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Superconducting magnet system in a fusion reactor

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Abstract

Higher magnetic field of a Toroidal field (TF) coil in a tokamak fusion reactor can offer better performance of the reactor. Therefore, fusion magnet development always drives a new superconductor to be used in a large magnet on an industrial basis. Magnets for the International Thermonuclear Experimental Reactor (ITER) use Nb_3Sn in order to generate a peak magnetic field of 13 T. Technologies for Nb_3Sn superconductor has made a significant progress through the extensive development in ITER including the manufacture of model coils. A next generation superconductor, Nb_3Al, has outstanding features of large critical current density at higher field and smaller degradation of the critical current due to a strain compared to Nb_3Sn. High temperature superconductor (HTS) is another candidate, and if it becomes available, a magnetic filed above 20 T can be realized in a large magnet. These materials have the possibility of being used for high performance fusion reactors.

1. Introduction

The first engineering concept of a fusion energy device was proposed by Sacharov and Tamm in 1950 on the base of magnetic confinement of plasma in tokamaks [1]. In the 1970s due to the maturity of superconducting magnet technology, it became clear that only superconducting magnetic systems could make the fusion energy devices economically efficient. In 1978, the first tokamak with superconducting magnetic system, T-7, was successfully built and tested in the USSR [2]. NbTi superconducting strands were used in this device because of the low magnetic field of 5 T. This was the first commercially applicable superconductor, but it can be operated only at low field owing to its low critical magnet field, as shown in Fig. 1. In the 1980s, international collaboration on the development of Toroidal field (TF) coil, the large coil task (LCT) [3], was performed by Japan, the US, EURATOM and Swiss. In this project, five large NbTi coils were developed and successfully operated at 9 T. The necessity to increase the magnetic field on the plasma axis in larger fusion devices demanded the use of A15 superconductors, such as Nb_3Sn and Nb_3Al, whose critical magnet fields are much higher than that of NbTi (Fig. 1). The first large-scale tokamak project with a Nb_3Sn superconducting system, Tokamak-15, was initiated in the USSR [4]. In parallel, a large Nb_3Sn coil was developed and successfully operated at 12 T in Japan in 1985 [5].

These successful experiences with large-scale Nb_3Sn superconducting magnet systems and impressive progress accumulated in the fusion experiments all around the world have stimulated the initiation of the International Thermonuclear Experimental Reactor (ITER) Project [6]. The superconducting magnet system of ITER consists of 18 TF coils, 6 PF coils, a central solenoid (CS), correction coils and related structures, shown in Fig. 2. Since high performance superconducting magnets are required for these coils, the model coil projects were conducted in the ITER engineering design activity (EDA) to verify the feasibility of the ITER magnet system.

The advanced superconductors, such as a high temperature superconductor (HTS) and Nb_3Al, are also being developed for the use in a future fusion reactor.

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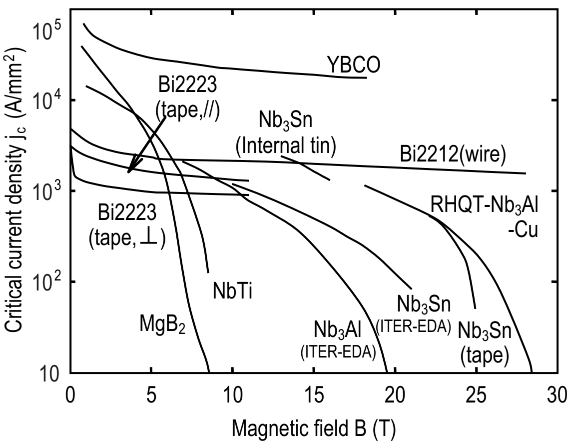

Fig. 1. Superconductor critical currents.

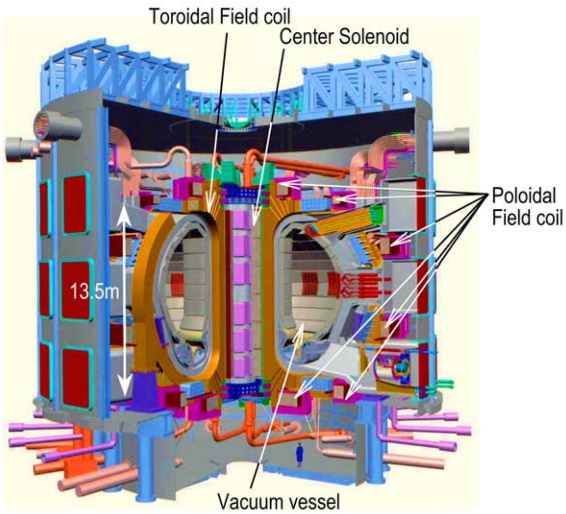

Fig. 2. Cutaway of ITER.

Nowadays, the achievements in the field of manufacturing of HTS tapes at an industrial scale are well known. However, HTS wires were mainly applied to current leads because of economical and technical difficulties in the application of HTS in the magnet of the fusion reactor. In contrast, the Nb_3Al conductor seems more practicable to be used in the next fusion reactor, although operating field becomes lower compared to HTS.

In this paper, the design requirements of the ITER superconducting magnets are first introduced as an example of requirements for the magnets to be used in the fusion reactor. Then, the development of the ITER superconductors is described. In addition, the recent activities in the development of the Nb_3Al and HTS advanced conductors for future fusion reactors are presented.

2. Requirements for superconducting magnets of fusion reactors

The superconducting magnets of the fusion reactor are required to operate with large current at high field. For example, in ITER, the operating current and field are 68 kA and 11.8 T in the TF coils and 40 kA and 13 T in the CS. Therefore, large electromagnetic loads are applied to each of the conductors as well as whole magnet system. The conductors have to be sufficiently stiff to sustain such large load.

The conductors of the fusion magnets are subjected to field variations as the result of the pulsed operation of the magnets and the change in plasma current. These field changes generate coupling current losses and hysteresis losses in the conductor [7]. The superconductor has limitations in temperature and magnetic field at which the conductor can maintain the superconducting state. Consequently, if the losses are large, the conductor temperature increases until the conductor transitions to the normal state. Therefore, the losses due to the magnetic field variation have to be small. Because the hysteresis loss is roughly proportional to the diameter of a superconducting filament, the loss can be reduced by making the filament diameter very fine, such as less than 10 μm. The coupling current loss can also be reduced by fabricating a conductor of a large number of fine strands (typical diameter is smaller than 1 mm). The high resistive layer between strands decreases the induced coupling current. Note that this high resistive layer has to be formed on the strand surface before heat treatment for A15 superconductor formation, to avoid strain of the heat-treated strand, which will degrade the superconducting performance [8]. For this purpose, chromium plating technique, which can withstand the heat treatment, has been established.

For these reasons, a cable-in-conduit (CIC) conductor, consisting of many strands within a conduit to provide mechanical reinforcement, is generally used in magnets for a fusion reactor. Fig. 3 illustrates the CS model coil conductor [9], which was developed in the ITER-EDA, as an example of the CIC conductor. The detailed performance of the conductor will be describer later.

The CIC conductor also has another advantage relative to stability. A large electromagnetic load may move the conductor during its operation. This movement originates local thermal perturbations. Because of the low heat capacity of metals at low temperature, the conductor temperature easily increases and returns to the normal state. The conductor, of course, has to be stable enough to recover to the superconducting state

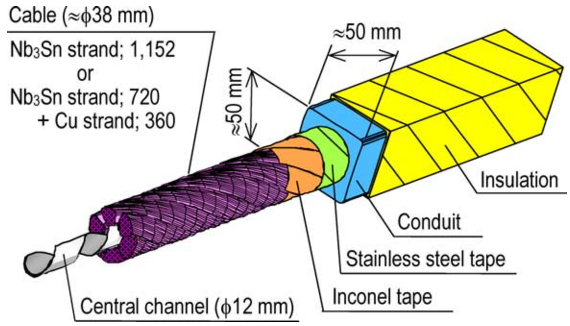

Fig. 3. Illustration of CS model coil conductor as an example of CIC conductor with Incoloy conduit.

against such perturbation. If the conductor consists of a lot of strands, the perimeter wetted by the coolant becomes quite large. Good cooling performance can therefore be achieved and the sufficient stability can be obtained in a CIC conductor. In addition, it is also important to keep Joule heating power small when the conductor transitions to the normal state. Low resistance copper is consequently necessary in a strand to decrease Joule heating after the normal transition. The low resistance copper is also necessary to avoid large temperature rise in case of conductor quench. Segregated copper wires can be used to include sufficient amount of copper in the conductor.

3. Development of superconducting coils for the ITER magnet system

Fabrication techniques for high performance Nb_3Sn strands were established and four model coils using the Nb_3Sn conductors were developed in ITER-EDA to demonstrate feasibility of the ITER magnets [10]. The development and test results of these model coils are described.

3.1. Nb_3Sn conductor development

Due to high performance parameters of the ITER magnet system, a new set of requirements was imposed for superconducting strands. For example, in accordance with the ITER specification of the HP-II strand, the level of non-Cu critical current density, j_c (A/mm^2), for the strands stabilized by 60% copper had to be more than 550 A/mm^2 at 12 T, 4.2 K and hysteresis loss had to be less than 200 kJ/m^3 for a ±3 T field change. Fig. 4 shows the typical relation between the hysteresis loss and critical current density of conventional Nb_3Sn strands [11]. The higher the critical current density, the larger is the hysteresis loss. The target for the HP-II strand was low hysteresis loss with keeping the critical current density sufficiently high. Since the hysteresis loss is roughly proportional to the filament diameter, such high performance strand can be obtained by reducing the filament diameter to about 3–5 μm [11]. The possibility of strand breakage during drawing increases if the filament diameter is reduced because of increased reduction ratio in the diameter. By the efforts at the manufacturers, the mass production techniques for the Nb_3Sn strand with such fine filaments could be established in ITER-EDA. For the ITER model coils, eight companies in the world fabricated around 30 tons of strand using two different techniques: the 'bronze' method, used by VAC, Furukawa, Bochvar Institute and Hitachi cable, and 'internal Sn' method, used by EM, IGC, TWCA and Mitsubishi [12,13]. Table 1 summarizes the major parameters of the developed Nb_3Sn strand. Two sets of the specifications, HP-I and HP-II, were satisfied: HP-I was achieved mainly by the bronze method and HP-II by the internal Sn method. Using those strands, two types of Nb_3Sn conductor were successfully fabricated. One of these has thick square conduit (Fig. 3), and was used in the CS model coil and

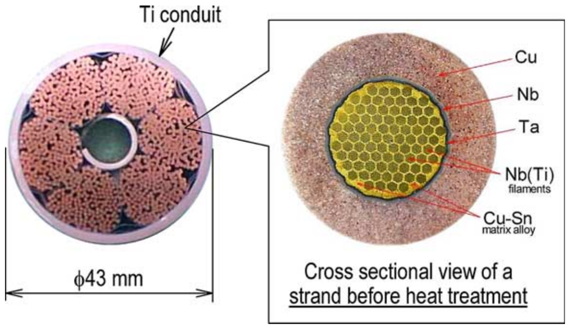

Fig. 4. Cross-sectional view of the TF insert conductor. The typical cross-section of bronze processed strand before heat treatment is also shown in the figure. Nb_3Sn is generated by reaction between Nb and Sn by heat treatment at 650 °C for about 200 h.

Table 1
Summarized major specification of the ITER-EDA Nb_3Sn strands

	HP-I	HP-II
Strand diameter (mm)	0.81	0.81
Critical current density at 12 T, 4.2 K (A/mm^2)	>700	>550
Hysteresis loss for ±3 T (mJ/cm^3)	<200	<600
Cu ratio	1.5	1.5
Residual resistivity ratio (RRR) of Cu	>100	>100
n Index	>20	>20
Thickness of Cr plating (μm)	2	2
Twist pitch (mm)	10	10

Table 2
Major parameters of the ITER model coil conductors

Conductor type	CS1	CS2	TF1	TF2
Number of Nb_3Sn strands	1152	720	1152	720
Number of Cu strands	0	360	0	360
Cable diameter (mm)	38.5	38	39	38
Conduit outer dimension (mm)	51×51	50×50	$\phi43$	$\phi42$
Conduit material	Incoloy908	Incoloy908	Ti	SS
Outer diameter of central channel (mm)	12	12	12	12
Coil	CSI, CSMC 1–5 layers	CSMC 5–18 layers	TFI	TFMC

CSMC: CS model coil, CSI: CS insert, TFMC: TF model coil, TFI: TF insert.

CS insert. The other has thin circular conduit, and was used in the TF model coil and TF insert. Incoloy conduit was used in the conductors for the CS model coil and CS insert, stainless steel conduit for the TF model coil, and titanium conduits for the TF insert. Fig. 4 shows a cross-sectional view of the TF insert conductor. Table 2 lists the major parameters of these conductors.

3.2. Nb_3Sn model coil development and test results

The CS model coil consists of two modules, inner and outer modules. The inner and outer modules have 10 and 8 layers of the conductor and fabricated by the US and Japan, respectively. These two modules were assembled and tested at Japan Atomic Energy Research Institute (JAERI), as shown in Fig. 5.

The CS model coil was stable during the charge to the design point of 46 kA at 13 T [8]. In addition, pulsed operation to 46 kA and 13 T with a ramp rate of 0.4 T/s was successfully performed [8] as shown in Fig. 6. The hysteresis and coupling losses of the CS conductor were found to be of the same order as the design target. The CS and TF inserts were also tested by inserting each of them into the bore of the CS model coil to apply a background field. These inserts were also successfully operated at the design currents of 40 and 46 kA at 13 T, respectively [8,14].

The TF model coil was developed by EU and tested at Forschunszentrum Karlsruhe (FZK) in Germany. The TF model coil was operated successfully in a nominal charge to 70 kA at 9 T and, in addition, was extend to a charge to 80 kA at 10 T in further tests [15]. The electromagnetic load applied to the TF model coil conductor in the extended charge was the same as that of the ITER TF coil.

Table 3 summarizes the major parameters and achievements of these model coils, which validate the ITER magnet design concept and demonstrate the feasibility of the magnet system construction.

Detailed evaluations of these results indicated that there was an unexpected degradation in the supercon-

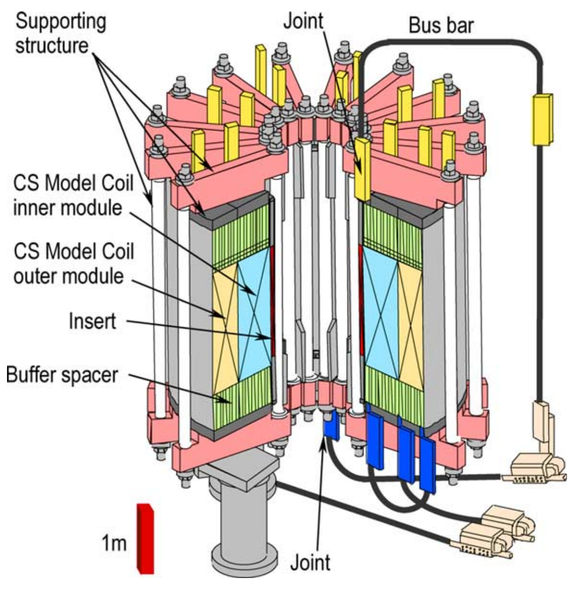

Fig. 5. Schematic view of the CS model coil and insert.

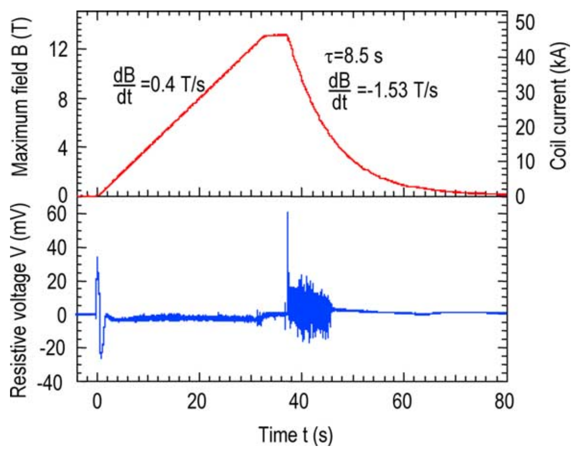

Fig. 6. Current and resistive voltage in the charge to 46 kA at 13 T with a ramping rate of 0.4 T/s.

Table 3
Major parameters and achievements of the ITER model coils

Coil	CSMC	CSI	TFI	TFMC
Nominal current (kA)	46	40	46	70
Nominal field (T)	13	13	13	9
Nominal ramping rate (T/s)	0.4	0.4	–	–
Stored energy (MJ)	640	0.58	0.13	
Winding shape	Solenoid	Solenoid	Solenoid	Racetrack
Achievement	46 kA,13 T	46 kA,13 T	46 kA,13 T	80 kA,10 T
Achieved ramping rate	0.6 T/s, 13 T	1.2 T/s, 13 T		

ducting performance in all of these model coils [16]. The critical current of these conductors was degraded by an increase of the electromagnetic load. Moreover, significant degradation was observed in n index, which represents uniformity of the strand quality and is defined by the following equation.

$$n = \frac{1}{\log_{10}(I_c 10/I_c)}, \tag{1}$$

where n denotes the n index, I_c (A) the critical current, I_{c10} (A) the current when 10 times electric field as that at the critical current appears, respectively. When the filament quality in a strand is uniform, the resistive voltage grows quickly after the current exceeds the critical current, and large n index is obtained. On the other hand, if the quality of the filaments is not uniform, parts of the filaments becomes normal state, resulting in gradual growth of the resistive voltage, i.e., low n index. Although the n index of the developed strand was quite high, such as more than 20, the measured n indexes in the conductors were less than 10. One of the explanations is local bending of the strand as a result of the electromagnetic load on each strand [17,18]. The local bending initiates non-uniform distribution of the strain in the strand cross-section and some of the filaments are exposed to a high strain, resulting in non-uniform performance of the filaments.

Design optimization was performed on the ITER conductors taking this effect into account. The fabrication technique for Nb_3Sn strand was enhanced owing to significant efforts carried out in the EDA. Now, strand with critical current density of more than 750 A/mm^2 at 12 T and 4.2 K is available. The degradation by the local bending has been overcome using this high performance Nb_3Sn strand.

4. Development of advanced superconductors

A future fusion reactor is conceptually designed at the maximum field of 16–20 T. Nb_3Al and HTS are candidates for the TF coil conductor, as shown in Fig. 7.

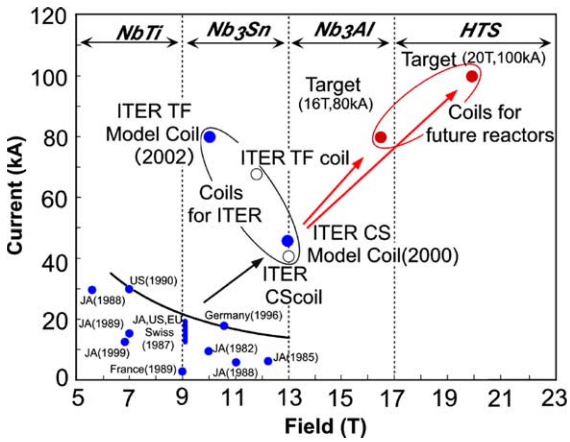

Fig. 7. Performance of superconducting coils constructed so far and target of coils for a future fusion reactor.

4.1. Nb_3Al conductor development

Nb_3Al inherently has outstanding features of large critical current with high upper critical magnetic field [18] and excellent strain tolerance compared to Nb_3Sn [9]. These characteristics provide the possibility to realize a fusion magnet that will operate at around 16 T. In addition, the superior strain tolerance of Nb_3Al simplifies the coil fabrication process, especially in case of a TF coil, by winding the conductor after heat treatment, whereas the winding has to be done before heat treatment for a Nb_3Sn coil.

Stoichiometric Nb_3Al having high critical magnetic field can be obtained by heat treatment at a high temperature more than 1800 °C. On the other hand, copper, whose melting temperature is around 1080 °C, is required in conductors for fusion reactors as described previously, and such high temperature heat treatment is not possible in the manufacture of the fusion magnets. Therefore, JAERI has developed the jelly-roll processed Nb_3Al strand, which enables generation of Nb_3Al at the practicable heat treatment temperature, 750 °C. One ton of Nb_3Al strand with high copper ratio was successfully produced at the middle of 1990s [19].

The Nb_3Al insert [20] was then fabricated using this strand and tested at JAERI by installing in the bore of the CS model coil as was done for the other inserts. Table 4 shows major parameters of the Nb_3Al insert. The Nb_3Al insert was successfully charged to the design point of 46 kA at 13 T and tested to an extended charge of 60 kA at 12.5 T. There was no unexpected degradation in the critical current in the case of the Nb_3Al insert, whereas it had been observed in the Nb_3Sn coils. This is probably because of the higher rigidity of the Nb_3Al strand than the Nb_3Sn strand. These results show that the Nb_3Al conductor is suitable for application to large magnets, such as TF coils of a fusion reactor, which experience large electromagnetic force. The success of the Nb_3Al insert encourages us to use Nb_3Al conductor in the modification of JT-60 to a full superconducting tokamak at JAERI [21].

In parallel, the rapid-heating and quenching transformation (RHQT) method was developed in 1990s and a Nb_3Al strand having high critical current density at high fields can be industrially fabricated [22]. Although a large amount of copper cannot be included in the strand at present, stabilization using segregated copper wires is under study. The Nb_3Al conductor is therefore one of the promising candidates for application in the next fusion plant.

4.2. HTS conductor development

HTS is an excellent material because some of them have very high critical current density (more than 1 kA/mm^2 at 4 K) even in a high field above 20 T. However, there are many issues in developing a large current capacity conductor for fusion application. While a CIC type conductor is the best candidate to sustain huge electromagnetic loads and reduce coupling losses, heat treatment in an atmosphere of oxygen is difficult in the case of a CIC conductor. In addition, the requirement of quite accurate control of the heat reaction temperature is not practicable in a large-scale. Many researchers are working to resolve these issues. JAERI developed a 12 T, 10 kA short conductor using Bi-2212 as the first step in HTS large conductor development [23].

Another important feature of HTS, namely low thermal conductance, offers an application to current leads that dramatically improve the economics of large-scale cryocooled magnets. HTS current leads, when maintained at an intermediate temperature, will carry current to a magnet with a fraction of the heat loss conducted by conventional copper leads. Lower refrigeration costs and enhanced magnet stability can therefore be achieved. In several large projects in the world, low temperature superconductor (LTS) magnet systems are already equipped with HTS current leads [24,25], and Japan has recently developed a 60 kA HTS current lead. They are used in LTS magnet systems to reduce the thermal load which is related to feeding large current to the LTS windings.

Table 4
Major parameters of the Nb_3Al insert

Strand	
Diameter (mm)	0.81
Critical current density at 12 T, 4.2 K (A/mm^2)	620
n-index	44
Hysteresis loss for ±3 T (MJ/m^3)	2.1
Cu/non-Cu ratio	1.43
Residual resistivity ratio (RRR) of Cu	120
Thickness of Cr plating (μm)	2
Conductor	
Number of strands	1152
Outer diameter (mm)	42.6
Conduit material	Stainless steel
Central channel diameter (mm)	12
Coil	
Winding shape	Solenoid
Nominal current (kA)	46
Nominal field (T)	13
Stored energy (MJ)	0.44

5. Summary

The Nb_3Sn conductor was well developed in ITER-EDA and test results of the model coils, which were fabricated using this conductor, demonstrate the feasibility of the ITER magnet system. It could therefore be stated that the superconducting magnet technology which is a key technology for magnet systems of fusion reactor is proven to be reliable.

Nb_3Al and HTS conductors are being developed for application in future fusion plants. Applicability of an advanced Nb_3Al conductor seems to be practical, but HTS conductor will be playing an increasingly important role, as development of this conductor proceeds.

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