IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), February 2018.
Invited presentation 3LO1-02 given at EUCAS 17-21 September 2017, Geneva, Switzerland.

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JST-ALCA Project
Japan Science and Technology Agency
Advanced Low Carbon Technology
Research and Development Program
Project Organizer: Prof. H. Ohsaki (the Univ. of Tokyo)

Prospect of Liquid Hydrogen Cooled Superconducting Power Apparatus and Carbon Free Energy System

P.L.: Yasuyuki Shirai*, Masahiro Shiotsu*, (Kyoto University)
Hiroaki Kobayashi, Satoshi Nonaka**, Yoshihiro Naruo** and Yoshifumi Inatani**, (JAXA)**
Hirokazu Hirai (Taiyo Nippon Sanso, Ltd.)
Seiichiro Yoshikawa (IHI)
Teiichi Tanaka (National Institute of Technology, Kumamoto College)
Orie Sakamoto, Tanzo Nitta (Jochi University)

Collaborating Group : Prof. Hamajima, (Mayekawa Mfg) Group
:MgB2 cable for SMES → 1MP4-03
Prof, Kumakura, (NIMS) Group
: MgB2 wire → 4MO2-01, 4MO2-02

Contents

- Background (Prospects)
- Project Target
  - Innovative Energy Infrastructure with low CO_2 emission
    - Hydrogen & Electricity Hybrid energy system with
    - Hydrogen cooled superconducting power apparatus as key components
- Project Status
  - Experimental Set-up for liquid hydrogen cooling property and for electro-magnetic property of LH_2 cooled superconductor
  - Some Experimental Results in Heat Transfer characteristics of LH_2, Critical current test of MgB_2 wire immersed in LH_2 under external magnetic field
- Conclusion

Background 1/3

- HTS (YBCO and BSCCO) superconducting wires: generally cooled by LN2(77K) .

However, it is considered that

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

→

- 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.

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?

Background 2/3

On the other hand,

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.→ H_2 natural energy

～Wind/Solar power plant　→ can produce H_2

H_2 energy supply chain is necessary

Large amount of H_2-Delivery

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

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

LH2 tanker, container are developing（Kawasaki Heavy Industry

LH2 will play an important role in future society

problem: large liquefaction Energy

Utilization of Cryogenic energy is important

Coolant for superconducting energy devices

Utilization of not only natural energy but also cryogen energy of LH2

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Background 3/3

Innovative energy infrastructure for reduction of CO_2 emission

→ We propose

hybrid system (electric power system + hydrogen energy supply chain)

Superconducting power devices can be free from cooling penalty using

Liquid Hydrogen which is major Energy Carrier of H_2 supply chain,

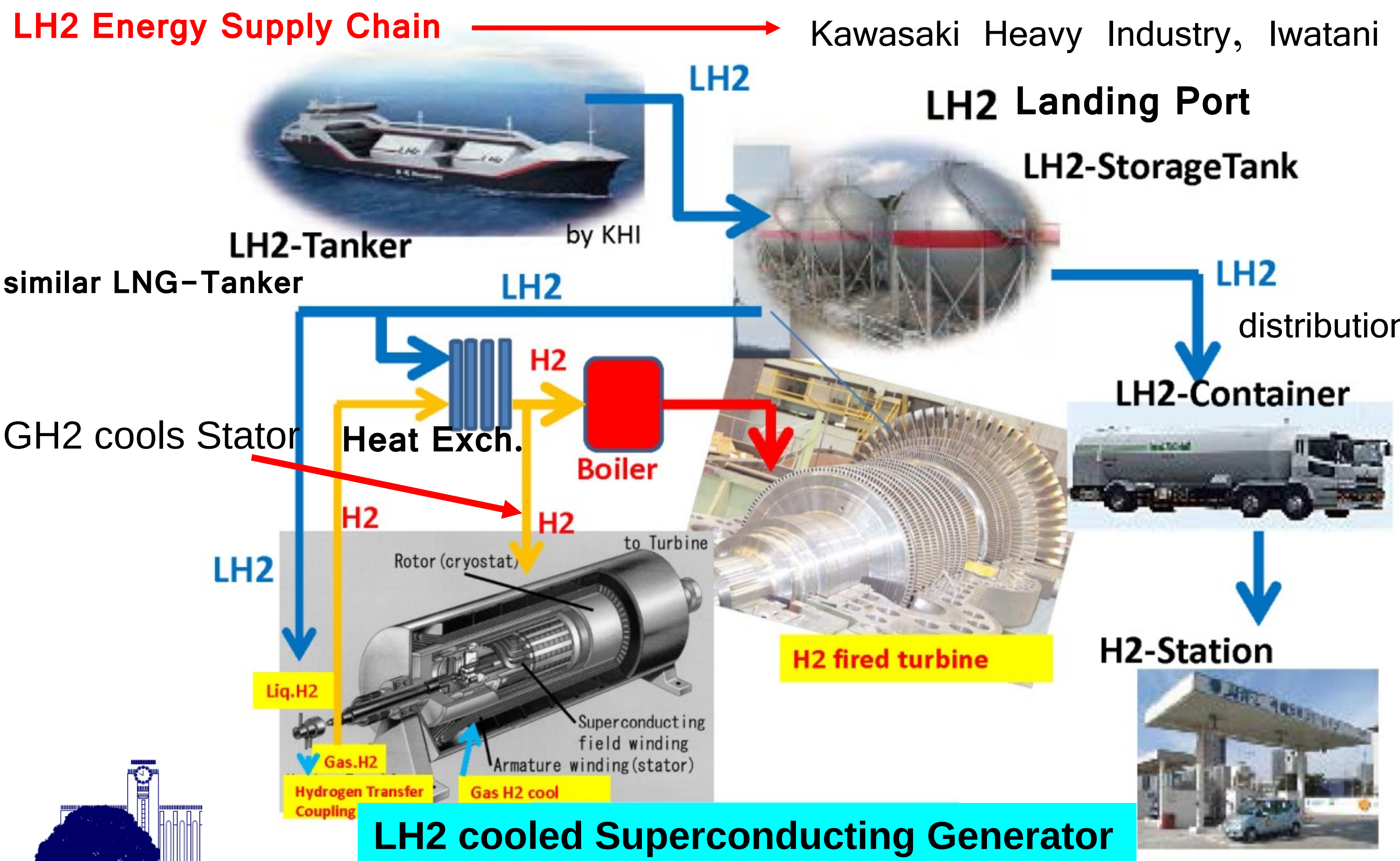
at the same time, used for energy storage for long period in power system

Synergy effect of hybrid energy system with electricity and hydrogen is expected using

hydrogen cooled superconducting power apparatus as key components.

- To Improve flexibility of Power system operation
- To promote renewable energy sources to Power System

LH2 Landing Port & H2 fired turbine LH2 cooled Superconducting generator



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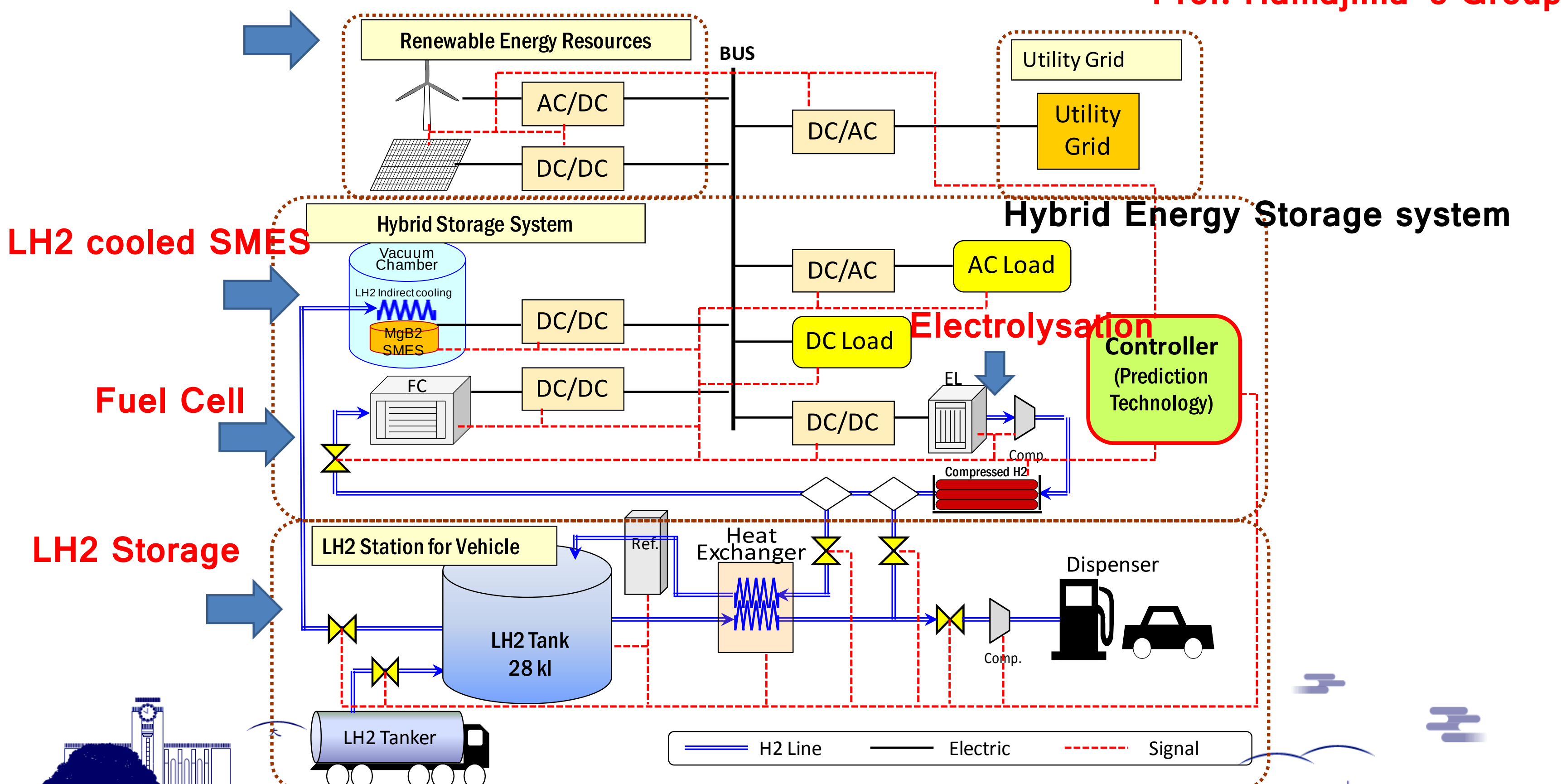
H2 & Elec. Coordinated System : SubStation Hybrid Energy Storage System

To mitigate the output fluctuation of Wind/Solar power plant

JST-ALCA
Prof. Hamajima´s Group

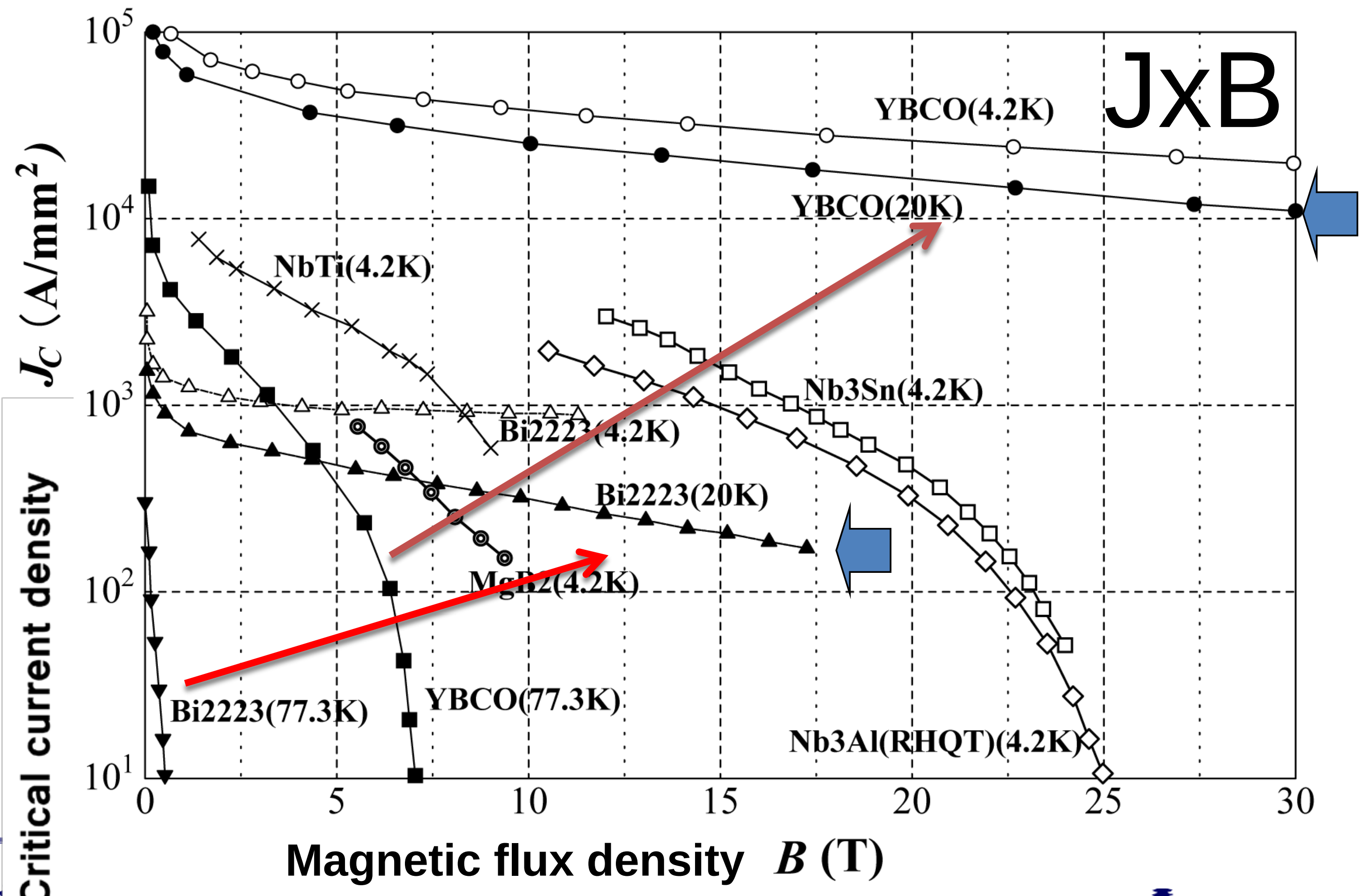


LH2 as a coolant

	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)

Jc-B characteristics of superconductors



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Heat capacity of materials

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

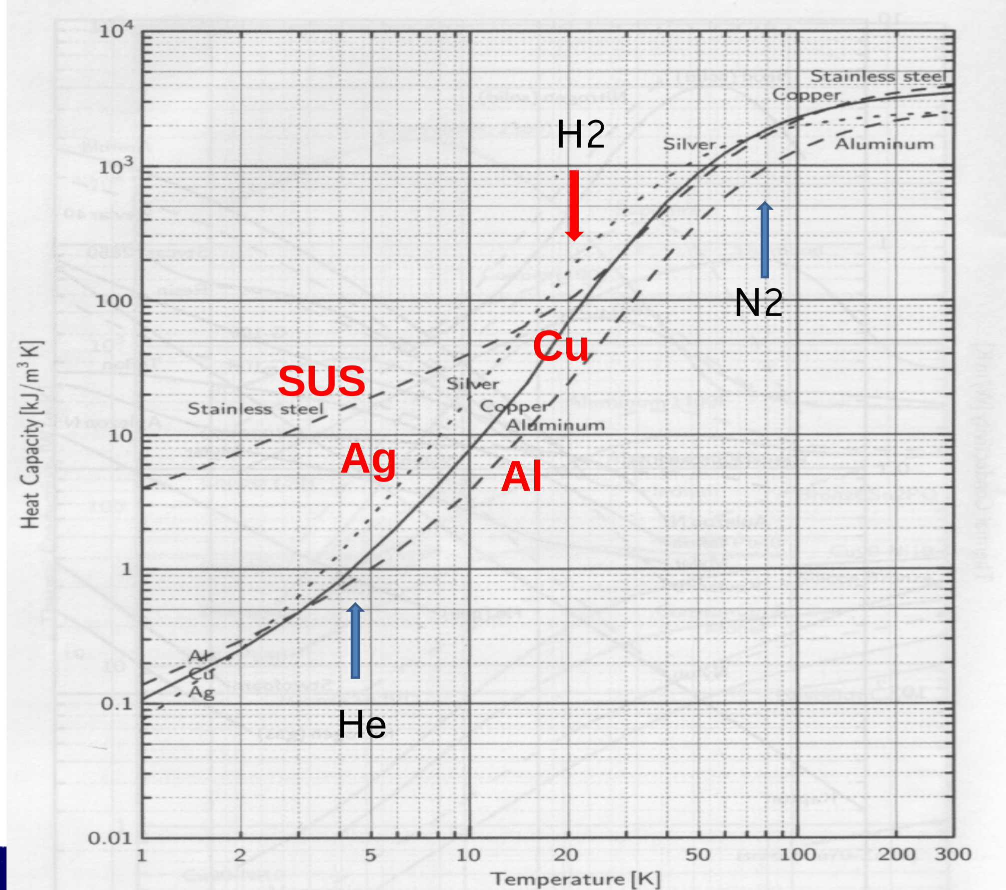

Fig. A3.2a Heat capacity vs. temperature plots for aluminum, copper, silver, and stainless steel. Converted from specific heat [J/kg K] data with constant densities: Aluminum (2700 kg/m^3); Copper (8960 kg/m^3); Silver (10490 kg/m^3); Stainless steel (7900 kg/m^3).

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

Cooling stability of superconductor is improved.

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Research Subjects

What is necessary to realize
such a innovative energy infrastructure?

1. Heat transfer properties of LH2
2. Electro-magnetic properties of LH2 cooled superconductors
3. Design of LH2 cooled superconducting device
4. Development of LH2 cooling system, forced flow system and key components (LH2 pump, etc.)
5. Safety-design criteria of LH2 applied facilities

Project Status 1/2

Fund

1. ２００８～２０１０ (JSPS) Japan society for the Promotion of Science
2. ２０１０～２０１５ (JST-ALCA PhaseI) Japan Science and Technology Agency
3. ２０１６～２０１９ (JST-ALCA PhaseII)

- Before Project: there were only a few study on liquid hydrogen cooled superconducting devices, as far as I know,
  - BSCCO wire test cooled by liquid hydrogen : Prof. Iwasa (MIT), Dr. Sato (SEI)
  - Energy Transfer with hydrogen and superconductivity: LH2 cooled MgB2 cable: Prof. V.S.Vysotsky(“JSC” Russian Scientific) 2011~
  - LH2 level sensor by MgB2 wire : Prof. Kajikawa (Kyusyu Univ.), Prof. Takeda (Kobe Univ.) ,
  - Conceptual design : Prof. B.A.Glowacki(Univ. of Cambridge), Prof. Yamada (NIFS), ………
- 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 ?
  - Hydrogen Brittleness of materials, Dielectric strength of hydrogen (Gas, Liquid), ………

Progress Status 2/2

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

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 forced flow velocity
→ for evaluation of electro-magnetic properties of superconductors cooled by LH_2

- 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 experiment has been safely carried out in 20 test-cools, about 400 test events/cool.

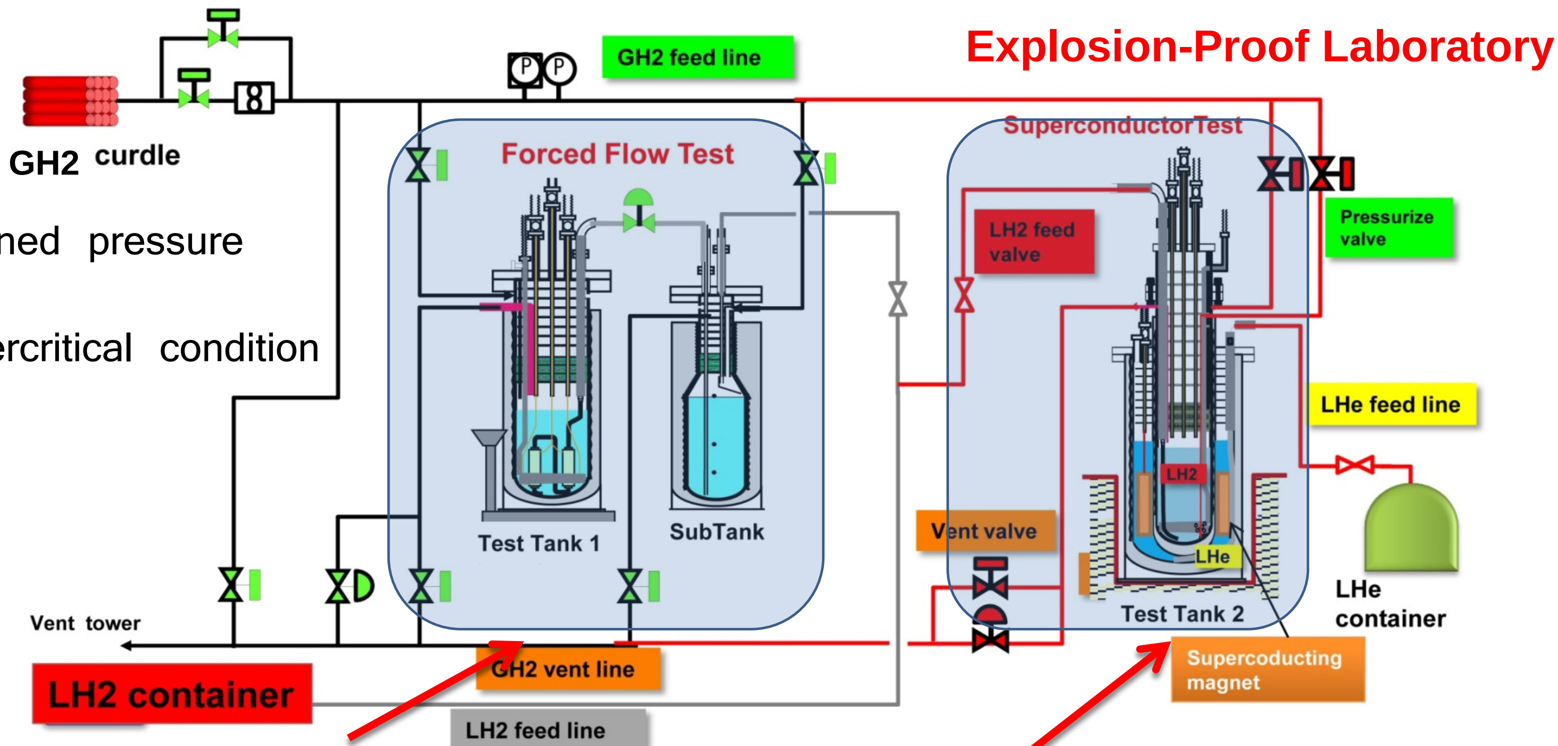
Our Test Facility Site

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.

Experimental Set-up



Designed pressure
2MPa
−supercritical condition

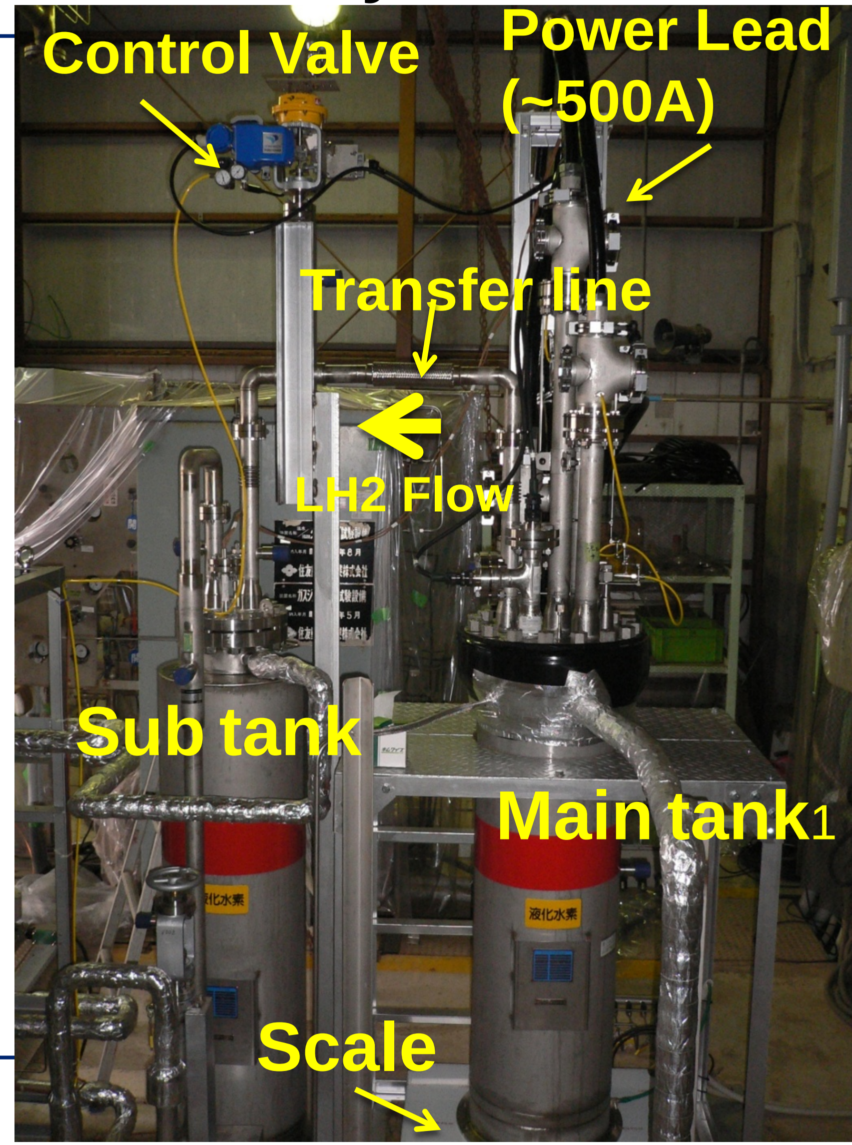
for investigating heat transfer characteristics of LH2 in a pool and also in forced flow

for evaluation of electro-magnetic properties of superconductors cooled by LH2 under external field

Thermal Hydraulic test system

Remote measurement / control

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



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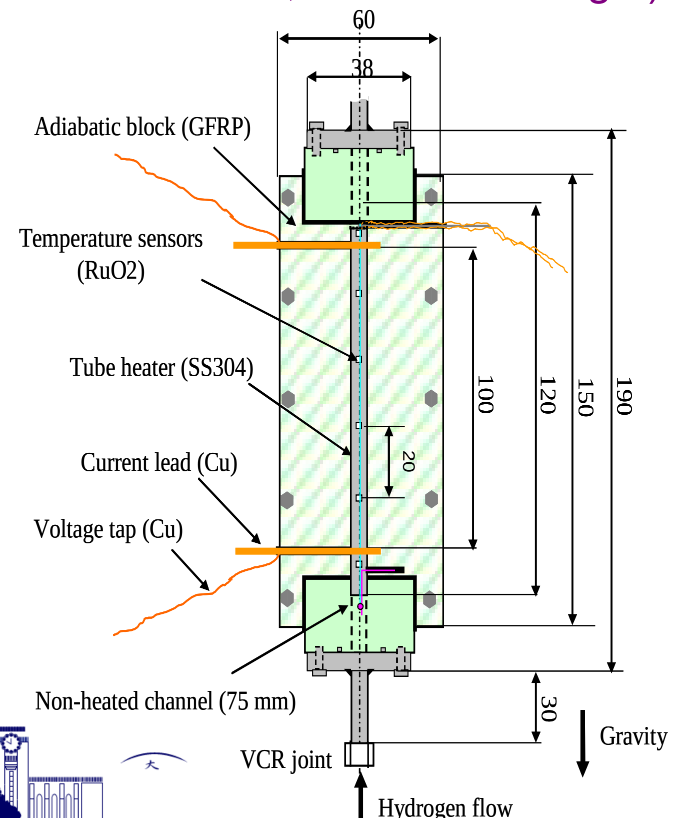
Cooling property Test of LH2

Experimental Approach is undergoing…

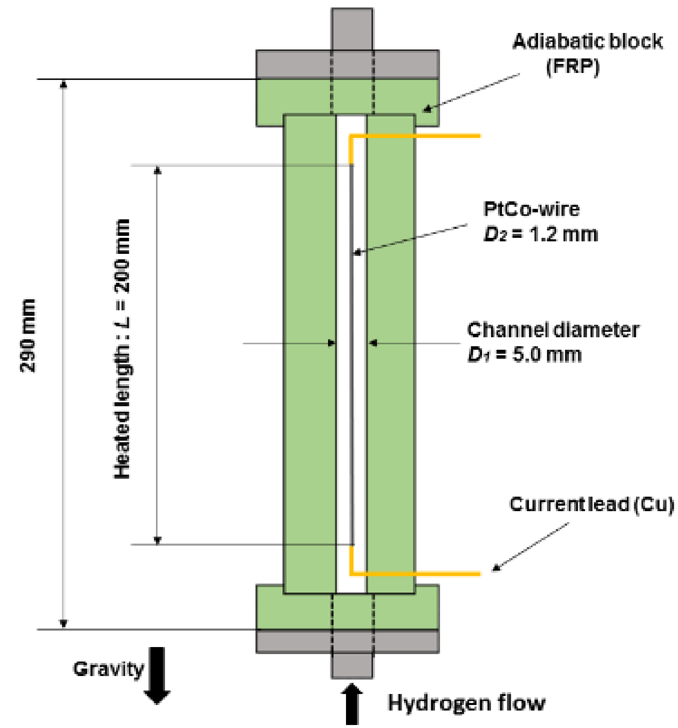
- Pool cooling/ Forced Flow Cooling
  (flow velocity : 0 ~ 30 m/s)
- Saturated/ Sub-cooling (20 ~ 31 K: 0.1 ~1.1MPa)
- Supercritical (1.32MPa~)
- Steady-state / transient state
  (exponential heat input)

Forced Flow cooling test samples

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



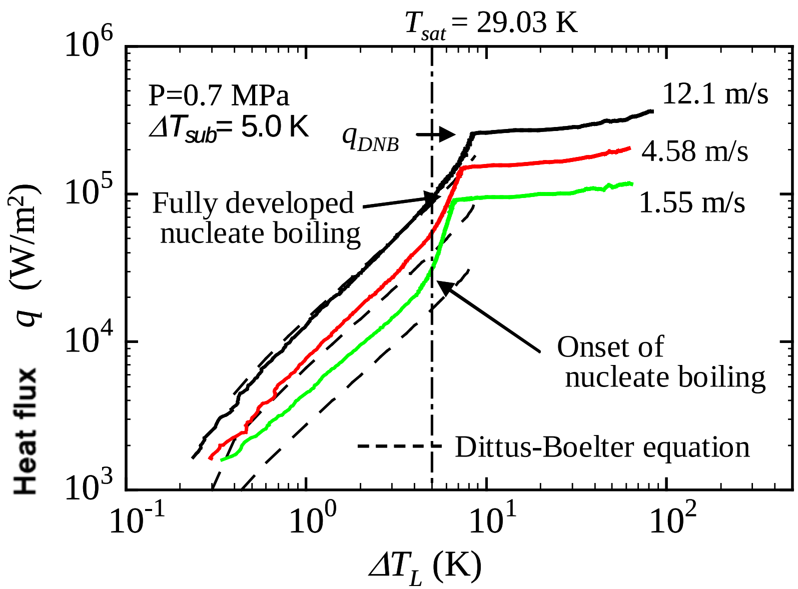
LH2 flow through FRP tube with heated PtCo thin wire



Forced Flow cooling Test Results

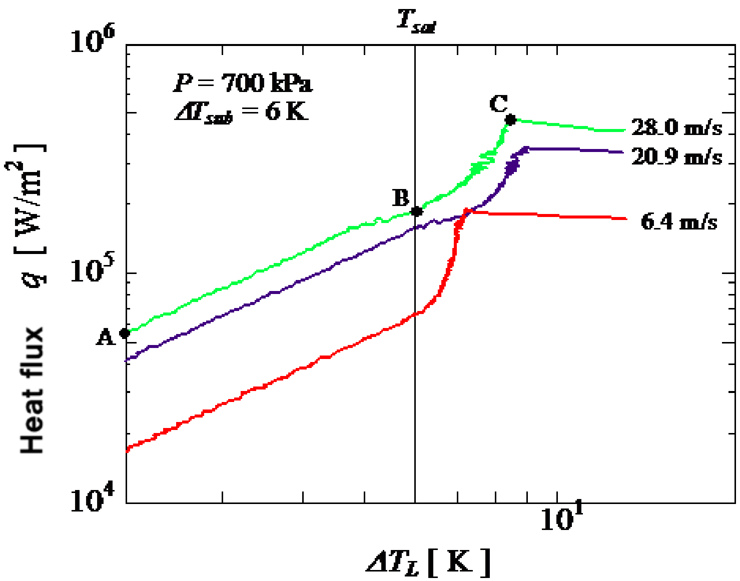
Heat transfer characteristics in subcooling condition

SUS-tube



Excessive surface temp.

PtCo wire

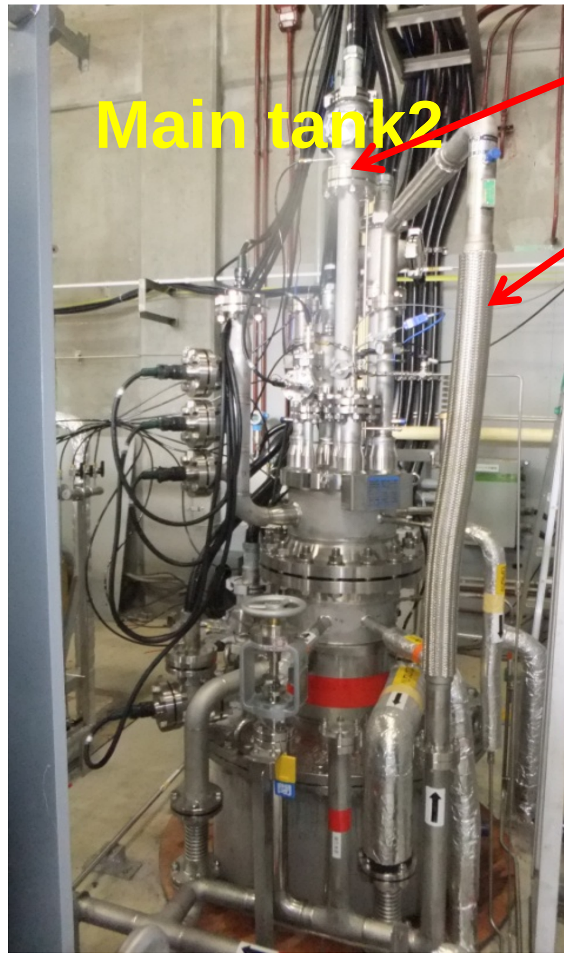


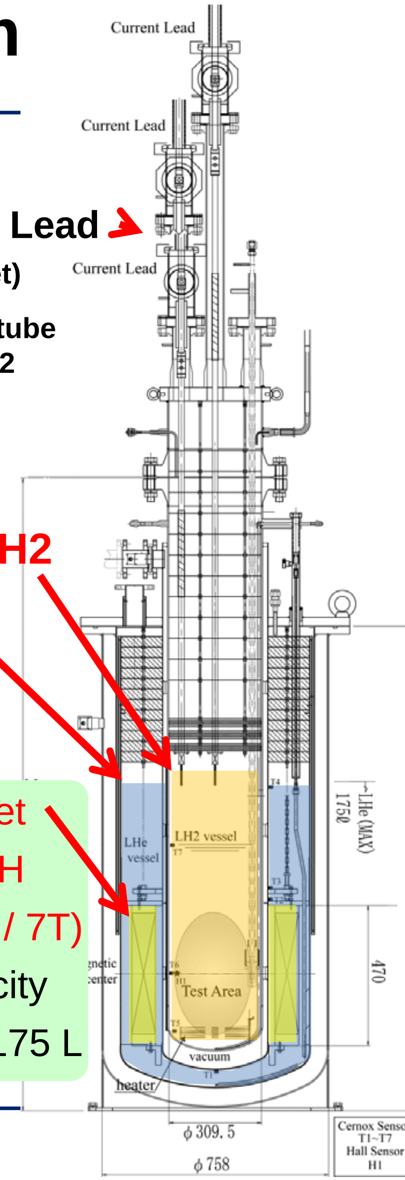
Excessive surface temp.

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

LH2 cooled superconductor test system

- pressure：
  2.0MPaG+0.1MPa
- capacity (LH_2)：61 L
- ID=309mm/h=2218mm
- **Power Lead ~500A**
  covered by blanket with
  GN_2(+5kPaG)





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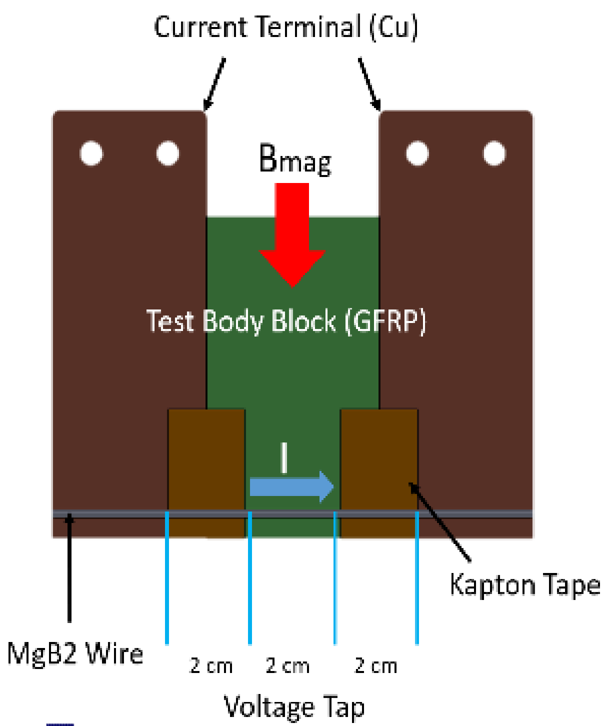
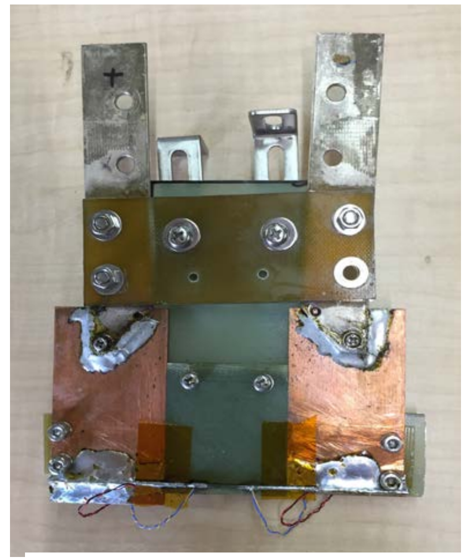
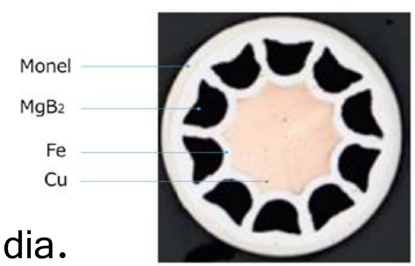
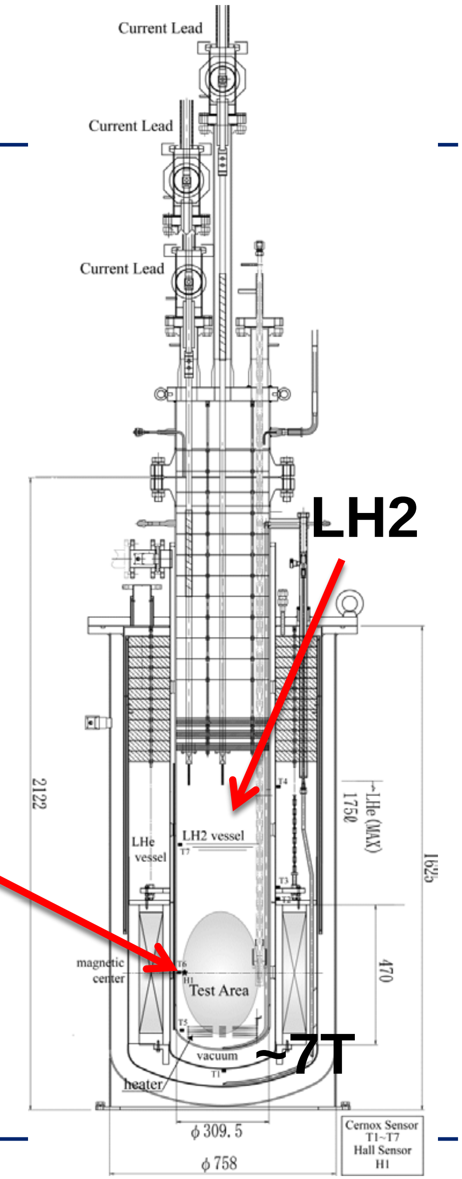
Critical current test of MgB2 short wire under magnetic field

Illustrated test sample of MgB2 short wire and set-up









Produced by Hitachi Ltd.

1.5mm dia.

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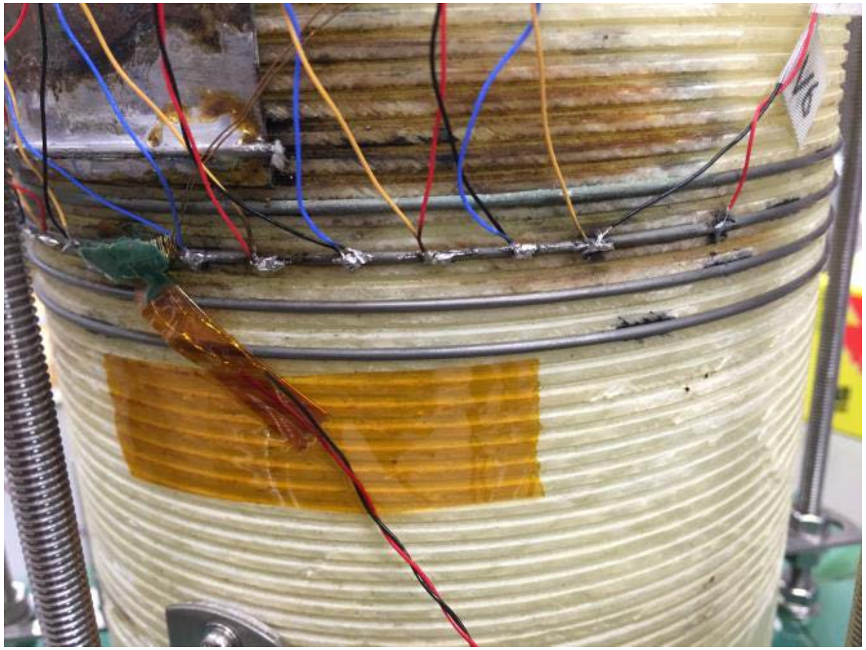
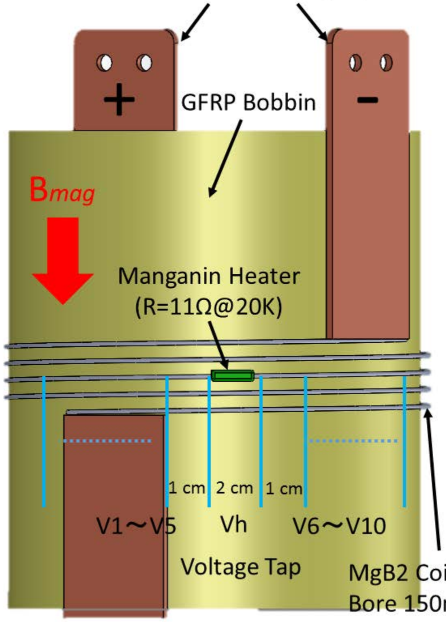
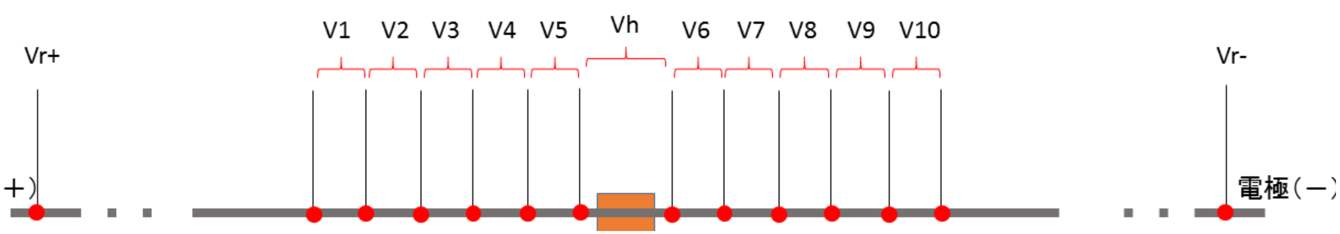
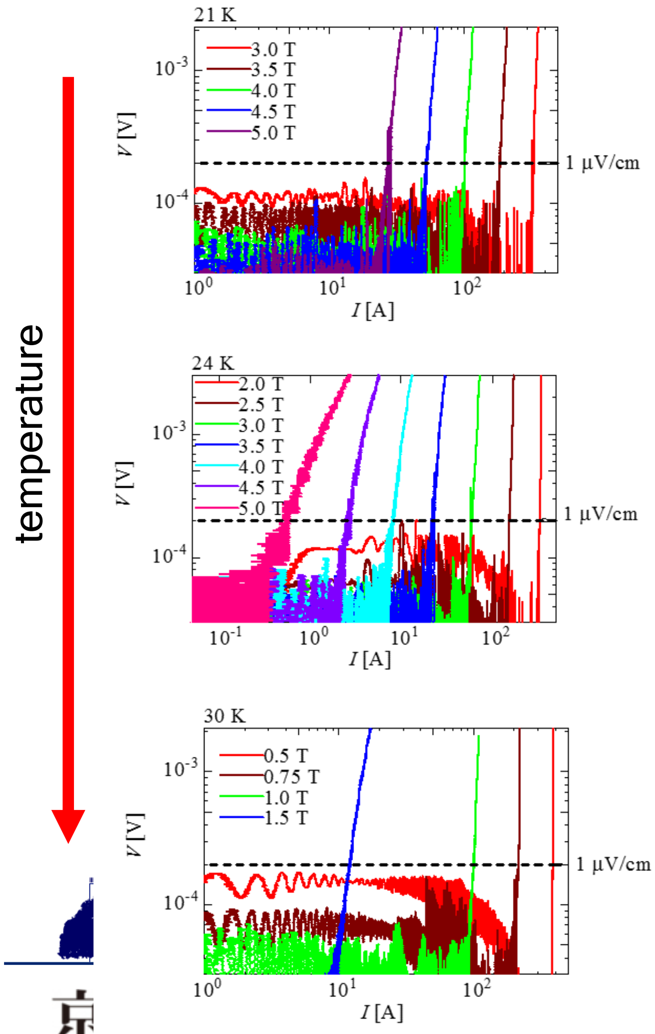
Small Coil (2m) : Normal propagation test

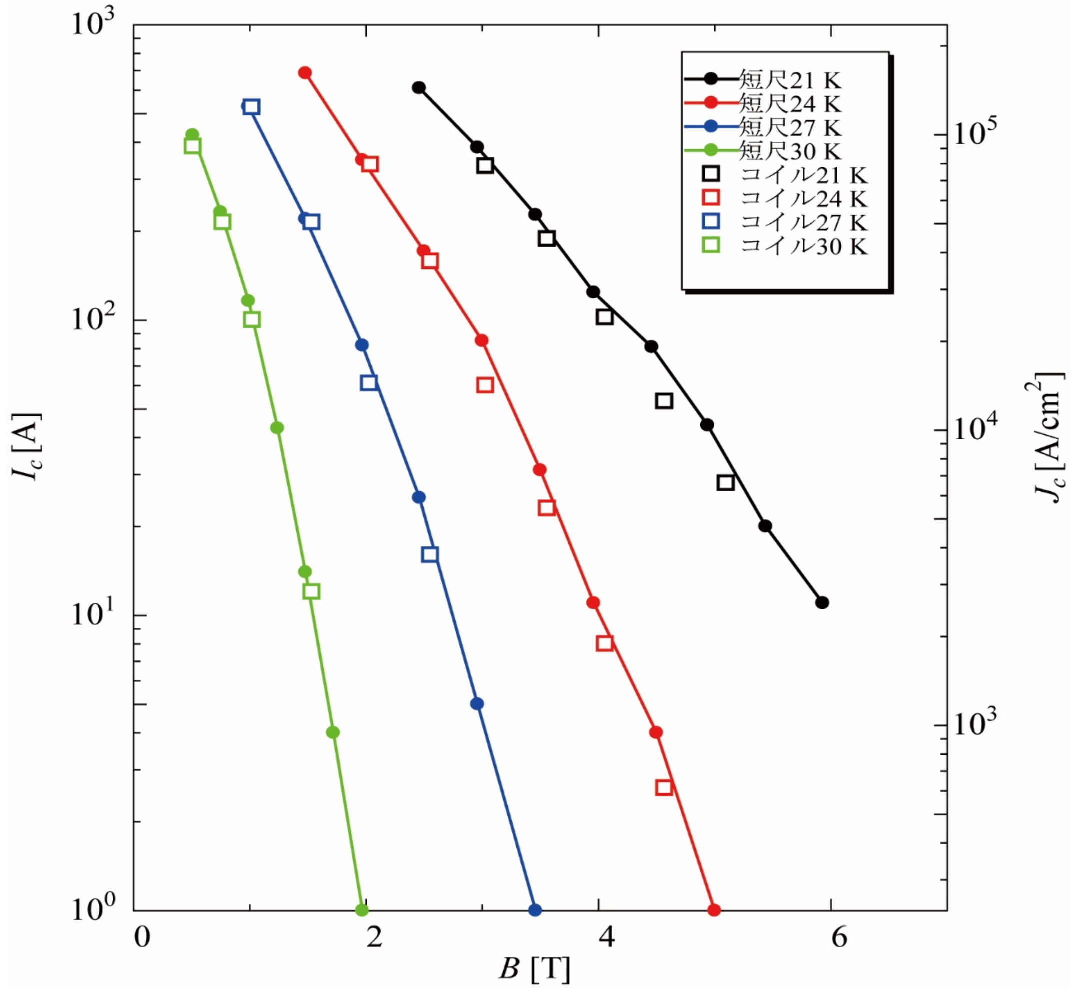






B-Ic characteristics of MgB2 wire in LH2

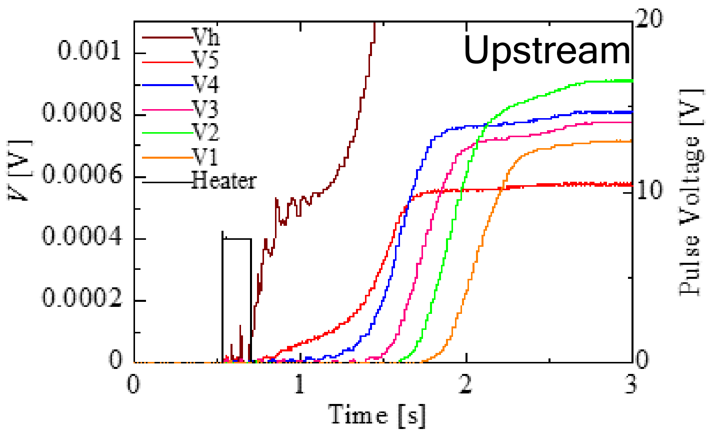


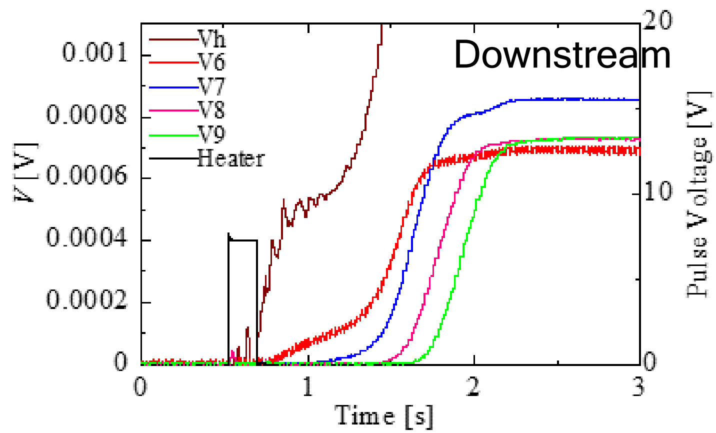


Normal Zone Propagation Test in LH2

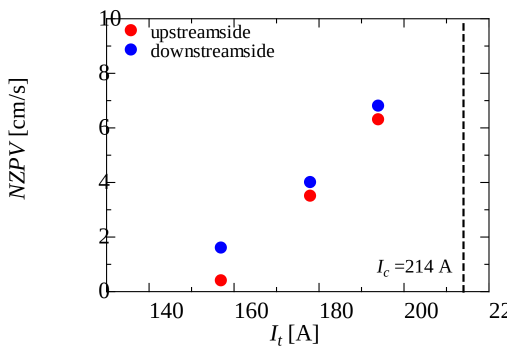
Test Condition:

① 30 K, 0.75 T(Ic= 214 A) It = 194A MQE=0.875 J
② 30 K, 0.75 T(Ic= 214 A) It = 178 A MQE=1.25 J
③ 30 K, 0.75 T(Ic= 214 A) It = 157 A MQE=2.75 J

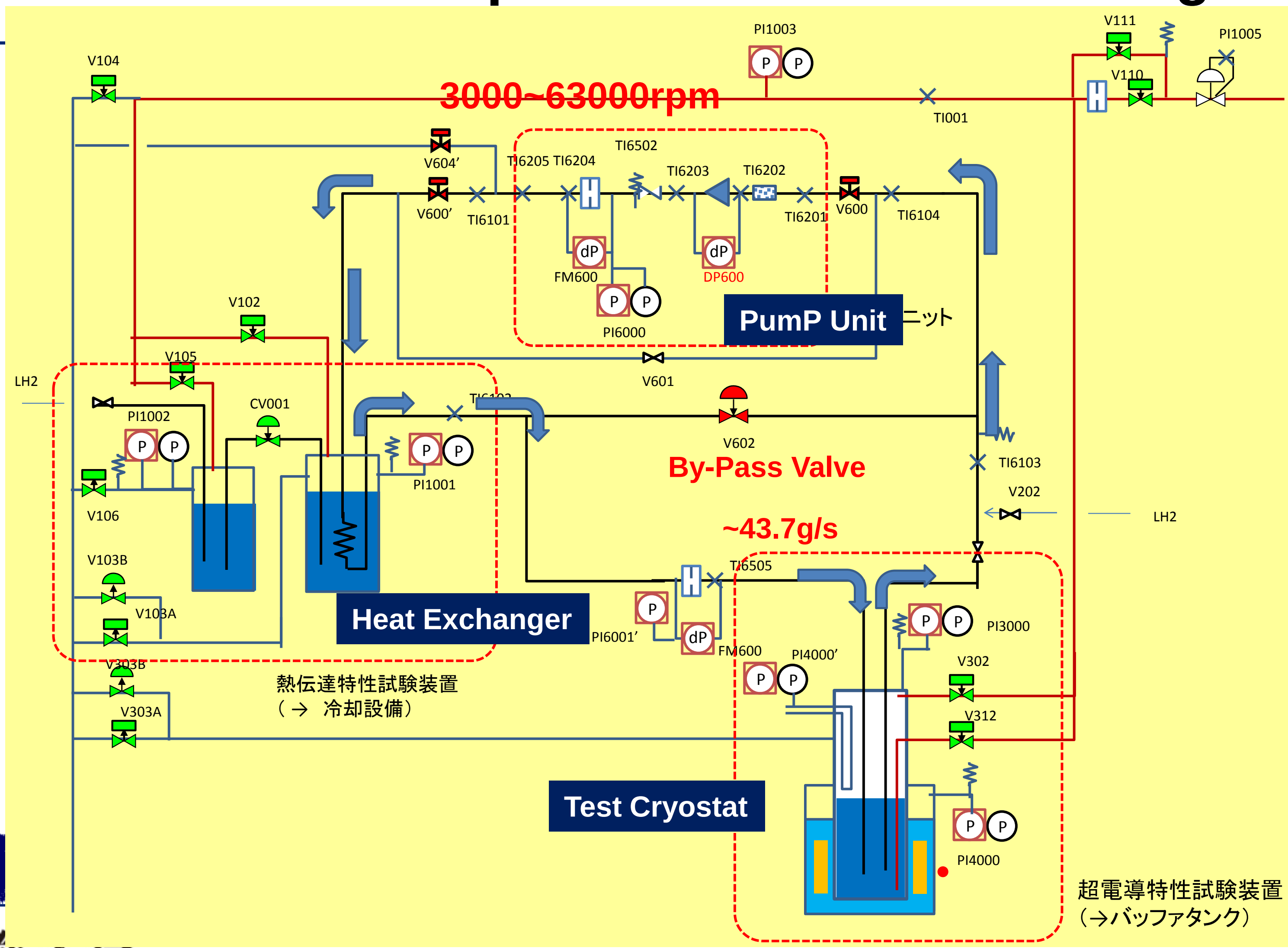




Propagation velocity



LH2 Circulation Loop for Forced Flow Cooling Test



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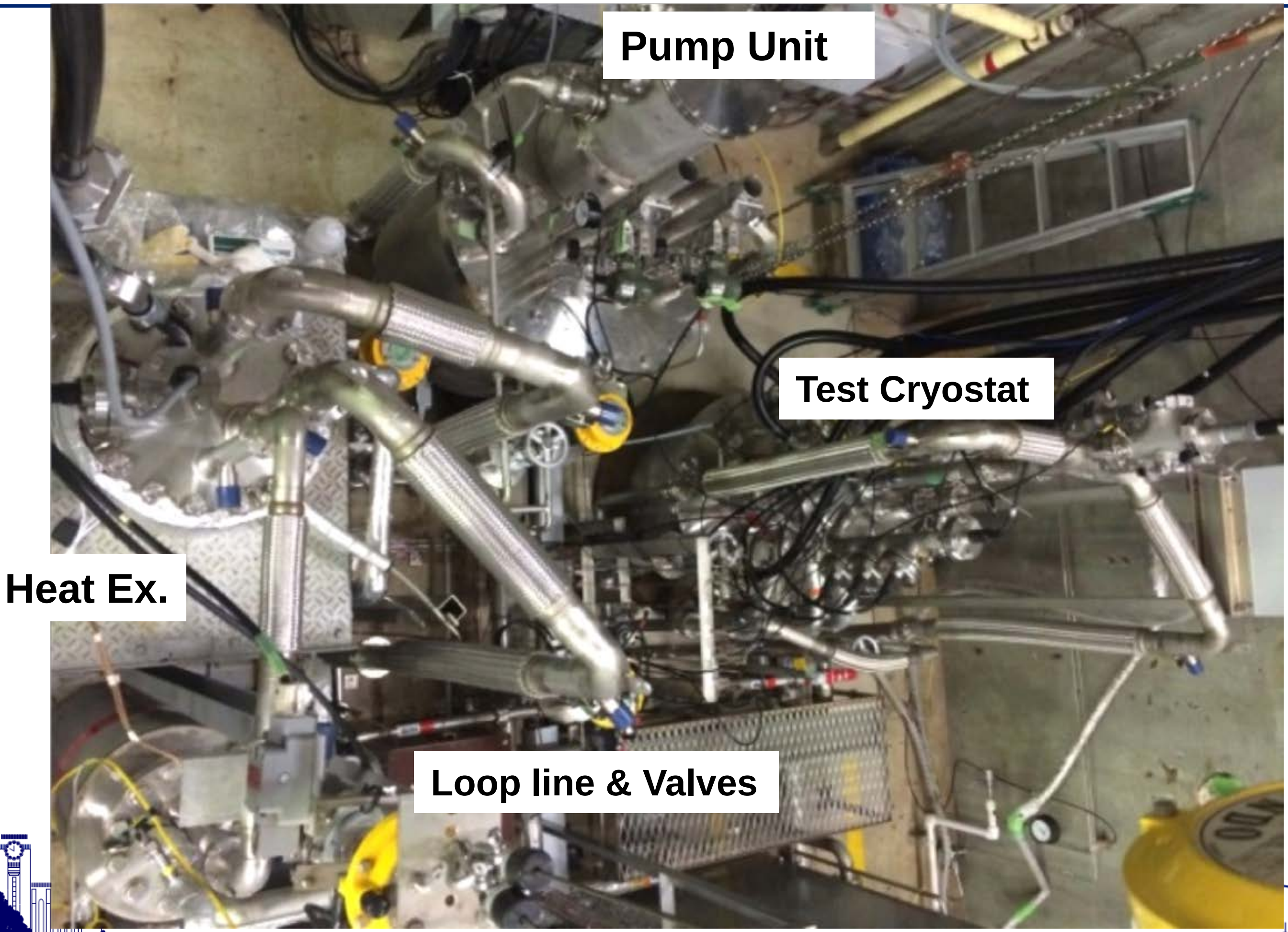
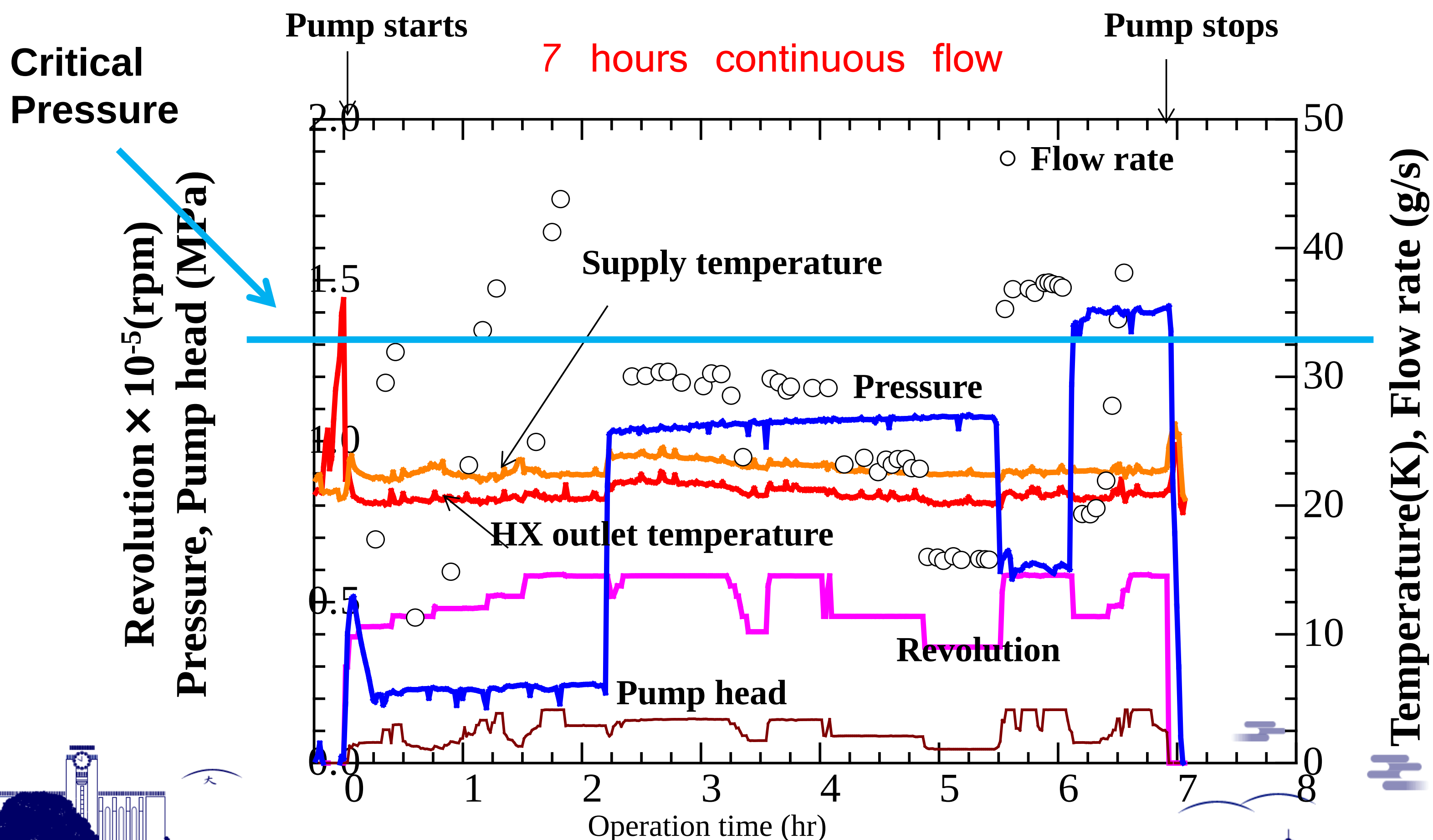
Top View of Facility



LH2 Circulation test



Future Development – power device, e.g. generator

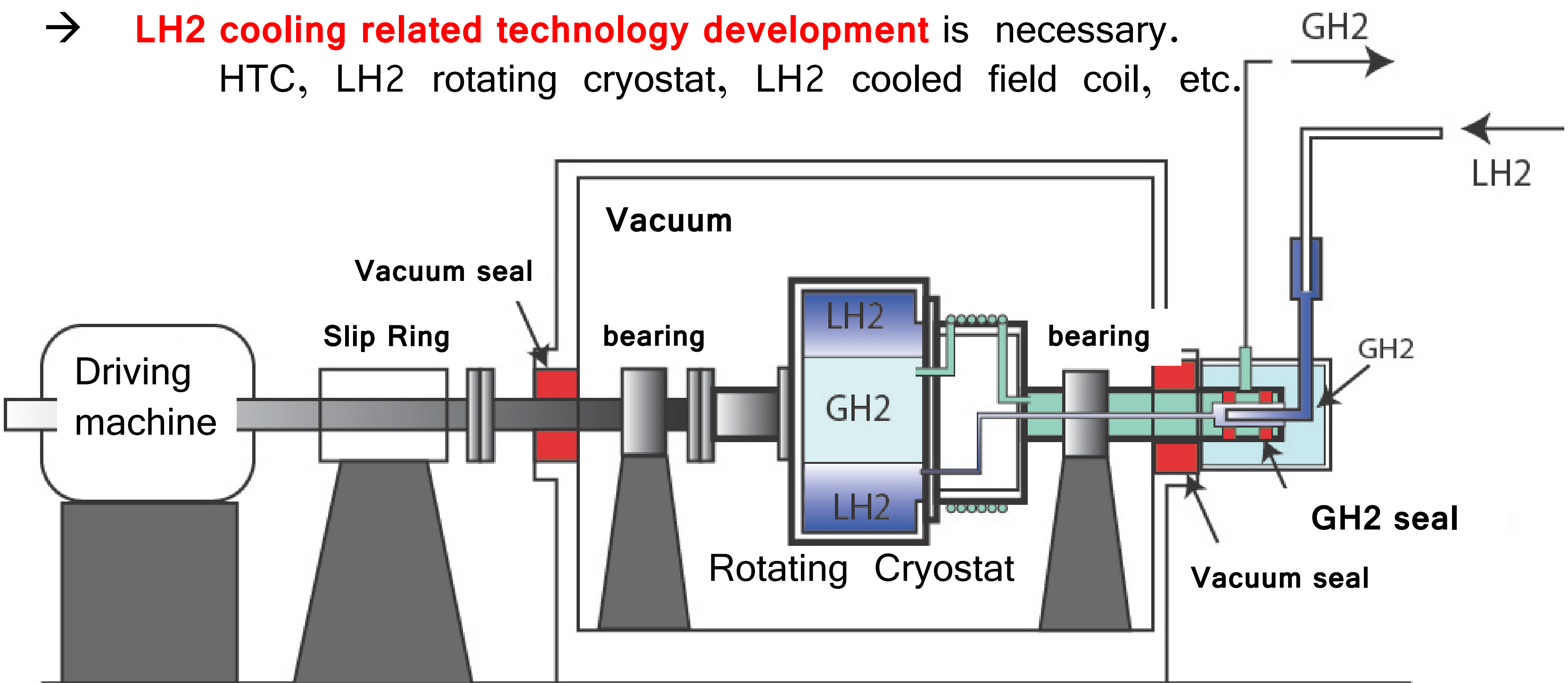
Based on the basic experiments, we are moving to
Component Technology Development stage

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 MgB2 coil 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**

Hydrogen Transfer Coupling Test Set is preparing

LHe cooled Superconducting Generator was fully developed in 1980~2000. Cooling penalty is one of the key issue to practical utilization.

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



Phase I → 2016 — Basic Dada for LH2 cooled device

Phase II → 2019 — Component Technology Development

Prototype — ?

LH2 features for superconductor Coolant
Basic data for cooling design
Design, fabrication, operation experience
Safety design

Elemental component model
LH2 Cooled rotating field coil
Hydrogen Transfer Coupling
Safety design for rotating machine

Heat transfer properties of LH2

Development of LH2 cooling system, forced flow system and key components (LH2 pump, etc.)

Electro-magnetic properties of LH2 cooled superconductors

Safety-design criteria of LH2 applied facilities
Safety Operation Experience

LH2cooled MgB2 Magnet
- Race track coil for generator field（40/80kAT)

Key component for LH2 cooling system
- Hydrogen Transfer Coupling (supply/vent to Rotating machine
- Thermal siphon, Self pumping in LH2
- Sealing, Bearing technology
- LH2 level control in rotating machine

LH2 cooled Superconductors
- （MgB2；GdBCO；BSCCO)
- Evaluation in LH2 cooling of Low cost wire & conductor (collaborating group)

Regulatory compliance
- Explosion proof structure of LH2 cooled rotating machine
- Protection at Emergency (e.g., quench) etc.

System investigation
- System advantages of Hydrogen/Electric hybrid energy infrastructure

Prototype model development of LH2 cooled superconducting energy devices

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Conclusion

- **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**.
- **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.
- **LH2 circulation test loop** was designed, made & successfully operated
- **LH2 experiment has been safely carried out**

  in 20 test-cools, about 400 test events/cool.

We are moving on to component technology development for

LH2 cooled Superconducting generator.

Thank you for your kind attention!

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