Status of the KSTAR Superconducting Magnet System Development

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Abstract. As The Mission of Korea Superconducting Tokamak Advanced Research (KSTAR) Project is to develop a steady-state-capable advanced superconducting tokamak for establishing a scientific and technological basis for an attractive fusion reactor. Because the KSTAR mission includes the achievement of a steady-state-capable 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) and 14 Poloidal Field (PF) coils. Both of the TF and PF coil systems use internally-cooled Cable-In-Conduit Conductors (CICC). 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 the KSTAR magnet system development includes the development of CICC, the development of a full size TF model coil, the development of a background magnetic field generation coil system, the construction of a large scale superconducting magnet and CICC test facility. TF and PF coils are in the stage of the fabrication for the KSTAR completion in the year 2007.

1. INTRODUCTION

In order to support the KSTAR project mission [1-3], three major research objectives have been established: (i) to extend present stability and performance boundaries of tokamak operation through active control of profile and transport, (ii) to explore methods to achieve steady state operation for the tokamak fusion reactors using non-inductive current drive, and (iii) to integrate optimized plasma performance and continuous operation as a step towards an attractive tokamak fusion reactor. To meet the research objectives of KSTAR, key design features are: (i) fully superconducting magnets, (ii) long pulse operation capability, (iii) flexible pressure and current control, (iv) flexible plasma shape and position control, (v) 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 and 0.8, respectively. Considering practical engineering constraints, activation issue, system cost and conventional facility requirements, the KSTAR tokamak is designed for a pulse length of 300 s. However, the 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 strongly shaped, double-null divertor plasma configuration. The KSTAR tokamak and ancillary system is shown in Fig. 1 and major parameters are summarized in Table I.

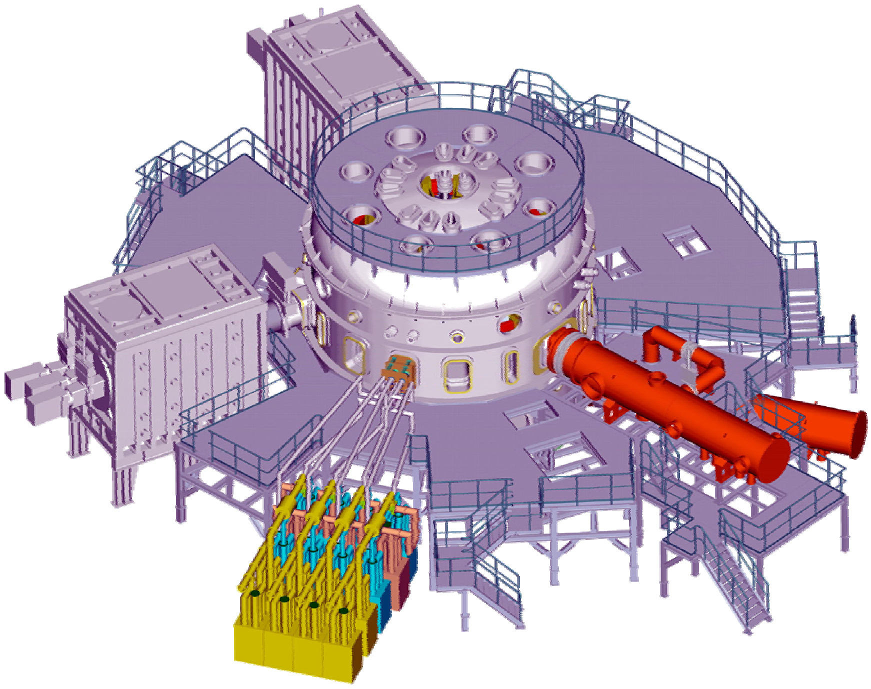


Fig. 1. KSTAR tokamak and ancillary system

Table I. KSTAR Major Parameters

Parameters	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}

The superconducting magnet system consists of 16 TF coils and 14 PF coils. Both of the TF and PF coil systems use internally cooled superconductors. The TF coil system provides a field of 3.5 T at a plasma center, with a peak flux density at the TF coils of 7.2 T and the stored energy is 470 MJ. Incoloy 908 conduit and Nb_3Sn superconducting cable are used for the TF CICC. The nominal current of the TF coils is 35.2 kA with all coils in series. The PF coil system, which consists of 8 coils in the CS (Central Solenoid) coil system and 6 outer PF coils, provides 17 V-sec and sustains the plasma current of 2 MA for 20 seconds inductively. PF 1-5 coils use Nb_3Sn CICC in an Incoloy 908 conduit and PF 6-7 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.

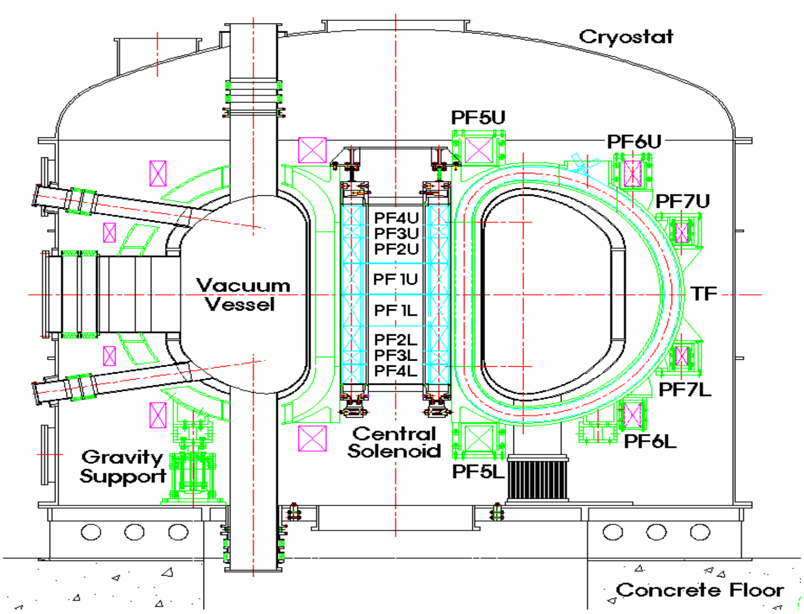


Fig. 2. KSTAR superconducting magnet system configuration

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 the thickness of 1 ± 0.2 μm. The cable pattern of TF and PF conductors are 3x3x3x3x6 of 486 strands and 3x4x5x6 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 stage of cable fabrication, the cable is wrapped with a thin stainless-steel strip, 30 mm wide and 0.05 mm thick, with 20 % overlap at 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 $\Upsilon'[(Ni_3(Al,Ti,Nb))]$ during the Nb_3Sn superconductor reaction heat treatment [8].

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

14 CICCs of 640 m in length are fabricated for the TF coils. CICCs for the background magnetic field generation coil system (900 m x 2) [9-10], PF3 (280 m x 2), PF4 (410 m x 2), PF6 (1300 m x 4) and PF7 (1700 m x 2) coils are also fabricated. The height of the welding back-bead is below 1 mm, which does not damage the superconducting cable. The final size of CICC is managed within the error of 0.05 mm and the void fraction of CICCs is above 36 %, which satisfies the specification.

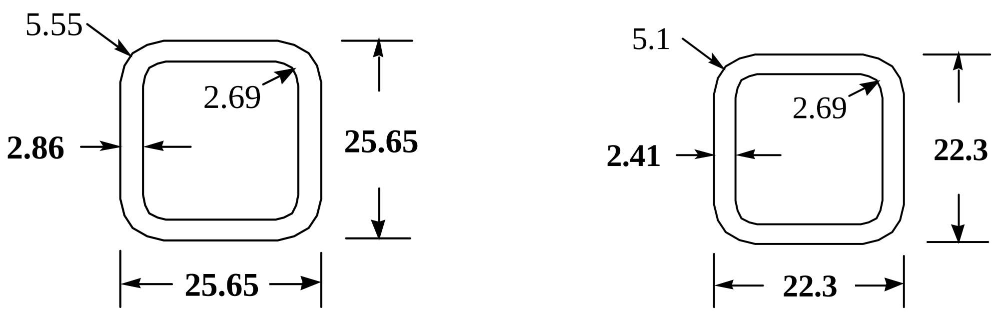


Fig. 3. Dimension of TF (a) and PF (b) CICC

Table II. 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

3. SUPERCONDUCTING MAGNET SYSTEM

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

Table III. Major Parameters of TF Coils

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

The dimensions of CS and PF coils are also listed in Ref. [11]. The designed peak currents are 25 kA 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 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 number of turns and will be operated with different current values to meet the strong 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 is : (i) CICC leak test; (ii) CICC winding with grit blasting; (iii) attachment of helium feed-throughs and joint terminations; (iv) A15 reaction heat treatment for Nb_3Sn superconducting magnets; (v) insulation taping and ground wrapping; (vi) vacuum pressure impregnation (VPI); (vii) encasing; and (ix) test and delivery.

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

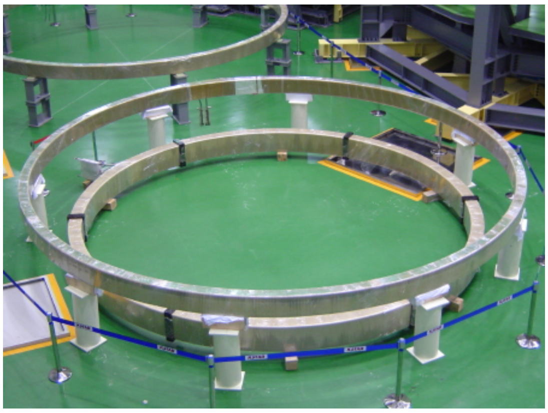
(a) TF Winding (b) PF7 Winding

Fig. 4. Winding Station for TF and PF coils

TF and PF1-5 coils use Nb_3Sn strand and require the reaction heat treatment process. After the winding process, 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 diameter is used for the A15 reaction heat treatment and another vacuum furnace of 6.4 m diameter will be installed. The temperature ramp rate during the heat treatment is 6 ℃/hour and there are three plateaus : 460℃, 100 hour to remove oxygen and contaminants from the cable, 570℃, 200 hour to enhance the diffusion of Sn to Nb filament and 660℃, 240 hour 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 performed 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. Thickness of Kapton and S2-glass tapes are 0.05 mm and 0.178 mm respectively. 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 2x10^{-2} torr. 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 to the molding die. The curing occurs at 80 °C for 12 hours and at 120 °C for 24 hours. The static ultimate tensile strength (UTS) for 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. Fig. 5 show TF and PF coils after VPI process.

(a) TF coils



(b) PF7 and PF6 coils

Fig. 5. TF and PF coils after VPI process

For the acceptance test, visual and dimensional checks, high voltage tests, and flow tests are performed. 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. For the PF7 coils, the error is less than 3 mm. For the ground insulation test, DC Hipot voltage was 15 kV and AC Hipot voltage was 10 kV (rms). For the layer and turn-by-turn insulation test, the impulse voltage was 2 kV. Fig. 6 shows the test result for the DC Hipot test of the PF7L coil, where the insulation resistance was remained above 20 GΩ. The flow test was performed in room temperature and the distribution of flow rates among cooling channels is maintained within 10 % variation.

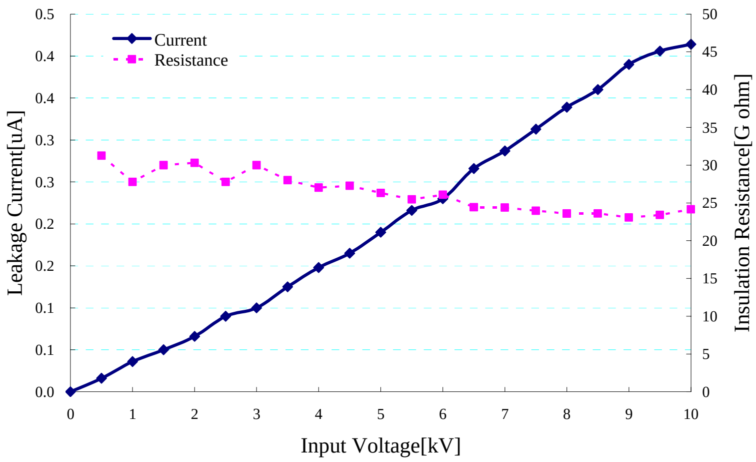


Fig. 6. Leakage current and insulation resistance for PF7L coil

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 out-of-plane force by CS, PF, and plasma current. To sustain these magnetic forces, each TF coil has a wedge shaped structure at the inboard leg and 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 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]. The major functions of the CS structure are both a mechanical support and a structure for supplying pre-compression of about 15 MN on CS coils [14]. The cooling lines of the CS structure 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.

4. CONCLUSIONS

The full size TF prototype coil, TF00, and the background magnetic field generation coils, BKG01 and BKG02, has been successfully developed and most of the fabrication procedures are settled down. At present, 5 TF, PF7L, PF7U, PF6L, and PF6U coils have been completed and 5 TF and PF3 coils are under fabrication for the KSTAR superconducting magnet system. A large superconducting coil test facility has been constructed and the performance test of the full size TF prototype coil, TF00, has been successfully completed. The performance test of the BKG01 and BKG02 coils is in progress. The advanced tokamak design based on a fully superconducting magnet system will make KSTAR a premier facility for development of steady-state high-performance modes of tokamak operation. Upon its successful commissioning in 2007, KSTAR will be delivered and serve for the world fusion community as an international fusion collaboratory.

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