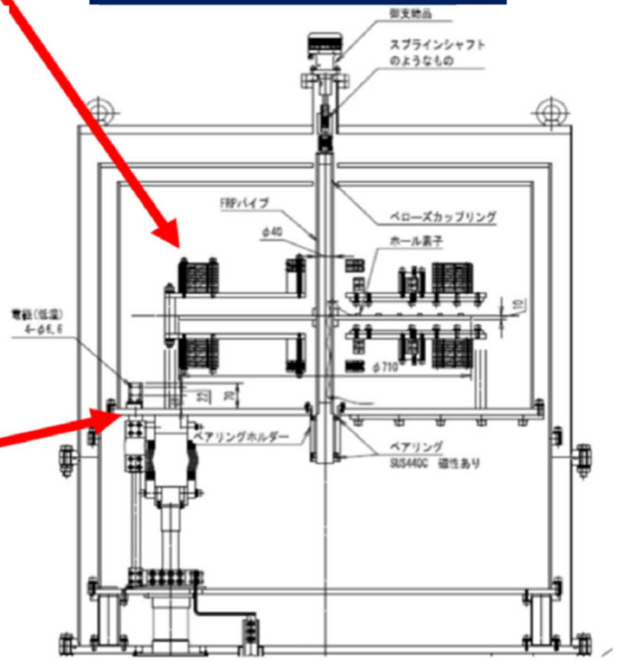
Red: main coils
Blue: sector coils



<REBOC tape>
- 6 mm width
- 0.1 mm thick

<Operating conditions>
- 540 A
- 30 K
- Particle extraction radius: 200 mm





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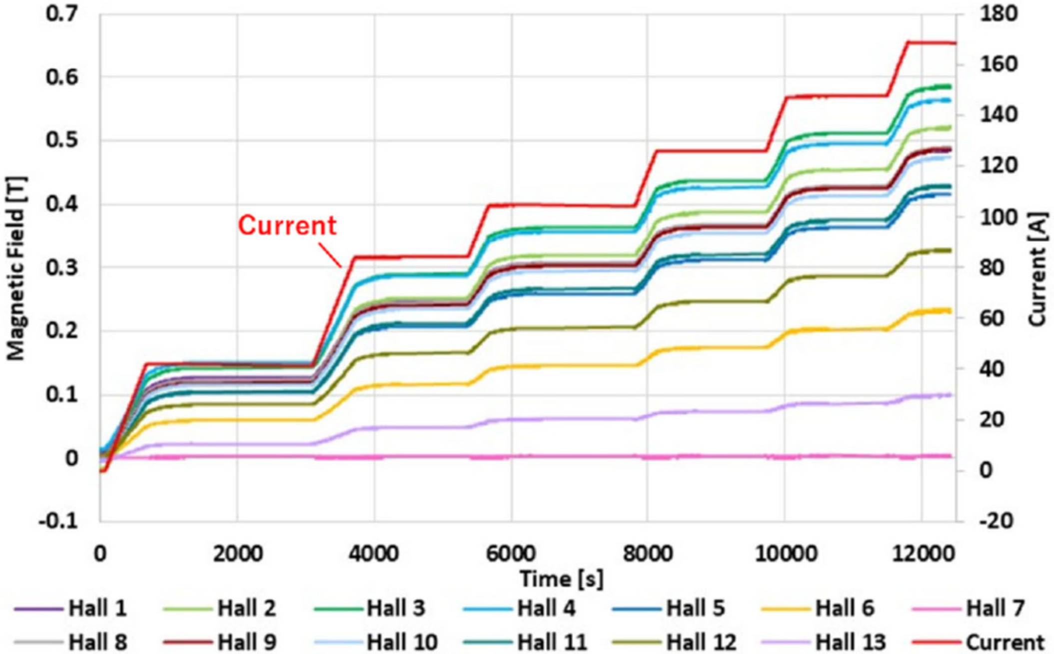
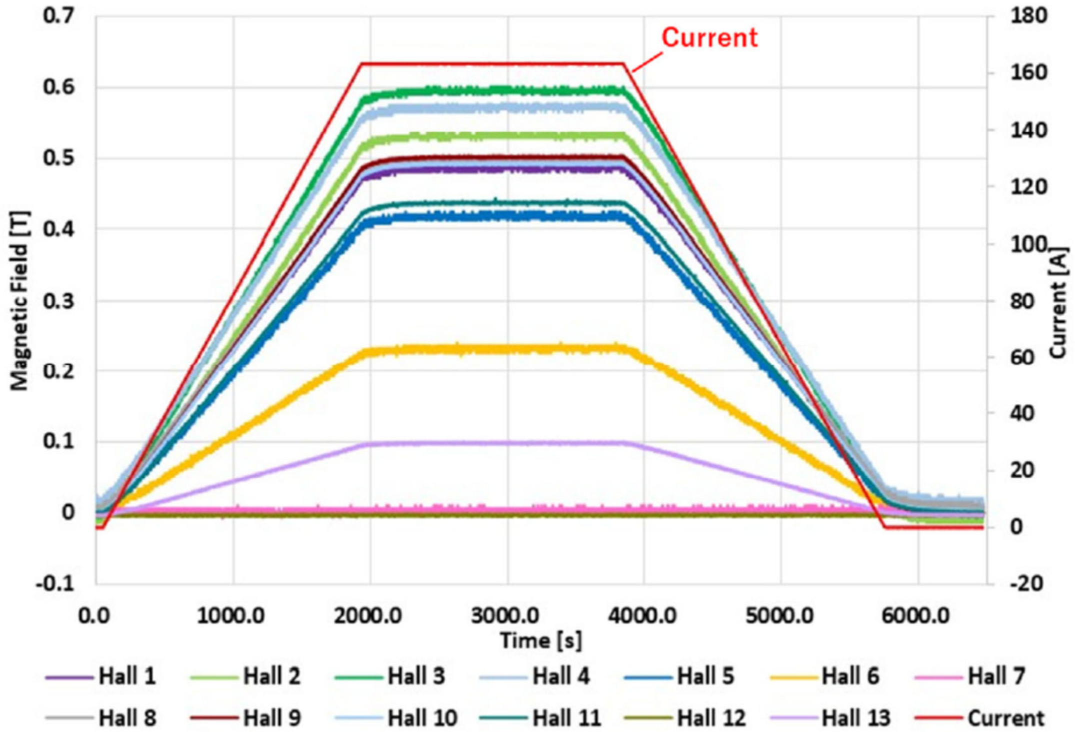
Experimental Results : Magnetic Field on the particle acceleration plane



Magnetic field (stepwise excitation)

- A delay in the magnetic field specific to the NI coil was observed.
- In the case of trapezoidal wave excitation, approximately 204 s lapsed to reach 99% of the stable magnetic field after the excitation was completed.



Magnetic field (trapezoidal wave excitation)

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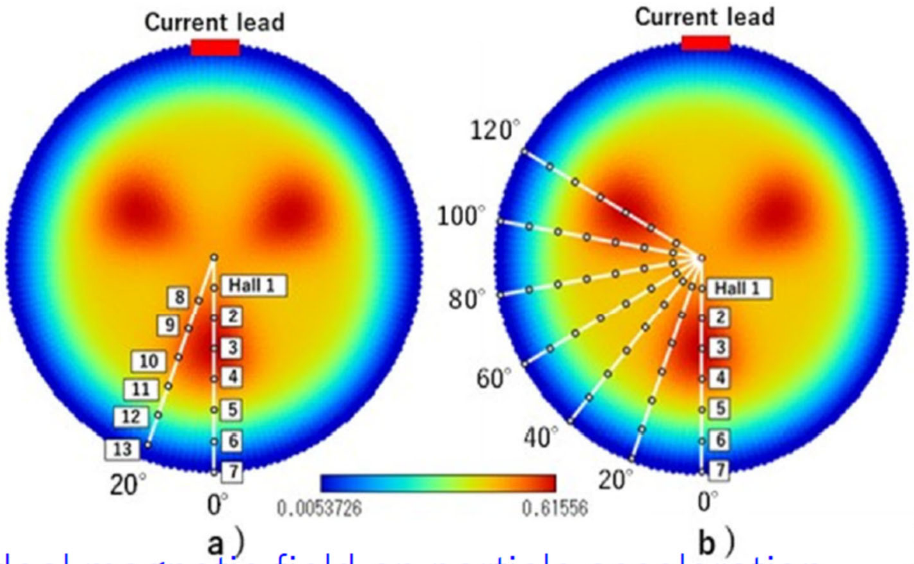
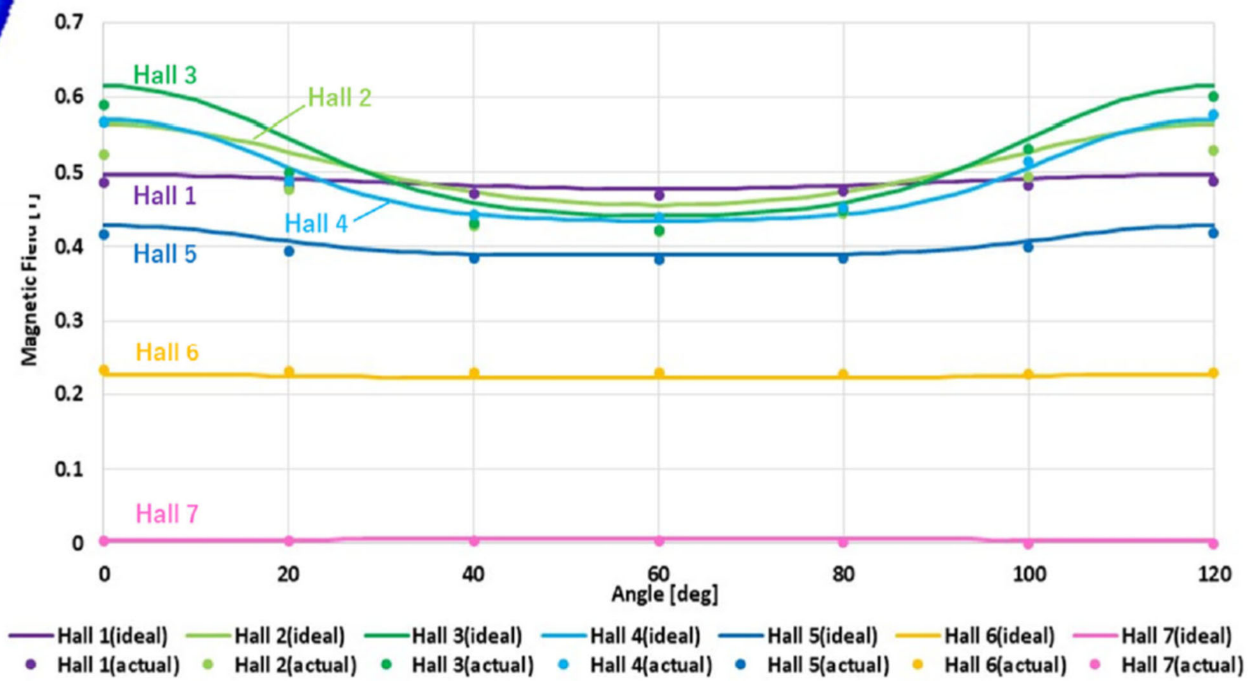
Experimental Results : Magnetic Field on the particle acceleration plane



Ideal magnetic field on particle acceleration plane and magnetic field measurement points.



Ideal and experimental values on the rotating disk at maximum current flow.

- After holding at the maximum current, the rotary disk was rotated 0° to 120° every 20° when the magnetic field became stable, and the magnetic field on the particle acceleration plane was measured.
- Ideal and experimental values on the rot ating disk at maximum current flow.

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Summary (Summer 2023)

- We designed and fabricated an NI-REBCO coil system for the UBSC, a half-scale demonstration model of the HTS-SC.
- The coils were cooled to 2–9.3K without any large temperature gradient in the coil system, although approximately 190 h was required for cooling. Thereafter, temperature gradient in all coils could be maintained within ±1K using 30K temperature control.
- The voltage, magnetic field, and temperature were measured by conducting energization tests up to 160A. Waveforms specific to the NI coils were observed for both the voltage and magnetic field.
- We plan to repeat these experiments by gradually increasing the maximum current to the rating current of 540 A.

R.Kumagai, A.Ishiyama, H.Ueda, S.Noguchi, T.Watanabe, M.Fukuda, G.Nishijima, and J.Yoshida,
“Fabrication and Experiments on a 1/2-Scale Demonstration NI-REBCO Coil System of a Skeleton Cyclotron for Cancer Therapy”,
IEEE Transactions on Applied Superconductivity, 34, No.5, 2023 (DOI: 10.1109/TASC.2023.3338594)

Evaluation technology for HTS wire and magnets (Special Invited A-01-SI)

by Kyushu University

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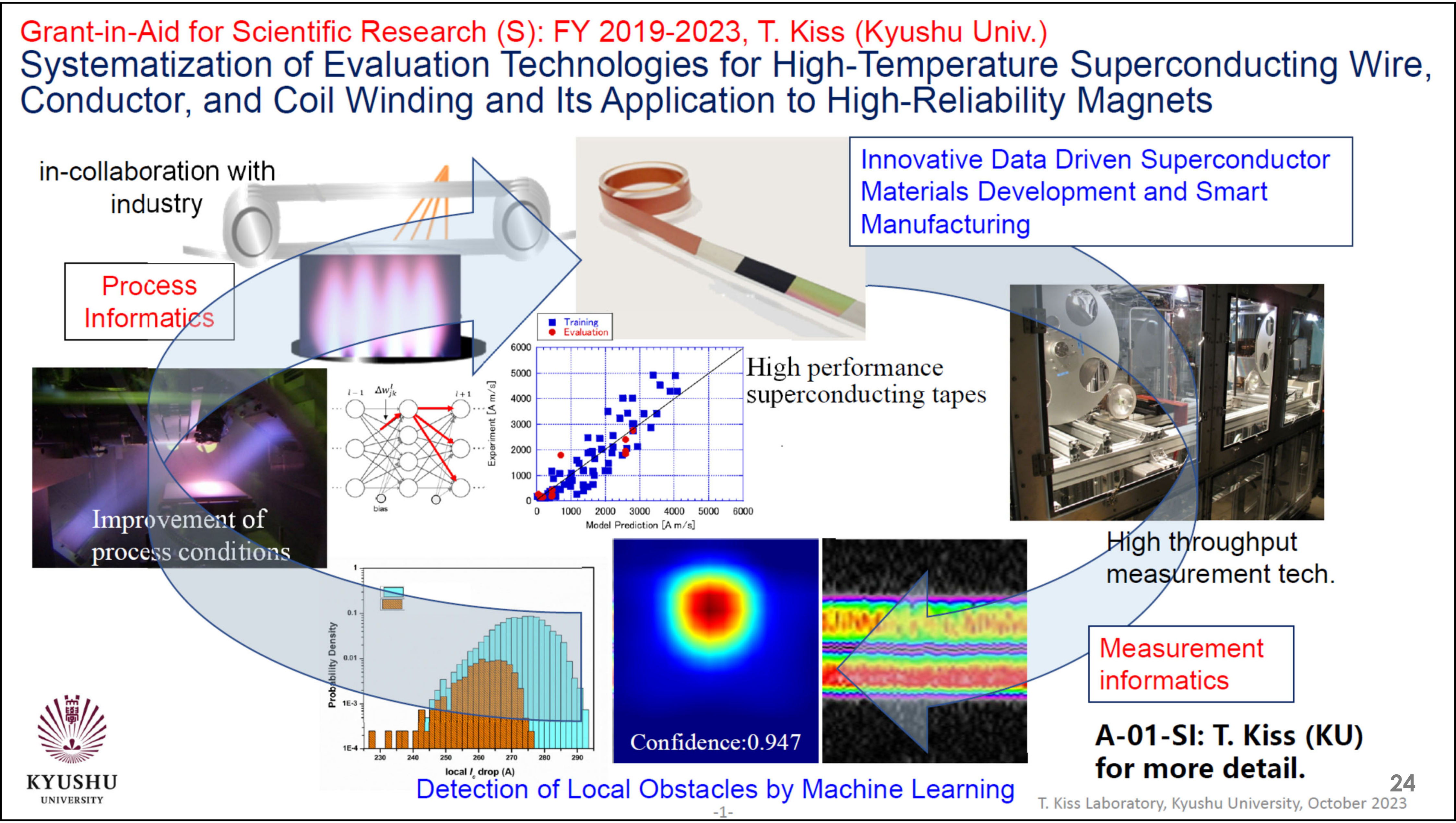

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Future Prospects as Key Technologies for Realizing Carbon Neutral Society

Hot Issue : Liquid hydrogen for Carbon Neutral Society

R & D Examples

*MgB_2 wire for AC use
*HTS motor for LH_2 pump
*LH_2 cooled generator

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Challenge to a Low-carbon Society

① Low-carbon emission power sources
② Energy-saving technology

demand side — high efficiency equipment

supply side — Low CO_2 intensity

↓

Significant CO_2 emission reduction

(Japanese Prime Minister announced carbon neutrality in 2050)

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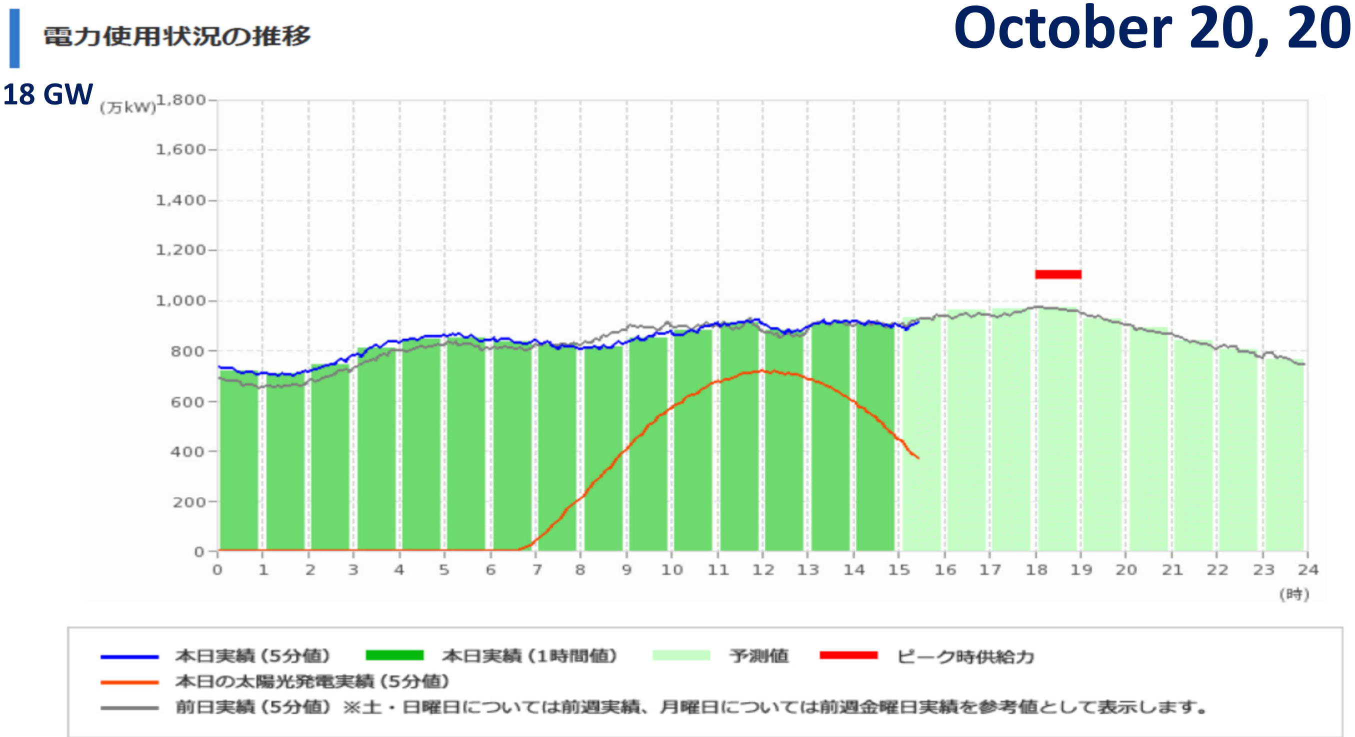
Supply and Demand Results of Kyushu Electric Power Co.

October 20, 2020



(Almost the world’s largest percentage of solar power generation)

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 55, January, 2024. Plenary presentation given at ACASC 2023, 30 Oct. 2023, Shanghai, China

Detailed Supply and Demand Results of Kyushu Electric Power Co.

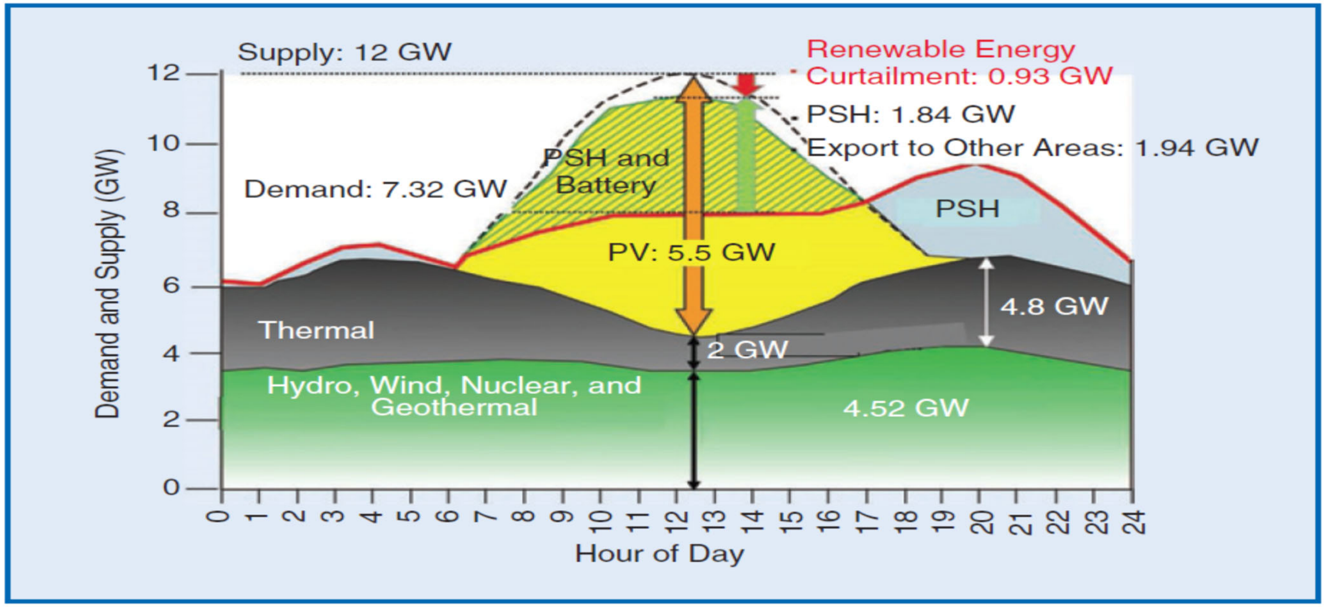


figure 5. The demand and supply operation on 21 October 2018. (Source: Kyushu EPCO; used with permission.)

(PSH : pumped-storage hydropower)

(Absorb surplus solar power by PSH)

"Making Renewables Work", by Kazuhiko Ogimoto and Hiroshi Wani IEEE Power & Energy Magazine November/December 2020 p.51

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 55, January, 2024. Plenary presentation given at ACASC 2023, 30 Oct. 2023, Shanghai, China

Liquid hydrogen for Carbon Neutral Society

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 55, January, 2024. Plenary presentation given at ACASC 2023, 30 Oct. 2023, Shanghai, China

水素基本戦略

令和５年６月６日

再生可能エネルギー・水素等関係閣僚会議

Basic Hydrogen Strategy by Japanese Government
June 6, 2023

Refers to the vision for year 2050 and action plan until 2030 to accomplish the goal of realizing a hydrogen society ahead of the rest of the world by making hydrogen a new energy option amongst other renewable energy sources.

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 55, January, 2024. Plenary presentation given at ACASC 2023, 30 Oct. 2023, Shanghai, China

図 1　神戸液化水素荷役実証基地の完成イメージ
Fig. 1　Rendering image of liquefied hydrogen loading/unloading demonstration terminal in Kobe

川崎重工技報・182号　2020年9月

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 55, January, 2024. Plenary presentation given at ACASC 2023, 30 Oct. 2023, Shanghai, China

図 3　液化水素タンク
Fig. 3　Liquefied hydrogen storage tank

Liquid hydrogen Tank
2500 m^3

川崎重工技報・182号　2020年9月

Proposal by COCN

2023（令和5）年9月

September 2023

「2023年度推進テーマ中間報告案（要約）」

『水素・超電導コンプレックス』
Hydrogen-Superconductivity Complex

推進テーマリーダー　来栖　努

（東芝エネルギーシステムズ株式会社

パワーシステム事業部・シニアフェロー）

COCN （Council on Competitiveness-Nippon:産業競争力懇談会）

Wide Area Connection of RE (広域再エネ連系構想)

液体水素の冷熱を利用した超電導発電機と水素ガスタービンとで、広域に再エネ電源を連系することで、再エネ中心の電力系統を安定化。
(送電インフラ増強のためのコストを大きく削減し、低コストなCN策となる期待あり)

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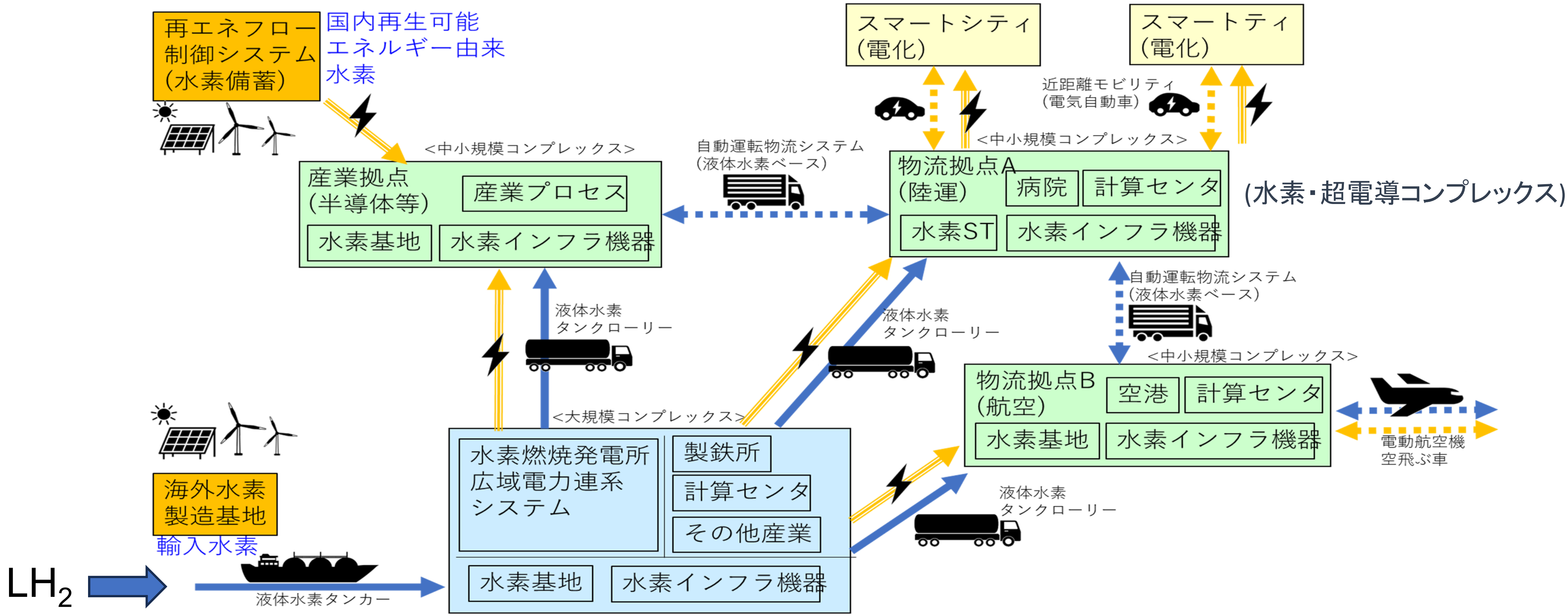
Hydrogen and SC Complex



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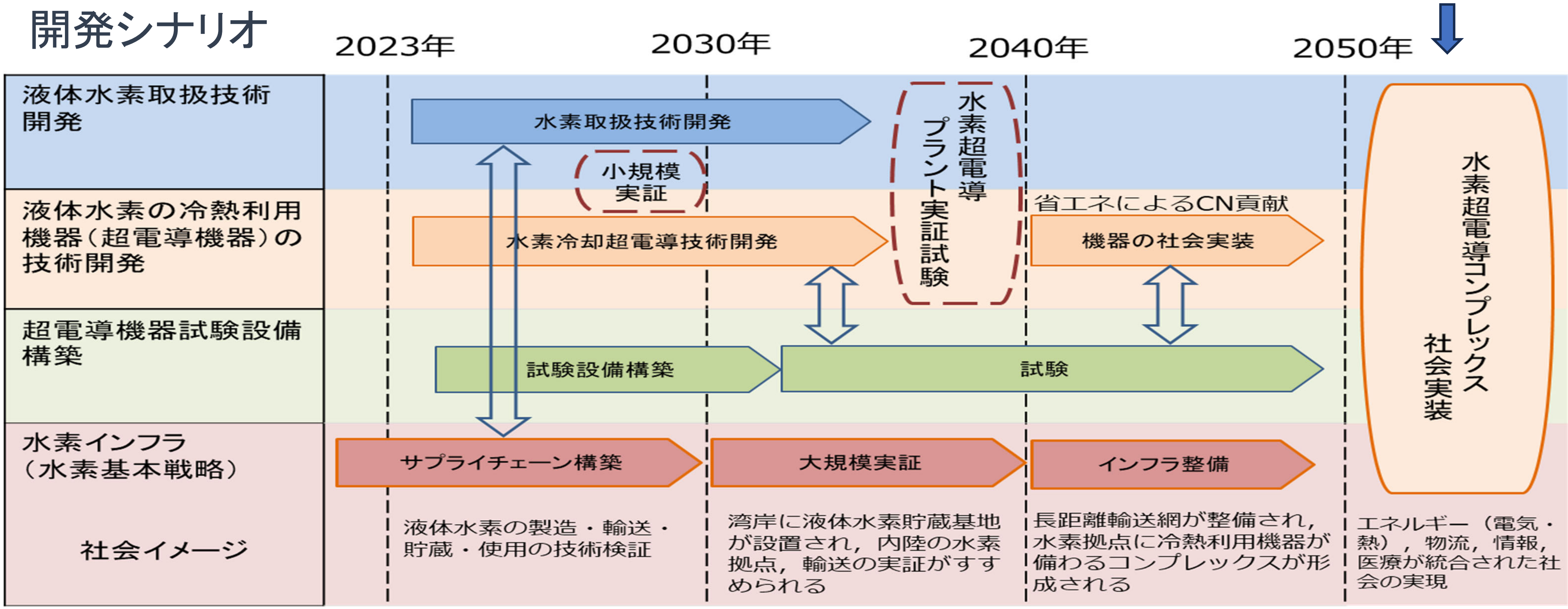
R & D Scenario

Deployment of
Hydrogen and SC Complex



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MgB_2 wire for AC use

by NIMS

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35th International Symposium on Superconductivity
I·S·S 2022
WEB-BASED SYMPOSIUM
AIST and VUW
November 29 – December 1, 2022

WB5-2-INV

Development of the ultrafine MgB_2 superconducting wires and stranded cables

Akihiro Kikuchi
National Institute for Materials Science

NIMS
Meiko Futaba
NEDO

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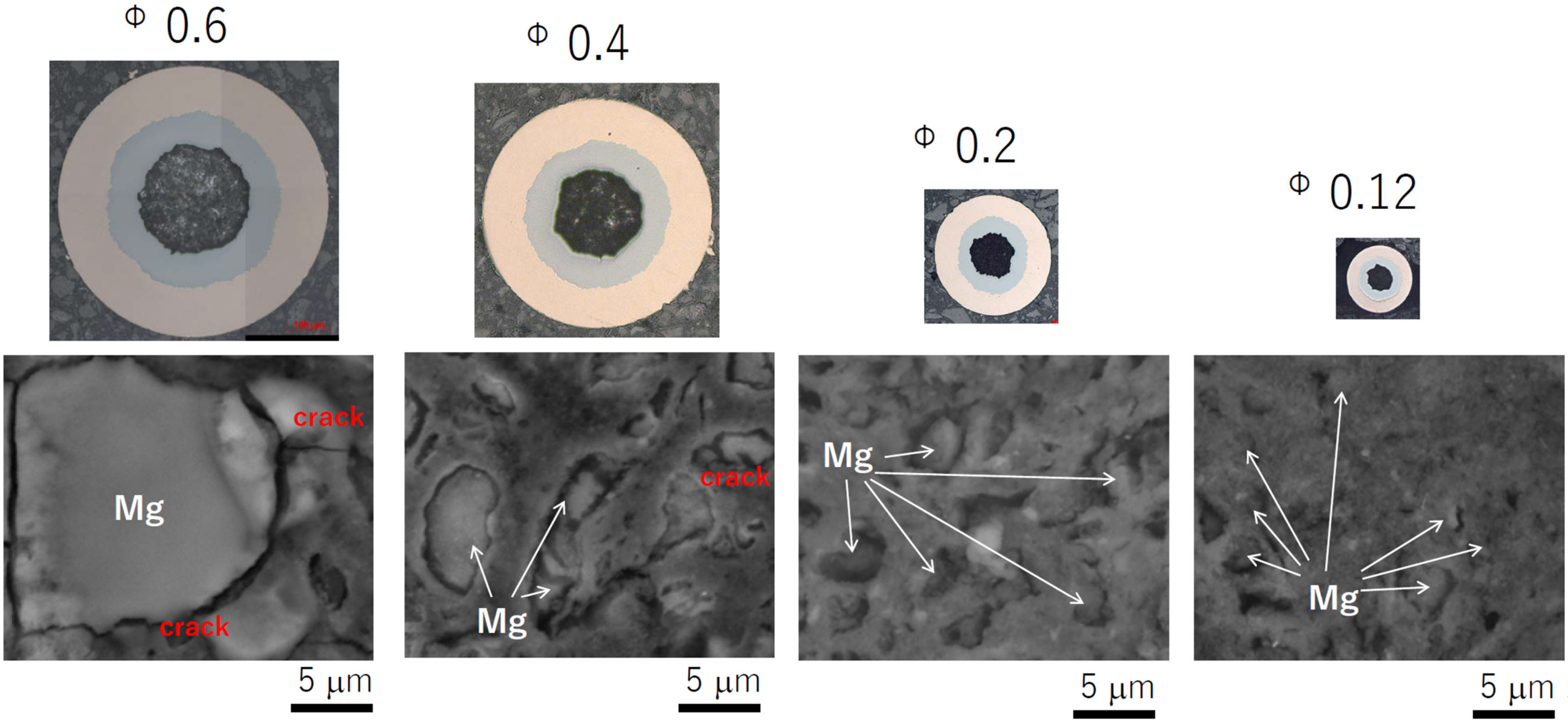
Coarse Mg powders would be gradually grounded through a drawing process



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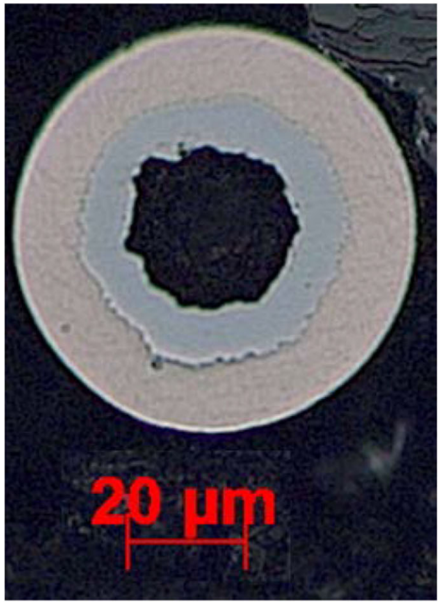
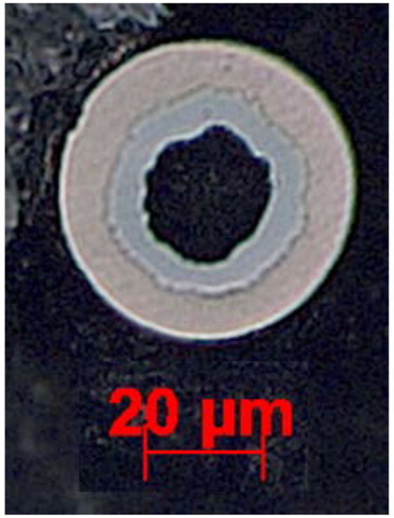
Drawing to ultrafine diameters

Φ 0.07



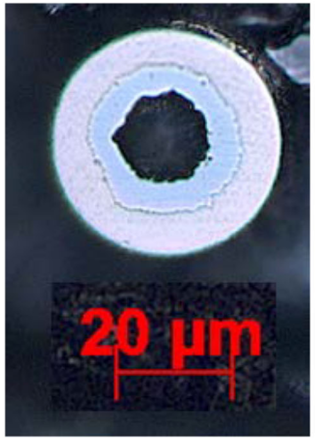
1,001 m
(100 m/min)

Φ 0.05



500 m
(100 m/min)

Φ 0.033



148 m
(50 m/min)

Φ 0.022

51 m
(50 m/min)

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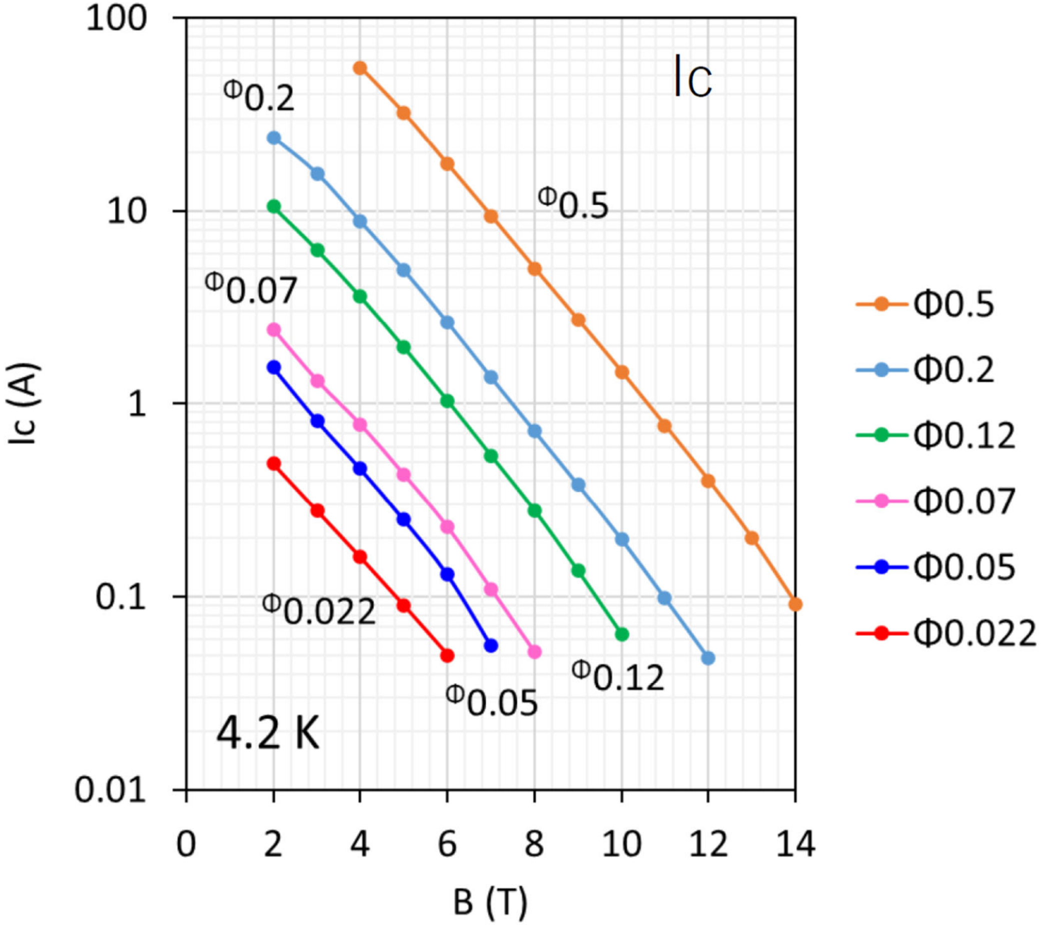
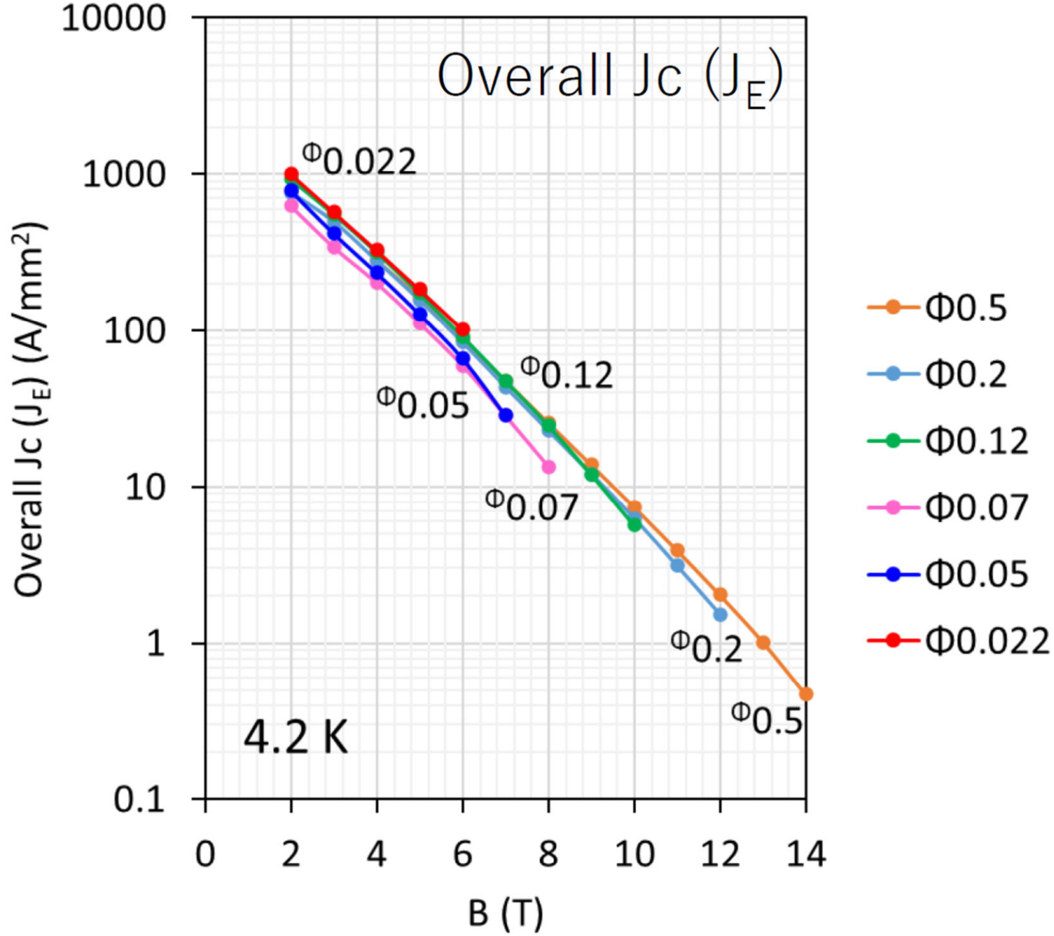
Critical Current & Critical Current Density





Heat Treatment : 650 °C for 30 min in vacuum

Criterion : 1 uV/cm

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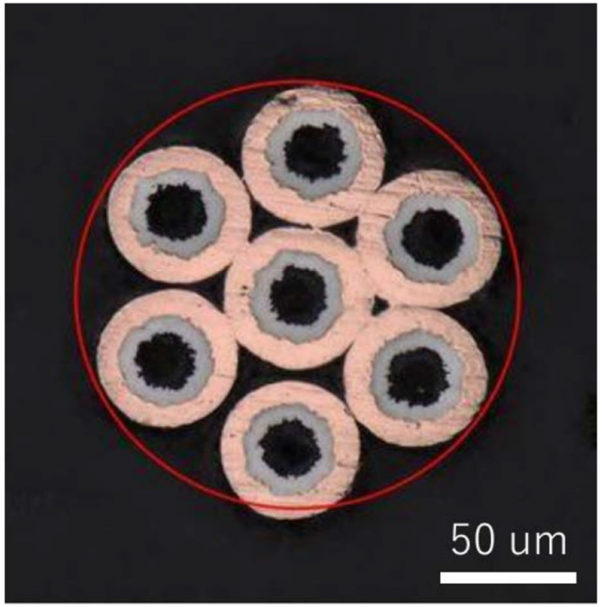
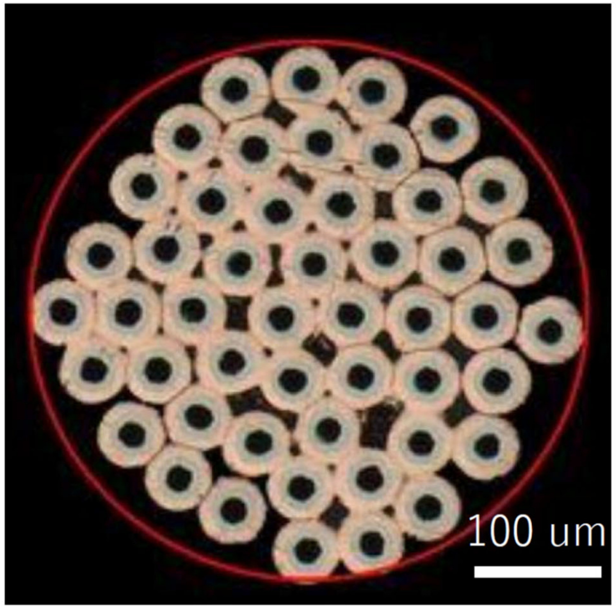
Ultrafine MgB_2 stranded cable

7/0.05	49/0.05





7/0.05

Outer sheath material : Oxygen Free Cu
Cu/non Cu ratio : 1.0
Strand diameter : 0.05mm
Num. of strand : 7
Twist pitch length : 5.0mm
Twist pitch direction : S (Left hand)
Cable diameter : ~0.15mm

49/0.05

Outer sheath material : Oxygen Free Cu
Cu/non Cu ratio : 1.0
Strand diameter : 0.05mm
Num. of strand : 49
Twist pitch length : 8.0mm
Twist pitch direction : S (Left hand)
Cable diameter : ~0.41mm

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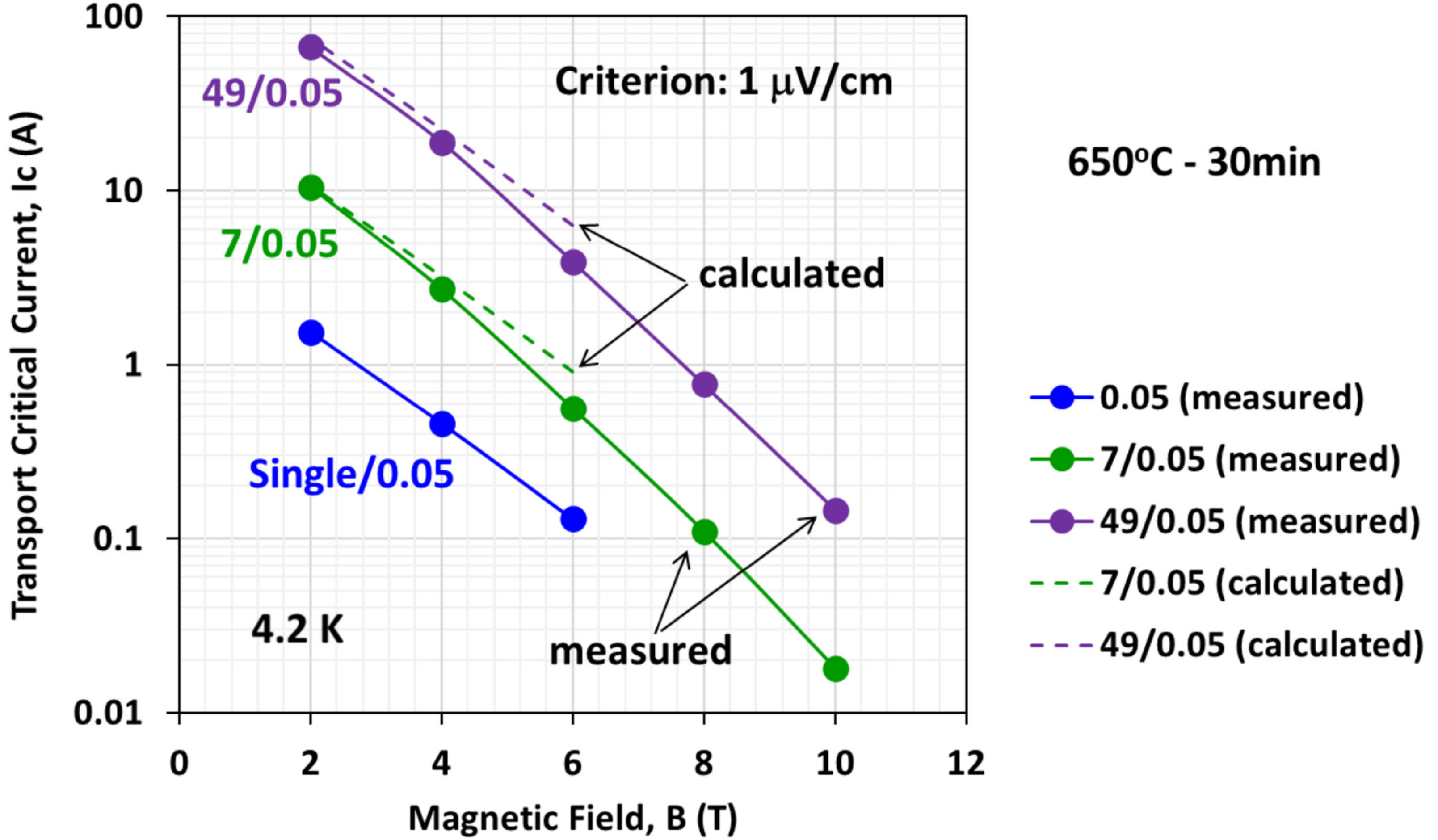
Critical Current & Critical Current Density



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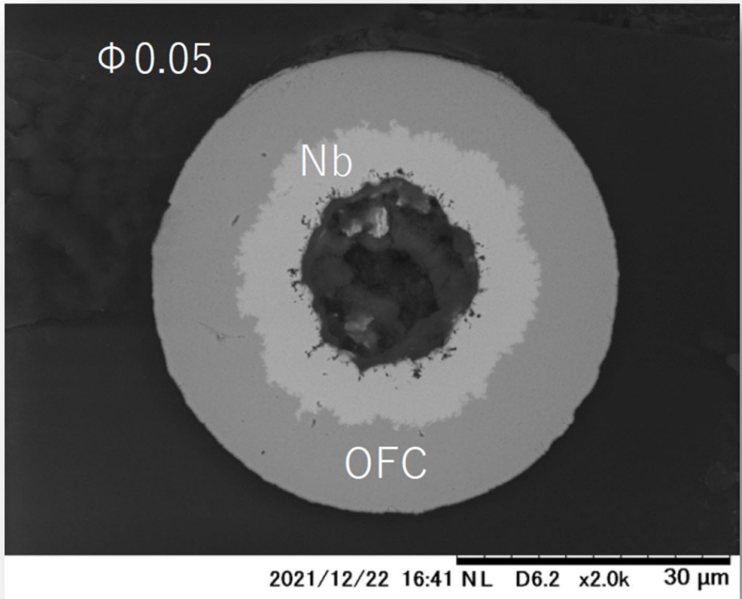
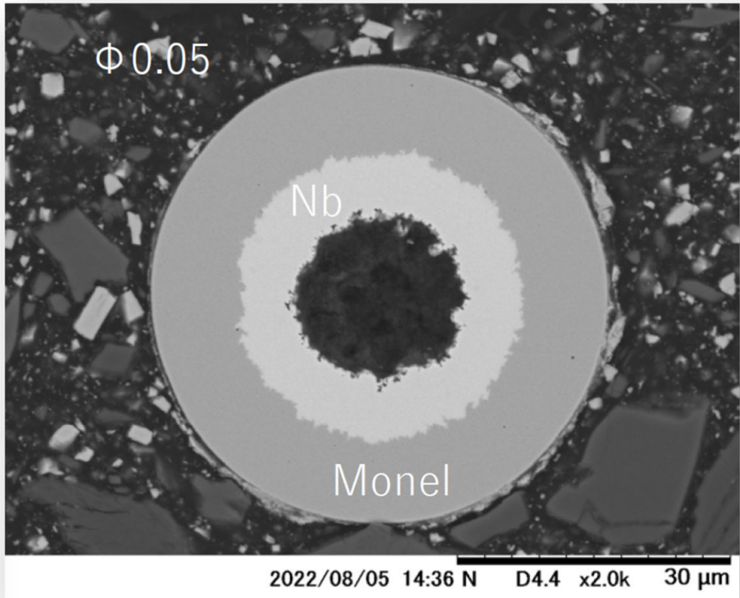
Remarkable improvement of wire drawability

Oxygen Free Cu



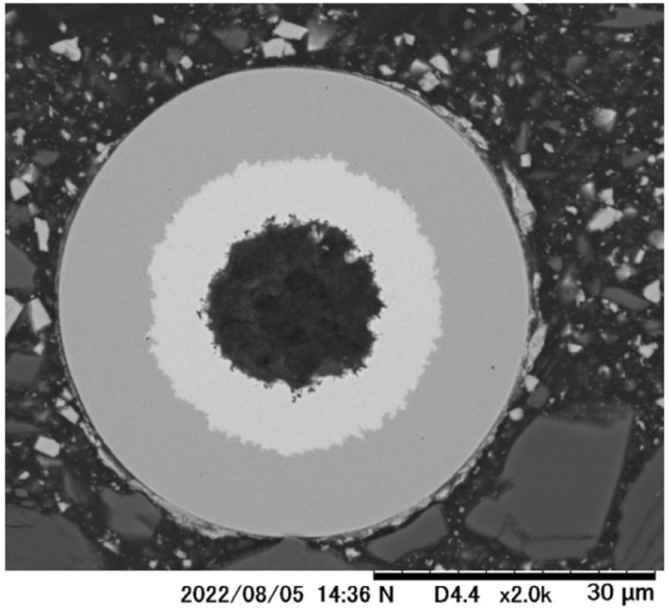
Monel (7Ni-3Cu)



Sheath Material	50 μm	Tensile strength (MPa)	Elongation (%)
Oxygen Free Cu	500 m	720	1.3
Monel (7Ni-3Cu)	4,000 m	1,450	2.4

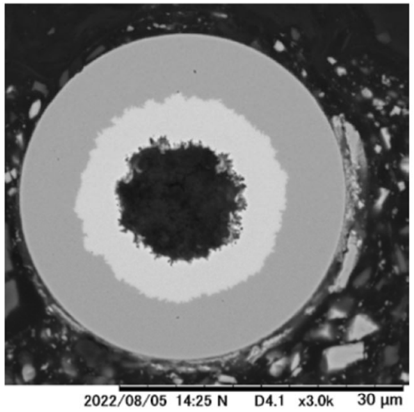
Drawing to ultrafine diameters

Φ0.05



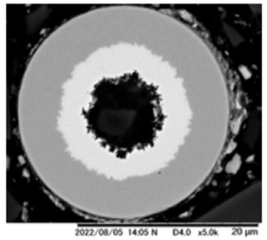
Outer Dia. : 50 um
SC Fil. Dia. : 18 um
Piece Length : 4,000 m

Φ0.033



Outer Dia. : 33 um
SC Fil. Dia. : 12 um
Piece Length : 3,000 m

Φ0.022



Outer Dia. : 22 um
SC Fil. Dia. : 8.5 um
Piece Length : 675 m

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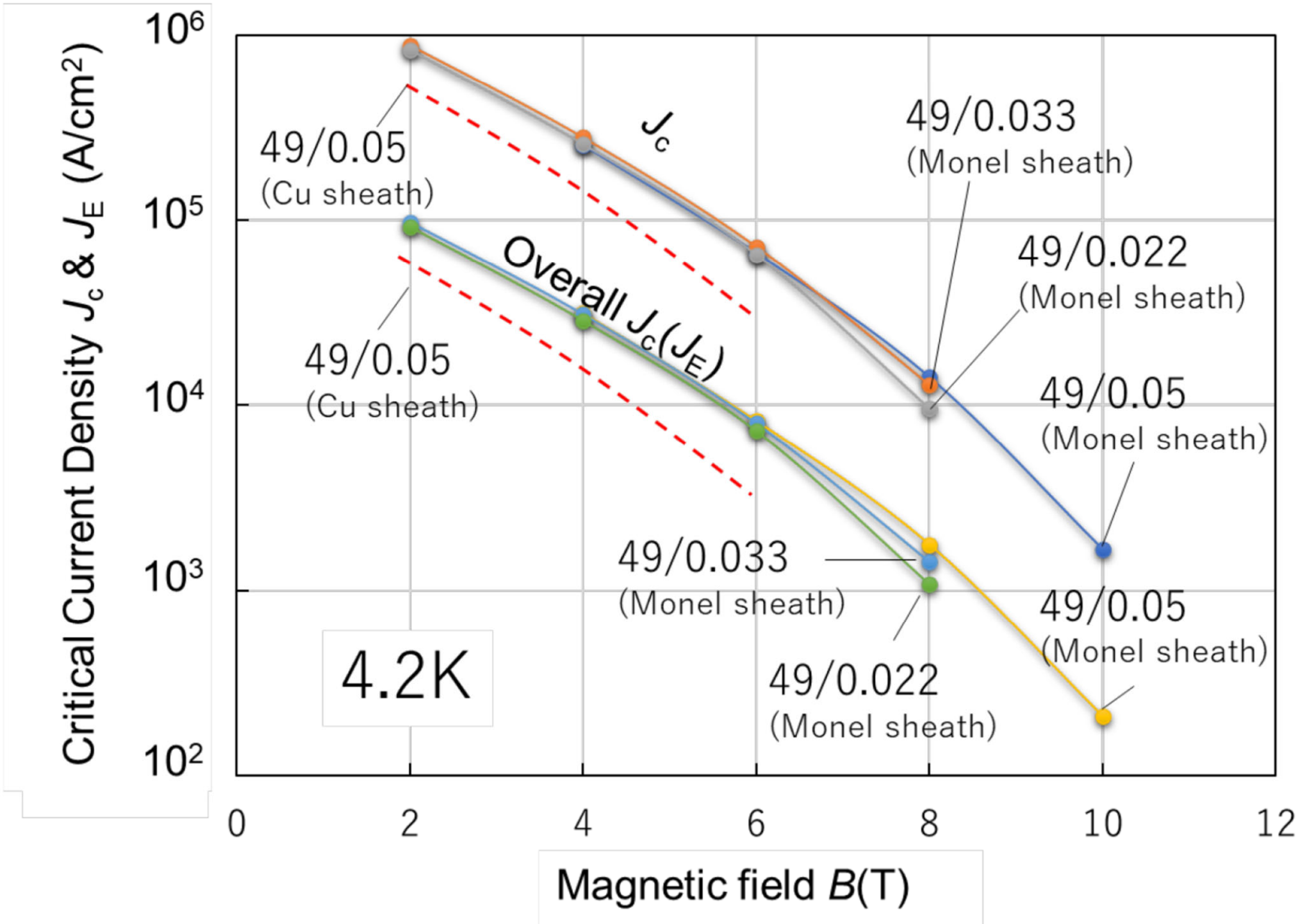
Critical current density of 49 Monel sheathed MgB_2 stranded cables



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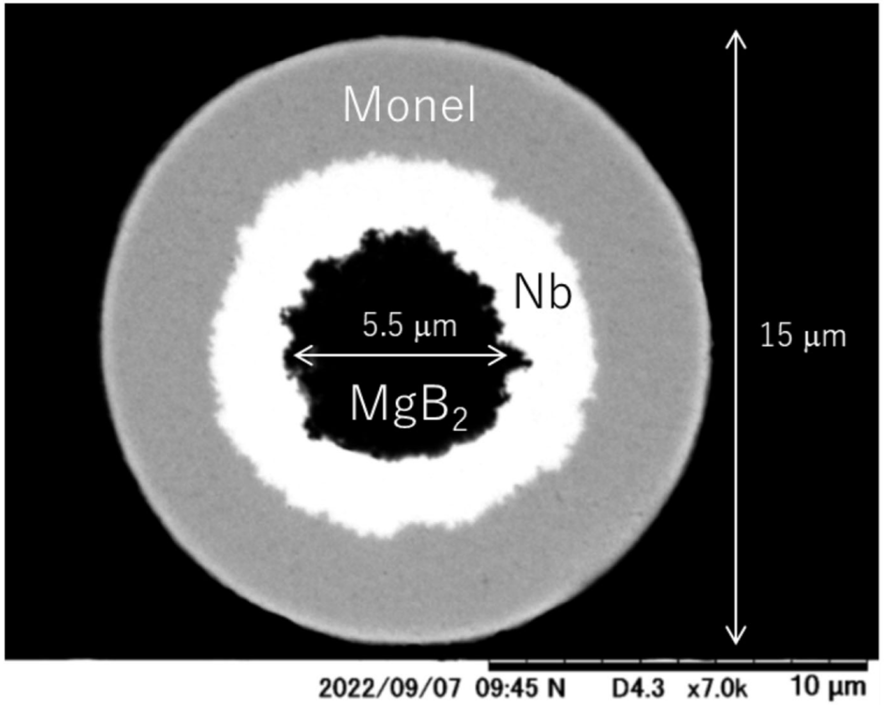
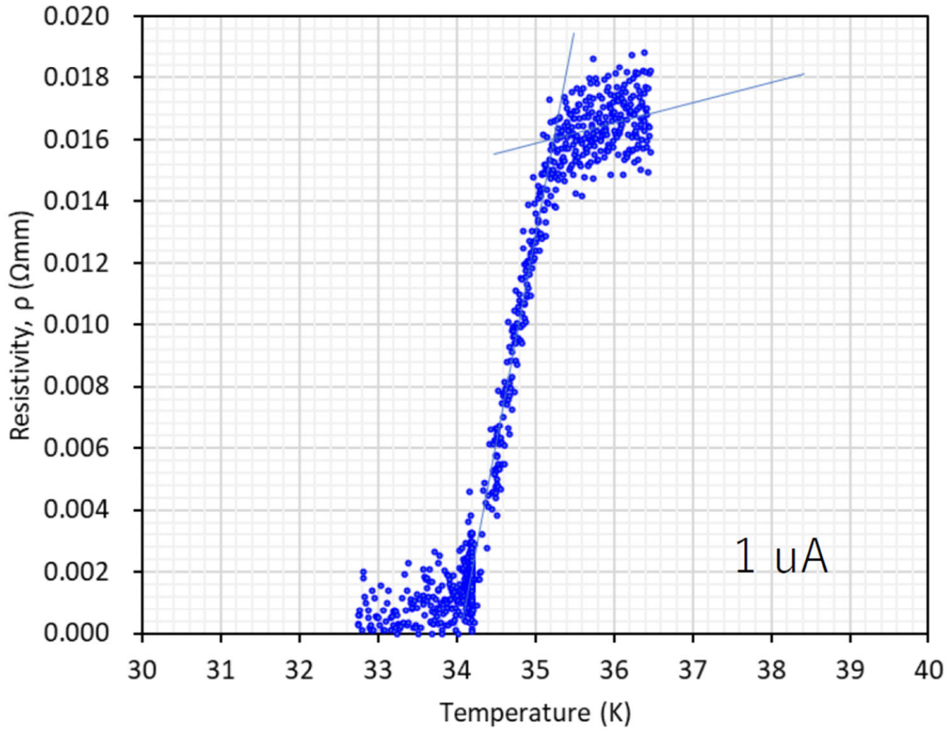
MgB_2 superconducting wire with the world's smallest diameter





Outer Dia. : 15 um
SC Fil. Dia. : 5.5 um
Piece Length : 135 m

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HTS motor for LH_2 pump

by Kyoto University

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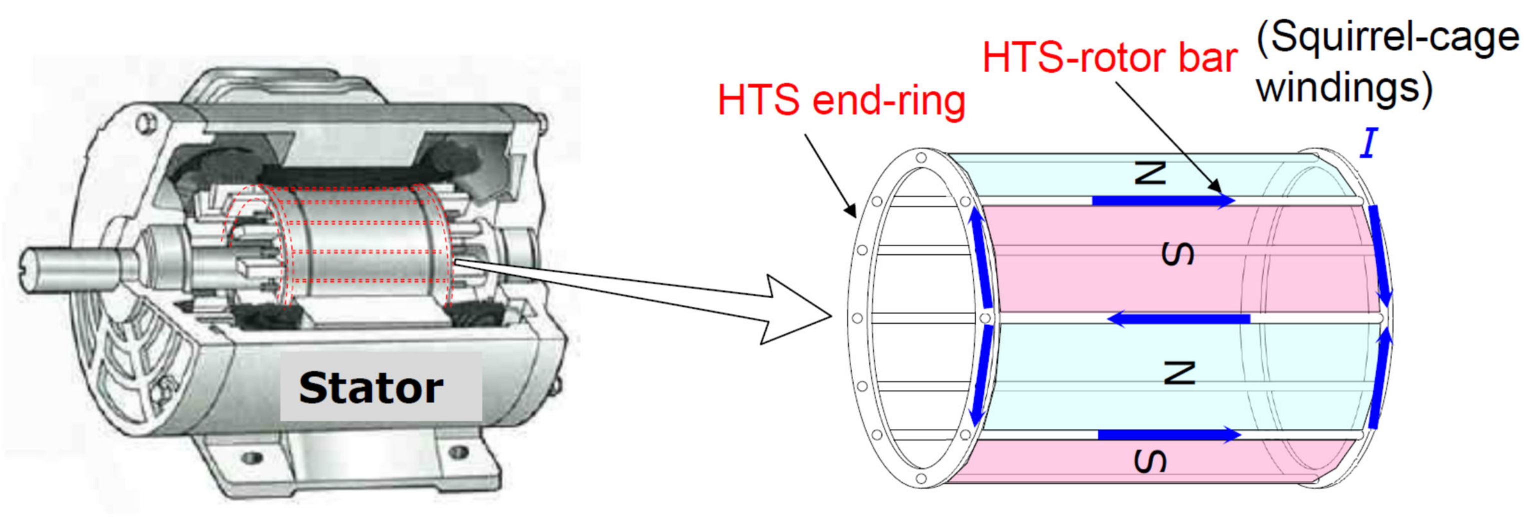
Developing superconducting drive pumps for liquid hydrogen that pump and pressurize liquid hydrogen ー Kyoto University ー

High Temperature Superconducting Induction/Synchronous Machine (HTS-ISM)



(a) Schematic figure (HP of NIDEC Co.)　　(b) Rotor windings

Fig. 1 Schematic diagram of HTS-ISM

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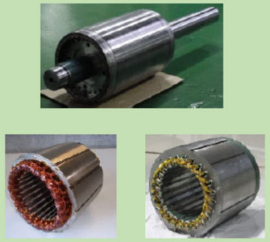
Developing superconducting drive pumps for liquid hydrogen that pump and pressurize liquid hydrogen

CRIEPI Central Research Institute of Electric Power Industry

R&D history

(2005–2010)
200 V, ～10 kW

(2009–2011)
400 V, 20 kW



(2012–2018)
200 V, 20 kW
Overload:
41.3 kW

(2017–2020)
200 V, 50 kW
Fully HTS

(2021–2022)
200 V, 60 kW
Partial HTS

←

- Maximum mechanical output: 61 kW
- Maximum efficiency: 99.75%

Fig. 2 R&D history of HTS-ISM in Kyoto U.

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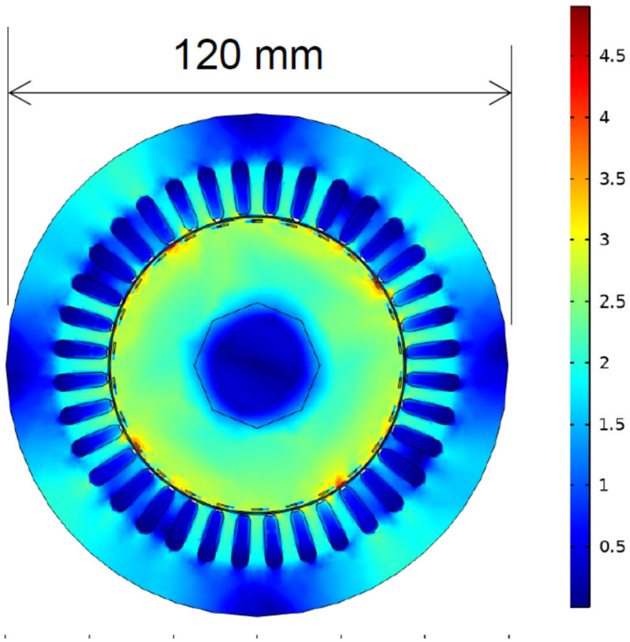
Developing superconducting drive pumps for liquid hydrogen that pump and pressurize liquid hydrogen

Liquid hydrogen pump for hydrogen engine vehicles

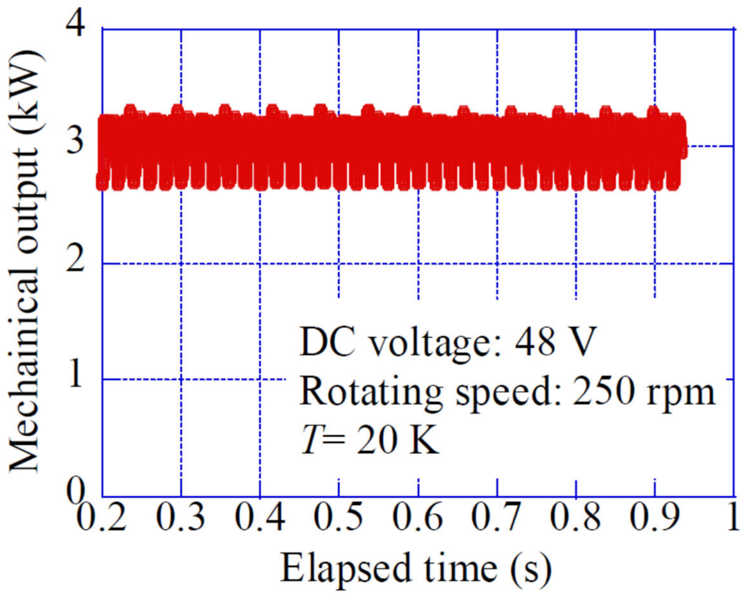
Developing superconducting drive pumps for liquid hydrogen that pump and pressurize liquid hydrogen

Liquid hydrogen pump for hydrogen engine vehicles

Achieves mechanical output of 3 kW even though the DC input voltage of the inverter is 48 V and the speed is low (250 rpm)



(a) Magnetic flux density contour



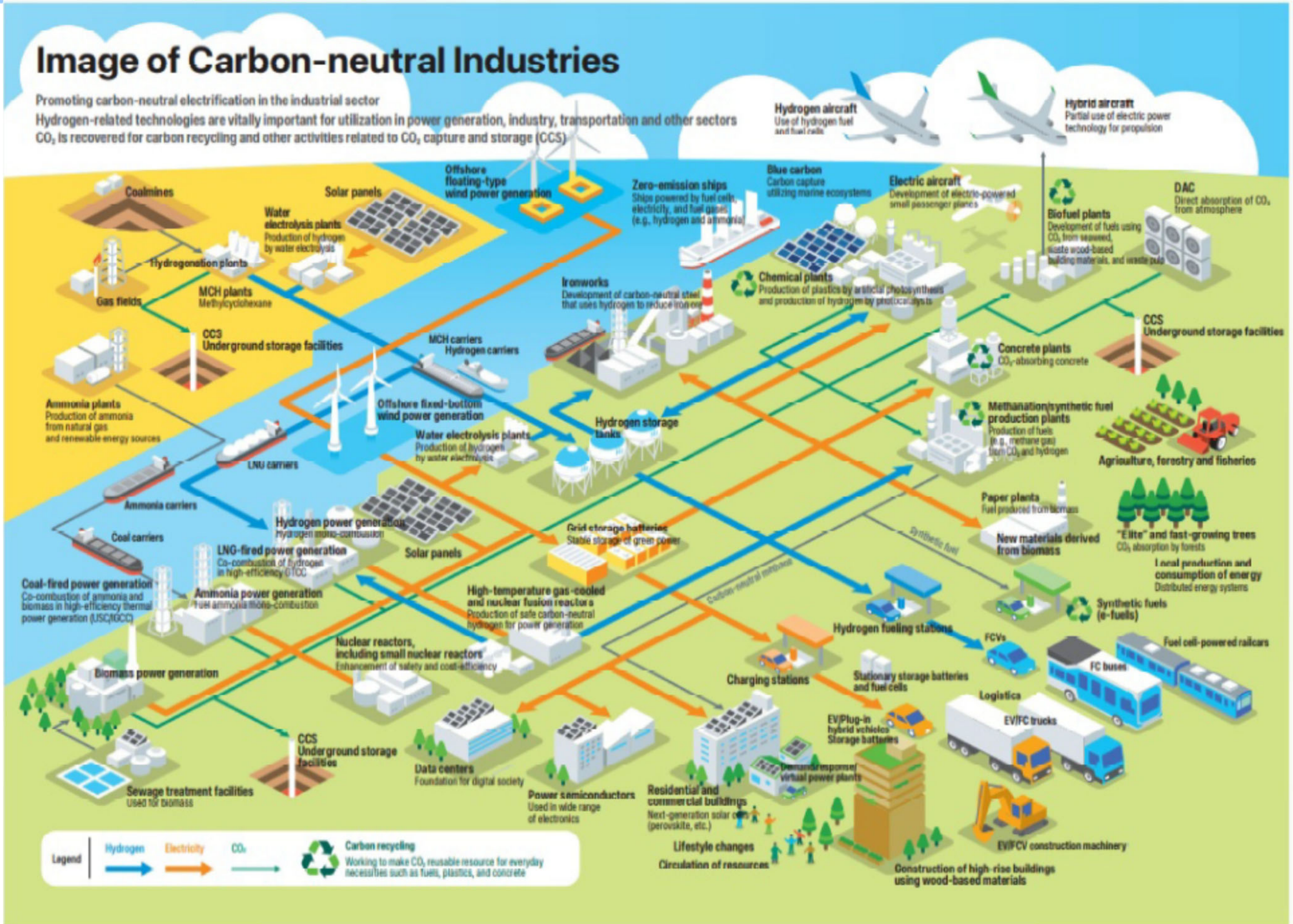
(b) Mechanical output curve

Fig. 4 Electromagnetic design result of 3 kW low speed high torque HTS-ISM

LH_2 Cooled Generator

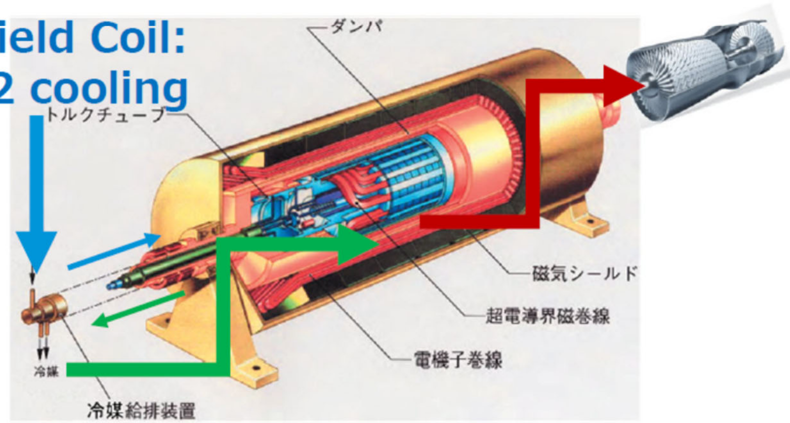
by NEDO Project

Background & Goal



③Hydrogen power generation

①Field Coil: LH2 cooling



②Armature Coil: GH2 cooling

Effective utilization of the cold heat of LH2

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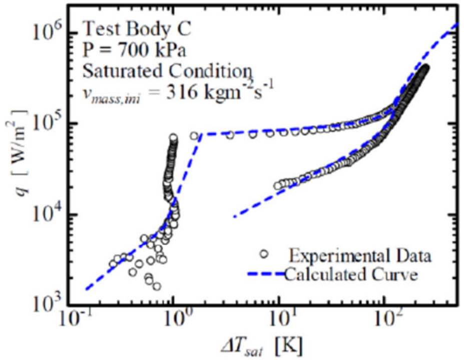
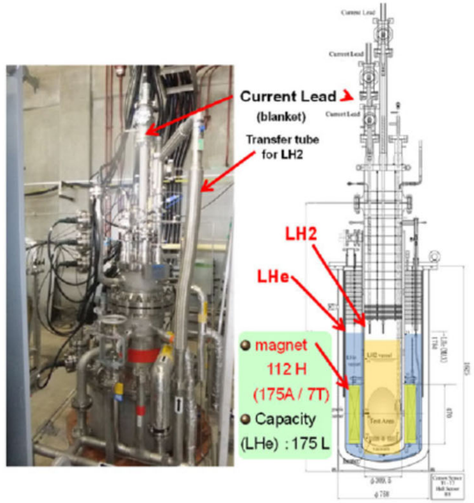
Basic technology development

Noshiro Rocket Testing Center

①Boiling heat transfer test



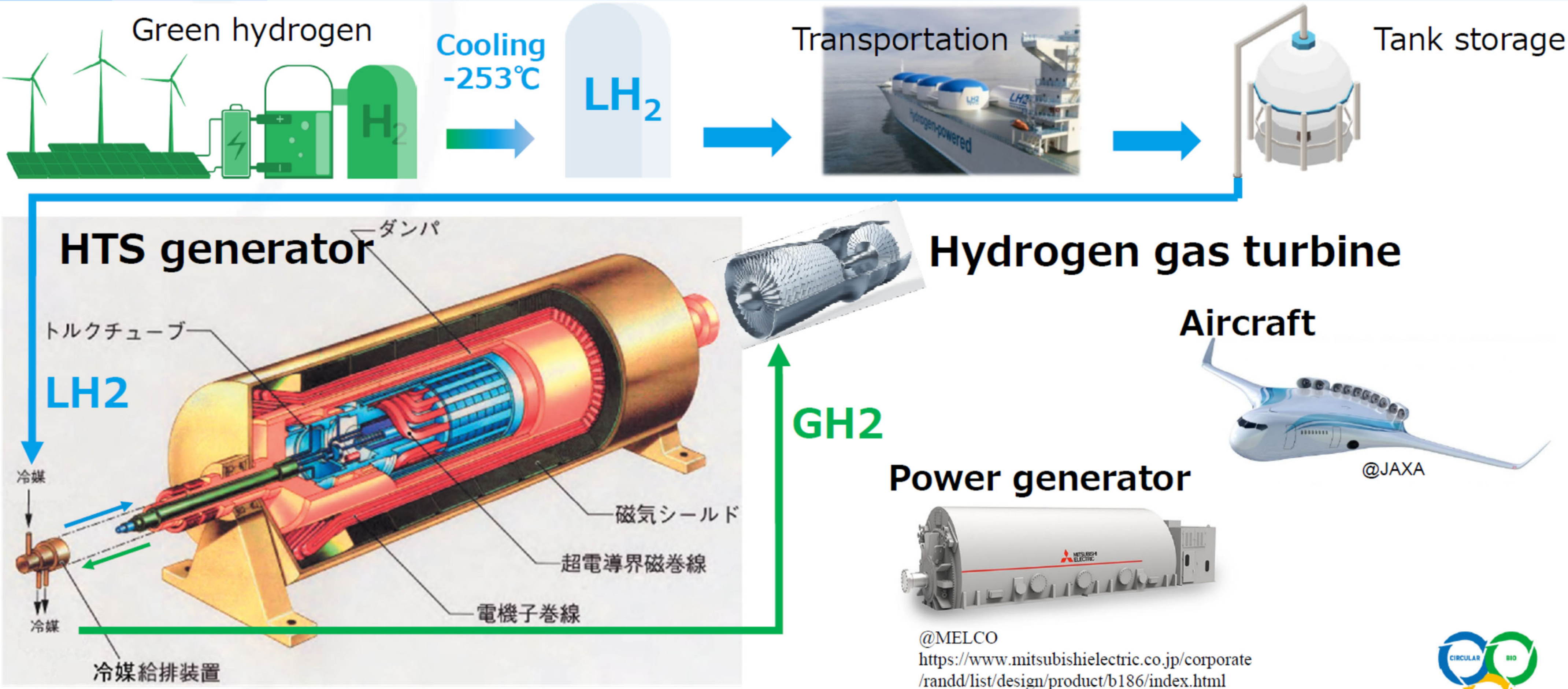
②Excitation test of HTS wires & coils



LH2 immersion cooling energization test apparatus

③LH2 supply test for rotating cryo.

Future image



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Development items

Item	Interim target	Final target
A) High-strength & high-stability	Centrifugal force 2,000×g Stability immersed in LH2	Centrifugal force 8,000×g Simulation of LH2 supply outage
B) HTS generator System	Design of 10 kW generator LH2 safety discussion Small superconducting bearing Heat balance model	Verification of 10 kW generator Safety measures Φ140 superconducting bearing Effective use of cold heat
C) Pathways to practical use	Cost estimate of 600 MW generator Power grid stability analysis Business feasibility	Concept design of 600 MW-class generator Advantage of HTS generator R&D Roadmap & scenarios

New Energy and Industrial Technology Development Organization

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Implementation system

Generator design
Road map & scenarios
(Power Grid)

MITSUBISHI ELECTRIC

NEDO

High-strength
High-stability

Heat balance
Road map & scenarios
(Aircraft)

Mitsubishi electric

Kwansei Gakuin

Tokyo Unv.

NEDO

Safety

JAXA

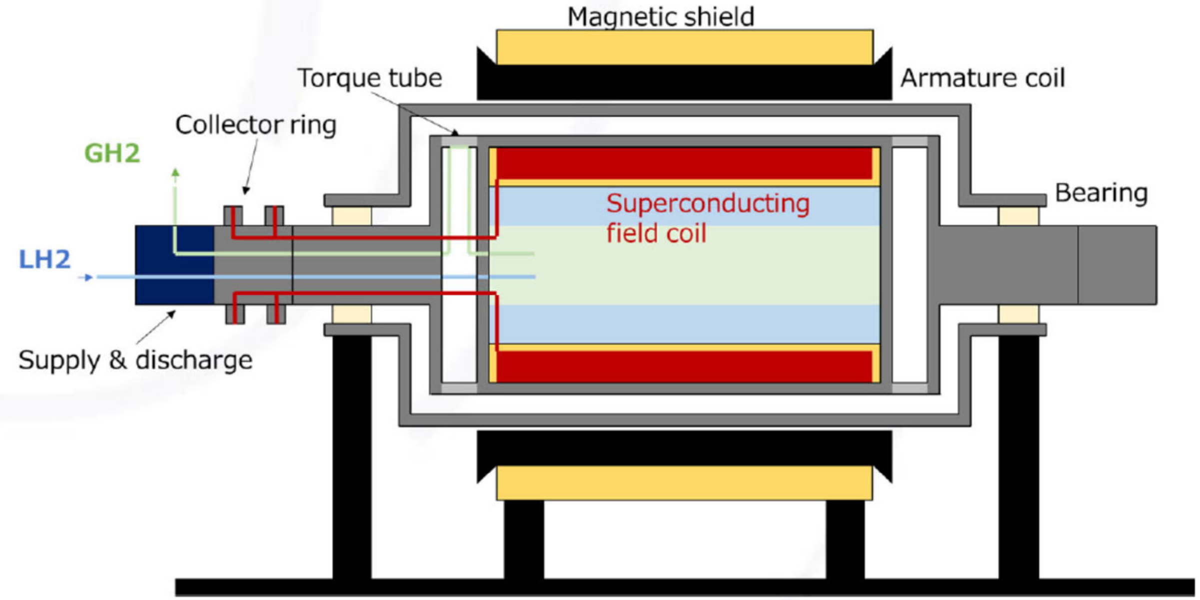
Sophia Univ.

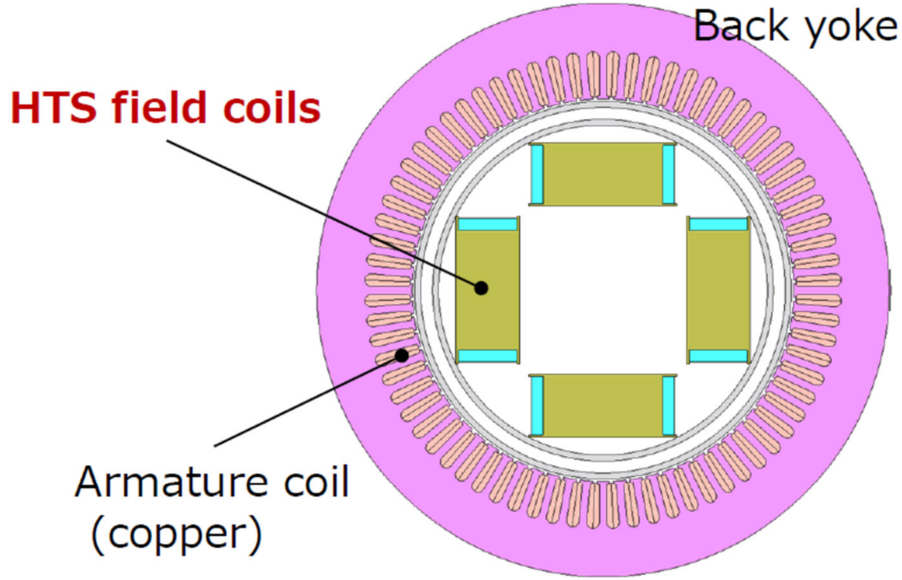
HTS bearing
Road map & scenarios
(Aircraft)

Power grid analysis

New Energy and Industrial Technology Development Organization

10 kW demonstrator





Items	Values
Output power	10 kW
Rotation speed	1,800 rpm
Number of poles	4
Field coil	REBCO (LH2 cooling)

Verification of a **10 kW-class HTS generator** with the superconducting field coil is scheduled in 2024.

- **LH2 cooling (20 K)**
- 1,800 rpm rotation

10 kW demonstrator

NEDO

Rotating section will be replaced with HTS generator

HTS rotor (4 poles) + Normal armature

Drive motors
& measurement slip rings

Hydrogen supply
& discharge pipe

Slip rings
& bearings

Hydrogen supply & discharge system

New Energy and Industrial Technology Development Organization

CIRCULAR BIO ENERGY DX

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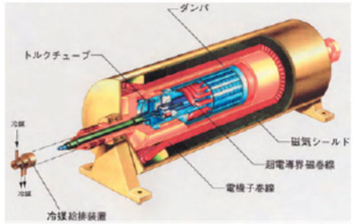
Next

2022 — 2024 — 2030

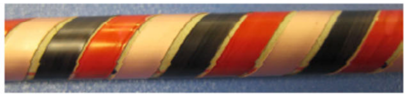
Demonstration

- High-strength & high stability
- 10 kW power generation demo
- Road map & scenarios

System Development



- 10 MW-class power generator development
- Hydrogen gas turbine coupling operation



Large-scale conductor

- 6kA class REBCO conductor

Social implementation

- 10 MW grid operation
- 600 MW generator development

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Summary

*Actual Application by LTS is progressing.
*High Magnetic Field Technology by LTS and HTS is underway.
* Precise Analyzation Method is Supporting R & D.
*Liquid hydrogen is the key for Carbon Neutral Society and Superconducting Application.

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