EUCAS2023-Bologna

EUCAS2023
Bologna, Italy
3rd-7th September

Focus Talk

Superconductivity and Hydrogen – the perfect wedding

Liquid Hydrogen Cooled Superconducting Power Apparatus and Carbon Free Energy System

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IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 55, January, 2024. Invited presentation given at EUCAS 2023, September 4, 2023, Bologna, Italy

Contents

NEDO : New Energy and Industrial Technology Development Organization, JAPAN

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Hydrogen-based Society

- **The energy system utilizing hydrogen as fuel or energy carrier is expected to greatly reduce the emission of CO2.**
- Japan experienced "Fukushima Disaster" in 2011. Nuclear power plant operations were halted and electricity supply from thermal power increased, resulting in a significant increase in carbon dioxide emissions.
- In 2017, **"Basic Hydrogen Strategy"** was formulated in Japan as the world's first national strategy for hydrogen.
- By now, 26 countries have formulated the similar strategy.
- In October 2020, Japan announced its **"2050 carbon neutrality declaration (Society 5.0 with Carbon Neutral)"**.
- February 2022 Russia's invasion of Ukraine caused **a tectonic shift in the global energy supply-demand structure**.
- Europe and the U.K. have significantly increased their hydrogen production targets, and tax incentives in the U.S. are accelerating hydrogen production at a rapid pace.

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Liquid Hydrogen in Hydrogen-based Society

Hydrogen technology is one of the important solutions for CO_2 reduction innovative energy infrastructure

Carbon Free Electric power is expected

～Thermal Power Plant LNG, coal, pet.□ H2 natural energy

～Wind/Solar power plant □ can produce H2

H2 energy supply chain is necessary

Large amount of H2-Delivery & storage :

Liquid Hydrogen(LH2 : -253deg : 20K : volume 1/800 of GH2)

~Liquid Natural Gas(LNG : -162deg : volume 1/600)□ LNG tanker, container

First hydrogen tanker put into service in 2022.(Kawasaki Heavy Industry)

LH2 will play an important role in future hydrogen-based society

problem: large liquefaction Energy

Utilization of Cryogenic (Cold) energy is important ⇨ **Coolant for superconducting energy devices**

Superconducting power devices can be **free from cooling penalty** using Liquid Hydrogen which is **major Energy Carrier** of H2 supply chain

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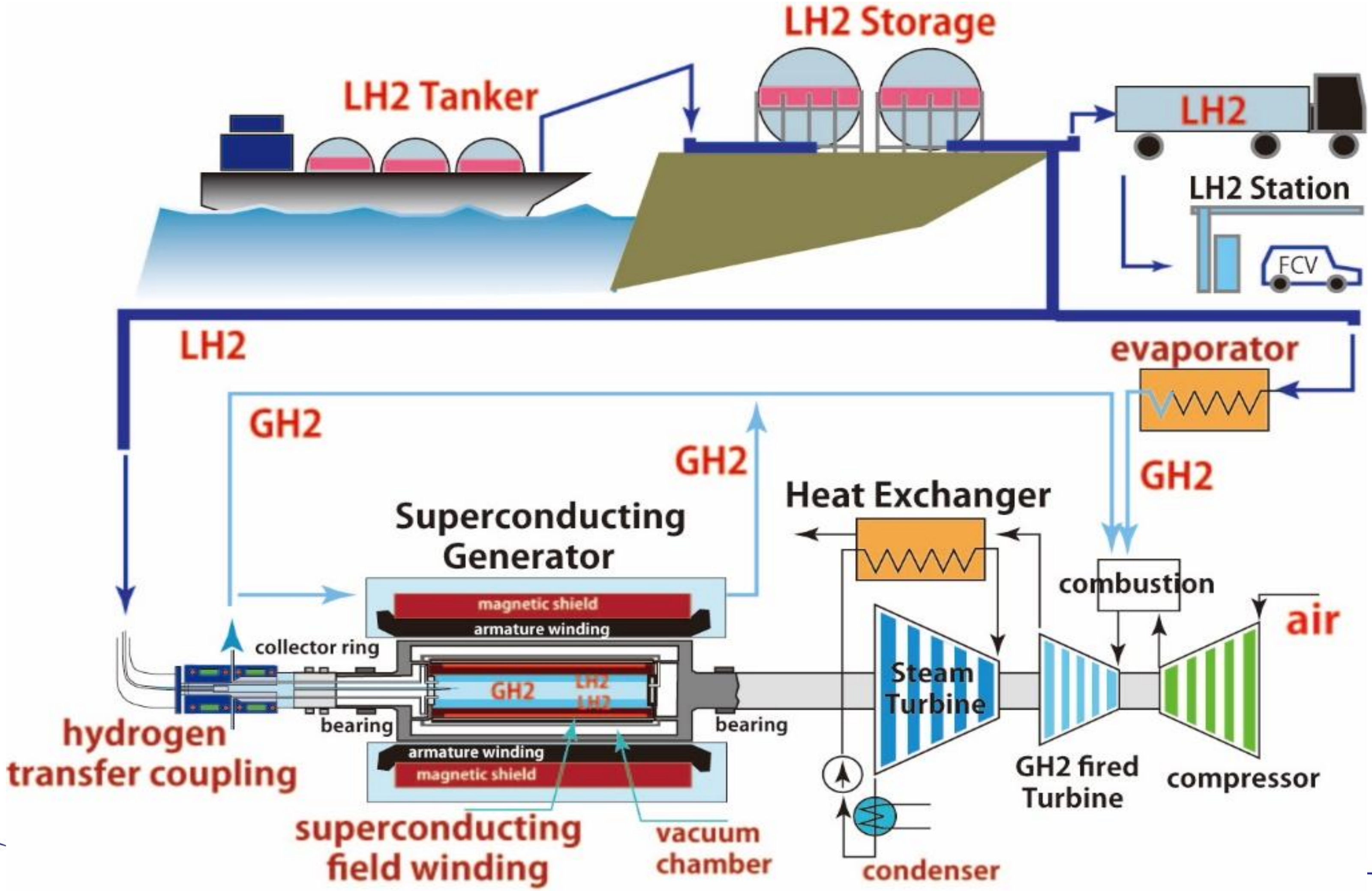
LH2 Landing Port & H2 fired turbine LH2 cooled Superconducting generator



LH2 cooled Superconducting Generator

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LH2 as a coolant

	LH2	LHe	LN2
Boiling Point (K)	20.3	4.22	77.3
density (kg/m^3)	70.8	125	808.6
latent heat (kJ/kg)	443	20.4	198.6
viscosity (μPa･s)	12.5	3.2	142.9
critical pressure (MPa)	1.314	0.227	3.4
critical temperature (K)	32.97	5.19	126.19

Large latent heat and small viscosity
□ storage, transportation, coolant
Temperature □ good property of (BSCCO,YBCO)
MgB2(39K)

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Heat capacity of materials

A3.2a Heat Capacity vs. Temperature Plots:
Aluminum, Copper, Silver, and Stainless Steel

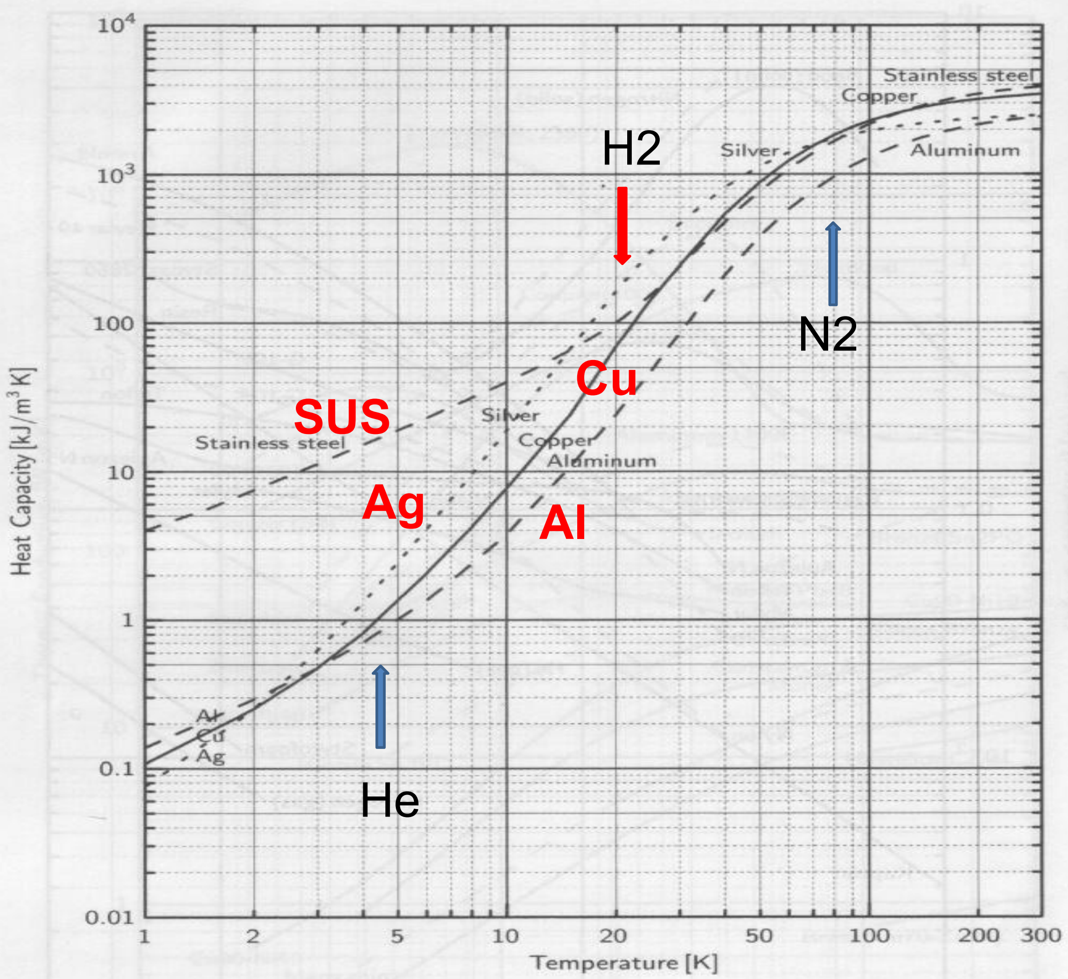

Fig. A3.2a Heat capacity vs. temperature plots for aluminum, copper, silver, and stainless steel. Converted from specific heat [J/kg K] data with constant densities: Aluminum (2700 kg/m³); Copper (8960 kg/m³); Silver (10490 kg/m³); Stainless steel (7900 kg/m³).

Heat capacity of materials in LH2 temp.
is
hundred times larger than that in LHe.

Cooling stability of superconductor is improved.

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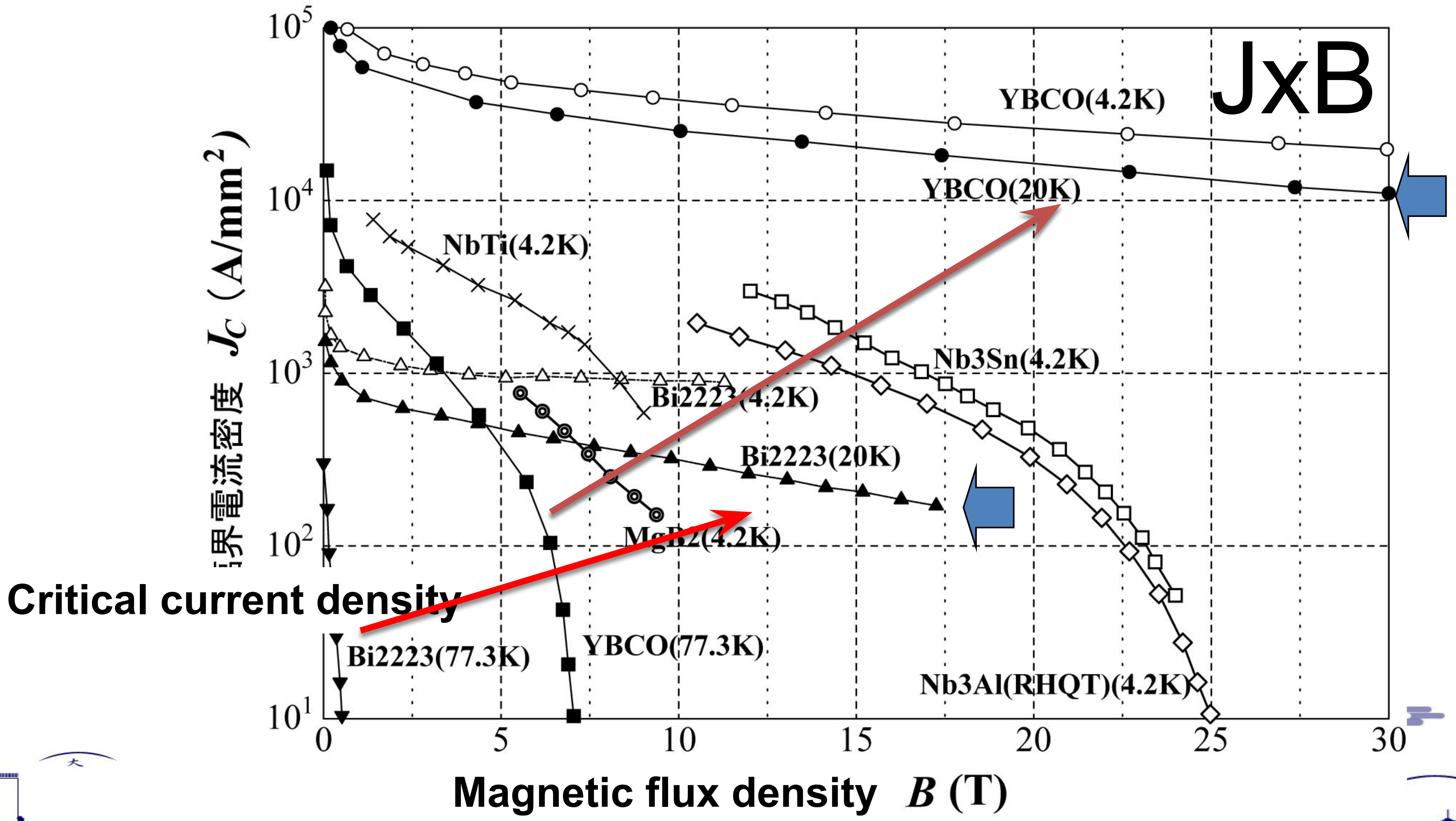
Jc-B characteristics of superconductors



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Superconductors @ around 20 K

- HTS (REBCO and BSCCO) superconducting wires: immersed cooling by LN2(77K)

However, it is considered that

- Excellent electro-magnetic properties are achieved with 15–40 K
- MgB2(Tc=39K) has been developed for practical wire

- Conduction cooling ? Gas helium cooling ? For energy application ?
- **LH2: 20 K** is expected as a coolant for a HTS superconducting magnet
  because of its excellent cooling properties, such as large latent heat, low viscosity coefficient etc.

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Background

- ✔ **Prof. Iwasa (MIT) and Dr. Sato (SEI) tested BSCCO wires in open-dewar Liquid Hydrogen (1990~).**
- ✔ **Some researchers (eg. Dr. Paul Grant(EPRI)..) showed the idea of LH2 cooled HTS superconductors along with MgB2 development (2000~).**
- ✔ **Prof. Hirabayashi's group (KEK, Japan) reported "Feasibility of Hydrogen cooled superconducting magnets". (2006).**
- ✔ **Prof. B.A.Glowacki's Group (Cambridge Univ.) proposed the concept of "Hydrogen cryomagnetics" (2008).**
- ✔ **Russian group (Dr. Vitaly Vysotski…) reported "MgB2 power cable prototype cooled by LH2 flow" fully tested (2011).**

However, only a few researches on LH2 cooling superconductor have been presented due to its explosive nature, brittleness of materials in LH2, ……

- Are they really unsolvable problems?
- Most of conventional generators are cooled by GH2 safely for many years. What are differences between GH2 and LH2?

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Project Overview

Before Project: only a few study on liquid hydrogen cooled superconducting devices, as far as I know,

Fund

1. **2008 ~ 2010 (JSPS)** Japan society for the Promotion of Science
   - ✔ Liquid hydrogen heat transfer characteristics for superconductor cooling.
   - ✔ Test facility design and fabrication.
2. **2010 ~ 2015 (JST-ALCA PhaseI)** Japan Science and Technology Agency
   - ✔ LH2 Re-circulation test system.
   - ✔ Electro-magnetic property of LH2 cooled HTC superconductor (MgB2 etc.) in external magnetic field.
3. **2016 ~ 2019 (JST-ALCA PhaseII)**
   - ✔ LH2 supply and exhaust system for rotating machine.
   - ✔ MgB2 magnet test immersed in LH2.
4. **2019 ~ 2021 (JSPS)** cont.
5. **2022 ~ (NEDO)** **New Energy and Industrial Technology Development Organization**
   - **LH2 cooled superconducting generator (demo and design). □ 9/5(11:05-12:55)2-LP-MG1-01I M**
   - **Air Craft Application (feasibility study).**

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Project Targets at the beginning

- There were many problems in designing LH2 cooled superconducting device.
  - There was no experience in **introducing large current and magnetic energy into LH2 Bath**.
  - How to assure **the explosion proof at a quench of LH2 cooled superconducting magnet** ? ………

In order clear these problems,

- **Design and fabricate the experimental set up** considering the LH2 cooled superconducting device. (e.g. blanket structure feed through for power lead)
- **Obtain permission from prefectural office** in Japan. (to meet the High pressure gas safety law ; the explosion proof related law,……)
- **Safety operation achievement** to prove the availability

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Project Status

we have designed and fabricated the following experimental setups

- for investigating heat transfer characteristics of LH_2 in a pool and also in forced flow for wide range of sub-cooling and flow velocity
- for evaluation of electro-magnetic properties of superconductors cooled by LH_2
- for LH2 supply & vent system of rotating machine(Hydrogen Transfer Coupling)

- A Fundamental database of heat transfer in LH_2 has been preparing for pool-cooling and also for forced-flow-cooling
- Critical current under external magnetic field of MgB2 wires cooled by LH2 were investigated using the experimental facility
- LH2 was successfully supplied and exhausted to/from the rotating cryostat
- LH2 experiment has been safely carried out in 30 test-cools, ~470 test events/cool.

We are moving on to component technology development for LH2 cooled Superconducting generators

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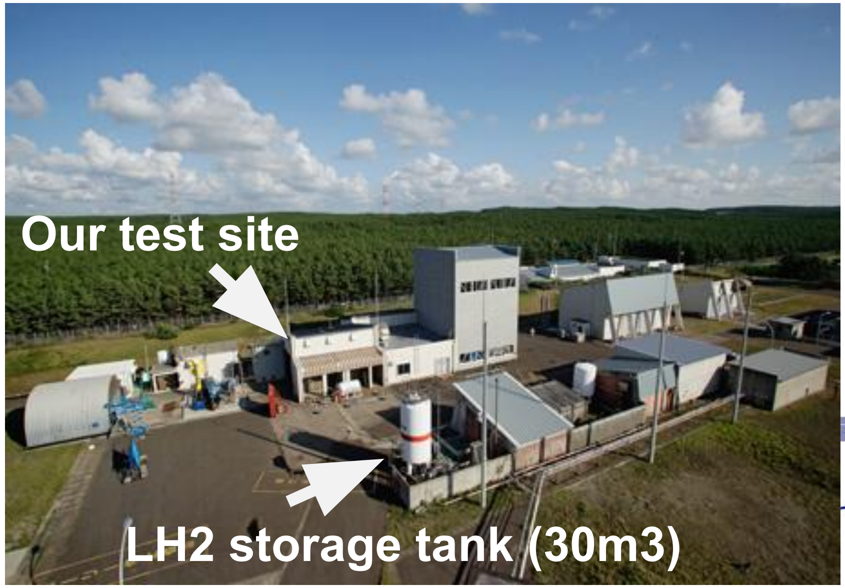
Our Test Facility Site

JAXA Noshiro Rocket Testing Center(NTC)

Japan Aerospace Exploration Agency

The NTC was established in 1962 to conduct various static-firing tests of solid motors necessary for researching and developing launch vehicles for scientific satellites and space probes.

The NTC has a big advantage of being able to maintain a 1-km (maximum) distance for safety, thus it plays an important role in Japan for R&D on propellant engines for space and also hydrogen related equipment.



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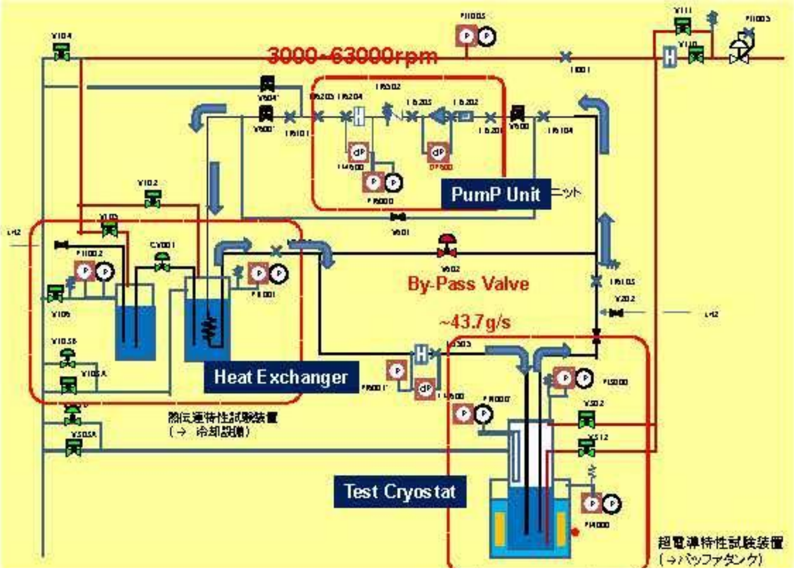
Overview of test facility



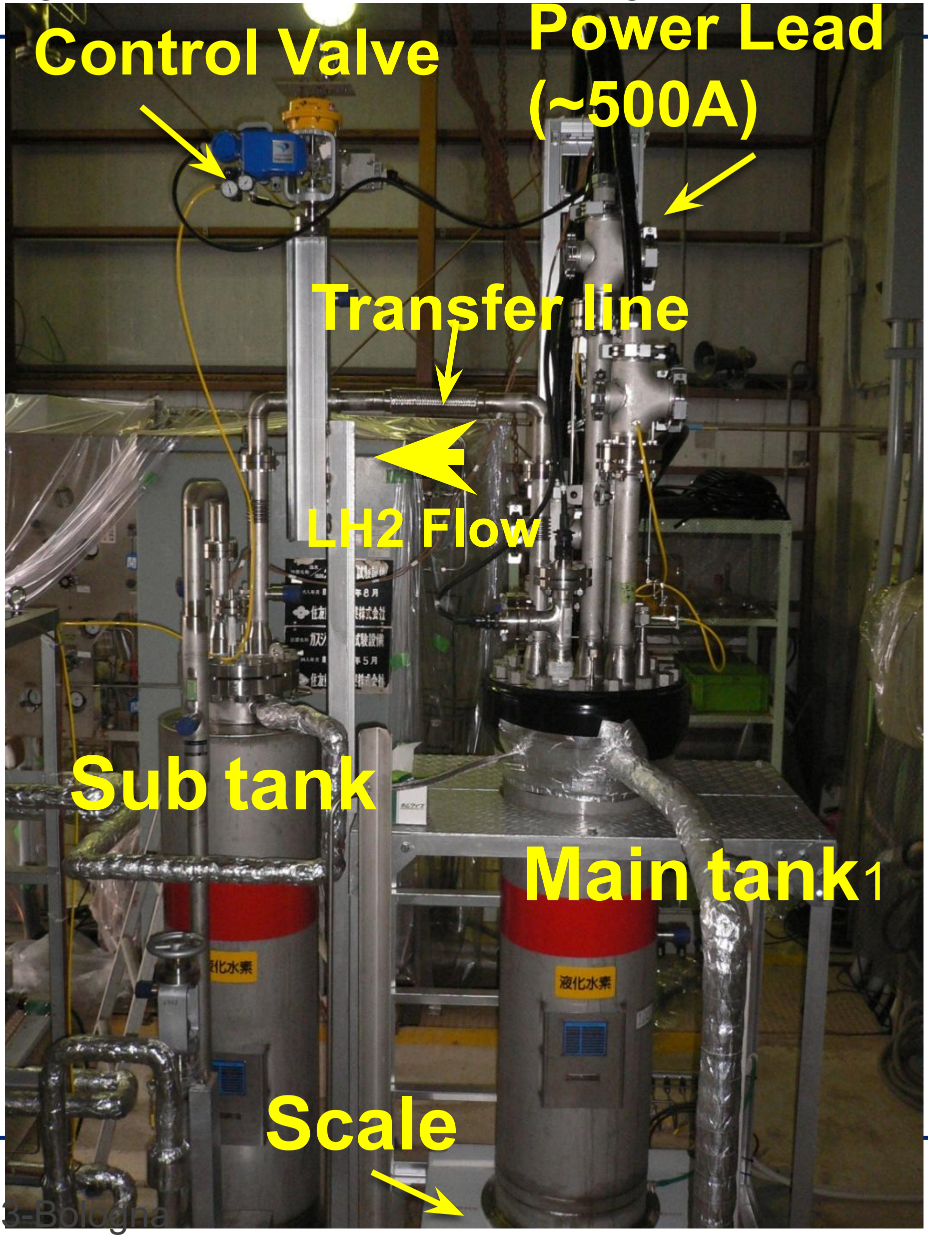
LH2 cryostats and recirculation system for LH2 cooled superconducting devices.

Power supply & measurement system. **Fully remote operation room.**

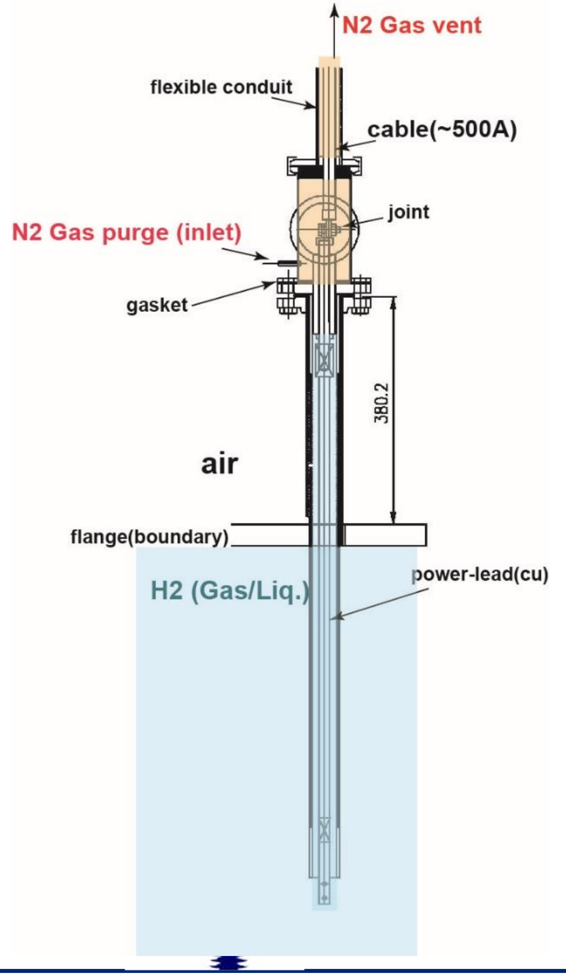
Thermal Hydraulic test system

Remote measurement / control

All measurement and control were carried out through optical LAN 100m away from test facility



Power lead design



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Cooling property Test of LH2

Experimental Approach is undergoing…

- Pool cooling/ Forced Flow Cooling
  (flow velocity : 0 ~ 30 m/s)
- Saturated/ Sub-cooling (20 ~ 31 K: 0.1 ~1.1MPa)
- Supercritical (1.32MPa~)
- Steady-state / Transient state
  (exponential heat input)

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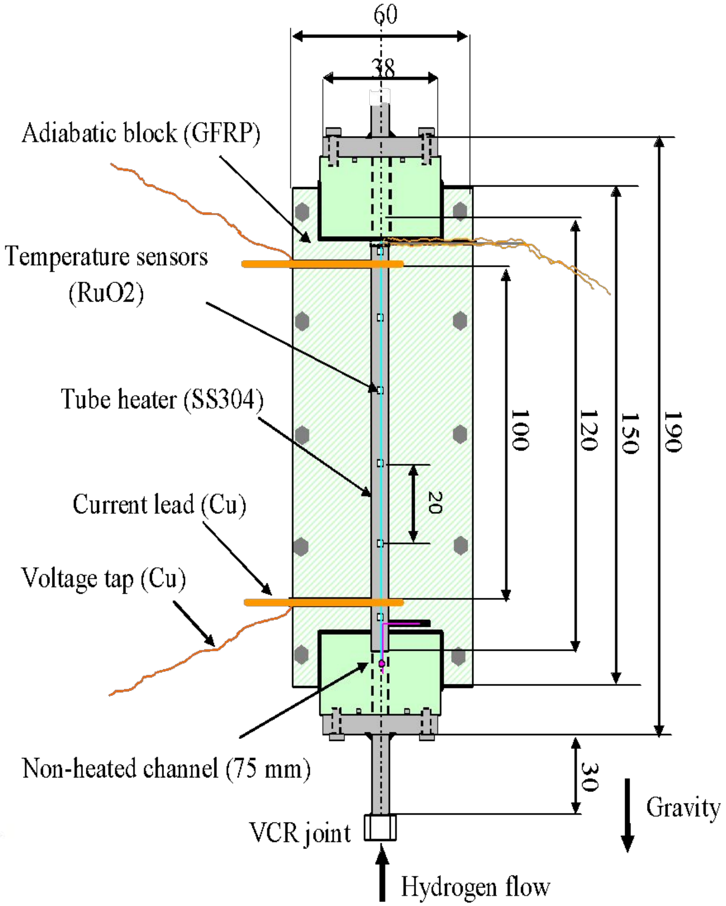
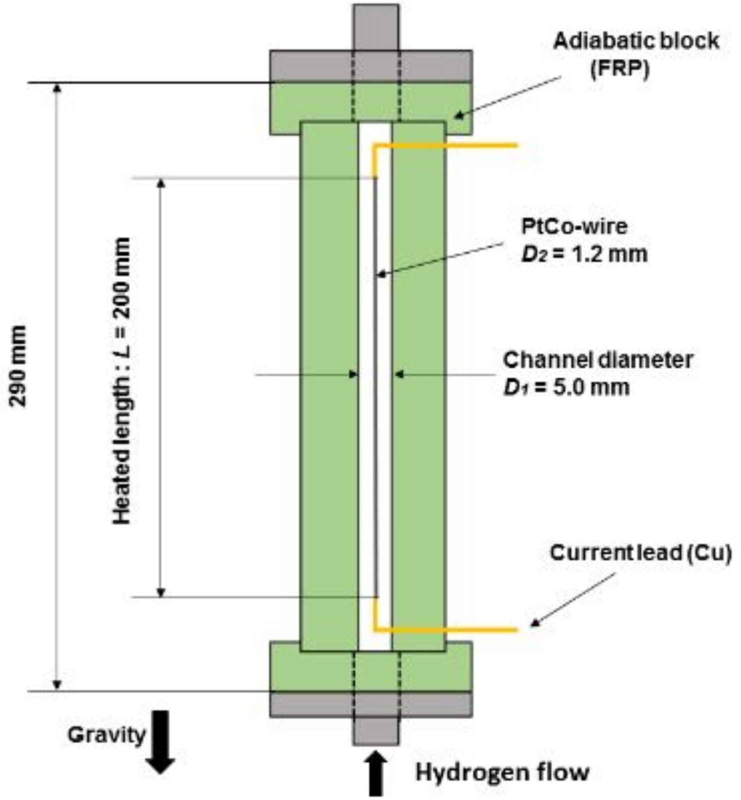
Forced Flow cooling test samples

LH2 flow through heated SUS tube
(3~9mm diameter, 50-250mm length)



LH2 flow through FRP tube with heated
PtCo thin wire



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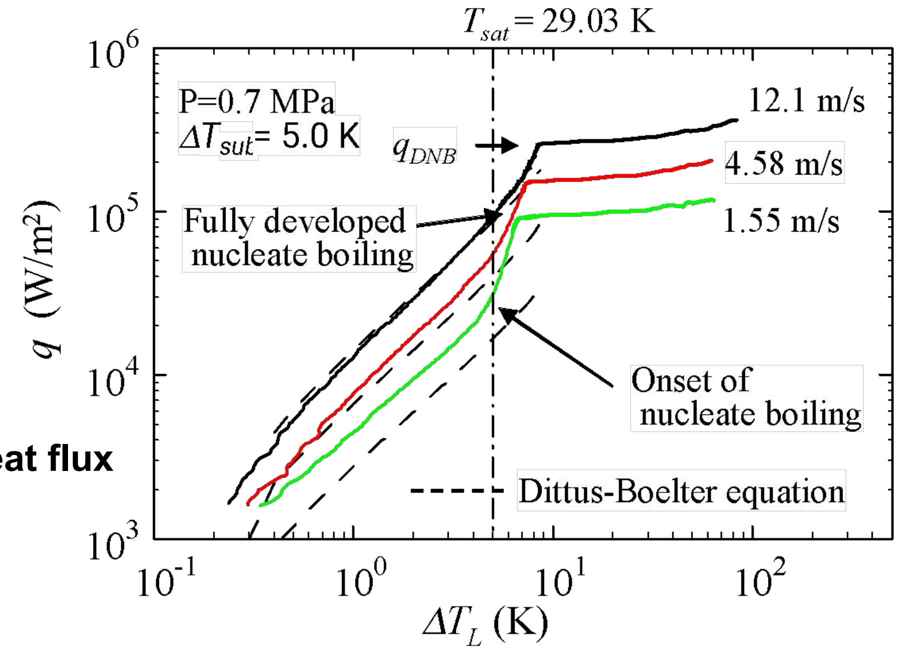
Forced Flow cooling Test Results

Heat transfer characteristics in subcooling condition

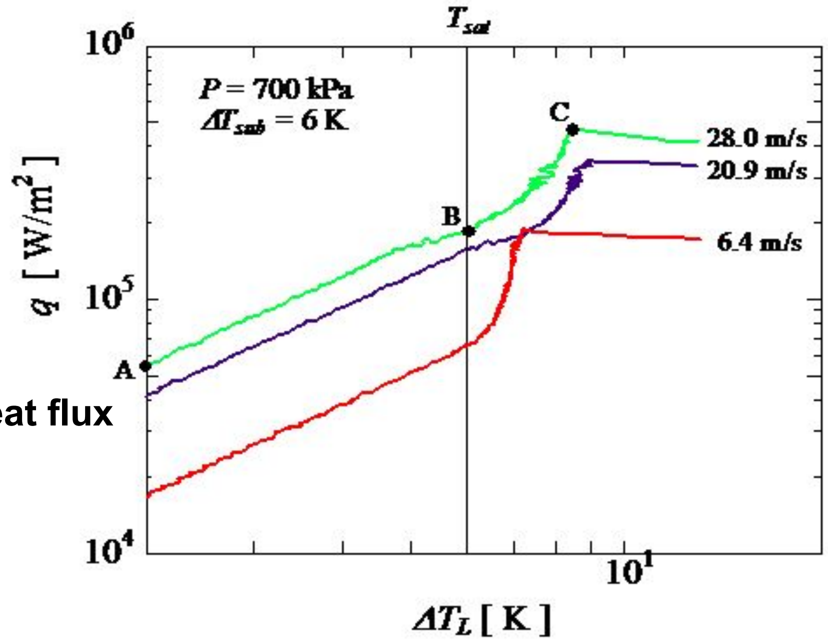
SUS-tube



Heat flux

Excessive surface temp.

PtCo wire



Heat flux

Excessive surface temp.

□Correlation of
DNB(Departure from nucleate boiling) heat flux
with wide range of pressure, temperature, flow velocity

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LH2 cooled superconductor test system

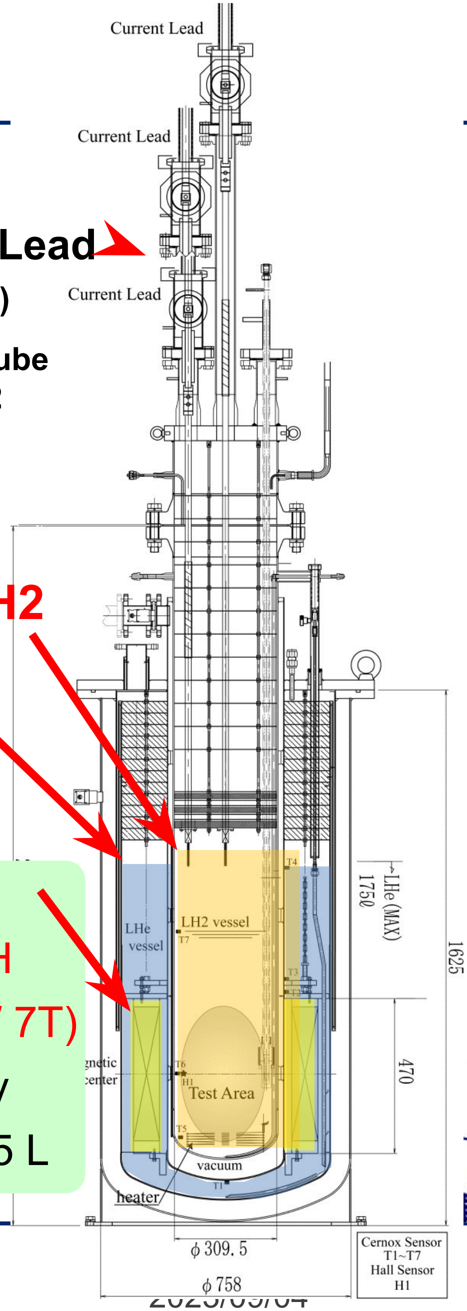
- pressure: 2.0MPaG+0.1MPa
- capacity (LH2) :61 L
- ID=309mm/h=2218mm
- **Power Lead ~500A** covered by blanket with GN2(+5kPaG)

Current Lead (blanket)

Transfer tube for LH2

LH2

LHe



- magnet 112 H (175A / 7T)
- Capacity (Lhe):175 L

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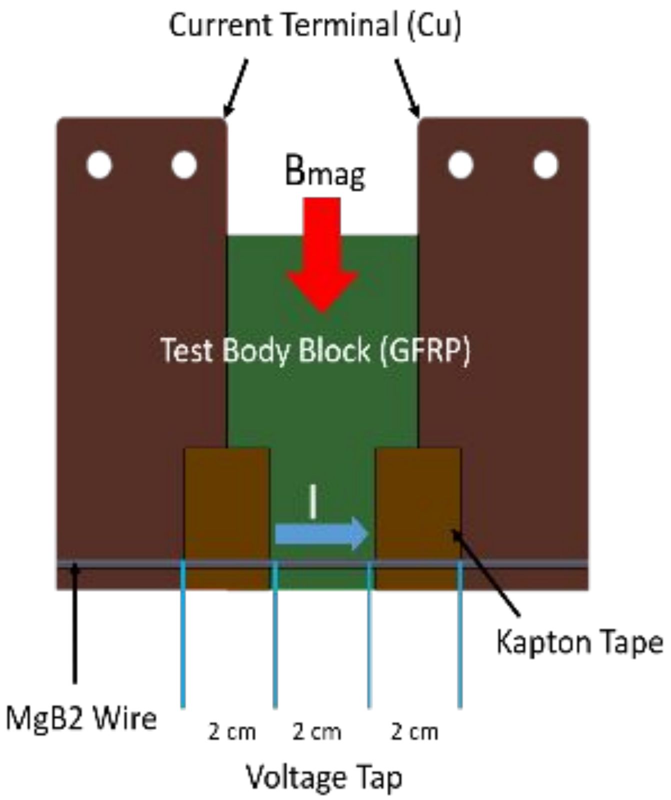
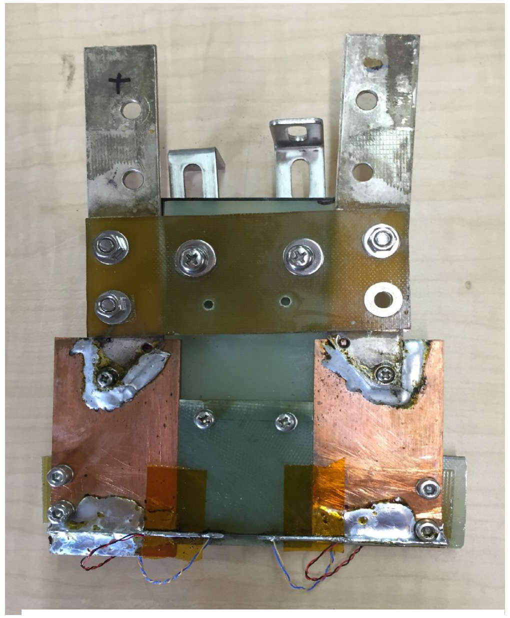
Critical current test of MgB2 short wire under magnetic field

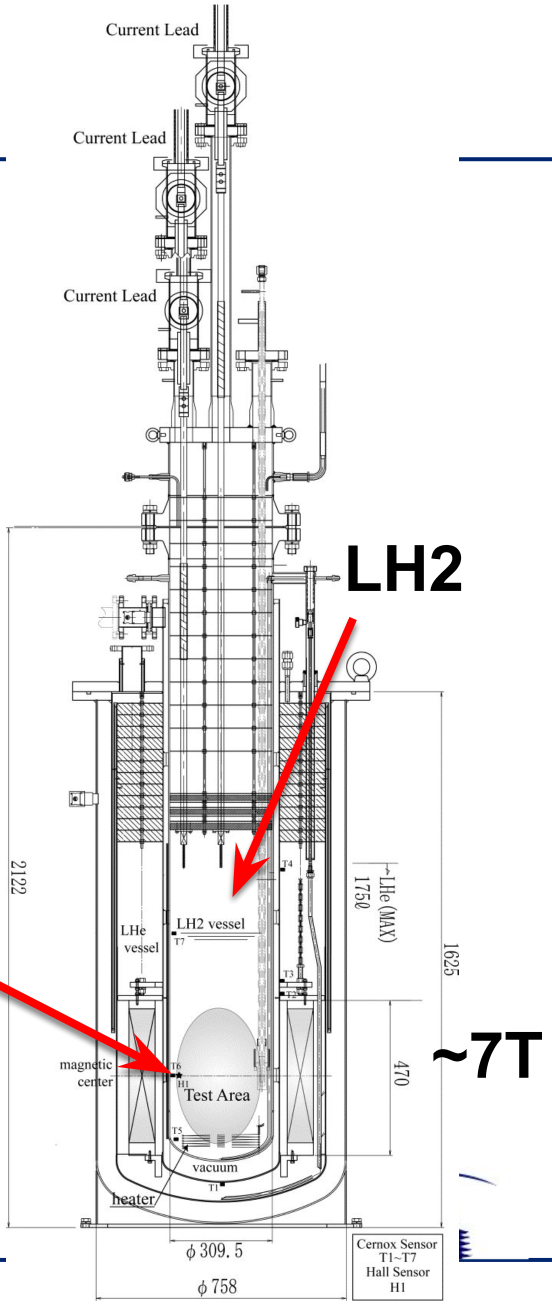
Illustrated test sample of MgB2 short wire and set-up





Produced by Hitachi Ltd.

1.5mm dia.



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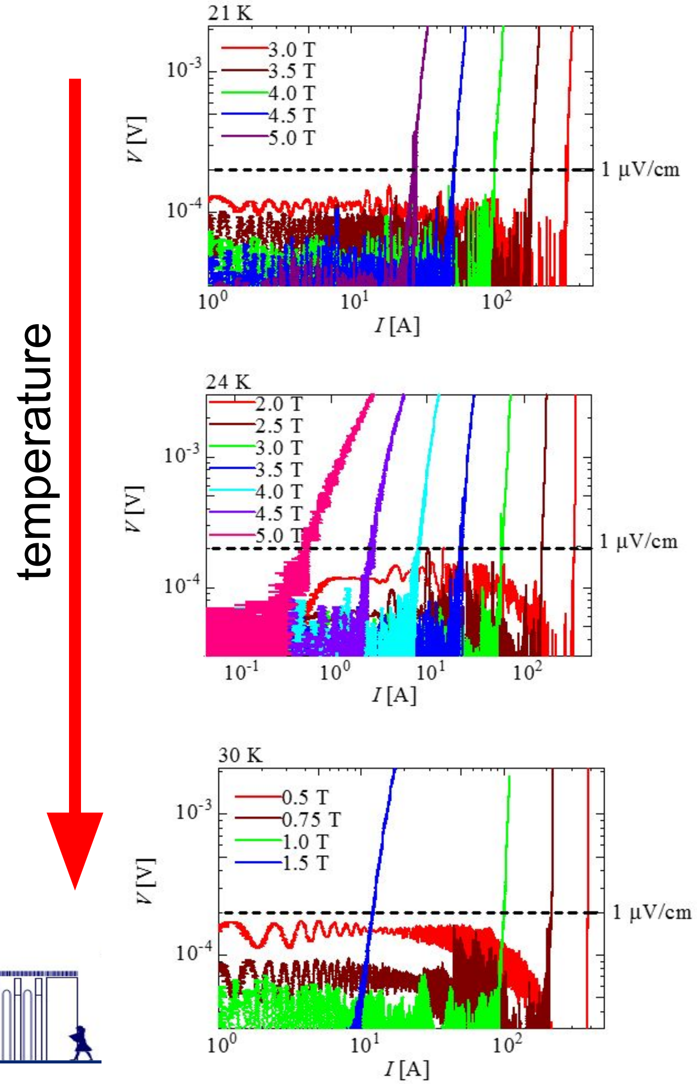
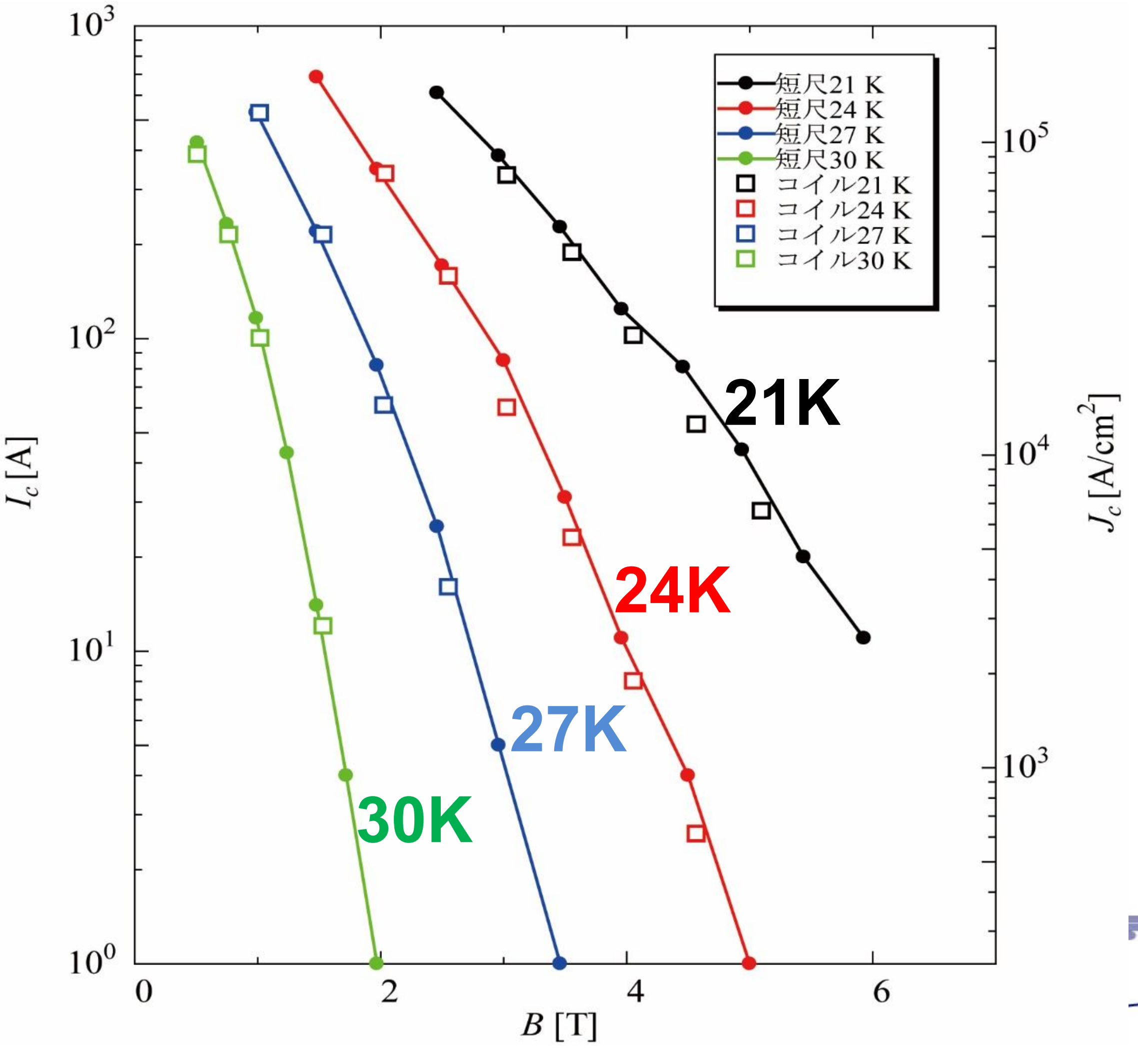
Ic-B characteristics of MgB2 wire in LH2





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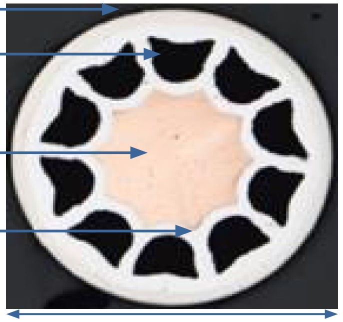
Component Technology Development stage
– power device, e.g. generator

Based on the basic experiments, we are moving to

Component Technology Development stage

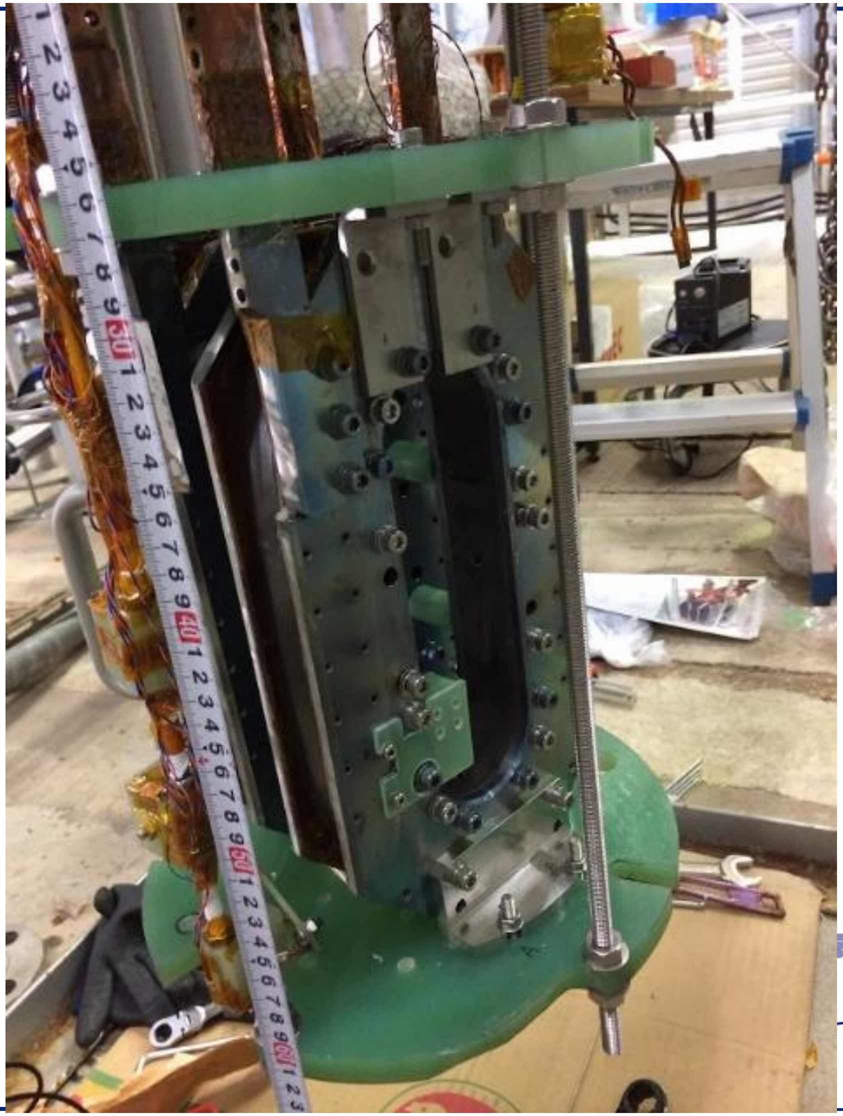
1. Heat transfer properties of LH2 (cont.)
2. Properties of LH2 cooled superconductors (e.g. MgB2 cont.)
3. Hydrogen Transfer Coupling (LH2 supply & vent system of rotating machine (e.g. generator))
4. LH2 cooled magnet for generator field
5. Regulatory compliance for e.g., explosion protection, high pressure gas safety law related to the LH2 cooled superconducting rotating machine
6. Experimental proof (demonstration)
7. Investigate system advantages of LH2 superconducting power apparatus in electric power system
8. Safety operation experience in LH2 handling with demonstration set up

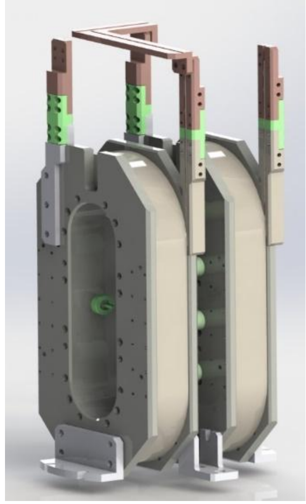
MgB2 race track coil (generator rotor)

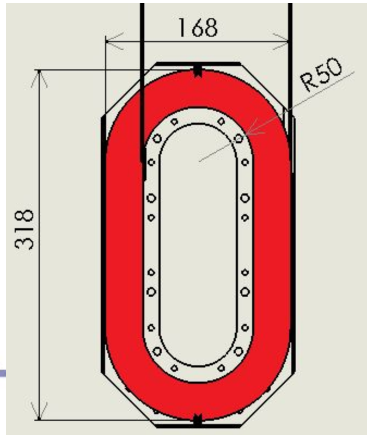


Race Track MgB2 Coils   ~ 0.2H   7.3kJ@21K

dimension	150mm(strait) 100mm(arc)
Coil	32mm(width) 30mm(thickness)
Turns	529 (23x23)
Voltage taps	Every 46 turns
Wire (Hitachi)	MgB2 multi filament 300m







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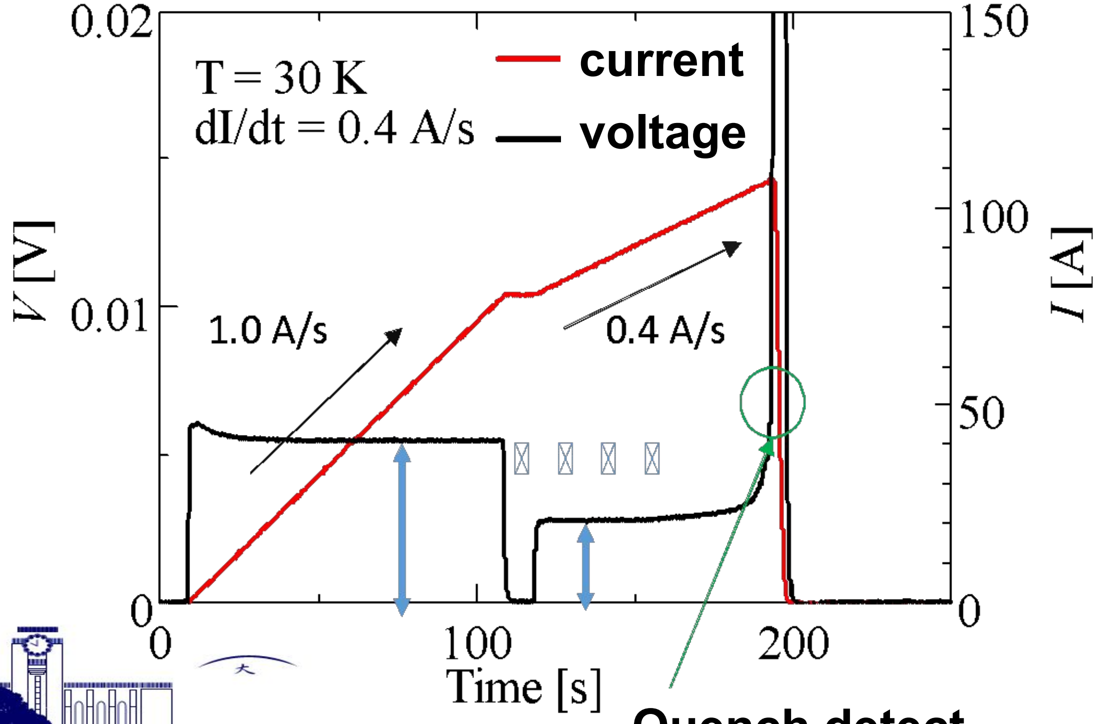
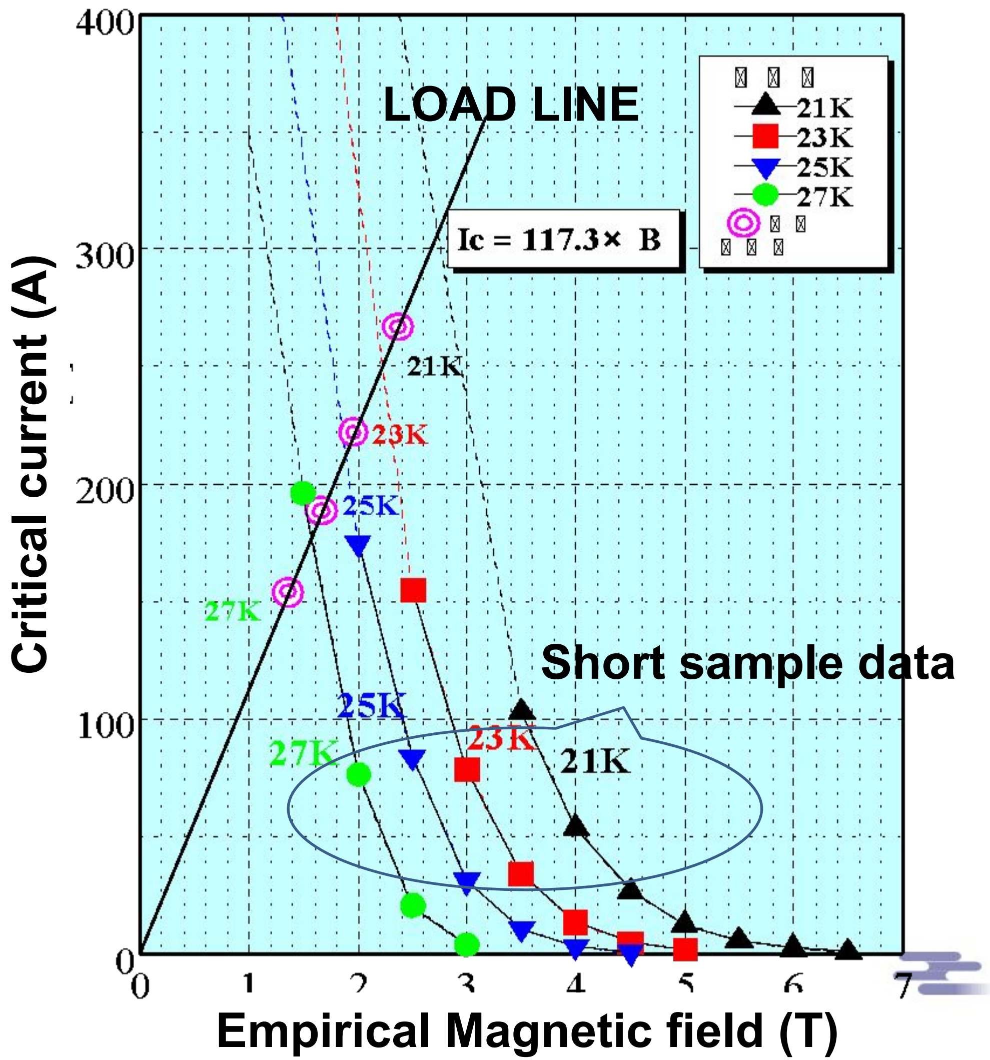
Load Line of the Race Track Coil

Liquid Hydrogen Pool cooling : 21-30 K @saturation
Sweep rate : 0.1, 0.4, 1.6 A/s
Normal Definition: 0.07 μV/cm
(3/46 turn -- 1 μV/cm)





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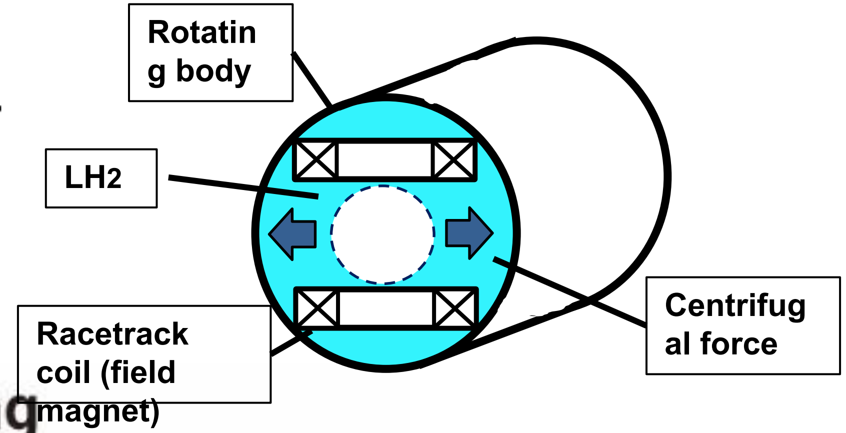
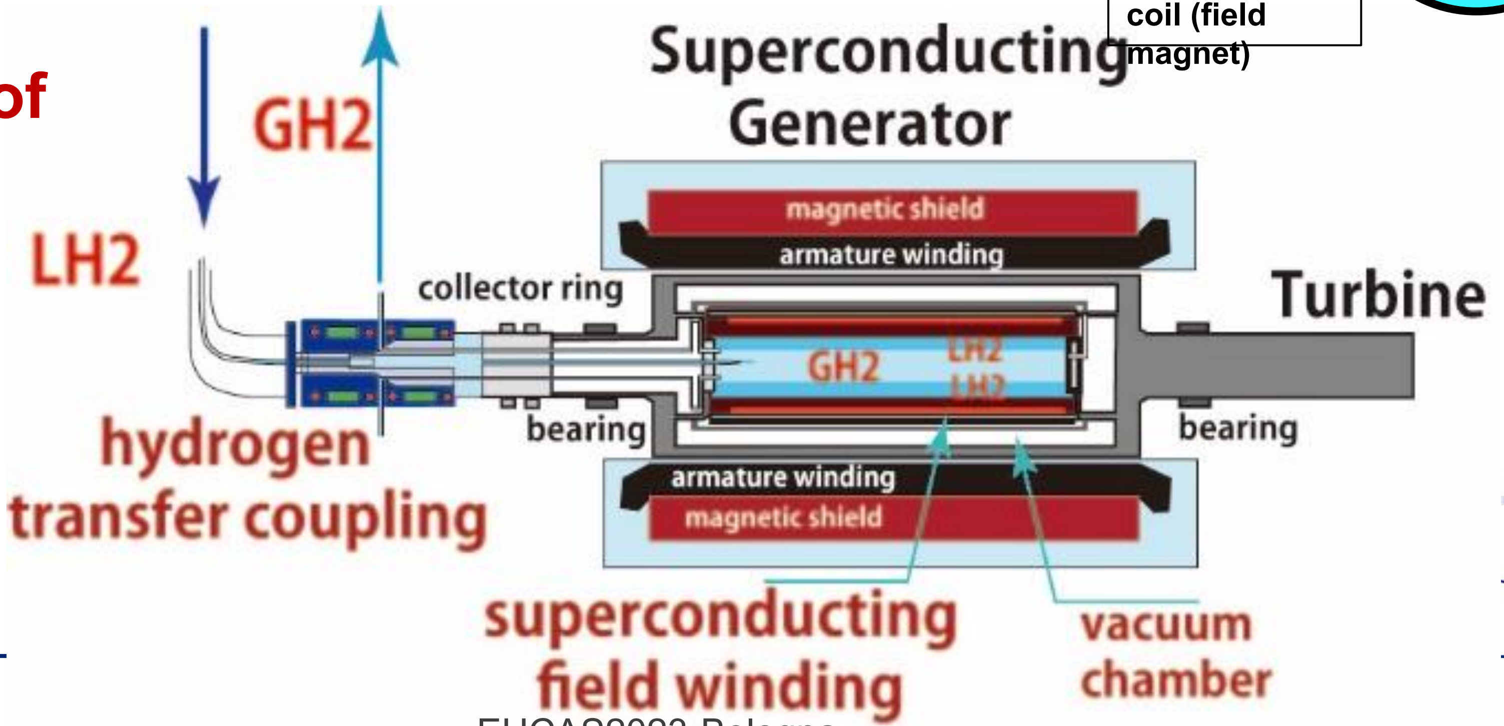
LH2 cooled Superconducting Field Rotor

LHe cooled Superconducting Generator was fully developed in 1980~2000.
Cooling penalty is one of the key issue to practical utilization.
→ Liquid hydrogen cooling is free from cooling penalty.

→ **LH2 cooling related technology development** is necessary.
HTC, LH2 rotating cryostat, LH2 cooled field coil, etc.



Explosion Proof



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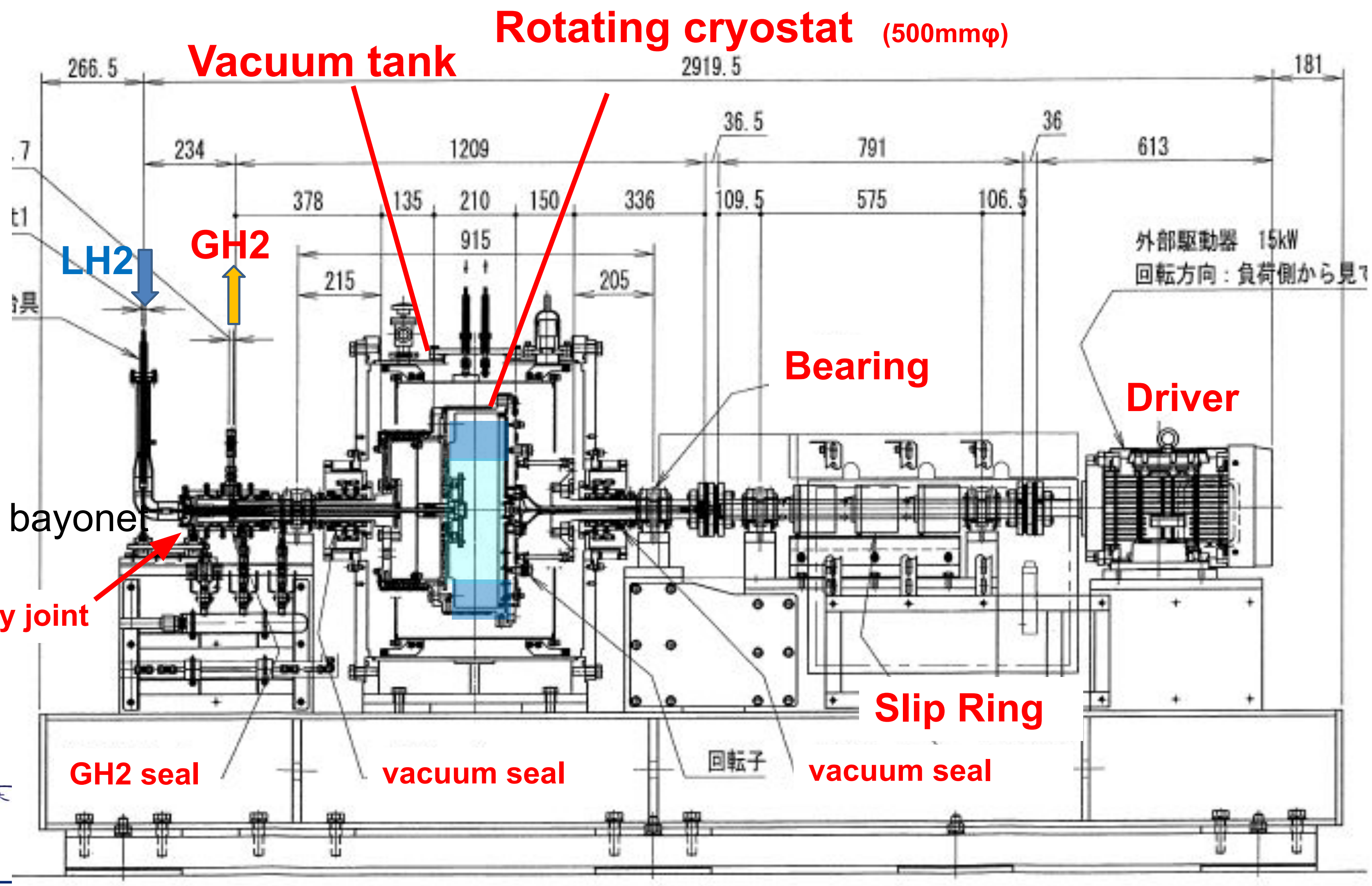
Hydrogen Transfer Coupling Test Set



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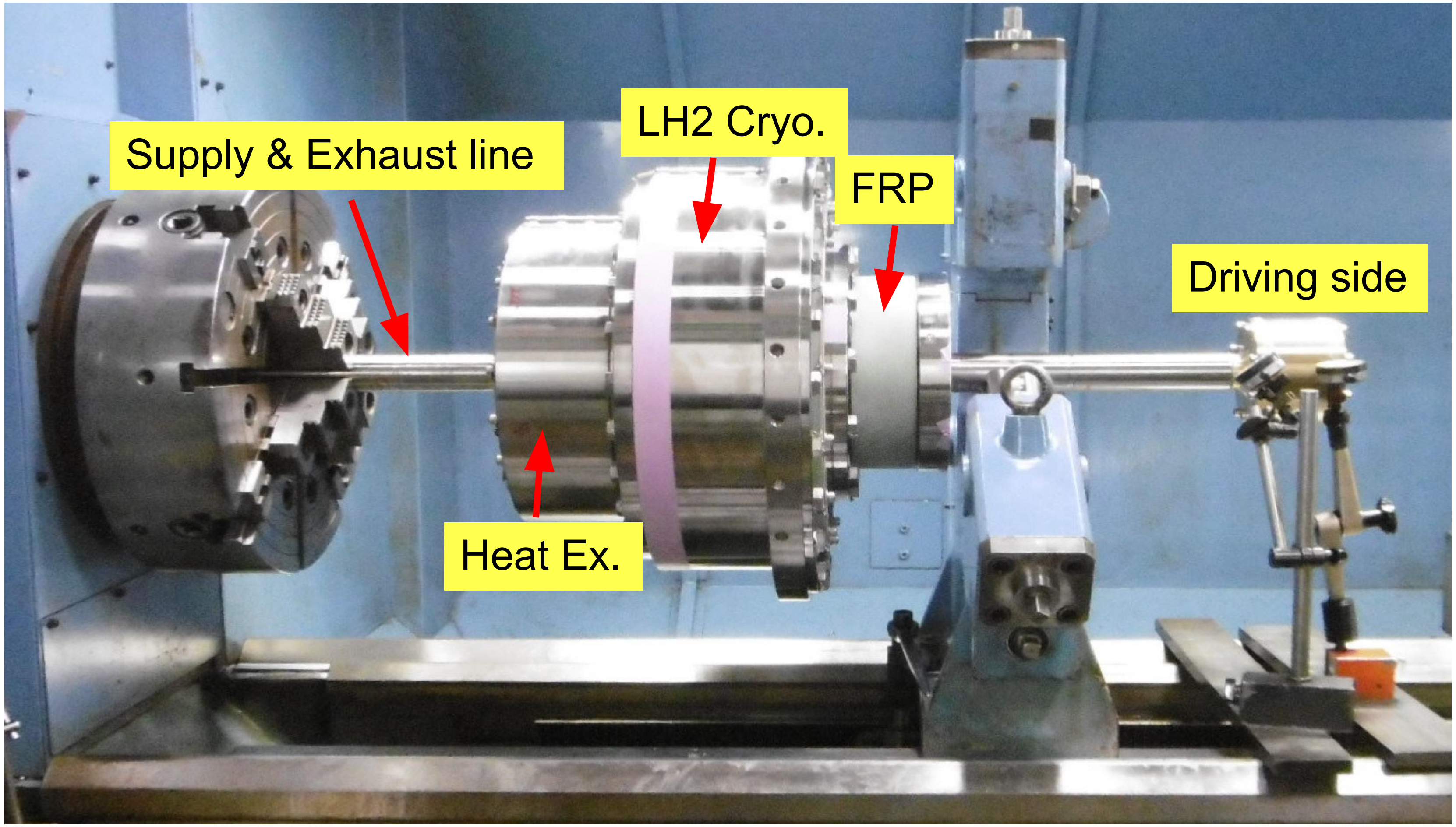
Rotating LH2 cryostat (is set inside the vacuum tank).



Overview of test set up for LH2 transfer to rotating cryostat

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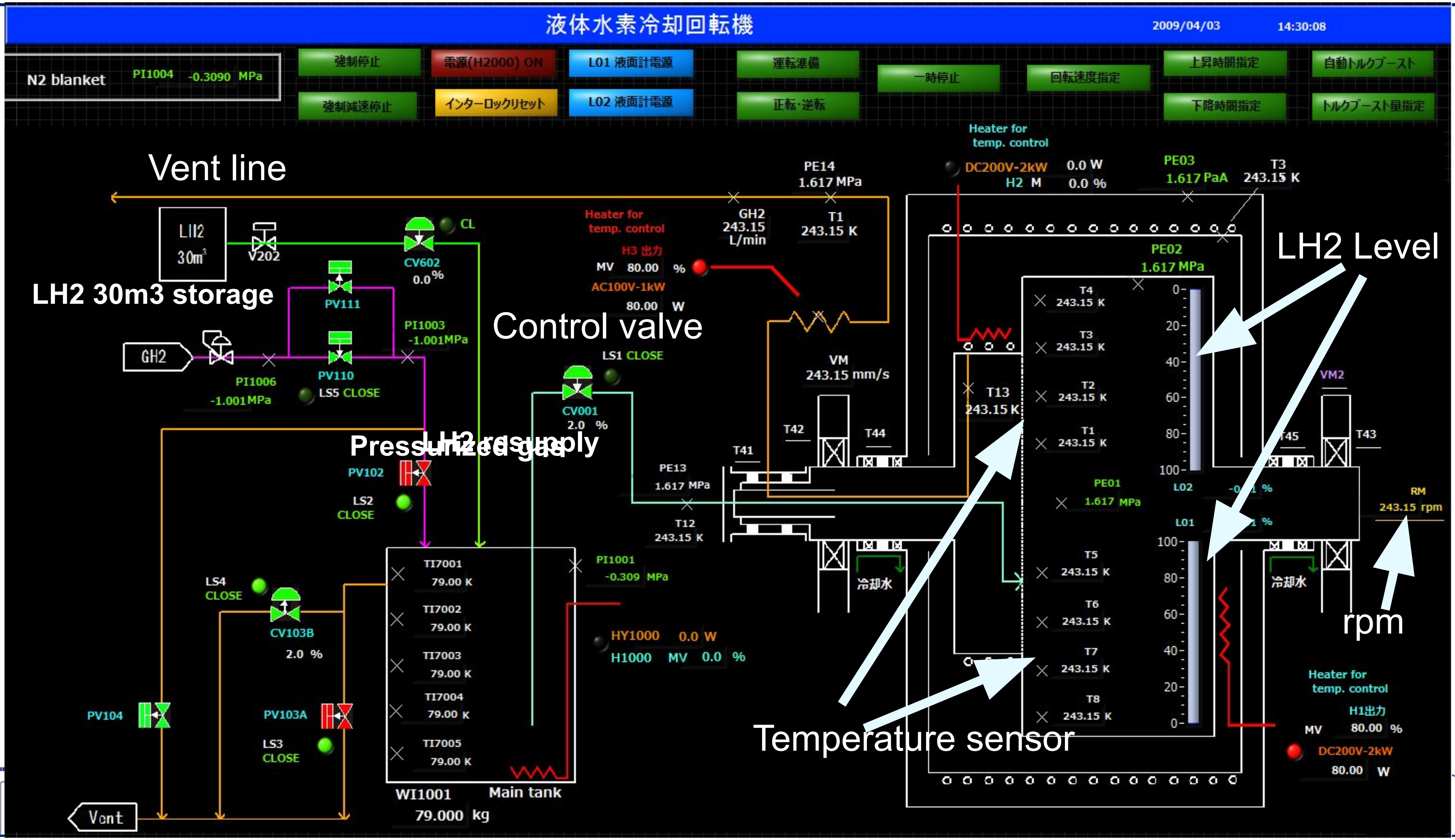
Control & Monitor Panel (full remote)



Reservoir

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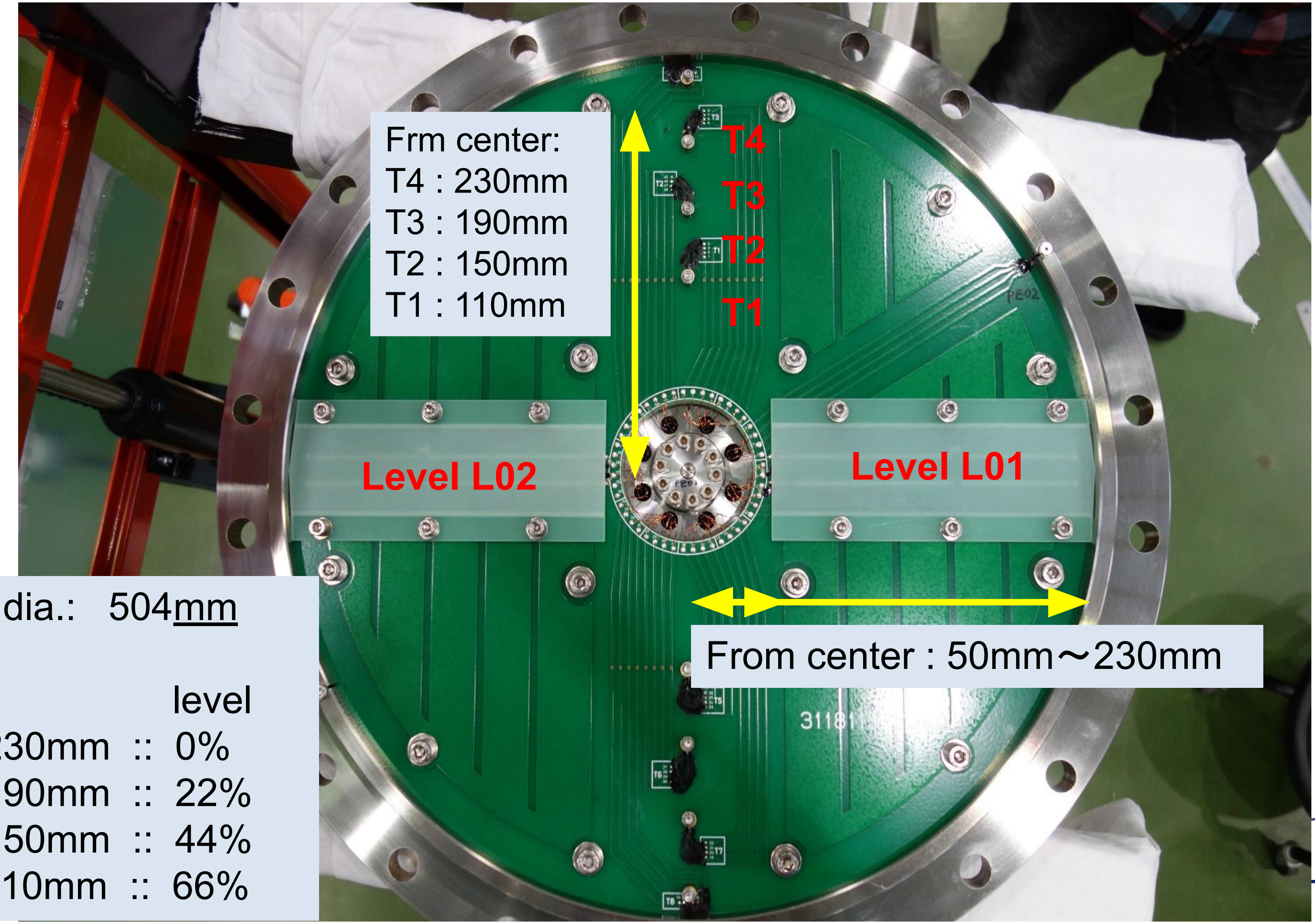
Temp.sensor : Level meter (MgB_2)



Frm center:
T4 : 230mm
T3 : 190mm
T2 : 150mm
T1 : 110mm

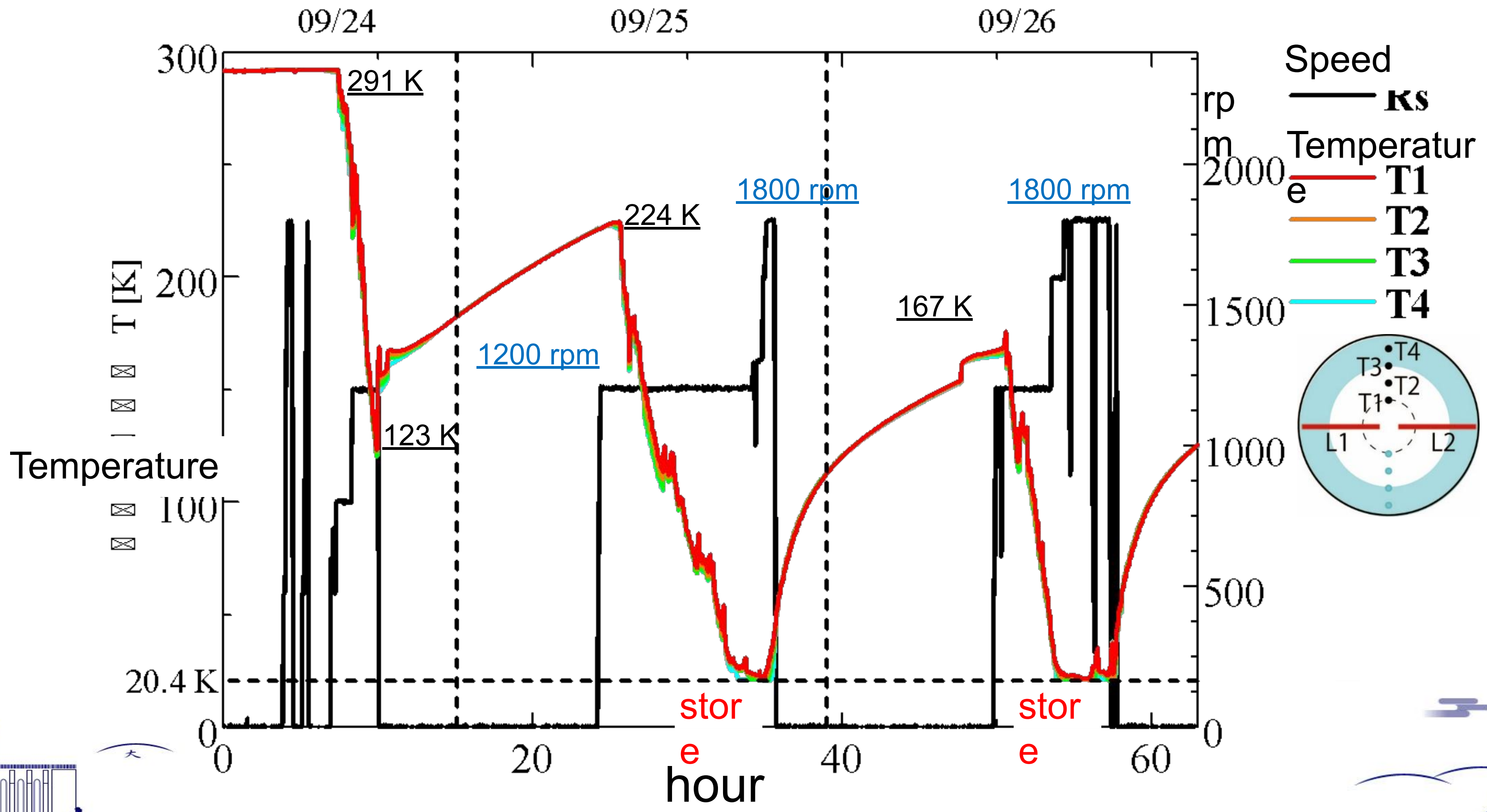
From center : 50mm～230mm

Inner dia.: 504mm

	level
T4 : 230mm ::	0%
T3 : 190mm ::	22%
T2 : 150mm ::	44%
T1 : 110mm ::	66%

LH2 cool down & storage test

NO hydrogen leak was observed throughout the test



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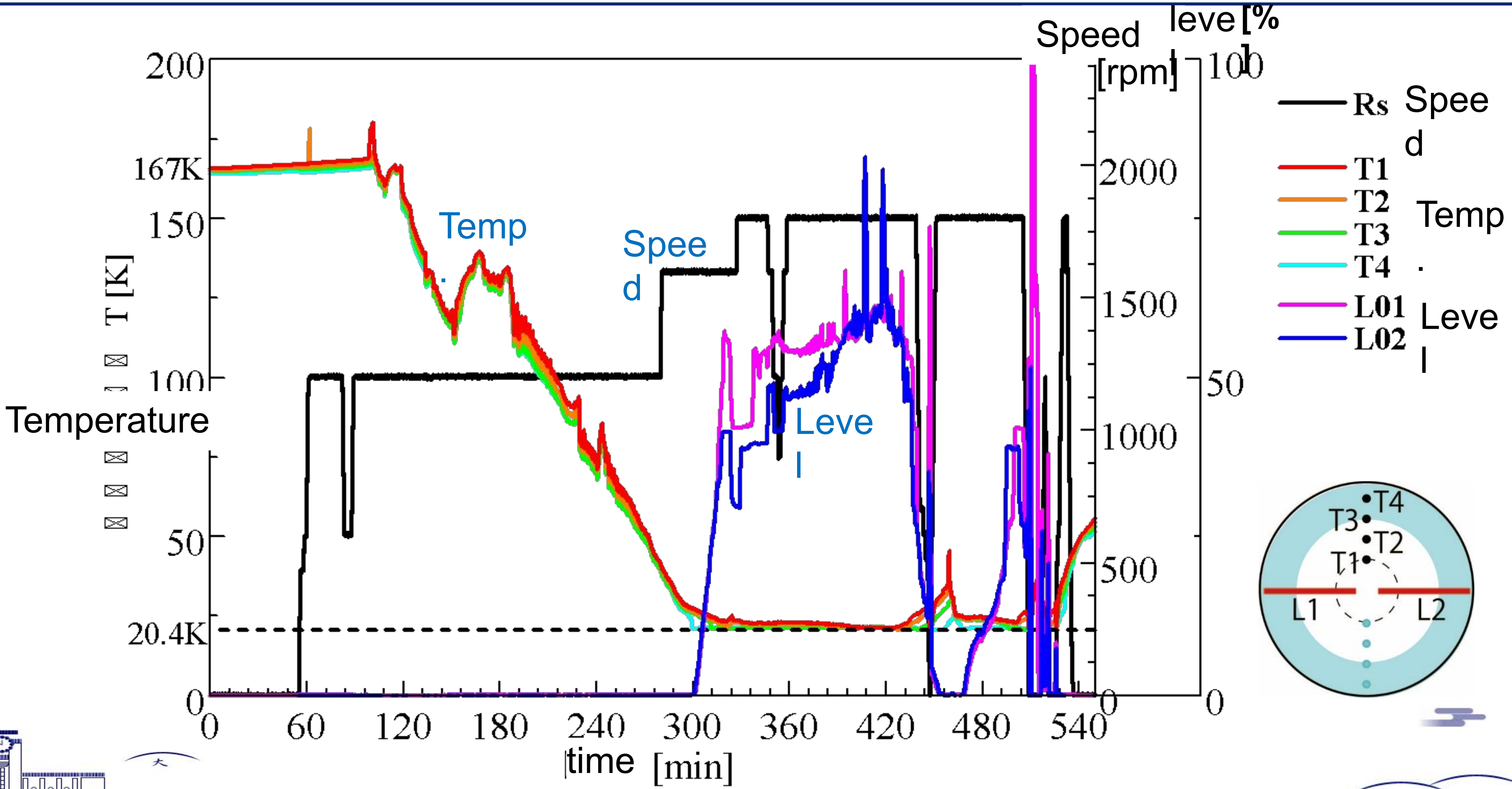
LH2 storage level



Storage level was successfully controlled by reservoir pressure.

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NEDO Leading Research Program (2022~

NEDO Feasibility Study Program (Feasibility Study Program on Energy and New Environmental Technology)

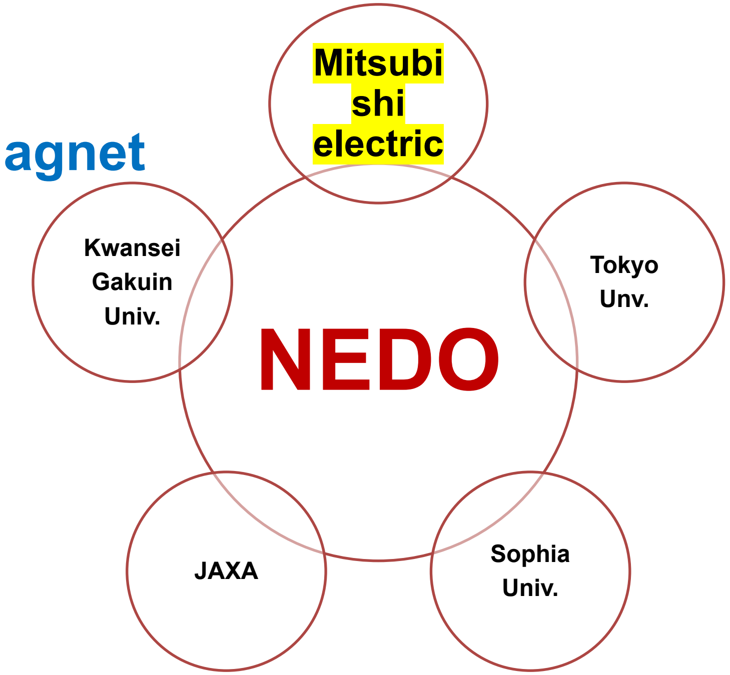
LH2-cooled SCG design (600MW class)
Road map & scenarios (Power Grid)

High-strength/High-stability LH2-cooled magnet
LH2 cooled demo SCG (10kW)

Demo SCG design
HTS bearing/Heat balance
Road map & scenarios (Aircraft)

Safety
Road map & scenarios (Aircraft)

Power grid analysis including LH2-cooled SCG



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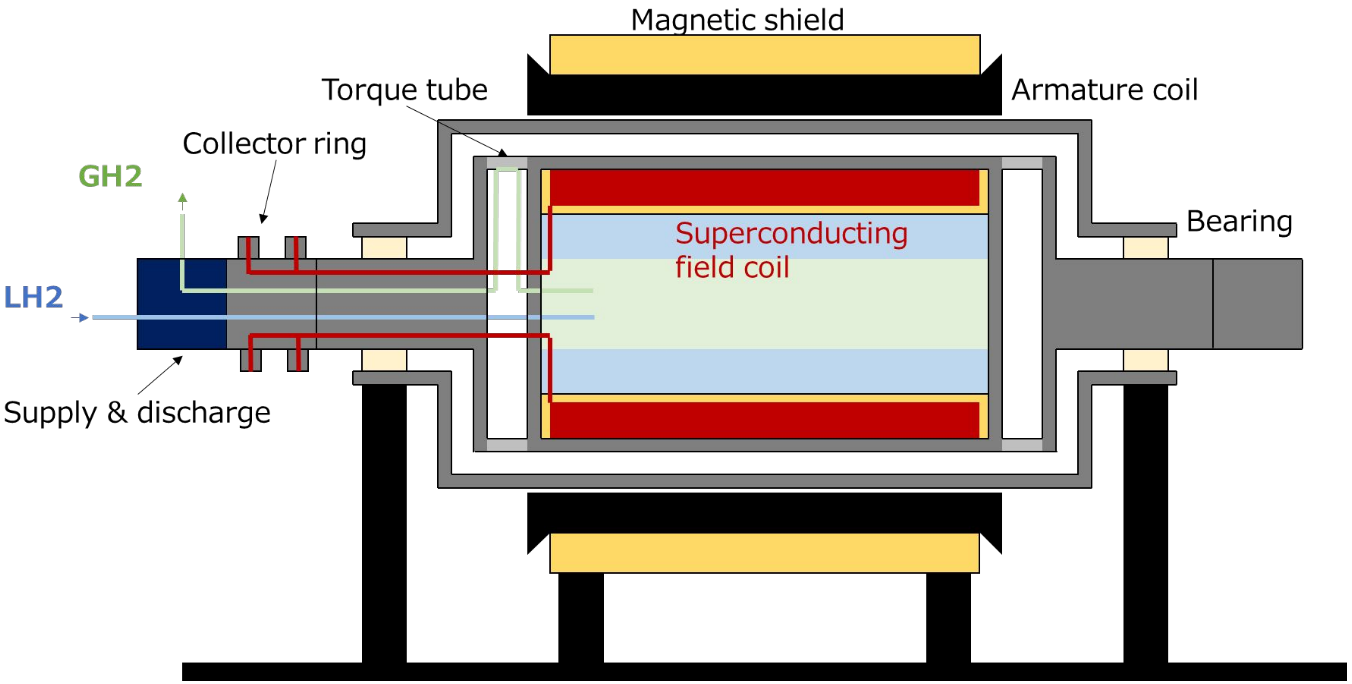
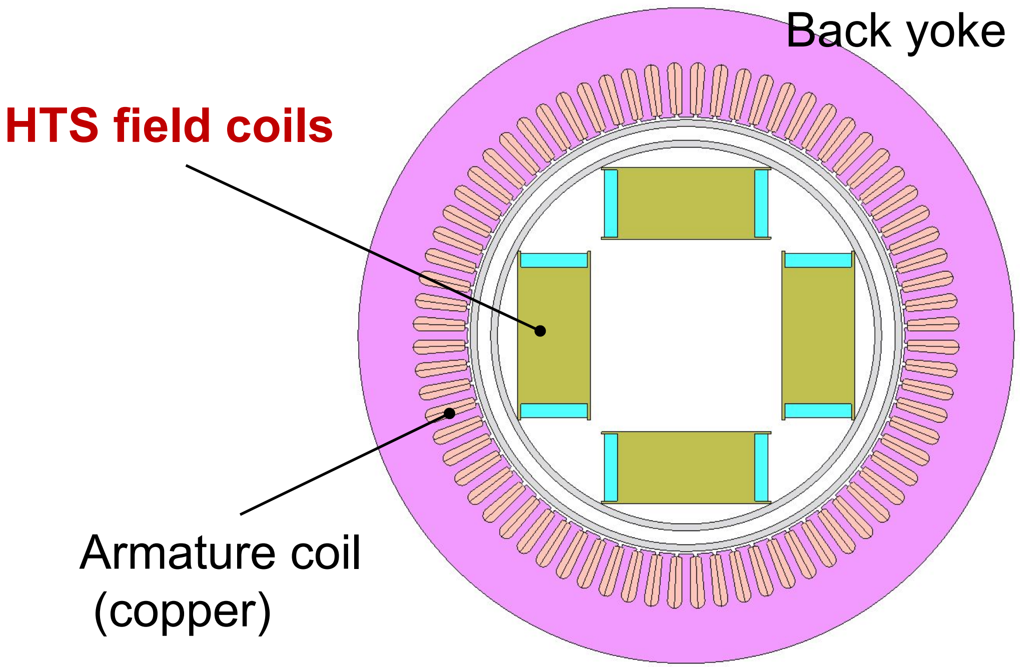
10 kW LH2 cooled SCG demonstrator

Related presentation by. Prof. Oya
☐ 9/5(11:05–12:55)2-LP-MG1-01I M





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

京都大学
KYOTO UNIVERSITY

Summary (1/2)

- The experimental setup for investigating heat transfer characteristics of LH2 in a pool and also in forced flow for wide range of sub-cooling, flow velocities and pressures up to supercritical condition, have been designed and fabricated.
- The additional test facility was designed and made for evaluation of electro-magnetic properties of super-conductors cooled by LH2 under external magnetic field.
- LH2 circulation test loop was designed, made & successfully operated
- Fundamental data of heat transfer in LH2 are introduced which has been preparing for pool-cooling and also for forced-flow-cooling.
- Critical current test of MgB2 short sample under external magnetic field was carried out.
- Excitation and quench tests of MgB2 magnet immersed in LH2 were successfully conducted.

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Summary(2/2)

- Hydrogen Transfer Coupling (LH2 supply & vent system of rotating machine and LH2 cooled rotor model was designed.
- LH2 was successfully supplied and exhausted to/from the rotating cryostat.
- LH2 level of the rotor was successfully kept and controlled.

- It is confirmed LH2 is promising cryogen for superconducting power devices.
- LH2 experiment has been safely carried out

  in 30 test-cools, about ~470 test events/cool.

We are moving on to component technology development for

LH2 cooled Superconducting generators.

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Thank you for your kind attention!

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