September, 2013 Date of Issue: September 15, 2013

# Superconductivity Web21

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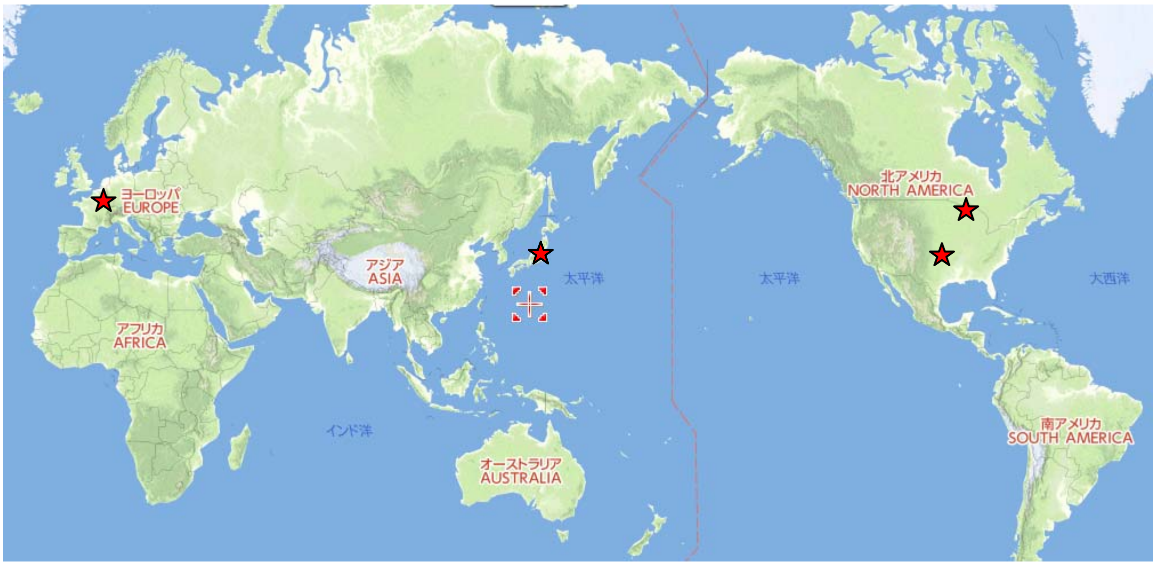
## What's New in the World of Superconductivity (July, 2013)

초전도 뉴스 –세계의 동향-

超导新闻 -世界的动向-

chāo dǎo xīnwén - shìjiè de dòngxiàng-

Yutaka Yamada, Principal Research Fellow
Superconductivity Research Laboratory, ISTEC




★News sources and related areas in this issue

### ▶Wire 선 재료 线材料 [xiàn cáiliào]

SUPERCONDUCTOR TECHNOLOGIES INC. **STI Shipped 2G HTS Wire to Three Multinational Smart Grid Companies**

**Superconductor Technologies Inc. (July 23, 2013)**

Superconductor Technologies Inc. (STI) has announced the successful shipment of Conductus® 2G HTS wire (with critical current performances of between 250 and 400 A/cm-width) to three multinational industrial companies. The wire will be used for various applicatio ns, including qualification testing for product designs such as superconducting fault limiters and HTS high-field magnets. Adam Shelton, STI's Vice-president of Marketing and Product Line Management, commented, "These shipments represent a significant milestone for STI as our potential customers look to secure a supply of HTS wire for 2014 and beyond… For our customers to successfully complete upcoming smart grid projects, they will require a significant quantity of superconducting wire at various lengths. Our wire performance, yields and wire length per run have dramatically improved over the first half of 2013. We expect our wire performance to continue to improve in these areas that are critical to achieving commercial volumes. By carefully aligning our 2013 production output with requirements from strategic target customers who are committed to the commercialization of superconducting devices, we are executing on our plan to bring Conductus wire to market in commercial volumes in 2014." At present, STI's wire production capacity for the next several months has been allocated to existing purchase orders for emerging smart grid applications. As the company's production capacity increases, STI hopes to secure business with industrial companies in the power sector as they prepare for the full commercial launch of Conductus® wire in 2014.

Source: "Superconductor Technologies Delivers on Conductus® 2G HTS Wire Orders"
Superconductor Technologies Inc. press release (July 23, 2013)
URL: http://phx.corporate-ir.net/phoenix.zhtml?c=70847&p=irol-newsArticle_Print&ID=1839874&highlight

Contact: Mike Beaumont, mbeaumont@suptech.com

## ▶Industrial Application 의료응용 医疗应用 [yīliáo yìngyòng]

TOSHIBA Leading Innovation >>>

### Toshiba Selected by Japan's NIRS to Supply World's First Rotating Gantry with Superconducting Magnets for Carbon Ion Radiotherapy

**Toshiba Corporation (August 2, 2013)**

Toshiba Corporation has received an order from Japan's National Institute of Radiological Sciences (NIRS) for the world's first rotating gantry irradiation system with superconducting magnets for a carbon ion radiotherapy system. The system will be installed in March 2015 in a new radiotherapy room that NIRS is constructing at its facility in Chiba, Japan. Carbon ion radiotherapy involves the acceleration of carbon ions to about 70% of the speed of light; these ions are then directed at cancerous tissue. The treatment is 2-3 times more efficient at destroying cancerous tissues than proton radiotherapy, thereby reducing radiation exposure. In addition, the depth of the energy peak can be controlled, preventing the exposure of healthy tissues in the vicinity of the target site.
Toshiba will be responsible for providing the beam transport system equipment, the rotating gantry, and other equipment necessary for the radiotherapy system. The rotating gantry is used to rotate the radiation port in a 360-degree circle, reducing both patient stress and the treatment time as the patient can be irradiated from any direction without changing their position. Rotating gantries are presently used for proton radiotherapy devices, but the gantries required for carbon ion radiotherapy are significantly larger. Thus, the downsizing of existing gantry designs is needed to make the device practical. Toshiba has successfully

achieved a much smaller rotating gantry design using superconducting magnets to bend the ion beam and a superconducting 4-pole magnet for beam focusing. These magnets have a high current density, enabling the generation of an intense magnetic field that bends the beam within a smaller radius. In addition to reducing electricity consumption, the use of the superconducting magnets has enabled reductions in weight (50 %) and size (from 25 m to 13 m), compared with designs based on conventional magnets.
Toshiba has already installed a carbon ion irradiation system for NIRS and has also received an order for a complete carbon ion radiotherapy system, including the accelerator, from the Kanagawa Cancer Center in Yokohama, Japan. In the future, Toshiba plans to promote its healthcare-related businesses, including its current medical diagnostic imaging business, as a potential core business.

Source: "Toshiba Selected by Japan's NIRS to Supply World's First Rotating Gantry with Superconducting Magnets for Carbon Ion Radiotherapy"
Toshiba Corporation press release (August 2, 2013)
URL: http://www.toshiba.co.jp/about/press/2013_08/pr0201.htm
http://www.businesswire.com/news/home/20130801006999/en/Toshiba-Selected-Japans-NIRS-Supply-Worlds-Rotating
Contact: Atsushi Ido, Corporate Communications Office, Toshiba Corporation
http://www.toshiba.co.jp/contact/media.htm

## ▶ Accelerator 가속기 加速器 [jiāsùqì]_

### Fermilab Successful Test of New U.S. Magnet for Large Hadron Collider

**Fermilab (July 11, 2013)**

The U.S. LHC Accelerator Research Program (LARP) has successfully tested a powerful superconducting quadrupole magnet intended to play a key role in the development of a new beam-focusing system for the Large Hadron Collider (LHC) at CERN. The new system, together with other major upgrades, will be implemented over the next decade and will allow the LHC to produce 10 times more high-energy collisions than allowed by the original design. The new high-field magnet was constructed from a high-performance superconductor (niobium tin [$Nb_3Sn$]) and is designed to operate at a higher magnetic field.
While the discovery of the Higgs boson has fulfilled one of the LHC's major goals, precise measurements remain to be made, in addition to further explorations of new physics including supersymmetry, dark matter, extra dimensions, etc. The quadrupole magnets currently used by the LHC are expected to reach performance limits that are well below the level required for the LHC's ambitious physics program. Thus, one of the main goals of LARP is to support CERN's plans to replace the focusing magnets in about 10 years as part of the High Luminosity LHC project. The new magnets will need to focus the proton beams at the interaction points. Not only are stronger magnetic fields needed, but a larger temperature margin and the ability to withstand intense radiation are also necessary. As niobium titanium cannot meet these requirements, the new magnets will be made from $Nb_3Sn$ wire (manufactured by Oxford Superconducting

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Technology), which can operate at a higher magnetic field and has a wider temperature margin but is also brittle and sensitive to strain. Large forces could potentially damage these fragile conductors and lead to quenching. Thus, accelerator magnets must be designed to withstand such disruptive and potentially damaging events. Accordingly, LARP has adopted a mechanical support structure based on a thick aluminum shell that has been pre-tensioned at room temperature using water-pressurized bladders and interference keys. This design (developed at Berkeley Lab under the U.S. Department of Energy's General Accelerator Development program) has been compared to the traditional collar-based clamping system and has been scaled-up to 4 m in length for the LARP Long Racetrack and Long Quadrupoles. The mechanical design approach was further refined by incorporating an ability to achieve full coil alignment.
The new magnet is designed to operate in superfluid helium, but it has a larger beam aperture than the present focusing magnets (120 mm, compared with 70 mm) and the magnetic field is capable of reaching 12 Tesla (compared with 8 Tesla at present). In addition, the new magnet is designed to minimize deviations from the precise magnetic field patterns required to focus the beams at the interaction point and to maintain a high field quality during the ramping up to full magnetic field strength. To meet these numerous requirements, LARP incorporated a newly designed cable to minimize induced currents and also ensured precise alignment at all phases of coil fabrication, assembly, and magnetic excitation (coil winding was performed at Berkley Lab, while Fermilab designed and procured the necessary parts). Berkeley Lab's GianLuca Sabbi, who directed the HQ02 development, commented, "The magnet quickly achieved its design field gradient with low sensitivity to ramp-rate effects. This result was made possible by the expertise and dedication of many scientists, engineers, and technicians at all the collaborating laboratories."

Source: "Successful test of new U.S. magnet puts Large Hadron Collider on track for major upgrade"
Fermilab press release (July 11, 2013)
URL: http://www.fnal.gov/pub/presspass/press_releases/2013/LHC-New-Magnets-20130711.html
Media contact: Kurt Riesselmann, Fermilab Office of Communication, media@fnal.gov
Science contact:Eric Prebys, prebys@fnal.gov

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# Feature Article: Reporting on the 2013 Forum on Superconductivity Technology Trends
# - Brief Summary of Materials and Power Applications of Coated Conductors (M-PACC) Project and the Anticipated Future Development of Basic Technology for High-temperature Superconductors

Yuh Shiohara, Director General
SRL/ISTEC

In order to realize a stable and efficient energy supply system of the electricity for economical social base, highly efficient power transmission technology being able to adequately govern power grids and provide electricity with minimal power loss is an important concern. To this aim, a project entitled Materials and Power Applications of Coated Conductor's Project (hereafter M-PACC project), was undertaken and aimed at the development of superconducting electric power equipment by utilizing superconductivity technology which our country has advanced world-leading technology. The project employed an yttrium (Y)-based high temperature rare earth copper oxide superconducting wire (Y(RE)BCO coated conductor; hereafter CC), which has the potential to realize a compact and large capacity power supply. The project involved collaborations between 11 institutions, including the International Superconductivity Technology Center (ISTEC), electric power companies, wire manufacturers, manufacturers of heavy electrical machinery and 23 universities/national research laboratories. The New Energy and Industrial Technology Development Organization (NEDO) commissioned the project over a period between 2008-2012, with its successful accomplishment on 28th February 2013.

The project developed important component technology necessary for the realization of superconducting magnetic energy storage (SMES) systems, superconducting power cables and superconducting transformers. Efforts also focused on development of the most suitable wires applicable for superconducting power equipment and investigating their standardization, which is basis for their realization. Superconducting power equipment (SMES, power cables, transformers) and CCs developed in this project have all been raised as important R&D issues in the four categories promoted by the Council for Science and Technology Policy, and based upon the third-stage basic plan for science and technology (2006-2010). A policy actions taken the Ministry of Economy, Trade and Industry (METI) has selected 21 innovative technologies aimed at significantly reducing $CO_2$ emissions under the Cool Earth - Innovative Energy Technology Program. Amongst these were efficient superconducting power transmissions, formulated in the energy/power equipment technologies category, under the Superconductivity Field Technological Strategy Roadmap (agreed as of April 2007). The fourth-stage basic plan for science and technology (2011-2015), approved in a Cabinet meeting on 19 August 2011, stated *"In order to realize stable energy supplies and* low-carbon society*, we aim to* distribution *energy system innovation, promote superconducting-based transmission R&D and* overseas deployment*"*.

At the "2013 Forum on Superconductivity Technology Trends", the R&D details of each project theme was reported together with a summary of the final research outcomes of the M-PACC project and an anticipated

  

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future outlook for basic high-temperature superconducting technology development. Furthermore, the future prospect of superconductivity research was reported by professors and researchers engaged and active at the forefront, highlighting the exploration of new superconducting materials, thin film devices including high-temperature SQUIDs, superconducting railway technologies, superconducting applications including high temperature superconducting technology applied to off-shore wind power generators and trends associated with the international standardization of high-temperature superconductor-related technology.

## 1. Summary of Final research results of the M-PACC project

The New Energy and Industrial Technology Development Organization (NEDO) commissioned the M-PACC project (2018-2012), which involved collaborations between 11 companies/23 universities and ISTEC who acted as a representative. The design concept of a superconducting large capacity stable electric power system being able to supply electric power to urban areas is shown in Figure 1. All the project objectives have been aimed towards improving the characteristics of CCs and developing important base elemental technology necessary to foresee the future practical usage and market introduction/ spread for power equipment, including superconducting magnetic energy storage systems (SMES), superconducting power transmission cables and superconducting transformer applications utilizing the characteristics of CCs.

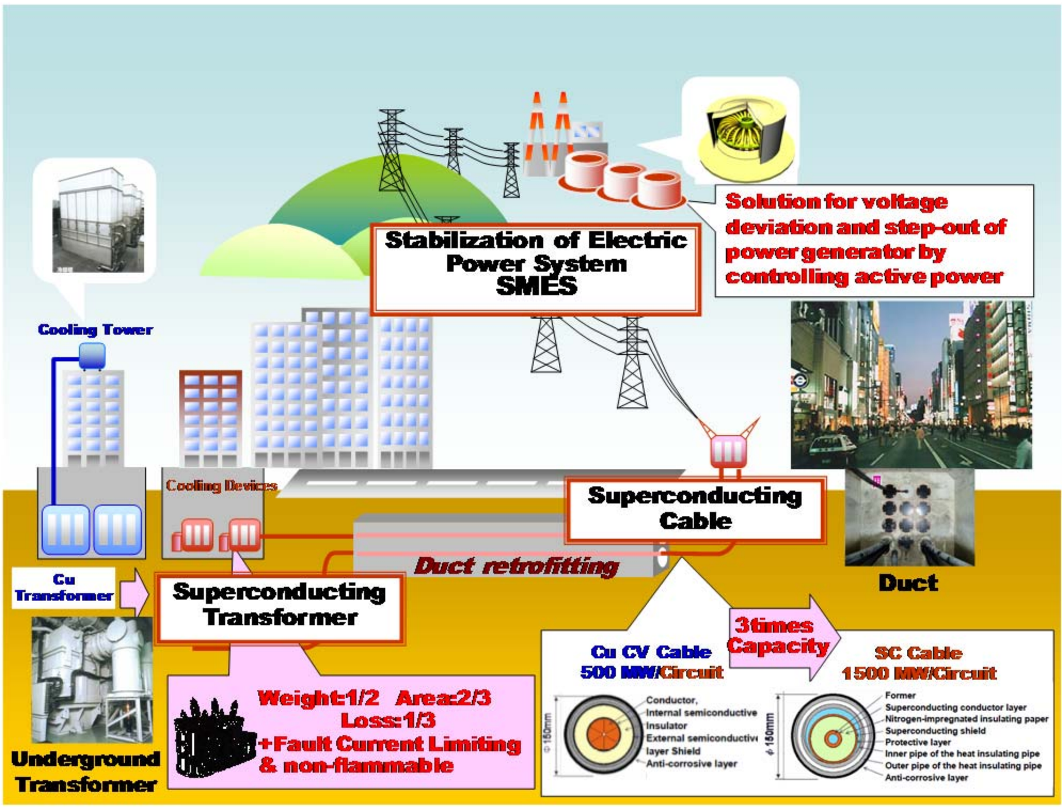


Fig. 1 Conceptual diagram of superconducting power equipment offering large capacities and stable power supplies to urban areas

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### 1.1 Superconducting magnetic energy storage system (SMES)

R&D on SMES has involved developing; 1) a 2 GJ-class high-field/high-current compact coil winding technology, 2) a highly efficient coil conduction cooling system, 3) stable manufacturing process of CCs applicable for SMES and 4) a highly reliable/high tolerance SMES coil elemental technology. Progress in these areas has resulted in the development of elemental technology for a high-field/compact coil that has enabled the construction of a 2 GJ-class large -capacity SMES coil utilizing CCs, which is of a suitable scale required for grid stabilization and able to accommodate load fluctuations compensation/frequency adjustment. Also, a conduction cooling system was developed with the assumption of higher temperature operation above 20 K. In the last year of the project, investigations and the characterization of components for high tolerance/highly reliable coils required for SMES coil system technology were carried out, aiming for the development of elemental technology and the establishment of a coil protection technology, which all contributed towards the realization of a 2 GJ-class SMES. One of the factors affecting coil current transport characteristics is the delamination of the CC characterization methods and results have been determined allowing probabilistic prediction of the delamination strength, including the wire tolerances needed to optimize coiling technology for SMES. These studies have resulted in a new coil architecture (Yoroi-coil), which suppresses the stress/strain generated by hoop stress. The complete coil architecture is shown in Figure 2. The coil architecture has favorable characteristics with an ability to tolerate a 1.7 GPa hoop stress. A stress analysis of the coil structure revealed that not only the coil winding, but also the frame materials and supporting side-plate of the coil share the electromagnetic force, thus influencing the coil characteristics. The superior coil tolerances have been verified.

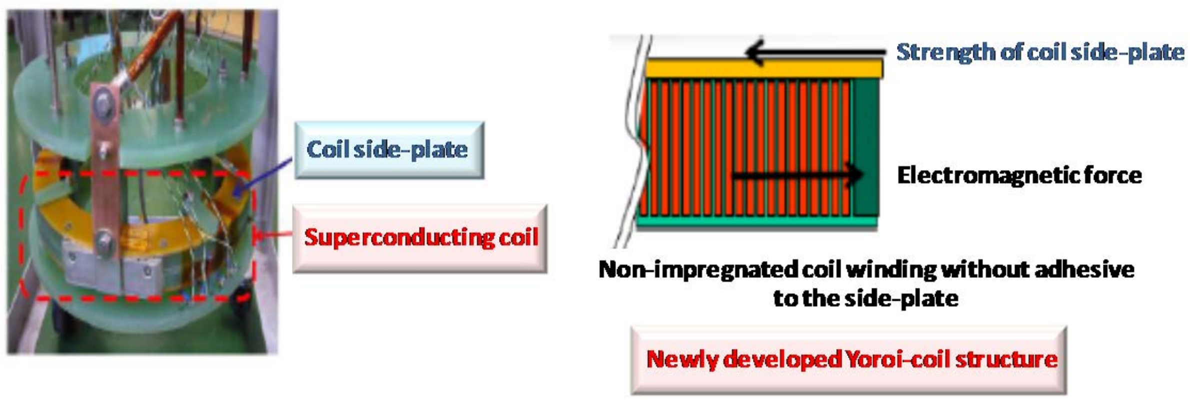


Fig. 2 Newly developed Yoroi-coil having structural reinforcement with non-impregnated coil and coil side-plate for reducing stresses during coil winding
*(Yoroi-coil:Y-based oxide superconductor and reinforcing outer integrated coil )*

### 1.2 Superconducting power cable

Superconducting power cables made up using CCs exhibit high capacities and low transmission loss characteristics within a compact structure and are therefore anticipated to increase transmission capacities utilizing existing cable ducts. To exploit this, a 66 kV/5 kA high current cable and a 275 kV/3 kA high voltage cable have been developed. Technological efforts have focused on the development of low-AC loss, high-current conductors, large -capacity joints, three-in-one cables, compactness, high voltage insulation

  

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(selection of high voltage insulation materials, insulation design, bushing), high voltage joints and low dielectric losses, which are all important parameters to consider for elemental technology required for cable development. In addition to investigations of cables cooling technology using slush nitrogen coolants, high current and high voltage cable systems combined with elemental technologies has been developed and their performance was verified

Verification of the 66 kV high current cable system has led to the fabrication of a compact three-in-one cable system exhibiting the world's lowest loss and the world's largest transmission density characteristics, as shown in Figure 3. During current loading testing (66 kV/three-in-one/5 kA, 15m-long), a cable loss (AC loss (conductor and shielding layers), dielectric loss) of less than 2.1 W/m-phase@5 kA has been successfully verified, with the cable being housed in a 150 mmϕ cable duct.

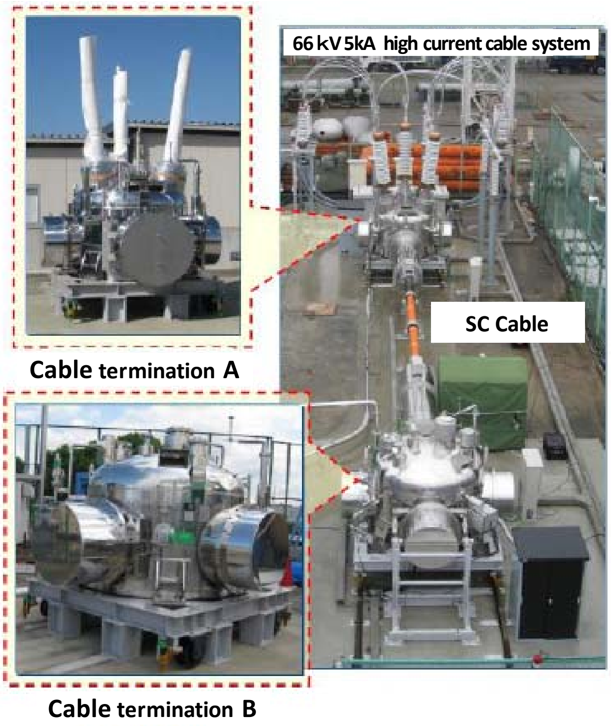


Fig. 3 System outline for demonstration of the 66 kV-5 kA high current cable

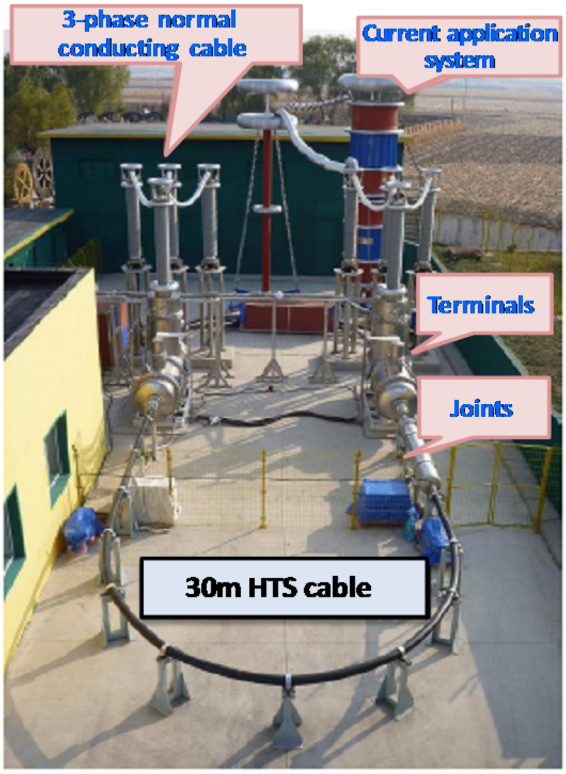


Fig.4 System outline for demonstration of the 275 kV-3 kA high voltage cable

Trials involving the 275 kV high voltage cable system have been verified leading to the construction of the world's lowest loss and compact cable system, as shown in Figure 4. Current testing (275 kV/single core/3 kA, 30m-long) has confirmed cable loss (AC loss (conductor and shielding layers), dielectric loss) characteristics of less than 0.8 W/m-phase@3 kA, and all with a cable having a diameter of less than 150 mmϕ.

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### 1.3 Superconducting transformer

A Y-based superconducting transformer is expected to be compact, lightweight and offer greater efficiencies. Additionally, the liquid nitrogen coolant required for its operation is non-flammable, has high insulating characteristics and offers excellent maintainability. Such attributes have therefore focused research efforts into developments for; 1) coil winding technology of CCs, 2) cooling system technology, 3) transformers with fault current limiting functions, 4) CCs applicable for superconducting transformer and 5) verification of a prototype 66/6.9 kV-2 MVA superconducting transformer, including the design of a 20 MVA-class superconducting transformer for power distribution applications. All this effort has produced important fundamental technology that contributes to the realization of a compact and highly efficient superconducting transformer for power distribution applications.

Verification of a prototype 2 MVA-class superconducting transformer has seen the development of a three-phase, large-scale, non-magnetic cryostat (GFRP product) having 10m$^3$-class capacity. The cold insulation performance (less than 20 W/m$^2$, corresponding to existing small-scale cryostat) was verified during testing trials. Following this was coil winding and transformer assembly trials designed to evaluate performance characteristics and intended for the construction of a prototype 66 kV/6.9 kV-2 MVA-class superconducting transformer. The superconducting transformer combined with a cryocool system is shown in Figure 5. Current loading tests have proved satisfactory. In the last year of the project, a 20 MVA-class superconducting transformer was designed. The design was based upon the test results of the 2 MVA-class superconducting transformer prototypes and demonstration of its performance characteristics along with verification of a high current coil winding prototype. This has produced the design of a superconducting transformer having characteristic losses reduced to 46 % compared to existing oil-immersed transformers, with a reduced weight and installation footprint of around 50 % because of a reduction in the iron core, even when considering the refrigerator cryocooling power consumption.

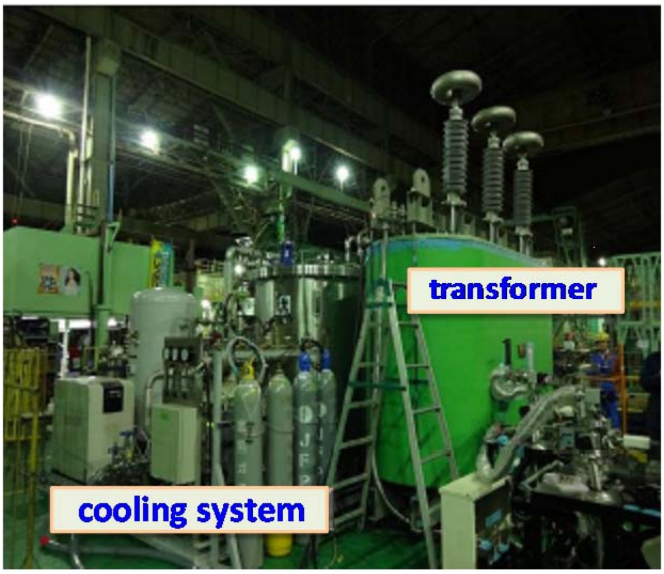


Fig. 5 System outline of a prototype 2 MVA-class superconducting transformer combined with a cooling system

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The development of a refrigerator and cryocooling system involved investigating the fundamental process of the refrigerator, the design of the cryostat and operational process simulations, confirming theoretical values of COP 0.06 (final target >0.06). The individual performance of the Ne refrigerator combined with a turbo compressor, expansion turbine and heat exchanger that utilizes Ne as the working gas has been evaluated and confirmed to have cooling capacities of 2.17 kW@65 K, COP 0.06@80 K, as shown in Figure 6. Further circulation cooling tests using sub-cooled liquid nitrogen have proved favorable with excellent follow-up property with respect to load fluctuations, verifying the reliability and tolerances of the cooling system under long-term continuous tests.

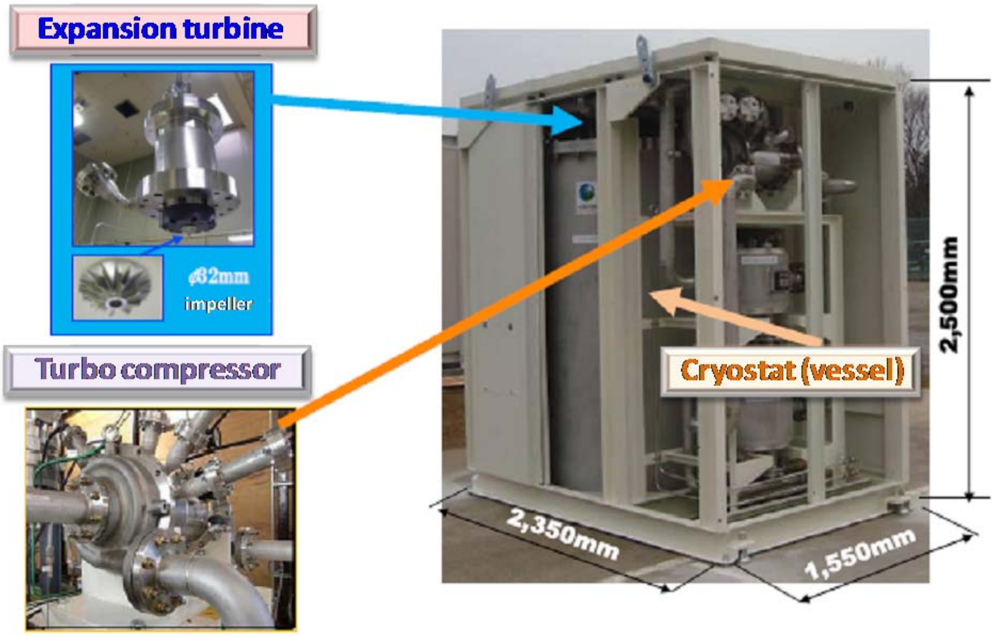


Fig. 6 Outline of Ne turbo Brayton refrigerator

At the conclusion of the project and based upon developmental outcomes, Taiyo Nippon Sanso plans to commercialize a 2 kW-class maintenance-free Brayton cycle refrigerator with no sliding parts.

### 1.4 Coated conductor development for superconducting power equipment

Y-based coated conductors can only be realized with further wire developments that meet the specifications required by respective equipment as well as improvements in CC characteristics. Research into PLD CCs grain-aligned on a metal substrate and IBAD-MOCVD in addition to IBAD-PLD and IBAD-MOD CCs has progressed by focusing on improving in-field critical currents characteristics, mechanical strengths and engineering critical current densities as well as enhancing homogeneity of superconducting characteristics, all of which are closely related to reducing AC loss and lowering overall technology costs. R&D has led to developments in wire fabrication technology, producing a stable manufacturing process that meets the demands of performance and throughput production rate necessary for future practical technology development, including long-term reliability tests. CC fabrication process technology developments have

  

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also concentrated on satisfying certain conditions such as the costs incurred during commercialization and the market penetration and spread of power equipment, assumed to be around 2020.

R&D has targeted the following five themes; 1) using simulation studies to investigate ways to maintain superconducting characteristics of CC in a variety of operational environments, particularly evaluating changes in $I_c$ properties both hourly and yearly, as well as analyzing and understanding mechanisms that lead to deterioration in wire characteristics and methods to limit such mechanisms, 2) development of CC fabrication process technology leading to high in-field critical current ($I_c$) characteristics and aimed at potential SMES applications in high magnetic fields (~10 T) along with potential superconducting transformer applications that utilize solenoid coils relating to the vertical magnetic field direction to the CC surface despite the relatively low magnetic field (~0.1 T), 3) the development of low AC loss CC fabrication process technology necessary for superconducting power cables and superconducting transformers designed for AC applications, thereby enabling the production of homogeneous CC filaments and scribing and slitting process technologies, 4) high strength/high engineering critical current density ($J_e$) CC fabrication process technology required by SMES applications with strong hoop stress characteristics under high magnetic fields and the high-current cables capable of withstanding stress loads during cooling as thermal contraction tolerances cannot be internally controlled and 5) CC fabrication process technology development produced at low cost and with greater production yields, achieved by CC fabrication process technology that meets the demands of performance, along with the manufacturing production rate required for the commercialization of practical power equipment applications.

Each R&D theme is summarized in Table 1.

Table 1 Summary of R&D results of CC for superconducting power equipment

| Subject | Final targets | Major research outcomes |
|---|---|---|
| ①Understanding wire characteristics | Tolerance evaluation for each type of equipment environment | . Analysis of delamination phenomenon mechanism→elimination of low, mid, high faults<br>. Tolerance evaluation for filamented CCs |
| ②Fabrication technology of high in-field $I_c$ CCs | 50A/cm-w @77K, 3T-200m | . PLD-CC: BHO addition 141A@77K,3T(short wires) 54A@77K, 3T-200m<br>. MOD-CC: YGdBCO+BZO 50A@77K, 3T-124m |
| | 400A/cm-w @65K, 0.1T-100m | . PLD-CC: 770A/cm-w@65k, 0.1T-158m<br>. MOD-CC: 524A/cm-w@65k, 0.1T-100m |
| ③Fabrication technology of low loss CCs | 2～4mm-width, 500A/cm-w-200m | . PLD-CC: 2mm-width, 540A/cm-w-200m<br>. MOD-CC: 4mm-width, 590A/cm-w-80m<br>. RABiTS-CC: 2mm-width, 400A/cm-w-72m |
| | 5mm-width 10-filament 100m, loss 1/10 reduction compared to non-filamented CC | . PLD-CC: 5mm-width-10 filament-100m-loss 1/10<br>. RABiTS-CC: $J_e$>52kA/cm$^2$ (short wires) |
| ④Fabrication technology of high strength high $J_e$ CCs | $J_e$=50kA/cm$^2$-200m | . PLD-CC: $J_e$>52kA/cm$^2$-200m (70μm$^t$ substrate)<br>. RABiTS-CC: $J_e$>52kA/cm$^2$ (short wires) |
| | 500A/cm-w-1GPa-200m | . PLD-CC: >500A/cm-w-1GPa-200m |
| ⑤Low costs and yield improvement technology | Technology cost 2 Yen/Am verified | . PLD-CC: 604A/cm-w-35m@30m/h→1.6￥/Am<br>. MOD-CC: 605A/cm-w-30m@10m/h→1.6￥/Am<br>. RABiTS-CC: 1600A/3cm-w@2.2m/h→2.7￥/Am |
| | Stable manufacturing technology for interim target | . All CC types: Yield evaluations of each type of several-km long wire undertaken by the wire manufacturers |

  

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**2. Future Prospects of Superconductivity R&D**

NEDO has progressed the M-PACC project till now, developing the basic elemental technology required to foresee its market introduction, penetration and spread by 2020. The project has focused on the development of superconducting magnetic energy storage systems (2 GJ-class SMES for grid stabilization) employing Y-based CCs that are expected to offer power supplies greater capacities with a compact design, along with the development of superconducting power cables (66 kV/5 kA high current cables and 275 kV/3 kA high voltage cables), and a superconducting transformer (66/6 kV/20 MVA-class distribution transformer). CC fabrication process technology was seen as a necessity for superconducting power equipment with R&D studies making intensive developments that include improvements in performance and production yields, cost reductions, high-speed and mass-production manufacturing, and all based upon Japan's technical know-how and expertise accumulated in this field.

Such R&D efforts have led to the determination of important factors crucial for market introduction, penetration and spread of superconducting power equipment, which include *"technology specifications"*, *"feasibilities"*, *"reliabilities"*, and *"cost/high efficiencies"*. The next phase of development is *"technology development designed for practical use"*. By validating long-term reliabilities of individual power equipment components, including CC fabrication process and cryocooling technologies as well as the testing of power equipment in power grids will clearly establish the superiority afforded by superconducting-based equipment over existing competitive technology. The Great East Japan Earthquake of 2011 significantly changed the environment surrounding the state of Japan's electricity usage. As of February 2013 there are only two operational nuclear power plants in the whole of Japan, namely, units 3 and 4 at Oi nuclear power plant, with the remaining power stations not expected to resume operation any time soon. The government is thus committed to promote power generation via the utilization of renewable energy such as solar and wind power. However, the amount of electricity generated via these methods is low and unable to meet demand. The government remains uneasy increasing the electricity generated by hydroelectric power plants because of the time taken to select suitable locations and construct plants. Therefore, for the time being it is anticipated that the demands of electricity will be met by increasing the numbers of thermal power plants. However, the recent financial situations of electric power companies have meant that plans to upgrade equipment have been shelved with only partial upgrades and maintenances having been performed, or the time intervals between overhauls have been extended, and then only replacing defective facilities and equipment. This has raised uncertainty over its future market potential, which is seen at a significant risk of market shrinkage. Despite this, large volumes of aged and deteriorated power equipment will ultimately require upgrading and therefore there exists an opportunity for SMES, superconducting power cables and superconducting transformers to be realized and introduced into the marketplace. The author believes that the outcomes from this world-leading project can contribute to the stabilization of future power grids and thus further promote the superconductor industry.

Accompanied by an increase in the amount of renewable energies is the introduction of an array of superconducting equipment. The efficiency advantages afforded by superconducting power equipment are expected to impact industrial, transportation and the medical fields, significantly contributing to reductions in $CO_2$ emission as well as energy savings. The project outcomes from fundamental superconducting applications are highly anticipated to ripple to a wider range of applications.

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**2.1 Fundamental technology development of high temperature superconducting coils for magnets**

The Ministry of Economy, Trade and Industry announced a project plan in 2013 to take advantage of Japan's high temperature superconductivity technology by promoting energy savings and low-cost in biomedical radiotherapy and diagnosis equipment, and performance enhancements of industrial motors. An aspect of this is high temperature superconducting coils, which are anticipated to deliver enhanced benefits of reducing the relative size of large-scale accelerators designed for medical-use, boosting performance of the next-generation vehicles and high-speed railway motors, as well as reducing losses in wind power generation. The announced plans specifically focus on developing new CC materials that will enable the realization of high temperature superconducting coils along with their designs and manufacturing methodologies. The objectives include the development of diagnosis/medical-use magnets and targeting MRI applications employing high temperature superconductors, medical-use synchrotron accelerators and gantry. Table 2 summarizes the superconducting magnetic field specifications required by each medical system.

Table 2 Required magnetic field specifications for heavy-ion accelerators designed for cancer treatment and MRI superconducting magnets

(a) Required magnetic fields specifications for heavy-ion accelerators for cancer treatment (homogeneity etc.)

| Cyclotron | Excitation form | Magnetic field configuration | Magnetic field strength | static homogeneity of magnetic field |
|---|---|---|---|---|
| Synchrotron | Pattern excitation | Two poles, four poles | 1.5T ～ 3T | Range of 10~100ppm/100mm |
| FFAG accelerator | DC excitation | Complex tilted magnetic field | Ditto | Ditto |
| Cyclotron | DC excitation | Uniform magnetostatic field | Ditto | 10ppm/over-all |

(b) Required magnetic field specifications for MRI superconducting magnet (homogeneity etc.)

| Magnetic field types | Magnetic field strength | static homogeneity of magnetic field | Time |
|---|---|---|---|
| External static magnetic field | 1T, 1.5T, 3T, 7T & 11T | 1ppm/resolution | Constant |
| External tilted magnetic field | Ditto | 10mT/m ～ | Temporary |

(1) High temperature superconducting magnets for MRI

Current MRI systems are significantly impacted by helium supply constraints because of the large volumes required for their cooling. Whilst this project is open to public subscription, it still aims to significantly reduce the use of liquid helium by employing high temperature superconducting materials instead. A public appeal is now planned for the development of; 1) basic technology R&D designed to provide a stable magnetic field coiling system exhibiting the equivalent performance, safety and economic viability compared to a conventional MRI low-temperature superconducting coil and 2) fundamental technology R&D designed to deliver greater coil magnetic field strengths, thereby allowing better MRI resolutions and contrast of radionuclides than conventional MRI systems. Additionally, there is a need to generate stable and homogeneous magnetic fields of around 10 T necessary for cyclotron applications.

The world MRI market is foreseen to grow and exceed 6 billion US dollars by 2018. The market in the USA has already reached saturation and a replacement cycle is now in progress. The future growth potential of this market is expected with the installation of newer magnetic field systems offering greater field strengths over low and mid field MRIs. Siemens Healthcare leads the worldwide market share (25 %), followed by GE Healthcare (20 %), Phillips Healthcare (13 %), Toshiba Medical Systems (12 %), and Hitachi Medico (9 %). The top three are overseas competitors, with world industry competing to "*catch up and overtake these leading contenders*". Japan is 100 % reliant on the importation of helium required by MRI systems, however there have been significant reduction in volumes since last year, with importation volumes reducing by 35 % last September compared to the previous four months. Around 80 % of liquid helium usage is employed for medical-use MRIs and it is despairing to note that importation volumes will not increase rapidly in the near future. Under the circumstances, future MRI magnets not reliant on liquid helium cooling can only be realized with further R&D work into high temperature superconducting magnets generating homogeneous magnetic fields by utilizing Japan's world leading high temperature superconducting CCs. Such developments are to be promoted with strong national support, paving the way for Japan's future position as a pioneer in the basic research in the medical equipment industry.

Nuclear magnetic resonance (NMR) spectroscopy measures specific resonance frequencies between atoms and molecules. On the other hand, ordinary MRIs used to analyze the human body, which contains around 75 % water, involves transmitting a high frequency magnetic field pulse at the resonance frequency of hydrogen nuclei and measuring the relaxation time of the atomic nuclei to return to the steady state, with different relaxation rates providing images related to the tissue water content from the binding states of between particles. The imaging data provides information on not only hydrogen atoms, but also carbon ($^{13}C$) and phosphorus ($^{31}P$), which are also present in the human body. Japan's MRI market can be divided into conventional mid-field superconducting systems offering magnetic field strengths of around 0.5 T-1.0 T and which are now being replaced by systems with permanent magnets, and other MRI systems offering magnetic field strengths greater than 1.5 T. It is forecasted that a 3 T full body system is expected to spread into the market in the future after pharmaceutical approval. Overseas trends related to MRI R&D are aimed at increasing magnetic field strengths to improve MR (magnetic resonance) signal strengths to allow higher image definitions and greater imaging speeds. Moreover, R&D for 7 T, 11 T magnets for full body are also in progress. The future sees the high critical temperatures and high specific heat (heat capacity) afforded by CCs, which also exhibit thermal stability and high magnetic field characteristics, paving the way for the development of high temperature superconducting MRI systems being able to avoid quenching during low temperature operations (breakage of superconductivity due vibration and excess current). Since spatial and temporal homogeneous magnetic field generation are required for this to be realized, developments to enhance the homogeneous superconducting CC characteristics, ultra-low resistance superconducting CC jointing technology connecting other superconducting wires enabling persistent current mode operations, and also fine-tuning of iron shims/yokes technology are important.

(2) High temperature superconducting heavy-ion medical accelerator for cancer treatment

Radiotherapy utilizing high-energy protons and heavy-ion beams can be used to precisely irradiate cancerous cells and limit damage to surrounding healthy cells. As a cancer treatment, this has been gathering attention as it has less physical burden on patients. However, the bottleneck preventing this technology to be introduced to the mainstream market is its large-scale system footprint and high capital costs. Thus, R&D plans involve utilizing variable high temperature superconducting magnetic field coils for use in heavy-ion medical accelerator systems, ultra-large-scale accelerators for R&D use and rotors for industrial use, aiming to be compact and low cost. Specifically, the call for participants plans of R&D is shown, which are the development of a high temperature superconduction coil that control of the magnetic field strength is possible in terms of time applicable to, 1) the magnet for a heavy-ion medical accelerator main unit and 2) magnet for the particle beam path and radiation area (gantry).

An elderly society as well as dietary changes has increased the numbers of cancer patients and the numbers of deaths from cancers. Despite this, patient numbers in Japan receiving radiotherapy remain low (around 25 %) compared to both Europe and USA. Anti-cancer measures basic plan led by the Japanese government promote radiotherapy technologies and R&D into treatment equipment.

Radiotherapy systems have currently become forerunners for world cancer treatments with their use increasing rapidly over the years, producing a 3.8 billion US dollar market as of 2008. Sales of radiotherapy systems (10-26 %) have increased far rapidly than sales of entire medical equipment (4-6 %). The market share by region is around 50 %, 34 %, 13 % for USA, Europe and Asia, respectively, with more than 90 % of the world market share dominated by the top three companies from Europe and the USA.

Radiotherapy offers equivalent or better effective treatment compared to surgical methods with fewer burdens to the physical body since the radiation dose is focused and targets only the cancerous cells. Heavy-ion radiotherapy treatments have a track record of treating over 5,000 patients thus far. The energy savings and compact footprint offered by utilizing high temperature superconducting technology have driven the desire for the development of low-cost heavy-ion medical accelerator systems. Further promotion of radiotherapy has been investigated in terms the industry strengthening its international competitiveness.

With regards to high temperature superconducting CCs applied to magnets in biomedical particle beam accelerators, current normal conducting synchrotron accelerators are on a scale of a football stadium. Hence, issues associated with costs remain as heavy-ion (carbon) accelerators costs between 12-34 billion Yen, and electricity consumption costs remain high at 15 million Yen per month. It is therefore contemplated whether utilizing high temperature superconducting CCs could offer the possibility of realizing compact systems along with energy savings and low power consumption. Thus, by combining Japan's world-leading radiotherapy technology with high temperature superconducting CCs, the aim is to develop a high magnetic field strength magnet designed for heavy-ion accelerators. Also, ongoing developments to reduce the size of ion injection area, accelerator, beam radiation components and gantry, along with the heavy-ion beam acceleration control technology combining these component equipment are all expected to lead to the realization of low-cost, compact heavy-ion medical accelerators, offering energy savings over conventional.

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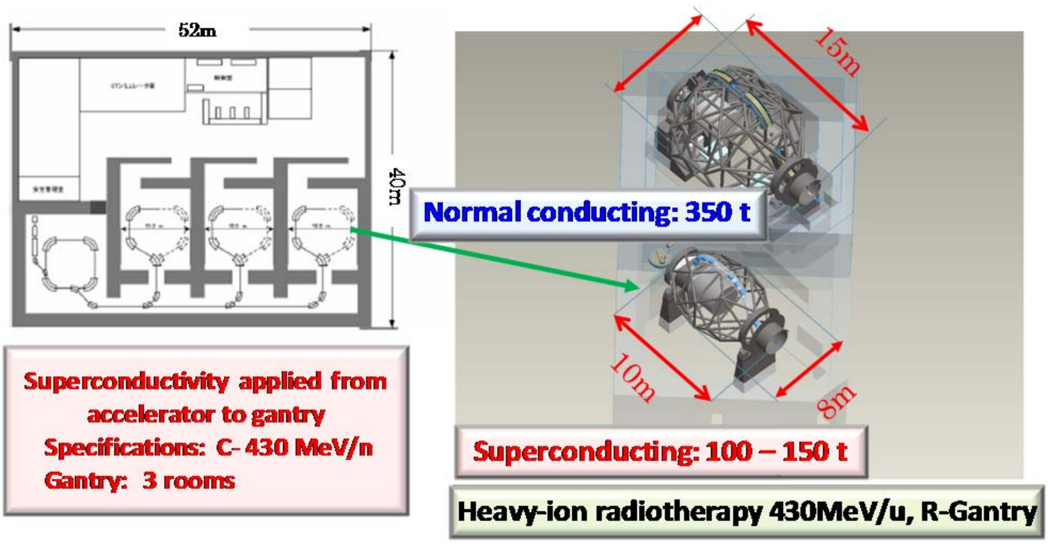
Fig. 7 shows expected size reductions of both accelerator main unit as well as gantry by introduction of high temperature superconductivity technology.

A charged particle moving in a magnetic field follows a curved path. A charged particle with mass (*m*) and an electrical charge (*e*) moving vertically in a uniform magnetic field with flux density *B* at a speed *v*, has a resulting Lorentz force F acting on the particle in a circular orbit is determined by evB and r. The following expression can be written when the centrifugal and Lorentz forces balance:

$$mv^2/r = evB$$

This suggests that the bend radius (r) of a heavy-ion beam can be reduced further with the application of an even greater magnetic field (high B), thus the system can be compacted further. Employing high temperature superconducting technology in place of currently available normal conducting magnets is anticipated to bring significant reductions in the heat generation and also reduce Joule heating losses, thereby significantly reducing electricity costs that are estimated to be equivalent to an annual saving of several 10's of millions of Yen, even when considering the costs associated with the superconducting cryocool system.




*Source: Koji Noda, Research Center Hospital for Charged Particle Therapy of the National Institute of Radiological Sciences*
*25th Int'l Sympo. On Superconductivity, Tokyo, Dec. 5, 2012*

Fig. 7 High temperature superconducting Super MINMAC

(3) Third-generation superconducting conductor development

Only coiling development utilizing existing high temperature superconducting CCs along with their associated processing technology, will allow the functional characteristics of high temperature superconducting CCs in the above-mentioned MRI systems to be realized in the main unit as well as in the gantry of particle beam medical accelerators. However, the cost effectiveness of high temperature superconducting technology applied to establish new pioneering technology is determined by further

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reductions in costs and the spatial and temporal homogeneity of the magnetic fields generated. A common basic technology to enable studies and evaluate performance characteristics including CC performance homogeneity/low costs, ultra-low resistance jointing technology, liquid helium-free cryocooling technology, and CC /coil performance (homogeneity in particular) to be determined is therefore inevitable. A planned developmental theme running in parallel with coiling technology development has been publicized, which clearly states the objectives of the intended development.

High temperature superconducting CC development has progressed with critical currents, conductor piece lengths and costs being benchmarks for future studies. The functional verification of superconducting equipment as a substitute over normal conducting equipment has also advanced. The future of R&D studies into high temperature superconducting CCs seeks to establish their absolute superiority over competitive equipment and technology employing normal- conductors, based upon functional verification tests conducted up until now. Furthermore, magnetic field applications require temporal/spatial homogeneity of the magnetic field generated. Here, being different to power equipment applications, significant improvement of CC in-field property uniformity and homogeneity, production yield improvement and low costs are highly desired.

Conductor performance enhancements will inevitably lead to low unit prices per Am, and the current aim from a material and capital facility cost viewpoint (facilities introduction expense /maintenance) is around 2,000-3,000 Yen/m. Future development of third-generation (3G) superconducting conductors is anticipated to result in establishing a world-leading superconductivity technology, producing 3G-conductor satisfying the following target characteristics that the author already proposed at the first time in the world.

. Ultra-high critical current: $I_c$, e.g.2000 A/cm-width, 2 μm-thickness, ($J_c$>10 MA/$cm^2$)@77 K, self-field
. Ultra high critical current in high magnetic field: $I_c$, $_{min}$-B, high $B_{c2}$ conductor e.g. 500A/cm-width@65K, 4T
. Degree of in-plane grain alignment: $\Delta\phi < 2°$
. Performance uniformity: conductor width & longitudinal homogeneity of less than 0.5 %, performance homogeneity between wires of less than 1.0 %
. Low cost: 1 Yen/Am@65 K, Figures 8~10 show the specific performance of 3G- *conductors compared to the theoretical critical current densities and 2G conductor (Fig.8), in-field critical current densities compared with 1G, 2G and 3Gwires(Fig.9), and $J_c$-B-T map compared to 2G and 3G- conductors (*Fig.10).

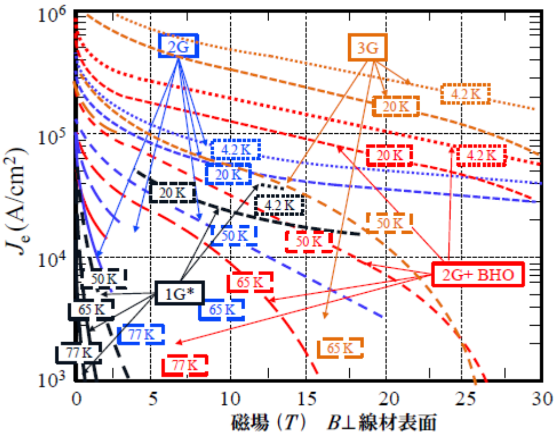


Fig. 8 Critical current density characteristics（$J_c$-T) and theoretical limitation value of pair breaking current （$J_d$-T) for 2G and 3G wires

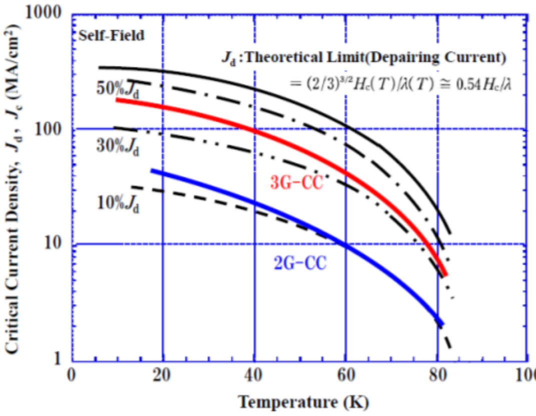


Fig. 9 In-field critical current characteristics of each type of wires

  

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3G- conductor development has progressed since last year thanks to large-scale wind power generators developed under the ARPA-E project led by Department of Energy (DOE), USA. Europe and Korea also plans to launch a new Y-based superconducting development project, thus intensifying future competition between Japan, USA, Europe and Korea in this field.

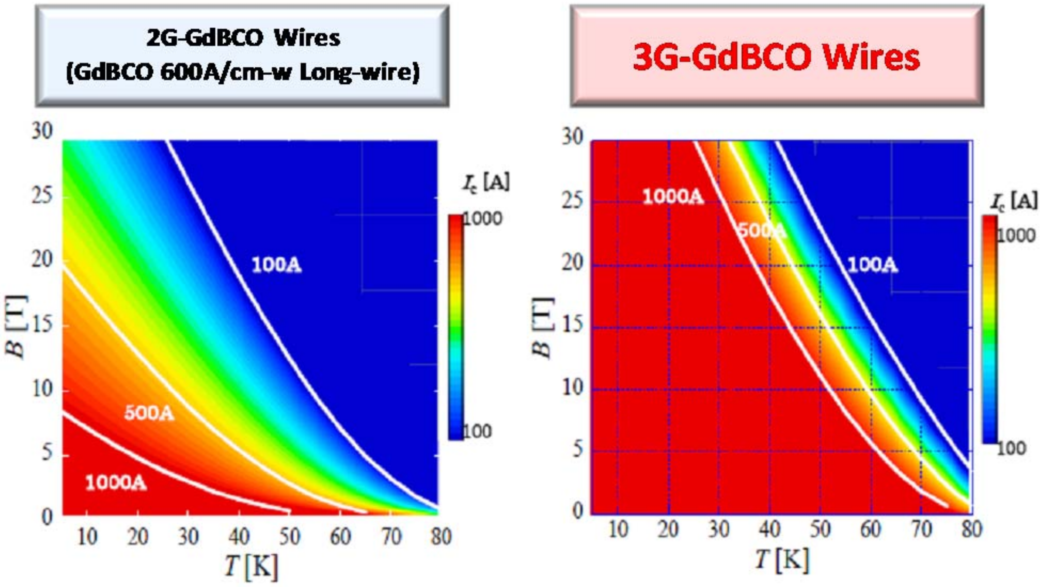


Fig. 10 $I_c$-T-B map of 3G-3GdBCO wires

## 2.2 Development of ultra-large-scale offshore floating wind turbine generators

Wind turbines have a vast interrelated industrial presence with each turbine comprising of more than 10,000 parts. Amongst renewable energies, it offers the greatest progressive market spread worldwide with a record-breaking wind power generation of 237 GW recorded at the end of 2011. In Japan, cost reductions associated with wind power generation are inevitable by improving the facility operation rate and will further promote the market. The generator components (generator, gears, blades, poles, floating platform, etc.) will need to be tolerant to Japan's specific climate (typhoons, air turbulence, lightning strikes) and are required to operate at their maximum efficiencies at all times. Additionally, it needs to offer significant operational improvements during such aforementioned natural conditions with reduced frequency of reported accidents or faults. As well as power generation performance enhancements made by improving wind turbine parts and components, the size of which increase on an yearly basis, equivalent reliability and performance factors need to be improved to realize reduced power generation costs. To develop practical wind turbine components with high performance characteristics the plans are to review materials selections, the wind turbine design and enhance the performance (greater efficiencies, large-scale, light-weight) of major components such as generator/gear/blade.

This R&D aims to develop innovative technologies ranging from basic to application research related to wind power generation, along with the planning and introduction of offshore wind power turbine guidelines

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and the preparation of a risk map highlighting areas at greatest risk to lighting strikes. These are all undertaken to further the market expansion of wind power, strengthening industrial competiveness and realizing power generation costs equivalent to other renewable energies over the mid and long-term future. Worldwide research and development has been undertaken for the production of a greater-than 5 MW large-scale offshore wind turbine. It is therefore expected that the future market will expand remarkably and moreover, will be an arena where the competitive strength of Japanese companies developing materials, parts and components and international market presence will be established.

Specific R&D topics required to develop practical wind turbine components with high performance characteristics include the necessity to enhance the performance, reliability and maintenance of major components and parts such as generator and blades. These are required to improve system integrity by reducing fault frequencies and their resulting downtimes, thereby increasing wind turbine operation rate / power generation capacity.

CCs exhibit high critical current characteristics ($I_c$) in high temperature/high magnetic fields. It is therefore expected that this will benefit a number of applications from an energy savings point of view. The power output from a rotor such as found in a synchronous motor increases proportionally to the numbers of revolutions. Future developments in this area are expected to benefit industrial motors (>1000 rpm) and ship propulsion motors (100-300 rpm), which will both realize significant energy savings. The permanent magnet found in the rotor of a synchronous motor can be replaced by a field winding coil (electromagnet) fabricated using CCs, the aim being to significantly reduce the consumption volume of rare-earth metals such as Nd and Dy, which make up permanent magnet materials.

Renewable energies aimed to reduce $CO_2$ emissions with the development of superconducting wind turbines (several tens rpm) will make them compact & lightweight, with greater efficiencies and higher capacities than their normal-conducting counterparts and thus further developments are planned in both USA and Europe. Figure 11 shows the limitations associated with normal-conducting power generator capacities and the necessity of ultra-large-scale wind power generators proposed for Japan. Normal-conducting power generators are now reaching their 10 MW limitations because of the nacelle weight. With Japan's characteristic shoreline with a little shallow seabed, issues with wind power generation need to take into account (large-scale, utilization/operation rate improvement, off-shore utilization expansion, cost reduction), which are to be addressed with the introduction of a floating offshore wind power generator. Considering the costs associated with building a floating-style supporting structure that can withstand tsunamis in Japan exceeding 20m, makes only the ultra-large-scale (>15 MW) wind turbine economically viable and therefore rules out normal-conducting wind generators. Important factors needed to realize this include a lightweight iron-core free generator and efficiency improvements by employing a synchronous generator as well as a speed-increaser gearbox for minimum maintenance requirements, all leading to more recognition that replacing the field winding coil with a CC electromagnet is important. Since the amount of wind power generated varies proportionally with two times the wind turbine blade size, an ultra-large-scale offshore floating wind power generator can generate the power capacity needed to breakeven. Therefore, by integrating Japan's world-leading high temperature superconducting technology and applying this to offshore floating wind power generators, is highly anticipated to bring about the realization of Japan's large-scale wind power generation.

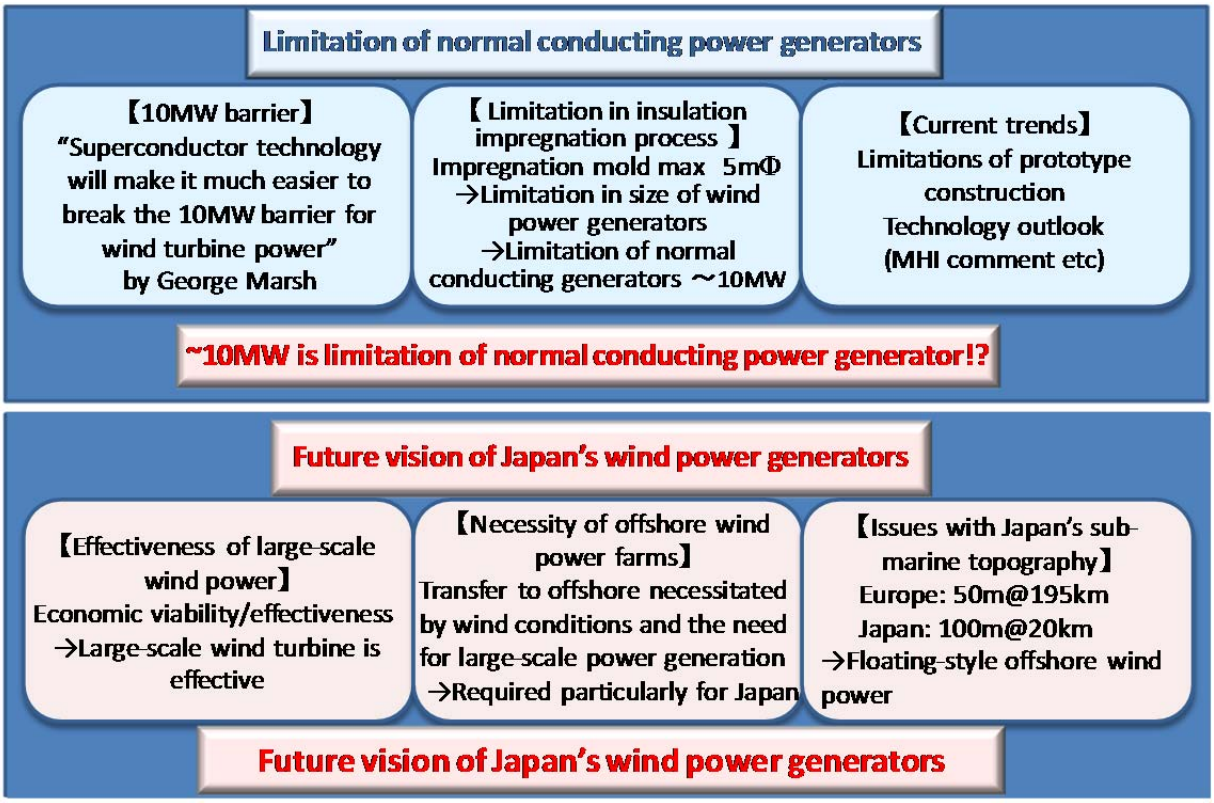


Fig. 11 Limitation of normal conducting capacity and Japan's future wind power generators

## 3. Current status of high temperature superconductivity R&D

Finally, the forum concluded with a summary of high temperature superconductivity R&D using a Gartner Inc. Hype cycle (http://www.gartner.co.jp/research/methodologies/resear_hype.php), which depicts the maturity, visibility and the degree of societal applicability of specific technologies. The phases in the evolution of this technology included, "*Technology Trigger, "Peak in Inflated Expectations, "Trough of Disillusionment", and "Slope of Enlightenment*". Along with this is the author's view of the stages related to the technological research on BSCCO (1G) conductors, REBCO (2G) conductors and 3G conductors, superconducting power equipment (transmission cables, transformers, SMES), magnets for offshore floating wind power generators, MRIs, HTS heavy-ion medical accelerators, and room temperature superconductivity (Refer to Figure 12).

The hype cycle allows analysis of the entire life cycle, which can be divided into the aforementioned five stages, enabling us to understand the maturity process and the market spread (adoption and applicability) of the wide-ranging technologies and applications. New emerging technologies and applications appearing in the market are initially praised (or there is hype surrounding them), and then go through a period where the initial hype subsides, finally reaching a stage where their place in the market becomes clearer and well defined. The hype cycle aims to show the typical pattern of behavior.

  

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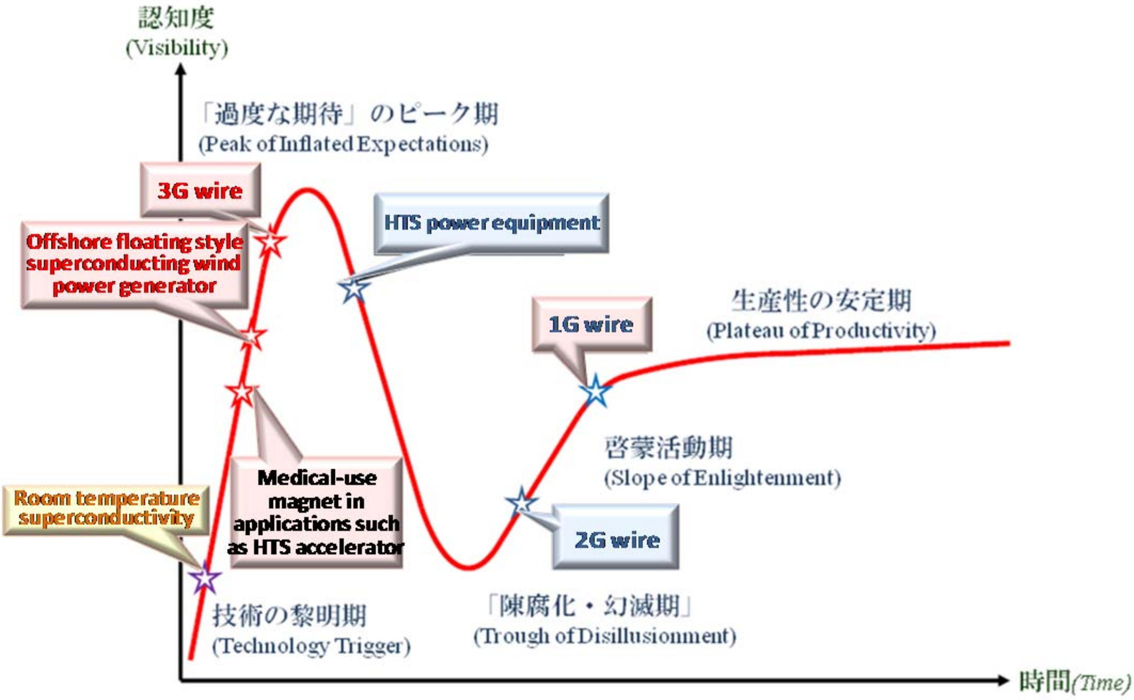


Fig. 12 Hype cycle of high temperature superconducting technology

The cycles can be defined as follows:

*Technology Trigger:* this could potentially be an epoch-defining technology, however, early PoC (proof-of-concept) technologies generate significant media exposure designed to grab publicity. Ordinarily, there is no usable product that PoC technologies can be directly applicable to and commercial viability is unproven.

*Peak in "Inflated Expectations":* Publicity fervently acknowledges only a few success examples of this technology during this stage of the cycle. However, in the background there often lie a number of failed attempts. Some companies react at this stage, but the majority adopt a 'wait and see' approach.

*Trough of Disillusionment:* Interests being to wane as the initial promise fails to deliver inflated expectations. There is a vendor shakeout where some survive and other become extinct. Technology investments only continue if vendors improve product offerings to the satisfaction of early adopters, and as such, reap the benefits.

*Slope of Enlightenment:* Learning from failures, the applicability of this technology gradually emerges from early-adopter experiences. It is when companies begin to understand and appreciate the viability of this technology. Surviving technology vendors supply second-generation products. Risk-taking companies begin adopting the technology whereas risk adverse companies take a certain degree of risk by funding pilots. Conservative companies on the other hand remain cautious.

*Plateau of productivity:* Market introduction and mainstream adoption begins. The technology's broad market applicability and relevance has matured to an appropriate level and the benefits to companies afforded by this technology are clear. The criteria for assessing vendor viability are more clearly defined. The final level in the plateau of productivity is determined by the market size, its viability and its applicability in a niche marketplace.

  

The author expects the future development of high temperature superconducting technology will emerge as one of Japan's important technologies, with integral collaborations between industries, government and academia.

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# Feature Article: Reporting on the 2013 Forum on Superconductivity Technology Trends
# High Temperature Superconducting Magnetic Energy Storage (SMES) R&D (2) ~ Operational Effects of Yoroi-Coil

Shigeo Nagaya, Director
Superconductivity Group, Electric Power R&D Center
Chubu Electric Power Co., Inc.

SMES is the greatest benefactor amongst coil applications exploiting current Yttrium-based coated conductors compared to other equipment and fields. The reason behind this is the functionality of the superconducting coil in an SMES is to store magnetic energy, which can be said to be satisfied as far as current flows.

The strength and weakness from the Yttrium-based materials viewpoint featured in a previous issue. Practical wires for coiling applications are restricted by their lengths. Development has aimed for the fabrication of long wires but has been actually limited to around 2~300m due to yield and cost issues. While such wire lengths are applicable for use in a research setting, the wires would need to be joined together for commercial level superconducting-equipment environments. It is not possible to join Yttrium-based wires because of their fabrication methods and wire structures.

Both MRI and accelerator applications require a precise and stable temporal magnetic field and thus the inability to join superconducting wires would be detrimental to their overall performance. On the other hand, SMES do not suffer from such issues since any joins are thermally loaded and moreover, only manage the cooling balance of the entire coiling system. Therefore, joining short length wires can be used to make up long wires without a restriction placed on wire supply.

Figure 1 shows comparisons between the storage costs incurred for original Yttrium-based wire applications and a Yoroi-coil applied this time, including a SMES operated as an instantaneous voltage drop compensator. The coil exhibiting 20 MJ of storage energy is currently in practical operations as an instantaneous voltage drop compensator. By employing a Yoroi-coil the resulting increase in strength is able to accommodate greater hoop stresses, thereby allowing large diameter coils to be fabricated. Furthermore, since the load factor of the wire improves at the same time the initial design of the 20 MJ-class SMES with a 60cm coil can now be improved with an 80cm coil, enabling about 10 times the energy storage. Costs increase by only 20% due to increases in wire utilization rates whilst the wire volume increases.

Figure 2 shows comparisons between the numbers of discharges and charges at a power output of 10,000 kW. SMES do not suffer from battery memory storage effects because of repeated discharge and charge cycles. However, the degree of memory storage effect is determined by the capacitor and battery, and which needs to be increased to accommodate large numbers of discharge and charge cycles.

  

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## Energy storage costs comparisons for Y-based SMES and Electric double-layer capacitor

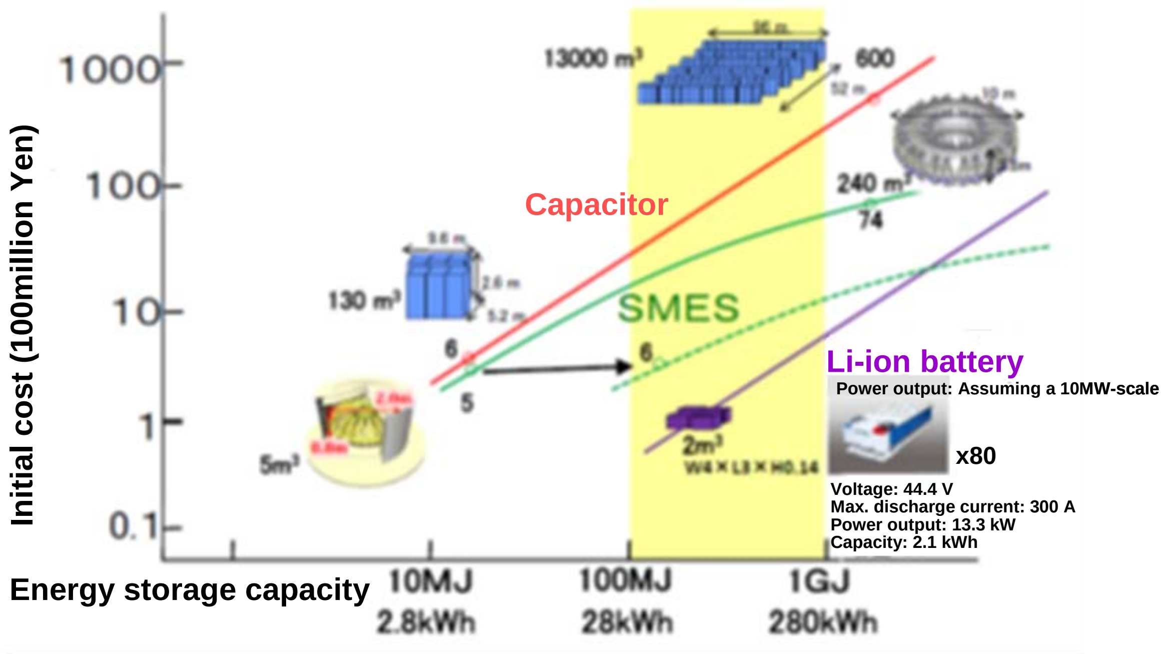


Fig. 1

## Energy storage costs comparisons for Y-based SMES, capacitor, and Li-ion battery (Power output 10,000kW)

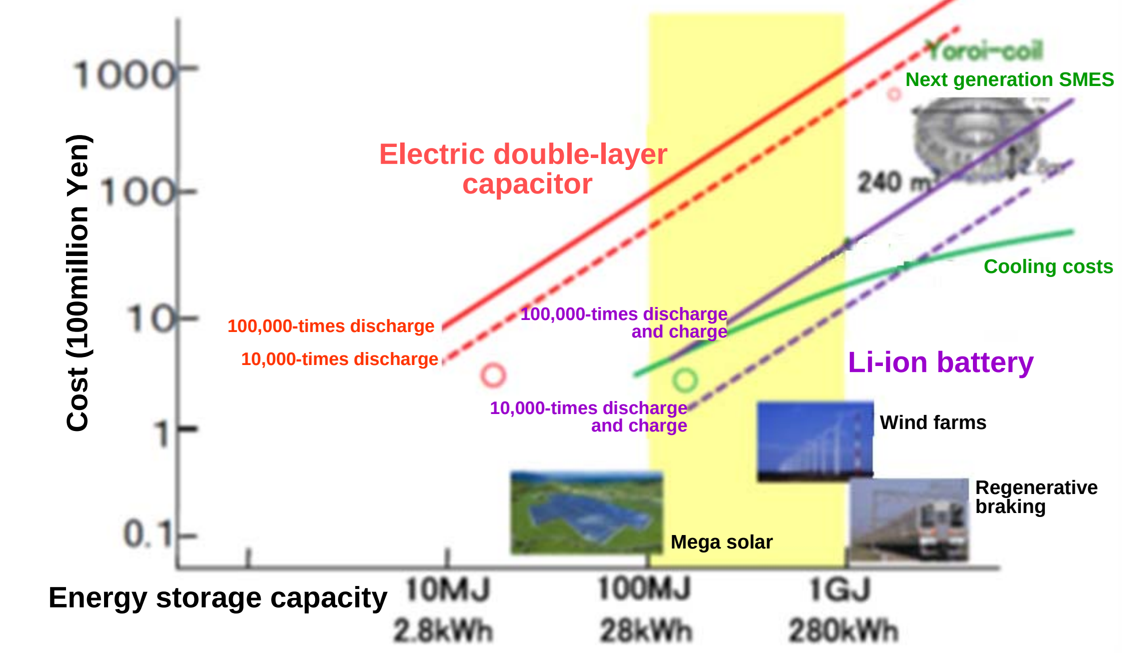


Fig. 2

  

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Table 3 shows comparisons between types of power storage system and SMES. The weak low energy density characteristics of the SMES have significantly improved with the application of the Yoroi-coil.

Table 3 Comparisons between types of power storage systems

| Type | Ni-hydrogen | Li-ion | NaS | Superconducting flywheel | Electric double-layer capacitor | SMES |
|---|---|---|---|---|---|---|
| Cost (10,000 Yen/kW) | △ **10** | △ **20** | △ **24** | ◎ **7** | ◎ **5** | ◎ **2～6** |
| Life (the number of cycles) | △ 5-7 years 2000 times | △ 6-10 years 3500 times | ○ 15 years 4500 times | ◎ Over 20 years no limitations | ○ 15 years more than 100,000 times | ◎ Over 20 years no limitations |
| Capacities | △ ~MW-class | △ Up to 1MW-class | ○ More than MW-class | ○ Single unit MW Parallel requirement | ◎ 10MW-class | ◎ More than 10MW |
| Measuring and monitoring charging status | △ | △ | △ | ◎ | ◎ | ◎ |
| Safety | ○ | △ | △ | ○ | ○ | ○ |
| Temperature management required | ○ Nil | ○ Nil | △ (≥300℃) | △ Cooling required | ○ Nil | △ Cooling required |
| Energy density (Wh/L) | 40～100 | 200～300 | 144 | 66 | 0.04 | Metal-based : 0.1 Y-based : 1 YOROI:6 |

SMES functionality has so far been investigated in terms of its applicability to large-power output fields with many second-order charge and discharge cycles. It is deliberated whether high strength coiling technology developed at this time will be a future device allowing the market expansion of renewable energies and smart grid power networks.

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