AP1-1-INV

The Iseult Whole Body 11.7 T MRI System

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A new innovative Whole Body 11.7 T MRI magnet was manufactured as part of the Iseult/Inumac project, a French-German initiative focused on very high magnetic-field molecular imaging.
It will be the most powerful whole body MRI equipment at Neurospin, a neuroscience research center operating in France at CEA Saclay since November 2006.
This actively shielded magnet system, manufactured from NbTi superconductor, will generate a homogeneous field level of 11.75 T within a 90 cm warm bore. After 7 years of activities, the fabrication has been successfully completed at Belfort by GE Power. The Iseult magnet was delivered to CEA in May 2017 and the final commissioning has started.
The first part of the talk deals with the magnet design and the technical challenges addressed during the R&D phase. The second part presents a summary of the manufacturing and of the final factory tests. An overall status of the commissioning and tests of the ancillary equipment at the site is finally presented, as well as the next steps to reach the nominal field of 11.75 T.

AP1-2-INV

Design and technical development of a high-resolution 1.3 GHz (30.5 T) NMR magnet in a persistent current (PC) mode

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A Japanese research team succeeded in developing a 1.02 GHz (24.0 T) NMR in 2014. The next target is a 1.3 GHz (30.5 T) NMR and we have commenced designing a magnet operated in a persistent current (PC) mode, which is to be used for human brain amyloid beta protein analysis to address Alzheimer's disease.

The magnet is composed of series connected HTS inner coils and LTS outer coils including magnetic shielding coils. Layer-winding is employed in the HTS coils for achieving a homogeneous field and a PC mode operation. The HTS coils are operated in high current densities, 130 - 250 A/mm^2, to generate > 23 T, enabling a compact magnet as small as 800-900 MHz LTS NMR magnets. Major part of the magnetic field is generated by high-strength Bi-2223 coils for reducing the screening current-induced field effect as well as avoiding unexpected degradation frequently observed for a REBCO coil. Two designs have been examined; one comprises a REBCO insert and a Bi-2223 midsert and the other a Bi-2223 insert and midsert. From a viewpoint of magnet size, the former is preferred; while from a viewpoint of reducing degradation and screening current effects, the latter is better.

The stress of the HTS coils are designed to be <335 MPa (Bi-2223) and <400 MPa (REBCO) in hoop stress, and <50 MPa in axial compressive stress. The hoop stresses are lower than stresses at 99% recovery of I_c of the conductors measured at 77 K. We plan to perform hoop stress tests at 4.2 K for more reliable stress design. A numerical simulation of the screening current in the REBCO coil showed the drift and gradient of the magnetic field. However, they are not as large as we expected, since the REBCO insert geometry is long and thin; the resultant error field can be addressed with conventional technologies. A similar simulation is being made on the Bi-2223 coils. A newly proposed layer-wound no-insulation (LNI) method, giving a short field delay and self-protection behavior, can be employed for the REBCO insert. For a PC mode operation, the total coil circuit resistance has to be as low as 0.1 nΩ. As a model experiment, we have been developing a PC mode 400 MHz (9.39 T) LTS/REBCO NMR using a superconducting joint between REBCO conductors with a short processing time of <1 day [1].

[1] K. Ohki et al., *Supercond. Sci. Technol.* in press.

This work was partly supported by the MEXT. Part of experimental data was obtained in the S-innovation Program of the JST.

AP1-3-INV

REBCO coated conductor layer winding for persistent current operation

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Following the recent report on the development of superconducting REBCO conductor joint, the much anticipated persistent current HTS-MRI magnet demands new technology to be developed. Our activities aim to contribute to this new technology by demonstrating a cryocooled REBCO-1T magnet with persistent current joints with resistances less than $10^{-12}\Omega$.

The main challenge here is the joint technology, however, it is also well known that a REBCO magnet fabrication itself is a challenge. The difficulty of layer winding a REBCO coated conductor is in its highly anisotropic tape form that handling process during helical winding may easily induce damages. Although the conductor with thick 75 μm substrate was successfully wound to generate then a record breaking 24 T [1], some difficulties with thinner conductors with 50 μm substrate have been reported [2].

We summarise here our ongoing development of layer winding and implementations necessary for constructing a layer wound REBCO magnet with a persistent current joint. The commercially available 4 mm and 6 mm width conductors are used to fabricate several test coils of different dimensions, as well as coil terminations that feed the wire to the joint. They are tested in gas cooled environment between 30 K and 77 K with applied field up to 12 T, and are compared against the short conductor sample performances measured separately.

Acknowledgements:

This work was conducted as a part of “Technology Development to Promote Commercialization of High-Temperature Superconductivity” sponsored by New Energy and industrial technology Development Organization (NEDO). Authors would like to thank Dr. Kitaguchi of NIMS for providing access to his experimental set up.

[1] S. Matsumoto et al., Supercond. Sci. Technol. 25, 025017, 2012.
[2] S. Matsumoto et al., IEEE Trans. Appl. Supercond. 22, 9501604, 2012.

Keywords: REBCO coated conductor, layer winding

AP1-4-INV

Highly Compact, High Magnetic Field, High Performance Fusion Reactors Using REBCO Conductor Technology

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High-field, high-temperature superconductors (HTS) would enable a new generation of compact fusion experiments and power plants, dramatically speeding the development path and improving the overall attractiveness of fusion energy. All design concepts for power producing commercial fusion reactors rely on superconducting magnets for efficient and reliable production of the magnetic fields. HTS, particularly Rare-Earth Barium Copper Oxide (REBCO) superconductors, represent a new game changing opportunity that could significantly advance the economic and technical status of magnetic confinement physics experiments and fusion reactors. It could revolutionize the design of magnetic fusion devices leading to very high performance in compact devices with simpler maintenance methods and enhanced reliability. The most revolutionary aspect of REBCO superconductors is maintaining high performance at very high magnetic fields. Historically, the maximum field on coil (limited by achievable current density in the superconductor) has been a primary driver for designing a magnetic fusion device. In this talk we describe how a tokamak fusion device using REBCO allows an increase in toroidal field at the plasma from ~5.5 T for LTS technology to 10-12 T for HTS conductors. (The field at the coil increases from 12T to ~20-25 T). In this talk we present a conceptual design for fusion reactor based on REBCO conductors, showing the physics performance and technological advantages to be gained over LTS conductor technology [1].

[1] B. N. Sorbom*et al.*, ARC: A compact, high-field, fusion nuclear science facility and demonstration power plant with demountable magnets. *Fusion Engineering and Design.***100**, 378–405 (2015).

Keywords: REBCO, Fusion Reactor, Superconducting Magnet, High Field

AP1-5

High Field Magnets for Future Circular Colliders

Presented by S. Izquierdo Bermudez on behalf of HL-LHC project and the FCC design study

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The upgrade of the Large Hardon Collider (High Luminosity LHC) relies on the installation of a new generation of superconducting magnets. The resulting peak field, in the range of 12 T, requires the use of Nb_3Sn as superconductor. A next step of energy increase of hadron colliders beyond the LHC requires high-field superconducting magnets capable of providing a dipolar field in the range of 16 T to 20 T with accelerator quality. This presentation summarizes the activities and plans for the development of these magnets at CERN, assessing the critical technical challenges and required R&D.

Keywords: High Field Magnet, LHC, FCC

AP1-6-INV

Progress of Fundamental Technology R&D toward Cryocooler-Cooled Accelerator Magnets

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We report the current status of an R&D project of fundamental technology for cryocooler-cooled HTS accelerator magnets funded by JST under its S-Innovation Program as well as some associated R&D. The topics of the recent progress are as follows.
1) Design and construction of a 2.5 T-class magnet for beam-line test
2) Three-dimensional design and ac loss evaluation technology of cosine-theta magnets wound with coated conductors
3) Quench behavior of conduction-cooled coated conductors subject to transient and localized thermal disturbances
With respect to the first topic, we designed a magnet consisting of racetrack coils and cold iron and are winding the coils. With respect to the second topic, we developed a new scheme for large-scale electromagnetic field analyses, and the magnetic field quality and ac losses of a cosine-theta dipole magnet were evaluated. The third topic is related to the behavior of coils which is subject to the injection of a particle beam. We estimated the disturbance energy caused by beam injection, and quench behaviors of short samples of coated conductor subject to transient and localized thermal disturbances were studied.
The plan of beam-line test will be also reported in the presentation.

This work is supported by the Japan Science and Technology Agency under the Strategic Promotion of Innovative Research and Development Program (S-Innovation Program).

Keywords: coated conductor, magnet, accelerator

AP1-7-INV

Technology priorities in large-scale HTS bulk devices

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Abstract- The design, alignment and the needs in research strategy of HTS bulk application to those of industrial and academic partners is identified and reported. A "Masterplan" for the next 10 years include an interdisciplinary development strategy with physics, material science, cryogenics - all are paired with engineering. We report practical current engineering problems as integrated cooling, vacuum insulation, and mechanical stabilization. Except the application-adapted REBCO bulk fabrication, single or multi-seeded in axial or radial geometry, cryostat design and fabrication technology are basic for application and commercialization. High –speed small rotational magnetic bearings with low hysteresis of less than 0.1 mm and 100 N load at 77 K are tested for He pumping. Journal superconducting magnetic bearings of 160 – 200 mm diameter handle and stabilize safely loads above 10 kN. Linear magnetic bearings operate in comparable lightweight portable cryostat modules. Magnetic forces of up to totally 6 ton load are obtained by assembling HTS bulk cryostats under the vehicles. Lightweight and flexible 500 mm axial HTS bulk bearings were developed for cosmic microwave background (CMB) radiation polarization detection. The key is a frictionless smooth rotational movement of a sapphire half-wave-plate (HWP) rotor which relies on the great magnet homogeneity of the PM rotor. Extremely safe conditions and requirements are the surrounding circumstances of manned spaceflight experiments. The space project Magvector/MFX in cooperation with Deutsche Luft- und Raumfahrt (DLR) and AIRBUS in Germany was built successfully within 15 month and launched to the International Space Station (ISS). Since two years the interaction of the Earth magnet field with a fast moving bulk superconductor has been measured systematically. The experiment is planned to continue within the next German Mission "horizons" in April 2018. By evaluating HTS devices and controlling the results the main technology priorities were identified for future industrialization. We estimate and report the necessary scaling of HTS bulk manufacturing process, the reliable and cost-efficient cryogenics including the fabrication of lightweight cryostats.

Keywords: Large-scale devices, space application, Magnetic bearings, Maglev devices

AP2-1-INV

High-Field Magnets for NMR and MRI: A Review of the Past 30 Years and a Vision for the Future Perspectives

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Although my talk here is on high-field NMR and MRI superconducting magnets, I will begin by briefly describing early NMR studies on biological samples and even tumor detection that were performed with *Bitter magnets* in the late 1960s at the National Magnet Laboratory, now FBML. The full-fledged results achieved in the early 1970s with *low-field* NMR spectrometers lead directly to MRI for medical science and health care. Of many high-field NMR and MRI magnets covered in this talk, I will highlight a 600- MHz NMR magnet manufactured by IGC (IGC600) that in 1979 began operation at the Carnegie-Mellon University. Because the IGC600 was constructed from a stack of double-pancake coils wound with Nb3Sn *tape*, issues encountered during its development remain highly relevant to today's HTS inserts, particularly those wound with REBCO tape. I will discuss challenges, and possible solutions, for NMR and MRI magnets that incorporate HTS. As for the future perspectives, the sky's the limit, technically, but in reality, development will not come easily or quickly.

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AP2-2-INV

Nuclear Fusion and Particle Accelerators: Past and Future Perspectives

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Particle accelerators and fusion plasma reactors have had what can be described as a demand pulled effect on the technology and development of applied superconductivity. Within months of the announcement of Nb3Sn by Bell Laboratories in 1961 there were papers reporting small superconducting magnets for bubble chamber particle detectors. Seven years later in 1968 at the Brookhaven National Laboratory Summer Study members of the international high energy physics community as well as commercial technologists had resolved and understood the stability and ac loss issues for composite conductors. That year also saw the completion of two very large bubble chamber magnets that were cryogenically stable. The next forty years witnessed the construction of a number of high energy particle accelerators including the Tevatron at Fermilab and the LHC at CERN. These and other projects nucleated major industrial production of NbTi based superconductors and magnets. Fusion applications have been a major source of development of Nb3Sn technology and its history will be discussed. Early in the new millennium HEP took a handoff of Nb3Sn technology from fusion with improvements to the performance of that conductor. Advanced Nb3Sn and HTS materials will be the enabling technology for the next generations of particle accelerators and fusion reactors. The daunting engineering challenges of these devices will be examined.

AP2-3-INV

Rotating Machine: A review of the past 30 years and future perspectives

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Research and development on superconducting rotating machines has history of more than 30 years. In the history, superconducting homopolar DC machines might be of the first practical use in superconducting rotating machines, which are not sure because of their war ship uses. Superconducting synchronous generators cooled by liquid helium are well developed, especially by SuperGM project in Japan. Fundamental subjects on design, manufacture, operate, control, power system performance and so on are definite, which will be presented in this paper. After developing oxide superconducting wires and bulks, superconducting electric motors by use of them, (mainly synchronous ones) are under developing, the structures of which are very similar to the generators above mentioned. They mucst be of speed change, differently from generators.
Increasing interest of hydrogen, synchronous generators by use of MgB_2 wires cooled by liquid hydrogen are under development. Generators of lower cost, smaller size and so on are expected. Superconducting equipment to solve several problems on power systems with large number of renewal energy power plants must be examined. It is very important to find subjects on superconductivity for meeting above mentioned problems.

Keywords: Superconducting electric machine, Liquid helium, Oxide superconductor, Liquid hydorogen

AP2-4-INV

Power applications: review of the past 30 years and future perspective

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Applied superconductivity will soon celebrate its 60 years. It was linked to the emergence of conductors (Nb_3Sn then NbTi) able to carry large currents under high fields. NbTi and Nb_3Sn still are the basic superconductors for applied superconductivity with well-established markets such as MRI. 30 years ago the first superconductor whose critical temperature breaks the liquid nitrogen barrier was discovered. The « Superconductivity revolution » was announced, but it did not really take place. On the other hand considerable works have been carried out about the strongly complex high Tc superconductors, which have so reached now a pre-industrial stage. In parallel the indispensable sustainable development among other things required new technologies and the high Tc superconductors are outstanding enablers. These loss free conductors are natural companions for sustainability. Renewable energies face several challenges such as very large wind turbines or the transport of huge energies over long distances. Superconducting wind generators, superconducting cables and superconducting fault current limiters offer for example new functions or possibilities in terms of footprint and weight performances breaking the conventional limits. The “Superconductivity revolution” is on track. The review of some works will be a basis for exploring the future of superconducting power applications.

Keywords: Superconducting Power Applications, Fault Current Limiter, Wind turbine, HVDC supergrids

AP3-1-INV

HTS flux pumps and the role of dynamic resistance in the HTS flux pump

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Flux pump devices enable large currents to be injected into a superconducting circuit without the requirement for normal-conducting current leads. The demonstration of an efficient HTS flux pump could reduce the system heat load incurred whilst energizing HTS coils. Furthermore, brushless HTS exciters can be implemented using flux pumps for HTS rotating machine application [1].

In recent years, we have developed and studied a series of HTS coated conductor dynamo-type flux pumps:(1) G1 (generation 1) flux pump with radial flux gap where permanent magnets mounted on a cylindrical rotor move across a coated conductor stator [2-4]; (2) G2 flux pump with axial flux gap and iron return paths for through-wall excitation of HTS coils [5]; (3) G3 flux pump with radial flux gap with continuous cylindrical coated conductor stator for kA-class current pumping; (4) G4 flux pump with radial flux gap with parallel connected coated conductors and iron return paths. The design features and the output characteristics of these flux pumps will be reviewed.

Dynamic resistance occurs in a HTS wire carrying a DC transport current whilst simultaneously experiencing an AC magnetic field. HTS flux pumps are found to possess an effective internal resistance, which varies linearly with frequency. This internal resistance, which is due to dynamic resistance [6], sets a limit for the maximum achievable output current from the flux pump.

We discuss the dynamic resistance characteristics in coated conductors in perpendicular magnetic fields first, and then present the role of dynamic resistance in various types of HTS flux pumps.

[1] C. Bumby *et al.*, *Supercond. Sci. Technol.* **29** 024008 (2016).
[2] C. Hoffman *et al.*, *IEEE Trans. Appl. Supercond.* **21** 1628-1631 (2011).
[3] Z. Jiang *et al.*, *Supercond. Sci. Technol.* **28** 115008 (2015).
[4] C. Bumby *et al.*, *Appl. Phys. Lett.* **105** 112601 (2014).
[5] C. Bumby *et al.*, *IEEE Trans. Appl. Supercond.* **26** 0500505 (2016).
[6] Z. Jiang *et al.*, *Appl. Phys. Lett.* **105** 112601 (2014).

Keywords: HTS flux pump, Dynamic resistance, Coated conductors

AP3-2-INV

Two-shell Superconductor/Ferromagnetic Cloaks for Shielding of Magnetic Fields

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Covering a superconducting shield with ferromagnetic layer allows to absorb the magnetic flux expelled from the shielded space. In difference to a common magnetic shield, such cloak could be made invisible to a detector of magnetic field. We have demonstrated such possibility utilizing rather common materials, the 2nd generation HTSC tape and an iron alloy tape.

Further development towards a possible application requires a substantial expansion of dimensions and a reduction of energy dissipation in AC fields. Several options for design of the cloak considered for operation at low fields, with amplitude below 1 mT, have been investigated. Dimensions of 10 cm scale can be reached using *RE*BCO coated conductor tapes arranged in helically wound co-axial layers. The outer ferromagnetic tube can be made of a composite containing ferrite powder in suitable compacting medium. Experimental verification of cloaking ferromagnetic and metallic materials brought satisfactory results. Possible ways of improving the cloak performance will be analyzed and imaginable applications of this novel superconducting device discussed.

Keywords: magnetic cloaking

AP3-3-INV

Numerical Analysis of Current Distribution and Stability in No-Insulation Coils Wound with REBCO Wires

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With the development of No-Insulation (NI) winding technique [1], coils wound with REBCO wires have been applied to generate a higher magnetic field than 20 T. MIT is making a 1.3-G NMR, and NHMFL has generated >40 T using the NI technique. The NI technique is the best way to protect REBCO coils so far. If a REBCO coil quenched, the coil would not be damaged. Although NI REBCO coils show good properties, the electric and thermal behaviors inside the coils are very complicated. To clarify such behaviors, we have developed a simulation method coupling with a partial element equivalent circuit (PEEC) method and a thermal finite element method (FEM) [2]. Fig. (a) and (b) shows the circumferential current and temperature distributions at 3 s after the bottom REBCO pancake entirely quenched. Using the PEEC and FEM method, the high thermal stability of NI REBCO coils were shown.
Many experiments of small-size NI REBCO magnet were done before, however a few experiments of high magnetic field generated by magnets of insert NI REBCO magnets and outsert LTS magnets have been reported recently. In such experiments, behaviors which have never seen in low magnetic fields can be observed, such as a torque and a Hall voltage. Therefore, we have developed a new simulation method to consider a torque and a Hall voltage after quenches, to investigate the stability of NI REBCO magnets as an insert magnet.

[1] S. Hahn, D. K. Park, J. Bascuñán, and Y. Iwasa, "HTS pancake coils without turn-to-turn insulation," IEEE Trans. Appl. Supercond., vol. 21, no. 3, pp. 1592–1595, Jun. 2011.
[2] T. Wang, S. Noguchi, X. Wang, I. Arakawa, K. Minami, K. Monma, A. Ishiyama, S. Hahn, and Y. Iwasa, "Analysis of Transient Behaviors of No-Insulation REBCO Pancake Coils During Sudden Discharging and Overcurrent," IEEE Trans. Appl. Supercond, vol. 25, no. 3, Jun. 2015, Art. no. 4603409.

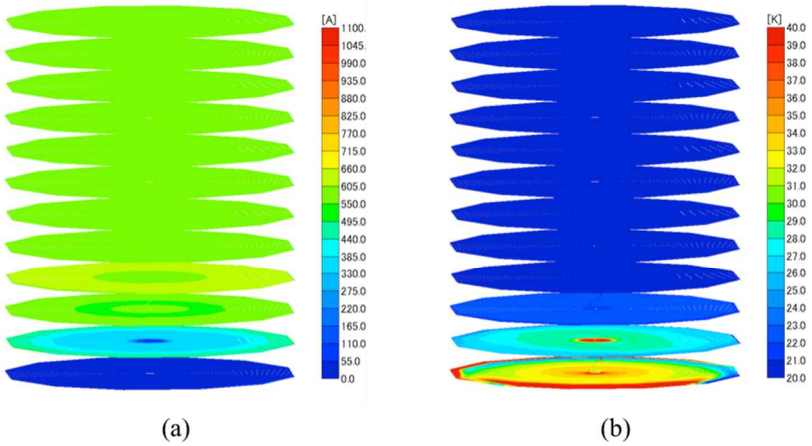

Fig. (a) Circumferential current distribution and (b) temperature distribution at 3 s after the bottom REBCO pancake quenched.

Keywords: No-Insulation winding technique, Thermal stability, Numerical simulation

AP3-4

Transient Heat Transfer Through the LHC Polyimide Cable Insulation

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During the operation of the LHC, the superconducting magnets are exposed to steady-state and transient heat loads. Knowledge of the thermal link between the superconductor and the He bath is essential to evaluate the stability of the superconductor. This work reports experimental data on the transient heat transfer between a stack of MB Rutherford superconducting cables and a He bath in saturated and pressurized conditions. The sample is prepared from machine insulated superconducting cable, instrumented with a Cernox temperature probe. The heat transfer is studied in the temperature range 1.7 K to 2.1 K and a deposited power range in 0.5 mW/cm3 to 5 mW/cm3.

From the experimental data, two parameters are extracted and are discussed. The first parameter is the steady-state temperature difference and the second parameter is the characteristic time for the temperature difference to reach steady-state. From the two parameters conclusions are drawn on the void volume in the sample and on the dominant cooling paths through the polyimide insulation.

Keywords: Helium II, Transient Heat Transfer, Polyimide Cable Insulation

AP4-1-INV

Large Rotating Machines using HTS

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The unique capability of superconductors to carry very high currents in small cross sections even at considerable magnetic fields has attracted engineers of rotating machines very early – even before the discovery of the high-temperature superconducting materials (HTS). There have been built motors and generators based on LTS-wires cooled by cryogenic Helium in the 70's of the last century.

The HTS avoiding the high cooling penalty of the low temperature operation of LTS opened up new opportunities for mid-power rotating machines. At the same time, the importance and share of synchronous machines increased and new fields for application became significant, e.g. wind power.

We will discuss the basic challenges and opportunities of different rotating machines for electric aircrafts, power generation and propulsion, and how aspects of material and machine will interplay.

Keywords: rotating machines, HTS, Propulsion, Power Generation

AP4-2-INV

Application of HTS for ship propulsion motor

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Superconducting rotating machines continue to attract technical and scientific interest and assessment, with progressive research and development ongoing in both academia and industry since the discovery of high-temperature superconductors. High power density and efficiency, even with possible compromise on cost would be a goal for ship propulsion motors. In the beginning, we illustrate the evolution of electric propulsion motors, and report the status of R&D of HTS motors in TUMSAT.
High-temperature superconducting (HTS) materials offer a mature technology for propulsion motor/generators in transportation. In Japan, 1-3 MW synchronous motors for ship propulsion have been developed by industry-national institute-academia liaison using HTS wires. As an alternative technology for the field poles, melt-growth bulk HTS materials have provided the basis of a successful design and prototype demonstration of modules for 10-30 kW proof-of-concept rotating machines. An effective magnetization technique for a high magnetic flux density of the HTS bulks is a key which potentially offers a superior field pole flux and torque density compared with conventional PM machines.
In large output power applications, such as wind/ocean renewable energy generators and ship/aeronautic propulsion motors, these machines are highly desirable because of their potential for a high energy density per weight and volume. In this paper, we report the current status of works concerning activity of the TUMSAT group and others towards the development of superconducting ship propulsion motors.

[1] Kiruba S. Haran et al., High power density superconducting rotating machines – Development status and technology roadmap, *Supercond. Sci. and Tech.*, http://iopscience.iop.org/article/10.1088/1361-6668/aa833e.
[2] Toshiyuki Yanamoto, Mitsuru Izumi, Minoru Yokoyama, Katsuya Umemoto, *Proceedings of the IEEE*, 103, No. 12, pp. 2333-2343 (2015).
[3] Miki et al., Novel Design of a 30 kVA Rotor System with Bulk High Temperature Superconductor for a Motor/Generator, Abstract and presented in Applied Superconductivity Conference, ASC2014, Charlotte, NC and M Izumi and M Miki, *Radial-gap-type superconducting synchronous machine, magnetization device, and magnetization method*, EP 3125415 A1, Feb. 2017, PCT/JP2015/059155.

Keywords: HTS synchronous motor, Ship propulsion motor

AP4-3-INV

Current Status of Superconducting motor for Aviation Application

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Sustainable development in the direction of electric aircraft, more electric aircraft (MEA) and fully electric aircraft (FEA) in order to diminish or completely exclude onboard hydraulic and pneumatic systems opens an opportunity to use superconducting electric drives in the frame of that conception. Two trends of their application are under consideration. The first is a drive of propeller or fan and relates electric machines of MW class with power supply according to scheme "turbine → superconducting alternator" or fuel cells. The second trend is the use of superconducting electric drives of kW class in onboard systems. Different types of synchronous superconducting electric drives are considered which can be developed with the use of modern superconducting materials: wires, tapes, bulk elements, foliate composites or their stacks. The peculiarities of development are given for synchronous superconducting electric hysteresis and reluctance motors as well as motors with permanent magnets and bulk materials in the rotor. The results of experimental comparison of output performances of reluctance motors with different superconducting materials in the rotor at temperatures 77K and 15…20K are presented. The project of business class aircraft with hydrogen fuel and electric drive of propeller is described.

Keywords: aircraft propulsion, electric motor, superconducting material, permanent magnet

AP4-4-INV

Development Status of 50 kW Class Fully Superconducting Induction/synchronous Motor for Transportation Equipment

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This paper presents development status of a 50 kW class fully superconducting induction/synchronous motor for next generation transportation equipment, e.g., train, bus, electric vehicle. We have proposed and developed so-called ring-windings for the superconducting stator, which could improve the critical current of such windings in iron core. 3-ply BSCCO superconducting conductor is utilized for the racetrack structured double pancake coils, and 4-pole stator windings have been successfully developed. DC and AC current transport property is reported. Furthermore, rotation test results of a fabricated fully superconducting motor, which adopt the above stator, is also presented and discussed.

This work has been supported by Japan Science and Technology Agency under the program of Advanced Low Carbon Technology Research and Development Program (JST-ALCA).

Keywords: Superconducting Motor, Induction/synchronous Motor, Transportation Equipment, Superconducting Stator

AP5-1-INV

Design of AC 23kV 50MVA Class HTS Cable in S. Korea

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LS Cable&System[1]

The world first commercial project for superconducting applications is already starting in S. Korea. The first step of named **SSS** (**S**uperconducting **S**mart platform **S**tation in S. Korea) project is to operate AC 23kV 50MVA class HTS cable system in power grid of Korea Electric Power Corporation (KEPCO) in order to increase power capacity and stable operation. This HTS cable system connects two substations between ShinGal and HeungDuk. Total length of HTS cable is approximately over 1km with 2 sets of normal joint box and 2 sets of termination which are outdoor type accessories for HTS cable system.

Before performing the type test, various preliminary tests with the short core were performed to confirm the HTS cable design. To meet design target values, HTS layers of each phase core consist of two conducting and one shield layer with non-magnetic 2G wire to reduce magnetization loss by adjacent HTS wires. Measured AC loss is around 0.3W/m at 1,255Arms and increasing trend of AC loss due to operating current is well fitted simulation results. In case of short-circuit test, reached maximum temperature at 5.5 bar.g is under 96.5K which is enough below boiled temperature of LN_2 at above pressure condition. A 100-meter HTS cable including unit test samples and 110-meter LN_2 return pipe were manufactured and installed for type test at KEPCO Power Training Center in Gochang, S. Korea. Type test is including various sample tests, 20 cycles load test, voltage tests such as AC withstand and impulse, repeated cooling process three times and visual inspection after disassembling. In the first quarter of 2018, LS Cable&System will supply and install AC 23kV HTS cable system in S. Korea.

Keywords: 23kV 50MVA class HTS cable, AC loss, short-circuit test, type test

AP5-2-INV

DEVELOPMENT OF TRI-AXIAL SUPERDONDUCTING CABLE SYSTEM

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We developed tri-axial superconducting cable system with the rated voltage of 35kV and operating current of 3kA at liquid nitrogen temperature. We designed superconducting cable, termination connection and cooling system with using overcooled liquid nitrogen. We used in-house YBCO tapes and a winding machine to prepare conductor having the *Ic* -value of 4,200A or more per phase at liquid nitrogen temperature. The outer diameter of the conductor and cryostat was approximately 50mm and 130mm, respectively. The length, diameter and weight of each termination connection are approximately 2,500mm, 700mm and 350kg. The thickness of the insulation layer, which was PPLP paper, was determined by estimation of minimum break down electric field with Weibull distribution analysis of results for break down tests of the model cable. Regarding the cooling condition of cooling system, the liquid nitrogen temperature of inlet and outlet of cable system was designed to be 65K and 70K, respectively. We manufactured 25m tri-axial superconducting cable and cut 2m out of it for critical current test and voltage test at liquid nitrogen temperature. The critical current of each phase was higher than 4,500A. There was no break-down of each insulation phase with 53kV for a 30minute at the voltage test. We also manufactured a pair of termination connection for system test and no break-down occurred each insulation phase with 53kV for a 30minute. Based on fundamental performance test, we performed type test of cable system with building up cable system including superconducting cable, termination connection and cooling system based on "Recommendations for Testing of Superconducting cables (CIGRE Technical Brochures 538)".

This paper is based on results obtained from a project subsidized by the New Energy and Industrial Technology, Development Organization (NEDO).

Keywords: Superconducting cable system, Tri-axial, Teremination, Overcooled liquid ntrogem

AP5-4-INV

Flywheel Energy Storage System Using Superconducting Magnetic Bearing for Demonstration Test

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The principle of the Flywheel Energy Storage System is simple, and there are already examples of its use within Japan. Some of these have been used for over 20 years, however, it was the problems with the bearings that obstructed wide spread dissemination. In order to increase storage capacity, it is necessary for the bearing to be able to withstand a high load and high-speed rotation, but there is no conventional bearing which can withstand these demands.
In light of this, RTRI has invented superconducting magnetic bearings with superconducting coils and bulk superconductors. We have developed a superconducting magnetic bearing utilizing a strong magnetic repulsive force by a combination of REBCO wire coils that generates more than 6 Tesla and large single crystal REBCO bulks. Then we demonstrated that 4 tons of flywheel can be supported non-contact and rotated to store energy. The experiment was conducted at the “Next Generation Flywheel Power Storage System Verification Testing Facility” at the Komekurayama Solar Power Plant in Yamanashi Prefecture. Various verification tests are been carried out the same facility, of various related technologies to hasten the practical application of the superconducting magnetic bearing.
This development was supported by NEDO in a part of "Development of next generation flywheel energy storage system".

Keywords: Flywheel, Magnetic bearing, Energy storage, High-temperature superconductivity

AP5-5-INV

Liquid hydrogen system toward hydrogen Society

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In Japan, hydrogen energy society is expected for CO2 (Carbon dioxide) reduction and energy security. In the future, hydrogen utilizations will become larger from fuel cell vehicles to hydrogen generating turbines, so that a large amount of hydrogen introduced into society is comparable to the current LNG (liquid Natural Gas) consumption. According to "The Strategic Road Map for Hydrogen and Fuel Cell" released in 2016 by the Japanese government, we will import CO2-free LH2 (liquid hydrogen) will from overseas countries having hydrogen source around 2030s. LH2 has not only chemical energy but also cold energy, differing from other hydrogen carriers (organic hydride, ammonia, etc.) for transportation and storage. This advantage can make it to be refrigerant of superconducting cooling system.
In this paper, I will describe the outline of a large scale LH2 system consisting of a hydrogen liquefier, a loading LH2 site, a LH2 carrier, a unloading LH2 site. And also, their related laws and regulations, LH2 safety technologies, and LH2 refrigerant for cooling superconducting magnets will be described.

Reference:
・METI, "Strategic Road Map for Hydrogen and Fuel Cell" (2016), in Japanese

AP5-6-INV

Progress in the development of refrigerator for HTS Cable

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The demonstration test of Yokohama project, the operational stability and long term reliability of the HTS cable system in a real grid was verified [1]. The test was successfully, but some problems related to the Stirling refrigerator have been revealed. Then, a high performance refrigerator has been developed in this project. Target values of the refrigerator are cooling capacity of 5 kW and COP of 0.1, maintenance interval of 30,000 hours. To achieve a cooling capacity 5 kW and COP 0.1, the reverse Brayton cycle is adopted, employing a turbo compressor and a turbo expander. Magnetic bearings are used in the compressor and expander to increase the maintenance interval to over 30,000 hours. This refrigerator was confirmed to have a cooling power of 5.8 kW and COP 0.1 at 77 K. The demonstration test utilizing the refrigerator in Asahi substation is underway.
To prioritize COP 0.1 of the refrigerator, pressure drop of heat exchangers was reduced. The size of the heat exchanger and the refrigerator was increased. More compact refrigerator commercial base is developed for practical use of HTS cable. Figure 1 shows Brayton refrigerator commercial base. The size of refrigerator is reduced to 35 % compare with the refrigerator for demonstration test in Asahi substation.
The progress in the development of Brayton refrigerator for HTS cable is outlined in this presentation.

[1] S. Honjo, et al., “Status of superconducting cable demonstration project in Japan,” IEEE transactions on Applied Superconductivity, vol.21, 2011, pp.967-971.

Keywords: HTS Cable, Brayton cycle, Refrigerator

APP1-1

Design and Test Results of a Quench Protection Circuit for a HTS Ship Propulsion Motor

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When a cryogenic cooling system for a high-temperature superconducting (HTS) motor stops due to blackout, mechanical failure, or others, the temperature of the HTS coils rises. If the operating current of the HTS coils are left despite the temperature rising of the HTS coils, a quench occurs in the HTS coils. Because HTS coils have low thermal conductivity, the quench instantaneously generates a hotspot which locally becomes high temperature and causes irreversible damage to the HTS coils. In order to protect the HTS coils from the damage caused by the quench, it is necessary to quickly attenuate the operating current of the HTS coils and suppress the generation of the hotspot after the stop of the cooling system.
In this study, we propose a novel configuration of a quench protection circuit for a HTS ship propulsion motor that protects the HTS coils from an unexpected stop of its cooling system. This quench protection circuit consists of conductor plates placed adjacent to the HTS coils and dump resistors placed at the normal temperature part and the low temperature part. With this configuration, it becomes possible to more effectively and quickly attenuate the operating current of the HTS coils by the mutual induction between the HTS coils and the conductor plates. In addition, since the energy of the HTS coils can be dispersedly absorbed by this configuration, the dump resistors can be made small size and become easy to mount on a HTS ship propulsion motor. We have designed with numerical simulations and fabricated the quench protection circuit for the one HTS field pole of the 3 MW HTS motor developed by Kawasaki Heavy Industries. The fabricated protection circuit was tested experimentally and its effect was validated. By comparing the design results with the test results, we have confirmed that our design has high accuracy.
This work includes the results supported by the New Energy and Industrial Technology Development Organization (NEDO).

Keywords: Quench Protection, HTS motor, HTS field pole, HTS coil

APP1-2

Optimal Design of a Superconducting Motor for Electric-drive Aeropropulsion Based on Finite-Element Analysis and Genetic Algorithm

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Electric-drive Aeropropulsion (EA) is one of the key technologies in design of future aircrafts because the electric motor drive has high efficiency and the EA would reduce both operational cost and pollutant emission [1]. However, it would have some problems like the cruising range and payload.To solve these issues, the introduction of superconducting rotating mashines (motors and generators) have been proposed [2] because it will allow integration of electric propulsion within the very stringent weight and volume constraints. Superconductors can carry electric current at high current density with quite low resistance thus enabling light machines. According to previous researches, a superconducting motor is supposed to achieve power density comparable to turbine engines in excess of 10 - 20 kW/kg [3]. And, to improve the power density and to reduce loss simultaneously, the optimization of the design is indispensable. In this paper, a 3.613 MWsuperconducting motor design optimized by the Finite-Element Analysis (FEM) and the Multi-Objective Genetic Algorithm (MOGA) for EA is presented. $YBa_2Cu_3O_{7-\delta}$ field windings in an air-core rotor construction and MgB_2 or copper armature windings in the stator without iron teeth are assumed in the synchronous motor design. Analysis formula and Finite Element Method (FEM) analysis have been used in the first-step design to acquire an initial model and constraint conditions. The FEM+MOGA has been used in the optimization to acquire the design of a motor with a good balance of power density, loss and torque ripple.

[1] Nishizawa A and Kobayashi H 2014 *Journal of IEE. Japan* **134** 84–7 [in Japanese]
[2] Luongo C A, Masson P J, Nam T, Mavris D, Kim H D, Brown G V, Waters M and Hall D 2009 *IEEE Trans.Appl. Supercond.* **19** 1055-1068
[3] Masson P J, Brown G V, Soban D S and Luongo C A 2007 *Supercond. Sci. Technol.* **20** 748-756

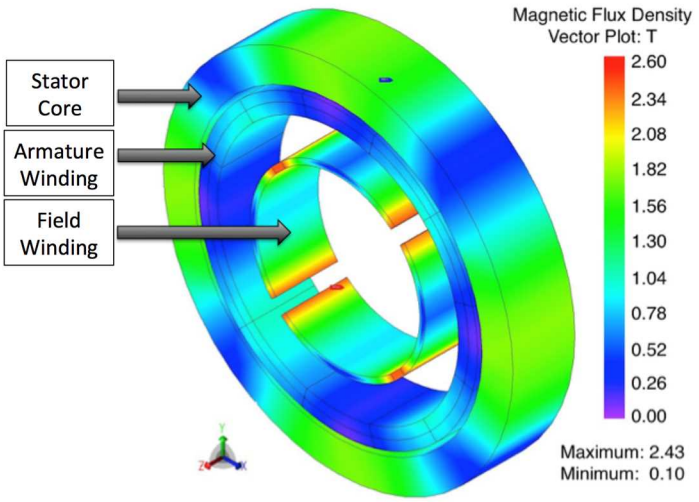

Fig. 1 Magnetic flux density distribution of the designed motor.

Keywords: Superconducting motor, Electric-drive aeropropulsion, Optimal design, Finite-element analysis

APP1-3

Design and Electrical Performance of Prototype Winding for Closed-Circuit Magnetization

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Innovative magnets brought by High-temperature superconductor (HTS) winding and bulk is an enabling technology to many advanced applications. For industrial application, HTS magnet provides smaller and more efficient motors and generators thanks to intensified magnetic flux.

Bulk HTS material which can provide strong magnetic field in compact space is effective to achieve high power density within the rotating machine. Our group has designed bulk HTS motor with Closed-Circuit magnetization (CCM) which is novel method to trap magnetic flux to field pole for radial gap rotating machine.

In this study, the design, concept and capabilities of the HTS armature coil which posess co-existence for magnetizing coil is demonstrated. The geometry for prototype machine was evaluated and optimized by using FEA in our work.

For further development and evaluation of feasibility about CCM with the rotating machine structure, prototype windings were manufactured by using Bi2223 HTS wire. To make the construction of armature coil simplified, trapezoidal shape with double pancake winding was adopted.

Electrical performance of the HTS prototype winding under DC/AC operation was measured. Prototype HTS windings were tested under various temperature including standard 77K self-field measurements and cryo-cooled condition. Finally, we also discuss in detail the implementation of armature construction and operating condition on CCM for our HTS rotating machine by referring measured parameter and FEA results.

Part of this work has been financially supported by KAKENHI 16H061336.

[1]M. Watasaki et al., Trapped Magnetic Flux of Bulk HTS Magnets in the External AC Magnetic Field at Low Temperatures, IEEE Transactions on Applied Superconductivity,23, 10.1109/TASC.2012.2236874 8201604,1-4

[2]Y. Suzuki and K. Tsuzuki, Consideration of captured magnetic flux density in cylindrical HTS using finite element method, Tokai-Section Joint Conference on Electrical, Electronics, Information and Related Engineering, Po2-9, 2016

[3]K. Tsuzuki et al., Magnetic Field Analysis of High-Temperature Superconductor Field Pole Using Convergence-Magnetized Method with Closed Magnetic Circuit, Abstracts of CSSJ Conference, Vol.94 1C-p09, 2017

Keywords: Armature winding, Synchronous motor, Bi2223, magnetization coil

APP1-4

Design and Analysis of Air-Core Superconducting Generator for Wind Power Applications

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In the movement towards reducing CO_2 emissions and our dependence on fossil fuels, wind power is considered one of the main technologies in delivering renewable energy to the world. With the introduction of a technology such as superconducting(SC) coils in to wind generator design, new spaces open up for novel topologies and implementations. One such topology is the actively-shielded air-core SC machine described in previous work [1]. Fig. 1(a) shows the component of the actively shielded air core design. The 2D cross section highlights the effect of the shielding coils on the magnetic field outside the machine. An example CAD model of a 4.8m diameter air-core SC wind generator is shown in Fig. 1(b). In Table I, design choices are presented for a variety of possible generators utilizing are air-core superconducting topology. The main differentiating factors between the designs are in their intended application and power rating, both of which result in different design choices. Even with this limited first-pass analysis, the 10 MW air-core design displayed a decreased active length when compared to the reference design, leading to a decrease in both copper and SC weight. While not explicitly analyzed, the lack of iron in the air-core machine also significantly decreases the overall machine weight.

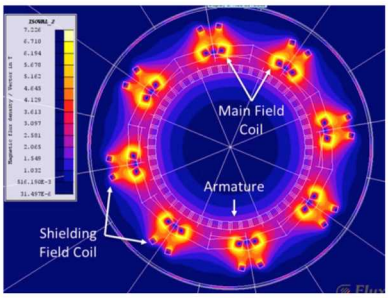

Fig. 1 (a)

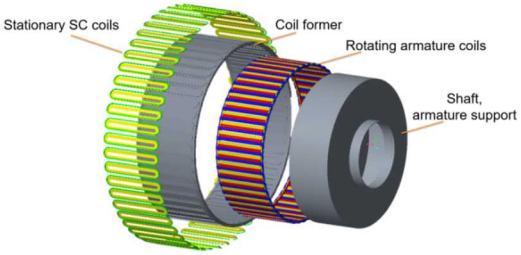

Fig. 1 (b)

Table I.

		Reference Design	Air-core design 1	Air-core design 2
Application		Offshore	Offshore	Land
Rated power	(MW)	10	10	6
Rated speed	(rpm)	10	10	10
Active length	(m)	1.88	1	1.5
Diameter	(m)	4.83	4.8	3.2
Pole count		36	52	34
Armature current density	(A/mm^2)	3.6	3.6	3.6
Armature copper depth	(mm)	127	127	127
SC coil material		NbTi	Nb_3Sn	Nb_3Sn
SC coil total length	(km)	720	380	300
SC coil total weight	(kg)	3840	1000	900
Armature copper weight	(kg)	9720	6000	5500

Fig. 1. (a) 2D FEA showing magnetic flux density distribution (b) Exploded view of air-core SC wind generator components.
Table I. Reference and final design parameters.

[1] K. Haran, D. Loder, T. O. Deppen, and L. Zheng, "Actively shielded , high field air-core superconducting machines," IEEE Trans. Appl., Supercon., vol.26, no.2,Mar. 2016, Art.ID.5202508.

Keywords: Air-core superconducting generator, wind power application, actively-shielded

APP1-5

Design of a Characteristic Evaluation Device for the Field Coil of Superconducting Wind Power Generator

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Globally, Superconducting (SC) wind power generator is being studied for having high capacity and compact volume of a wind turbine. Most of MW class SC wind power generators have characteristic of high capacity and low-speed machines, the load due to a very high torque affect the superconducting coils. In this case of generator get some problem that electromagnetic field and high torque from armature coils may cause damage to the coil. So, SC wind power generator need to analyze operating characteristic for superconductor field coil and stability in high magnetic field. That is mean, it is need to design the characteristic evaluation device for design verification and characterization before creating the entire SC wind power generator system.
This paper performed a characteristic evaluations device (CED) design for the field coil of 4MW, 10MW, 12MW SC wind power generator.
MagNet was used as a finite elements method analysis tool to design CED and its characteristics. This CED was simulated considering the field coil of 4MW, 10MW, 12MW Wind power generator. The CED is made like a vertical linear generator. It is composed of 2 pole field coil which is the rotor part of the wind generator and 1pole armature coil which is the stator part of the wind generator. The stator body falls freely about six meters next to the fixed 2 pole field coil. By crossing the superconducting coils and stator body be owing to gravity, generate capacity of 1pole SC wind power generator and it is possible to visually judge whether or not the superconductor coil is damaged by electromagnetic force.
As a result, when tested by the parameter value of a 12MW generator, the same result was obtained when comparing the results of the analysis of 12MW generator and the results of the characteristics evaluation device. The characteristic evaluations device will confirm the characteristic of field coil. This device can be evaluated whether field coils are usable for superconducting generators.

Keywords: superconducting, coil evaluation, linear generator, superconducting wind power generator

APP1-6

Design and thermal analysis of an HTS module coil for a 12 MW wind power generator

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Changwon National University, Republic Of Korea[1]

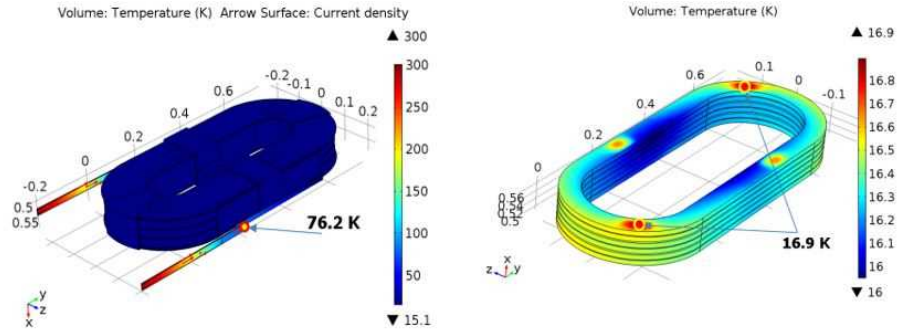

Fig 1.1 Temperature distribution in HTS coil

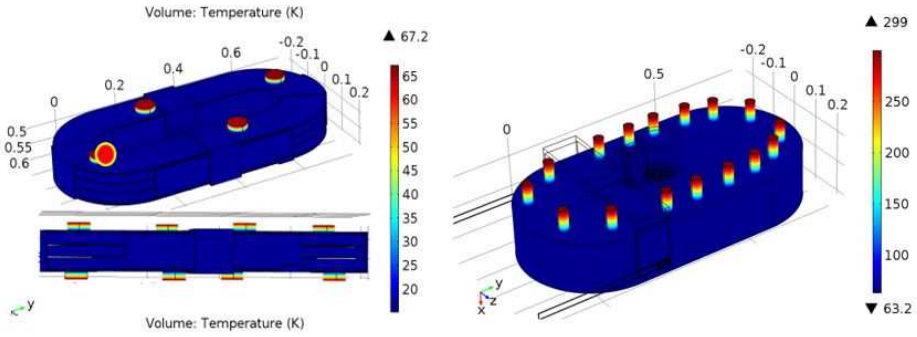

Fig 1.2 Temperature distribution in the supports

A large-scale high-temperature superconducting (HTS) wind power generator requires a huge vacuum vessel to cool the HTS coils together and needs high stability of the series connected multi-pole structure of the HTS coils. If one of the HTS poles fails to operate, the rest of the poles will stop working due to the series connection of the HTS coils. In order to avoid these weaknesses, an HTS generator module coil has been suggested, through which all the HTS poles can be structurally separated with a small vacuum vessel, and independent operation can be ensured with high reliability. A heat loss analysis considering the module structures is of importance for an effective design of the HTS module coil based generator. However, the heat loss analysis of a large-scale HTS generator or the module coil has rarely been studied and is becoming a new challenge. This paper deals with the design and thermal analysis of an HTS module coil for a 12 MW wind power generator.

Heat losses of the HTS module coil include radiation loss, eddy current loss of the structures of the coil bobbins, ac loss of the HTS magnet, conduction loss of the current leads and supports of the magnet, and Joule loss of the current leads and joint with the HTS magnets. The two-stage cryo-cooler of RDK-415D was used to achieve the operating temperature of 20 K. Current leads were designed optimally for reducing the conduction and Joule heat losses. The total heat losses of the HTS magnet module were analyzed using 3D finite elements program (FEM). The supports were located in the 1st layer and 2nd layer of the HTS module coil. The size of all of supports was calculated to estimate the conduction heat loss from outside to the 1st layer and between the 1st and 2nd layers.

The results of heat losses and temperature distribution were confirmed by using FEM program. As a result, the temperature of the magnet was achieved under the operating temperature of 20 K, and the total heat loss was less than the cooling capacity of the cryo-cooler. The results will be utilized for structure design of a large-scale HTS generator module coil.

Keywords: HTS wind power generator, HTS module coil, thermal analysis, two-stage cryo-cooler

APP1-7

Structural Design and Heat Load Analysis of a Flux Pump based HTS Module Coil for a Large Scale Wind Power Generator

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Abstract - Recently, high temperature superconducting (HTS) generators are suitable for large scale wind power systems. The superconducting generator typically requires a power supply, a current lead and a slip ring for transferring the DC current into the HTS coils. The current lead can be a bridge between the cryogenic environment and room temperature, which causes heat transfer loss. On the other hand, the flux pump (FP) is possible to supply DC current into the HTS coils of the generator without the heat transfer loads. However, a novel structural design and the heat load analysis considering the connection with the flux pump and the HTS coils are required for the HTS wind power generator.

This paper deals with a structural design and heat load analysis of a FP based HTS module coil for a 12MW wind power generator.

The structures such as HTS coil bobbins, coil supports, and the connection components between the flux pump and the HTS coils were designed. The conduction and radiation heat loads of the FP based HTS coils were analyzed using a 3D finite element method program considering the two-stage cryo-cooler (RDK-415D). The results of the FP based HTS coil of the generator were compared with a conventional current lead based HTS module coil.

As a result, the heat load of the FP, that is the sum of Joule heat and iron losses was 10.2 W. Therefore, the total head loads of the FP based HTS module coil were lower than the conventional current lead based HTS module coil. The structural design and heat load analysis results of the FP based HTS module coil can effectively be utilized to develop a large scale HTS wind power generator.

Keywords: Current lead, Flux pump, Heat load, Module coil

APP2-1

Heat Leak and Pressure Drop Measurements of the 1000 m Class Superconducting DC Power Transmission System in Ishikari

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500 m class and 1000 m class superconducting DC power transmission systems were constructed in Ishikari, Japan (Ishikari project). The 500 m system connects a photovoltaic power plant to an internet data center. On the other hand, the 1000 m system has been used to obtain data for construction of future longer transmission lines. In the summer of 2016, the second cooling and circulation test of the 1000 m system was performed, which was followed by the first cooling test performed in the winter of 2015. In these tests, characteristics of the cryogenic system, including a heat leak and a pressure drop, were measured. The heat leak of the system was estimated from the temperature rise and the flow rate of the liquid nitrogen. The measured values were 1.746kW and 2.091kW at the outer pipe temperature of -2.4°C and 17.4°C, respectively, for the cable including the terminals. The pressure drops were measured with pressure gauges for the liquid nitrogen. The pressure drop at 36.03L/min was 42.80kPa for the circulation distance of 2000m.
This work was supported in part by the Japanese Ministry of Economy, Trade and Industry (METI) and by the New Energy and Industrial Technology Development Organization (NEDO).

Keywords: DC power transmission, Heat leak, Pressure drop

APP2-2

Fluid characteristic of liquid nitrogen flowing in HTS cable

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Tokyo Electric Power Company Holdings[1]

For long distance design and operation of High-temperature superconducting (HTS) cables, evaluations of heat transfer and fluid flow dynamics of liquid nitrogen (LN2) flowing in the HTS cable is important. However, the LN2 flow is complicated when the cable core is housed in a double corrugated stainless steel cryostat-pipe and positioned at an eccentric position to the center of the cryostat-pipe. In this paper, the fluid characteristic, such as the pressure drop and the temperature, of liquid nitrogen flowing HTS cable will be discussed by comparing the measured values of the HTS cable system, which was constructed in NEDO project, with the simulated values of computer simulation analysis.

Keywords: High-temperature superconductors, Power transmission cable, Liquid nitrogen, Fluid flow

APP2-3

Hydraulic Evaluation of Pressure Drops and Temperature Profiles in Liquid Nitrogen Circulation Coolings for HTS Power Transmission Cables

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Kyoto University, Japan[4]
Taiyo Nippon Sanso Corp., Japan[5]

The research and development of power transmission cables using high temperature superconducting (HTS) wires have been in progress all over the world. Although a liquid nitrogen circulation pump for the cooling of HTS cable with long length is needed, a pump with discharge pressure, maintenance interval and high efficiency required for its realization has not been developed yet. Our group is now developing a maintenance-free circulation pump composed of magnetic bearings and superconducting motor. In this study, the pressure drops and temperature profiles along typical types of HTS cable systems circulating the subcooled liquid nitrogen are preliminarily evaluated for optimal design of the circulation pump.
The target of circulation pump for liquid nitrogen to be developed by our group is the discharge pressure of 1 MPa, volumetric flow rate of 100 L/min and temperature of 65 K at the outlet of pump (or the inlet of HTS cable). In order to estimate the pressure drops and temperature profiles of subcooled liquid nitrogen, it is necessary to determine the structures and sizes of HTS cables in advance. Therefore, two types of HTS cables are focused here on the basis of the existing projects for HTS cable developments. One is a three-in-one AC cable located inside a corrugated pipe [1], whereas the other is a DC cable inside a straight pipe [2]. The pressure losses and temperature profiles in two types of HTS cable systems under the assumption of constant mass flow rate are estimated using a commercial package for cryogen properties [3] and some expressions for Reynolds number, friction factors, pressure drop, temperature rise, and so on.
This work was supported by the Advanced Low Carbon Technology Research and Development Program (ALCA) from the Japan Science and Technology Agency (JST).
[1] H. Yumura et al.: IEEE Trans. Appl. Supercond. 23 (2013) 5402306.
[2] N. Chikumoto et al.: IEEE Trans. Appl. Supercond. 26 (2016) 5402204.
[3] Horizon Technologies: GASPAK v. 3.32.

Keywords: Circulation pump, Friction factor, Liquid nitrogen, Superconducting power transmission cable

APP3-1

Three-Dimensional Thermal Analysis of an SFCL REBCO Coil Immersed in Liquid Nitrogen

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A resistive type SFCL using REBCO tapes has high potential to limit fault currents quickly and to improve the reliability of a power system for its compactness and rapid increasing of resistance [1]. We have studied the thermal characteristics of a SFCL REBCO coil by numerical analysis using more precise analysis models. Influence of bubbles of boiling nitrogen is also considered in some cases. If bubbles are generated under fault conditions, a rapid local temperature rise may occur and even result in a permanent degradation of J_C of REBCO layer.

In this paper, we upgrade the previous FEM analysis model [2] for 3D thermal analysis of a REBCO coil in a resistive type SFCL (Fig.). Coupled problems of electromagnetic and thermal fields are solved for studying thermal characteristics of an SFCL REBCO coil immersed in liquid nitrogen. In computation of current distribution in the SFCL coil, a thin-plate approximation is applied to the REBCO tapes and FEM based on current vector potentials $\boldsymbol{T}$ is utilized. Current density $\boldsymbol{J}$ is defined by $\boldsymbol{J}=\nabla\times\boldsymbol{T}$. The governing electromagnetic equation is given by $\nabla\times(\rho\nabla\times\boldsymbol{T})=-\partial\boldsymbol{B}/\mathrm{d}t$ (ρ: electric resistivity; $\boldsymbol{B}$: magnetic flux density) [2]. In thermal analysis, the 3D structure of SFCL coil is modeled and the temperature rise is calculated under the condition of Joule heating, heat conduction, heat transfer, and cooling characteristics of liquid nitrogen.

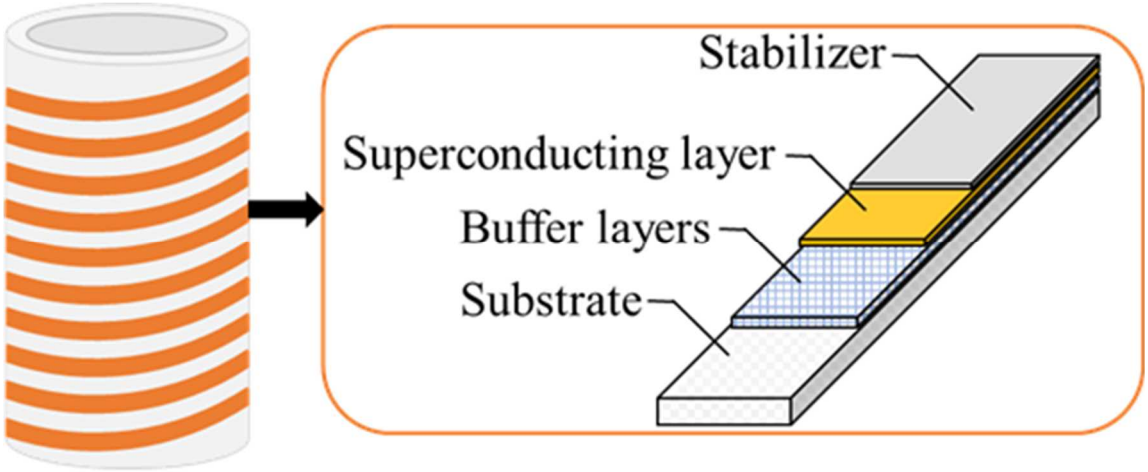

Fig. Schematic drawing of a solenoid coil wound with REBCO tapes for resistive type SFCL

[1] H. S. Ruiz, et al., "Resistive-Type Superconducting Fault Current Limiters: Concepts, Materials, and Numerical Modeling," IEEE Transactions on Applied Superconductivity, vol. 25, no. 3, pp. 1–5, 2015.
[2] H. Ohsaki, et al., "Characteristics of Resistive Fault Current Limiting Elements Using YBCO Superconducting Thin Film with Meander-Shaped Metal Layer," IEEE Transactions on Applied Superconductivity, vol. 19, no. 3, pp. 1818–1822, 2009.

Keywords: superconducting fault current limiter, finite element method (FEM), coated conductor, thermal analysis

APP3-2

Combined Use of SFCL and SMES for Augmenting FRT Performance and Smoothing Output Power of PMSG Based Wind Turbine

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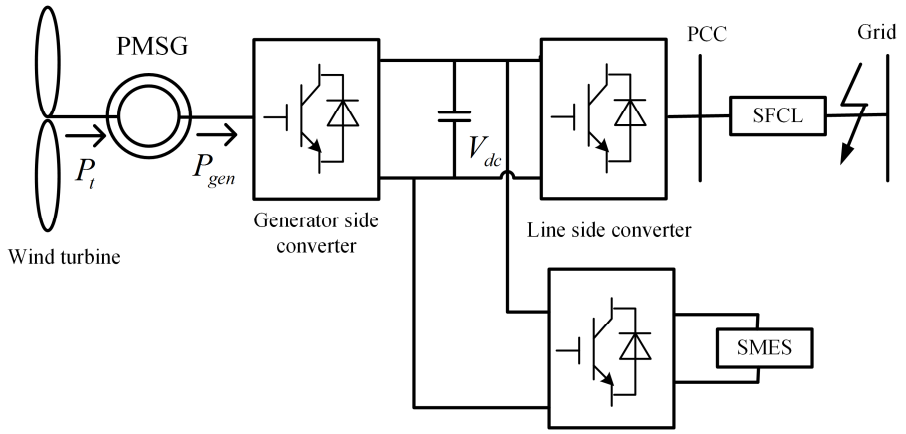
Concerning the integration of wind energy in the power grid, some key technical issues should be given enough attention, such as the capability of fault ride through (FRT) and the smoothness of output power. In this paper, the combined use of a resistive-type superconducting fault current limiter (SFCL) and a superconducting magnetic energy storage (SMES) is proposed, and it is expected to improve the transient performance of a permanent magnet synchronous generator (PMSG) based wind turbine system under fault conditions. The SFCL is installed near the line side converter (LSC) of the wind turbine system, and its functions are to suppress the fault current and compensate the terminal voltage. The SMES is coupled to the wind turbine system's DC-link, and it aims to alleviate the power difference between the generator side converter (GSC) and the LSC. Thus, the output power can be smoothed, and the DC-link overvoltage will be mitigated. Related theoretical analysis and control strategy are conducted, and further a detailed simulation model of 1.5 MW PMSG-based wind turbine integrated with the SFCL-SMES is built in MATLAB/SIMULINK. The simulations are performed to check the effects of the SFCL-SMES on handling different fault cases. From the results, the effectiveness of the proposed approach on augmenting the FRT capability and smoothing the power fluctuation of the PMSG can be well confirmed.



Keywords: Superconducting fault current limiter, Superconducting magnetic energy storage, Permanent magnet synchronous generator, Wind turbine system

APP3-3

HILS of Transmission Line Protection System for the application of the SFCL to Korean power system

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KERI[1]
KEPCO[2]

In Korea, a 154 kV SFCL system was developed and installed at the Gochang Power Test Center of Korea Electric power Corporation (KEPCO) in 2016. Korea Electrotechnology Research Institute (KERI) proposed a novel protection algorithm for the application of the 154 kV SFCL to a real power system and designed a protection scheme of the Gochang Power Test Center.

This paper verified the protection scheme using the Hardware In the Loop Simulation (HILS) that a commercial protective relay system with the novel algorithm is tested by Real Time Digital Simulator (RTDS). The commercial relay system was installed and operated at a real power system in the Gochagn Power Test Center after the PHILS verification.

Keywords: SFCL, HILS, Protection scheme, Protective relay system

APP3-4

A feasibility study of smart high-temperature superconducting cable to improve stability of KEPCO system

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The Korean system is a very tightly coupled island system. The installed capacity is about 100 GW and the load demand is gradually increasing. Especially in metropolitan areas where the load is concentrated, the system fault current often exceeds the breaker capacity due to the strong connection. The system operator limits the fault current by bus split operations considering the breaker capacity but this reduces system stability. Therefore, various efforts have been made using a fault current limiter to overcome these problems. A smart superconducting cable is a type of superconducting power transmission cable. It has not only standard structure of the existing superconducting power cable but also a fault current limiter. The cable has a superconducting characteristic in a normal state, while when a fault occurs, it can limit a fault current through generating impedance that adjusts electrical and thermal properties of superconducting cable and material and cross-sectional area of superconducting cable. In this paper, a technique is proposed to reduce system fault current while improving the system stability using a smart high-temperature superconducting cable. In addition, the appropriate cable capacity and locations are selected to improve the reliability of the Korean power systems using smart superconducting cables. The proposed locations and capacities will be applied to the smart superconducting cable development project that started in May.

Keywords: fault current limiter, power system stability, superconducting cable, smart superconducting cable

APP3-5

Study on Configuration of a Single-phase Air-core Bi2223 High Temperature Superconducting Transformer for a Large AC Current Supply

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The authors have developed a large AC current supply with a high temperature superconducting transformer to grasp current conduction characteristics of high temperature superconductors [1] [2]. The supply consists of a primary current supply and a superconducting transformer. Small current flows thorough a primary coil of the transformer from a primary current supply and then large current is outputted from its secondary coil. One of the developed supplies consists of a single-phase Bi2223 air-core superconducting transformer and its volume and weight are respectively about 1/20 and 1/14 of a commercial supply and can output current of 200 A [3]. Moreover, efficiency of the transformer is almost same as that of an iron-core Bi2223 superconducting transformer. However magnetic coupling between a primary coil and secondary one of the air-core transformer is weak and therefore more primary current is needed to output secondary current than that of the iron-core transformer. That means to need a primary current supply with a large capacity. In this presentation, the authors propose configuration of the air-core transformer for stronger magnetic coupling than that of the conventional transformer and show its usefulness through experimental results.

[1] N. Nanato, Y. Kobayashi, Quench Detection and Protection for High Temperature Superconducting Transformers by Using the Active Power Method, Physics Procedia, Vol. 58, pp. 264-267 (2014)
[2] N Nanato, S Nakamura and S Tanaka: Detection of normal transitions in a hybrid single-phase Bi2223 high temperature superconducting transformer by using the active power method and a magnetic flux detection coil, Journal of Physics: Conference Series, Vol. 871, 012085 (2017)
[3] N Nanato, N Kishi, Y Tanaka and M Kondo: Basic study for a large AC current supply with a single phase air-core Bi2223 high temperature superconducting transformer, Journal of Physics: Conference Series, Vol. 871, 012101 (2017)

Keywords: Large AC current supply, Air-core HTS transformer, Magnetic coupling

APP3-6

Design and Performance analysis of a 1,500 A, 400 mH Class Superconducting DC Reactor Coil using 2G Multi-ply HTS wire

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A DC reactor is a power system application device that reduces current ripple and harmonics generated by thyristors during AC-DC conversion. It is usually used in high-voltage direct current systems. Conventional DC reactor has been manufactured using metal conductors. However, there are some disadvantages when using metal conductors. First, a metal conductor has a resistance, which inevitably causes electrical loss. As the current increases, the power loss also increases. In addition, when DC reactors are made using metal conductors, the volume and weight become very large, which limits the installation space and insulation structure. These disadvantages can be overcome by using a superconducting wire that has zero resistance and high current density.

This paper deals with the design and performance analysis of a superconducting DC reactor using multi-ply HTS wire to increase the critical current.

In the fabrication, 2G multi-ply HTS wire (SuNAM Co., Ltd.) is used for high ampacity. The critical current was measured according to the bending radius to confirm the bending characteristics of the two-ply and three-ply wires. The HTS coils for 1,500 A, 400 mH class superconducting DC reactor was designed considering multi-ply HTS wire banding radius. The target is based on the same current capacity and higher inductance as compared with a copper conductor DC reactor used in a conventional HVDC system. Coils were wound with D-shape double pancake type bobin, then 30 DPC coils were arranged in a toroidal form. The performance of the toroidal magnet was measured in a liquid nitrogen vessel. The performance analysis results were compared with the results obtained by the finite element method analysis.

The measured critical current of each coil was about 350 A at a temperature of 77 K according to the design value, and the target performances of 1500 A, 400 mH were achieved.

The results will be effectively utilized for design and fabricate of a superconducting DC reactor that can be used in real power systems.

Keywords: DC reactor, Two ply HTS wire, Bending radius

APP3-7

Design and Demonstration of a Double-Pancake Coil for SMES using MgB_2 multi-strand cable

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Sophia University[1]
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MgB_2 round wires are now commercially available with applicable critical current density in magnetic field up to 5 T. One of promising application using MgB2 is Superconducting Magnetic Energy Storage (SMES) coil. In our project, multi-strand cables with 600 A nominal current are designed for double-pancake (DP) coils with 400 mm in inner diameter. The coil production processes in our project are wind-and-react (W&R) and react-and-wind (R&W) method, in which Rutherford type cable consists of ten wires with specific twist pitch is reacted then used to wind DPs, to investigate the suitable manufacturing process for MgB2 coils. The final goal is to fabricate five stacked DP coils, in which four DPs by R&W method and one DP by W&R method with total number of turn is 512, forming 30 kJ SMES coil to demonstrate compensation of DC voltage fluctuation in a micro grid consists of renewable energy source and liquid hydrogen supply system. The first DPs made by two manufacturing process are constructed and tested their property such as critical current density in liquid helium to keep uniform temperature distribution throughout the coils. We will report the results including small test coil results, feasibility study of the manufacturing processes for MgB_2 SMES coil.

Keywords: MgB2, double-pancake coil, SMES, Rutherford cable

APP4-1

Solenoidal Magnet for Multi-Purpose Detector at NICA

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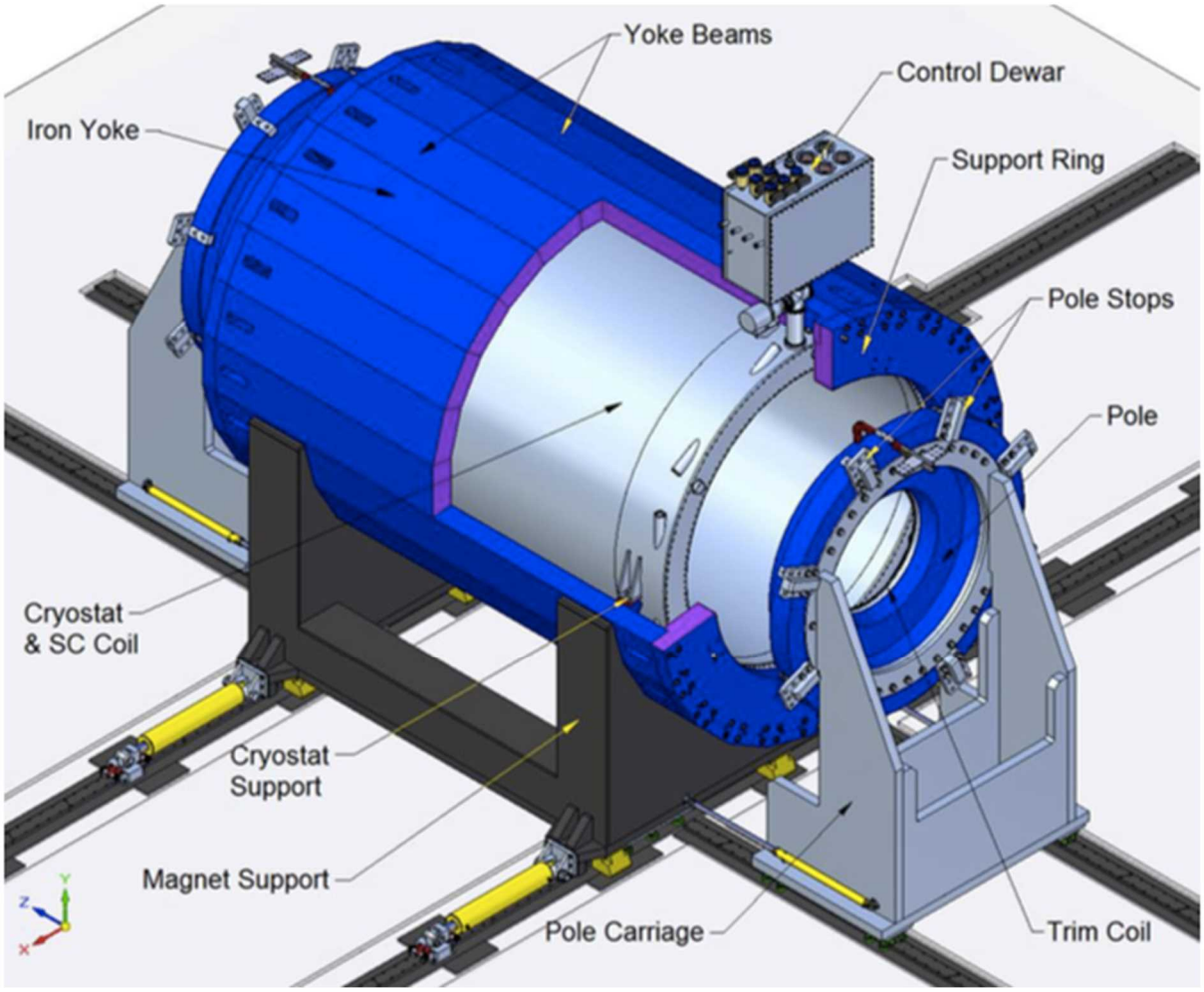
Joint Institute for Nuclear Research (Russia)[1]
Research-and-production enterprise "Neva-Magnet" (Russia)[2]
ASG Superconductors s.p.a. (Italy)[3]

The multipurpose detector (MPD) is a 4π spectrometer to be used for studying charged hadrons, electrons, and photons generated in heavy ion collisions at energies provided by the NICA collider of the Joint Institute for Nuclear Research (Dubna). A constituent part of the MPD is a superconducting solenoid magnet with a superconducting NbTi coil and a steel flux return yoke. The superconducting magnet of MPD is intended for providing a highly homogeneous magnetic field of 0.5 T in an aperture 4596 mm in diameter to ensure the transverse momentum resolution within the range of 0.1–3 GeV/c at NICA. Paper describes a main parameters, general view and the production status of the SC solenoidal magnet for MPD.



Keywords: magnet, accelerator, solenoid

APP4-2

Effect of electromagnetic force on the hydraulic characteristics of a quad-pancake coil wound with a Nb_3Sn CIC conductor

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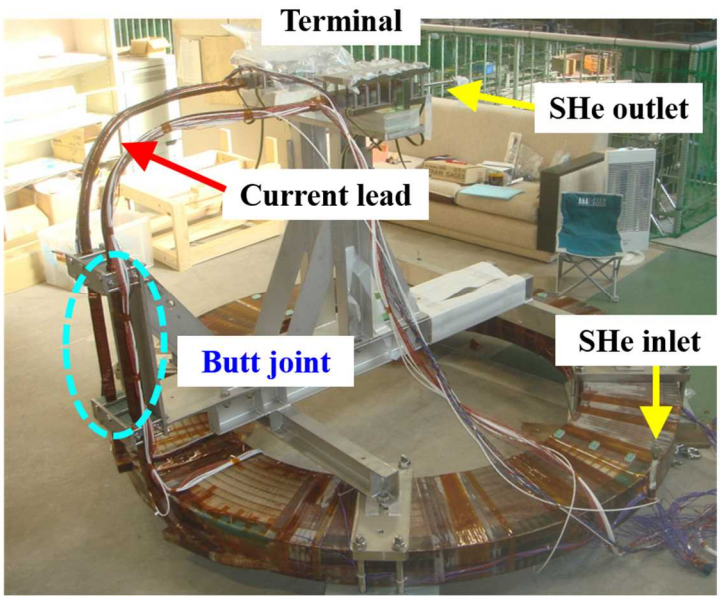
National Institute for Fusion Science[1]
National Institutes for Quantum and Radiological Science and Technology[2]

The superconducting magnet system for the JT-60 super advanced (JT-60SA) comprises a central solenoid (CS) coil, six equilibrium field coils, and 18 toroidal field (TF) coils [1]. With regards to the CS coil, a model coil was developed to verify the CS coil manufacturing and fabrication jig [2-4]. The configuration of the model coil is a quad-pancake coil wound with cable-in-conduit (CIC) conductors composed of Nb_3Sn strands. The model coil was tested using the coil test facility of the National Institute for Fusion Science, which can accommodate testing of a forced-cooled superconducting coil. The test results of critical current, joint resistance, and pressure drop in the model coil have already been described in Refs [2,4]. In this paper, the hydraulic characteristics of the model coil are described. In addition, the relations between the coil current operation and hydraulic characteristics are discussed while comparing several superconducting coils wound CIC conductors.

[1] K. Yoshida, et al., Development of JT-60SA superconducting magnet system, Physica C, 470 (2010) 1727-1733.
[2] T. Obana, et al., Performance verification tests of JT-60SA CS model coil, Physica C: Superconductivity and its Applications, Vol. 518 (2015)96-100.
[3] T. Obana, et al., Magnetic field measurements of JT-60SA CS model coil, Fusion Engineering and Design, Vol. 90 (2015)55-61.
[4] H. Murakami, et al., Development and Test of JT-60SA Central Solenoid Model coil, IEEE Transactions on Applied Superconductivity, 24 (3) (2014) 4200205.



Keywords: Hydraulic characteristics, Nb3Sn Cable-in-conduit (CIC) conductor, JT-60SA central solenoid (CS)

APP4-3

Thermal Properties of Heat Pipes for Conduction Cooled HTS Coils

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National Institute for Fusion Science, Japan[2]
CHUBU Electric Power Co, Japan[3]

High-Temperature Superconducting (HTS) coils can generate high magnetic fields with low loss, so the HTS coils are expected to be applied to various fields. Recently, a liquid hydrogen storage system using an HTS levitation coils has been proposed. This system is high efficiency because low heat invention. In addition, it has robustness against earthquake by controlling HTS levitation coil to suppress the tank motion corresponding to the ground shaking. In order to apply the HTS coil to such applications, conduction cooling type are required for the coils. And, in this case of cooling pass by solid thermal conduction, heat generation in the coil cannot be sufficiently removed. Therefore, we have proposed an HTS coils with conduction cooling by using a self-oscillation-type heat pipes (OHP), which have excellent thermal transport properties. We fabricated a dummy coil without HTS winding and cooling tests on the dummy coil were carried out in order to clarify the good conditions of OHPs for cooling the HTS coils. And then a test coils wound with Bi-2223 tapes were fabricated and tested. We report the details of these coils and results of experiments.

Keywords: Heat Pipes, HTS, Hydrogen, Levitation

APP4-4

Effect of Surface-treated Carbon Nanotube (CNT) Fillers in Epoxy Composites on Thermal and Electrical Stabilities of Superconducting Coils

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This study investigates the thermal and electrical stabilities of superconducting coils impregnated with an epoxy/acid-treated carbon nanotube (CNT) composite evaluated using cool-down, over-current, and repetitive-cooling tests. Carboxylic acid groups, which facilitate uniform CNT dispersal within the epoxy resin, successfully attached at the CNT surfaces using acid treatment, and formed preferential paths for heat conduction. The coil impregnated with epoxy containing acid-treated CNTs exhibited superior cooling performance and thermal/electrical stabilities compared to untreated CNTs; it effectively facilitated heat transfer between the coil and liquid nitrogen owing to its higher thermal conductivity. Moreover, the proposed epoxy composite reduced the thermal contraction difference between the superconducting tape and epoxy composite. This epoxy composite containing acid-treated CNTs is highly recommended for developing a mechanically dense superconducting coil with enhanced thermal and electrical stabilities.

Keywords: Carbon Nanotube, Epoxy, Thermal and electrical stabilities, Superconducting coil

APP4-5

Ac Loss Measurements of High Current HTS Cables

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Kyoto University[1]

High current HTS cables are promising for the HTS applications such as magnets and electric machines because of their larger current capacities than those of single coated conductors. High current HTS cables of various architectures have been proposed: Roebel cable, conductor on round core (CORC) cable, twisted stacked-tape cable (TSTC), etc. The reduction of ac losses is one of the major issues for the applications of high current HTS cables, because many of them are operated in a pulse or ac modes. Subsequently, the understanding of their ac loss characteristics is substantially important for their practical applications.
We measure the ac losses of high current HTS cables under the conditions which they carry an ac transport current and/or are exposed to an ac external magnetic field. This experimental condition simulates the actual situation at which high current HTS cables are used. The dissipated power due to an ac transport current is called transport loss, and that due to an ac external magnetic field is called magnetization loss. The former is measured by four probe method, and the latter is measured using a linked pick-up coil (LPC). We measure the amplitude dependencies of the transport losses and the magnetization losses at a couple of frequencies and the frequency dependences of the magnetization losses at a small amplitude.

Acknowledgement
This work was supported by the New Energy and Industrial Technology Development Organization in the Project for the Promotion to the Commercialization of High-Temperature Superconductivity Technology.

Keywords: ac loss, high current HTS cables, CORC, Roebel cable

APP4-6

Ac Loss Analyses of Twisted Stacked-Tape Cables

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Kyoto University[1]

Various types of high current cables are proposed by using coated conductors. Among them, we focus on twisted sacked-tape cables and examine the ac loss characteristics of coated conductors composing the cables through electromagnetic field analyses. In these types of cables, because the direction of a tape-shaped coated conductor in a cable varies along the cable axis, the critical current of the tape varies along it as well under a transverse magnetic field. This variation in the critical current naturally influence its ac loss characteristic. Moreover, due to complex three-dimensional structures of twisted tape, the current distribution becomes complicated and affect the ac loss characteristic. We also examine the effect of striating coated conductors to reduce ac losses in the twisted tapes in the cables. We use striated and copper-plated coated conductors, in which filaments are not insulated electrically in order to allow current sharing, and the electromagnetic coupling between filaments are studied. The parameters representing cable geometry such as number of stacks, separation between tapes, cabling pitches are varied to study their influence on ac loss characteristics.

This work is supported by the Japan Science and Technology Agency under the Strategic Promotion of Innovative Research and Development Program (S-Innovation Program).

Keywords: ac loss, coated conductor, high current cable, twisted stacked-tape cable

APP5-1

A Study on Active Protection for Prototype 1.0-T MgB_2 Magnet

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Magnesium diboride (MgB_2) has been actively studied for MRI magnets owing to its critical temperature of 39 K in zero field, which can be operated in liquid helium (LHe) free cooling system. However, when quenching occurs in MgB_2 magnets, the heat generated by the quench is scarcely dissipated because of slow normal zone propagation velocity of MgB_2 wires compared to the low temperature superconductors. Hence, the heat would be chiefly accumulated within the MgB_2 magnet, which consequently leads to the permanent damage of the magnet. Therefore, a proper protection scheme for the MgB_2 magnet should be investigated to practically utilize the magnet in real-scale superconducting applications. In this study, we investigated the detect-and-activate-heater technique for the protection of a prototype 1.0-T MgB_2 magnet. The detailed parameters for the detect-and-activate-heater protection, such as power requirement, minimum detection time required, and minimum normal zone area for the protection, will be discussed thoroughly.

Keywords: MgB2 magnet, Active Protection, Detect-and-activate-heater protection, Quench

APP5-2

Protection System for Normal Transitions in a Single-phase Bi2223 Full Superconducting Transformer by the Active Power Method under Flowing Various Frequency Current

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Okayama University, Japan[1]

The authors have developed a large AC current supply [1][2] with a single-phase Bi2223 full superconducting transformer [3]. The supply is very small and light and can output current of various value and frequency. In order to operate the supply safely, a protection system for normal transitions in the transformer is essential. The authors have proposed the system based on the active power method [3], which detects the normal transitions as dissipated active power in the normal area. Previous studies have shown that the protection system can work well for the transformer in transporting constant current of 60 Hz [3]. The supply is used under transporting current of various value and frequency. AC loss and iron loss in the transformer are increased by increasing the value and frequency and then they are detected as active power in a superconducting state. Therefore these losses cause incorrect recognition of the normal transitions. In this presentation, the authors propose the system which can detect correctly the normal transitions regardless of the losses. The experimental results show its usefulness for the transformer.

[1] N Nanato, S Nakamura and S Tanaka: Detection of normal transitions in a hybrid single-phase Bi2223 high temperature superconducting transformer by using the active power method and a magnetic flux detection coil, Journal of Physics: Conference Series, Vol. 871, 012085 (2017)
[2] N Nanato, N Kishi, Y Tanaka and M Kondo: Basic study for a large AC current supply with a single phase air-core Bi2223 high temperature superconducting transformer, Journal of Physics: Conference Series, Vol. 871, 012101 (2017)
[3] N. Nanato, Y. Kobayashi, Quench Detection and Protection for High Temperature Superconducting Transformers by Using the Active Power Method, Physics Procedia, Vol. 58, pp. 264-267 (2014)

Keywords: Normal transition, Protection, Active power method, HTS Transformer

APP5-3

High Resolution Location of Normal Transitions in A High Temperature Superconducting Coil by Capacitor Type Voltage Terminals

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Okayama University, Japan[1]

It is important to locate positions of normal transitions in a high temperature superconducting (HTS) coil for identifying its design and fabrication weakness. The authors have presented capacitor type voltage terminals as a contactless method to measure voltages of the coil windings through insulation of the windings [1]. It was shown that this method was useful for locating the positions of the normal transitions [2][3]. High resolution of the location is achieved by attaching many terminals to the coil. Then shorter electro-conductive sheets of capacitor type voltage terminals are needed. However, the shorter sheets make the measured voltage signals small and the signals are supposed to be incorrectly measured. In this presentation, the authors propose a method to achieve high resolution location by long electro-conductive sheets of capacitor type voltage terminals. Numerical values of the measured voltage by the terminals depend on the positions of the normal transitions and therefore analysis of the value can achieve high resolution location without increasing the number of the terminals. Through experimental results for a Bi2223 HTS coil, it was confirmed that the proposed method achieved high resolution location.

[1] Type references here if any. N. Nanato, K. Nishiyama: Non-destructive Detection of Normal Transitions in High Temperature Superconducting Coil, Physics Procedia, Vol. 58, pp. 260-263 (2014)
[2] N. Nanato, K. Nishiyama: Locating of normal transitions in a Bi2223 high temperature superconducting coil by non-contact voltage measurement method, Cryogenics, Vol. 72, pp. 53-56 (2015)
[3] N Nanato, K Okura, H Kumagai and H Aoyama: Locating of normal transitions in a Bi2223 high temperature superconducting coil by using capacitor type voltage terminals and the active power method, Journal of Physics: Conference Series, Vol. 871, 012084 (2017)

Keywords: Normal transition, Location, Capacitor type voltage terminals, High resolution

APP5-4

Study on a Magnetic Flux Detection Coil for Detection of Normal Transitions in a Hybrid Single-phase Bi2223 Superconducting Transformer by the Active Power Method

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Okayama University[1]

The authors have been developing a small and light AC power source [1][2] with a hybrid single-phase Bi2223 superconducting transformer [3]. The transformer consists of a primary copper coil and a secondary Bi2223 superconducting coil and can output current of 500 A. For safety operation of the transformer, it is important to detect normal transitions in the transformer and to protect it from excessive heating in the normal area. The authors have presented a protection system based on the active power method and a magnetic flux detection coil attached on the inside of the secondary coil [3]. The normal transitions are detected by measuring active power dissipated in the only secondary coil by the method. However, in the conventional method, the active power does not become zero in a superconducting state due to iron loss and AC loss and therefore incorrect recognition of the normal transitions may be caused. In this presentation, the authors propose a method to reduce the loss signals by configuration and mounting position of the magnetic flux detection coil. Through experimental results for a hybrid single-phase Bi2223 superconducting transformer, the authors show that the proposed method can detect the normal transitions more accurately than the conventional one.

[1] N. Nanato, Y. Kobayashi, Quench Detection and Protection for High Temperature Superconducting Transformers by Using the Active Power Method, Physics Procedia, Vol. 58, pp. 264-267 (2014)
[2] N Nanato, N Kishi, Y Tanaka and M Kondo: Basic study for a large AC current supply with a single-phase air-core Bi2223 high temperature superconducting transformer, Journal of Physics: Conference Series, Vol. 871, 012101 (2017)HTS
[3] N Nanato, S Nakamura and S Tanaka: Detection of normal transitions in a hybrid single-phase Bi2223 high temperature superconducting transformer by using the active power method and a magnetic flux detection coil, Journal of Physics: Conference Series, Vol. 871, 012085 (2017)

Keywords: Normal transition, Bi2223 superconducting transformer, Active power method, Magnetic flux detection coil

APP5-6

Investigation on Thermal and Electrical Characteristics of Metal-clad GdBCO Coil

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Department of Materials Science and Engineering, Korea University, Seoul, Korea[1]

This study reports the effectiveness of the metal-cladding (MC) winding technique that employs a GdBCO tape with a micrometre-thick SUS-cladding layer in comparison with that of the partial insulation (PI) winding technique, using the results of charge-discharge, sudden discharge, and overcurrent tests. The charge-discharge and the sudden discharge tests showed that the charge-discharge delay of the coil using the metal-clad GdBCO tape was considerably lower compared to that of the PI coils, because the characteristic resistance of the MC coil was higher than that of the PI coil. Although the MC coil exhibited lower thermal/electrical stabilities compared to the PI coils at conditions of excessive current flow, the MC coil was more stable than the fully insulated coil. This study demonstrates that the MC winding technique is promising for the development of electrically stable high-temperature superconducting magnets with fast charge-discharge rates.

Keywords: Metal-cladding, Partial insulation, Thermal/electrical stabilities, HTS magnet

APP6-1

Deign of a high temperature superconducting magnet for a single silicon crystal growth system

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Nowadays, the Czochralski (Cz) technology is widely used as a single silicon crystal growth method. This method uses a crucible to hold the melt from which the crystal is grown. In order to improve the quality of the crystals, the static magnetic fields of external magnets around the crucible are used. There are three types of magnetic field used in the Cz method: horizontal magnetic field, vertical magnetic field and cusp magnetic field. The cusp magnetic field, in which the free surface of the melt is centered between two opposite fields generated by two magnets, can adopt the advantages of both horizontal and vertical magnetic. However, the Cz method needs a strong magnetic field, that causes a very big size of the system in case of using the conventional magnet. Hence, the superconducting magnet technique can be one of attractive alternatives to optimize the dimensions and energy consumption in a crystal growth system. In this paper, the author designed a high temperature superconducting (HTS) magnet for a small-scale silicon crystal growth system and analyzed the temperature and flow distributions of the silicon melt with the cusp magnetic field. An HTS magnet for silicon crystal growth system was designed using 2G HTS wire. The metal insulation method using stainless steel tape was applied for quench protection and improving thermal conduction, and then the characteristic analysis of the magnet was conducted by the finite element method (FEM) program. Also, the 2D and 3D FEM models were built in order to consider the effect of the magnetic field on the temperature and flow distributions in the silicon melt. The simulation results showed that the melt flow was significantly suppressed by Lorentz force and the temperature distribution was uniform in the silicon melt. The fundamental design specifications and the data obtained from this study can be applied to the development of a real silicon crystal growth system.

Keywords: Silicon crystal growth, Cusp magnetic field, High temperature superconducting, Superconducting magnet

APP6-2

Development of a low temperature superconducting magnet with MgB_2 wire for a 10 kW DC induction furnace

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Generally, Nb_3SN and NbTi wires are used widely in superconducting applications and have low critical temperature (Tc of Nb3SN=18 K, Tc of NbTi=9.8 K). To maintain the low-temperature condition, liquid helium is required continuously for cooling the wire and this causes lots of maintenance cost. However, MgB2 wire has higher critical temperature than Nb_3SN and NbTi wires as 39 K and is able to make under the critical temperature condition using conduction cooling system. Therefore, if we adopt MgB2 wire to superconducting applications, we get advantages such as operating temperature, price, and cryogen free cooling system.
In this paper, the authors develop a low temperature superconducting (LTS) magnet with MgB2 magnet for a 10 kW superconducting induction heater.

First, MgB2 magnet is designed and analyzed using finite elements method for a 10 kW superconducting induction heater. Second, the magnet is fabricated using dry-winding method. Finally, MgB2 magnet is assembled to evaluate its performance and characteristics. As a result, the low temperature as 20 K, which is the operating temperature of the MgB2 magnet, can be achieved by a conduction cooling system. This study will be effectively utilized for a 300 kW superconducting induction heater and other superconducting magnet applications.

Keywords: Superconducting induction heating, MgB2 magnet, Conduction cooling

APP6-3

Analysis of a Superconducting Inductive Pulsed Power Supply for Electromagnetic Railguns

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The pulsed power supplies used in the electromagnetic railgun system should possess the capabilities of storing MJ-level energy, generating MA-level current, and delivering GW-level energy. Compared with the conventional capacitive pulsed power supplies, the inductive pulsed power supplies have become an attractive option with the major strength in energy storage density. However, great coil energy loss and short energy storage duration are two weaknesses that severely restrict their practical application and further development. Superconductivity is a promising solution to these problems. This paper focuses on the foresight of this solution, namely the theoretical feasibility of the application of the superconducting technology in the electromagnetic launch technology. First, a brief review of the inductive pulsed power supplies with superconducting magnetic energy storage (SMES) and high-temperature superconducting (HTS) coils is presented. Then, on the basis of our previous fundamental research, a technical scheme of a superconducting inductive pulsed power supply is proposed. Afterwards, a detailed analysis on its working process concerning electric-, magnetic-, and thermo-fields is conducted. Finally, the key technical obstacles in designing the superconducting coils and the overall module are further discussed, and the corresponding suggestions are concluded.

Keywords: electromagnetic railgun, inductive pulsed power supply, superconducting magnetic energy storage, high-temperature superconducting

APP6-4

Study on the basic design of multiple HTS magnets for single-sided compact MRI device

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Magnetic resonance imaging (MRI) is a useful tool for evaluating disease activity. In general, the conventional whole-body MRI devices are needed the large space and high operating cost. The whole-body MRI device has the act of over performance in order to image and diagnose parts of body such as eyes, ears, teeth and skin. Therefore, we proposed the single-sided compact MRI device which can image parts of body simply. In single-sided magnetic resonance technique, the magnets are placed on one side of the target. Thus, we have been developing the HTS magnet for single-sided compact MRI device. In this application, the required strength and homogeneity of magnetic field at upper 50 mm of the HTS magnets in the proposed single-sided compact MRI device are 0.2 T and 100 ppm/cm^3, respectively. In this study, we have designed the basic shape of MRI magnet wound with GdBCO tape wires, and racetrack HTS magnets stacked with double-pancake coils are adopted. Multiple racetrack HTS magnets were arranged in the longitudinal direction to obtain the magnetic field strength and homogeneity in the measuring space. Moreover, we have improved the homogeneity of magnetic field by placing the magnetic substance around the HTS magnets. Therefore, the electromagnetic analysis based on finite element method (FEM) was curried out to design the basic shape of HTS magnets and optimize a shape of multiple HTS magnets for single-sided compact MRI device will be presented.

Keywords: superconducting magnet, single-sided MRI

APP7-1

Study of bulk HTS rotating machine using Closed-Circuit Magnetization

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High-temperature superconductor (HTS) provide intensified magnetic flux which makes conventional rotating machine more powerful and higher power density. Target applications of HTS rotating machine will be in large sized transporter as represented by ship electric propulsion. If further miniaturization realized, large sized EVs such as electric cargo trucks is able to be taken into consideration as an application of HTS rotating machine.

In this study, Closed-Circuit Magnetization(CCM) for radial gap rotating machine was designed based on FCM. Combined structure of HTS bulk and 2G HTS winding which are installed in the motor structure achieve higher magnetic flux excitation. To apply 2G wire for combined use for armature and magnetizing winding, modified structure of conventional armature was installed.

Thanks to this structure and CCM method, all the field poles is able to be magnetized in only one routine of the excitation and demagnetization with 2G winding. And trapped magnetic flux distribution of each HTS field pole is expected to be uniformed compare with the one of PFM.

In this study, 2D analysis using FEA was conducted to verify the effectiveness of CCM. The armature of the rotating machine was composed by Bi2223 HTS winding and RE123 bulks were installed into four-pole motor. Two types of HTS rotor structure, which are Salient and cylindrical pole design, for prototype model with kW class design was evaluated and optimized.

The design of bulk HTS field pole with CCM was modified by fitting various operating parameters on FEA. Optimized design of the rotating machine will also be presented and discussed.

Part of this work has been financially supported by KAKENHI 16H06136.
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Keywords: FEA, Synchronous motor, HTS bulk, magnetization

APP7-2

Development and Load Test of a Radial Gap Bulk HTS Synchronous Machine for Marine Applications

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Superconducting rotating machines continue to benefit from considerable research and development and have the potential to significantly improve the performance of industrial machinery or even aerospace applications in the future. The power density they display, and thus, their high power/volume ratio, constitute an authentic technological breakthrough and a critical asset for marine applications.
Since 2001 we have been studying the scientific and technical aspects of the HTS bulk superconducting motor concept. Starting from the fundamental understanding and control of the crystal growth to improve the flux trapping performance [1], going through the elaboration of a stable and efficient thermosiphon cooling system [2], and up to the motor electrical, mechanical and thermal designs. In order to do so, we designed individual components and constructed a prototype for proof of concept.
The structure underwent consequent modifications leading to the radial gap machine of today. Featuring single grain RE-123 HTS bulk magnets (QMG, NSSMC) organized in arrays on its rotor four poles, and a conventional copper stator winding, this motor aims for a 30 kVA power output under 5 T magnetization at 190 RPM [3,4]. This presentation, after introducing the machine electrical and mechanical design, will report the results we obtained after load testing at full rated rotational speed and up to 3 T magnetization for field pole.

Part of this work has been financially supported by KAKENHI 21360425 16H04597 and 09F09305 as well as ABB Corporate Research.

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Keywords: HTS synchronous motor, HTS bulk, Thermosiphon

APP7-4

Evaluation of trapped field characteristic of bulk magnet system using various type refrigerators

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We developed several type superconducting bulk magnets with the goal of their industrial application, and study to improve a magnetic field activated by pulsed field magnetization (PFM). It is important problem to choose a suitable refrigerator to cool a bulk superconductor. This paper investigated trapped field characteristics when using several type refrigerators; one is a Stirling refrigerator, in which an ultimate temperature was up to 50 K and cooling capacity was 11 W at 77 K. The other is a two-stage type GM type refrigerator, in which an ultimate temperature was 13 K and cooling capacity was 5 W at 20 K. When cooling and magnetizing tests were carried out using a GdBCO bulk with dimensions of 60 mm in diameter and 20 mm thick, the maximum trapped field of 3.0 T was achieved at 50 K in the bulk magnet system using a Stirling refrigerator.
This work was supported by JSPS KAKENHI Grant Number JP15K05951.

Keywords: REBCO bulk magnet, refrigerator, pulsed field magnetization, trapped magnetic field

APP8-1

Removal of humic acid and hazardous heavy metals in water environment by magnetic separation utilizing rice hull magnetic activated carbon

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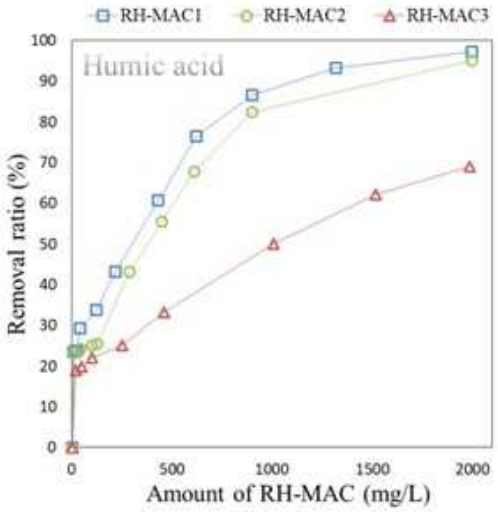
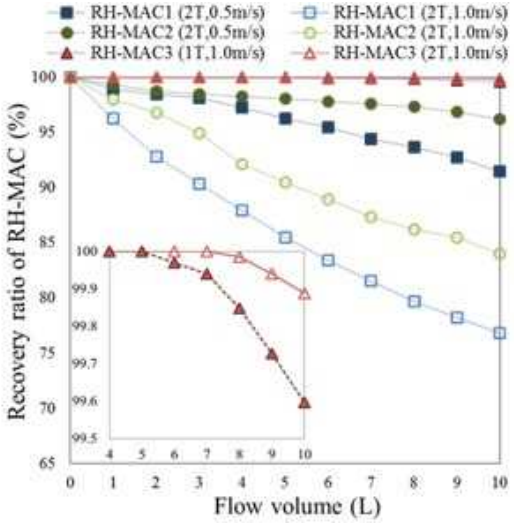
We have newly developed a rice hull magnetic activated carbon (RH-MAC) and studied its adsorption properties for humic acid, lead, cadmium, mercury and arsenic from water and its high gradient magnetic separation. RH-MAC had efficient adsorption properties for such hazardous materials. RH-MAC was synthesized by impregnating rice hull with an iron nitrate solution and heat-treatments in nitrogen and carbon dioxide atmosphere. In those processes, many meso-pores and nano-size magnetite were generated inside the activated carbon grains. The magnetization of RH-MAC increased with increasing concentration of iron nitrate solution. The magnetization of RH-MAC3 made from 1.6 mol/L iron nitrate solution reached 22.2 Am^2/kg at 1 T. RH-MAC was put into a humic acid solution of 25 ppm with a ratio of 0 - 2000 mg/L and stirred for 120 minutes. RH-MAC with the lowest magnetization showed the highest adsorption property for humic acid. The maximum removal ratio achieved 97.2% with a ratio of 2000 mg/L for RH-MAC1. RH-MAC with the lower magnetization also showed the higher adsorption property for lead. The maximum removal ratio achieved 98.3% with a ratio of 2000 mg/L for RH-MAC1. RH-MAC showed the similar adsorption properties for Cd. The maximum removal ratio achieved 99.3% with a ratio of 2000 mg/L for RH-MAC1. Likewise, for mercury and arsenic, RH-MAC showed effective adsorption properties. For magnetic separation studies RH-MAC3 having high magnetization of 22.2 Am^2/kg was magnetically collected of 99.4% by using the high gradient magnetic separation system with a rotary magnet drum with 0.5 T permanent magnets with the flow rates of 230 mL/min. Furthermore, 99.9% of RH-MAC3 **in water of 10 L was captured in the magnetic filter at the high flow speed of 1.0 m/s setting in a superconducting solenoid magnet of 2 T.** These results reveal that this system has a high potential for removal of humic acid, lead, cadmium, mercury and arsenic in water environment.





Keywords: Rice hull magnetic activated carbon, Hazardous heavy metals, Adsorption, Magnetic separation

APP8-2

Numerical Simulation on Behavior of Magnetic beads in Magnetic Filter for Medical Protein Screening System using High Gradient Magnetic Separation

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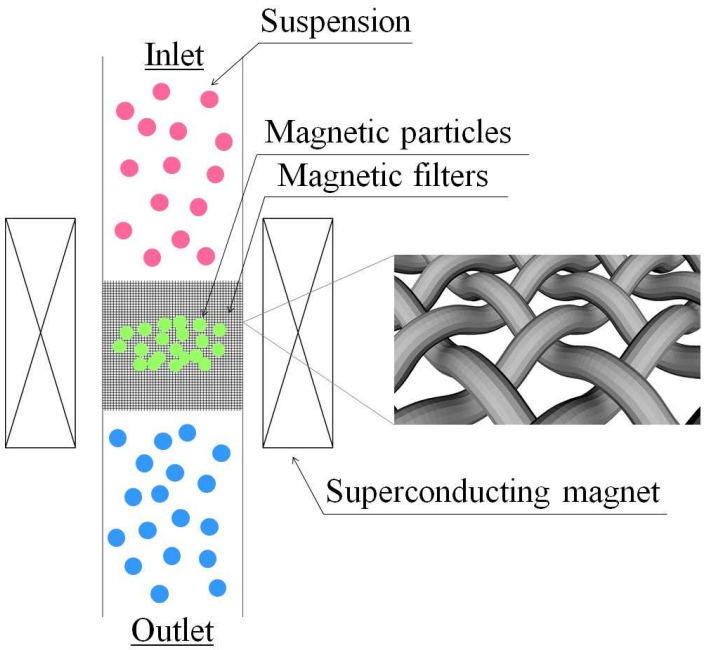
Biopharmaceuticals are indispensable medicines for modern medicine aiming for treatment of serious diseases such as cancer and diabetes and research and development of biopharmaceuticals are actively conducted both in Japan and overseas. Especially, Antibody drug with high efficacy and low side effects, is expected to become the mainstream of future medicine. Indispensable technologies for development and practical application of this antibody drug are continuous, large amount and high speed separation or purification technology of medical protein. Therefore, we have proposed superconducting high gradient magnetic separation system (HGMS) for pharmaceutical protein. In this device, a medical protein is attached to the surface of magnetic beads, and then, capture with magnetic beads using the magnetic force generated around the magnetic filter disposed in the high magnetic field by the superconducting magnet as shown in FIG..
If high gradient magnetic separation device using superconducting magnet is realized, processing time of separation and purification work can be greatly shortened, and it is expected to greatly contribute to development and practical application of antibody drugs.
In the previous studies, it was successful to separate 200-nm magnetic beads suspended in pure water, with the result that the capture ratio was 97.8% and the collection ratio was 94.1%. However, depending on the type of the suspension, the clogging of the magnetic filter and non-trapping the magnetic nano-beads have been confirmed.
Therefore, in this study, the numerical simulation on the behavior of magnetic beads around the filter are carried out by using magnetic fluid analysis.



Keywords: magnetic separation , superconducting magnet, particle tracing

APP8-3

Magnetic separation system of boiler feed water scale in thermal power plants with superconducting magnet

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We are developing a magnetic separation system to remove scale from boiler feed water in thermal power plants with a superconducting magnet.
Most of electric power is generated by thermal power in the world and Japan. Thermal power plants discharge enormous amount of CO_2. Reduction of CO_2 is an important issue to prevent global warming. We expect that increment of energy conversion efficiency of thermal power plant reduces fuel consumption and discharged CO_2. A thermal power plant consists of steam turbine generators, boilers and a system to feed water to boilers. Used steam is condensed to water and supply to boilers again. Deposition of scale in the water circulation system and boilers degenerate energy conversion efficiency of thermal power plants. If we can reduce scale, we may decrease fuel consumption and discharged CO_2.
Scale consists of iron oxides. Iron is transferred from walls of pipes and devices to boiler feed water at low temperature (~ room temperature) and flows to the boiler. When temperature of water > 200℃, most of irons form magnetite (Fe_3O_4) and deposits on walls of pipes.
We expect that the magnetic separation system is required to treat large amount of water and run in high temperature and high pressure with low pressure loss. We adopt the high gradient magnetic separation that consists of a superconducting magnet and matrix. Feed water flows in a bore in the superconducting magnet and the matrix is located in the water. The matrix is constructed by metal wire sheets which are magnetized by the magnet and extract magnetite suspended particles from feed water by the magnetic force.
One candidate of the suitable install locations of the system is the drain of high pressure heater where a part of feed water flows and concentration of scale is high. The system is required to remove scale from 400 ~500 m3/h of water at 200℃ and 20 atm. A superconducting magnet is crucial for the system.
We examine some conditions of the system by experiments and simulation study. We found conditions when the system runs for long time without substantial drop of capture efficiency and increment of pressure loss. We estimated that, if the system is installed in a thermal power plant, capture ratio is higher than 90% for more than one month without significant increment of pressure loss.

Keywords: Magnetic separation, superconducting magnet, thermal power generation, global warming

APP8-4

Levitating separation of precious metals utilizing magneto-Archimedes effect in high gradient magnetic fields

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We propose a magnetic separation using magneto-Archimedes effect for valuable resources recovery from urban mine. Magneto-Archimedes effect is a phenomenon that materials levitate at a particular position in a paramagnetic liquid medium by applying magnetic field gradient due to the difference of magnetic susceptibility and density between the liquid medium and the materials. We had studied the magnetic levitation properties for various precious metals and electronic substrate powders etc. However, there are limits to the magnitudes of the magnetic field and the magnetic field gradient due to the realistic specifications of the current superconducting magnet, and therefore some metals that are difficult to levitate exist. In this study, we challenged the magnetic levitation of precious heavy metals by high gradient magneto-Archimedes effect utilizing ferromagnetic materials arranged in high magnetic fields. By setting the iron cylinder at the center of the superconducting magnet, BdB/dz increased from 434 T^2/m to 1060 T^2/m at the applied magnetic field of 10 T. As a result, all precious metals, including precious metals that were previously incapable of separating, levitated at own position. It was confirmed that the levitating position for of each material was almost the same as the theoretical one.

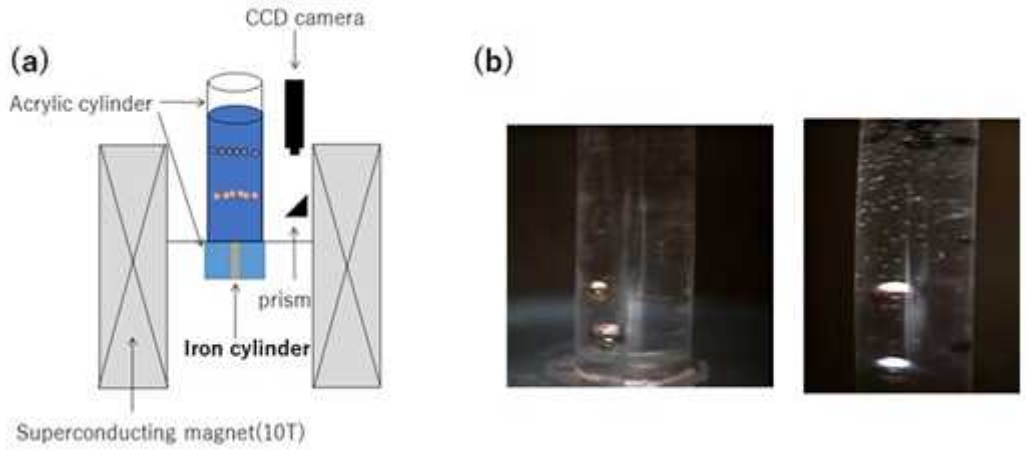

Fig. (a) Experimental device. (b) Levitating precious metals (Au, Ag, Pt, Cu).

Keywords: magneto-Archimedes effect, valuable resource recovery, urban mine, precious metal

APP9-1

Numerical studies on the dynamic responses of levitated high-temperature superconductor with a strongly coupled thermo-electromagnetic model

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In this paper, we present a 2-D numerical model of based on H-formulation and nonlinear E-J relationship to study the dynamic responses of a high-temperature superconductor (HTS) levitated above a permanent magnetic guideway (PMG). Being different from the existing related models and results of this subject, the effects of thermal are taken into account by a strong coupled model of electromagnetic, thermal and force. The levitation forces are calculated by finite element software and then the vertical motion of the levitated HTS subject to external disturbance is characterized by a second-order dynamic equation which couples the electromagnetic model via the levitation force. We study the thermal effects on the vertical dynamic characteristics of the HTS levitated above a Halbach-derived PMG. The obtained results reveal that this strongly coupled model can better simulate the dynamic response of HTS levitation system.

APP9-2

A man-loading hybrid maglev vehicle employing PML and SML

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In a bid to enhance the competitiveness of maglev technology advancing in passive stability and simple structure, a hybrid maglev system employing permanent magnetic levitation (PML) and superconducting magnetic levitation (SML) was developed. Based on the magnetic rail of "Super-Maglev" system, the hybrid maglev vehicle (1.34 m in length, 1.0 m in width) was designed for one passenger with a levitation height of 10–30 mm. It is composed of PML part and SML part, and a maglev frame is employed to support the vehicle body and connect the maglev components. The PML part with repulsive force is designed to support the main load, and the SML part with pinning forces is used to guarantee the lateral stability and support the weight of the maglev frame. The PML part is fixed to the maglev frame by linear sliders, and is able to move freely in the vertical directions. The bogies are designed and installed for basic curve negotiation function and the damper function. The driving is accomplished by a linear induction motor. The linear motor is installed at the middle of the magnetic rails, interacting with the induction plate mounted on the SML part. Measurements of static load characteristic of the hybrid maglev vehicle were performed. The rated load of this hybrid maglev vehicle was designed as 400 kg with small size maglev components, when the levitation height of PML part was 28 mm and the field cooling height of SML was 20 mm. The operation results imply that the man-loading hybrid maglev vehicle possesses excellent advantages of load ability and passive stability at the same time. The system component and test data are reported in detail in this paper.

Keywords: man-loading, hybrid maglev, permanent magnetic levitation, superconducting magnetic levitation

APP9-3

Operating characteristics of high-temperature superconducting maglev under a low-pressure environment

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For higher speed, the evacuated tube transportation (ETT) was proposed to be a hotspot. The high-temperature superconducting (HTS) maglev with self-stable, low noise and high efficiency is a perfect choice to be employed in the ETT system. A preliminary assessment on the low-pressure effect on the safety and stability of the HTS maglev vehicle was conducted. The experiments were based on the latest research result of a 45-m-long HTS Maglev-ETT Test System. The operating characteristics including lateral displacement (LD), damping and vibration acceleration under different pressure were investigated under different field-cooling-height (FCH) conditions. Experimental results show that the maximum lateral displacement (MLD) will be obviously decreased at 20 kPa and 60 kPa, compared to the condition of 100 kPa. It implies that the low-pressure environment is beneficial to improve the operating safety. The results provide basic data of the pressure effects on the HTS maglev system which proves that the low-pressure environment can improve the operating characteristics particularly on the performance of the MLD and further demonstrate the superiority of the HTS Maglev-ETT. Finally, a comparatively appropriate FCH (30 mm) is proposed for low-pressure environment, which will make reference for the future study and application of the HTS Maglev-EET.

Keywords: HTS maglev, low pressure, operating characteristics, damping

APP9-4

Levitation Stability of Superconducting Stator adding Ring Shaped Magnet

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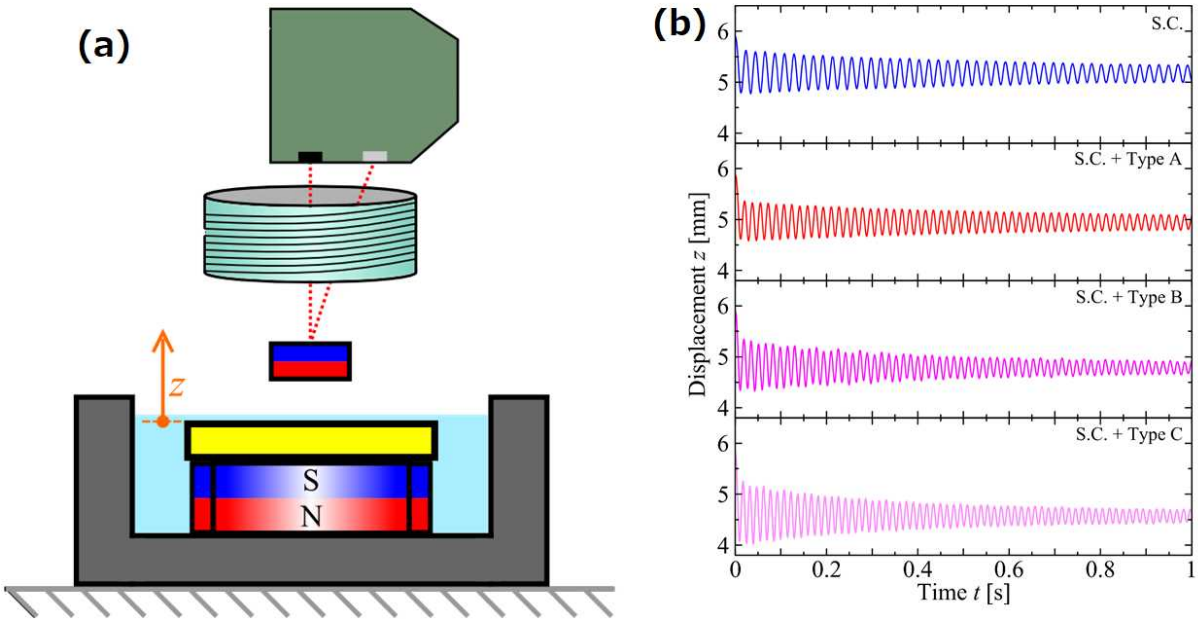
High magnetic rigidity is needed in order to make optimum use of the high performance of superconducting levitation. In this study, we proposed a hybrid stator comprising a superconductor and a ring-shaped permanent magnet, and measured the oscillation characteristics of a magnet levitating above various hybrid stators.
The magnetic force between the hybrid stator and a levitating magnet was measured by displacing at semi-statically. By adding a ring shaped magnet, the vertical attractive magnetic force and stiffness were increased compared with those of a simple superconducting stator. The magnetic force showed a hysteresis against the displacement of the levitating magnet. It was observed that the hysteresis energy loss was larger as the adding ring magnet was thicker.
The oscillation frequency of levitating magnet above the hybrid stator is higher than that of the simple superconducting stator. With the hybrid stator, a faster decay due to the hysteresis energy loss and Small amplitude from the Enhanced magnetic stiffness were observed. An improvement in the stability of the levitating magnet is realized by the hybrid stator using a superconductor and a ring-shaped magnet.



Keywords: Superconducting Levitation, Damping Oscillation, Magnetic force, Superconducting Hybrid Stator