Hitachi’s Leading Superconducting Technologies

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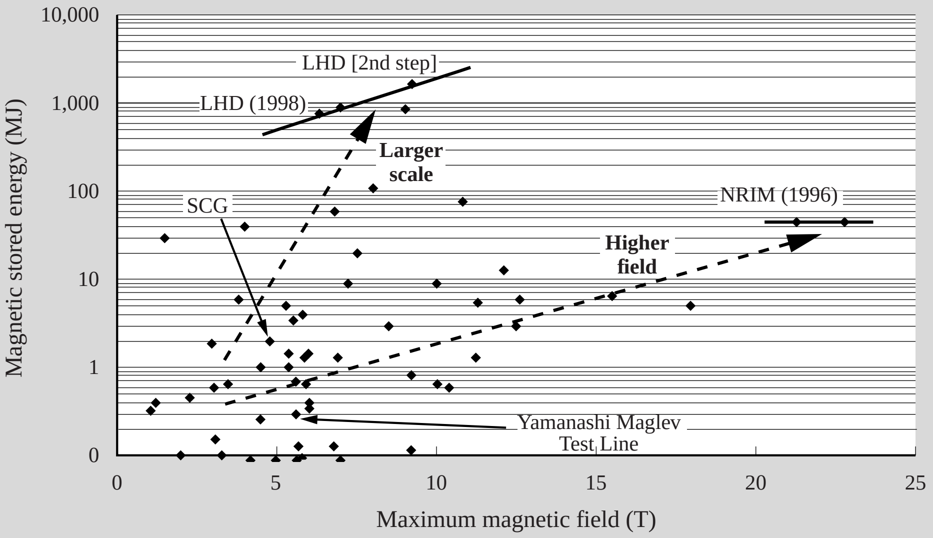
OVERVIEW: Over 30 years have passed since Hitachi began researching superconductors and superconducting magnets. Its scope of activities now encompasses everything from magnetically levitated vehicles and nuclear fusion equipment to AC generators. Three big projects that use Hitachi superconductors are currently underway in Japan: the Yamanashi Maglev Test Line, the Large Helical Device (LHD) for nuclear fusion and the 70-MW model of superconducting power generator. Hitachi has played a vital role in these projects with its materials and application technologies. In the field of high-temperature superconducting materials, Hitachi has made a lot of progress and has set a new world record for magnetic fields.

INTRODUCTION

HITACHI started developing superconducting technology in the late 1950’s. At first, it focused on superconducting magnets for magneto-hydro-dynamics (MHD) power generators, but eventually broadened its research to applications such as magnetically levitated vehicles, nuclear fusion equipment, and high energy physics. Recently Hitachi’s activities have spread to the medical field (magnetic-resonance-imaging technology) and other fields (AC power generators and superconducting magnetic energy storage).

One of the problems of superconducting technology is cryogenic stability because of the extremely low temperatures, but we have almost solved this problem by developing fine multiple-filament superconductors and various materials for stabilization matrixes, both of which operate at liquid helium temperature (4 K), as well as superconductor integration technology and precise winding technology. These new developments have led to a number of large projects in Japan. They are (1) the world’s largest (70 MW) model super-conducting generator for generating electric power, (2) the Yamanashi Maglev Test Line train, which may eventually be able to transport people at a speed of up to 500 km/h, and (3) large helical device (LHD), which



NRIM: National Research Institute for Metals

Fig. 1— Superconducting Magnets Manufactured by Hitachi.
The amount of stored energy and magnetic fields of superconducting magnets have recently become high.

is the world's biggest superconducting system for nuclear fusion.

Hitachi has played a vital role in these projects and contributed to their success. In this paper, we introduce new developments at Hitachi and their relation to these big projects.

RECENT SUPERCONDUCTING TECHNOLOGY

Fig. 1 shows Hitachi's superconducting magnets classified by maximum magnetic field and magnetic stored energy. The biggest one of stored energy the large helical device (LHD) of the National Institute for Fusion Science (NIFS) has the highest magnetic stored energy capacity. The magnet with the highest magnetic field is the one for the Multi-core Project of National Research Institute for Metals (NRIM), which made a world record. They show that Japanese superconductor technology is among the best in the world.

Because the heat capacity of metals at very low temperatures reduces to several thousandth of the capacity at room temperature, the superconducting state is easily affected by small perturbations such as conductor movement and friction. To solve this problem, we developed various stabilization matrixes and methods. For example, we used a pure aluminum stabilizer in the conductors of the LHD and the superconducting generator. We chose Niobium-Titanium (NbTi) superconductors for the three big projects, because of their three-dimensional shaped winding. For forced-flow-cooled superconductors, other compound materials such as $(Nb\text{-}Ti)_3Sn$ and Nb_3Al have been developed. These technologies will be applied to large nuclear fusion reactors and energy storage uses. In the high-temperature superconducting field, we developed a coil made by oxide material which made world record of maximum magnetic field.

SUPERCONDUCTING APPLICATION SYSTEMS

Superconducting Generator

The site tests of the 70-MW-class superconducting generators (SCGs) were finished in June 1999 in collaboration with Mitsubishi Electric Corporation and Toshiba Corporation. This project, called Super-GM project, was carried out as part of the New Sun Shine Program of Japan's Ministry of International Trade and Industry (MITI) and was consigned by the New Energy and Industrial Technology Development Organization (NEDO). The site tests provided valuable data for future 200-MW superconducting pilot generators.

Fig. 2—70-MW Class Superconducting Generator in the Super-GM Testing Center.
A world record output of 78.7 MW was recorded in November 1997.

The 70-MW-class SCGs have been improved over previous SCGs as follows:

(1) Better power system stability (120% to 150% sending power capacity improvement)
(2) Better efficiency (0.5% to 1.0%)
(3) More compact (30% to 50% lighter)

The rotor comprises multiple cylinders and the gaps between the cylinders are vacuums for thermal insulation. The field winding of the rotor is a NbTi superconductor and is cooled by liquid helium (4 K). The liquid helium is supplied in the rotating rotor (3,600 rpm) through a helium transfer coupling (HTC) sealed by the magnetic fluid.

The stator uses a water-cooled double-transposed armature winding to endure the strong flux density of the superconducting field winding. This armature winding is supported by fiber reinforced plastic (FRP) teeth.

This SCG recorded the highest output ever (78.7 MW) in the Super-GM Testing Center in Osaka in November 1997 (Fig. 2). The former record was 20 MW in the US. This stator was also assembled with another rotor and evaluated under a 1,500-hour long-term test in August 1998. A quick-response excitation test was also carried out with the other rotor in 1999, successfully.

In the final stage, this generator was connected to the power system in order to investigate the power system stability in collaboration with the Kansai Electric Power Co., Inc.

Based on these results, we are going to research the 200-MW SCG development as the next step.

Nuclear Fusion and High-energy Physics

(1) Nuclear fusion

The big fusion systems of the magnetic confinement type need superconducting coils to reduce power loss. The Large Helical Device (LHD) of National Institute for Fusion Science (NIFS) is the world's largest stellarator. It has two superconducting helical coils, and a vacuum vessel 3.9 m in major radius and 1.6 m in minor radius. The helical coils produce a magnetic field of 3 T and a stored energy of 0.92 GJ in the 1st phase (the field and energy will be improved to 4 T and 1.64 GJ in the 2nd phase). The plasma specifications require a very high current density of 40 A/mm^2 (53A/mm^2 in the 2nd phase). Many new technologies, such as high-purity aluminum stabilizer and high accuracy 13-axis numerical controlled winding machine have been developed to satisfy this requirement. The first plasma was produced on March 31, 1998, and the LHD is currently being operated satisfactorily.

The fusion reactor of the next generation is the International Thermonuclear Experimental Reactor (ITER), which will need a large superconducting system. The Japan Atomic Energy Research Institute (JAERI) is developing a central solenoid coil (CS coil) which comprises $(Nb\text{-}Ti)_3Sn$ and Nb_3Al superconducting coils. They will be tested by JAERI.

(2) High energy physics

In the field of high-energy physics, we completed the final focus superconducting magnet system for the interaction region of KEK-B project constructed by High Energy Accelerator Research Organization (KEK). It is in stable operation and the first collision event was observed on June 1, 1999.

Superconducting Ring Cyclotron (SRC) for the Radioisotope Beam Factory (RIBF) of RIKEN (Institute of Physical and Chemical Research) is under construction. Once completed, it will be the world's largest superconducting cyclotron.

Magnetically Levitated Transportation System

(1) The Yamanashi Maglev Test Line

Test runs of the superconducting magnetic levitation (maglev) railway were started at the Miyazaki Test Course in 1977. Yamanashi Maglev Test Line was constructed in Yamanashi Prefecture, where test runs are being conducted today. The Yamanashi Maglev Test Line began operation in 1990 under a project team consisting of the Central Japan Railway Company, the Railway Technical Research Institute, and Japan Railway Construction Public Corporation. Hitachi contributed to this project by developing superconducting magnets and making the ground coils, lightweight car bodies and trucks, and power converters.

Fig. 3—External View of the Yamanashi Maglev Vehicle.
Achieved a world record of 552 km/h in April 1999.
(Photo by Railway Technical Research Institute)

The test runs started in April 1997, and after several efforts to increase the speed, a record of 550 km/h was reached on schedule in December 1997 (Fig. 3).

When the record was achieved, the car formation consisted of three vehicle bodies with a total length of 78 m. It included two superconducting magnets made by Hitachi. Four other magnets were delivered later.

(2) Superconducting magnet

The superconducting magnet for the Yamanashi Maglev Test Line is 5.4 m long, has a current at 700 kA of each coil (quadrupole), and a levitation force per superconducting magnet of 108 kN.

A superconducting magnet for magnetic levitation is quite a bit different from that for other uses, particularly in its operation in dynamic force and fluctuating magnetic fields, which cause the superconducting instability. The aim of the developing superconducting magnet for the Yamanashi Maglev Test Line was to find the countermeasure against these fluctuating magnetic field and mechanical vibration.

The eddy current flows in the vacuum vessel by being exposed to the fluctuating field from the ground coils, and the eddy current and the field of the superconducting coils generate vibrating electro-magnetic force. In the cryogenic portion, mechanical vibration generates heat by friction and the fluctuating magnetic field generates heat by joule loss. This heat generation evaporates the liquid helium at these cryogenic portions. The main problem in the development of superconducting magnets is to suppress the heat generation to below 8 W, which is the gas helium liquefying capacity of the refrigerator.

For this, we have newly developed the eddy current analysis technology and the compounding vibrational analysis technology with the cooperation of the Central Japan Railway Company, and fixed the optimum support system and whole structure by these analyses.

The Central Japan Railway Company and the Railway Technical Research Institute conducted this research. The Ministry of Transport is subsidizing the Yamanashi Maglev Test Line.

DEVELOPMENT OF SUPERCONDUCTING MATERIALS

High-temperature Superconducting Wires

The development of a high-temperature superconducting (HTS) wire operable at the temperature of liquid nitrogen (77 K) has eliminated the need for liquid helium, which is expensive and difficult to handle without an understanding of cryogenics, in operating superconducting apparatus. The HTS crystal is ceramic with a platelet shape. To obtain a large current-carrying capacity in inter-grain of the superconducting wire, the crystals must be aligned in one direction. A typical HTS wire comprises more than a few hundred thousand crystals per centimeter, so Hitachi's scientists are developing advanced technologies for controlling the alignment of the crystals as.

(1) CUTE silver tape substrate

One of these technologies, developed in collaboration with the University of Kyoto, is called "CUTE (cube textured) silver tape." This technology enables us to tile the HTS crystals on a tape. Although the CUTE silver tape looks like conventional silver, the surface of the tape shows a microscopic, ordered structure (Fig. 4). HTS tapes formed on this silver tape are aligned by the CUTE structure in one direction so that the superconducting current can flow easily. Since CUTE silver tape is made by rolling, it is easy to mass produce. So far, we have fabricated 100-m length of the HTS tape conductor.

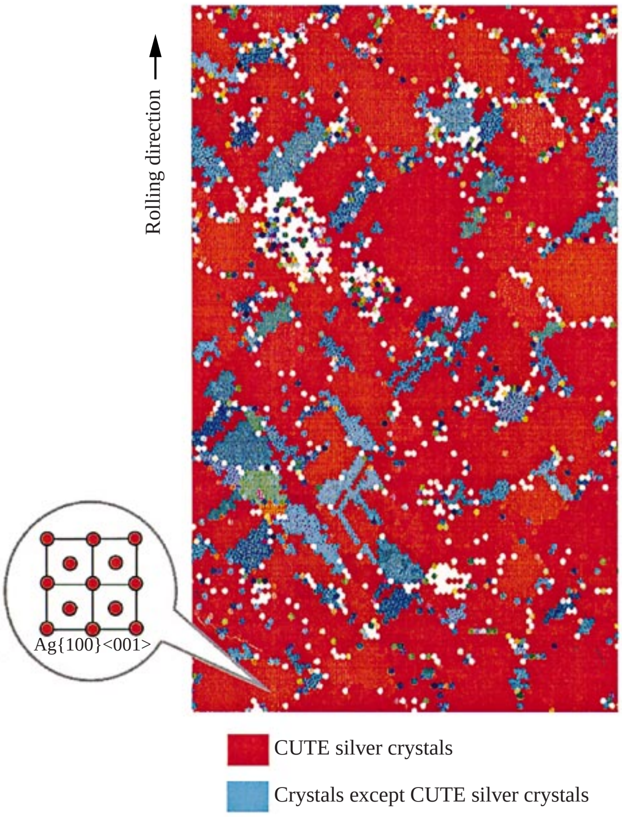


Fig. 4— Mapping of the Crystal Alignment of CUTE Silver Tape.
Almost 90% of silver crystal could govern the alignment of the direction of HTS crystals to be formed on this surface.

(2) Tl-1223 wires

Under MITI's "New-Sunshine Project," Hitachi is proceeding with the "Tl-1223 HTS wire development program," conducted by NEDO. While many scientists form the HTS films by using a vacuum, Hitachi employs an ambient pressure condition by spray-pyrolysis processing. The method is quite simple. Vaporized mist of a precursor material of HTS is sprayed directly on a heated silver tape substrate, then the film is heat treated in a thallium vapor atmosphere. Today, these tape conductor can be produced at a rate of about 1 m per hour. However, because this method is so simple, the rate could easily be increased to industrial levels. The Tl-1223 crystals formed on the CUTE silver metal show a microstructure aligned in one direction, which allows current to flow easily. The critical current density of the tape is 100 kA/cm^2 at 77 K, 0 T.

Conductors for High Magnetic Field

Bi-2212 which is also an HTS material like Tl-1223, shows an excellent critical field property as compared with conventional metallic superconductors at low temperatures. Bi-2212 HTS wires of some km-class are now available and are getting a new position of conductors in the practical high magnetic field applications. Advanced metallic superconductors are also being developed. The critical current density of Nb_3Al is improving, opening the possibility of 23.5-T magnetic field applications. These conductors are expected to be used in such applications as fusion

Fig. 5— Photograph of 20-Stack Double Pancake Magnet.
Outer diameter is 158 mm, inner diameter is 64 mm, height is 220 mm. Tapes totaling 1 km were used for winding. Max. field 18 T at 18-T backup magnetic field.

reactors, accelerators, and MRI magnets.

(1) Bi-2212 wires

The crystals in Bi-2212 conductors must also be aligned in one direction so that current can easily flow. Hitachi employs a special powder-in-tube (PIT) method, modified to control the power density and oxide/silver interface area. The multiple-filament tape-shaped wire shows one of the best transport current density (4,700 A/mm^2 at 4.2 K and 0 T and 1,700 A/mm^2 at 4.2 K and 30 T). Fig. 5 shows 20-stack double pancake magnets (outer dia. 158 mm, inner dia. 64 mm, height 220 mm) wound by tapes with a total length of 1 km. This magnet operates as the inner magnet of 21-T-class superconducting magnet at the Tsukuba Magnet Laboratory of NRIM. As of March 1999, the magnet has generated a maximum magnetic field of 5.4 T with a backup field of 18 T, thus the total magnetic field reached 23.4 T.

Because it is not easy to control the width or thickness of the tape, round- or rectangular-shaped wire should be developed as the next-generation high-quality magnets. In collaboration with Hitachi Cable, Ltd. and NRIM, Hitachi recently developed a new Bi-2212 round-shaped wire with a large enough current carrying capacity for practical application. This wire, called ROSATwire (rotation-symmetric arranged tape-in-tube wire), consists of multiple tape-shaped filaments with triple rotation symmetry. Because a large number of tape-shaped filaments are stacked in the round-shaped wire, the Jc of the ROSATwire shows an excellent transport property comparable with tape shaped wire, i.e. 2,500 A/mm^2 at 4.2 K and 0 T.

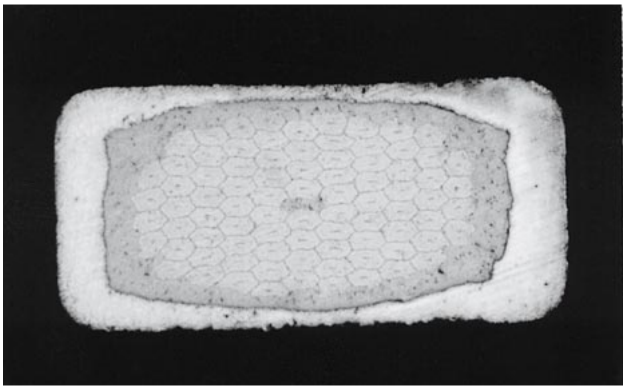


Fig. 6— Cross Section of Nb_3Al Wire Made by the Rapid-heating/Rapid-quenching Method.
Outermost bright part is copper, the part just inside the matrix (dark area) is Nb, and the hexagonal part is Nb_3Al.

(2) Rapid-heating/rapid-quenching method for Nb_3Al

Since the stoichiometric ratio of 3:1 between Niobium to Aluminum shifts during heat treatment through previous Nb_3Al wire processing, the transport property begins to degrade at over a 16-T magnetic field region. Hitachi, in collaboration with Hitachi Cable, Ltd. and NRIM, has developed a new process that enables Nb_3Al wire to be used in magnetic fields of up to 23.5 T, which is the best performance so far for a metallic superconductor. This wire has fine Nb_3Al filaments in Nb matrix, and is covered by copper for stabilization of superconductivity (Fig. 6). Using a rapid-heating/rapid-quenching method in which a precursor wire consisting of Nb and Al is heated up to 2,000°C, then exposed to continuous quenching at low temperature with a metallic Ga bath, we can overcome the problem of stoichiometric ratio shift. A critical current density of 200 A/mm^2 at 1.8 K and 23.5 T was achieved.

CONCLUSIONS

This paper described Hitachi's recent development in superconducting technology. This technology will become more familiar as the number of applications grows. The advantages of this technology are continuous high magnetic fields and no joule loss, so it will have an effect on energy conservation and reduction of environmental pollutants. We will continue with our efforts to improve superconducting technology, which is responsible for social needs.

REFERENCES

(1) N. Suzuki et al., “Hitachi Research Development on Superconducting Technology,” JAPAN, 21st (1192-7).

(2) O. Motojima et al., “Progress Summary of LHD Engineering Design and Construction,” 17th IAEA Fusion Energy Conference, Yokohama, Japan, 19-24 (1998-10).

(3) K. Tsuchiya et al., “Final Focus Superconducting Magnet System for the Interaction Region of KEKB,” EPAC98, 20-38 (1998).

(4) H. Tsuruga et al., “Superconducting Magnetic Levitation Transportation Systems on the Yamanashi Maglev Test Line,” *Hitachi Review* **46**, No. 2 (1997), pp. 89-94.

(5) M. Terai et al., “Superconducting Magnet and Ground Coils for the Yamanashi Maglev Test Line,” *Hitachi Review* **46**, No.2 (1997), pp. 95-100.

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