Status of the KSTAR Project

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Synopsis: The KSTAR project was started in 1996 and conducted in three phases, the conceptual design phase (1996–1998), the R&D and engineering design phase (1998–2002), and the construction phase (2002–2007). The mission of the 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. Since 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 and the long pulse current drive and heating systems are also the important aspect of the KSTAR design features. The advanced tokamak aspect of the mission is incorporated in the design features associated with flexible plasma shaping, double-null divertor and passive stabilizer, internal control coils. All the major components are in the stage of the fabrication and assembly for the completion of the KSTAR construction in the year 2007.

Keywords: KSTAR, tokamak, superconducting magnet

1. Introduction

In order to support the KSTAR project mission^{1,2)}, three major research objectives have been established: (i) to extend present stability and performance boundaries of tokamak operation through active control of plasma 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. The KSTAR auxiliary heating system uses neutral beams, ion-cyclotron waves, electron-cyclotron waves, and lower-hybrid waves. It will heat the plasma to high temperature and high beta, drive the current non-inductively, and control current and pressure profiles. Although the PF (Poloidal Field) coil system is able to provide a flux swing of 17 V-s, an electron cyclotron heating (ECH) 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 coils and divertor are based on a strongly shaped, double-null divertor plasma configuration. To control the MHD behavior of high beta plasmas, in-vessel conducting structures are provided for passive stabilization and a set of segmented in-vessel control coils is utilized for active position control, field-error correction and resistive wall mode stabilization. The schematic layout of KSTAR tokamak and ancillary system is shown in **Fig. 1** and major parameters are summarized in **Table 1**.

2. Vacuum Vessel System

2.1 Vacuum vessel and ports

The KSTAR vacuum vessel (VV) is an all-metallic, all-welded, double-walled, and D-shaped structure³⁾. It consists of the inner and outer shell, horizontal, vertical and slanted ports, and the leaf spring-typed supports. Double walls are connected by poloidal and toroidal ribs and filled with water for bake-out, cooling and neutron shielding. Reinforcement by

Fig. 1 Schematic layout of KSTAR Tokamak system.

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Table 1 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}

thirty-two equally spaced poloidal ribs and two toroidal ones provides a robust structure. **Table 2** shows the major parameters of the KSTAR vacuum vessel.

The vacuum vessel material is SA240-316LN. The most severe load condition for the vacuum vessel is the combination of static load and electromagnetic load due to a vertical disruption event. The details of the fabrication procedure are summarized in Ref. 4). The KSTAR vacuum vessel was fabricated in three separated parts, 180° sector 1, 157.5° sector 2, and 22.5° sector 3. The welding test result using a 1/3 mock-up showed that the major distortion was a horizontal shrinkage by 9 mm. Because the sectors 1 and 2 were set to have larger gap for the sector 3 by 14 mm, the 337.5° sector after on-site welding have wider gap by 5 mm, which is the provisional margin for the additional shrinkage in the final welding of the sector 3.

2.2 In-vessel components

The in-vessel components⁵⁾, which are shown in **Fig. 2**, consist of divertor, inboard limiter, passive stabilizer (including

Fig. 2 KSTAR in-vessel components. **Fig. 3** Segmented KSTAR in-vessel control coils.

ripple armor), neutral beam shinethrough armor, poloidal limiter, in-vessel cryopumps and internal control coils. The plasma facing components (PFCs) are bolted graphite or carbon-fiber-composite (CFC) tiles supported by SA240-316LN (for divertor, inboard limiter, neutral beam shinethrough armor, and poloidal limiter) and CuCrZrMg (for passive stabilizer) back plates. Though the PFCs are designed for the baseline operation, inboard limiter and passive stabilizer can accommodate the upgrade operation conditions of 300 second pulse length and 28 MW heating power. All baseline PFCs will be water-cooled during plasma operation to maintain the surface temperatures of graphite and CFC tiles below 600°C and 1,200°C, respectively. The baking temperature of the PFCs, at least 300°C, can be achieved within 24 hours using nitrogen gas.

In-vessel copper coils will be used for the fast plasma position control, field error correction (FEC), and resistive wall mode (RWM) feedback stabilization. **Figure 3** shows the design, where the two sets of coils are unified into a single set by utilizing the concept of segmented coil system. Several important advantages of the design include: (i) simplification in fabrication and installation; (ii) easy maintenance; (iii) improvement in the reliability, with inter-segment joints located outside the vacuum vessel; (iv) substantial saving in in-vessel space by reducing the two coil sets to one.

Table 2 Major parameters of vacuum vessel

Parameters	Values
Height/width	3.387 m / 1.880 m
Shell, rib thickness	12 mm, 20(40) mm
Wall thickness	50 – 190 mm
Total weight	54 ton (with support)
Surface area (inner shell)	100 m ² (without port)
Base pressure	1×10^{-6} Pa
Material	SA240-316LN
Baking temperature	130°C @inner shell
Magnet permeability	1.10 (after welding)
Loop resistance	$\geq 40 \Omega$
Number of shell plates	180
Number of rib plates	120
Number of ports	72
Length of welding joint	1,542 m ($\times 7$)

Fig. 4 KSTAR superconducting magnet system configuration.

3. Superconducting Magnet System

3.1 Description of superconducting magnet system

The superconducting magnet system consists of 16 TF (Toroidal Field) coils and 14 PF coils^{6,7)}. Both the TF and PF coil systems use internally cooled superconductors. The TF coil system provides a magnetic field of 3.5 T at the 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 Nb₃Sn superconducting cable are used for the TF Cable in Conduit Conductor (CICC). The nominal current of the TF coils is 35.2 kA with all coils connected in series. The PF coil system, which consists of 8 coils in the CS (Central Solenoid) coil system (PF1-4) and 6 outer PF coils (PF5-7), provides 17 V-s and sustains the plasma current of 2 MA for 20 seconds inductively. **Figure 4** shows the KSTAR superconducting magnet system configuration.

The design parameters of the TF coils are listed in **Table 3**. The total cold mass of the TF magnet system is ~150 tons. The coolant of TF coils is supercritical helium with an inlet temperature of 4.5 K and an inlet pressure of 0.5 MPa. There are four cooling channels per each TF coil and the design value of the total helium mass flow rate in the 16 TF coils is ~300 g/s.

Table 3 Major parameters of TF coils

Parameters	Values
Superconductor / conduit	Nb ₃ Sn / Incoloy 908
Number of coils	16
Toroidal field at plasma center	3.5 T
Peak field in coil	7.2 T
Operating current	35.2 kA
Stored magnetic energy	470 MJ
Centering force	15 MN
Number of turns per coil	56
Number of pancakes per coil	8
Number of turns per pancake	7
Conductor length per coil	610 m
Number of cooling channels per coil	4
Overall height	4.2 m
Overall width	3.0 m

The design parameters of the CS and PF coils are listed in **Table 4**. The designed peak currents are 25 kA and 20 kA for Nb₃Sn conductor and NbTi conductor, respectively. The upper and lower coils of PF1, PF2, and PF7 are connected in series inside the cryostat and the other coils can be operated separately for the 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. Though the inlet temperature and pressure of the supercritical helium for the CS and PF coils need to be adjusted according to a given operation scenario, the cooling conditions for the CS and PF coils are similar to those of TF coils. The total helium mass flow rate in CS and PF coils is ~250 g/s.

3.2 TF and PF Conductors

The Nb₃Sn superconducting strand meets the KSTAR HP-III specification, where the non-copper critical current density is above 750 A/mm² at 12 T, 4.2 K and -0.25% strain, and the hysteresis loss is below 250 mJ/cc for a 3 T cycle. Both Nb₃Sn and NbTi strands are chrome plated with the thickness of 1 ± 0.2 μm. The cable patterns of the TF and PF conductors are 3x3x3x3x6 of 486 strands and 3x4x5x6 of 360 strands, respectively. 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 PF conductors are

Table 4 Major parameters of PF coils

Parameters	CS coils				PF coils		
	PF1	PF2	PF3	PF4	PF5	PF6	PF7
Superconductor	Nb ₃ Sn	Nb ₃ Sn	Nb ₃ Sn	Nb ₃ Sn	Nb ₃ Sn	NbTi	NbTi
Conduit	Incoloy908	Incoloy908	Incoloy908	Incoloy908	Incoloy908	STS316LN	STS316LN
Number of coils	2	2	2	2	2	2	2
Radial position, R [mm]	570	570	570	570	1,073	3,090	3,730
Axial position, Z [mm]	249	699	1005	1264	229.5	1,920	980
Coil width, dR [mm]	230.5	230.5	230.5	230.5	326.3	206.6	158.8
Coil height, dZ [mm]	493.7	398.0	206.6	302.3	398.0	398.0	302.3
Number of turns per coil	180	144	72	108	208	128	72
Number of pancakes per coil	20	16	8	12	16	16	12
Number of turns per pancake	9	9	9	9	13	8	6
CICC length per coil [m]	663	537	283	410	1,422	2,505	1,707
Number of cooling channels per coil	10	8	4	6	8	8	6
Weight per coil [ton]	2.34	1.81	0.96	1.39	4.8	8.22	5.65

Table 5 Cabling parameters for TF and PF CICC

TF cable				PF cable			
Stage	Element	Pitch[mm]	Dia. [mm]	Stage	Element	Pitch [mm]	Dia. [mm]
1	2SC+1Cu	40±4	1.65	1	2SC+1Cu	40±4	1.65
2	3x3	73±8	3.3	2	3x4	80±8	3.64
3	3x3x3	157±16	5.7	3	3x4x5	145±15	8.14
4	3x3x3x3	227±23	9.9	4	3x4x5x6	237±24	19.9
5	3x3x3x3x6	355±36	22.2				

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. The cabling parameters for the TF and PF cables are summarized in **Table 5**.

Incoloy 908 is designed to match the thermal expansion coefficient of Nb₃Sn strand^{11, 12}). The general micro-structure of Incoloy 908 is a single phase austenitic structure. The strengthening is achieved by precipitation of $\gamma'[(\text{Ni}_3(\text{Al}, \text{Ti}, \text{Nb}))]$ during the Nb₃Sn reaction heat treatment. A modified stainless steel 316LN (316LN+) is used as the jacket material of PF 6-7 NbTi CICC and the **Table 6** shows the chemical composition of the 316LN+. The Nitrogen content of the 316LN+ is nearly the twice of the normal stainless steel 316LN.

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

Table 6 Chemical composition of stainless steel 316LN+(wt%)

Ni	C	Si	Mn	S	Cr	Mo	N
12.0–12.5	<0.02	<0.5	1.6–2.0	<0.01	17.0–18.0	2.3–2.7	0.16–0.22

Table 7 Major parameters of TF and PF conductors

Parameters	TF	PF1-5	PF6-7
Conductor	Nb ₃ Sn	Nb ₃ Sn	NbTi
Strand diameter [mm]	0.78±0.01	0.78±0.01	0.78±0.01
J_c at 4.2 K [A/mm ²]	>750(@12T)	>750(@12T)	>2700(@5T)
n-value	>20	>20	>25
Hysteresis loss (±3 T) [mJ/cc]	<250	<250	<200
RRR	>100	>100	>100
Cu/Non-Cu ratio	1.5±0.15	1.5±0.15	2.8±0.28
Number of 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
$A_{\text{non-Cu}}$ [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
Temperature margin T_{margin} [K]	> 2	> 2	> 1

is ground by bead grinding machine. The specification for the height of the welding back-bead is below 1 mm. However, the shape of the bead is smooth and the height is maintained below 0.5 mm, which does not damage the superconducting cable. Then, the conductors are formed to the final dimension of CICC as shown in **Fig. 5**. The final size of CICC is managed within the error of 0.05 mm. Major conductor parameters are summarized in **Table 7**. However, the smaller void fraction is preferred and the actual void fractions of CICC are ~36% by controlling the jacket thickness during the compaction process.

18 CICC of 640 m in length are fabricated for the TF coils. CICC for the background magnetic field generation coil system (920 m x 2), PF1 (670 m x 2), PF2 (550 m x 2), PF3 (290 m x 2), PF4 (420 m x 2), PF5L (1,560 m x 1), PF6 (1,300 m x 4) and PF7 (1,710 m x 2) coils are also fabricated. One CICC for PF5U (1,440 m x 1) are scheduled to be fabricated by the end of March 2006. The background magnetic field generation coil system consists of two split coils^{13, 14}). The primary function of the background magnetic field generation coil system is providing a background magnetic field for the CICC sample test. However, it uses the same CICC as the KSTAR CS coils and it is also called KSTAR CS model coil system.

3.3 Fabrication procedure of superconducting magnet

The procedure of the coil fabrication is : (i) CICC leak test; (ii) CICC winding with zirconia bead blasting; (iii) attachment of helium feed-throughs and joint terminations; (iv) A15 reaction heat treatment for Nb₃Sn 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 joint is adopted to reduce the joint losses. In other words, each coil is wound using a single CICC except PF6U and PF6L coils, which have one internal joint for each coil. However, helium

Fig. 5 Dimension of TF and PF CICC.

feed-throughs are attached per each double pancakes and the number of cooling channels is listed in **Tables 3** and **4**. **Figure 6** 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-through attachment and Kapton and S2-glass insulation taping are carried out during the winding process.

The TF and PF1-5 coils use Nb₃Sn strand and require the reaction heat treatment process. After the winding, the coils are placed in a structure for the heat treatment and the preparation for heat treatment including the installation of magnet lead holding fixtures, the attachment of feed-throughs for an argon purging system and also the preparation of joint termination is carried out. In order to minimize the deformation of the winding pack during the heat treatment process, 3-dimensionally machined stainless steel pieces are also installed to the empty space of layer transition area. Two vacuum furnaces of 5.8 m diameter and 6.4 m diameter are used for the heat treatment. The temperature ramp rate during the heat treatment is 6°C/hour and there are three plateaus : 460°C, 100 hours to remove oxygen and contaminants from the cable, 570°C, 200 hours to enhance the diffusion of Sn to Nb filament and 660°C, 240 hours for the

A15 reaction of Nb₃Sn. 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 the TF and background magnet field coils and no sign of SAGBO has been found.

After the heat treatment, 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 the Kapton and S2-glass tapes are 0.05 mm and 0.178 mm respectively. S2-glass roving filler 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 insulation wrapped using S2-glass tape with the thickness of 0.254 mm. As a quench detection sensor of PF1-5 coils, an externally co-wound voltage tap, which is made of a conducting polymer tape, has been developed for the minimization of the induced voltage during the operation.

The coil bundle is placed in a molding die and vacuum impregnated. Before the resin injection, the vacuum pressure is maintained below 2.5 Pa. After the resin injection, the VPI die is

(a) TF coil winding

(b) PF coil winding

Fig. 6 Winding stations for TF and PF coils.

(a) TF coil

(b) PF6 and PF7 coils

Fig. 7 TF and PF coils after VPI process.

pressurized to 0.25 MPa. 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 1,035 MPa, which are more than twice stronger than a commercially available G10 material. Thermal contraction from 273 K to 4 K for the composite material is 0.23%, which is approximately 10% less than Stainless Steel¹⁵⁾. **Figure 7** shows the 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 main 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 high voltage was 15 kV and AC high voltage was 10 kV (rms). For the layer and turn-by-turn insulation test, the impulse voltage was 2 kV. **Figure 8** shows the test result for the DC high voltage test of the PF7L coil, where the insulation resistance was kept above 20 GΩ. The flow test was performed at room temperature and the distribution of flow rates among the cooling channels is maintained within 10% variation.

At the present time, the fabrication of 17 TF coils including a spare coil, 4 PF coils, 2 CS coils have been completed. All of the KSTAR superconducting magnets will be fabricated by the end of July 2006.

3.4 Magnet structure

The KSTAR magnet structure consists of 16 TF structures, one CS structure, and 80 PF structures. Most of structures are made of stainless steel 316LN. The TF magnet structure consists of case, inner inter-coil structure (IIS), outer inter-coil structure (OIS), cooling line, joint box, and other interfacing structures¹⁶⁾. On each TF coil, an in-plane magnetic force of 15 MN is generated by TF charging and an out-of-plane force by the CS, PF, and the plasma current. To sustain these magnetic forces,

Fig. 8 Leakage current and insulation resistance for PF7L coil.

Fig. 9 Final machining of TF coil case after the coil encasing.

each TF coil has a wedge shaped structure at the inboard leg and the inter-coil structure with shear keys. There are 18 cooling tubes embedded inside of the structure around the coil and an additional cooling tube on the TF structure surface. The major fabrication procedure of the TF structures are; (i) fabrication of C-shaped coil case welded with inter-coil structure, (ii) fabrication of flat cover plate welded with inter-coil structure, (iii) coil encasing, (iv) final enclosure welding, (v) second vacuum pressure impregnation, (vi) final machining and delivery, and (vii) toroidal insulation attachment. **Figure 9** shows the final machining of TF coil case after the coil encasing.

The CS structure consists of inner and outer shells, top and bottom blocks, and stoppers¹⁷⁾. The major functions of the CS structure are both a mechanical support and the pre-compression of ~ 15 MN¹⁸⁾. The peak stress including pre-compression is ~ 500 MPa at the neck part of the inner shell during operation.

3.5 Coil performance test

A large superconducting coil test facility has been constructed and the performance test of the full size TF prototype coil, TF00, and the main background magnetic field coils, BKG01 and BKG02, were carried in the test facility. The major objective of the test is to confirm the validity of the design and the fabrication process. **Figure 10** shows the installation of TF00 and the background magnetic field coil system into the large vacuum cryostat of the test facility^{19, 20)}.

After the installation of TF00 in the vacuum cryostat, the cryostat was evacuated and a vacuum pressure of 5.3×10^{-4} Pa was achieved at room temperature. TF00 and helium cooling lines were purged. After filling liquid nitrogen into the thermal shield of the cryostat, TF00 was cooled down in 10 days within a maximum temperature variation of 50 K. The residual resistivity ratio (RRR) of the coil was measured to be over 200. The superconducting phase transition of TF00 occurred around 18 K. No helium leak in the coil was measured and the vacuum pressure of the cryostat was below 2.7×10^{-5} Pa. When the coil temperature was reached below 5 K, supercritical helium was supplied. The temperature and pressure of the helium supply

lines were ~ 5.0 K and ~ 0.53 MPa, respectively. The void fraction of the CICC for TF00 is approximately 32%, which is 4.5% lower than the CICC for the KSTAR TF coils, and the length of the cooling channel is 152 m. The helium flow rate of the coil was ~ 15 g/s in total with the pressure drop in the coil of ~ 0.22 MPa. The helium flow unbalance between the four channels in the coil was within 10%. The DC power supply for the KSTAR TF coil was stably operated up to 80 A/s ramping rate. 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 and the operation of the quench detection and protection system has been confirmed. Then, TF00 was repeatedly charged and discharged with various scenarios. The coil was operated well without any quench up to 30 kA. The result of repeated current charge tests shows that TF00 is fabricated robustly and auxiliary systems, such the power supply system, the quench detection and quench protection system, are also designed reliably.

The background magnetic field coil system could provide a background magnetic field of 8 T with a ramp rate of 3 T/s. Though the blip coil system, which consists a pair of blip coils and a pair of passive cancellation coils was not installed at this

time, the blip coil system can be installed inside the main background magnetic field coil system and it could provide a magnetic field of 1 T with a ramp rate of 20 T/s for 50 ms. The supporting structure of the main background magnetic field coil system was made of G10 material for the reduction of the eddy current during pulsed operations. Though GFRP (Glass Fiber Reinforced Plastic) electric breakers were successfully used for the test of TF00, total 22 ceramic electric breakers were installed instead of GFRP electric breakers because of the helium leak during the first cool down of the background magnetic field coil system using GFRP electric breakers. The main coil system was cooled down to 5 K in 9 days. However, the temperature of the G10 coil support structure was approximately 30 K due to the low thermal conductivity. The void fraction of CICC for the main coil is approximately 37% and the length of the cooling channel is 105 m. The total helium flow rate was ~ 45 g/s and the pressure drops ~ 0.1 MPa. The coil was successfully excited to 20 kA, where the peak field is 8.62 T, using the DC power supply for the KSTAR TF coil. In the view point of temperature margin, the operating condition of the coil at 20 kA is a similar operating condition of the KSTAR CS coil at 25 kA. However, the prototype AC power supply showed a logical error during the crossing of zero current and the AC test was performed with a DC offset current, which prevents the control failure of the AC power supply near zero current. The coupling time constant, τ_r , which was measured by changing the frequency and the amplitude of sinusoidal current, was less than 30 ms, which is approximately half of the design specification.

4. Cryostat and Thermal Shields

The KSTAR cryostat consists of single-walled cylindrical shell, dome-shaped top lid, and flat bottom lid. It provides feed-through penetrations for all the connecting components inside and outside the cryostat with 102 ports including 72 VV port penetrations with bellows. The cryostat is mounted on a base plate for transferring the loads to main building support structure through 8 base beams. Main material selected for the

(a) TF00 coils

(b) Background magnetic field coil

Fig. 10 Installation of TF00 and background field coil.

Fig. 11 Installation of TF coils in VVTS and VV assembly.

cryostat is ASME SA-240 type 304L. Extensive information of cryostat structural analyses can be found in Ref. 21).

There are four types of thermal shields: (i) the vacuum vessel thermal shields (VVTs) located 5 cm off the outer wall; (ii) the cryostat thermal shields (CTS) located 15 cm off the inside cryostat; (iii) the transition thermal shields (TTS) around ports; and (iv) the support thermal shields (STS) that cover the gravity supports and base plate. **Figure 11** shows the VVTs installed on the KSTAR vacuum vessel and a few installed TF magnets.

5. Ancillary System

The design and development of the KSTAR diagnostic system was discussed in Ref. 22). With the specific mission of long-pulse operation, the diagnostic system should be able to provide real-time data for the plasma control in long pulse operation. And their output must be integrated into the control system in addition to provide data for physics analysis. The integration of profile measurements into control systems is the area of a significant research in the period prior to KSTAR operation.

The baseline heating and current drive system on the KSTAR consists of neutral beam injection (NBI) and radio-frequency (RF) systems. The flexibility to provide a range of control functions, including current drive and profile control, derives from the use of multiple heating technologies: tangential NBI (energy < 120 keV, 8 MW), ion-cyclotron waves (25–60 MHz, 6 MW), and lower-hybrid waves (5 GHz, 1.5 MW). The launched wave spectra is controlled to provide flexibility in the heating and current-drive profiles. The NBI system is designed to provide a local heating capability at constant plasma density and profile shape. The ICRF capabilities will allow physics experiments over a range of magnetic fields and provide electron heating and drive current near the axis. The LH antenna

Fig. 13 KSTAR assembly tool.

design will provide a wave-number spectrum optimized for localization of electron heating and current drive off-axis. **Figure 12** shows a layout of the main diagnostic system and the main heating systems.

6. Assembly of Tokamak

The KSTAR tokamak is under the stage of assembly. The assembly sequence is; (i) assembly tools preparation, (ii) assembly of the cryostat base and the magnet gravity support, (iii) assembly commissioning with the prototype TF coil rotation, (iv) lower PF6-7 coil assembly, (v) assembly of the vacuum vessel and VVTs, (vi) TF coil assembly, (vii) assembly of upper PF coils and CS coils, (viii) assembly of the current feeders and helium lines, (ix) assembly of the cryostat and CTS, and (ix) welding of vacuum vessel and ports²³⁾.

A special assembly tools has been developed to give the accurate system assembly. **Figure 13** shows the assembly tool.

Once a TF coil is loaded into the loading vehicle, the coil transporter locates the TF coil between the 22.5° slit of the vacuum vessel. Then the TF coil is rotated to the final position for the assembly. Up to now the assembly of the cryostat base, magnet gravity support, vacuum vessel and VVTs has been completed. 12 TF coils are installed and all TF coils will be assembled with the vacuum vessel by the end of March 2006.

7. Conclusion

The KSTAR project is in the phase of construction. The fabrication of vacuum vessel, VVTs, a cryostat has been completed. The performance test of the prototype TF coil and the CS model coil has been accomplished and all of the superconducting magnets will be fabricated by the end of July 2006. The KSTAR tokamak is in the stage of site assembly. At the present time, the overall

Fig. 12 Layout of the KSTAR heating and diagnostic systems.

progress is over 90%. The advanced tokamak design based on a fully superconducting magnet system will make KSTAR a premier facility for the research of the steady-state high performance modes of tokamak operation. Upon its successful commissioning in 2008, the KSTAR device will be delivered and serve for the world fusion community as an international fusion collaboratory.

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