Recent Technical Trends of Superconducting Magnets in Japan, Part I: Magnet Data Base and Recent Progress in Magnet Winding Current Density

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Abstract—The committee on applied superconducting apparatuses and characteristics of superconductors, the Institute of Electrical Engineers of Japan (IEEJ) has made a data base on low temperature superconducting magnets which have been built over the last ten years in Japan. Based on the data base trends of magnet technology are investigated. In this paper (Part I), out-line of the data base is explained and based on the data base the recent trends of the magnet technology are investigated focusing on sizes and configurations of magnets, current density of magnet windings and conductor configurations. The stability and quench protection of magnets are also investigated in other paper (Part II).

I. INTRODUCTION

A wide variety of superconducting magnets from small-scale magnets for laboratory use to large-scale magnets for nuclear fusion experiments, SMES, and high-energy physics have been constructed and operated in Japan. From the stand point of the magnet technology, increasing the current density of magnet windings is becoming a key of the magnet technology, as superconducting magnet applications become more realistic. The current density directly influences the weight and cost of the magnet while, in turn, the cost, together with operational reliability, is a major factor in determining realistic superconducting applications. The current density is related to various factors, sizes and configurations of magnets, configurations of conductors, the stability and the quench protection method. Magnet designers coordinate those factors based on their experience and know-how but there are no established rules to design stable and high current-density magnets.

An activity to derive empirical magnet design rules from the design and operation experience of existing magnets is conducted by the committee on applied superconducting apparatuses and characteristics of super-

conductors organized by IEEJ (Committee chairman O. Tsukamoto). As a part of this activity, the committee has made a data base of superconducting magnets which has been built over the last 10 years [1]. Data on design parameters and operation results of magnets have been collected on 27 low temperature superconducting magnets for DC and pulse uses. The magnets are of wide variety, from small scale magnets for laboratory use to large scale for SMES, high energy physics experiments, fusion experiment. Stored energy of the magnets ranges from 10 kJ to 0.7 GJ, operating currents from 50 A to 46 kA and maximum fields from 3 T to 18 T. The data were collected by cooperation with Japanese magnet makers and users including universities, industries and research institutes. From the data base, we can obtain magnet design references, investigate the design trends and extract R&D items. Based on the data base and analyses, the committee is aiming at obtaining the general empirical design rules for stable and high current density magnets.

A decade before, a preceding committee of IEEJ had made a similar data base on magnets and investigated the status of magnet technology focusing on the stability and quench protection [2], [3].

In this paper (Part I), we report out-line of the data base and the investigation of recent trends of the magnet technology concerning to current density of the winding, conductor current, magnetic field and stored energy, comparing with that of a decade before. The stability and quench protection are studied in other paper (Part II) [4].

II. DATA BASE

We collected about 50 items of data on each magnet by sending questionnaires to magnet makers and users in Japan. The data items are summarized in Table I. 20 magnets out of 27 magnets have the stored energy larger than 100 kJ. Major parameters of those 20 magnets are listed in Table II. There are 11 DC magnets including 2 persistent current mode magnets, and 7 pulse magnets. 15 magnets were cooled by pool boiling, 2 magnets by conduction cooling and 3 magnets by forced flow cooling. Types of the magnets are solenoids, round and D shape pancakes and race tracks. Recent 10 years technical trends of magnets (1989-1998) are investigated based on the data base of these 20 magnets listed in Table II,

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TABLE I
DATA ITEMS

Outline
Date of answer, Answerer, Magnet name, Purpose, User name, Manufacturer, Manufacturing term, Start year of operation, Operation experience, Excitation mode
Conductor
Manufacturer, Features, Grading, Criteria of I_c , Critical current, Stranded pitch and direction, Conductor size and tolerance, Structure and size, Material of superconductor, Insulation method and material of conductor, Strand diameter and tolerance, Structure of strand, Surface treatment of strand, Insulation of strand, Filament number, Filament diameter and spacing, Filamentary zone diameter, Twist pitch and direction
(For Pulse and AC magnet only)
AC quench current, AC loss
Cooling method
Cooling method
(For pool boiling only)
Cooling channel and direction, Cooling perimeter, Temperature and pressure, Inventory, Pre-cooling
(For forced flow cooling and the other)
Coolant, Input temperature, Pressure and mass, Flow rate, Length of cooling path, Void, Refrigerator
(For conduction cooling and the other)
Feature of refrigerator, Performance of refrigerator, Operation temperature, Thermal insulation, Heat in-leak, Initial cooling time
Magnet
Features, Magnet size and structure, Detail of winding, Turn and layer number, Weight, Support structure and material, Support method of winding tension, Maximum stress, Fixing method, Winding tension, Epoxy impregnation, Semi cure, Transport current, Training, Current density at winding, Rated magnetic field, Magnetic field uniformity, Maximum temperature at quench, Temperature margin at operation, Conductor length, Inductance, Maximum voltage at energy dump, Magnet insulation method, Insulation voltage
For pulse and AC magnet only
Rated capacity, AC loss
Power supply, et al.
Rated output of power supply, Type of power supply, Quench detection, Magnet protection
Remarks
Comments, References

and compared with the preceding trends (1979-1988).

III. CURRENT DENSITY OF WINDING

A. Dependence on Stored Energy

In Fig.1, current density of winding is plotted against the stored energy at the rated conductor current for magnets of recent 10 years and preceding 10 years.

The current density of the winding is limited by three factors, critical current density of superconductor J_c , stability and energy dump for the quench protection. Those limits, the superconductor limit, stability limit and energy dump limit, are shown also in Fig.1 [5]. J_c depends on the magnetic field and superconducting materials but, from the stand point of over all current density of the winding, the superconductor limit can be expressed with some band

Fig. 1. Relation between stored energy and current density of winding.

width as shown in Fig.1. More details on the dependence of the superconductor limit on the magnetic field are discussed later. The stability limit is determined based on the cryostatic stability criteria. The energy dump limit is determined to protect the magnet from burning-out at a quench and energy dump event. When the value $V_0 I_{op}$ (V_0 : initial terminal voltage of the magnet at the energy dump, I_{op} : operation conductor current) is large enough, the stored energy can be dumped-out from the magnet quick enough to protect the magnet from a damage. The necessary value of $V_0 I_{op}$ to protect the magnet depends on the winding current density and the stored energy of the magnet. The upper limit of $V_0 I_{op}$ depends on technological limits of the electric insulation and conductor size. In Fig.1, we assume that $V_0 I_{op} = 0.2 \sim 5.0 \times 10^8$, lower value for the pool cooling and higher value for the forced flow cooling. As seen from Fig.1, the winding current densities of the recent 10 years magnets have been much improved and closer to the superconductor limit and the energy dump limit than the preceding magnets. The stability limit based on the cryostatic criteria is becoming less important and the metastable criteria are more important. To increase the current density of a large scale magnet, R&D of technologies for large scale conductor and the electric insulation is important.

B. Dependence on Magnetic Field

Dependence of the winding current density on the maximum magnetic field of the winding is shown in Fig.2.

TABLE II
THE MAJOR DATA OF 20 MAGNETS OVER 0.1MJ

No.	Mode	Year	SC	I_{op} (kA)	B_0 (T)	B_m (T)	E (MJ)	EP	Tr	d_{in} (mm)	d_{out} (mm)	T (K)	CL	Purpose Shape
1	DC	1991	NS*+NT*	1.33	13	13.9	4.80	Yes	No	240	700	4.2	PB	Sample test Solenoid
2	DC	1992	NT*	2.86	8		38.04	No	Yes	1480	1960	4.22	PB	Sample test Solenoid
3	DC	1989	NT	1	4.2	4.5	1.06	No	No	350	760	4.22	PB	SMES Pancake
4	DC	1990	NS+NT	1.33	13	13.9	4.57	Yes	Yes	260	629	4.2	PB	Sample test Solenoid
5	DC	1989	NT	0.407	8	8.9	0.265	Yes	Yes	120	334	4.2	PB	Sample test Split
6	DC	1989	NS+NT	0.436	13	13.2	0.266	Yes	No	59	262	4.2	PB	Sample test Solenoid
7	DC	1990	NT	3.405	4.9	6	0.342	No	Yes	140 $\circ$	217.7 $\circ$	4.4	FF	Accelerator Quadrupole
8	DC	1990	NT	0.52	1.2	2.2	0.811	Yes	No	989.6	1000	4.4	CC	Detector Thin solenoid
9	DC	1993	NT	12	1.5	3.8	44.64		Yes	3675.6	3684.4	4.4	CC	Detector Thin solenoid
10	DC	1994	NT	13.2	10	10.2	0.305	No	Yes	50 $\circ$	112.2 $\circ$	1.9	PB	Accelerator Dipole
11	DC	1991	NT	1	4.7	5.4	1.04	No	No	360	814	4.22	PB	SMES Double pancake
12	DC	1990	NT	0.6		5.43	0.364	Yes	No			4.2	PB	Meglev Race track
13	DC	1990	NT	0.372	8	8.4	0.180	No	No	139	256	4.2	PB	SMES Solenoid
14	PLS	1994	NT	0.35	3.8	5	0.422	No	Yes	340	592	4.2	PB	SMES Double pancake
15	PLS	1994	NS	0.35	3.3	4.6	0.421	No	No	340	700	4.2	PB	SMES Double pancake
16	PLS	1996	NT	1	1.96	5.45	0.6	No	No	$\sim 539 \times 175$	917×553	4.6	PB	SMES Modified D-shape
17	PLS	1997	NT	1		5.3	0.6	No	No			4.2	PB	SMES Modified D-shape
18	PLS	1997	NT	1	4.41	5.68	0.6	No	No	$\sim 525 \times 151$	930.9×556.9	4.2	PB	SMES Modified D-shape
19	PLS	1998#	NS*	46		13	643	Yes		1600	3580	4.5	FF	Fusion Solenoid
20	PLS	1990	NS	24			2.67	Yes	No	1000	1800	4.5	FF	DPC-TJ Double pancake

Mode: The operating mode, DC: DC operation and PLS: Pulse excitation.

Year: The year that the magnet was constructed. # denotes the magnet that has not been constructed when we investigated.

SC: Material of superconductor. NT: NbTi, NS: Nb₃Sn and NT+NS: NbTi+Nb₃Sn. * denotes the grading magnet.

I_{op} : Rated operating current.

B_0 : Rated magnetic field density at the operating area.

B_m : The maximum magnetic field density of the magnet.

E : Rated stored energy.

EP: Epoxy impregnation.

Tr: Training up to the rated current.

d_{in} : The inner diameter of magnet. $\circ$ denotes the inner diameter of dipole or quadrupole magnet.

d_{out} : The outer diameter of magnet. $\circ$ denotes the outer diameter of dipole or quadrupole magnet.

T : The operating temperature.

CL: The cooling method. PB: Pool boiling cooling, CC: Conduction cooling and FF: Forced flow cooling.

Fig. 2. Relation between maximum magnetic field and current density of winding. The point denoted by (1.9) is 1.9 K He-II cooling. (Symbols in the all figures of this paper are same as in Fig.1.)

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In the figure, the superconductor limit for NbTi wire is the magnetic field range lower than 10T and for Nb₃Sn in the range higher than 10 T. NbTi is dominant in the magnet whose maximum magnetic field is lower 10 T and Nb₃Sn is used in the magnet of higher magnetic field than 10 T. This situation is not changed for more than 20 years. However, the current density of the winding of NbTi progresses remarkably over last 10 years and reaching to the stability limit and that of the Nb₃Sn winding also shows significant progress in the magnetic field higher than 10 T. Technology increasing J_c both of NbTi and Nb₃Sn is being developed. The increase of the winding current density reflects the increase in J_c together with the progress of the winding technique.

IV. CONDUCTOR CURRENT

A. Relation to Stored Energy

Relation between the operation current of the conductor and the stored energy is shown in Fig.3. Larger capacity conductors of NbTi and Nb₃Sn have been developed over last ten years. Conductor current of a pulse magnet is smaller compared with that of a preceding pulse magnet. This is because the electric insulation technique has been improved and the conductor current could be decreased keeping the stored energy unchanged. Electric utility companies have been interested in SMES in recent years and developed SMES coils which were pulse-operated. Lower conductor current is preferable from the stand point of AC/DC converter, which is another reason that the conductor current of the pulse magnet decreased.

Fig. 3. Relation between stored energy and operation current.

B. Ratio of Operation Current and Critical Current

The ratio of the operation current and critical current of a conductor I_{op}/I_c is an important design parameter. In Fig.4, I_{op}/I_c is plotted against the stored energy. The data can be divided in three groups, I, II and III as shown in Fig.4. Magnets in the group I are aiming at high current density windings and the designers tried to use full of the conductor current capacity at the risk of losing the stability. Actually, two magnets of large stored energy 38~44.6 MJ have suffered from training and some others in the group I also have suffered from training. Most magnets in the group II are SMES magnets for the electric utility users and designers of those magnets tried to make the magnets highly reliable by reducing I_{op}/I_c . Most of

Fig. 4. Relation between rated stored energy and ratio of operation current and critical current I_{op}/I_c . The numbers at data points are magnet figure caption reference numbers in Table II.

magnets in the group III are for laboratory experiment uses and I_{op}/I_c seems to have been determined by other factors than the winding current density and the stability. Nb_3Sn conductors have relatively high I_{op}/I_c , which is because the Nb_3Sn conductor has high temperature margin.

Fig. 5 shows I_{op}/I_c vs the maximum magnetic field of a magnet. I_{op}/I_c tends to increase as the maximum magnetic field increases, which is because that a magnet designer try to use full of the conductor current capacity because I_c decreases at higher magnetic field and also because a Nb_3Sn wire which is used in a high magnetic field magnet has high temperature margin and is stable even with high I_{op}/I_c .

V. MAGNET BORE

The magnet bore significantly affects magnet design parameters.

A. Relation to Winding Current Density

Relation between the magnet bore and current density of the winding is shown in Fig. 6. Improvement of the current density over the past 10 years can be seen, which is due to the improvement of the performance of the superconductor and winding technology. In the range where the bore is larger than 1 m, there is a tendency that the winding current density is limited by the energy dump limit because a large bore magnet has large stored energy. Therefore, to increase the winding current density of a large bore magnet, it is necessary to develop a technology to push up the energy dump limit together with a technology for conductor/winding reinforcement.

Fig. 5. Relation between maximum magnetic field and ratio of operation current and critical current I_{op}/I_c .

Fig. 6. Relation between magnet bore and current density of winding.

B. Relation to Central Magnetic Field of Magnet

Relation between the central magnetic field and bore of a magnet is plotted in Fig. 7. Manufacturing limit of a magnet which was estimated from the performance levels of reinforce materials and superconductors at 1973 [6], is also shown in Fig. 7. In the range of magnetic field higher than 10 T, this limit was already exceeded more than 10 years before, which was due to the development of Nb_3Sn conductors with high current density at high magnetic field. Exceeding the limit in the range less than 10 T is not so remarkable. In this range, the performance limit is determined mainly by the performance of reinforce materials and the data in Fig. 7 means that the technology for reinforce material has not been well developed for over the last 20 years.

Fig. 7. Relation between central magnetic field density and magnet bore.

Fig.8 shows the relation between the conductor current and bore of the magnet. In the graph, solid and broken lines are the least square error approximations of the data for the recent and preceding magnets respectively. Sizes of the bore and conductor have been increased over the last 10 years.

VI. CONCLUDING REMARKS

Technical trends of low temperature superconducting magnets have been investigated based on the data base of magnets which have been built over the last 10 years in Japan. Followings are conclusions of the investigation.

1. Current density of the winding is increasing and becoming closer to the superconductor limit and the energy dump limit over the last 10 years.
2. Current density of the winding exceeds the stability limit based on the cryostatic stability criteria in most of the magnets. Therefore, the metastable stability criteria are becoming more important to design a magnet.

Fig. 8. Relation between magnet bore and operation current.

3. To more increase winding current density of a large scale magnets, it is necessary to push up the energy dump limit by increasing value of $V_0 I_{op}$ more than $0.2 \sim 5.0 \times 10^8$ VA.
4. The manufacturing limit of the magnet bore has not much progressed for the last 10 years, which means that the performance of the materials to reinforce the winding has not been well developed.

The authors are aware that the magnet data base is very useful to investigate the technical trends, to extract future R&D items, to obtain design references and to derive empirical design rules. The authors and the committee will be continuing in their effort to compile a more comprehensive data base of magnets.

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