Journal of the Korean Physical Society, Vol. 44, No. 5, May 2004, pp. 0∼0

Present Status of the KSTAR Superconducting Magnet System Development

Keeman Kim,* H. K. Park, K. R. Park, B. S Lim, S. I. Lee, M. K. Kim, Y. Chu, W. H. Chung, S. H. Baek, J. Y. Choi, H. Yonekawa, A. Chertovskikh, Y. B. Chang, J. S. Kim, C. S. Kim, D. J. Kim, N. H. Song, K. P. Kim, Y. J. Song, I. S. Woo, W. S. Han, D. K. Lee, Y. K. Oh, K. W. Cho, J. S. Park and G. S. Lee
Superconducting Magnet Team, Korea Basic Science Institute, Daejeon 305-333

H. J. Lee†
Korea Atomic Energy Research Institute, Daejeon 305-600

T. K. Ko‡ and S. J. Lee
Yonsei Unversity, Seoul 120-749

(Received 2 September 2003)

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 TF (toroidal field) and 14 PF (poloidal field) coils. Both of the TF and the 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 achievements in the KSTAR magnet system development include the development of CICC, the development of a full-size TF model coil, the development of a background magnetic field generation coil system, and the construction of a large-scale superconducting magnet and CICC test facility. The TF and The PF coils are being fabricated for the KSTAR completion in the year 2005.

PACS numbers: 74
Keywords:

I. INTRODUCTION

In order to support the KSTAR project mission [1-3], three major research objectives have been established: (i) extend the present stability and performance boundaries of tokamak operations through active control of profile and transport, (ii) explore methods to achieve steady-state operation for tokamak fusion reactors by using a non-inductive current drive, and (iii) 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, and (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 an elongation and a triangularity of 2 and 0.8, respectively. Considering practical engineering constraints, activation issues, 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 a poloidal magnet system. Although the PF (poloidal field) coil system is able to provide a flux swing of 17 V-sec, an electron cyclotron heating (ECH) power of 0.5 MW at 84 GHz will be installed to assist plasma initiation to allow a low-voltage startup at 6 V. Poloidal coils and a divertor are based on a strongly shaped, double-null divertor plasma configuration. The overall tokamak configuration of the KSTAR is shown in Figure 1, and major parameters are summarized in Table 1.

The superconducting magnet system consists of 16 TF (toroidal field) coils and 14 PF coils. Both the TF and the PF coil systems use internally cooled superconductors. The TF coil system provides a field of 3.5 T at the plasma center, with a peak flux density at the TF

*E-mail: kkeeman@kbsi.re.kr
†E-mail: hjlee1@nanum.kaeri.re.kr
‡E-mail: superlab@bubble.yonsei.ac.kr

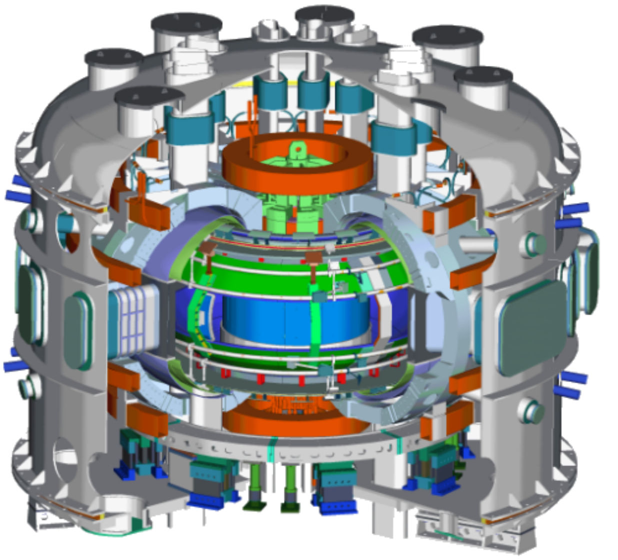

Fig. 1. KSTAR Tokamak Configuration.

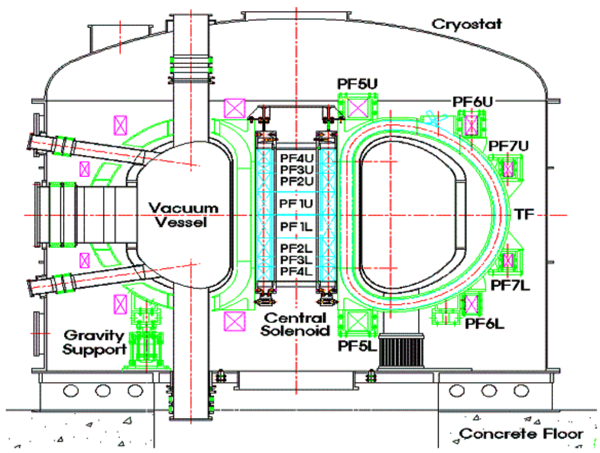

Fig. 2. KSTAR superconducting magnet system configuration.

Table 1. Major KSTAR parameters.

Parameters	Baseline	Upgrade
Toroidal field, B_T(T)	3.5	
Plasma current, I_P (MA)	2.0	
Major radius, R_O (m)	1.8	
Minor radius, a (m)	0.5	
Elongation, k_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 x 10^{16}	2.5 x 10^{16}

coils of 7.5 T and a stored energy of 470 MJ. Incoloy 908 conduit and a 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 provides 17 V-sec and sustains a plasma current of 2 MA for 20 seconds inductively and consists of 8 coils in the CS (central solenoid) coil system and 6 outer PF coils. 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 twice that of the normal STS316LN. Figure 2 shows the KSTAR superconducting magnet system configuration.

II. PF AND TF CONDUCTOR

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 and the hysteresis loss is below 250 mJ/cc per 3 T cycle. Both the Nb_3Sn and the NbTi strands are chrome plated with thicknesses of 1 ± 0.2 μm. The cable patterns of the TF and the 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 the TF and the PF conductors are 40-80-160-240-360 mm and 40-80-145-237 mm, respectively. At the final cabling stage, 6 voltage-tap sensors (VTS) are inserted at the center of the cable. Though the location of the VTS is not the best choice in the view of noise reduction, it is the most safest against the deformation of VTS. The VTS has the structure of a stainless-steel core wire (0.3 m dia.) at the center, S-2 glass braid, stainless-steel filament (65 μm dia.) braid, and a stainless-steel capillary tube (1.32 mm dia.) outermost. 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 20% overlap at each side.

Incoloy 908 is designed to match the thermal expansion coefficient of the Nb_3Sn strand [7]. The general micro-structure of Incoloy 908 is a single-phase austenitic structure. The strengthening is achieved by precipitation of [(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, and consists of forming, welding, sizing, and squaring procedures. A strip is wrapped around the superconducting cable and welded. A welded sheath should be quenched immediately with water, and the welding bead is ground due to the bead-grinding machine. Then,

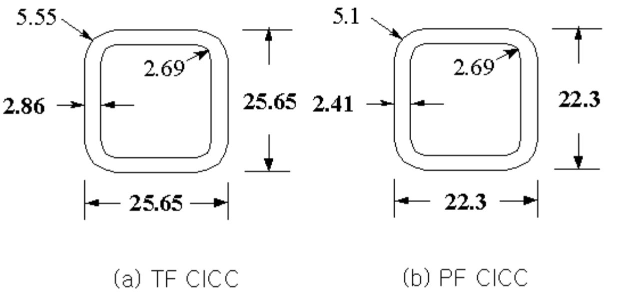

Fig. 3. Dimension of TF(a) and PF(b) CICC.

Table 2. TF and PF conductor parameters.

Parameters	Units	TF	PF1-5	PF6-7
Conductor		Nb_3Sn	Nb_3Sn	NbTi
Strand diameter	mm	0.780.01	0.780.01	0.780.01
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	320	320
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

the tube is formed to the final dimension of the CICCs, which is shown in Fig. 3. Major conductor parameters are summarized in Table 2.

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

III. SUPERCONDUCTING MAGNET SYSTEM

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

Table 3. Major parameters of the 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	500 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

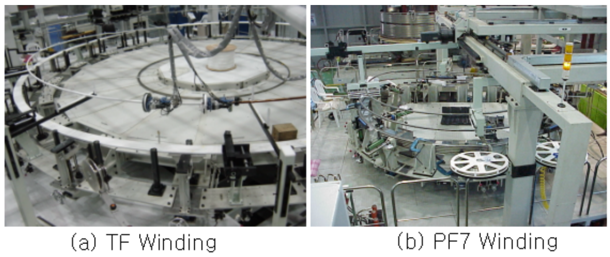

Fig. 4. Winding Station for TF and PF coils.

The dimensions of the CS and the PF coils are also listed in Ref. 11. The designed peak currents are 25 kA and 20 kA for the Nb_3Sn conductor and the NbTi conductor, respectively. Upper and lower coils of PF1, PF2, and PF7 are connected in series inside a cryostat; other coils could be operated separately for a single-null configuration. The CS coils are segmented by four pairs of solenoid coils with different numbers of turns and will be operated with different current values to meet the strong requirement of plasma shaping. The cooling conditions for the CS and the PF coils are similar to those of TF coils. The total helium mass flow rate in the CS and the PF coils is about 250 g/s.

The procedures of coil fabrication are as follows: (i) CICC leak test; (ii) grit blasting; (iii) coil winding; (iv) attachment of helium feed-throughs and joint terminations; (v) heat treatment; (vi) insulation taping and ground wrapping; (vii) vacuum pressure impregnation (VPI); (viii) encasing; and (ix) test and delivery.The continuous winding scheme without internal joints is adopted to reduce the joint losses. Figure 4 shows two winding stations operating for the windings of the TF and the PF coils. Since PF6 and PF7 coils use NbTi CICC and the reaction heat treatment process is not required, the helium feed-through attachments and Kapton and S2-glass insulation taping are carried out during the winding process.

The TF and the PF1-5 coils use Nb_3Sn strands and require a 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-throughs attachment and joint termination, is carried out. A vacuum furnace 5.8 m in diameter is used for the A15 reaction furnace and another vacuum furnace 6.3 m in diameter will be installed. The temperature ramp rate during the heat treatment is 6 °C/hour and there are three plateaus: 460 °C, 100 hour to remove oxygen and contaminants from the cable; 570 °C, 200 hour to enhance the diffusion of Sn to the Nb filament; and 660 °C, 240 hour for the A15 reaction of Nb_3Sn. An Argon gas-purging system is 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 analysis was performed after the heat treatment of the TF and the background magnet field coils, and no sign of SAGBO was found.

After the heat-treatment process, each turn of the coil was individually separated, and the CICC was insulated with 50% overlapped layers of Kapton and S2-glass tapes. The thicknesses of the Kapton and the S2-glass tapes were 0.05 mm and 0.178 mm, respectively. S2-glass roving is applied at the corner of the CICC to minimize the resin rich area. G10 pieces, which are shaped to fill the empty space of layer transition area, are inserted, and the coil bundle is ground wrapped using S2-glass tape. The thickness of the S2-glass tape for the ground wrapping is 0.254 mm. The coil bundle is placed in a molding die and vacuum-pressure impregnated. VANICO GY282, HY918, and DY073-1 are used as the epoxy resin, the hardener, and the 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 dimensional error is maintained below 1.7 mm in the full-size TF prototype coil after VPI. For the background magnetic field coils, the dimensional error is less than 1 mm.

The TF magnet structure consists of a case, a inner inter-coil structure (IIS), an outer inter-coil structure (OIS), a cooling line, a joint box, and other interfacing structures [12]. On each TF coil, an in-plane magnetic force of 15 MN is stressed by TF charging and out-of-plane force due to the CS, PF, and plasma current. To sustain these magnetic forces, TF coil has a wedge shaped structure on inboard leg and inter-coil structure with shear keys. The cooling routes of the TF structure are connected to the TF coils in series. The cooling line is embedded inside between 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]. The major functions of the CS structure are both mechanical support and a structure for supplying a pre-compression of about 15 MN on the CS coils [14]. The cooling lines of the CS structure are connected to CS coils in series. The peak stress, including pre-compression, is about 500 MPa at the neck part of the inner shell during operation. [15, 16]

IV. 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 have settled down. Three of the TF coils and the PF7L coil are under fabrication at present. A large supercondcuting coil test facility has been constructed, and the first 30 kA charging test of TF00 has been successfully finished. 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 2005, KSTAR will be delivered to and will serve the world fusion community as an international fusion collaboratory.

REFERENCES

[1] G. S. Lee, *et al.*, Nuclear Fusion **41**, 1515 (2001).
[2] G. S. Lee, *et al.*, Nuclear Fusion **40**, 575 (2000).
[3] G. S. Lee, *et al.*, Fusion Engineering and Design, **46**, 405 (1999).
[4] S. Lee, *et al.*, IEEE Trans. on Applied Superconductivity, **12**, 583 (2002).
[5] B. Lim, *et al.*, IEEE Trans. on Applied Superconductivity, **12**, 591 (2002).
[6] B. Lim, *et al.*, *IEEE Trans. on Applied Superconductivity Conference 2002* (Houston, Aug. 4-9, 2002).
[7] M. Morra, *Alloy 908 - new high-strength, low coefficient thermal expansion alloy for cryogenic applications*, M.S. Thesis, MIT, 1989.
[8] I. Hwang, *et al.*, Adv. Cry. Eng. Mat. **38**, 1-10 (1992).
[9] S. Baang, *et al.*, IEEE Trans. Appl. Supercond., **10**, 645 (2000).
[10] S. Baang, *et al.*, IEEE Trans. Appl. Supercond., **11**, 2082 (2001).
[11] Y. K. Oh, *et al.*, IEEE Trans. Applied Superconductivity, **11**, 2066 (2001).
[12] H. J. Ahn, *et al.*, IEEE Trans. Appl. Supercond., **12**, 492 (2002).
[13] Y. K. Oh, *et al.*, IEEE Trans. Appl. Supercond., **12**, 615 (2002).
[14] C. H. Choi, *et al.*, IEEE Trans. Appl. Supercond., **12**, 534 (2002).
[15] J.-S. Ko, *et al.*, Journal of the Korean Physical Society, **41**, 212 (2002).
[16] O. Kwon, J. Korean Phys. Soc. **42**, 118 (2003).