Commissioning Results of the KSTAR Cryogenic System

Y. S. Kim, Y. M. Park, Y. J. Lee, S. W. Kwag, Y. B. Chang, N. H. Song, I. S. Woo, H. T. Park, K. W. Cho, H. S. Chang, D. S. Park, J. J. Joo, K. M. Moon, K. R. Park, Y. Chu, H. Yonekawa, Y. O. Kim, E. N. Bang, H. K. Kim, K. P. Kim, M. K. Park, S. Baek. J. S. Hong, T. H. Ha, Y. J. Kim, I. S. Hwang, H. L. Yang, Y. K. Oh, J. S. Bak, M. Kwon, G. S. Lee and the KSTAR Team

National Fusion Research Institute (NFRI), Daejeon, Korea

e-mail : kimys@nfri.re.kr

Abstract. The cryogenic system for the KSTAR superconducting magnets has been commissioned. It consists of a cold box, distribution boxes (DB) and cryogenic transfer lines. The cold box and DB #1 provide 600 g/s of supercritical helium to cool the superconducting (SC) magnets, their SC bus-lines, and the magnet support structures. It also provides 17.5 g/s of liquid helium to the current leads and supplies cold helium flow to the thermal shields. The cooling power of the cold box at 4.5 K equivalent is 9 kW which is extracted by 6 turbo-expanders. The DB #1 includes 49 cryogenic valves, 2 supercritical helium circulators, 1 cold compressor, and 7 heat exchangers immersed in a 6 m^3 liquid helium storage bath. The main duties of the DB #2 are the relative distribution of the cryogenic helium among the cooling channels of each KSTAR cold component and the emergency release of over-pressurized helium during abnormal events such as quenches of the SC magnets. After individual commissioning, the system was integrated and cooled down with the KSTAR device. In this paper, the construction and commissioning results of the KSTAR cryogenic system will be introduced. In addition, we will present the cool-down results of the KSTAR device.

1. Introduction

KSTAR device is a tokamak with fully superconducting (SC) magnets and has also the world's largest Nb_3Sn SC coils. It consists of 16 toroidal field (TF) coils, 8 central solenoid (CS) and 6 poloidal field (PF) coils. The TF, CS, and PF5 coils use Nb_3Sn cable-in-conduit conductor (CICC) in Incoloy908 conduit and PF 6-7 coils use NbTi CICC in a modified stainless steel 316LN conduit [1]. All the SC coils are cooled with 4.5 K forced flow supercritical helium (SHe). The additional cold components to be cooled down with SC coils are the current feeders, SC bus-lines, and current leads (CL), which transfer the current from the power supply to the magnet. The thermal shields (TS) that protect the SC magnets and feeders from ambient radiation consist of a vacuum vessel thermal shield (VVTS), a cryostat thermal shield (CRTS) and current feeder shields (CFS). The total cold mass of the KSTAR SC magnet system (SCMS) is about 300 tons. The cooling requirements of the cold components are summarized in table I.

The first cool-down commissioning of KSTAR device was started in April 3, 2008. All of the SC magnets including other cold components were cooled down to their operating temperature within 23 days without serious trouble disturbing the cool-down process, even though the helium refrigeration system (HRS) temporarily stopped 3 times due to electrical and facility faults. The HRS quickly and smoothly could be restarted without disturbing the cool-down process. The cool-down was successfully controlled within the limitation that the temperature difference between all parts of the SCMS should be less than 50 K. At the end of cool-down process, the two SHe circulators and cold compressor were started to achieve the final part of the cool-down with high density helium. During the cool-down we measured the SC transitions of all SC coils, joint resistances, and stresses of the supporting structures to verify the performance of the KSTAR SCMS.

TABLE I: KSTAR COOLING REQUIREMENTS

Cold component	**Coolant**
TF / PF magnet	each 300 g/s of SHe at 4.5 K, 5.5 bar
SC Bus-line	40 g/s ~ 80 g/s SHe at 4.5 K, 3.5 bar
Thermal shield	140 g/s ~ 280 g/s GHe at 55 K, 18 bar
Current lead	17.5 g/s LHe at 4.5 K, 1.3 bar,

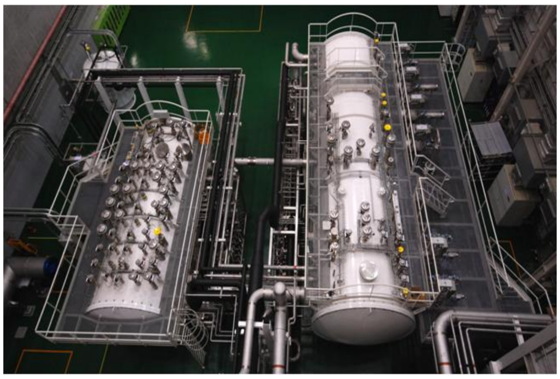

FIG. 1. KSTAR helium refrigeration system with 9kW @ 4.5 K

2. Cryogenic System

2.1. Helium Refrigeration System (HRS)

Figure 1 shows the KSTAR HRS, which was commissioned and tested at full capacity in all the operating modes with a dummy load in Mar. 2008. The HRS consists of a warm compressor station (WCS) with oil removal system (ORS), cold box (CB), primary helium distribution box (DB), and gas management system including helium storage, and a liquid nitrogen (LN2) storage and vaporizer unit. The main specifications of the HRS are summarized in table II. The total exergetic equivalent cooling power of the HRS at 4.5 K turned out to be 9.54 kW, roughly 6 % higher than the supplier guaranteed design value of 9 kW which is close to the 5 % design margin [2]. The CB is equipped with 6 ALDTA model TC4-500 and TC5-500 oil-free static gas bearing turbo expanders, 11 plate-fin type aluminum heat exchangers (HX's), double-bed 80 K adsorbers, and single-bed 20 K adsorbers.

The actual thermal loads on the KSTAR SCMS and current feeding system are strongly time dependent and exhibit large peak values. However, the operation scheme of the HRS is based on the daily average thermal load of the SCMS [3]. In the KSTAR baseline reference scenario, the plasma shot time is only 70 sec and pulse repetition time is 1200 sec. During a plasma shot, 14 PF coils are pulsed to their maximum current and the plasma current rises up to 2 MA. In order to absorb the peak value of thermal load during the shot we installed a thermal damper system inside the DB, which includes a 6 m^3 LHe bath, two 300 g/s SHe circulators, a cold compressor for decreasing the temperature of the LHe bath down to 4.3 K, and 6 heat exchangers. The high efficiency SHe circulator, which has IHI corporation foil type dynamic gas bearings, pressurizes the SHe to 6.5 bar and deposits the acquired heat from the SCMS via a heat exchanger into the LHe of the thermal damper. Fig. 2 shows the thermal damper configuration of the TF coil cooling loop.

TABLE II SPECIFICATION OF THE KSTAR HRS

System	Features
Cold Box	Design Capacity : 9 kW at 4.5 K Turbines : 6 oil-free static gas bearing Heat exchanger : 11 aluminum fin plate Adsorber : double bed at 80 K and single bed at 20 K
Distribution Box	Thermal damper : 6,000 liter with 7 heat exchanger SHe circulator : each 300 g/s for TF and PF magnet Cold compressor : max. 310 g/s, 4.3 K at 1.1 bar
Compressor	Type : two stage oil flood screw compressor Total flow rate : 1,040 g/s at 22 bar ORS : three stage, oil content < 10 ppbw Recovery compressor : 32 g/s at 25 bar
Purifier	Capacity : 32 g/s at 22 bar Purity : < 1 ppm

2.2. Helium Distribution System (HDS)

The main duties of the KSTAR HDS are the redistribution of the mass flow proper to operate the SCMS and the emergency release of over pressurized helium during abnormal events such as quenches of SC coils. For the redistribution of helium mass flow the HDS includes five separate cooling loops, which are respectively dedicated to the TF coils and structure, PF coils, SC bus-lines, current lead systems, and thermal shields. The HDS consist of 24 cryogenic control valves, 21 safety valves including 4 quench valves, and 5 cryogenic transfer lines (CTL) [4]. Each CTL consists of multi internal piping with a maximum of 25 lines and has been categorized in such a way as to optimize the helium line routing inside the cryostat.
The heat in-leak exergetic equivalent to 4.5 K of the HDS is designed to be less than 400 W. The cooling loop of the TF coils and structure is shown in figure 2. A pressurized 300 g/s of SHe from the cryogenic circulator is supplied to 16 TF coils. The 4 cryogenic valves redistribute the mass flow in each of the TF coils, which are grouped in quadrants. The return helium from the TF coils is supplied to the TF structures after being cooled down to 4.5 K by heat exchanger 2 (HX2) with 4.3 K LHe in the thermal damper.

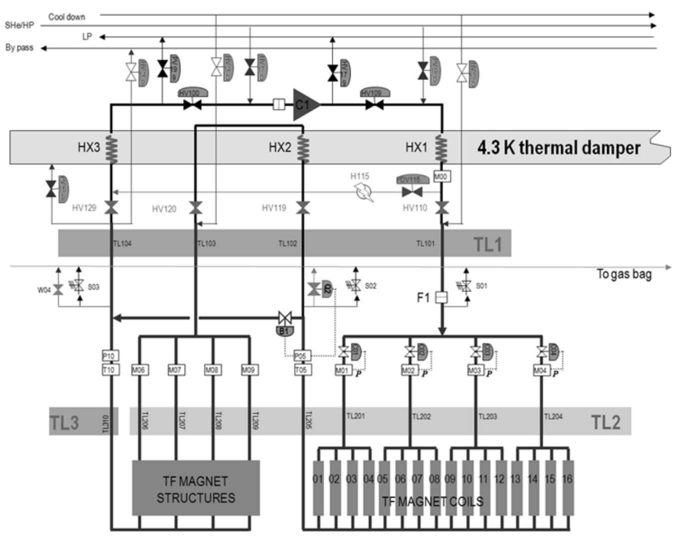

FIG. 2. Cooling loop of the TF magnet system

On each supply and return line of the HDS quench and manual safety valves were installed to release the overpressure helium gas (GHe) at 20 bar. The PF coil cooling scheme is similar to that of the TF coil scheme but the SHe for the SC bus-line was designed to be directly supplied from the cold box because the required mass flow for the SC bus-line is neither so high nor so variable

3. Results of the Cool-down

3.1. SC Coil Cleaning

After final connection between helium facility and SCMS, coil cleaning at room temperature was performed in two steps. The first step was a pumping & filling process, in which the insides of the CICC and helium tubes were pumped out to be below 0.3 mbar by roots pump and pure helium was filled up to 8 bar. Then the coil was flushed by process pure helium gas supplied from the WCS until the impurity level of the outlet gas was less than 10 ppm. During the coil flushing process, we could finally confirm the total helium leak from the all helium passages inside the cryostat and helium transfer lines by measuring the vacuum pressure and helium partial pressure, 2.7×10^{-6} mbar and 2.2×10^{-9} mbar, respectively

3.2. Cool-down

The cool-down was performed by manually controlling the inlet temperature from room temperature to around 5 K. As shown in figure 3, the gradual decreasing of inlet temperature is produced by mixing warm and cold GHe by using cool-down valves inside the CB. At the initial stage of cool-down, turbine #1, #2 and turbine #3 were turned on to lower the supply temperature to 260 K. Then the other turbines (#4 ~ #6) were started in sequence after arriving at the proper temperature to operate them. Figure 4 shows the main temperatures recorded for the KSTAR first cool-down, which are in good agreement with the initial plan based on preliminary calculations. The temperature difference across the coils and structures was well within the allowable limit of 50 K. The highest temperature difference was observed at the outermost coil (PF6 and PF7) structure because of the local low thermal conduction. After the SCMS arrived at around 5 K, the two SHe circulators were turned on and the TF and PF coils were filled to their normal operating condition with 4.5 K SHe. As shown in figure 5, the flow rate of the coil was kept almost constant during cool-down, and then increased up to 300 g/s by the SHe circulator to achieve the normal operation condition below 5 K

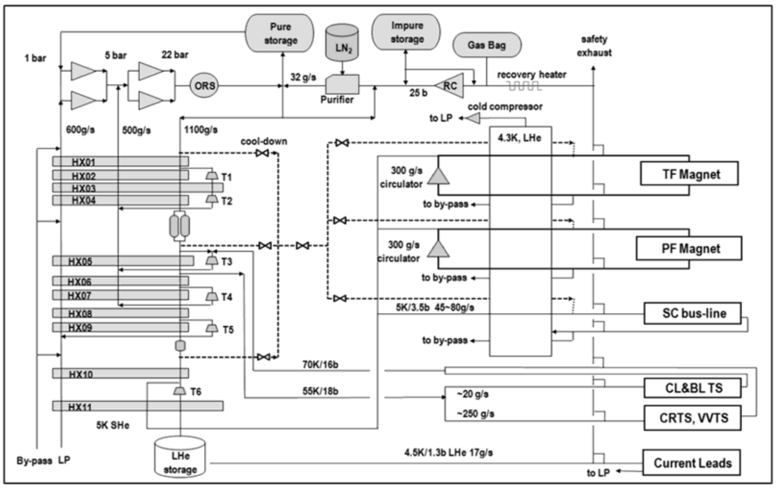

FIG. 3. Process flow diagram of the KSTAR cryogenic system

The KSTAR thermal shields were designed to be cooled by 140 g/s ~ 280 g/s GHe at 55 K and 18 bar via turbine #3 of CB without the LN2 pre-cooler. The temperature distribution of the shields is shown in figure 6. The CRTS temperature with multi-layer insulation (MLI) shield panels was in good agreement with the design value. However, the temperature distribution on the VVTS was higher than expected although the lowest GHe at 42 K was supplied to achieve as low as possible temperature of the VVTS. As a result, we think that the results were caused by the degradation of the emissivity of the VVTS, which has silver coated shield panels. In ITER, it is thought to be reasonable to have the magnet temperature during cool-down be less than that of the shield to avoid degradation of the emissivity of the thermal shields by possible water ice formation on their surfaces [5].

During cooling down the trends of the cryostat vacuum and partial pressure of residual gas are shown in figure 7. The cryostat pressure falls smoothly from 2.7×10^{-6} mbar to 2.6×10^{-8} mbar. Although the helium signal in the 230 K region abruptly increased an order of magnitude from 10^{-10} mbar to 10^{-9} mbar, it kept almost the same pressure level until cooled to the base temperature. This proves that the cryostat has no cold helium leak, at least at the level of the detector sensitivity. This result also indicates the high quality welding of the CICC and their joints, cooling tubes, electrical breakers, feed troughs, as well as good device assembling quality.

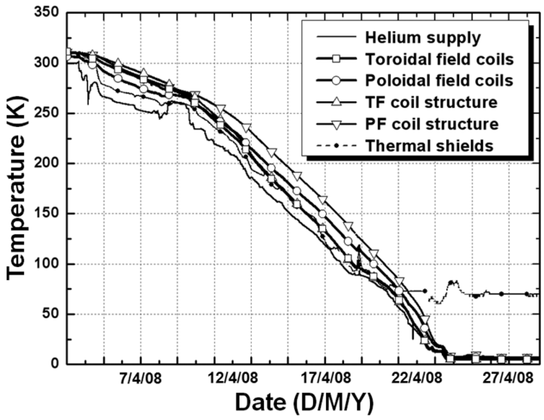

FIG. 4. KSTAR cool-down curves

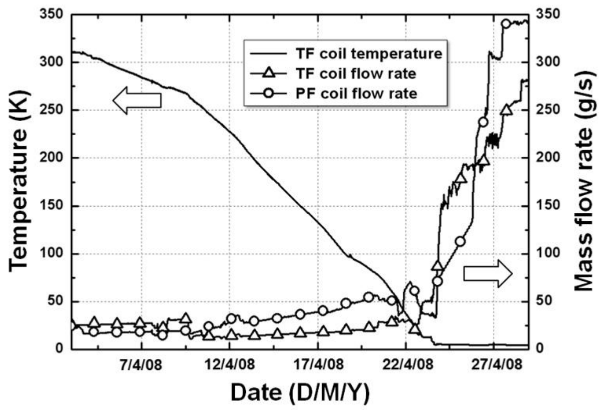

FIG. 5 Mass flow rate of TF and PF coils

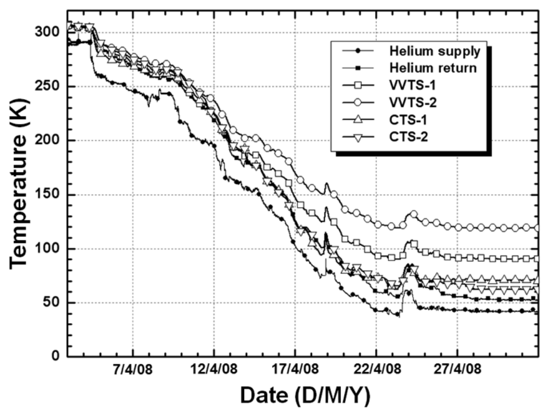

Fig. 6. Temperature of the Thermal Shield

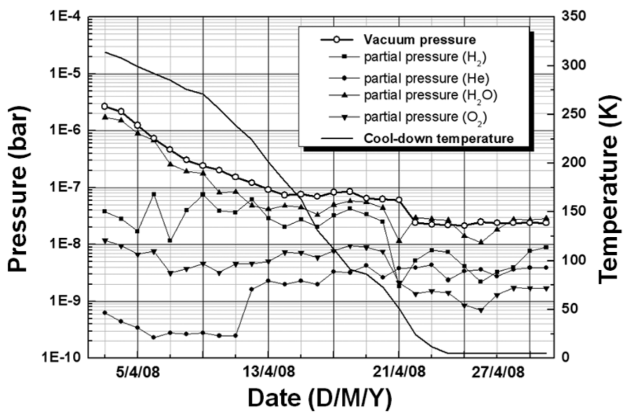

FIG. 7 Cryostat vacuum during cool-down

3.3. Mechanical Stress

The support structures of the SC coils were instrumented with 239 strain gauges to monitor the structural stress behavior during cool-down. To eliminate the non-informative signals due to temperature and magnetic fields, the active and compensating gauges were connected in a half-bridge configuration, in which the non-informative signals were subtracted with a compensation gauge [6].

The stresses in the TF structures from the cool down itself are shown in figure 8. They were measured in the range of 60 MPa ~ 82 MPa, which is just within 12.6 % of the maximum allowable stress. A maximum hoop stress of 93 MPa was observed at the lower outboard leg due to a relatively larger hoop stress because there are more constraint structures on the lower part, i.e. the gravity supports. On the other hand, tensile and compressive stresses were observed in the PF7 and PF6 structures, which were thought to have resulted from the relative difference of the thermal contraction between the TF structure and PF coils. Radial displacements of the toroidal ring from 293 K to 11 K were measured in the range of 7.66 mm ~ 7.93 mm, which is comparable to the FEM analysis result as shown in figure 9. The maximum deviation of the segments is just 0.006 % as compared with the diameter of the ring, 5780 mm.

The KSTAR central solenoid (CS) was mechanically preloaded at room temperature. The achieved preload at room temperature was about 747 tons, which is 58 % of the required preload of 1300 tons estimated by numerical analysis. However, the reduced preload by cool down itself was about 146 tons. As a result the remaining preload of the CS structure after cool-down is about 600 tons. A similar result was also reported in a test of the ITER CSMC [7]. From the analysis, it can be concluded that compression at coil interfaces can locally disappear due to cool-down. However, this won't give severe structural impact to the CS coil system.

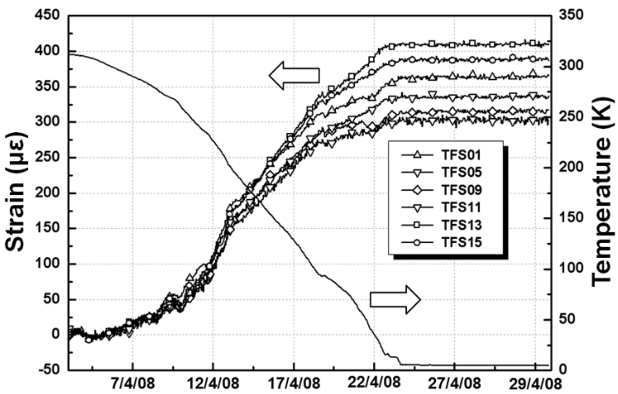

Fig. 8. Stresses of TF structures

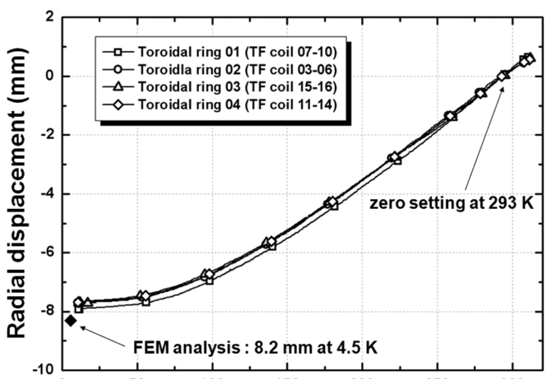

Fig. 9. Radial displacement of toroidal ring

3.4. SC Transition and Joint Resistance

When the coil temperature reached 20 K, the transition into superconducting state of the Nb3Sn coils; 16 TF, and PF1-PF5 coils, was observed by directly measuring the coil voltage drop at a current of 100 A in the coils. The measured transition temperature of the 16 TF coils is shown in figure 10. After the temperature was reduced further below 10 K, the superconducting state was registered by a direct resistance measurement in all coils, including NbTi PF6 and PF7, as well as in the TF coil links and all SC bus-lines.

Two types of joints were developed for the KSTAR SCMS and tested during an extensive R&D program; a lap joint for the coil termination and a SC bus-line and strand to strand (STS) joint for series connection between TF coils [8]. Results of joint resistance measurements are shown in table III. Most of the joints showed resistances less than 2 nΩ, comfortably below the design allowance of 5 nΩ.

TABLE III LAP JOINT RESISTANCE

Coil	**No. of Lap joints** [EA]	**Total Resistance [nΩ]**	**Average resistance [nΩ]**
TF	6	11.1	1.85
PF1	7	15.6	2.23
PF2	7	11.1	1.59
PF3	12	20.3	1.69
PF4	12	17.4	1.45
PF5	12	25.2	2.1
PF6	14	11.2	0.80
PF7	8	4.11	0.51

3.5. Static Heat Loads

The static heat loads of each cold component were analyzed during steady state operation without current charging on the SC coils. The heat load on the 4.5 K level was determined by measuring the mass flow rate in each SC coil and SC bus-line. The mass flow rate of the 50 K helium used to cool the thermal shield was also measured. Temperature sensors as well as pressure transducers were positioned along the coil part to measure the temperature profile and pressure across the coil to determine the pressure drop. The static heat loads at 4.5 K equivalent are listed in table IV. The measured heat load was almost the same as the design value, although heat load on the shield was higher than that of the design.

TABLE IV STATIC HEAT LOADS

System	**Design Power (kW@4.5K)**	**Measured Power (kW@4.5K)**
Coil & SC Bus	1.37	1.4
Thermal Shield	0.8	1.2
Current Leads	1.0	0.5
SHe Circulator	1.8	1.8
Heat leaks in HDS	0.4	0.3
Total	5.37	5.2

4. Conclusion

The KSTAR cryogenic system has been constructed and commissioned during the first cool down period. The system was then running smoothly with no problems and ready for electrical testing prior to powering and for future powering for first plasma. This results confirmed proper KSTAR construction procedures and performance validation.

Long-term steady state operation of the KSTAR cryogenic system was carried out from April 3 to August 2 without any critical troubles. Even though the HRS had been temporarily stopped by an electrical fault (April 20 and April 21) during cool-down, the HRS quickly and smoothly could be restarted without disturbing the cool-down process. In steady state operation, there was no trouble due to impurities, such as blocking of turbines or the coil inlet filters, chocking of control valves, decrease of heat exchanger efficiency, etc. One interruption of steady state operation happened due to a fault of a compressor oil pump. The total time to recover the HRS was 1 day.

The 825 sensors in the cryostat itself were installed for monitoring the cryogenic and structural behavior of the KSTAR SCMS. During the 1st cool-down, about 13 sensors (1.5%) were either broken or thought to give wrong information.

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