Cryogen-free Superconducting Magnet

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Cryogen-free superconducting magnets are becoming popular due to their simple operation compared with conventional liquid helium cooled magnets. JAPAN SUPERCONDUCTOR TECHNOLOGY INC. has manufactured more than a hundred cryogen-free superconducting magnets based on technologies developed by the R&D division of Kobe Steel. The company has the largest worldwide market share. This report describes the basic features of cryogen-free magnets, as well as related recent and future developments.

1. Features and structures of cryogen-free superconducting magnets

Superconducting magnets are advantageous for use in applications for which conventional electromagnets are not applicable, such as high magnetic fields in large spaces, because they can utilize large current densities. However, their application has been limited to physical experiments and chemical analysis, because cooling by liquid helium requires specialists having expert knowledge of cryogenics.

Although a concept of cooling superconducting magnets for operation, using a compact cryo-cooler instead of liquid helium, was discussed in 1982 [1], the concept could not be brought into practice, due to the limited cooling power of the compact cryo-cooler and to the heat penetration from metallic leads, required to carry high current to charge the magnet. A Cryogen-free superconducting magnet was realized in the 1990s, after the development of Gifford-MacMahon (GM) refrigerators[2], which enabled cooling down to around 4K, or the boiling point of liquid helium, using magnetic regenerator materials, and current leads made of oxide superconductors (high temperature superconductors) [3], which maintain superconductivity up to about 70K.

Figure 1 shows a general structure of cryogen-free superconducting magnets. There are provided two stages of cold heads for refrigeration, the first stage of which cools the thermal shield to prevent heat radiation from outside and the second stage of which, connected to a superconducting magnet, is used to cool the magnet. Since no cryogen is used, the cryogen-free magnets are featured by 1) ease of handling, 2) free rotation of magnetic field axes, 3) ease of operation in clean rooms and 4) ease of access toward the centers of magnetic fields. Those features are exploited in a variety of fields including photophysical property measurements, electrochemical reactions, semiconductor device developments, orientational controls, physical property measurements, magnetic resonance, gyrotrons, magnetic separation and structure analyses.

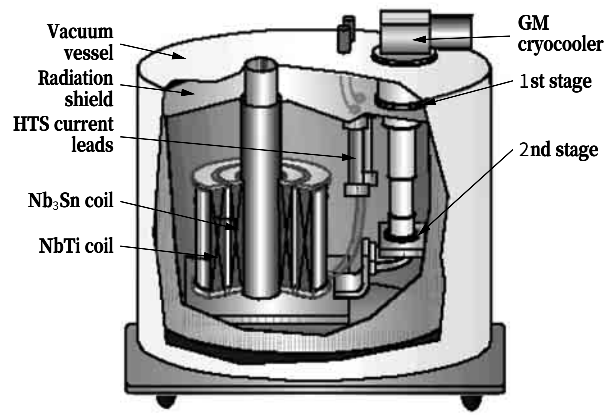

Fig. 1 Schematic view of cryogen-free superconducting magnet

2. Development to higher magnetic fields

2.1 Outline

As described above, because there is no need for cryogen, cryogen-free superconducting magnets have spread rapidly among researchers and technicians, who are not familiar with the handling of cryogenic equipment, as tool to produce magnetic fields up to about 10T with moderate ease[4]. However, the cryogen-free magnets are operated at higher temperatures compared with a conventional cryogen cooled magnet, which decreases critical current densities especially for magnetic fields higher than 13T, making it difficult to design a magnet for the higher magnetic field. In order to solve this issue, modifications have been made, in which a multiple of refrigerators are used[5)-7)], the GM-JT refrigerators having higher cooling power (is)were used[6] or the operating temperatures of the inner and outer coils

Note) Cryogen free magnets are also denoted as "conduction cooled superconducting magnet", "directly cooled superconducting magnet" and "cryocooler cooled superconducting magnet". Cryogenic Assciation of Japan recently recommends the denotation "cryocooled superconducting magnet", however, JASTEC uses the term "cryogen-free superconducting magnet" in compliance with the past publications and sold products.

were changed using a multiple power supplies[5)-7)]. However, those modifications prevent the ease of handling that is the main feature of cryogen-free magnets, prohibiting wider use of the magnets.

Because of the aforementioned problems, we developed a cryogen-free magnet which can generate a magnetic field of 15T within a sample space having a bore diameter of 52mm at the ambient temperature (hereinafter called the "15T 52mm bore magnet"), based on the concept of increasing magnetic fields while maintaining the ease of handling of cryogen-free magnets. The magnet is compact enough to fit into any ordinary room and operates with one refrigerator and one power supply to cool and charge the magnet, without inhibiting the ease associated with cryogen-free magnets. This section outlines the design and the results of performance tests.

2.2 Magnet design

Figure 2 shows the outside view and overall size of the magnet recently developed, and **Table 1** summarizes its specifications. The coil dimensions and superconducting wire specifications are shown in **Figure 3**. The magnet comprises one Nb_3Sn inner coil and one NbTi outer coil, both of which are optimized by grading the Nb_3Sn and NbTi wires through five different sizes based on experimental magnetic fields. The weights of the wires used were 43 kg for Nb_3Sn and 63 kg for NbTi, and the Nb_3Sn wire was prepared by the Wind & React method (a method for first winding a wire, consisting of Nb filaments and bronze matrix, and heat-treating the wire after winding to precipitate Nb_3Sn). Each coil was impregnated with a resin in vacuum and cooled conductively by a copper cylinder covering the outer circumference.

By downsizing the magnet and optimizing the cooling capacity of the refrigerator, the critical temperature at 15T was set to 5.2K. All the coils were connected serially and energized as one circuit, so as to preserve the ease of operation of the cryogen-free superconducting magnet, which enables charging within 30 minutes with a power supply of 125A×9V output. The operating current for 15T was 121A, in which Nb_3Sn generates 7T and NbTi generates 8T.

For quench protection, each coil was divided into 8 sections, each section having a circuit using diodes connected in parallel[8)]. When a quench occurs in a section, the current in the section is diverted to the diode to prevent the damage caused by local heat generated in the wound wire. In addition, a portion of the accumulated energy of the quenched portion is transferred to a neighboring section, so that the inductance distribution of the sections is optimized

Fig. 2 Outside view and overall size of 15T52mm cryogen-free superconducting magnet

Table 1 Specifications of 15T52mm cryogen-free superconducting magnet

Central field (guaranteed) (maximum)	15.0 T 16.1 T
Ramp time	30 min/15 T
Operating current	121 A/15 T
Field uniformity	<0.1%/10 mmDSV
Initial cool down time	80 h
0.5 mT stray field Axial Radial	4.2 m 3.3 m
Room temperature bore size	52 mm
Overall size (excluding cooler etc.)	820 mm dia. ×680 mm height
GM cryocooler	1.0 W @ 4.2 K/50 W @ 43 K 1 unit

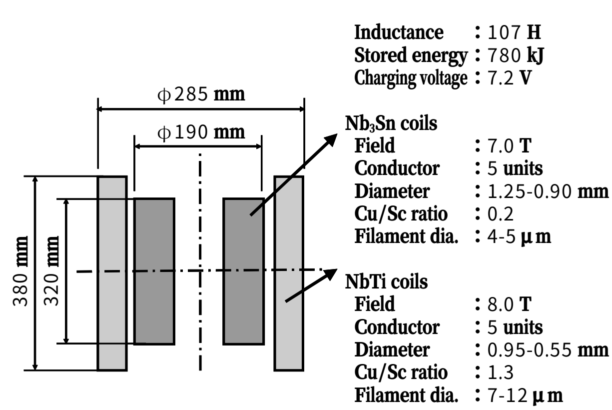

Fig. 3 Coil layout and wire specifications of 15T52mm cryogen-free superconducting magnet

and thus prevents damage due to excessive magnetic force, even though the magnetic force increases with increasing current. The magnet is thus securely protected. The diodes are placed in the cryogenic portion with the magnet, configuring a closed circuit in the cryostat. This protects the magnet even during problems due to cutting of the connections between the magnet and power supply.

The magnet is cooled by a two stage GM refrigerator having a freezing capacity of 1W at 4.2K. The heat balance is shown in **Figure 4**. The heat loads are 710mW in total, including 450mW, 15T/30min (0.067A/s) for the infiltration heat due to conduction and radiation, 240mW for the alternate current loss of the coils charging at a rate of 15T/30min (0.067A/s), suppressed by the use of fine filament NbTi conductor, and 20 mW for Joule heat and others. The temperature at the cooling end of the refrigerator is calculated to be 4.0K, while the magnet temperature of the Nb_3Sn coil, which has a longer cooling path, is calculated to be 5.1K. The magnet temperature, corresponding to the heat load of 450mW at an unloaded condition, is calculated to be 4.5K for the Nb_3Sn coil. By using a heat switch sealed in pressure controlled nitrogen, the cooling from the ambient temperature employs the first stage refrigerator having a higher cooling power. This shortened the initial cooling time to approximately 80 hours [9].

2.3 Experimental Results

The magnet was cooled down to the ultimate temperature of 3.7K within about 80hrs. It was then charged at a rate of 60min/15T and displayed a training quench three times at 14.5-14.8T before reaching 15T. The temperature before the quench was approximately 4.8K. Since the temperature is much lower than the critical temperature of the wires, the training quench was presumed to be due to wire movements. After that, the magnetic field reached 15T without quenching at a rate of 30min/15T. The magnet temperature at this time was 5.1K, which corresponded well with the heat balance calculation.

The charging was continued after the magnet temperature became low enough and, as a result, magnetic fields of 15.5T(125A) and, further, 16.1T (130A) were achieved without quenching.

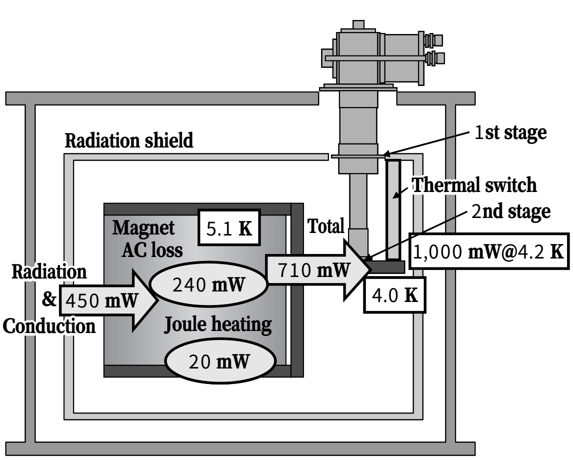

Fig. 4 Heat balance of 15T52mm cryogen-free superconducting magnet

3. Development to industrial applications

3.1 Outline

Recently there has been a strong trend to use cryogen-free superconducting magnet for industrial applications, by taking advantage of the ease of obtaining high magnetic fields, even for those who are not familiar with cryogenic equipment.

Figure 5 shows a relation between fields generated by cryogen-free magnets and bore sizes[10]. Though it is difficult to define clearly the industrial applications from this classification, magnetic separation, magnetic orientation, metal phase transformation, bulk magnetization and such are considered to be potential industrial applications. The magnets used for those applications are featured by relatively low magnetic fields and large bore sizes. This section introduces and outlines a few examples of products actually used for industrial applications, manufactured by JASTEC.

3.2 Magnetic annealing for semiconductor materials

Figure 6 shows the appearance and inside view of magnetic annealing equipment for MRAM (Magnetoresistive Random Access Memory) device materials, which are expected to be materials for next generation nonvolatile memories. The superconducting

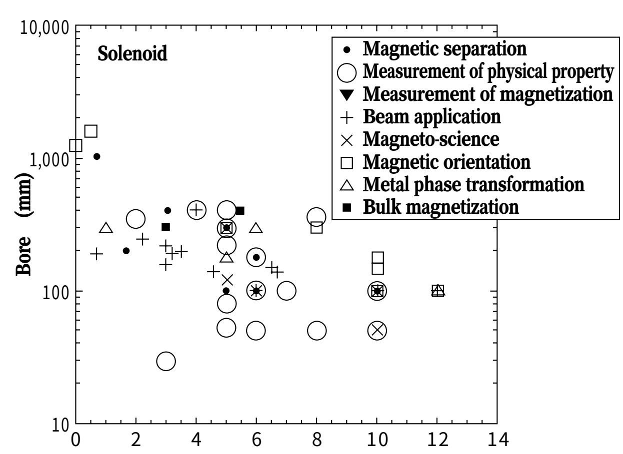

Fig. 5 Magnetic field/bore size and purpose of cryogen-free superconducting magnet

magnet, the key part of the equipment, is disposed in a magnetic shielding box made of mild steel and generates an uniform magnetic field of 1T within an ambient temperature split gap of 310mm. Wafers are annealed in the magnetic field and magnetized unidirectionally to create memory materials. The magnet is cooled by a 4K-GM refrigerator and operated under a cyclic condition of charging 20 min, magnetic filed holding 90 min and discharging 20 min.

Similar equipment is also used for the magnetic annealing of magnetic head materials for hard disk drives.

3.3 Magnets for magnetic separation

Figure 7 shows an outside view of equipment used for production of pure kaolin (mixed with products, such as high-grade papers, colorants and cosmetics, to make them whiter) by removing iron from ores. The key superconducting magnet generates a magnetic field of 0.6T at maximum within a vacant space of ϕ1,015mm$\times$500mm at the ambient temperature. A steel core, passing through a multiplicity of pipes, is placed in the magnetic field space to increase the magnetic field to approximately 1.3T. Metal meshes are inserted inside the pipes and iron is absorbed and removed on the meshes from the liquid suspensions, containing ore powder, passing through the pipes. Absorbed iron is water washed after discharge.

In order to operate the equipment at a high efficiency, charging and discharging have to be repeated within a short cycle. The magnet is cooled by a 4K-GM cryo-cooler and operated under a cyclic condition of charging 1 min, magnetic filed holding 6 min and discharging 1 min.

Similar apparatus is used for cleaning dirty lake water and waste water treatment for paper mills[11].

3.4 Challenges for industrial applications

A few examples have been introduced for cryogen-free superconducting magnets used for industrial applications. They commonly have low magnetic fields and large magnetic field spaces. This is considered to be due to the fact that the industrial superconducting magnets are replacements of original electrical magnets, which are made of wound copper wires, cooled by water. In contrast, many cryo-cooler cooled type magnets, used for research purposes, are replacements of liquid-helium cooled type magnets.

At the time of replacement of an electrical magnet by a superconducting magnet, the superconducting magnet is required to have the same level of ease of operation as the electrical magnet. In the current condition, magnets for industrial applications, nonetheless, are magnets for research purposes and no special magnets or refrigerators have been used for the applications. Researchers, who shifted from liquid-helium submergence type magnets, may feel advantages of ease of operation without having to go

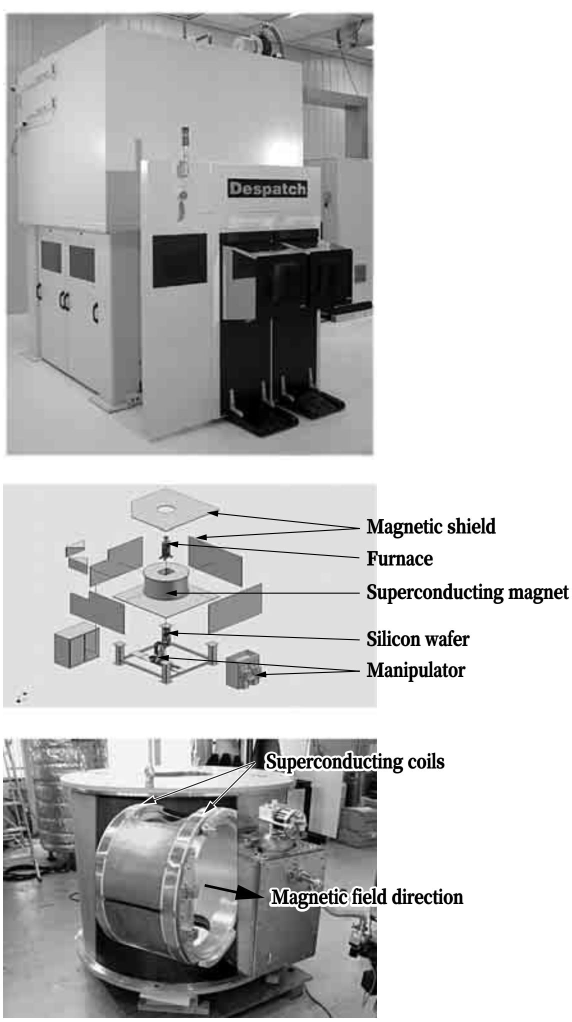

Fig. 6 Outside and inside view of annealing equipment for MRAM and superconducting magnet cut model

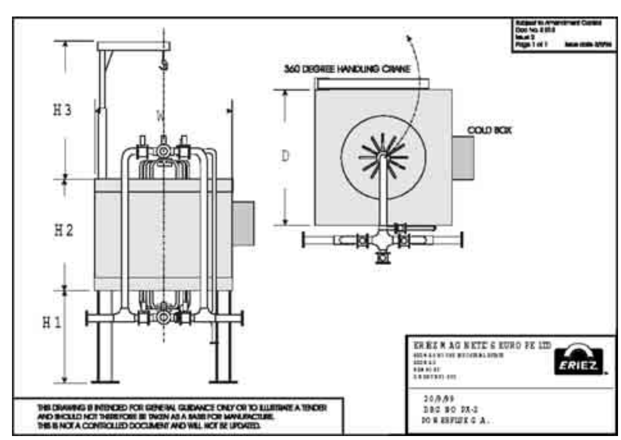

Fig. 7 Outside view of magnetic separation equipment for kaolin

to the trouble of supplying cryogen, however, people in industries, who shifted from electrical magnets, take it as a matter of course to be able to run the magnets with electrical power only. Rather, superconducting magnets are tend to be taken as disadvantageous, because of the control of gas helium and high vacuum and complexity of maintenance. In addition, the magnets for industrial applications run 24 hrs a day without any disruption in almost all the cases. Accordingly they are required to have high reliabilities and robustness, which makes daily maintenance almost unnecessary. Reduction and simplification of regular maintenance are also important factors. These are key factors not only to reduce maintenance costs themselves, but also to directly improve productivity by reducing equipment downtime for the maintenance.

In addition, as can be understood from the above examples, industrial magnets are installed in a variety of environments; e.g. dirty environments such as for magnetic separation and, on the contrary, clean room environments such as for semiconductor material processing.

The demand for cryogen-free superconducting magnet in industries is expected to grow drastically by developing magnet systems, taking those factors into consideration.

Conclusions

Practical applications of cryogen-free superconducting magnets has lead to discoveries and understandings of new phenomena, under strong magnetic fields, in wider than conventional applications, which are now being developed into a "magneto science". In addition, a recent trend indicates that applications of cryogen-free superconducting magnets are increasing. We will continue to develop superconducting technologies and bring them into practice by reflecting the needs of users in an appropriate manner.

Finally, we would like to express our sincere gratitude to Mr. Dan Roach of Despatch Industries, Inc., for the provision of the materials for magnets for annealing semiconductor materials, and to Mr. Tadashi Honma of ERIEZ MAGNETICS JAPAN CO., LTD., for the provision of the materials for magnets for magnetic separation.

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