Present Status of the KSTAR Superconducting Magnet System Development

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Present Status of the KSTAR Superconducting Magnet System Development *

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Abstract The mission of Korea Superconducting Tokamak Advanced Research (KSTAR) project is to develop an advanced steady-state superconducting tokamak for establishing a scientific and technological basis for an attractive fusion reactor. Because one of the KSTAR mission is to achieve a steady-state operation, the use of superconducting coils is an obvious choice for the magnet system. The KSTAR superconducting magnet system consists of 16 Toroidal Field (TF) coils and 14 Poloidal Field (PF) coils. Internally-cooled Cable-In-Conduit Conductors (CICC) are put into use in both the TF and PF coil systems. The TF coil system provides a field of 3.5 T at the plasma center and the PF coil system is able to provide a flux swing of 17 V-sec. The major achievement in KSTAR magnet-system development includes the development of CICC, the development of a full-size TF model coil, the development of a coil system for background magnetic-field generation , the construction of a large-scale superconducting magnet and CICC test facility. TF and PF coils are in the stage of fabrication to pave the way for the scheduled completion of KSTAR by the end of 2006.

Keywords: superconducting magnet, KSTAR, CICC

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1 Introduction

In order to support the KSTAR project mission [1~3], three major research objectives have been established: (1) to extend present stability and performance boundaries of tokamak operation through active control of profile and transport, (2) to explore methods to achieve steady-state operation of the tokamak fusion reactors by using non-inductive current drive, and (3) to integrate optimized plasma performance and continuous operation as a step towards an attractive tokamak fusion reactor. To fulfil the research objectives of KSTAR, key design targets are set as: (1) fully-superconducting magnets, (2) long-pulse operation capability, (3) flexible pressure and current control, (4) flexible plasma shape and position control, (5) advanced profile and control diagnostics.

The KSTAR device is a tokamak with a fully-superconducting magnet system, which enables an advanced quasi-steady-state operation. The major radius of the tokamak is 1.8 m and the minor radius is 0.5 m with the elongation and triangularity of 2 κ_x and 0.8 δ_x, respectively. When practical engineering constraints, activation issue, system cost and conventional facility requirements are taken into acco-

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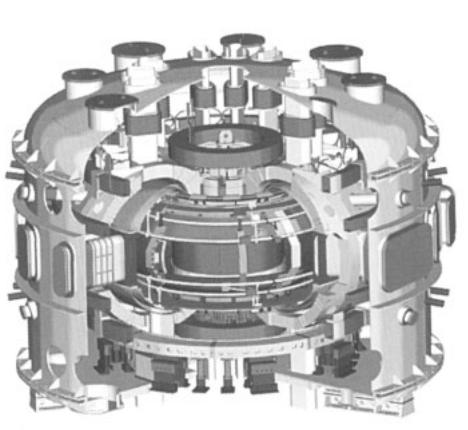


Fig.1 KSTAR tokamak configuration

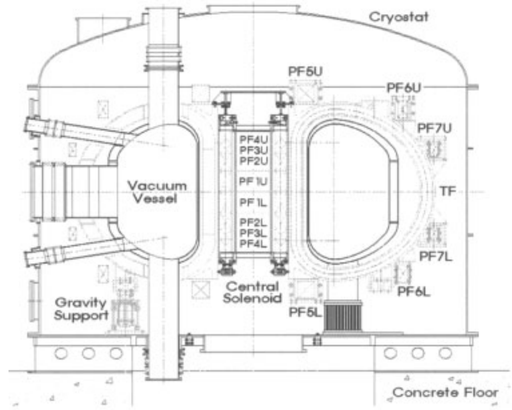


Fig.2 KSTAR superconducting magnet system configuration

Table 1. KSTAR major parameters

Parameters	Unit	Baseline	Upgrade
Toroidal field, B_T	T	3.5	
Plasma current, I_P	MA	2.0	
Major radius, R_0	m	1.8	
Minor radius, a	m	0.5	
Elongation, κ_x		2.0	
Triangularity, δ_x		0.8	
Poloidal divertor nulls		2	1 & 2
Pulse length	s	20	300
Heating power	MW		
Neutral beam		8.0	16.0
Ion cyclotron		6.0	6.0
Lower hybrid		1.5	3.0
Electron cyclotron		0.5	1.0
Peak DD neutron source rate	s^{-1}	1.5×10^{16}	2.5×10^{16}

account, the KSTAR tokamak is designed for a pulse length of 300 s. However, its initial configuration will provide a pulse length of 20 s driven by the poloidal magnet system. Although the PF coil system is able to provide a flux swing of 17 V-sec, an ECH (Electron Cyclotron Heating) power of 0.5 MW at 84 GHz will be installed to assist the plasma initiation to allow a low voltage startup at 6 V. Poloidal field coils and divertor are based on a plasma configuration with a strongly-shaped, double-null divertor. The overall tokamak configuration of the KSTAR is shown in Fig. 1 and its major parameters are summarized in Table 1.

The superconducting magnet system consists of 16 TF coils and 14 PF coils, in both of which internally-cooled superconductors are used. The TF coil system provides a field of 3.5 T at a plasma center, with a peak flux density of 7.2 T at the TF coils and the stored energy is 470 MJ. Incoloy 908 conduit and Nb_3Sn superconducting cable are used in the TF CICC. The nominal current of the TF coils is 35.2 kA with all coils in series. The PF coil system, consisting of 8 coils in the CS (Central Solenoid) coil system and 6 outer PF coils, provides 17 V-sec and sustains inductively the plasma current of 2 MA for 20 seconds. PF 1$\sim$5 coils use Nb_3Sn CICC in an Incoloy 908 conduit and PF 6 $\sim$ 7 coils use NbTi CICC in a modified stainless steel 316LN (STS316LN+) [4~6]. The Nitrogen content of STS316LN+ is the twice of the normal STS316LN. Fig. 2 shows the KSTAR superconducting magnet system configuration.

2 TF and PF conductors

The Nb_3Sn superconducting strand meets the KSTAR HP-III specification, where the critical current density is above 750 A/mm^2 at 12 T at 4.2 K and the hysteresis loss is below 250 mJ/cc per 3 T cycle. Both of Nb_3Sn and NbTi strands are chrome-plated with a thickness of 1 ± 0.2 μm. The cable pattern of TF and PF conductors are $3 \times 3 \times 3 \times 3 \times 6$ of 486 strands and $3 \times 4 \times 5 \times 6$ of 360 strands, respectively. The two superconducting strands and one OFHC copper strand are cabled together to become a triplet in the first cabling stage. The cabling pitch of TF and PF conductors are 40-73-157-227-355 mm and 40-80-145-237 mm, respectively. At the final cabling stage, 6 VTS (voltage-tap sensors) wires are inserted at the center of cable. Though the location

Table 2. TF and PF conductor parameters

Parameters	Units	TF	PF1-5	PF6-7
Conductor		Nb_3Sn	Nb_3Sn	NbTi
Strand diameter	mm	0.78 ± 0.01	0.78 ± 0.01	0.78 ± 0.01
Jc at 4.2 K	A/mm^2	> 750 (@12T)	> 750 (@12T)	> 2700 (@5T)
n-value		> 20	> 20	> 25
AC loss (±3 T)	MJ/cc	< 250	< 250	< 200
RRR		> 100	> 100	> 100
Cu/Non-Cu		1.5 ± 0.15	1.5 ± 0.15	2.8 ± 0.28
N_{strand}		486	360	360
Conduit size	mm	25.65	22.3	22.3
Conduit thickness	mm	2.86	2.41	2.41
$A_{conduit}$	mm^2	244.6	175.6	175.6
A_{non-Cu}	mm^2	61.9	45.9	30.2
A_{Cu}	mm^2	170.3	126.1	141.8
A_{Helium}	mm^2	142.6	112.1	112.1
Void fraction	%	36.5	37.5	37.5

of the VTS is not the best choice in view of the noise reduction, it is the safest against the deformation of VTS. The VTS is of a multi-layer structure, containing: 1) a stainless steel core wire (0.3 mm dia) at the center; 2) a sandwiched layer of a S-2 glass braid-overlapped stainless-steel filament braid (0.065 mm dia); 3) a stainless-steel capillary tube (1.32 mm dia) outmost. Stainless-steel 316L is used both for the filament and the tube. At the final stage of cable fabrication, the cable is wrapped with a thin stainless-steel strip, 30 mm wide and 0.05 mm thick, with a 20 % overlap on each side.

Incoloy 908 is designed to match the thermal expansion coefficient of Nb_3Sn strand [7]. The general micro-structure of Incoloy 908 is a single-phase austenitic structure. The strengthening is achieved by precipitation of ϒ'[(Ni_3(Al,Ti,Nb))] during the Nb_3Sn superconductor reaction heat treatment [8].

The tube mill process, consisting of forming, welding, sizing and squaring procedures, is used for the fabrication of CICC. A strip, which is milled, is wrapped around the superconducting cable through a series of progressive roller dies and is welded with GTAW (Gas Tungsten Arc Welding). The welded sheath should be cooled immediately by water and the face-bead of the weldment is ground by a bead-grinding machine. Then, the tube is formed to the final dimension of CICCs as shown in Fig. 3. Major conductor parameters are summarized in Table 2.

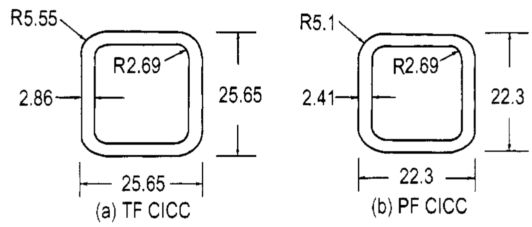


Fig.3 Dimension of TF (a) and (b) CICC

Seven CICCs of 640 m in length are fabricated for the TF coils. CICCs for the background magnetic field generation coil system (900 m ×2) [9~10], PF6 (1300 m ×4) and PF7 (1700 m ×2) coils are also fabricated. The height of the welding back-bead below 1 mm does not damage the superconducting cable. The final size of CICC is managed to be within the error of 0.05 mm and the void fraction of CICCs is above 36 %, which satisfies the specification.

3 Superconducting magnet system

The design parameters of TF coils are listed in Table 3. The total cold mass of TF magnet is about 150 tons. The coolant of TF coils is supercritical helium with an temperature of 4.5 K and an inlet pressure of 5 bars. There are four cooling channels per TF coil and the designed value of the total helium mass flow rate in 16 TF coils is 300 g/sec.

The dimensions of CS and PF coils are also listed in Ref. [11]. The designed peak currents are 25 kA

Table 3. Major parameters of TF coils

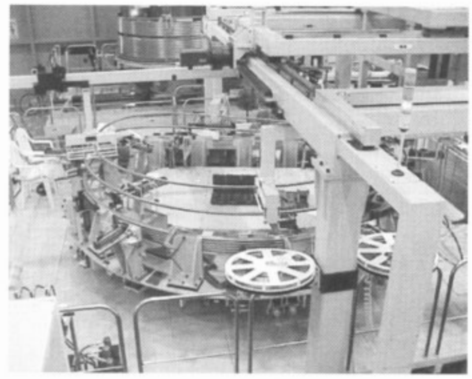
Parameters	Unit	Values
Superconductor / conduit		Nb_3Sn / Incoloy 908
Number of coils		16
Toroidal field at major radius	T	3.5
Peak field in conductor	T	7.2
Operating current	kA	35.2
Stored magnetic energy	MJ	470
Centering force	MN	15
Number of windings	turns	56
Conductor length per coil	m	640
Overall height	m	4.2
Overall width	m	3.0

and 20 kA for Nb_3Sn conductor and NbTi conductor, respectively. Upper and lower coils of PF1, PF2, and PF7 are connected in series inside a cryostat and other coils could be operated separately for single-null configuration. The CS coils are segmented into four pairs of solenoid coils with different numbers of turns and will be operated with different current values to meet the stringent requirement of plasma shaping. The cooling conditions for CS and PF coils are similar to those of TF coils. The total helium mass flow rate in CS and PF coils is about 250 g/sec.

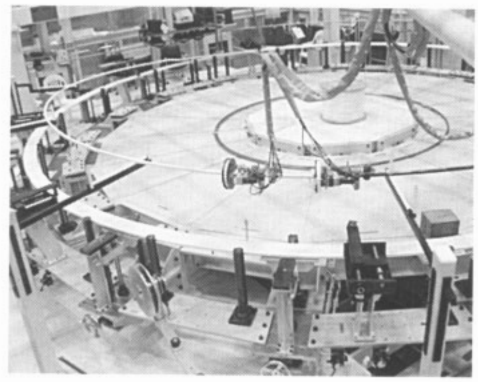
The procedure of the coil fabrication contains : (1) CICC leak test; (2) CICC winding with grit blasting; (3) attaching helium feed-through to joint terminations; (4) A15 reacting heat treatment of Nb_3Sn superconducting magnets; (5) insulation taping and ground wrapping; (6) vacuum pressure impregnation (VPI); (7) encasing; and (8) test and delivery.

The continuous winding scheme without internal joints is adopted to reduce the joint losses. Fig. 4 shows the operation of two winding stations operating for the winding of TF and PF coils. Since the PF6 and PF7 coils used in NbTi CICC which do not require the reacting heat treatment process, the helium feed-through attachment, and Kapton and S2-glass insulation taping are carried out during the winding process.

TF and PF1-5 coils used in Nb_3Sn strand require the reacting heat treatment process. After the winding process, the coils are placed in a heat treatment jig and the preparation for heat treatment, such as feed-through attachment and joint termination, is carried out. A vacuum furnace of 5.8 m in diameter is used in the A15 reacting heat treatment and



(a) TF winding



(b) PF7 winding

Fig.4 Winding station for TF and PF coils

another vacuum furnace of 6.4 m diameter will soon be installed. The temperature ramp rate during the heat treatment is 6 °C/hour and there are three plateaux : 460 °C/100 hs for removal of oxygen and contaminants from the cable, 570 °C/200 hs for enhancement of the diffusion of Sn into Nb filament and 660 °C/240 hs for the A15 reaction of Nb_3Sn. An Argon gas purging system is being operated during the baking process to prevent the SAGBO (Stress Accelerated Grain Boundary Oxidation) of Incoloy 908 and the oxygen content is maintained below 0.1 ppm. EDS (Energy Dispersive Spectroscopy) analysis has been carried out after the heat treatment of TF, and background magnet-field coils and no sign of SAGBO has been found.

After the heat treatment process, each turn of the coil is individually separated and the CICC is insulated with 50% overlapped layers of Kapton and S2-glass tapes. The thickness of Kapton and S2-glass tapes are 0.05 mm and 0.178 mm, respectively.

The S2-glass roving is applied at the corner of CICC to minimize the resin rich area. G10 pieces, which are shaped to fill the empty space of layer transition area, are also inserted, and the coil bundle is ground wrapped using S2-glass tape. The thickness of S2-glass tape for the ground wrapping is 0.254 mm. The coil bundle is placed in a molding die, and vacuum-pressure impregnated. Before the resin injection, the vacuum pressure is maintained below 2.667 Pa. After the resin injection, the VPI die is pressurized to 2.5 bar. VANTICO GY282, HY918, and DY073-1 are used as the epoxy resin, hardener, and accelerator, respectively. The pre-mixed resin is warmed to 40 °C and injected into the molding die. The curing lasts for 12 hours at 80 °C and for 24 hours at 120 °C. The static ultimate tensile strength (UTS) of the S2-glass fiber composite material at 300 K and 77 K are measured to be 896 MPa and 1035 MPa, which are more than twice stronger than a commercially available G10 material. Thermal expansion from 273 K to 4 K for the composite material is 0.23%, which is approximately 10 % less than Stainless Steel. The dimensional error in the full-size TF prototype coil after VPI is maintained below 1.7 mm. For the background magnetic field coils, the dimensional error is less than 1 mm.

The TF magnet structure consists of case, inner inter-coil structure (IIS), outer inter-coil structure (OIS), cooling line, joint box, and other interfacing structures [12]. On each TF coil an in-plane magnetic force of 15 MN is generated by TF charging and the out-of-plane force caused by CS, PF, and plasma current. To sustain these magnetic forces, each TF coil has a wedge-shaped structure on the inboard leg and an inter-coil structure with shear keys. The cooling routes of the TF structure are connected in series with the cooling channels of the TF coil. The cooling line is embedded inside between the TF structure and the cooling pad, which is brazed on the TF structure. The CS structure consists of inner and outer shells, top and bottom blocks, flexible joints, and stoppers [13]. Its major functions are of both a mechanical support and a structure for supplying pre-compression of about 15 MN on CS coils [14]. Its cooling lines are connected in series with CS coils. The peak stress including pre-compression is about 500 MPa at the neck part of the inner shell during operation.

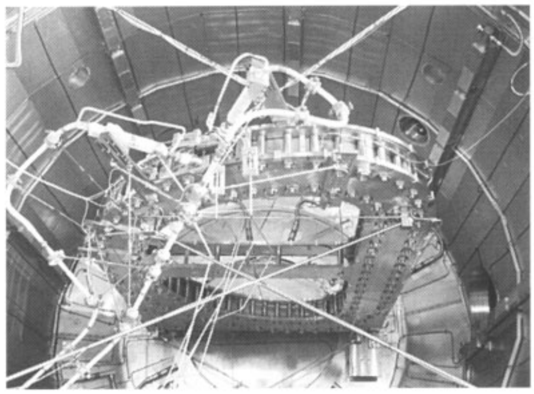


Fig.5 Installation of TF00 for the performance test

4 Coil test

A large superconducting coil test facility has been constructed and the performance test of the full-size TF prototype coil, TF00, was carried out in the test facility. The major objective of the TF00 test is to confirm the validity of the design and the fabrication process. Fig. 5 shows the installation of TF00 in the large vacuum cryostat of the test facility.

TF00 was cooled down to the operating temperature twice. After the installation of TF00 in the vacuum cryostat, the cryostat was evacuated and a vacuum pressure of 5.33×10^{-4} Pa was achieved at room temperature. TF00 and helium cooling lines were purged to remove residual gas. After filling liquid nitrogen into the thermal shield of the cryostat, TF00 has been cooled down within the specified temperature difference. The coil cool-down periods were 15 days in the first cool-down process and 10 days in the second cool-down process. The residual resistance ratio (RRR) of the coil was measured to be over 200. The superconducting phase transition of the coil occurred around 18 K. No helium leak from the coil was measured at the helium pressure of 6 bar and the vacuum pressure of the cryostat was below 2.667×10^{-5} Pa. When the coil was fully cooled, supercritical helium was supplied. The temperature and pressure of the helium supply lines were about 5.0 K and 5.3 bar, respectively. The helium flow rate of the coil was about 15 g/sec in total with the pressure drop in the coil of about 2.2 bar. The helium flow unbalance between four channels in the coil was within 10 %.

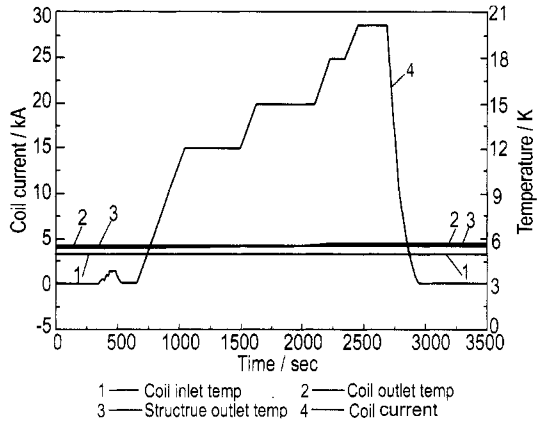


Fig.6 Current ramping and discharge of TF00

The current ramp-up and discharge test were carried out 23 times. Prior to the high current test, an adjustment of the TF power supply controller was carried out. The power supply was stably operated up to ramping rate of 80 A/s. For the reliable operation test of quench detection and protection systems during the current ramping, artificial quenches were generated at 5 kA by heating helium inlet lines, so the operation of the quench detection and protection system has been confirmed. Then, TF00 was repeatedly charged and discharged with various scenarios. Fig. 6 shows the result of a TF00 operation, where the maximum current is 29 kA. The temperature of the coil and structure was not changed. The coil was operated well without any quench over 30 kA. The result of repeated current charge tests shows that TF00 is fabricated robustly, and auxiliary systems, such as the power supply system, the quench detection and quench protection system, are also well designed and fabricated.

5 Conclusions

The full-size TF prototype coil, TF00, and the background magnetic field generation coils, BKG01 and BKG02, have been successfully developed and most of the fabrication procedures are fulfilled. Four of TF coils, PF7L, and PF7U are under fabrication at present. A large supercondcuting coil test facility has been constructed and the first test of TF00 has been completed successfully. The advanced tokamak design based on a fully superconducting magnet system will make KSTAR a premier facility for the development of steady-state high-performance modes in tokamak operation. Upon its successful commissioning in 2006, KSTAR will be delivered and serve the world fusion community as an international fusion collaborator.

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